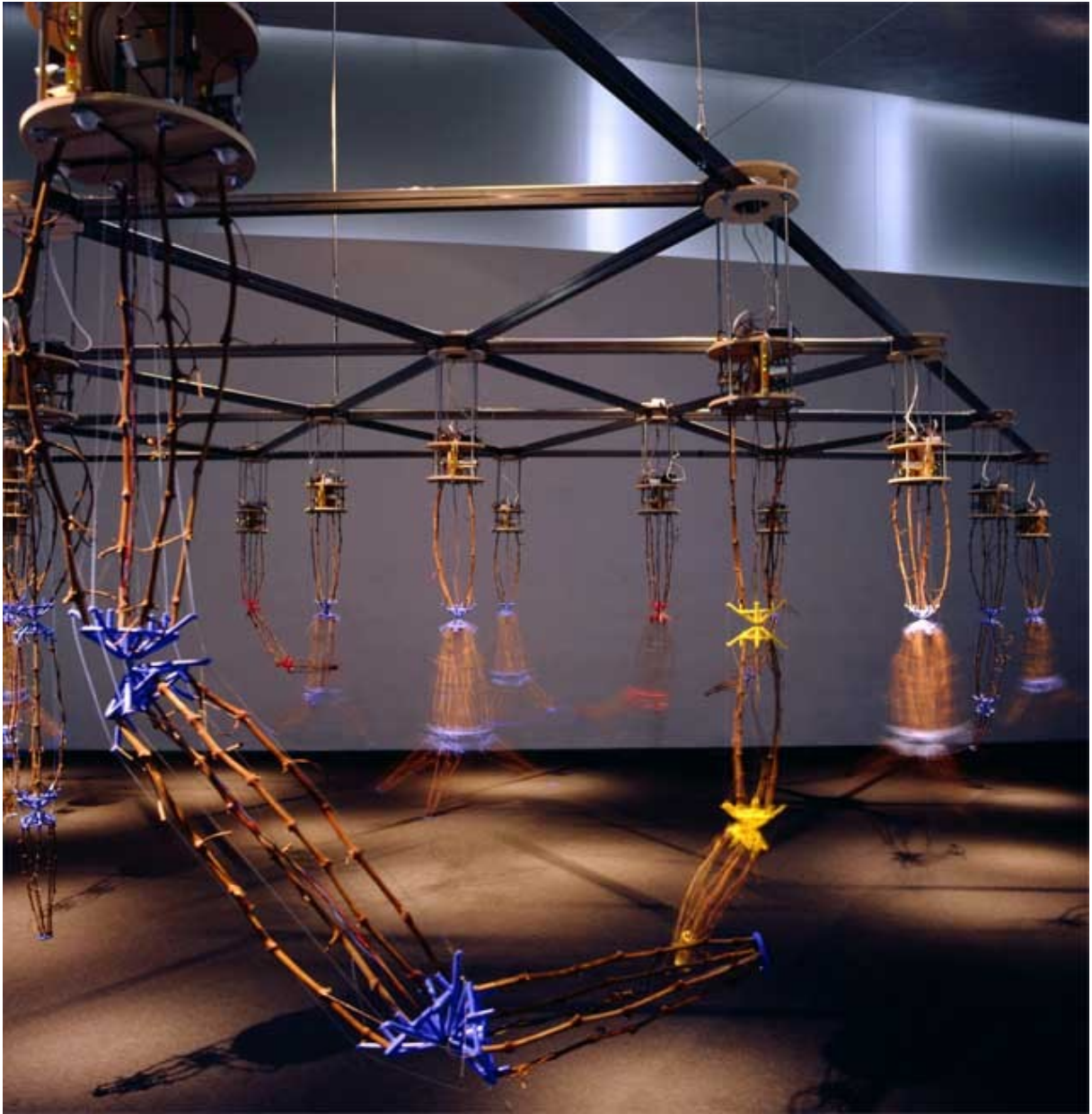


Interactive Electronics for Artists and Inventors

by Ken Rinaldo

newmediaartist.org

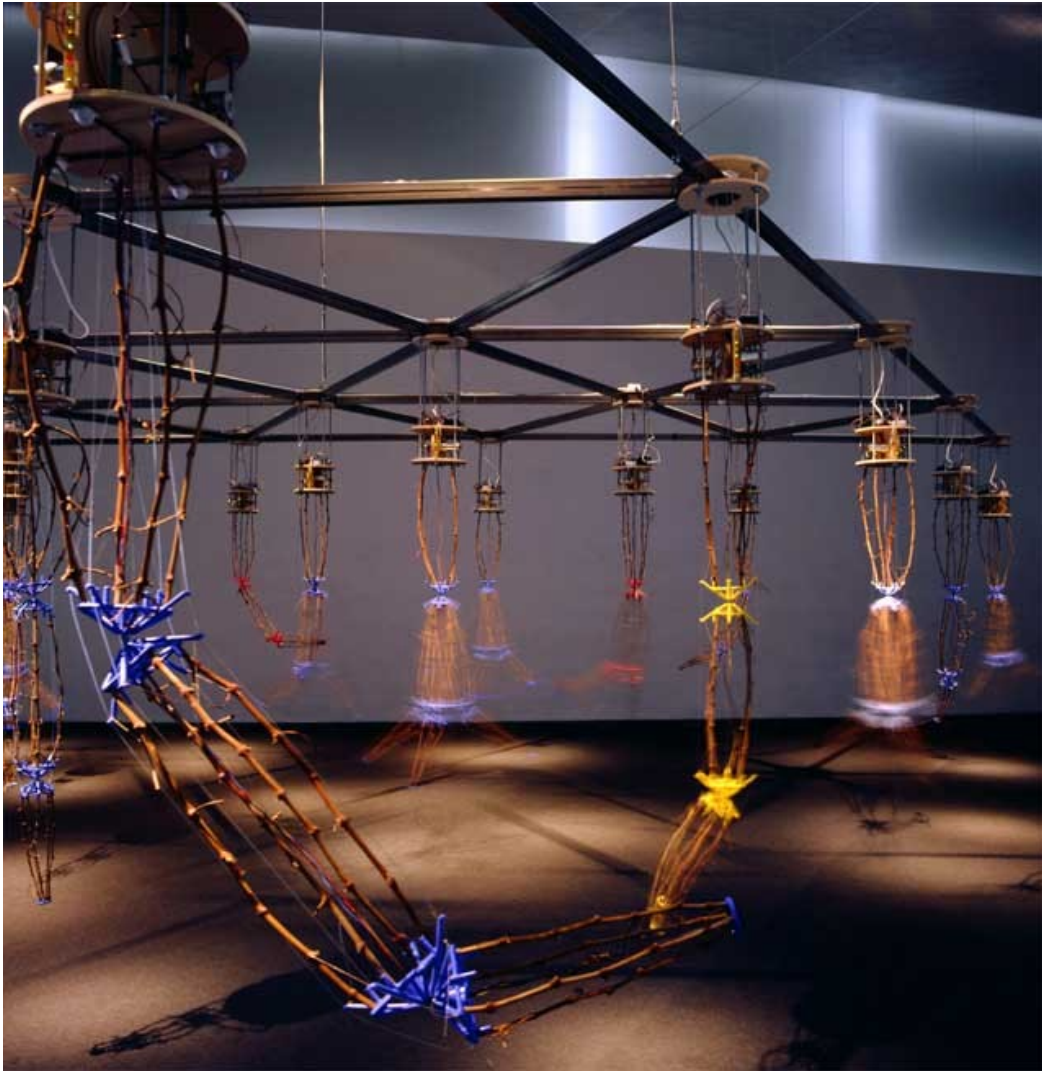


Autopoiesis 2000 by Ken Rinaldo, at the Kiasma Museum, Helsinki, Finland

Ken Rinaldo has provided this text as a gift to artists, inventors, and experimenters.

SECTION: INTRODUCTION

Interactive Electronics for Artists and Inventors by Ken Rinaldo



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By using this text as a learning and experimentation tool, you take full responsibility for your electronics experimentation.

Author Welcome

Ken Rinaldo is an Academy Emeritus Professor of Art in the [Art & Technology Program](#) at The Ohio State University. He has been teaching a course called *New Media Robotics* for 22 years, and many of the lessons in the book have been tested in his classes. Most of the artwork/inventions within are from professional artist/inventors from around the globe and some are from graduates of the Art & Technology Program at the Ohio State University and our undergraduate inventors.

[Ken Rinaldo](#) has been exhibiting his robotic, 3D modeling rapid prototyping and biological artworks and lecturing about his invention and ideas nationally and internationally for over 38 years. Rinaldo has an Associates degree in Computer Science from Canada College California, a BA in Communications from the University of California, Santa Barbara, and a Masters of Fine Art from San Francisco State's Conceptual Information Arts Program.



Emeritus Professor Rinaldo still offers guest classes teaching robotics, graduate critiques and lectures about AI, around the world.

This book is dedicated to the love of my life Amy Youngs for her ongoing inspirational conversations surrounding the intersection of the arts, electronics, and biology and for all the wonderful collaboration throughout the years.

Special Contributors

Ken Rinaldo and the community of makers and thinkers would like to thank the many who have directly and indirectly supported the writing and production of this book. Like any endeavor in Art and Science this is work of collaboration and a labor of love.

Thanks to TradeMark G. (aka Mark Gunderson), a musician and artist and friend, perhaps best known as founder of

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Thanks to Chris Coleman, who creates sculpture, performances and videos as well as interactive installations, and Ali Momeni, who works with kinetics, electronics, software, sound, light, people, plants and animals, for their original MAXUINO code and for their ongoing work in supporting the use of Arduino with MAX MSP and Jitter through their MAXUINO website.

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Thanks to Billy Kluver and Robert Rauschenberg for creating E.A.T., Experiments in Art and Technology, which fostered the intersection of the artist and engineering communities. As a ten-year-old, I will never forget seeing *Heart Beats Dust* (1968) by Jean Dupuy at the Brooklyn Museum, New York. By putting a stethoscope on your heart you were able to see a diaphragm send dust into the air to the beat of your own heart.

Thanks to Steve Wilson, Brian Rogers, and George LeGrady, who created the Information Arts program at San Francisco State University. This art program framed the importance of conceptual thinking as the driving force in using and challenging technology in the creation of art works. Steve Wilson's website, as well as his book *Information Arts*, has been an ongoing inspiration and point of research for this community.

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writings and artworks, and for the Machine Culture Show at SIGGRAPH in 1993. This one show was the trunk of a tree that led to so many other international exhibits, and I am grateful for Simon's early vision and curatorial efforts.

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Thanks to AI and Claude from Antropic for invaluable help in updating this book. Thanks to Open AI for working with me in re-imaging many of the 3D models of this book.

Thanks to all the artists and inventors who have contributed work to this book, and to those who are documented within. Without these artists and inventors, the field of interactive art, installation, kinetics, industrial design, robotic sculpture, dance and technology, art and biology, and neon art would not exist as we know it:

Stelarc, Michael Rodemer, Jennifer Hall, Nick Baginsky, Ulrike Gabriel, Eduardo Kac, Perry Hoberman, Tiffany Holmes, Myron Krueger, Joel Slayton, Lynn Hershman Leeson, Sheldon Brown, Simon Penny, Victoria Vesna, Jason Ditmars, Shawn Decker, Steve Waldeck, Christian Schiess, Michael Hayden, Ned Kahn, Michael Sturtz, Yianni Yessios, Sabrina Raaf, Dan Miller, Bill Vorn, Todd Slaughter, Philippe Demers, Nancy Patterson, Rafael Lozano-Hemmer, Ken Feingold, Norman White, Mark Pauline, Nam June Paik, James Seawright, Joe Davis, Ted Krueger, Ken Kaplan, Jim Pallas, Jim Zalewski, Chico MacMurtrie, Rick Sayre, Marcellí Antúnez Roca, Chris Csikszentmihalyi, Susan Collins, Martin Spanjaard, Nina Sobell, Emily Hartzell, Garnet Hertz, Max Dean, Christian Ristow, Heidi Kumao, Daniel Rozin, Edwin van der Heide, Marnix de Nijs, Matt Heckert, Victoria Scott, Theo Jansen, Barney Haynes, Cynthia Lawson, Eric Forman, Maywa Denki, Keith Piper, Marie Sester, Magali Desbazeille, Siegfried Canto, Ali Momeni, and Chris Coleman.

Preface

“Reality is merely an illusion, albeit a very persistent one.”

— Albert Einstein

Introduction

This book is designed for creators who wish to demystify electronics, physical computing, robotics, and intelligent systems. Through the lessons presented here, artists, inventors, engineers, industrial designers, architects, scientists, educators, and hobbyists will gain hands-on experience with electronic components, sensors, actuators, microcontrollers, robotics, embedded systems, computer vision, artificial intelligence, and practical fabrication techniques.

By studying the artworks, inventions, and experimental systems documented throughout this book, readers will discover creative design strategies and innovative engineering solutions developed by artists and inventors working at the intersection of art, science, and technology. The photographs, diagrams, and discussions accompanying each project provide insight into both the conceptual and technical aspects of the creative process. Collectively, these examples explore contemporary questions surrounding interactivity, embodiment, biological systems, autonomous behavior, user interfaces, artificial intelligence, and the evolving relationships among humans, machines, and living systems.

Guide

This book is intended as a primary text for courses in interactive electronics, physical computing, robotic art, kinetic sculpture, interactive installation, industrial design, beginning engineering, embedded systems, wearable computing, sound sculpture, dance and technology, cybernetic fashion, entertainment engineering, puppetry, new media art, and interdisciplinary design. It is equally valuable for independent makers who wish to develop projects from concept through fabrication.

The field has evolved dramatically in recent years. Robotics now extends well beyond industrial automation into collaborative robots, soft robotics, swarm robotics, autonomous mobile robots, bio-inspired systems, social robots, and intelligent environments. Computer vision allows machines to recognize people, gestures, objects, plants, insects, and environments in real time. Affordable LiDAR sensors, depth cameras, inertial measurement units, machine learning accelerators, and wireless microcontrollers have made sophisticated interactive systems accessible to individual artists and inventors. Today's projects increasingly combine electronics, mechanics, software, artificial intelligence, computer vision, networking, and cloud services into unified creative systems.

Perhaps the most significant development since the first editions of this book is the emergence of powerful AI assistants such as ChatGPT, Claude, and similar large language models. These systems have fundamentally changed how creators learn electronics and programming. They can explain unfamiliar concepts, generate code, identify bugs, suggest alternative circuit designs, optimize algorithms, and translate ideas into working prototypes in minutes rather than days. AI assistants function much like an experienced collaborator who is available at any hour to answer questions, review code, and propose solutions.

At the same time, these tools should be viewed as collaborators rather than authorities. Electronic circuits obey the laws of physics, not the confidence of an AI-generated response. Code generated by an

AI assistant should always be understood, tested, measured, and verified through experimentation. Learning electronics remains a hands-on discipline in which careful observation, debugging, and iterative refinement develop genuine understanding. AI can dramatically accelerate the creative process, but it cannot replace curiosity, critical thinking, or the satisfaction that comes from building and discovering.

Because art and invention are tangible processes involving both conceptualization and physical realization, they provide unique opportunities for understanding scientific, mathematical, and engineering principles through making. Building projects transforms abstract ideas into concrete experiences and develops intuition that cannot be acquired solely through reading or simulation.

The text offers step-by-step instruction in prototyping circuits on breadboards, interfacing sensors and actuators with microcontrollers, programming embedded systems, integrating computer vision, testing, debugging, fabrication, and conceptual development. Readers will learn practical methods for designing reliable interactive systems while developing confidence in experimentation and iterative design.

Concise lessons and detailed parts specifications are provided for the Arduino family of microcontrollers, ESP32 platforms, and MAX/MSP/Jitter. Readers will learn to control LEDs, servo motors, precision gear motors, solid-state relays, infrared sensors, magnetic sensors, ultrasonic ranging devices, inertial measurement units, audio systems, cameras, wireless communication modules, and numerous environmental sensors. Increasingly, these microcontrollers are capable of supporting edge AI, allowing machine learning and computer vision to operate directly on inexpensive embedded devices. Although hardware platforms continue to evolve, the underlying principles of electronics—including voltage, current, resistance, timing, signal conditioning, and Ohm's Law—remain constant across generations of technology.

Design considerations and aesthetic questions remain central throughout the book. Material selection, fabrication methods, mechanical construction, and the cultural meanings embedded within technological objects are examined alongside technical instruction. Throughout the projects, attention is given not only to functionality, but also to audience experience, interaction design, embodiment, and expressive potential. Practical discussions of mechanical construction, adhesives, fabrication methods, parts suppliers, exhibition strategies, and presentation venues complement the technical lessons.

No single volume can encompass the rapidly expanding fields of electronics, robotics, and artificial intelligence. Fortunately, today's learners have unprecedented access to knowledge. Online documentation, open-source communities, technical forums, research publications, and AI-assisted development environments provide immediate access to expertise from around the world. Modern AI assistants can help explain concepts, generate prototype code, compare alternative approaches, and troubleshoot difficult problems. Nevertheless, the most reliable solutions emerge from combining these resources with careful experimentation, measurement, and a willingness to test ideas directly in the physical world.

This book is suitable for one or two semesters of study, depending upon the balance between conceptual readings and hands-on projects. Instructors may choose to emphasize fabrication, programming, robotics, artificial intelligence, conceptual design, or interdisciplinary practice according to the goals of the course. Extended project work naturally shifts the emphasis toward experimentation and making, while additional readings provide historical, theoretical, and cultural context for the technologies explored here.

The references and suggested readings included throughout the text are intended not simply as technical resources but as invitations to broader inquiry. They connect electronics and robotics to developments in contemporary art, cybernetics, biology, design, artificial intelligence, philosophy, and emerging technologies, encouraging readers to understand invention as both a technical practice and a cultural endeavor.

Throughout the book, hundreds of original technical illustrations, exploded diagrams, photographs, and three-dimensional visualizations clarify concepts that are often difficult to explain through words alone. The structure of the book emphasizes creative thinking alongside technical competence, guiding readers from initial curiosity through design, prototyping, fabrication, debugging, and ultimately the realization of original interactive works.

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You take full responsibility for your electronics experimentation no matter how life threatening they may be.

Chapter 1

Connections: Art, Science, and Technology

Connections

“Humanity has just entered what is probably the greatest transformation it has ever known . . . something is happening in the structure of the human consciousness. It is another species of life that is just beginning.”

— Pierre Teilhard de Chardin

Question: What can artists and scientists learn from each other? We are living through one of the most remarkable periods in the history of invention. Human creativity, amplified by global communication networks, open-source communities, artificial intelligence, and increasingly accessible fabrication technologies, is dissolving traditional boundaries between disciplines. Artists, scientists, engineers, biologists, architects, computer scientists, designers, musicians, and inventors now collaborate across continents in real time, sharing ideas, software, hardware designs, datasets, and discoveries at an unprecedented pace. The convergence of these once largely separate communities has accelerated innovation, giving rise to entirely new forms of creative practice at the intersection of art, science,



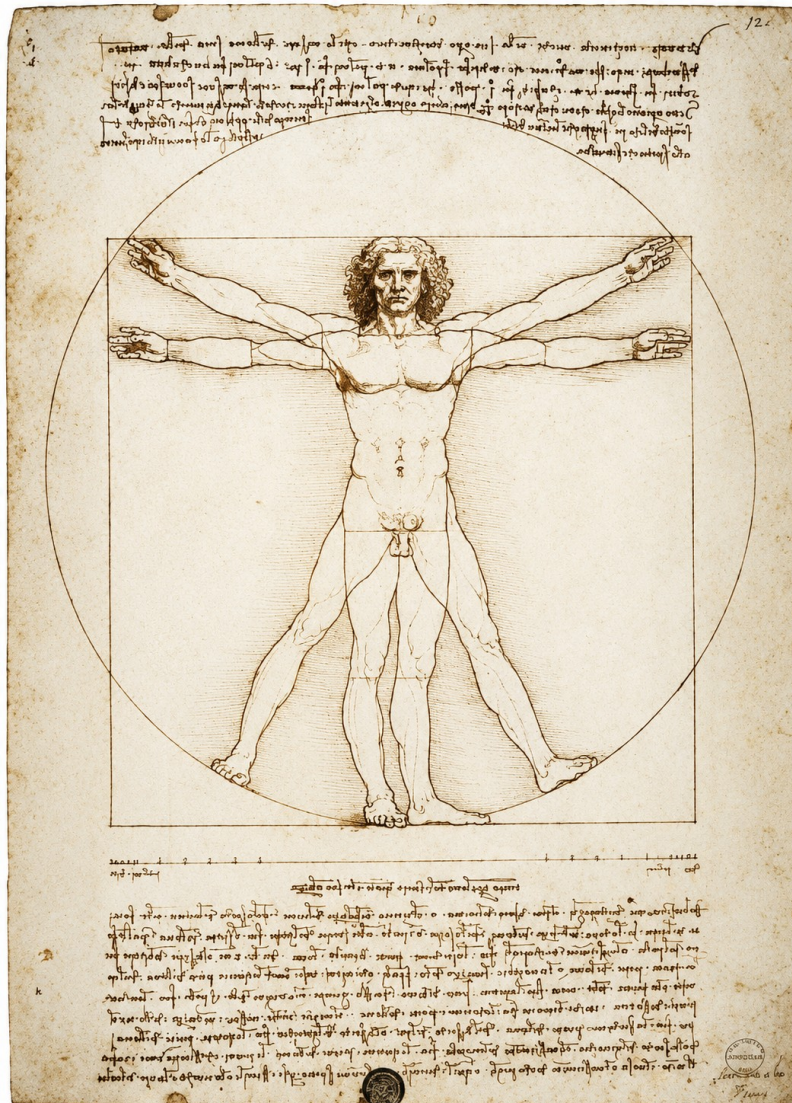
Anicca Antenna: Soil as Brain by Ken Rinaldo 2020. Robots that are controlled by soil and isopods. Photo Fatemeh Baigordi

engineering, biology, robotics, and artificial intelligence.

Both art and science are fundamentally research practices. Both begin by asking questions, proposing hypotheses, conducting investigations, building models, testing assumptions, and communicating discoveries. Artists and scientists have always been explorers, using observation and experimentation to reveal new ways of understanding the world. Whether through painting, robotics, biology, mathematics, or engineering, both disciplines investigate the physical universe, material behavior, perception, consciousness, and the complex relationships that connect living and technological systems. Creativity is therefore not exclusive to either discipline; it is the common language that enables progress in both.

Perhaps no historical figure better represents this union than the Italian artist, engineer, anatomist, and inventor Leonardo da Vinci (1452–1519). Leonardo's investigations moved effortlessly between art and science. His anatomical studies informed his paintings and sculptures while simultaneously advancing scientific understanding of the human body. His notebooks reveal investigations into optics, mechanics, hydraulics, flight, and automation. Among these designs is what many historians consider the first humanoid robot—a mechanical knight capable of moving its head, arms, and torso.

Developed from his anatomical studies and investigations surrounding the Vitruvian Man, Leonardo's work illustrates how artistic observation and scientific inquiry can reinforce one another to generate entirely new forms of invention.



Vitruvian Man by [Leonardo Da Vinci](#). 1487. 34.4cm x 25.5cm.

The Dutch painter Johannes Vermeer (1632–1675) similarly embraced the technologies of his era. His remarkable understanding of light and perspective is widely believed to have been informed by the camera obscura, an optical device that projected an inverted image onto a surface for careful study. Vermeer's friendship with Antonie van Leeuwenhoek (1632–1723), the pioneering microscopist whose observations revealed previously invisible worlds of microorganisms, exemplifies the intellectual exchanges that often occur between artists and scientists. Leeuwenhoek famously wrote, "No more pleasant sight has met my eye than this of so many thousands of living creatures in one small drop of water," reminding us that scientific instruments frequently transform not only scientific understanding but artistic imagination as well. More recently, the documentary *Tim's Vermeer* explored the hypothesis that Vermeer employed sophisticated optical techniques to achieve the extraordinary realism of his paintings.

In observations that allowed him to see life in a drop of water, Leeuwenhoek wrote: "No more pleasant sight has met my eye than this of so many thousands of living creatures in one small drop of water..."

Throughout history, advances in science have repeatedly transformed artistic practice. Pablo Picasso's Cubist explorations have often been associated with the changing conceptions of space, time, and observation emerging from Albert Einstein's theories of relativity. Whether or not this influence was direct, both men challenged inherited assumptions about how reality could be represented and understood, demonstrating how scientific and artistic revolutions often unfold in parallel.

During the twentieth century these interdisciplinary relationships became increasingly intentional. Engineer Billy Klüver (1927–2004) and artist Robert Rauschenberg (1925–2008) founded Experiments in Art and Technology (E.A.T.), creating an organization dedicated to collaborations between artists and engineers. Their landmark 1966 event, *9 Evenings: Theatre and Engineering*, demonstrated that artists and technologists could become equal creative partners.

These collaborations helped shape the practices of artists including John Cage, Merce Cunningham, Robert Whitman, and many others while establishing a foundation for the field now known as art and technology.

The significance of these systems extends well beyond software development. Modern robotics increasingly combines artificial intelligence with computer vision, depth sensing, LiDAR, tactile sensing, machine learning, and autonomous planning. Robots are becoming embodied intelligent systems capable of perceiving and responding to complex environments rather than simply executing predetermined sequences of motion.

Collaborative robots work safely alongside humans in factories and laboratories. Swarm robots cooperate through distributed intelligence inspired by insect colonies. Soft robots borrow strategies from plants and animals to achieve compliant movement impossible with traditional rigid mechanisms.

Artists are employing these technologies to create works that learn, adapt, evolve, and respond to living

systems in real time.

Working across installation, sculpture, painting, and immersive environments, Anicka Yi explores the shifting boundaries between biology and technology, humans and non-human intelligence, and natural and artificial systems. Her studio functions as an interdisciplinary laboratory where she collaborates with scientists, engineers, chemists, and perfumers to develop works using unconventional materials including bacteria, fungi, yeast, soap, fragrance, and living organisms.

Rather than treating these materials as passive media, Yi embraces their agency and continual transformation, allowing biological and environmental processes to shape the work. Her recent installations increasingly incorporate robotics, artificial intelligence, and synthetic biology, creating speculative ecosystems that imagine new relationships between living and technological worlds.



Installation image of Anicka Yi's *In Love With The World*, Hyundai Commission 2021, Turbine Hall, Tate Modern; October 2021 – January 2022; Anicka Yi born 1971; Will Burrard-Lucas; I03277

Despite these extraordinary advances, the role of the human creator has become even more important. Artificial intelligence can propose possibilities, but it cannot determine which questions are worth asking, what experiences should be created, or why a work matters culturally or aesthetically. Those decisions remain uniquely human.

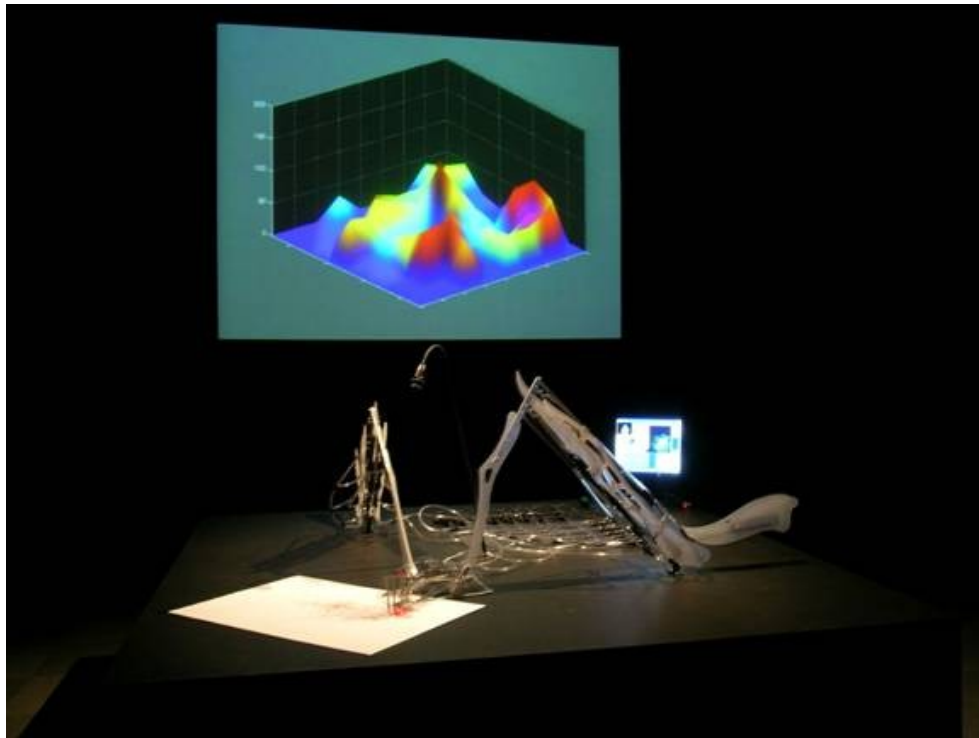
Artists continue to define the conceptual framework, ethical questions, material choices, and emotional resonance of their work, while AI functions as another creative instrument—no different in principle than the camera obscura, the microscope, the microcontroller, or the robot itself.

The author Ken Rinald exemplifies this continuing dialogue between living bodies and technological systems. His work investigates the nature of intelligence in natural and technological systems and they can be better coupled.

Projects such as Anicca Antenna: Soil as Brain define contemporary robotics today: Where does intelligence reside—in the body, in the machine, in the environment, or in the relationship among them? As artificial intelligence becomes increasingly integrated into robotic systems, these questions become even more compelling. The future of invention will not be determined solely by advances in technology, but by the ways artists, scientists, engineers, and inventors imagine new forms of collaboration among humans, machines, and the living world.

Art and Science Collaborations

Another example of sustained collaboration between artists and scientists is the project, [*MEART that*](#) used embryonic cortical mice neurons to drive an aluminum and acrylic rubber-muscle robot.



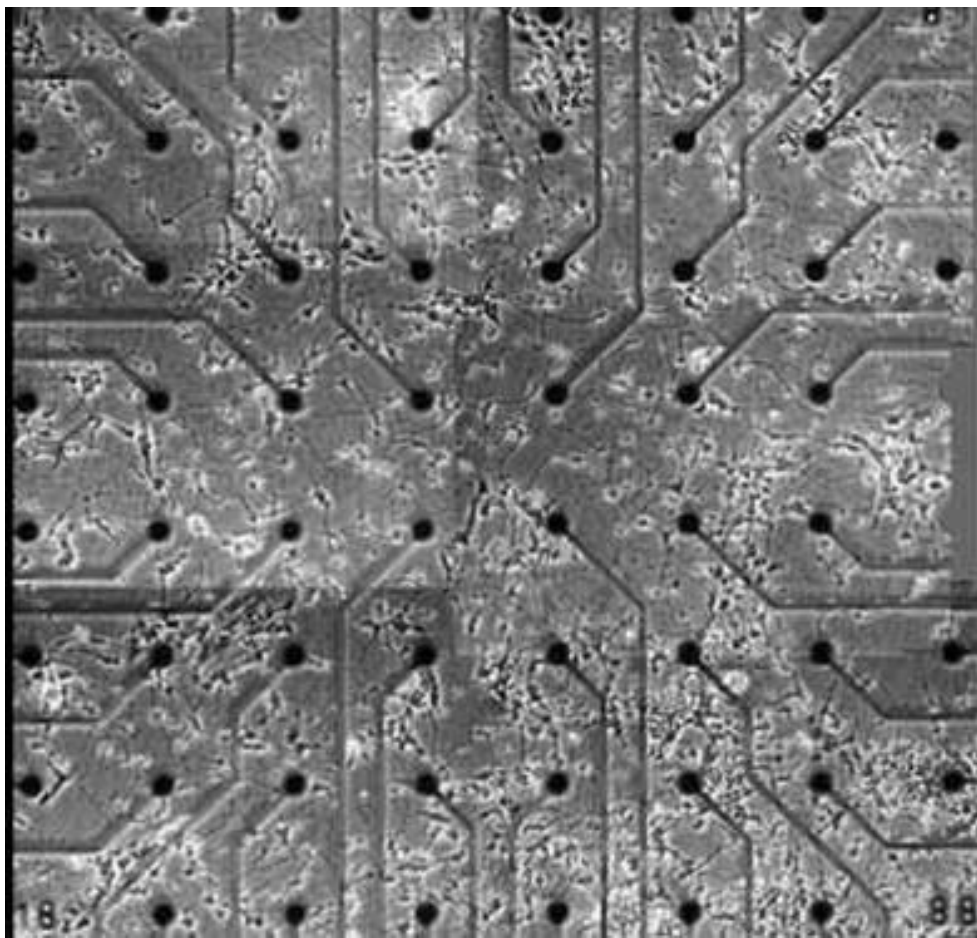
MEART by the [SymbioticA](#) research group. 2004. New York. MEART is a combination “brain” and “body” that work together to create a “Semi Living Artist.”

The Semi-Living Artist, an evolving artwork that combines living neuronal tissue, robotics, computer networks, and machine drawing. Developed by Guy Ben-Ary, Oron Catts, Ionat Zurr, and the Tissue Culture & Art Project in collaboration with neuroscientists and engineers, MEART employed dissociated neurons cultured from embryonic rat cortex grown on a Multi-Electrode Array (MEA).

The neuronal network served as a living computational system that both received electrical stimulation and generated electrical activity, allowing it to influence the movement of a custom-built robotic drawing arm.

MEART – The Semi-Living Artist. SymbioticA Research Group. The project integrates a living neuronal culture with a robotic drawing system, creating a hybrid "body" and "brain" whose drawings emerge through interactions among biological tissue, electronics, computation, and human participants.

During public exhibitions, a camera captures the image of a visitor and converts it into digital information. This information is transmitted to the neuronal culture, where patterns of electrical stimulation evoke changing neural activity. The electrical responses are recorded through the Multi-Electrode Array, amplified, interpreted by custom software, and translated into motor commands that actuate a robotic arm. Pneumatic artificial muscles and precision mechanics guide the pen across paper, producing abstract drawings that reflect the continuously evolving behavior of the living neural network. The resulting images are neither entirely human nor entirely machine-generated; rather, they emerge from the dynamic interaction between living neurons, computational systems, robotic mechanisms, and audience participation.



The mice neurons from the cortex associate and connect with tiny electrodes. Image by Professor [Steve M. Potter](#).

Neurons cultured on a Multi-Electrode Array. Dissociated cortical neurons form synaptic connections with microscopic electrodes, allowing neural activity to be both recorded and electrically stimulated. Image courtesy of Professor Steve M. Potter.

MEART exemplifies a broader transformation in contemporary art, in which artists increasingly participate in scientific research rather than simply borrowing its imagery or technologies. As artist and

author Stephen Wilson argues in *Information Arts*, artists frequently generate original questions, develop novel research methods, and contribute meaningfully to scientific and technological discourse. Their investigations often illuminate ethical, cultural, ecological, and philosophical dimensions of emerging technologies that may otherwise receive little attention.

Today this dialogue has expanded even further through artificial intelligence, computational biology, and robotics. Artists now work alongside scientists while also collaborating with AI systems capable of assisting in programming, data analysis, simulation, image generation, and experimental design.

Yet the most important contribution of artists remains unchanged: they ask different kinds of questions. They explore uncertainty, ambiguity, empathy, aesthetics, and ethics—areas that often lie beyond the objectives of conventional scientific research. As AI increasingly becomes part of both scientific and artistic practice, these complementary modes of inquiry become even more valuable.

The distinction between "artist" and "scientist" is therefore less a boundary than a cultural convention. Both rely upon observation, experimentation, imagination, analysis, and the communication of ideas. Whether working with paint, neurons, robots, algorithms, or artificial intelligence, the most significant advances often emerge when disciplinary boundaries dissolve and curiosity becomes the common language.

The artist Amy Youngs' robotic sculpture, *Rearming the Spineless Opuntia*, was designed to protect a genetically engineered spineless *Opuntia* cactus. Amy Youngs employed electronic ultrasonic sensors, a microcontroller, a motor, copper, steel, aluminum, and rubber to complete this work.

The cactus inside is both interactive with people and protected from them. When this work is approached, the sensors trigger motors to control and close metal armor with sharp spikes, which serves to rearm a cactus that has been genetically engineered through cloning and micro propagation technologies to no longer have its original spine defense mechanism, against those who eat them. Spineless *Opuntia* is commonly found in southwestern burritos and in cow feed.

Artist Amy Youngs' robotic sculpture *Rearming the Spineless Opuntia* explores the intersection of biotechnology, ecology, and robotics. Inspired by the genetically engineered spineless *Opuntia* cactus, the work imagines a technological defense system for a plant made vulnerable by the removal of its natural spines.

The installation combines ultrasonic proximity sensors, a microcontroller, electric motors, and fabricated components of copper, steel, aluminum, and rubber. As viewers approach, the sculpture detects their presence and deploys mechanical "spines" in a protective response. By combining living plants with responsive electronics, Youngs raises questions about genetic engineering, ecological responsibility, and the increasingly intertwined relationships among nature, technology, and human intervention.



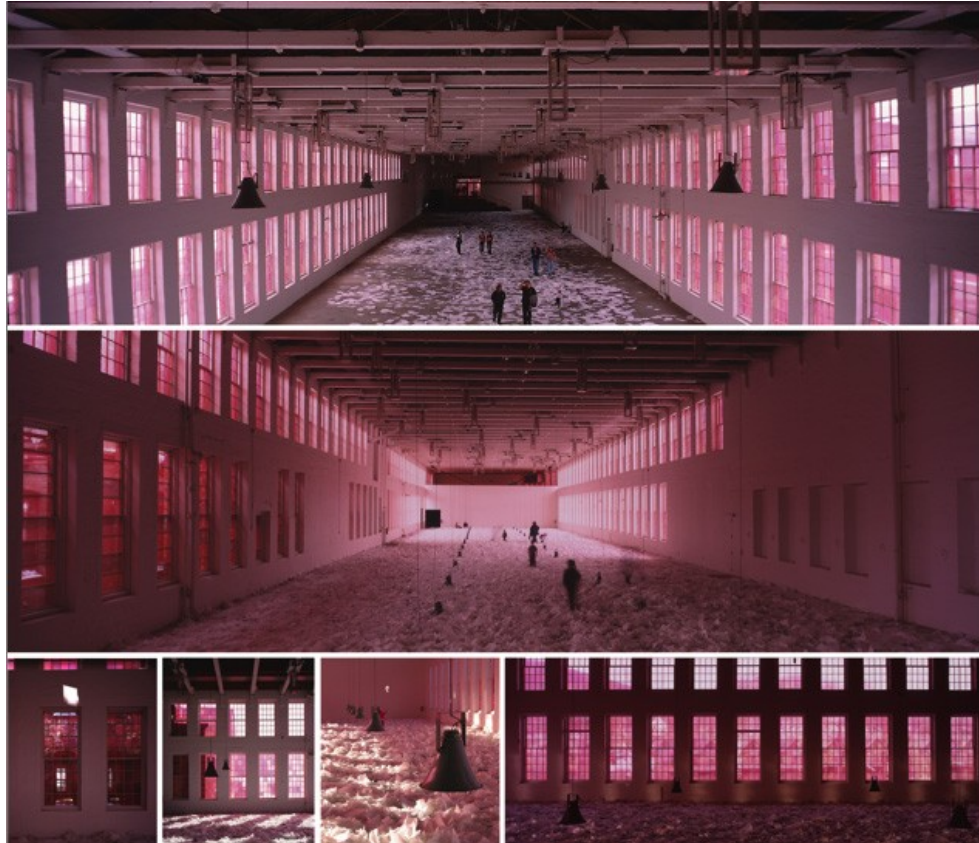
Rearming the Spineless Opuntia by [Amy Youngs](#). 1999. 60" x 30" x 30".

Creative Examples of Art–Science Intersection

Artist Ann Hamilton is internationally recognized for large-scale immersive installations that combine architecture, history, sound, movement, and material to create richly sensory experiences. Her works invite viewers to slow down and engage with space through touch, light, sound, memory, and physical presence.

In her installation *the event of a thread* at MASS MoCA, a series of pneumatic mechanisms rhythmically lift and release delicate sheets of translucent onionskin paper. The machines inhale as they raise each sheet and exhale as they release it, allowing the paper to drift gently to the floor in motions that evoke breathing. Suspended horn-shaped speakers slowly ascend and descend from the ceiling while playing voices that alternate between individual speech and moments of unified chorus, creating an ever-changing sonic environment.

The installation is illuminated solely by daylight filtering through hundreds of mill windows covered with red and magenta silk organza, bathing the enormous space in a warm, ethereal glow. By integrating light, sound, movement, texture, and architecture, Hamilton transforms an industrial building into an emotionally resonant environment that encourages reflection, contemplation, and an acute awareness of the body moving through space.



Corpus by Ann Hamilton at MASS MoCA. Photo copyright Ann Hamilton.

The artists, scientists, and inventors discussed throughout this chapter reflect the growing convergence of disciplines that is reshaping contemporary creative practice. Their research has given rise to new forms of interactive sculpture, robotic art, media installations, bio-art, kinetic sculpture, sound art, telematic art, immersive environments, and intelligent systems that integrate electronics, computation, biology, and mechanical design.

This flourishing of interdisciplinary work has been made possible by affordable microcontrollers, sensors, robotics platforms, digital fabrication tools, and open-source hardware and software communities such as [Arduino](#), [Espressif Systems](#), and [OpenCV](#).

Equally important has been the unprecedented availability of technical documentation, online education, and collaborative communities through the World Wide Web. More recently, artificial intelligence systems or Large Language Models, such as [ChatGPT](#), [Claude Qwen](#), Baidu's ERNIE Bot, and DeepSeek have further accelerated this transformation by helping creators understand electronics, generate software, debug hardware, analyze data, and rapidly prototype ideas. Together, these

resources have lowered the barriers to innovation while expanding the range of what individuals and small collaborative teams can accomplish.

Future historians may well look back on this period as the beginning of a new Renaissance—not one defined solely by human achievement, but by an increasingly creative partnership between humans and intelligent machines. As computation and artificial intelligence become woven into our cities, homes, clothing, tools, and even living systems, artists and inventors have an unprecedented opportunity to shape how these technologies are imagined, experienced, and integrated into society. The future of innovation will not emerge from technology alone, but from the creative dialogue between human imagination and the intelligent systems we continue to build.

In many respects, we have already become cyborgs. Not the cinematic cyborgs popularized by science fiction, but humans whose perception, memory, communication, and creativity are continuously extended through technology. From binoculars and telescopes that collapse distance, to microscopes that reveal invisible worlds, to smartphones, wearable devices, and artificial intelligence, our tools have become cognitive as well as sensory extensions. Over time these interfaces become increasingly transparent, fading into the background as our bodies and minds adapt to new ways of perceiving, thinking, and interacting with the world.

Consider the simple act of moving a computer mouse or using a touchscreen. Do you consciously distinguish your physical hand from the cursor or virtual object that responds instantly to your movement? Or does your perception seamlessly extend into the digital environment? Today this fusion extends even further through AI-assisted systems that help us write, design, compose music, generate images, analyze data, and develop software. Rather than replacing human intelligence, these technologies increasingly function as cognitive partners, expanding our ability to imagine, create, and solve problems.

This evolving relationship between humans and machines has long fascinated artists. Contemporary artist [Alan Rath](#) explores this theme by reversing the traditional notion of humans becoming machines. In works such as *Family* (1994), the machine itself appears to acquire human qualities through expressive movement and behavior. Rath's kinetic sculptures investigate perception, embodiment, artificial intelligence, and human interaction, demonstrating how relatively simple mechanical gestures can evoke empathy and suggest remarkably lifelike personalities.

His work reminds us that the boundary between human and machine is not fixed but continually renegotiated as technology becomes an increasingly natural extension of ourselves.



Family by [Alan Rath](#). 1994. 35" x 36" x 68". Custom Electronics.

Electromechanical systems coupled with computers have long extended human physical capabilities. Robotic excavators reshape landscapes, autonomous mining equipment operates in hazardous environments, and tower cranes enable operators to position massive structural elements with extraordinary precision during the construction of increasingly sophisticated buildings and infrastructure. Industrial robots, collaborative robots, and autonomous vehicles now perform tasks that demand strength, endurance, and accuracy beyond human limits.

Yet the true significance of this technological renaissance lies not in mechanical power, but in the information that guides it. Digital communication networks, satellite navigation, fiber-optic communication, cloud computing, artificial intelligence, and distributed sensing have transformed how we perceive, model, and control the physical world.

Systems once requiring teams of specialists can now be coordinated through intelligent software operating across global networks. Increasingly, robots combine computer vision, machine learning, and real-time sensing to navigate complex environments, while AI assists humans in designing,

programming, and optimizing these systems. Together, these technologies are reshaping not only our physical surroundings but also the informational landscape through which knowledge, creativity, and innovation now flow.

As our cities, laboratories, factories, and homes become increasingly interconnected, intelligence is no longer confined to individual machines. It is distributed across sensors, embedded computers, communication networks, and human collaborators, creating environments in which people and intelligent systems work together to solve problems that neither could accomplish alone.

Cyborg and Extended Self

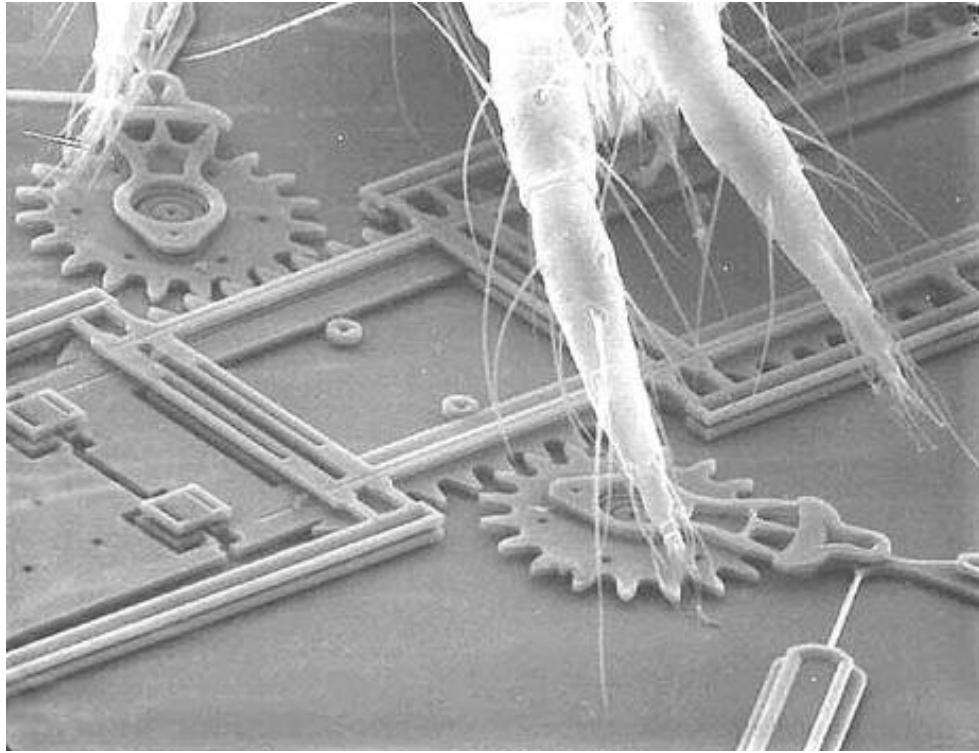
When we pick up our smartphones and instantly call, text, or video chat with a friend across town—or across the globe—we rarely think about the extraordinary technological infrastructure that makes such communication possible. The interface has become so familiar that it is nearly transparent. Our devices have become extensions of ourselves, augmenting memory, perception, communication, navigation, and increasingly, cognition through AI assistants. We simply reach for our technological companion, speak, and expect an immediate connection.

It remains remarkable that we can extend our voices, hearing, images, and ideas around the world almost instantaneously through fiber-optic networks, satellites, and wireless communications. This ability gives us agency at a distance, allowing us to collaborate, learn, create, and conduct commerce regardless of location. E-commerce, cloud services, telepresence, and remote collaboration have fundamentally transformed how we work and interact, making physical distance increasingly irrelevant for many aspects of daily life.

We often overlook these technologies because they work so seamlessly. An automatic door senses our approach and opens before we reach it; our phone recognizes our face; a navigation system anticipates traffic and suggests a better route; an AI assistant answers questions or helps write software. These are all examples of sensor-actuator feedback systems in which embedded microcontrollers, networked computers, and increasingly artificial intelligence continuously interpret and respond to human activity. At the same time, we adapt our own thinking to these technologies, creating a reciprocal relationship in which humans and machines learn to work together.

Anyone who drives a car, rides a bicycle, pilots a drone, or manipulates a robotic arm understands this sensation of becoming one with a machine. The body rapidly extends its sense of self into the mechanical system until the technology feels like a natural part of our perception and action. This expanding notion of embodiment continues to evolve as intelligent systems become more deeply integrated into our homes, workplaces, cities, and even our bodies.

While controlling large machines remains an extraordinary achievement, an equally transformative revolution is unfolding at the opposite scale. Advances in Micro-Electro-Mechanical Systems (MEMS), miniature sensors, edge computing, and intelligent embedded devices have made it possible to distribute computation almost everywhere. Combined with artificial intelligence and networked communication, these tiny systems are quietly reshaping medicine, environmental monitoring, robotics, wearable technologies, and the Internet of Things, creating a world in which intelligence is increasingly embedded within the fabric of everyday life.



Dust mite on a nano-etched machine, image by Jay Jakubczak at the Sandia National Laboratory.

Micro-Electro-Mechanical Systems (MEMS) integrate miniature sensors, actuators, mechanical structures, and electronic circuits onto silicon using the same microfabrication technologies employed in semiconductor manufacturing. Today, MEMS devices—including accelerometers, gyroscopes, pressure sensors, microphones, and magnetometers—are embedded in billions of smartphones, automobiles, drones, robots, medical devices, and wearable technologies, providing machines with an increasingly sophisticated awareness of motion, orientation, and the surrounding environment.

Artists [Laura Beloff](#), [Erich Berger](#), and [Martin Pichlmair](#) explored the creative potential of MEMS technology in *Seven Mile Boots* (2003–2004). Inspired by the enchanted boots of European folklore that allow their wearer to travel vast distances in a single stride, the installation uses MEMS accelerometers and a microcontroller to sense the wearer's movement. The sensor data are transmitted to a wearable computer, which communicates with a remote server and retrieves location-specific audio from the Internet. As participants walk only a short distance through physical space, they simultaneously navigate expansive virtual and sonic landscapes, demonstrating how embedded sensing, networking, and computation can transform ordinary movement into an immersive interactive experience.

Today, the ideas explored by *Seven Mile Boots* have become commonplace. MEMS sensors, wireless networking, smartphones, cloud computing, and artificial intelligence now work together to create responsive environments in which physical actions are seamlessly linked to digital information. Projects such as this anticipated the interconnected, sensor-rich world that has since become an integral part of everyday life.



Seven Mile Boots by Laura Beloff, Erich Berger, and Martin Pichlmair. 2003/2004.

In *Seven Mile Boots*, the web-based conversations are synthesized and broadcast through speakers embedded in the tips of the boots, allowing each walk to be accompanied by voices gathered from the network. As participants move through physical space, they simultaneously experience a virtual social landscape, blurring the boundaries between the physical body and its digital presence.

Today, our extensions into virtual space are even more deeply integrated into everyday life. Rather than relying solely on the mouse, keyboard, and computer monitor, we interact through smartphones, wearable devices, voice assistants, touchscreens, virtual and augmented reality headsets, and increasingly through AI-assisted interfaces. These technologies allow us to navigate seamlessly between physical and digital worlds while expanding our ability to communicate, create, and access information.

Many contemporary interfaces also incorporate haptic technologies that simulate the sensation of touch. Force-feedback joysticks, game controllers, robotic interfaces, surgical simulators, and wearable devices provide tactile responses that make virtual interactions feel increasingly physical. As haptic systems continue to evolve alongside artificial intelligence and robotics, the boundary between human perception and machine interaction becomes progressively more fluid, creating richer and more immersive experiences.

Haptics is the science of creating the sensation of touch through computers using sensors, actuators, motors, and sophisticated control algorithms. By combining force, vibration, texture, pressure, and increasingly temperature and tactile feedback, haptic systems allow users to interact with virtual and remote environments as though they were physically present. Haptics has become a critical technology in robotics, virtual and augmented reality, teleoperation, surgical simulation, wearable computing, and advanced prosthetics.

Early haptic systems primarily added vibration or force feedback to computer mice, joysticks, and game controllers. Today, high-resolution haptic devices can simulate the weight, resistance, texture, and

compliance of virtual objects, while robotic exoskeletons and dexterous robotic hands allow users to manipulate remote or microscopic environments with remarkable precision. Modern game controllers, smartphones, and VR systems routinely employ sophisticated tactile feedback that greatly enhances immersion.

The next frontier extends well beyond force feedback. Contemporary systems increasingly combine haptic interfaces with computer vision, artificial intelligence, physiological sensing, and wearable electronics. Heart rate, eye tracking, skin conductance, muscle activity, respiration, and even emerging neural interfaces can provide computers with insight into a user's physical and emotional state. AI systems can then adapt virtual environments, robotic behaviors, educational experiences, artistic installations, or assistive technologies in real time. These developments promise a far richer form of human-machine interaction—one in which both humans and intelligent systems continuously sense, learn from, and respond to one another, opening new possibilities for artists, designers, engineers, and inventors alike.

Interfaces and Telematics

Artist [Joseph DeLappe](#) has created a humorous series of sculptural computer mice that playfully parody one of the most familiar human-computer interfaces. Rather than focusing solely on the mouse as a device for translating physical movement into virtual action, DeLappe reimagines it as a cultural object whose exaggerated forms reflect human desires, habits, and technological obsessions. His sculptures invite viewers to reconsider an interface so ubiquitous that it has become almost invisible.

These works also acknowledge the remarkable legacy of the computer mouse itself. Originally developed in the 1960s by [Douglas Engelbart](#) and his colleagues at the [Stanford Research Institute \(now SRI International\)](#), the mouse transformed the way humans interact with computers and helped make graphical user interfaces practical for everyday use.

Although touchscreens, voice interfaces, gesture recognition, eye tracking, and AI-assisted interaction have expanded the ways we communicate with digital systems, the mouse remains one of the defining inventions in the history of human-computer interaction.

James Auger and Jimmy Loizeau are among the pioneers of **critical and speculative design**, creating fictional yet technically plausible devices that question our assumptions about technology rather than solving conventional engineering problems. Working together as **Auger-Loizeau** from 2000 onward, they imagined products that blur the boundaries between science fiction, industrial design, engineering, and conceptual art.

Their projects invite viewers to ask not "Can we build this?" but rather "Should we?" and "How might this technology change the way we live?"

Among their best-known projects are the **Audio Tooth Implant**, which imagines wireless communication delivered through a dental implant using bone conduction; **Carnivorous Domestic Entertainment Robots**, a family of robotic furniture that captures insects and converts their energy into electricity; **Afterlife**, a speculative system in which household appliances are powered by microbial decomposition after death; **Isophone**, a wearable device that creates private sound zones; and **Social Tele-presence**, a system allowing a person to experience the world through another person's body using cameras, microphones, and head-mounted displays.

These works use humor, irony, and technical plausibility to challenge assumptions about convenience, sustainability, surveillance, communication, and our growing dependence on intelligent technologies.

Rather than presenting technology as inevitable progress, Auger and Loizeau encourage audiences to see design as a powerful cultural tool capable of provoking debate, revealing hidden assumptions, and imagining alternative technological futures. Their work demonstrates that electronic devices can function as philosophical questions every bit as much as useful products—a perspective that has had a lasting influence on contemporary interaction design, speculative design, and media art.



Golan Levin, often treat computers with wit and irony, turning software, interfaces, and algorithms into playful experiences that expose the conventions of digital media.

One of the most exciting developments in haptics and human-machine interaction is its integration with teleoperation and telepresence. Through the science and art of telematics, people can now manipulate distant physical environments while receiving visual, auditory, and increasingly tactile feedback. These technologies allow human skill and perception to extend far beyond the limits of the body, creating new possibilities in medicine, engineering, scientific exploration, art, and space research.

Perhaps the most widely recognized application is robot-assisted surgery. Systems such as the [da Vinci Surgical System](#) enable surgeons to control robotic instruments with extraordinary precision through computer-mediated interfaces. Motion scaling translates large movements of the surgeon's hands into microscopic movements of robotic instruments, while filtering unwanted tremor to improve surgical accuracy. High-resolution imaging, force sensing, and increasingly artificial intelligence assist surgeons in planning, visualization, and decision support while maintaining the surgeon's direct control over the procedure.

Whether the robotic system is located across an operating room or connected through high-speed communication networks to a distant location, the principles remain the same: human expertise is extended through intelligent machines. As communication networks, robotics, haptics, and artificial intelligence continue to advance, teleoperation is expanding beyond medicine into underwater

exploration, hazardous environments, manufacturing, disaster response, and even space robotics, allowing humans to work safely and effectively in places that would otherwise be inaccessible.

Telematics explores the technical, artistic, and philosophical possibilities of sensing, communicating, and acting at a distance through computers, networks, sensors, and robotic systems. As communication technologies have evolved from early Internet connections to broadband, wireless networks, cloud computing, and artificial intelligence, telematics has expanded beyond simple remote communication to include telepresence, collaborative robotics, remote sensing, autonomous systems, and shared virtual environments.

Artists and researchers [Ken Goldberg](#), [Eric Paulos](#), Chris Myers, and Mat Fogarty explored these ideas in Tele-Actor (2004). The project connected a human participant equipped with cameras, microphones, and a wireless communication system to audiences on the Internet. Remote viewers experienced the actor's surroundings in real time while collectively determining where the participant should move and what actions to take. Using a "Spatial Dynamic Voting" (SDV) interface, the system continuously aggregated the decisions of online participants, allowing collective behavior to guide the tele-actor's movements.



Tele-Actor by [Ken Goldberg](#), Eric Paulos, Chris Myers, and Mat Fogarty. 2004. Photo by Bart Nagel.

Rather than emphasizing individual agency, Tele-Actor investigated how distributed networks can produce a shared intelligence in which decisions emerge from the interactions of many participants. Today, similar ideas appear in telepresence robotics, remote scientific exploration, citizen science,

collaborative virtual environments, and AI-assisted robotic systems, where humans increasingly work together across networks to observe, navigate, and interact with distant physical environments.

In another work, *Essay Concerning Human Understanding* (1994), [Eduardo Kac](#) and Japanese artist [Ikuo Nakamura](#) created an interspecies communication experiment linking a philodendron plant and a canary separated by approximately 600 miles through telephone lines. Microphones captured the canary's song and transmitted it to the plant. Electrodes attached to the plant measured subtle bioelectrical fluctuations in response to the sound, and these signals were used to select prerecorded bird songs that were played back to the canary, establishing a continuously evolving dialogue between two very different living organisms.

Although the work did not claim that the plant "understood" the bird in a human sense, it explored how sensing technologies, computation, and telecommunications could create new forms of interaction among living systems.

Extended Self

Artist [Rafael Lozano-Hemmer](#) explored telepresence and large-scale public interaction in *Vectorial Elevation* (1999–2000), an ambitious installation that allowed Internet users from around the world to choreograph an array of powerful robotic searchlights mounted on buildings surrounding Mexico City's historic Zócalo Square. Through a custom web interface, participants designed three-dimensional light compositions that were transmitted over the Internet and executed in real time. A live camera streamed the resulting light sculptures back to participants, allowing them to witness their designs projected across the night sky.

Unlike many interactive artworks that respond only to local audiences, *Vectorial Elevation* transformed a major public space into a globally networked environment where thousands of remote participants collectively shaped the visual experience of the city. Each participant's light composition was archived alongside their location and comments, creating a growing record of worldwide engagement.

The project anticipated many aspects of today's networked culture, including cloud-based collaboration, remote participation, Internet-of-Things (IoT) systems, and globally distributed interactive events. More importantly, it demonstrated that telematics could move beyond simply controlling distant machines to create shared public experiences in which physical architecture, robotic systems, communication networks, and collective human creativity converge across geographic boundaries.



Vectorial Elevation, by Rafael Lozano-Hemmer (part of the Cultural Olympiad – CODE). Photo by [Magalie L'Abbé](#).

The work also had an important local dimension. As the photograph above indicates, people gathered in the Zócalo could experience the constantly changing patterns created by participants distributed around the world. With *Vectorial Elevation*, the programmer of the light sequence could be standing nearby or thousands of miles away, yet the resulting searchlight choreography became a shared public event visible to everyone in the square. The work connected remote individual action with collective, local experience.

The future of telematics promises further refinements in interface design, sensing, robotics, and communication between humans, machines, and other species. Motion-capture systems, wearable sensors, computer vision, and haptic interfaces can increasingly record the precise movements of artists, engineers, craftspeople, and surgeons and translate those actions into robotic behavior. These systems may allow expertise to be transmitted, scaled, preserved, and enacted through distant robotic avatars.

As networks become faster and robotic systems more responsive, telematics will provide humans with increasingly sophisticated forms of agency at a distance. At the same time, artists will continue to

question who controls these systems, whose intentions are represented, and how remote actions transform the social and ecological spaces in which they occur.

High-speed robotic assembly systems accurately place microscopic surface-mount components onto circuit boards—tasks that are impractical for human hands—making modern electronics reliable, affordable, and widely accessible.

Computers in our cars, homes, and workplaces are highly visible, but millions more operate unseen, coordinating agriculture, manufacturing, logistics, energy, and transportation. The global just-in-time economy depends on vast networks of computers and microcontrollers that continuously monitor supply, demand, and distribution through real-time feedback loops.

Computer systems have become indispensable to financial markets, communication, healthcare, and critical infrastructure and now AI and indeed body extensions. Who would not be interested in four arms instead of two?



The **Jizai Arms**, developed by Professor **Masahiko Inami** and his research team at the University of Tokyo, are a wearable robotic system designed to extend human capabilities through four detachable robotic arms mounted on a backpack-like base. Rather than replacing human movement, the system explores new forms of collaboration between the body and machines, allowing users to develop novel modes of perception, expression, and creativity. Inspired by the Japanese concept of **jizai**—the freedom to act autonomously—as well as traditional Japanese puppetry and a story by Nobel laureate **Yasunari Kawabata**, the project imagines technology not as a tool, but as an extension of the human body and imagination.

Broadband and Neural Extensions

An even greater augmentation of the human mind and body is unfolding through the vast connectivity of the Internet, cloud computing, and artificial intelligence. Media artist and theorist [Roy Ascott](#) describes this expanded cognitive landscape as a "noetic network," in which human minds and information systems converge to create new forms of collective consciousness that reflect our shared values. As Ascott writes, "Cyberspace cannot remain innocent. It is a matrix of human values; it carries a psychic charge."

Today, social media, collaborative platforms, and AI-assisted communication have transformed the Internet into a primary space for political discourse, creative collaboration, education, and scientific discovery. Whether these globally connected systems constitute an emergent consciousness remains an open question.

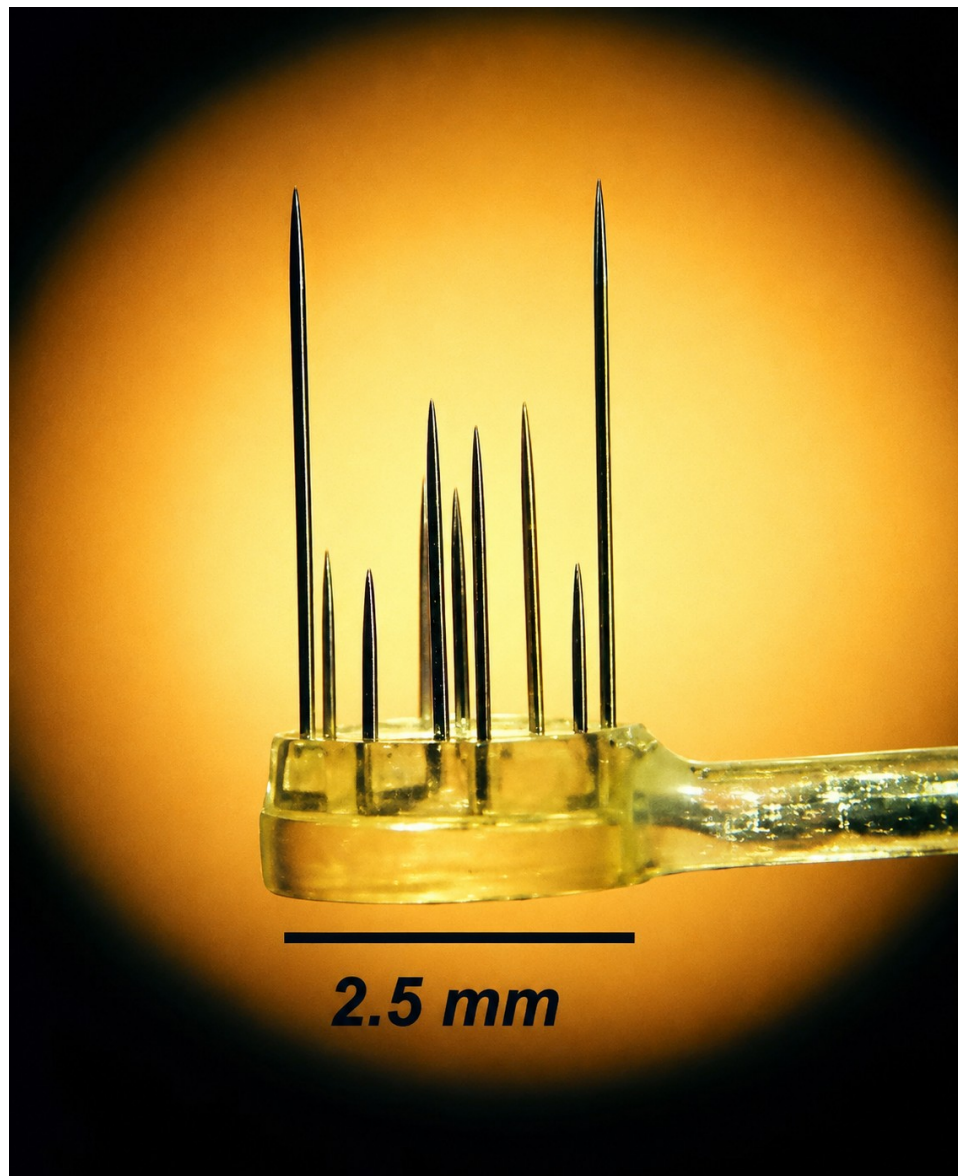
What is clear is that high-speed networks, distributed computing, and intelligent algorithms increasingly mediate how we create, communicate, and understand the world through data, images, language, sound, and video.

With the widespread availability of Wi-Fi, 5G, and satellite Internet, network connectivity now extends into homes, public spaces, and remote environments, providing continuous access to voice, video, data, and cloud-based services.

These distributed networks increasingly resemble neural systems, with billions of connected devices exchanging information much like dendrites forming pathways for communication, memory, and cognition. Broadband is now delivered through fiber, cable, cellular, and wireless mesh networks, making high-speed connectivity an essential infrastructure for everyday life.

Nevertheless, computers are no longer confined to our physical environments or our creative expression—they are increasingly becoming integrated with the human body and nervous system.

Neural engineering has produced implantable devices that restore lost sensory and motor functions, including cochlear implants that stimulate the auditory nerve, allowing many profoundly deaf individuals to perceive sound. Researchers, including Douglas McCreery at the Huntington Medical Research Institute's Neural Engineering Laboratories, have helped advance these technologies, demonstrating how electronics can directly interface with the nervous system to augment human capabilities.



Cochlear implant. [Dr. Douglas McCreery](#), Huntington Medical Research Institution.

Researchers have also developed auditory brainstem implants that bypass damaged auditory nerves by directly stimulating the cochlear nucleus in the brainstem. Advances in electrode design and materials have improved the precision and safety of these implants, allowing many recipients to distinguish speech and pitch more effectively than was previously possible. Building on this work, programs such as DARPA's neurotechnology initiatives have explored implantable brain-computer interfaces to restore movement, communication, and sensory function following traumatic brain injury, stroke, or spinal cord injury.

The next question is what kinds of neural implants might eventually extend, rather than simply restore, human perception. Could hearing be expanded into ultrasonic or infrasonic ranges, allowing us to perceive the echolocation calls of bats or the low-frequency vocalizations of whales? Such capabilities might deepen our understanding of other species and open new forms of interspecies communication.

What if we could perceive the subtle vibrations that precede earthquakes or monitor environmental changes through senses unavailable to us today?

Could vision, touch, smell, or balance be augmented beyond their biological limits? Might new sensory modalities emerge, allowing us to perceive magnetic fields, chemical signals, or entirely new forms of information?

As neuroscience, bioengineering, and artificial intelligence continue to converge, these questions are moving from speculative fiction toward active scientific exploration.

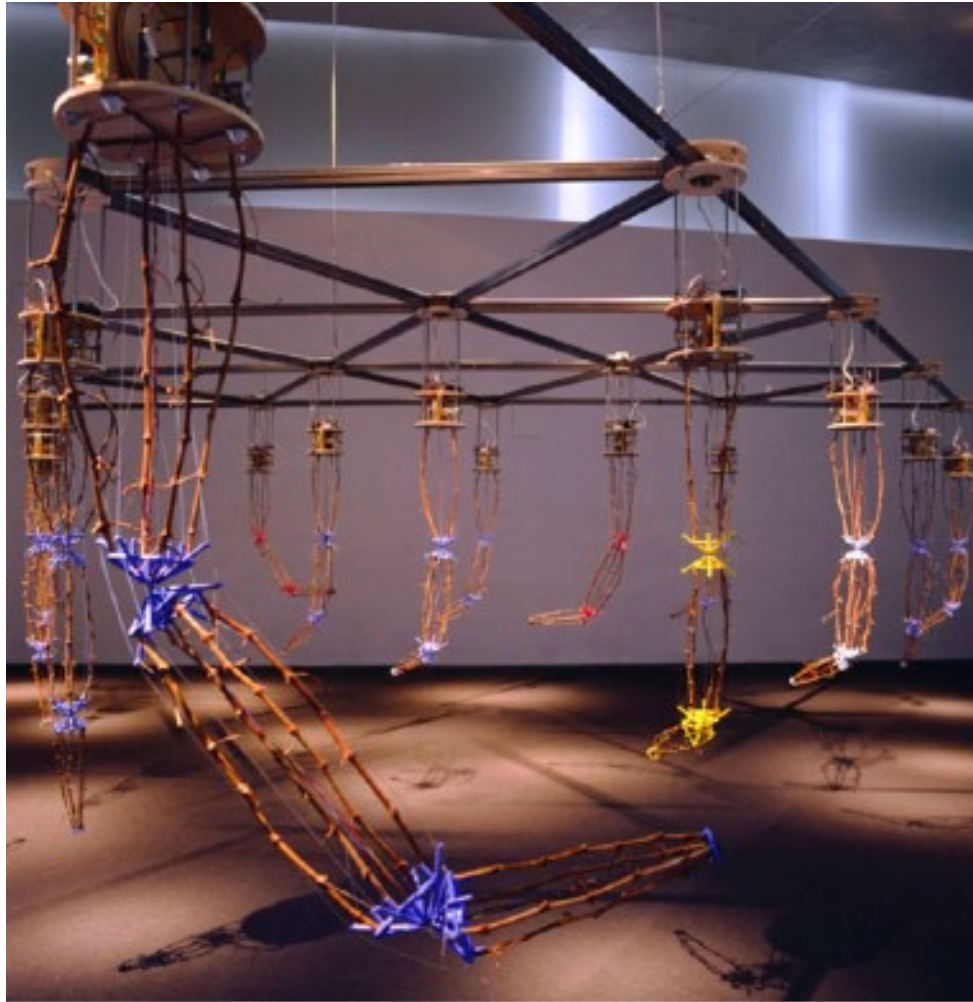
Artificial Life

Indeed, we are witnessing a co-evolution between humans and increasingly intelligent machines, while machines themselves are becoming capable of learning and adapting. The field of artificial life explores how principles of biological evolution can be applied to computation through genetic algorithms, evolutionary computation, and other adaptive methods. Rather than being explicitly programmed with every solution, these systems evolve increasingly effective strategies over successive generations, discovering novel approaches to complex problems and adapting to changing environments.

Autopoiesis (2000–04), created by the author, is a robotic installation commissioned by the Kiasma for Ouotoäly (Alien Intelligence), curated by Erkki Huhtamo. The installation consists of fifteen robotic sound sculptures that interact with visitors and adapt their behaviors over time.

Their behaviors evolve through feedback from infrared sensors, the presence of participants, and communication among the sculptures. The robots exchange information over a computer network and through audible telephone tones, creating a shared musical language that coordinates the behavior of the group.

Autopoiesis—meaning "self-making"—describes a defining characteristic of living systems, a concept developed by Humberto Maturana and Francisco Varela. In the installation, visitors become active participants in the evolving system, influencing the robots' behaviors and the emergence of the work's collective aesthetic. Moving beyond conventional mouse-and-screen interfaces, Autopoiesis creates an immersive environment that evolves continuously through real-time sensing, feedback, communication among the robotic sculptures, and audience interaction.



Autopoiesis by [Ken Rinaldo](#), 2000.

As the installation adapts to its changing environment, each sculpture modifies its behavior while contributing to the collective dynamics of the group. The result is a cybernetic ballet in which autonomous machines and participants continually sense and respond to one another, producing an ever-changing choreography of sound, movement, and interaction. Rather than presenting a fixed sequence of events, the installation generates a unique experience with each encounter, emphasizing emergence, adaptation, and the evolving relationships between humans and autonomous systems.

Cybernetics is the science of communication and the control of computer and human interaction.

Are computers now able to give birth to themselves? At Brandeis University, in August of 2000, the researcher Jordan Pollack and his colleague Hod Lipson of Cornell developed a system that would allow a set of robots to evolve in the virtual space of the computer first and then manifest in the physical world using rapid prototyping technology.

Symbiotic Intertwining

These works suggest a broader role for computers as creative collaborators capable of generating novel forms and solutions, extending ideas found in artificial life and evolutionary computation. Likewise, contemporary biology increasingly recognizes that evolution is shaped not only by competition but also by cooperation, symbiosis, and co-evolution. This provides a compelling model for thinking about our evolving relationship with intelligent machines.

Computers have become essential tools for discovering knowledge, augmenting creativity, and solving increasingly complex problems. Their greatest potential lies not in replacing human imagination but in extending it. For artists, inventors, researchers, and designers, electronics, microcontrollers, robotics, and artificial intelligence offer unprecedented opportunities to imagine and create new futures.

This is an extraordinary time to be an artist and inventor, but it is also one that demands responsibility. The technologies we develop increasingly influence culture, society, and the natural world. The systems we build become part of the ongoing evolution of our civilization and our relationships with other species, making thoughtful design and ethical stewardship as important as technological innovation.

It is easy to see how technologies such as the automobile, airplane, and firearm have transformed human society, often bringing both extraordinary benefits and profound consequences. In *War in the Age of Intelligent Machines*, Manuel De Landa examines the emergence of autonomous weapons as part of a broader historical shift in which humans increasingly transfer cognitive functions to machines. Today, advances in artificial intelligence have made these questions even more urgent, raising ethical concerns about autonomy, accountability, and human oversight. Publications such as *CTheory* continue to provide an important forum for examining both the promises and risks of technological change.

As inventors and creators, we have the opportunity—and the responsibility—to shape how technology evolves and how it is applied. In Chapter 2 you will meet the experimenters who established the foundations of modern physics. In many ways, they were the hackers of their era, challenging accepted ideas through curiosity, experimentation, and careful observation.

We also share a responsibility to be good citizens within the broader community of life. This means respecting other living organisms, designing technologies thoughtfully, and disposing of electronic materials responsibly to minimize environmental impact. Like many of you, I remain inspired by the beauty and complexity of the natural world, and believe our work with electronics should reflect both creativity and environmental stewardship.

The primary purpose of this book is to present practical electronic and mechanical techniques that enable artists, engineers, researchers, and inventors to transform ideas into working projects as efficiently and creatively as possible.

The secondary purpose of this book is to highlight artistic, design, and scientific research at the intersection of the arts, engineering, and the sciences—fields that have always been deeply interconnected. Artists have long used emerging technologies to reveal the underlying forces shaping culture, while artists, engineers, researchers, and inventors together explore the hopes, challenges, and possibilities that new technologies present for society and the planet.

What these communities share is curiosity. Whether creating an artwork, designing a device, or conducting scientific research, the process of experimentation, discovery, and problem solving is immensely rewarding. It is this spirit of inquiry that drives innovation and makes inventing, building, and creating such an exciting endeavor.

Rich Gold (1950–2003) of Xerox PARC is quoted as saying: “Artists have always made art with the mud and water at the river's edge, though now the river is information and the mud has become silicon.”

When I first began studying electronics, it seemed like a daunting subject. I was pleasantly surprised to discover that engineers had developed logical symbolic languages and visual systems that artists could readily understand. In fact, artists and engineers often share a valuable ability: three-dimensional visualization—the capacity to imagine and manipulate forms, structures, and processes in space.

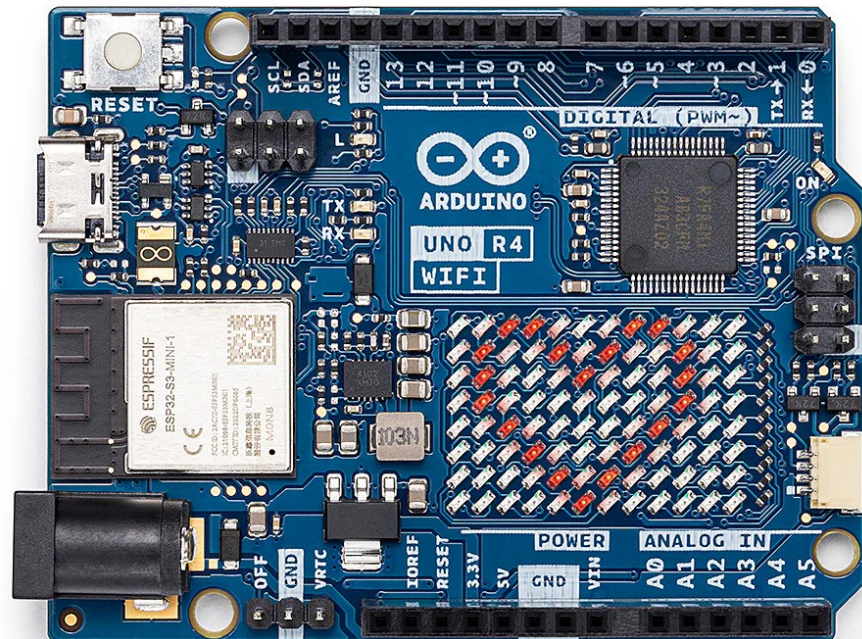
Accordingly, this book emphasizes visual models of electronic processes alongside diagrammatic representations of components and circuits. I believe it is important to visualize what is happening at the atomic level, where electrons move through materials, because developing an intuitive mental picture often makes complex concepts much easier to understand.

At the same time, it is important to remember that diagrams, illustrations, and analogies are models rather than literal representations. They are tools for understanding specific aspects of a process and are most useful when considered alongside other models and scientific descriptions.

This edition features two of the most influential embedded computing platforms available today: the Arduino family and the powerful Wi-Fi and Bluetooth-enabled counterpart, the ESP32.

Both can be programmed through the Arduino IDE, (Integrated Development Environment) allowing projects and code to be shared across platforms. The book also explores MAX/MSP and Jitter, including communication with Arduino and ESP32 devices using Firmata and serial protocols, enabling real-time interaction between software and the physical world.

s.



This is the Arduino UNO R4 WiFi, a modern successor that shares the same foundational pinout and programming approach as the classic Arduino UNO that will be featured throughout this book.

While this book provides a comprehensive introduction to electronic control systems and mechanical techniques, the featured projects and installations also explore broader conceptual and artistic concerns. Along the way, you will be introduced to contemporary developments in interactive art, kinetic sculpture, electronic invention, interface design, entertainment engineering, robotics, and creative AI.

Many of the projects presented here use Arduino or ESP32 microcontrollers, while others employ a wide range of commercial and custom hardware, embedded computers, sensors, actuators, motors, relays, computer vision, and software. The emphasis is not on a single platform, but on understanding the underlying principles common to interactive systems and electronic invention.

To support further exploration, the book concludes with extensive technical and artist resources, including books, organizations, manufacturers, software, and online references that will help you continue developing your own projects long after you have finished reading.

Parts List.

You can purchase kits online for many of the lessons in this book.

The lessons in this book focus on the Arduino Uno and the ESP32 working with MAX/MSP and Jitter. Although the examples use these specific platforms, most Arduino-compatible microcontrollers can be adapted with only minor modifications. Regardless of the hardware you choose, always consult the appropriate schematics and pin assignments before connecting electronic components.

Communication between MAX/MSP and embedded hardware is demonstrated using serial communication and Standard Firmata, providing an accessible framework for building interactive systems. A short chapter also introduces web-connected devices through a project by artist Amy Youngs, illustrating how networked electronics can extend interaction beyond the local computer.

Both Arduino and ESP32 are open-source platforms supported by large international communities that continually develop libraries, hardware, and educational resources. Their affordability, flexibility, and extensive ecosystem make them excellent choices for artists, designers, researchers, and inventors. Development boards and complete starter kits remain inexpensive and widely available, making sophisticated interactive projects accessible to almost anyone.

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Chapter 2

The Structure of the Atom

Electrostatic Glue

“There are children playing in the street who could solve some of my top problems in physics because they have modes of sensory perception that I lost long ago.”

— Robert Oppenheimer

Question: Why Don't Things Fall Apart?

Observation, visualization, imagination, and speculation—augmented by tools such as telescopes, spectrometers, electron microscopes, scanning tunneling microscopes, and other imaging technologies—have become fundamental ways of exploring the universe. These instruments extend our senses across vast scales, from the cosmic to the atomic, allowing scientists, artists, philosophers, and even mystics to develop models that help explain the world around us. Together, these perspectives continually reshape our understanding of reality while reflecting the curiosity, creativity, and values that define our humanity.

Spectrophotometers are devices used to measure the wavelength of light that is created by [atoms](#) emitting and absorbing [electromagnetic radiation](#).

Systems of thought and ways of seeing shape how we understand the world and influence the future of culture, science, and technology. Today, statistical analysis, experimentation, and the scientific method remain among our most powerful tools for testing hypotheses and establishing reliable knowledge. Yet our understanding of the universe is always constrained by the instruments, models, and languages we use to investigate it. Every tool reveals some aspects of reality while obscuring others, reminding us that there may be additional ways of observing, analyzing, and knowing still to be discovered.

The visualization of the atom presented in this chapter illustrates how knowledge evolves through observation, hypothesis, experimentation, and increasingly sophisticated imaging technologies. As new instruments and analytical methods emerge, both science and art will continue to refine—and sometimes radically transform—our understanding of matter and the nature of reality.



Fresh-water Bamboo shrimp (Atyopsis moluccensis) by [Adrian Fernandez](#). 2008.

Through these discoveries, we have learned that the matter composing both the living and nonliving universe is built from the naturally occurring chemical elements. These atoms are held together by electromagnetic forces—the "electrostatic glue" that binds electrons and atomic nuclei into stable atoms, molecules, and materials, making the complex structures of our universe possible.

Elements are the fundamental building blocks of the material world. Each element consists of only one kind of atom and may exist as a solid, liquid, gas, or plasma, depending on temperature and pressure. Familiar examples include lithium, carbon, helium, and copper, which can be isolated in nearly pure form through natural and industrial processes.

Electrostatic glue refers to the electromagnetic attraction between positively charged atomic nuclei and negatively charged electrons that holds atoms together and enables atoms to bond into molecules. These interactions underlie the structure and stability of all matter.

Even more remarkable is that approximately 99% of the mass of living organisms is composed of just four elements: hydrogen (H), carbon (C), oxygen (O), and nitrogen (N). The unique chemical properties of these elements, together with the electrostatic forces that bind them into stable molecules, provide the foundation for the extraordinary complexity and diversity of life.



Small Lizard by William Ospina. 2008.

These elements combine to form compounds, which in turn make up our bodies, brains, computers, automobiles, and every other material object around us. If we imagine humans, animals, plants, fungi, bacteria, viruses, and the Earth itself as symbiotically interconnected, the resulting web of elements and compounds represents one of the most extraordinary outcomes of billions of years of evolution. Guided by the laws of chemistry and physics, these electrostatic interactions have given rise to the remarkable complexity and diversity of life on our planet.

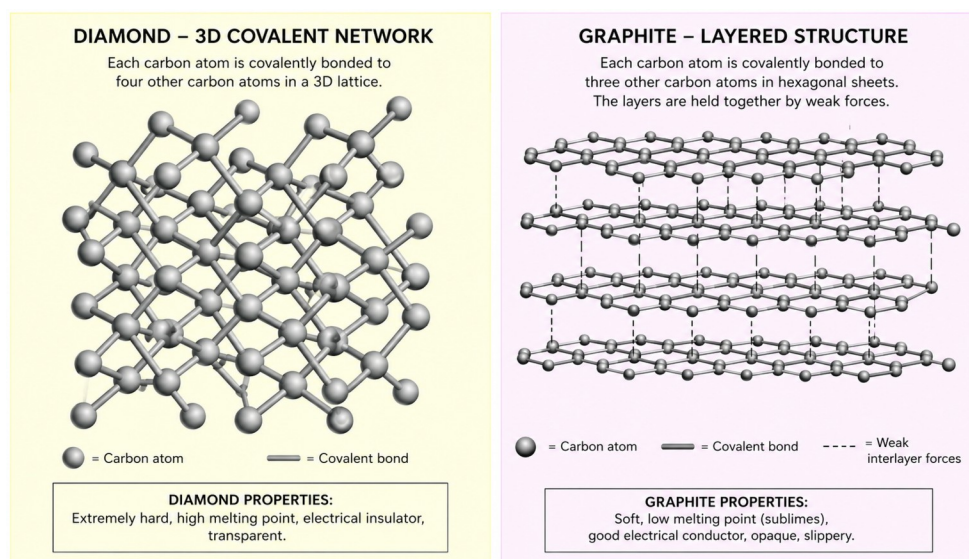


Compounds are materials composed of mixtures of *many* kinds of atoms.

The arrangement of atoms determines the properties and states of matter. A relatively small number of common elements combine in countless ways to form the solids, liquids, and gases that make up the material world. When two or more atoms are chemically bonded together they form a molecule. Molecules may consist of atoms of the same element, such as oxygen (O_2), or of different elements, such as water (H_2O), giving rise to the immense diversity of materials found in nature.

Organization of Matter

The soft graphite in a lead pencil and the hard, transparent diamond are both composed entirely of the element carbon. Their dramatically different properties arise from the way the carbon atoms are arranged and bonded. In diamond, each carbon atom forms four strong covalent bonds in a rigid three-dimensional lattice, producing one of the hardest materials known. Notice the three-dimensional network of covalent bonds in the diamond model shown in the image on the left.

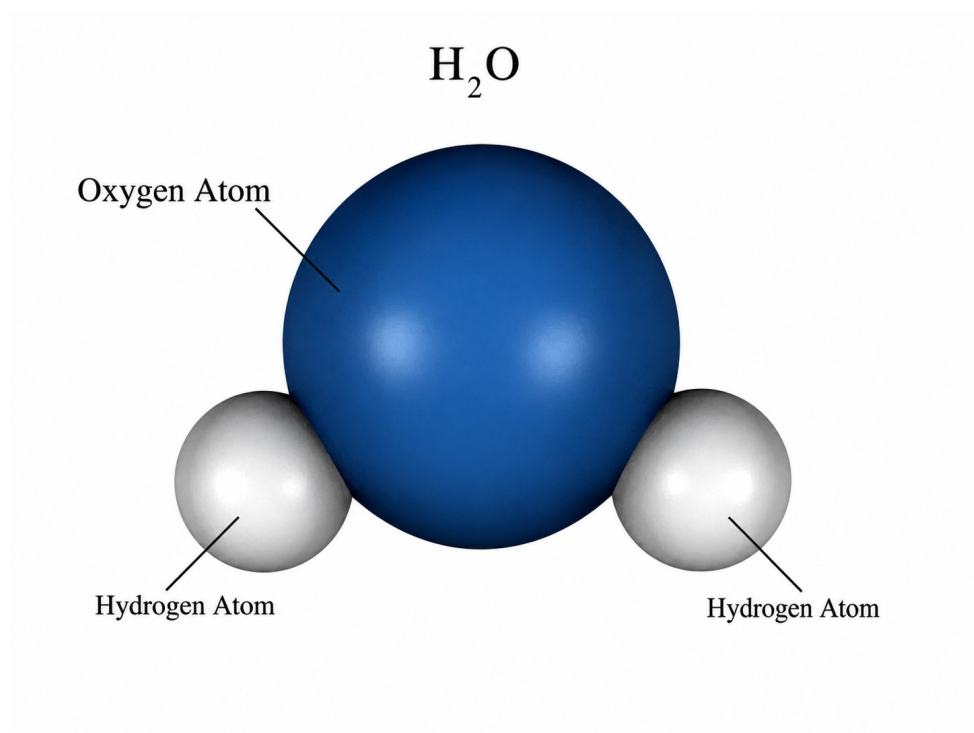


The interlocking strength, with each carbon atom bonding to four others, forms a stable and very hard “molecule” consisting of millions of atoms.

Atoms by [Jeremy Harvey](#)

Notice the layered arrangement of carbon atoms in the graphite (pencil lead) shown to the right of the diamond structure. Within each horizontal layer, the carbon atoms are joined by strong covalent bonds, forming rigid hexagonal sheets. Between these layers, however, only weak intermolecular forces hold the sheets together, allowing them to slide easily over one another. This layered structure makes graphite soft, slippery, and ideal for use in pencils and as a dry lubricant.

We have established that the different states of matter—solids, liquids, gases, and plasma—are composed of the same atoms but can exhibit very different properties depending on how those atoms or molecules are organized and how they interact. Water provides an intuitive example. In solid water (ice), water molecules are arranged in a rigid crystal lattice held together by hydrogen bonds. In liquid water, the molecules remain loosely connected but are free to move past one another, allowing the liquid to flow and fill the shape of its container. This cohesion is also why water forms droplets on glass surfaces. Water is often called the universal solvent because more substances essential to life dissolve in it than in any other liquid. Indeed, our own cells consist primarily of water enclosed within thin membranes.



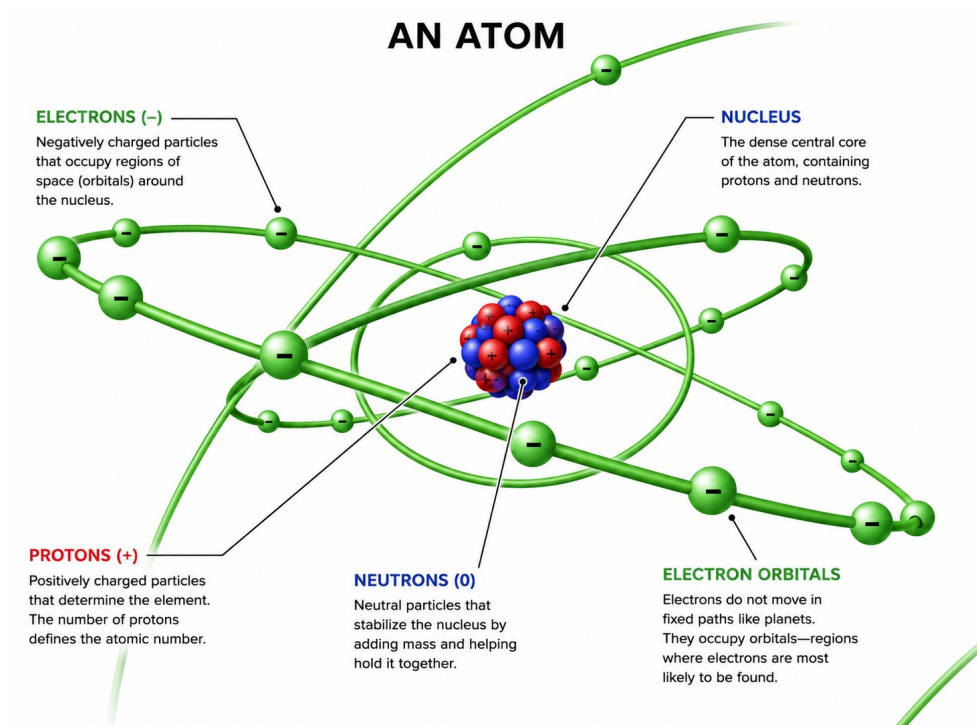
Water Molecule

In the gaseous state (steam), water molecules move freely and expand to fill all available space because of their higher thermal energy. If we could magnify steam or any gas millions of times, it would resemble trillions of tiny rubber balls moving rapidly in all directions, constantly colliding with one another.

An atom of an element typically contains an equal number of negatively charged electrons and positively charged protons, making it electrically neutral. At its center is the nucleus, composed of protons and neutrons packed tightly together. Surrounding the nucleus is a cloud of electrons occupying regions called orbitals. Although these are often illustrated as planet-like paths to simplify the concept, electron orbitals are actually regions where electrons are most likely to be found rather than fixed circular trajectories.



Electrons carry a negative charge numerically equal to that of protons and orbit the nuclei of atoms in shells. Their mass is about 1/1836 the mass of a proton.



The red spheres are protons, the blue spheres are neutrons, and the green orbitals are electrons

The nucleus is an extraordinarily small structure, measuring only about 1/10,000 the radius of the atom. As a result, most of an atom consists of empty space between the dense nucleus and the surrounding cloud of electrons occupying orbitals. If the nucleus were the size of a marble, the outermost electrons would be hundreds of meters away.

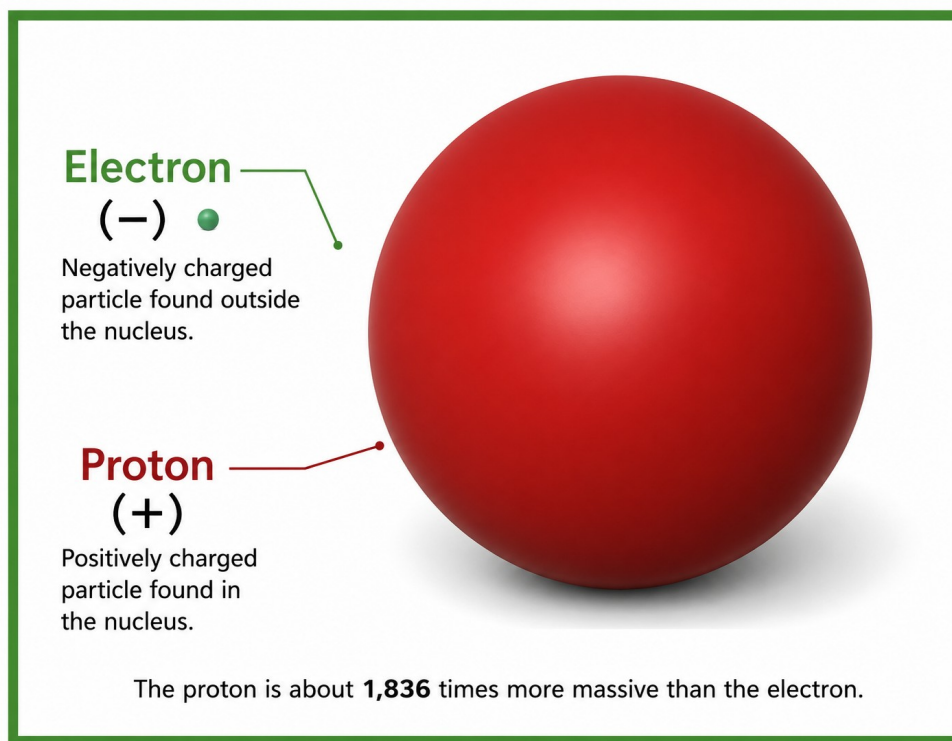


Protons are positively charged particles found in the nuclei of all atoms and have a mass similar to that of neutrons.



Neutrons are uncharged particles found in the nuclei of all known atoms but hydrogen.

The nucleus is also much smaller than the atom but enormously more massive than its surrounding electrons. A single proton has approximately 1,836 times the mass of an electron, and because the nucleus contains protons and neutrons, it accounts for more than 99.9% of the atom's total mass.



The relative mass of proton vs. electron.

In both elements and compounds, the attraction between negatively charged electrons and positively charged atomic nuclei acts as an electrostatic glue, binding atoms together into increasingly complex molecules and giving rise to the remarkable diversity of materials that compose our world.

Electrostatic Forces

Electrostatic forces make the chair you sit on rigid, the floor you stand on solid, and the water you drink a liquid. The hamburger you consumed for dinner that powers your eyes was made possible by the hay the cow ate. The hay, in turn, was produced through photosynthesis, which captures the electromagnetic energy of sunlight and stores it as chemical energy. Indeed, electromagnetic forces govern the behavior of matter, from the binding of atoms into molecules to the electrical signals that flow through our nervous system. Electrons, as charged particles, are central to these interactions.

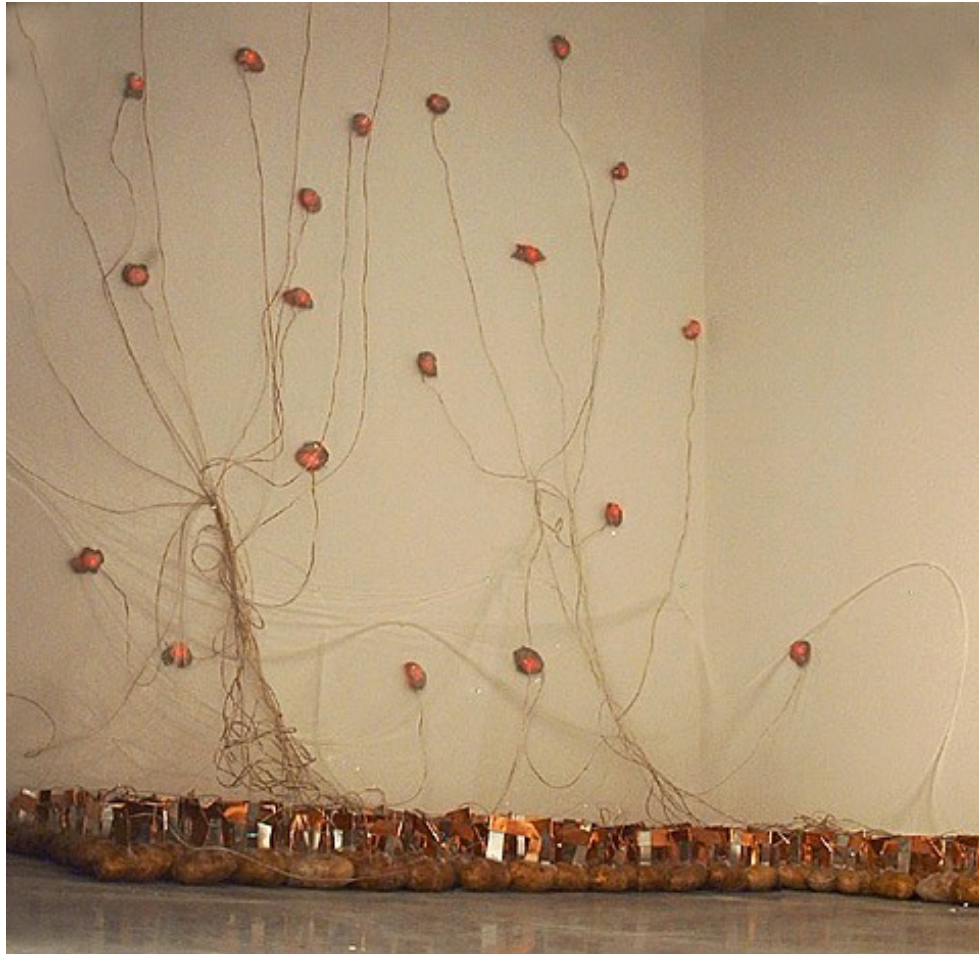
One of the pioneers of electrical experimentation, Alessandro Volta (1745–1827), was fascinated by electricity and experimented with gases and electrical sparks. As a student he became so engrossed in this research that he wrote a poem in Latin describing his experiments. In 1774, Volta became a professor of physics and, through further experimentation, developed the electrophorus, a simple device capable of generating and storing static electric charge. Volta, who also discovered methane, performed many experiments in which he ignited gases inside glass vessels using electrical sparks.

Volta also conducted pioneering experiments that led to the invention of the electric battery. He discovered that by immersing dissimilar metals, such as zinc, silver, and copper, in brine (salt water), he could generate an electric current. Later, he stacked alternating discs of zinc and silver separated by cardboard soaked in brine, producing a steady current. This device, known as the voltaic pile, became the forerunner of the modern battery.

Some contemporary artists have explored this same electrochemical principle by immersing dissimilar metals in acidic or saline solutions to generate electricity. The artist Norman Tuck, for example, created a work titled *Alchemy*, which uses zinc, copper, and salt water to produce a current that causes a pendulum to swing between magnetic poles, creating a simple form of electric motor.

The contemporary artist Joseph Smolinski uses potatoes as batteries in *Potato Cells* (2003). In this installation, potato batteries generate enough electricity to power red light-emitting diodes (LEDs), which are embedded in cast resin.

The work demonstrates that, given the proper electrochemical combination of materials, batteries can be created from common foods such as potatoes and lemons. It also serves as an elegant reminder that the energy stored within the potato originated as sunlight, captured through photosynthesis and later converted into electrical energy to illuminate the LEDs.



Potato Cells, by [Joseph Smolinski](#). 2003.

[André-Marie Ampère](#) (1775–1836) was a largely self-educated French mathematician and physicist, as well as a prodigious reader. He was reputed to possess an extraordinary memory and, according to accounts of his life, could recite extensive passages from Diderot and d'Alembert's *Encyclopédie*. Ampère later became a professor of mathematics and experimental physics. Following Hans Christian Ørsted's 1820 discovery that an electric current could deflect a compass needle, Ampère conducted experiments demonstrating the forces between current-carrying wires and developed a mathematical

theory unifying electricity and magnetism. He called this new field electrodynamics and became one of the principal founders of what we now call electromagnetism.



Ampere uses the symbol **A**, which is also referred to as **amp** or amperage.

Both of these researchers provided important insights that later influenced the work of James Clerk Maxwell (1831–1879), who demonstrated mathematically that light is an electromagnetic wave. Maxwell unified the experimental discoveries of Volta, Ampère, Michael Faraday, and Charles-Augustin de Coulomb into a single theory describing electricity, magnetism, and light as manifestations of the same electromagnetic phenomenon.

Charles-Augustin de Coulomb (1736–1806) formulated the fundamental law describing the forces between electric charges:

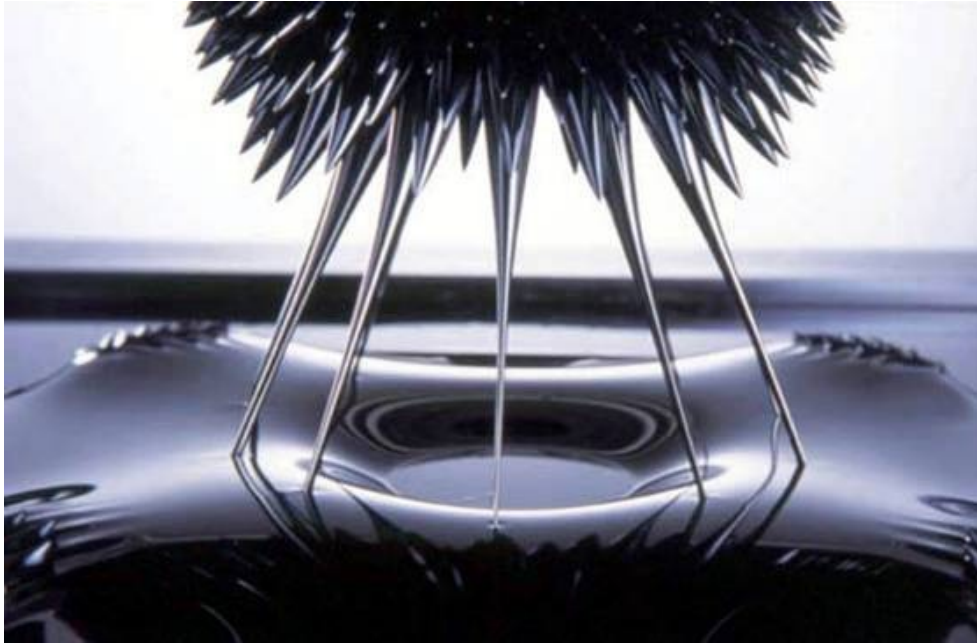
Like charges repel one another; unlike charges attract.

In other words, two objects carrying the same electrical charge repel each other, while objects carrying opposite charges attract.

This principle explains why, on a dry day, your hair may stand on end after being combed. As the comb passes through your hair, electrons are transferred from one material to the other through the triboelectric effect. If electrons are removed from your hair, the individual strands become positively charged and repel one another. Meanwhile, the comb acquires an excess of electrons, allowing it to attract small bits of paper through electrostatic forces. This gives new meaning to the phrase, "I'm having a bad hair day."

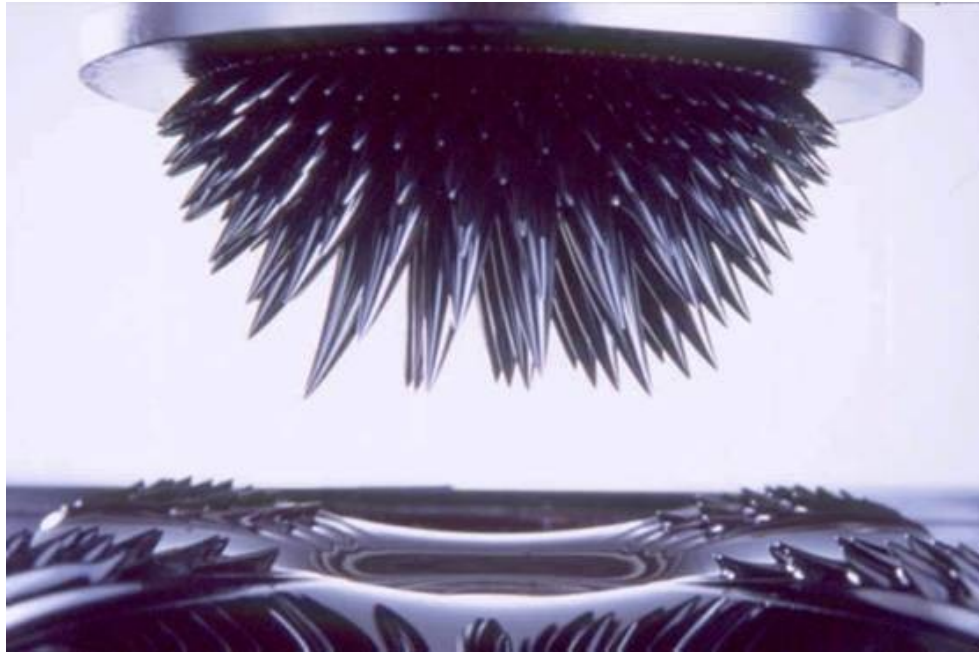
Artists, Astronomers and Physicists

The contemporary artists [Sachiko Kodama](#) and Minako Takeno created [*Protrude, Flow* \(2001\)](#), an interactive installation that uses computer-controlled electromagnets to manipulate ferrofluid, a liquid containing microscopic magnetic particles. As changing magnetic fields pass through the ferrofluid, it rises into dynamic spikes, ripples, and sculptural forms, making normally invisible magnetic fields visible as constantly evolving physical structures. The work responds to environmental sound and viewers' voices, translating invisible electromagnetic forces into a mesmerizing physical and visual experience.



Protrude, Flow by [Sachiko Kodama & Minako Takeno](#). 2001.

[*Protrude, Flow*](#) is composed of ferrofluid, a liquid containing microscopic ferromagnetic particles, whose movement is modulated by the sounds and moving images of viewers as they enter the installation space. Computer-controlled electromagnets transform the ferrofluid into complex, continuously evolving sculptural forms that reveal the invisible dynamics of magnetic fields. These mesmerizing transformations are simultaneously projected onto a large screen, extending the physical behavior of the ferrofluid into an immersive visual experience.



Protrude, Flow by [Sachiko Kodama & Minako Takeno](#). 2001.

In 1861, [James Clerk Maxwell](#) unified decades of research on electricity and magnetism into a remarkably elegant mathematical framework, now known as Maxwell's equations. These equations described electricity, magnetism, and light as different manifestations of the same electromagnetic field. From this theory, Maxwell predicted the existence of electromagnetic waves traveling at the speed of light. These waves were later experimentally confirmed by the physicist Heinrich Hertz, providing one of the great triumphs of nineteenth-century physics.

Understanding that like charges repel while unlike charges attract also helps explain many familiar experiences. For example, when you press your hand against a table, it does not pass through the surface because the electron clouds surrounding the atoms in your hand and the table strongly repel one another. At the atomic scale, electromagnetic forces—and the quantum mechanical rules governing electron behavior—prevent ordinary objects from occupying the same space. These forces also keep you from falling through the floor.

The same electromagnetic interactions hold your body together. Electrons are attracted to the positively charged nuclei of neighboring atoms, allowing atoms to bond into molecules and molecules into tissues, organs, and living organisms. In a very real sense, we are held together by an invisible electromagnetic glue.

To better understand electricity, we must first examine the structure of the atom and the remarkable process of experimentation, observation, and visualization that enabled scientists to uncover its composition. Equally important is understanding the history of these discoveries, for it reveals how scientific knowledge evolves through careful experimentation, creative insight, and the continual testing of new ideas.



M3 (NGC 5272), a globular cluster consisting of approximately 500,000 stars, located within our galaxy at a distance of approximately 30,600 light years. Taken with the Newtonian telescope at Fremont Peak State Park in California. By [Adrian Fernandez](#).

Humans have been working for 2,000 years to provide better visualizations of what atoms look like. These progressive and collective experiments, along with important visualization by hundreds of scientists, philosophers, and artists, all contribute to our current modern conception of what the atom is, and there is more to be discovered as string theory begins to sew the divide between Albert Einstein's General Relativity and Richard Feynman's Quantum Electrodynamics.

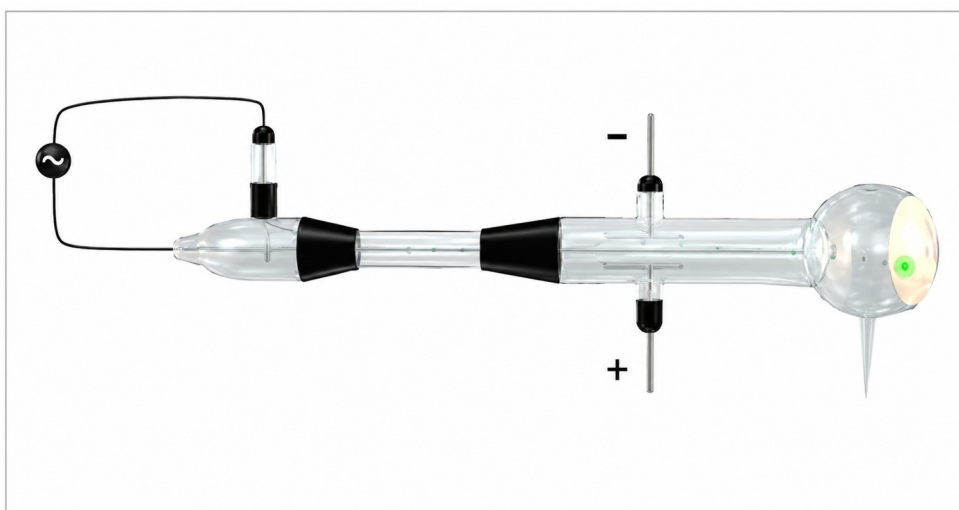
While the word *atom* comes from the Greek word *atomos*, which means *cannot be further divided*; we now know that atoms are complex entities that can be divided.

In 1808, John Dalton (1766–1844) was experimenting with evaporating liquid water inside enclosed containers. While observing the results of his experiment, he realized that water could exist inside the container as a gas, which is separate from the air. He noticed that when the gaseous water would condense, it would then return to its liquid state. Pondering this experiment, Dalton suggested that all atoms of a particular kind are the same weight and size and that atomic elements combine chemically into molecules, which then form compounds.

Physicist and Refinement of Atom Model

In 1897, physicists were investigating mysterious streams of particles known as cathode rays, produced inside evacuated glass discharge tubes. Building upon the earlier work of Sir William Crookes, Joseph John (J. J.) Thomson conducted a series of experiments at the Cavendish Laboratory at the University of Cambridge to determine the nature of these rays.

By passing cathode rays through carefully controlled electric and magnetic fields, Thomson demonstrated that they were composed of particles carrying a negative electric charge. He further showed that these particles possessed the same charge-to-mass ratio regardless of the material used to produce them, indicating that they were a universal constituent of all atoms. Thomson initially called these particles corpuscles, although they soon became known as electrons. His discovery revealed that atoms were not indivisible after all, but instead contained smaller, negatively charged particles.



In early cathode ray tubes, the wire was embedded in both ends of the tube and most of the air was pumped out. Heinrich Geissler was able to evacuate more air, and then the scientists noticed light with a fluorescent glow. These cathode ray tubes are the progenitors of neon and fluorescent lighting, as well as your computer monitor and TV.

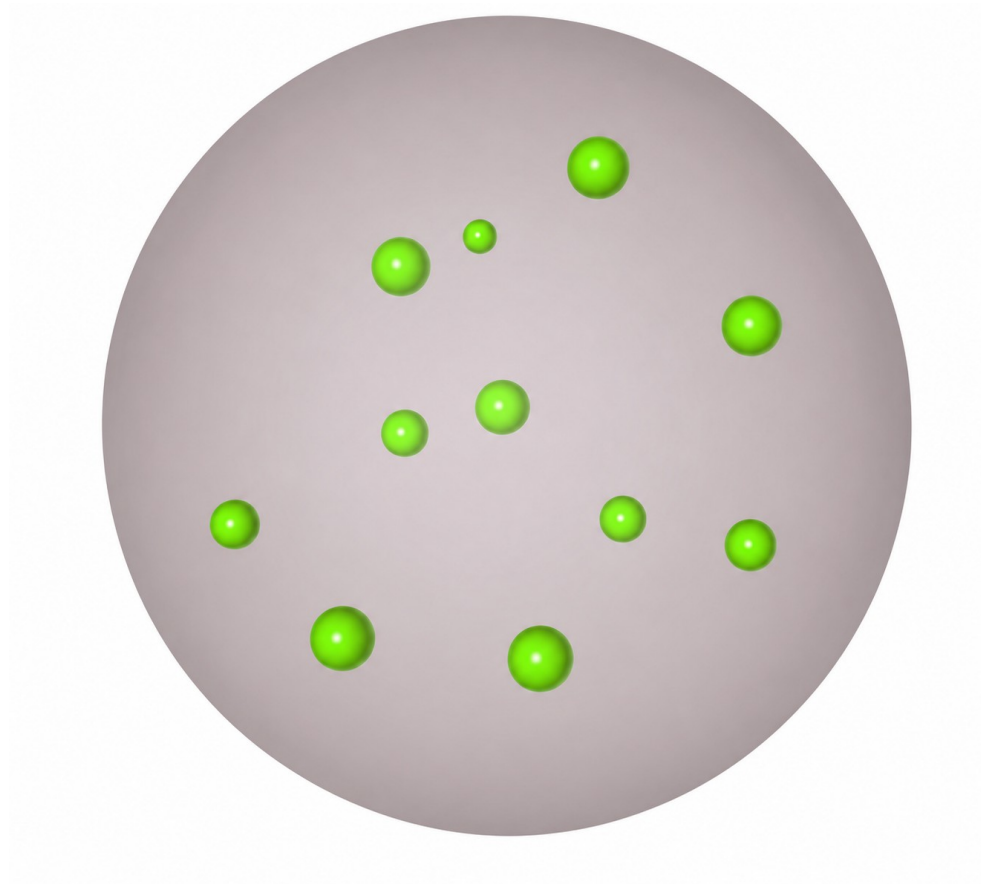
Thomson proposed that these corpuscles, later named electrons, were much smaller than atoms and represented a previously unknown class of subatomic particles. He further suggested that electrons were a constituent of every atom. This was a bold proposal for its time, as most scientists still believed that atoms were indivisible and represented the smallest units of matter.

To account for this new discovery, J. J. Thomson proposed a model of the atom in which negatively charged electrons were embedded within a diffuse sphere of positive charge. Although Thomson did not use the term himself, this model later became known as the "Plum Pudding Model," after the traditional English dessert in which raisins are distributed throughout a pudding. In this analogy, the electrons resemble the raisins suspended within a positively charged matrix.

Reflecting on the discovery of the electron, Thomson wrote:

"Could anything, at first sight, seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? which itself is so small that a crowd of these

atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science.”

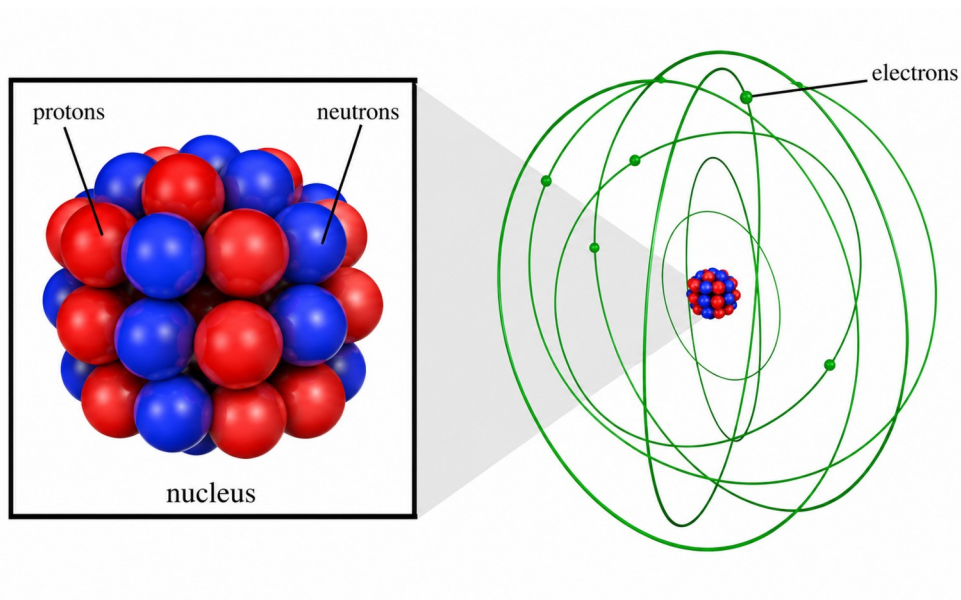


Thompson's Plum Pudding model of the atom. With green spheres being the electrons, or “corpuscles”, and the surrounding gray mass a zone of positive charges.

In 1911, [Ernest Rutherford](#) (1871–1937), a former student of J. J. Thomson, overturned the plum pudding model through a series of experiments that revealed the existence of the atomic nucleus. Rutherford directed a beam of alpha particles at an ultrathin sheet of gold foil and observed that, while most of the particles passed straight through the foil, a small fraction were deflected at large angles, with a very few even rebounding almost directly backward. These unexpected results demonstrated that nearly all of an atom's mass and positive charge are concentrated within an extremely small, dense nucleus, while the remainder of the atom consists largely of empty space occupied by electrons.



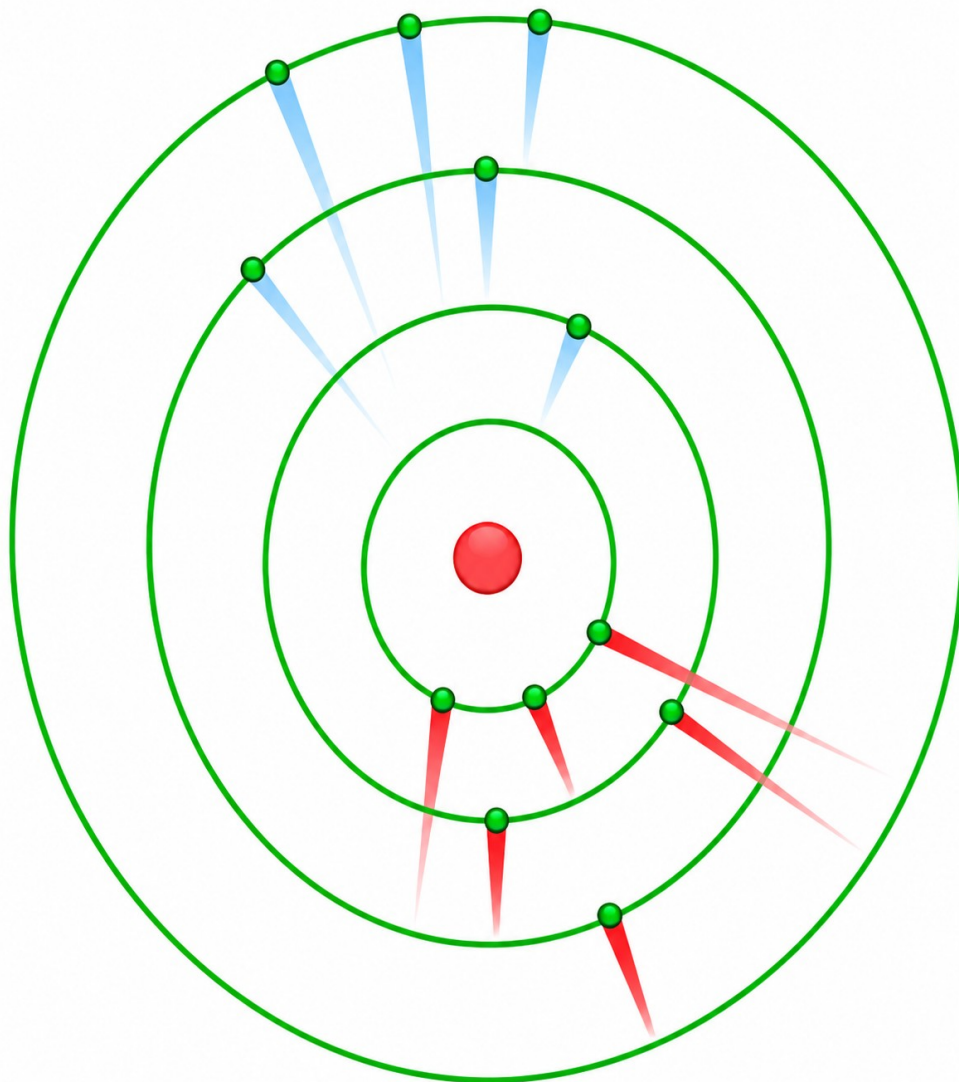
Alpha particles are a kind of particle that comes from radioactive nuclei. They consist of two neutrons and two protons.



Rutherford's model of the atom with imprecise electron orbit.

[Rutherford](#) proposed that the atom resembled a miniature solar system, with a tiny, dense, positively charged nucleus at its center surrounded by orbiting electrons. Although this planetary model would later be refined by quantum mechanics, it represented a major advance over Thomson's plum pudding model by recognizing that nearly all of an atom's mass is concentrated within its nucleus. In subsequent years, the nucleus was shown to consist primarily of protons and neutrons.

In 1932, James Chadwick (1891–1974) discovered the neutron, completing the basic picture of the atomic nucleus. Neutrons reside alongside protons within the nucleus and possess nearly the same mass as protons but carry no electrical charge. Although electrically neutral, neutrons play a crucial role in stabilizing atomic nuclei by helping offset the strong electrostatic repulsion between positively charged protons through the strong nuclear force.



Bohr atom has energy shells, which the electrons can jump up to and down to. The nucleus is in red with protons and neutrons.

Building upon [Ernest Rutherford's](#) nuclear model of the atom and the emerging ideas of quantum theory introduced by [Max Planck](#), Niels Bohr (1885–1962) proposed a new model of the atom in 1913. Bohr suggested that electrons occupy discrete energy levels, or shells, surrounding the nucleus and that they can move between these levels only by absorbing or emitting specific amounts of energy.

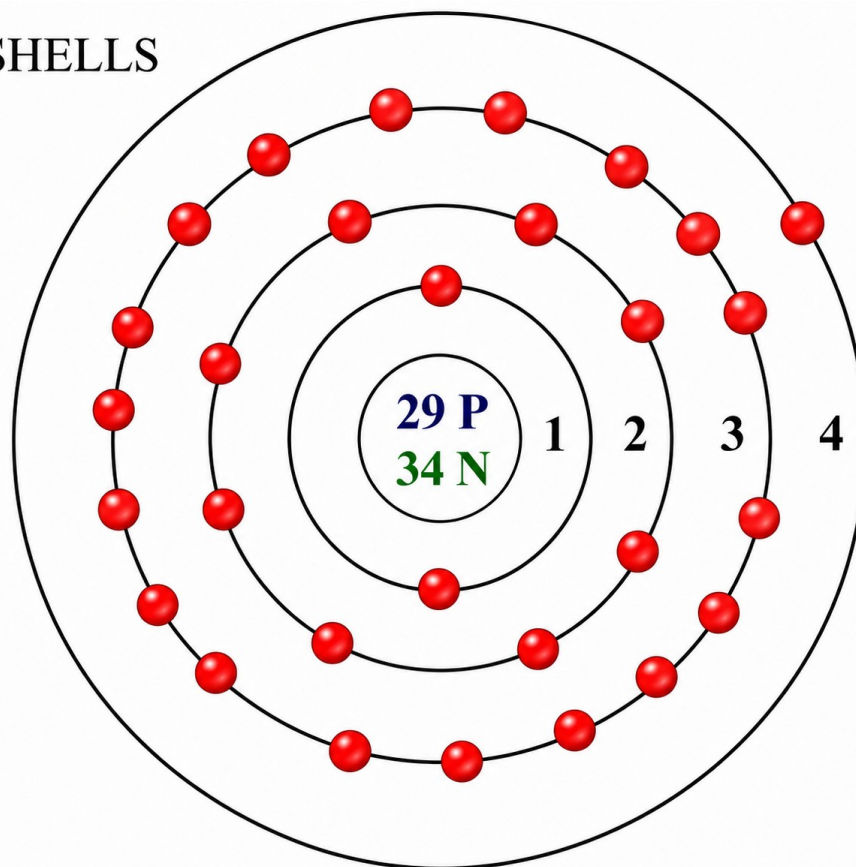
The Bohr model, often illustrated as a miniature planetary system, remains one of the first models taught in schools because it is intuitive and easy to visualize. Although modern quantum mechanics has replaced this picture with a probabilistic description of electron orbitals, the Bohr model remains an important stepping stone in understanding atomic structure. Bohr also recognized that the arrangement of electrons—particularly those in the outermost energy levels—largely determines an atom's chemical properties, an idea that was further developed by Gilbert N. Lewis through his theory of chemical bonding and valence electrons.

Convergent Creators

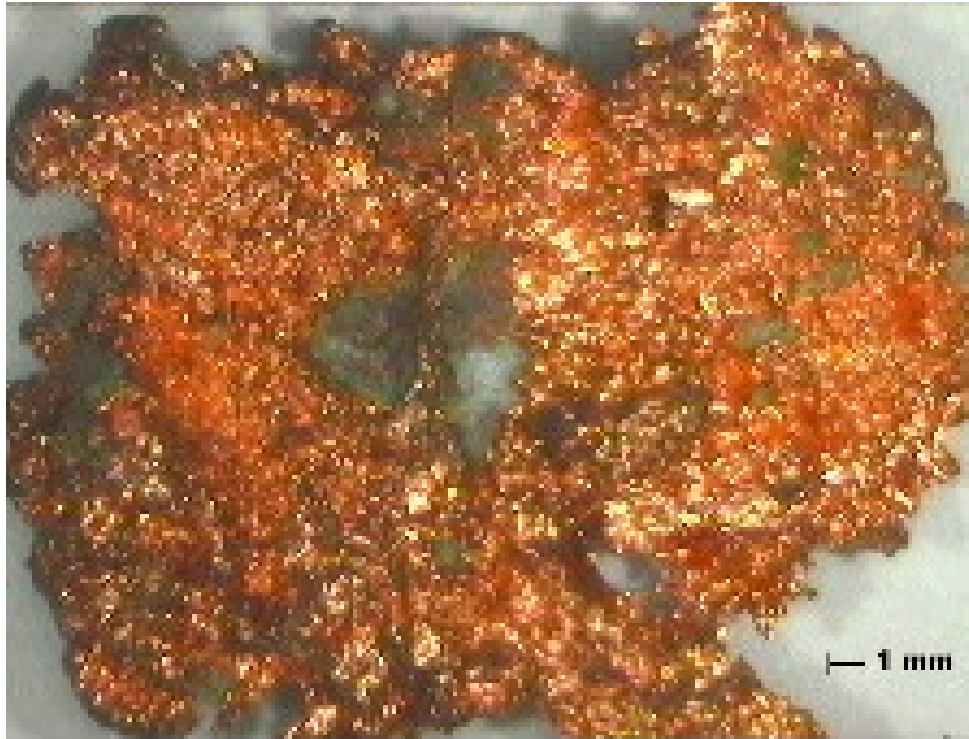
The idea that electrons could move between discrete energy levels was one of Niels Bohr's most important contributions to the emerging field of quantum theory. In the Bohr model, an electron moves to a higher energy level farther from the nucleus by absorbing a photon with precisely the required amount of energy. When it returns to a lower energy level, it emits that energy as a photon. The wavelength—and therefore the color—of the absorbed or emitted light depends upon the difference between the two energy levels. In the diagram, blue and red are used to distinguish absorption from emission rather than to indicate colors that always occur.

Bohr represented electrons as occupying distinct energy shells around the nucleus. In the modern quantum-mechanical model, however, electrons do not travel in fixed circular paths. Their locations are instead described by probability distributions called atomic orbitals, which indicate the regions in which an electron is most likely to be detected. The copper atom illustrated below has a single electron in its outermost energy level, commonly described as a valence electron, although copper's chemical behavior also involves electrons in its partially filled inner d orbitals.

SHELLS



A simple model of a copper atom with 29 protons and 29 orbiting electrons. The atomic number of copper is 29. Copper has one electron in its outer shell. The atomic weight of the atom is the combined weight of all particles including neutrons, which also have mass.



Natural Copper Ore. Image 2-8x by Dr. James Mayer.

As the atom gains electrons, increasing the density of electrons in a shell, the atom increases in size.



Valence electrons orbit in the outermost shell of the atom.

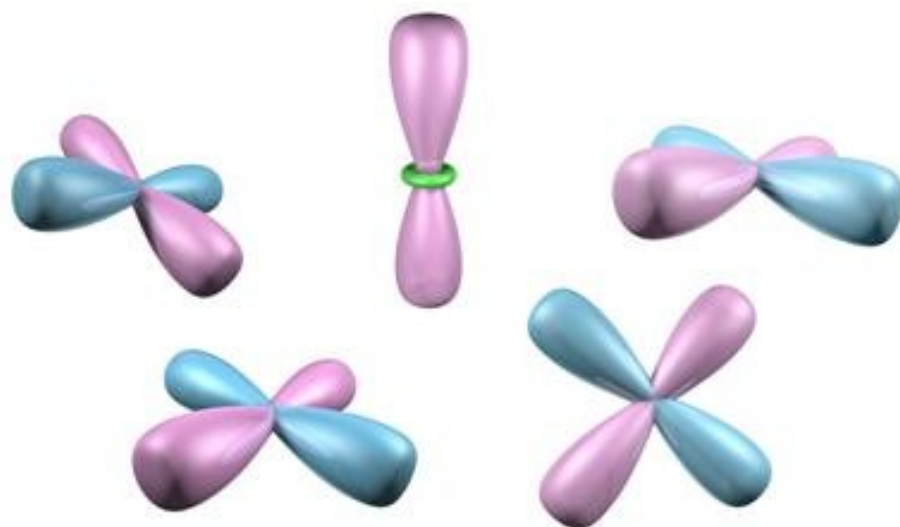


Rotative Plaques (precision object in motion) by [Marcel Duchamp](#) (1887–1968) and Man Ray (1890–1976). 1920. This was perhaps one of the first interactive works as it required the viewer to first plug the work in and then stand back and observe the work at a distance.

Louis de Broglie (1892–1987), whose 1924 theory proposed that matter possesses both wave-like and particle-like properties, inspired [Erwin Schrödinger](#) (1887–1961) to develop his theory of wave mechanics. Building on de Broglie's ideas, Schrödinger formulated an equation describing the wave-like behavior of electrons within atoms, laying the foundation for modern quantum mechanics.

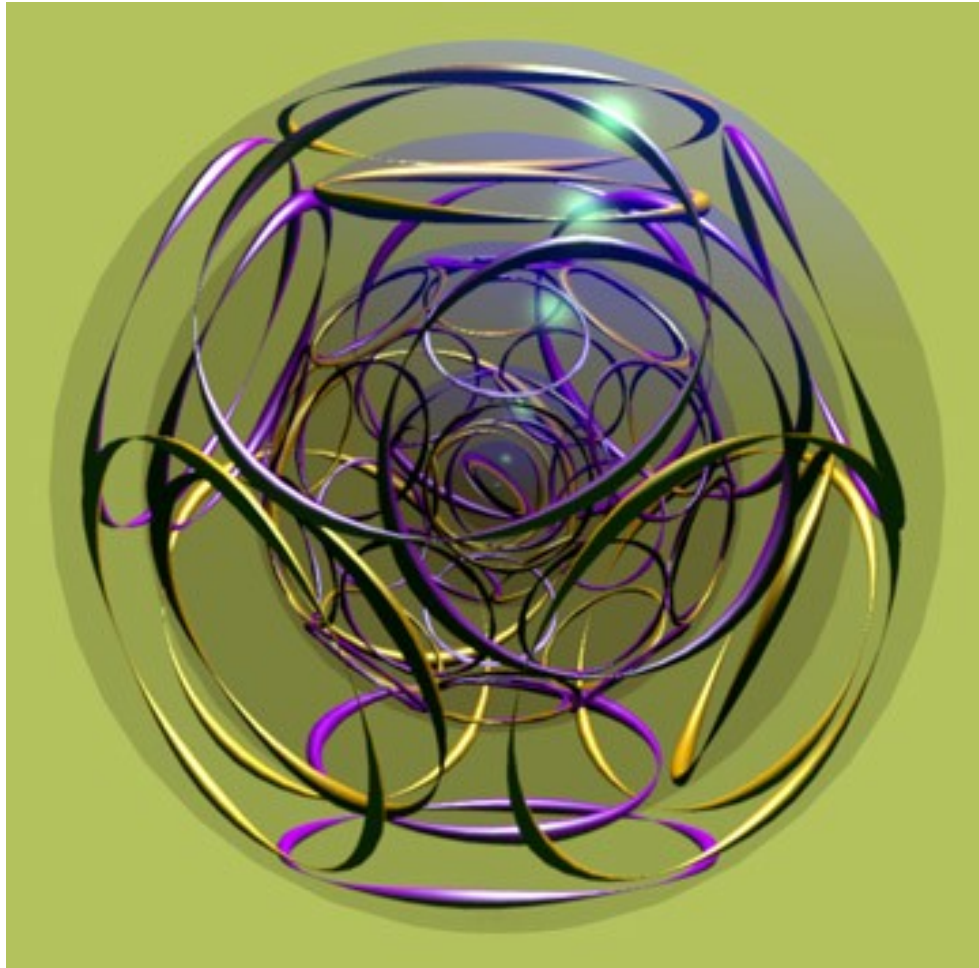
Schrödinger discarded the idea of electrons traveling in precise planetary orbits around the nucleus. Instead, he described electrons in terms of wavefunctions, which define the probability of finding an electron within a particular region of space surrounding the nucleus. These probability distributions are known as atomic orbitals.

In the figure below, the balloon-like forms represent three-dimensional atomic orbitals—the regions of space in which electrons are most likely to be found. Although these orbitals are often illustrated as solid shapes, they actually represent probability distributions rather than physical boundaries.



Schrödinger's atomic model

The contemporary artist [Kenneth Snelson](#) has created a remarkable body of work inspired by the structure of the atom and the wave nature of matter. In his atom models, the particle-like electrons are reimagined as de Broglie matter-wave forms—interacting circular structures that occupy the space surrounding the nucleus and suggest an architectural organization of the atom. While these visualizations are artistic interpretations rather than scientific models, they provide a compelling way to imagine the complex spatial relationships described by quantum mechanics. Snelson has produced hundreds of striking three-dimensional renderings and animations exploring his vision of atomic electron architecture, many of which are available on his YouTube channel.



[Kenneth Snelson's](#) model of the atom. The circles represent electron probabilities pushing against each other.

The contemporary artist Richard Harned has also explored ways to visualize quantum phenomena through large-scale kinetic neon sculpture. In *Quantum Ladder* (1987), Harned created an installation that evokes the wave-particle duality central to quantum mechanics. As illuminated neon tubes rotate within a steel framework, they generate the illusion of a luminous spherical form that appears to exist simultaneously as both a discrete object and a continuous field. Rather than illustrating quantum mechanics literally, the work offers a poetic interpretation of the elusive relationship between waves, particles, motion, and perception.



Wave/particle duality is the notion that matter and energy can exhibit properties of both particle mechanics and wave physics. For example, light, which is electromagnetic radiation and in the realm of waves, can exhibit the properties of particles.



Quantum Ladder Installation by [Richard Harned](#). 1987. 16ft high x 62ft wide x 30ft deep. Bevier Gallery, RIT, Rochester, NY.

Quantum Ladder hypnotically oscillates through changing reflections that transform curved forms into straight ones and straight forms into curved ones, creating a shifting visual metaphor for the elusive nature of quantum reality. The work also incorporates sound. BBs enclosed within the sculpture's square steel tubing produce delicate, tinkling oscillations that echo the visual rhythms of the piece, creating an immersive audiovisual experience.

In the modern quantum-mechanical model, electrons occupy discrete energy levels associated with atomic orbitals surrounding the nucleus. In general, electrons with higher energy occupy orbitals that extend farther from the nucleus than those of lower energy, although the exact arrangement depends upon the quantum properties of each orbital rather than simply its distance from the nucleus.

Models of the Atom

The number of protons in an atom's nucleus identifies the element by its atomic number. For example, hydrogen, with an atomic number of one, is the lightest and simplest element on the periodic table. The atomic mass of the most common isotope of hydrogen is approximately 1.008 atomic mass units (u), with its single proton accounting for nearly all of that mass. Electrons contribute only a tiny fraction, and the slight difference between the combined masses of the particles and the measured atomic mass results from the nuclear binding energy that holds the nucleus together.

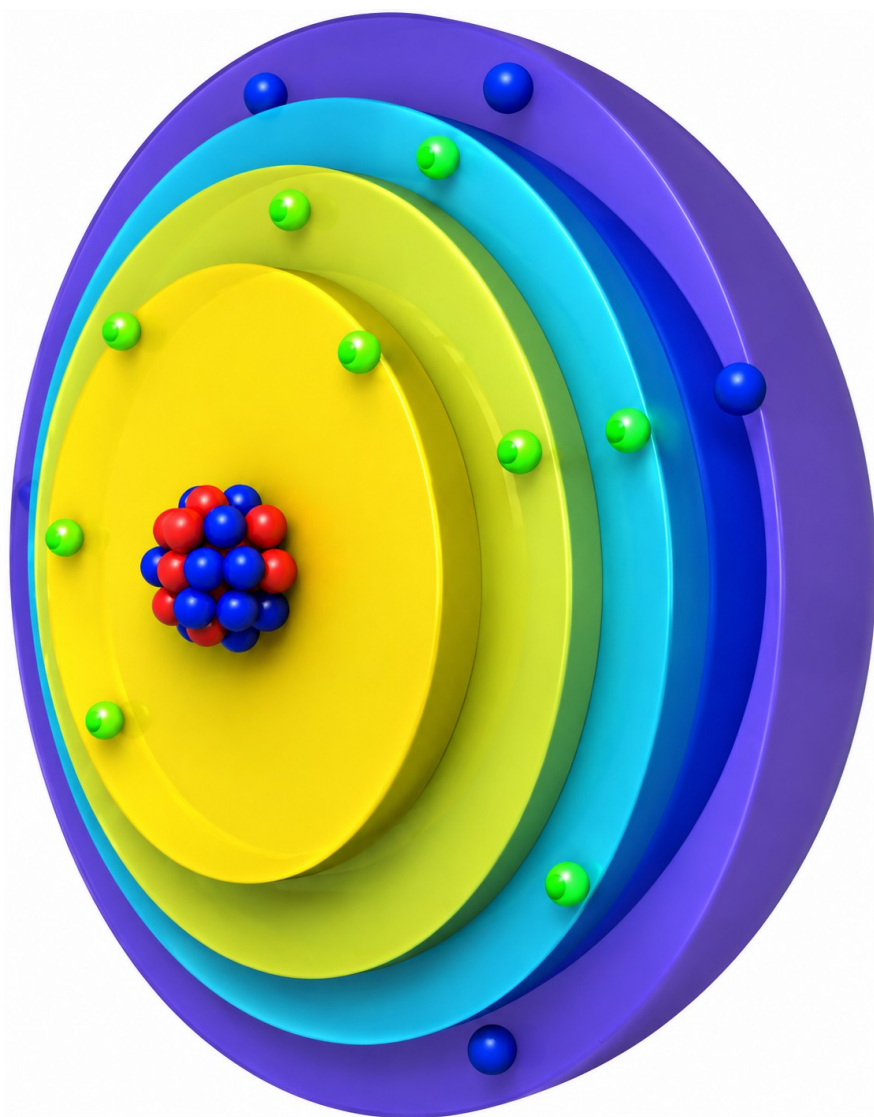
Hydrogen is both the lightest element and the most abundant element in the universe. It is found in water and in every known living organism, and in the interiors of stars it exists as an extremely hot plasma where nuclear fusion produces the heavier elements from which planets—and ultimately life—are formed. So when poets say that we are made of stardust, they are remarkably close to the truth. Nearly every element in our bodies, from the calcium in our bones to the iron in our blood, was forged within ancient stars before becoming part of the Earth.



Atomic number represents the number of protons in the nucleus, and, if it's a neutral atom, the number of electrons orbiting the nucleus.



Atomic weight is the mass of one atom of an element.



An atom with four shells of electrons. There are four valence electrons in the outermost shell.

While all of these models visualize and describe certain characteristics of atoms, quantum mechanics tells us that an electron's exact position and momentum cannot be known simultaneously with complete precision. Rather than behaving as tiny planets orbiting the nucleus, electrons are described by wavefunctions, mathematical descriptions that allow scientists to calculate the probability of finding an electron in a particular region of space. Instead of imagining fixed planetary orbits, imagine diffuse probability clouds surrounding the nucleus.

Although the exact location of an electron is inherently uncertain, other properties of the atom are well established. Protons within the nucleus carry a positive electric charge, neutrons are electrically neutral, and electrons possess a negative charge. Early atomic models described atoms as being composed only of protons, neutrons, and electrons. Today, physicists know that these particles are themselves part of a much richer subatomic world described by the Standard Model, which includes quarks, leptons, gluons, bosons, and other fundamental particles, with the possibility that additional particles remain to be discovered.

Many of these particles have been identified using powerful particle accelerators, such as the Large Hadron Collider. These machines accelerate protons or other subatomic particles to velocities approaching the speed of light before colliding them at enormous energies. The collisions convert energy into new particles, allowing scientists to observe and study the fundamental building blocks of matter and the forces that govern them. Much like examining the fragments of a shattered object reveals clues about its construction, these high-energy collisions help reveal the underlying architecture of the universe.



Supercolliders are machines that accelerate and smash particles together using very powerful magnets.

With the aid of powerful particle accelerators, physicists have discovered that protons and neutrons within the atomic nucleus are themselves composed of even smaller particles called quarks. Six types, or flavors, of quarks have been identified: up, down, charm, strange, top, and bottom. Ordinary matter is built almost entirely from just the up and down quarks.

Particles composed of quarks are known as hadrons, and protons and neutrons are the most familiar examples. As far as current science can determine, quarks themselves are fundamental particles—they are not known to be composed of anything smaller.

I have heard physicists joke that if you confidently claim, "I understand the atom," you are probably not a very good physicist. Although our understanding of matter has advanced enormously over the past century, each discovery has revealed new layers of complexity, and much remains to be explored and understood.

Quarks are the fundamental particles that make up protons and neutrons. Each proton and neutron is composed of three quarks. Up quarks have an electric charge of $+2/3$, while down quarks have a charge of $-1/3$. A proton, with an overall charge of $+1$, contains two up quarks and one down quark ($+2/3 + +2/3 - 1/3 = +1$). A neutron, with no net electric charge, contains two down quarks and one up quark ($-1/3 - 1/3 + 2/3 = 0$). In 1964, physicist Murray Gell-Mann proposed the quark model, fundamentally changing our understanding of matter.

It is illuminating to follow the progressive visualization of the atom and to recognize that scientific knowledge advances through an evolving process of observation, experimentation, imagination, and visualization. Each new model builds upon earlier ideas while revealing new questions to explore.

The same creative process applies to invention and art. If you can visualize and imagine your idea, then progressively refine your understanding of what it is you are creating, your idea itself will evolve and become more clearly defined.

It is wise to keep a sketchbook of your ideas and return to it often. The reward may be a new invention, a work of art, or an entirely new way of seeing. Knowledge is cumulative, and the processes of ideation, creation, and invention often require that established knowledge recede temporarily into the background, allowing unexpected connections and genuinely new ideas to emerge.

Current Flow and Electromagnetism

In studying the intricacies of the atom, it is important to remember that negatively charged electrons are attracted to the positively charged nucleus. Early models compared electrons to planets orbiting the Sun, but this analogy is only partly useful. Just as planets remain in orbit because they are continually falling through the curved gravitational field surrounding the Sun, electrons are bound to the nucleus by the electromagnetic force. Unlike planets, however, electrons do not travel in fixed paths but are described by quantum-mechanical probability distributions.

All atoms have one or more valence electrons, the electrons occupying the atom's outermost energy level. These electrons participate most readily in chemical reactions and electrical conduction. Here it is important to distinguish between the simplified planetary model and the modern quantum-mechanical picture. While illustrations often show electrons circling the nucleus, valence electrons are better understood as occupying atomic orbitals that may overlap with those of neighboring atoms.

When atoms bond together to form molecules or solids, valence electrons may be shared, transferred, or become free to move through a material. The movement of these charge carriers produces electric current, a concept we will explore further in Chapter 3

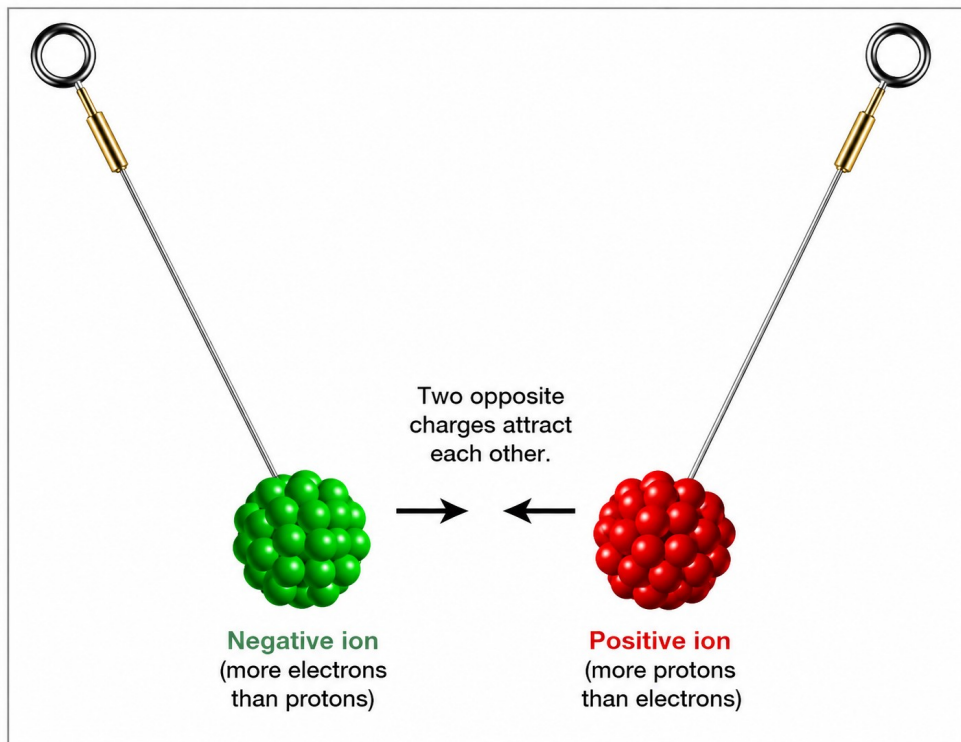
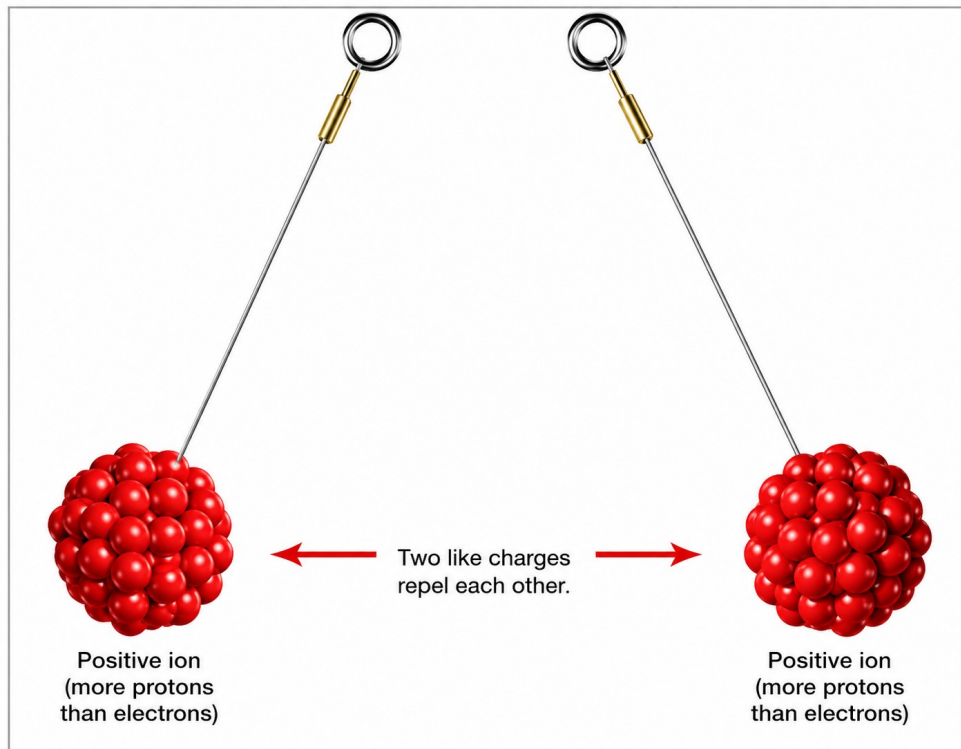


Current flow is the free movement of electrons through a conductor.

In most atoms, the positive charges of the protons are balanced by the negative charges of the electrons, giving the atom no overall electrical charge. Large collections of atoms are therefore usually electrically neutral. Nevertheless, electrons can become detached from atoms and move to other atoms or through materials. Friction, heat, light, and electric fields can provide enough energy for electrons to move from one atom to another or to become free to travel through a material.

When an atom loses one or more electrons, it becomes a positive ion (cation), because it now contains more positively charged protons than negatively charged electrons. When an atom gains one or more electrons, it becomes a negative ion (anion), because the electrons outnumber the protons. The atom now possesses a net negative electrical charge. For example, when the single electron is removed from a hydrogen atom, the remaining positive ion is simply its nucleus—a lone proton.

One of the fundamental principles of electricity is that like electric charges repel one another, while opposite charges attract. Thus, if we bring two positively charged ions or two negatively charged ions close together, they will repel each other. Conversely, a positively charged ion and a negatively charged ion will attract, an interaction that underlies chemical bonding, electrostatic forces, and many electrical phenomena.



This same principle tells us that when two unlike ions—a positive ion and a negative ion—come together, they attract one another. Perhaps our grandmothers were right when they said that "opposites attract."

The attractive and repulsive forces between charged particles are among the fundamental interactions of nature. By controlling these invisible forces, scientists and engineers have developed countless electrical technologies. Artists, too, have long explored these phenomena, creating works that harness electricity, magnetism, and electromagnetism to produce movement, sound, light, and dynamic interactions.

The artist Takis Vassilakis (Takis), a pioneer of kinetic and electromagnetic art, created numerous sculptures and installations that employed magnetic fields as active artistic materials. Although entirely self-taught, Takis became one of the most influential artists working with invisible forces. In 1960 he produced the large-scale installation *Télémagétique* at the [Alexander Iolas Gallery](#) in New York, where suspended metal forms responded to magnetic forces, creating an environment animated by invisible fields.

The contemporary artist [Mona Hatoum](#) explored similar ideas in *Socle du Monde* (1992–93), a work consisting of a steel table containing a powerful magnet beneath its surface and covered with iron filings. The filings continually rearrange themselves into intricate patterns that reveal the otherwise invisible magnetic field, producing a constantly shifting landscape of elegant curves and branching forms.



Socle du Monde by Mona Hatoum. 1992–1993. 163.6 x 199.5 x 199.5 cm. © 2000 Mona Hatoum.

Summary

We have learned that our understanding of the structure of matter has continually evolved and that experimentation, observation, imagination, visualization, discussion, and testing are all essential to understanding our material universe.

We have discovered that the valence electrons farthest from the nucleus are the electrons primarily responsible for chemical bonding and the flow of electrical current. We have also seen that electrons and electromagnetic forces can be manipulated in fascinating and artistic ways, and that artists and scientists both contribute to this ongoing dialogue. Through visualization and modeling, as with [Kenneth Snelson](#), and through material, formal, and process-based explorations by artists such as Richard Harned, Sachiko Kodama and Minako Takeno, [Mona Hatoum](#), and Takis Vassilakis (Takis), invisible physical forces become tangible, experiential, and poetic.

Future

Our understanding of the universe continues to evolve. Physicists are still searching for a deeper theory that can unify quantum mechanics, which governs the microscopic world of atoms and elementary particles, with general relativity, which describes gravity and the large-scale structure of the universe. Such a theory would bring together our understanding of the four known fundamental forces: gravity, electromagnetism, the strong nuclear force, and the weak nuclear force.

One of the most ambitious proposals is string theory, which suggests that the elementary particles we observe may arise from extraordinarily small vibrating strings of energy existing in higher-dimensional space. Although mathematically elegant and influential, string theory has not yet been experimentally confirmed, and other approaches—including loop quantum gravity, causal set theory, and new ideas emerging from quantum information theory—continue to be actively explored.

Whether or not a single "Theory of Everything" is ultimately discovered, the pursuit of deeper explanations reminds us that science is an evolving creative endeavor. Every generation develops new instruments, new experiments, and new ways of visualizing nature that challenge previous assumptions and expand our understanding of reality.

*In the preface to *The Elegant Universe*, Brian Greene writes:*

"By fearlessly taking on science, and leveraging its intrinsic fascination to produce entertaining works of substance and drama, the arts may well be the perfect medium to fully integrate science into the world's conversation. We may even find that the art world's scientifically inspired works will provide new stimulus to the scientific imagination and, in some possibly intangible way, prepare us for the next step in understanding the universe."

I believe this observation has become even more relevant today. As artificial intelligence, biotechnology, quantum computing, robotics, and new forms of scientific visualization increasingly shape our understanding of the world, artists continue to play an essential role—not only by interpreting these discoveries but also by imagining new questions, revealing unseen relationships, and helping society envision possible futures. The dialogue between art, science, and technology has never been more important.

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Chapter 3

Current, Voltage, and the Multimeter

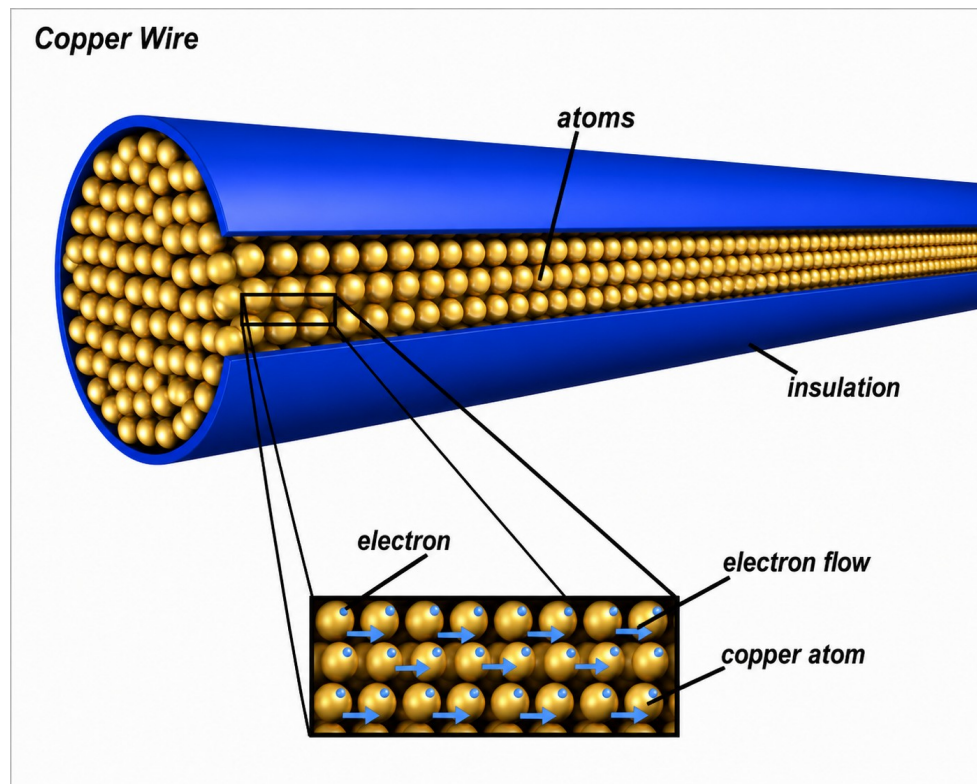
Dominoes

*"The most beautiful thing we can experience is the mysterious."
— Albert Einstein*

Question: What is the nature of electron movement?

Imagine a metal doorknob containing an enormous number of atoms whose outermost, or valence, electrons are only loosely bound. In a metal, many of these electrons are free to move throughout the material, forming what is often described as an electron sea. Although each individual electron moves only very slowly when an electric current flows, countless billions of billions of electrons collectively respond to electric fields, allowing electrical energy to travel rapidly through the conductor.

Now imagine walking toward the door while shuffling across a carpet. Friction between the soles of your shoes and the carpet causes some electrons to transfer from one material to the other, a phenomenon known as the triboelectric effect. As a result, your body accumulates an excess electrical charge. When you finally touch the metal doorknob, the excess electrons rapidly discharge through the conductive metal and into the surrounding environment. The tiny spark and sudden current produce the familiar shock—ouch!



Visualization of electron flow through the wire.

To establish a workable relationship with electron flow, we must first establish a way of counting the number of electrons flowing past a point in time. Approximately 6,250,000,000,000,000,000, or 6.25×10^{18} , electrons pass a point each second in a current of one ampere. These quantities

can be measured in a number of ways, one of which we will explore in the lab for this chapter. Artists such as [Walter De Maria](#) have also explored the immense power and beauty of electrical phenomena in works that reveal the invisible forces present in nature.

Copper is one of the most common conductors because it contains a large number of mobile conduction electrons and has relatively low electrical resistance. As electrons are pushed into one end of a copper wire, they cause neighboring electrons to move, transmitting electrical energy rapidly through the conductor.

To move electrons through a wire, we create a closed electrical circuit and apply a voltage, usually supplied by a battery or power supply. This voltage creates an electric field that causes the free electrons in the wire to drift. You can also imagine dominoes knocking one another down in sequence. The dominoes themselves do not travel across the floor, but they transmit energy from one to the next, just as electrical energy propagates rapidly through a conductor while the individual electrons drift much more slowly.

Metal wire is an excellent conductor because its outermost, or valence, electrons are only loosely bound to their atoms and are free to move throughout the material. Although electrons move easily through a conductor, they continually collide with vibrating metal atoms and other imperfections within the material. These collisions impede their motion and give rise to electrical resistance.

[Walter De Maria](#) created an artwork that reveals the immense electrical forces generated within turbulent storm clouds. [The Lightning Field](#) (1977) consists of 400 polished stainless steel poles, each two inches in diameter, arranged in a precise grid measuring one mile by one kilometer in the high desert of western New Mexico. The carefully positioned poles increase the likelihood that lightning will discharge through the installation into the Earth, transforming a natural electrical phenomenon into a sublime artistic experience while making viewers acutely aware of the invisible forces present in the atmosphere.



The Lightning Field by Walter De Maria, 1977. Stainless steel rods, lightning, and friction from rain clouds in Southwestern New Mexico. Image compliments of [Cranberries on Flickr](#).



Horizontal Lighting in Vienna, Austria by [Adrian Fernandez](#).

A good way to visualize the relationship between wire width and current flow is to imagine a wide pipe carrying a large volume of water. Now imagine trying to force that same volume of water through a much narrower pipe. You can easily visualize that the increased pressure would place greater stress on the smaller pipe. Similarly, if too much electrical current is forced through a wire that is too thin, the wire's electrical resistance causes it to heat up. If the current becomes excessive, the wire may become hot enough to melt, breaking the circuit. This intentional weak point is the principle behind a fuse, which sacrifices itself to protect the more sensitive components connected elsewhere in the circuit.



Electrons cascade through the wire like marbles bumping up against each other, but we need to push on the electrons with some electromotive force. This is a cross section and in order for electrons to move, you need a complete circuit.

We have just described a fuse. A fuse is designed to melt and disconnect the circuit if too much current is forced through its thin wire. As electrons move through the wire, the wire's electrical resistance converts electrical energy into heat. If the current becomes too great, the metal heats until it melts, opening the circuit and protecting the more sensitive components beyond it.

A fuse also tells us, intuitively, that the thickness of a wire is directly related to its ability to safely carry electrical current. If the wire is not thick enough for the amount of current flowing through it, excessive heating can damage electronic components or, in the worst case, start a fire.

Intuition is a wonderful way to develop a feel for current flow, but to understand and measure electricity accurately, we must also learn to work with actual numbers.

Current and Frequency

Current (I) is measured in units called amperes (A). One ampere is equal to the flow of one coulomb of electric charge per second. Since each electron carries a very small amount of charge, one ampere in a metal wire corresponds to approximately 6.25×10^{18} electrons passing a point each second.



Current (I) is the number of electrons flowing past a point during a fixed period of time.

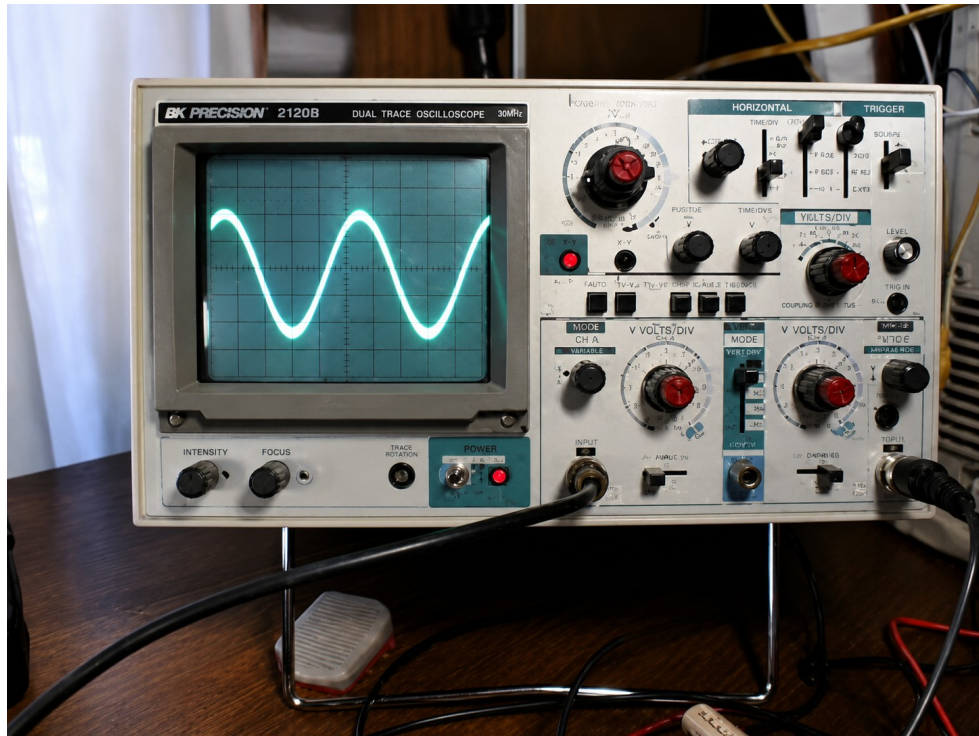
While current refers to the flow of electric charge, there are different kinds of current. Direct current (DC) flows in only one direction. In metal conductors, the electrons drift in the same direction throughout the circuit.

DC powers most microcontrollers and many consumer electronic devices. This type of power comes from DC sources such as batteries or from AC power that has been converted to DC by a power supply.

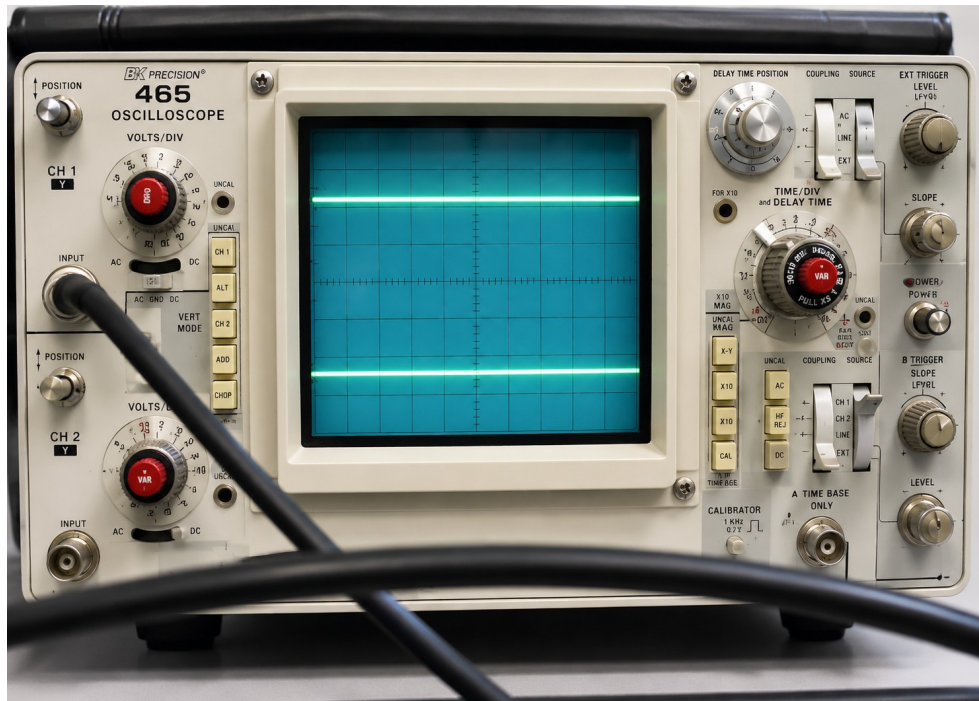
Alternating current (AC) is current that periodically reverses direction while continually changing in magnitude. AC is the form of electricity distributed by power stations because its voltage can be efficiently increased or decreased using transformers. By transmitting electrical power at very high voltages and relatively low currents, energy losses due to heating in transmission lines are greatly reduced.

The electrical power supplied by a standard wall outlet in North America is 60 hertz (Hz) AC, meaning the current reverses direction 60 times each second. Many other parts of the world use 50 Hz AC. The ability to transmit electricity efficiently over long distances is one of the primary reasons alternating current became the worldwide standard for electrical power distribution.

The word Hertz (Hz) honors the German physicist [Heinrich Rudolf Hertz](#) (1857–1894), who was the first to experimentally generate and detect electromagnetic radio waves, confirming the predictions of [James Clerk Maxwell](#).
Hertz is the SI unit of frequency, where one hertz (1 Hz) is equal to one cycle per second.



This is an image of an oscilloscope used to read and observe the waveforms of AC and DC signals. Here the scope is set to read AC, and the waveform shows how when the sine wave is in the middle of the scope the voltage is going one way, and when it is below the middle of the scope it is traveling in the opposite direction.



Frequency is the number of cycles occurring during a given period of time and is measured in hertz (Hz).

Although direct current (DC) flows in only one direction, its voltage or current can still vary over time. Many of you are familiar with the term gigahertz (GHz) from the operating frequency of computer

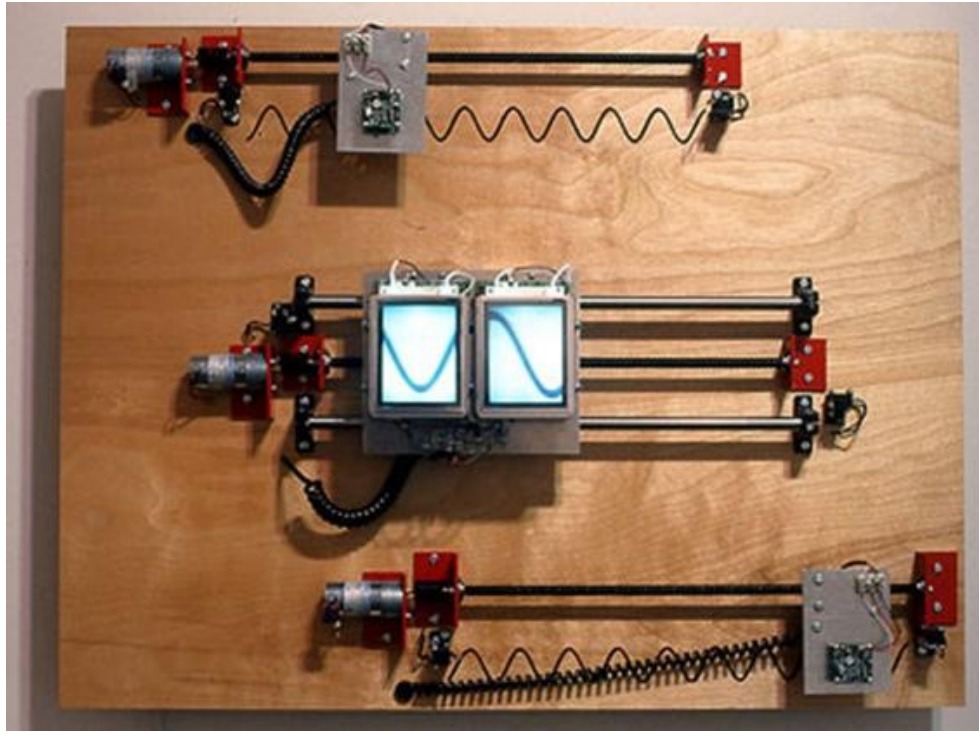
processors. One gigahertz is equal to one billion hertz, or one billion cycles per second. A signal may have a frequency of 20 Hz, 50 Hz, or billions of cycles per second. Digital computers use rapidly switching DC signals, often in the gigahertz range, to perform arithmetic and logical operations. These signals are typically square waves, rapidly switching between two voltage levels—for example, 0 volts and 5 volts, or 0 volts and 3.3 volts in many modern microcontrollers. This differs from alternating current because the voltage changes in magnitude but does not reverse polarity. A typical AC cycle progresses from a positive voltage, through zero volts, to a negative voltage before returning to positive again.

At the end of the nineteenth century, the inventor [Thomas Edison](#) developed the practical incandescent light bulb and recognized that it required an electrical distribution system. Edison established local DC generating stations to supply power for lighting and motors. At the same time, the [Westinghouse Electric Company](#), working with the brilliant inventor [Nikola Tesla](#), championed alternating current (AC) and developed efficient AC motors and transformers. This rivalry became known as the War of the Currents, a competition between Edison's DC system and Westinghouse's AC distribution network. During this public campaign, animals—including dogs and cats—were tragically electrocuted in demonstrations intended to influence public opinion about electrical safety. Ultimately, AC proved far more practical for transmitting electrical power over long distances and became the worldwide standard for electrical power distribution.

The contemporary artist Andrew Neumann has created a work that uses the AC sine wave as a formal element. Rather than displaying an actual electrical waveform on an oscilloscope, Neumann translates its characteristic shape into bent wire sculptures. Two cameras capture these sculptural waveforms and transmit live video to two LCD monitors, reinforcing the visual language of electrical transmission and oscillation.

Neumann's work engages questions surrounding technology, communication, and the distribution of power—both electrical and social. This piece is from his Constructures series, which recontextualizes iconic technological forms and invites viewers to reconsider their cultural and political meanings.

In Neumann's words, the work examines power systems while "questioning its main function as a reflection of the authoritative and corporate powers that it is most clearly aligned and supported by."



Dual Asynchronous Sine Waves by Andrew Neumann, 2001, 24" x 32" x 8".

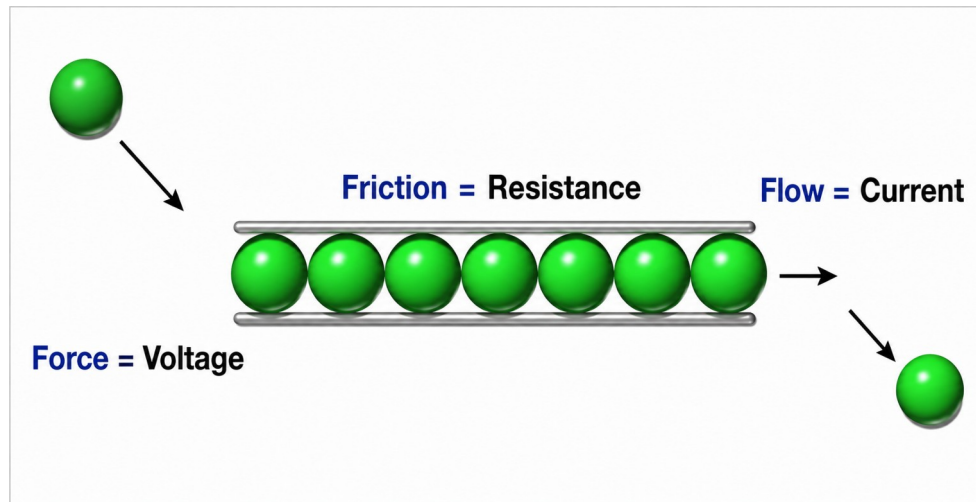
In answer to the earlier question, "How do you get electrons to move through materials?", I stated that you need to pile up a bunch of electrons near one end of a wire and create a complete circuit. More precisely, you create a difference in electrical potential (voltage) across the wire. When the circuit is closed, this voltage establishes an electric field that causes electrons throughout the conductor to drift, producing an electric current.

Voltage

The function of Art is to disturb. Science reassures.

— George Braque

Well, we can think of this "pile of electrons" as creating voltage, designated as V (or sometimes E , for electromotive force), which is measured in volts. More precisely, voltage is the difference in electrical potential between two points that provides the force needed to move electric charge through a circuit. In North America, the alternating current supplied by a standard wall outlet is typically 120 volts (historically 115 volts), while many other countries use 220–240 volts.



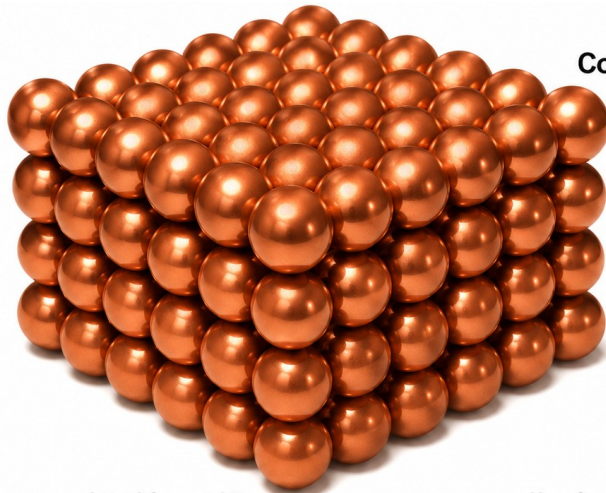
Force = Voltage, Friction = Resistance, Flow = Current

Voltage (V or E) is electrical potential, or more precisely, the potential difference between two points, and is measured in volts (V).

Voltage can be thought of as electrical pressure or the force that pushes electric charge through a conductor. More precisely, it is the difference in electrical potential between two points. This electrical pressure provides the energy that causes current to flow when a circuit is complete.

To better understand this, think of water flowing through a pipe as analogous to electric current flowing through a wire. Imagine a small bucket filled with water connected to a pipe. The higher the water level, the greater the water pressure available to push water through the pipe. In much the same way, a greater voltage provides a stronger electrical "push" to move charge through a circuit.

If you replaced the bucket with a bathtub—or even a large water tower—the available water pressure and stored energy would be much greater. Likewise, increasing the voltage increases the electrical potential available to drive current through a circuit.

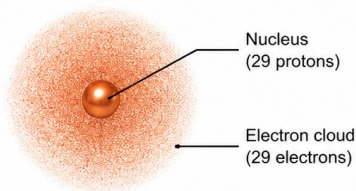


Copper Atoms in Solid Copper

In solid copper, atoms are arranged in a face-centered cubic (FCC) crystal structure.

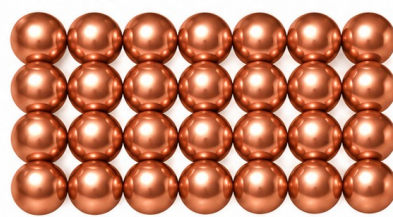
Copper atoms are not individual spheres in reality; they are the atomic nuclei surrounded by clouds of electrons.

Actual Copper Atom



The electron cloud is not a solid surface—it shows the probability of finding electrons around the nucleus.

How Copper Atoms Are Often Modeled



In models, atoms are shown as spheres occupying fixed positions in a lattice.

A Copper molecule showing regular bonds of copper atoms.

We use the letter I as the symbol to represent electron current moving through a conductor.

Types of Copper Electrical Cables



Coiled Copper Wire
Flexible stranded copper conductor



Flat Ribbon Cable
Multiple copper conductors in a flat arrangement



Single-Core Copper Cable
Solid copper conductor with insulating jacket



Coaxial Cable
Copper center conductor, insulation, braided shield, and outer jacket

Wire and conductors.

As we learned in Chapter 2, the electrons that move through conductors are called valence electrons. These are the electrons farthest from the nucleus of an atom and are therefore least affected by its attractive force. Metals are good conductors because they have many loosely bound valence electrons that are free to move throughout the material. When a voltage is applied, these mobile electrons drift through the metal, carrying electric charge.

Activity 1: Reading a Transformer Voltage with a Multimeter

In this activity, you will learn to use a multimeter to read DC voltages while learning about a new part called a **transformer**.



Transformers are used for converting one voltage to another using induction.

Parts Required

An AC transformer and a digital multimeter capable of measuring AC and DC voltage. (Warning: Always confirm the maximum voltage and current ratings of your multimeter and test leads before making measurements.)

A suitable microcontroller development board (such as an Arduino, ESP32, or Raspberry Pi Pico) and one or more DC power sources, such as batteries or a regulated DC wall adapter ("wall wart").



When electric current flows through a metal wire, it creates a magnetic field surrounding the conductor. A changing magnetic field can, in turn, induce a voltage in a nearby conductor—a process known as electromagnetic induction. As you recall from Chapter 2, when a changing magnetic field cuts across a wire, a voltage is induced that can cause current to flow if the circuit is complete.

Two of the fundamental principles embodied in the work of [James Clerk Maxwell](#) are:

Moving electric charges create magnetic fields.

Changing magnetic fields induce electric fields that can drive electrical current.

Thus, current flowing in one wire can induce a voltage in another nearby wire. This interaction between electricity and magnetism is exploited in many electronic devices, especially transformers.

The ratio of turns in the primary coil compared with the number of turns in the secondary coil determines the relationship between the input and output voltage. For example, if the primary winding has 100 turns and receives 100 volts AC, while the secondary winding has 50 turns, the output will be approximately 50 volts AC.

In a traditional linear power supply, the transformer's primary winding accepts approximately 120 volts AC (historically 115 volts) from the wall outlet and steps the voltage down—for example, to about 12–18 volts AC. A rectifier, filter capacitors, and voltage regulator then convert this AC into a stable DC voltage, such as 5 volts, suitable for powering electronic circuits.

Many countries, including most of Europe and parts of Asia, use 220–240 volts AC rather than North America's 120 volts AC. Regardless of the input voltage, the power supply converts and regulates the output to the voltage required by the electronics. Today, most electronic devices use highly efficient switch-mode power supplies (SMPS) rather than the larger linear transformers found in older equipment, but both rely on the principles of electromagnetic induction.

Introducing Another New Part

A digital multimeter is one of the most important tools for measuring the electrical characteristics of components and circuits. Although we cannot see the electrons moving through wires directly (we can, however, detect the photons emitted by LEDs and other light sources, which are part of the electromagnetic spectrum), a multimeter allows us to measure electrical quantities such as voltage, current, resistance, and often continuity. It is also one of the most valuable tools for debugging and discovering why a circuit is not working as expected.

A multimeter is often the first tool you will reach for when troubleshooting. It allows you to verify that voltages are what you expect, determine whether wires and components are electrically connected, and quickly isolate problems in a circuit.

Note: If you are using a different multimeter, be aware that many modern digital multimeters are auto-ranging and do not require you to manually select a measurement range. Also, make sure that the Hold function is not activated, as it can freeze the display and easily confuse beginners. When using a multimeter, always pay close attention to the maximum voltage, current, and input jack ratings for the measurement you are making. These specifications can be found in the manual supplied with the meter.

Always exercise caution when using a multimeter. The metal probe tips can accidentally short adjacent wires or electrical components, potentially damaging the circuit, the meter, or both. Whenever possible, keep the probes steady and avoid allowing the exposed metal tips to touch more than one conductor at a time.

The reason we use a multimeter is that we should never assume a voltage has a particular value or polarity. Always use your meter to verify both the voltage and its polarity before connecting a circuit.

Spending a few seconds making these measurements will save you from circuits that fizzle, pop, smoke, or burn.

Get into the habit of measuring first and connecting second. It is one of the simplest practices you can develop, and it will save both your components and your time.

Polarity refers to the + or – side of a DC source of voltage. You will be measuring polarity later in this chapter.

Note: Be aware of the absolute maximum ratings of your multimeter. Before measuring voltages outside the range covered in this book, consult the manual supplied with your meter to verify its maximum voltage, current, and input ratings. Never exceed these ratings, as doing so can damage the meter and may create a safety hazard.

Reading DC Voltages with the Multimeter

1. Plug the power adapter into a wall outlet. Note: Standard household electrical service is approximately 120 volts AC in the United States and Canada, and typically 220–240 volts AC in most of Europe and many other countries.
2. Set your multimeter to measure DC voltage. If you are using a manual-ranging meter, select a range that is higher than the expected output voltage of the power supply (for example, 20 V DC for a 5 V or 12 V supply, or 200 V DC if the output voltage is unknown). If your meter is auto-ranging, simply select the DC voltage (V $\overline{\text{=}}$) setting.



Most Digital Voltage Meters can be used for this lesson if they have AC and DC reading capabilities.

When measuring voltage with a manual-ranging meter, and you are uncertain of the exact value, begin with the highest suitable voltage range. You can then move to progressively lower ranges until you obtain a clear, more precise reading. With an auto-ranging meter, simply select the appropriate AC or DC voltage function.

3) Insert the red probe tip into the center contact of the power adapter's barrel connector. Carefully touch the black probe tip to the outer metal sleeve of the connector. Avoid allowing the probe tips to touch each other, as this would short-circuit the adapter output.

A small but important correction: the red probe does not always belong in the center. This depends on the adapter's polarity. Many adapters are center-positive, but some are center-negative. The polarity symbol printed on the adapter should be checked first, and the meter reading can then confirm it.

4) What is your multimeter reading? _____

5) If you are using a manual-ranging meter, switch to the 200 V DC range. What is your meter reading?

6) Now switch to the 20 V DC range. What is your meter reading? _____

This range provides the best resolution for measuring a voltage of approximately 17 volts, allowing your meter to display the reading with the greatest precision.

7) Now reverse the meter probes so that the black probe touches the center contact of the barrel connector and the red probe touches the outer metal sleeve. What is your multimeter reading?

8) Do you notice the – (minus) sign in front of the voltage displayed? This indicates that the probe polarity is reversed.

When you switch the probes back so that the red probe touches the center contact and the black probe touches the outer sleeve (assuming a center-positive power adapter), the meter will display a positive voltage. Most digital multimeters do not display a + sign for positive voltages because positive is assumed. Instead, you will simply see a reading such as 17.05 V DC.

Congratulations! You have just measured a DC voltage and confirmed its polarity.

Extra Fun: If you have a few batteries (such as a 1.5 V AA, 9 V, or a 3 V coin cell), practice measuring their voltages. If you are using a manual-ranging meter, try selecting the most appropriate voltage range to obtain the clearest reading.

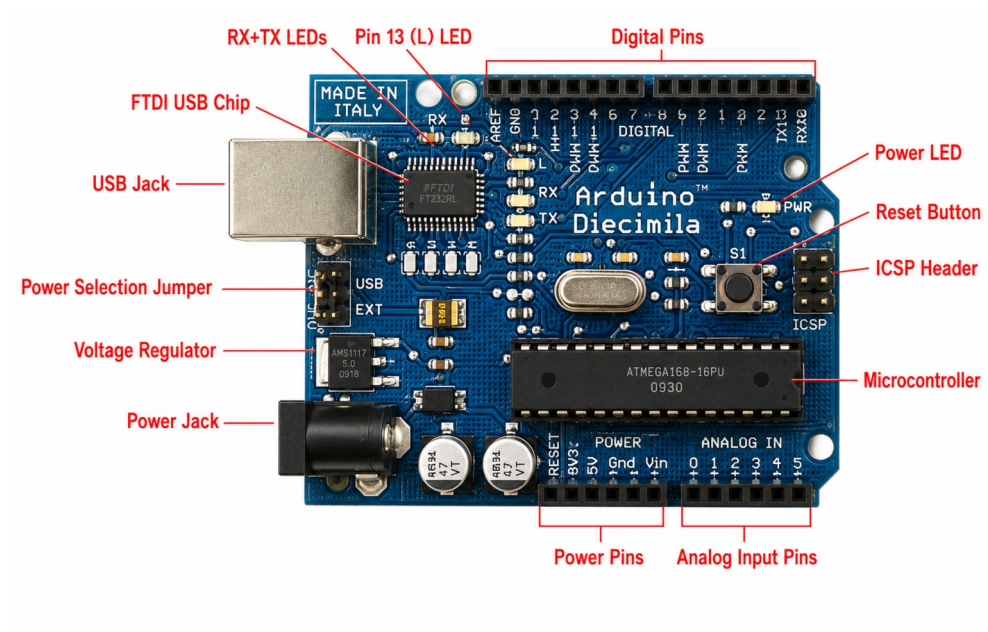
In Activity 2, you will continue building your multimeter skills by measuring DC voltages on an Arduino or ESP32 development board.

Activity #2: Protecting the Underside of Your Microcontroller

Notice that the underside of an Arduino or ESP32 development board contains exposed solder joints and electrical connections. These must be insulated from accidental contact with metal objects or conductive surfaces, or you may short-circuit the board and permanently damage the microcontroller or other components.

You can protect the underside of the board by attaching rubber feet, using plastic standoffs, or placing the board on a non-conductive surface while you work.

When prototyping with a breadboard, be especially careful that jumper wires, component leads, or other metal objects do not accidentally touch either the underside or the top of the development board, where they could create unintended electrical connections.



The back of your board may not look exactly like this with the logos, though the exposed wires are the issue to be resolved before you go on to read voltages.



Arduino Uno R3 Back

You can place rubber feet on the undersides of boards. Here you can find a detailed [PINOUT of the Arduino UNO R3](#). Notice on this page that one pin can source and sink 40 mA and 20 mA is recommended. The sum total of milliamps for a series of pins is 100 mA, so for driving many LEDs, you should consider Ohm's law here, and for the complete board no more than 200 mA. These are absolute maximum ratings—never to be exceeded.



Place rubber feet under the Arduino board if they are provided with your kit. Remember to wash your hands after touching any lead on the board.

We will be using an Arduino or ESP32 development board to practice measuring additional DC voltages while learning how to use a solderless breadboard for rapid circuit prototyping.

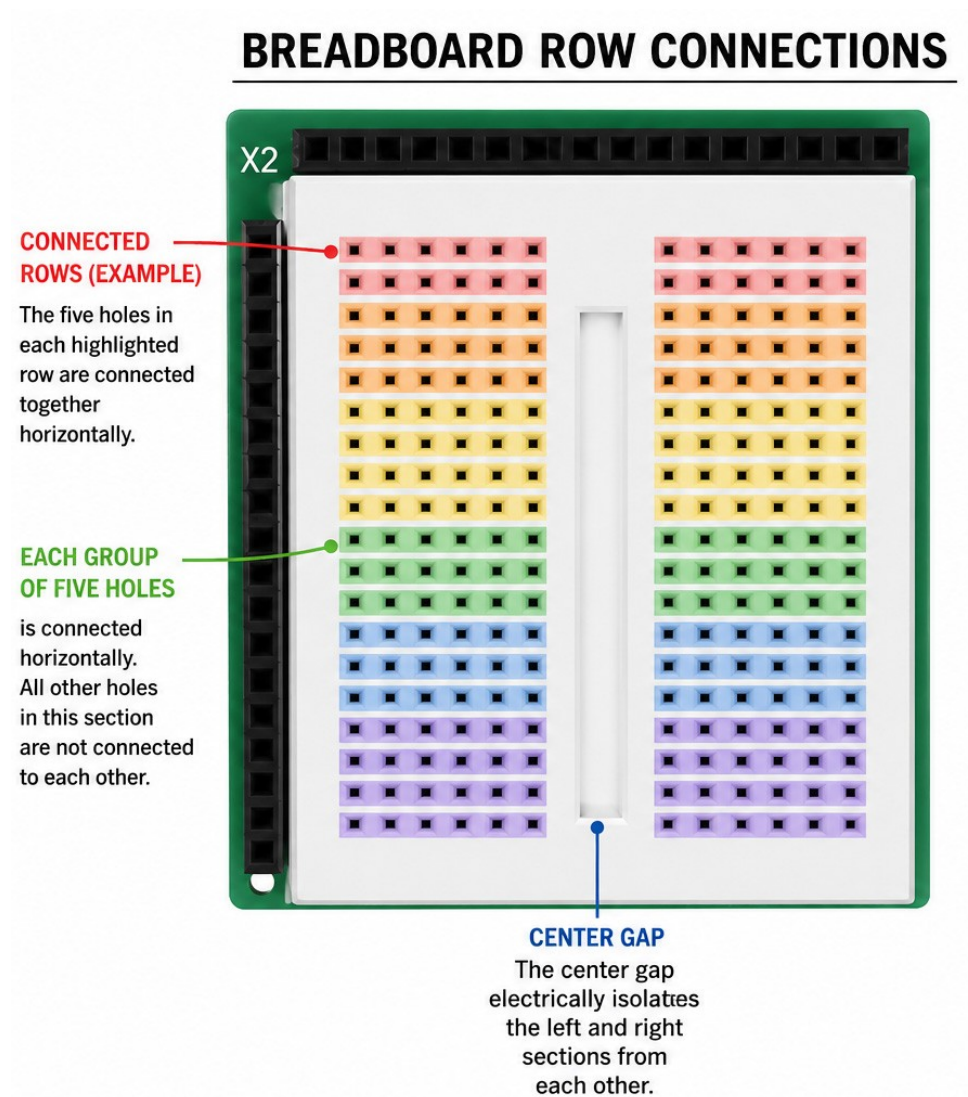
Parts Required

- (1) Digital multimeter
- (1) Arduino UNO or ESP32 development board
- (1) Red jumper wire
- (1) Black jumper wire

Introducing a Breadboard

The solderless breadboard (shown below) is a flexible prototyping platform that allows you to build, test, and modify electronic circuits without soldering. Components and jumper wires are simply inserted into the holes, making it easy to experiment with different circuit designs. Breadboards work especially

well with microcontroller development boards such as the Arduino and ESP32, allowing you to quickly connect sensors, LEDs, switches, and other electronic components while developing and testing your projects



White prototyping area. The valley between the rows can accept chips and electrically isolate the pinouts from each side of the board.

Probing the Board with Your Multimeter

Now connect your Arduino or ESP32 development board to your computer using a USB cable. The USB connection powers the board and provides the voltages you will measure.

Using two jumper wires, connect one wire to the 5 V pin and another to a GND (ground) pin on the development board. These wires will provide convenient test points for measuring the board's output voltages with your multimeter.

Set your multimeter to measure DC voltage. Place the black probe on the GND wire and the red probe on the 5 V wire. You should measure approximately 5.0 volts DC.

Next, move the red probe to the 3.3 V output pin while leaving the black probe connected to GND. Record the voltage you measure.

5 V output: _____

3.3 V output: _____

Notice that most Arduino and ESP32 development boards provide both 5 V and 3.3 V outputs. Many sensors and modules require one of these two supply voltages, so learning to identify and measure them is an essential electronics skill.

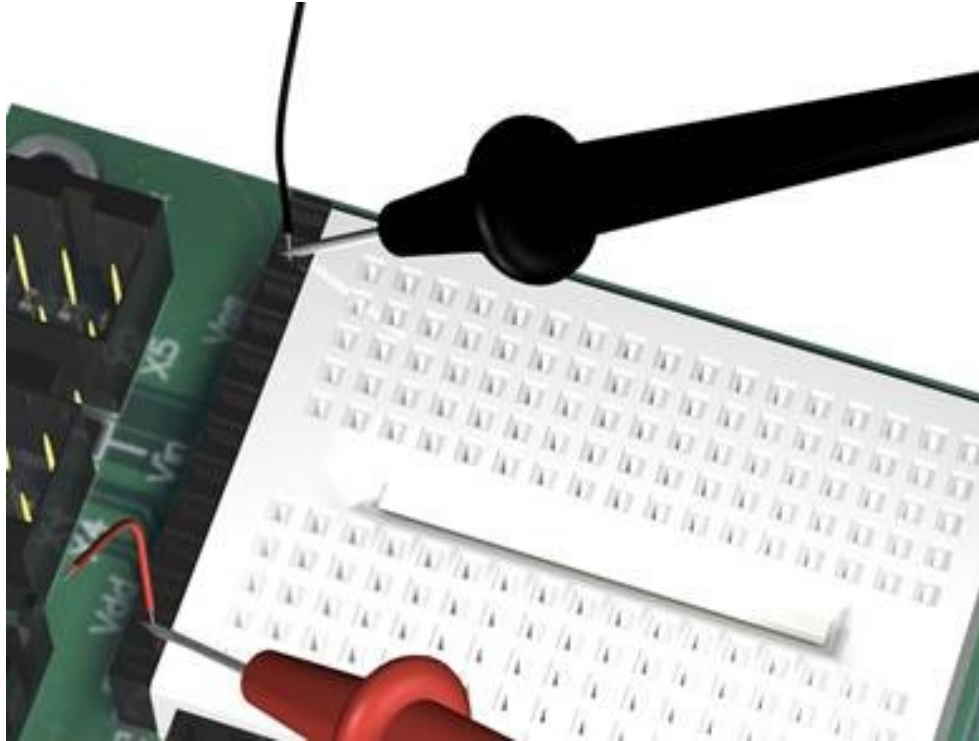
Notice on the Arduino that the LED will glow green indicating it is on.

If you are using an ESP32 instead, plug it in via USB and confirm its power LED is lit before proceeding, and take the same care not to allow any unshielded wire or metal to touch the metal contacts or traces on the underside of the board.



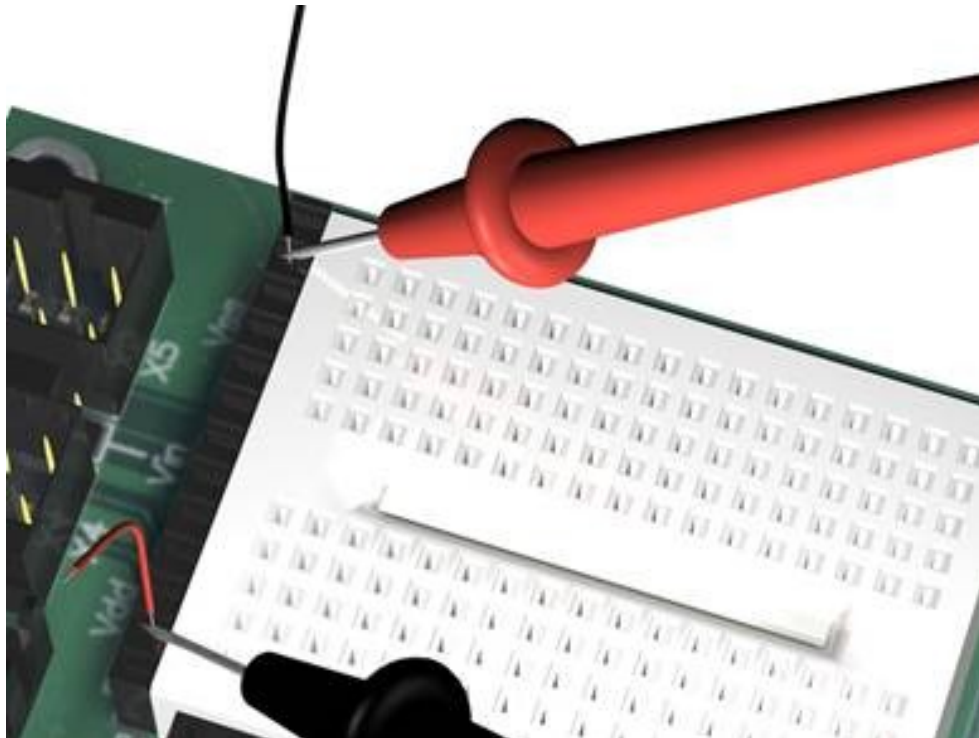
Take the red connector wire and lay it in the header pin labeled 5V (or 3V3 if you're using an ESP32), and take a black wire and lay it in a header pin labeled GND. Allow them to stick straight up, as shown below.

Set your meter to the 20-volt DC setting. Wedge the red probe so it is touching the wire and lightly pushed into the socket that the wire is nestled into. Do the same for the black on the black wire.



Measuring DC with multimeter

What is your voltage reading on the multimeter? _____ Reverse your red and black multimeter probes so the metal tip of the red probe touches the metal of the black wire and the tip of the black probe touches the metal of the red wire. What voltage do you read? _____ Do you notice a – minus sign in front of your voltage reading?

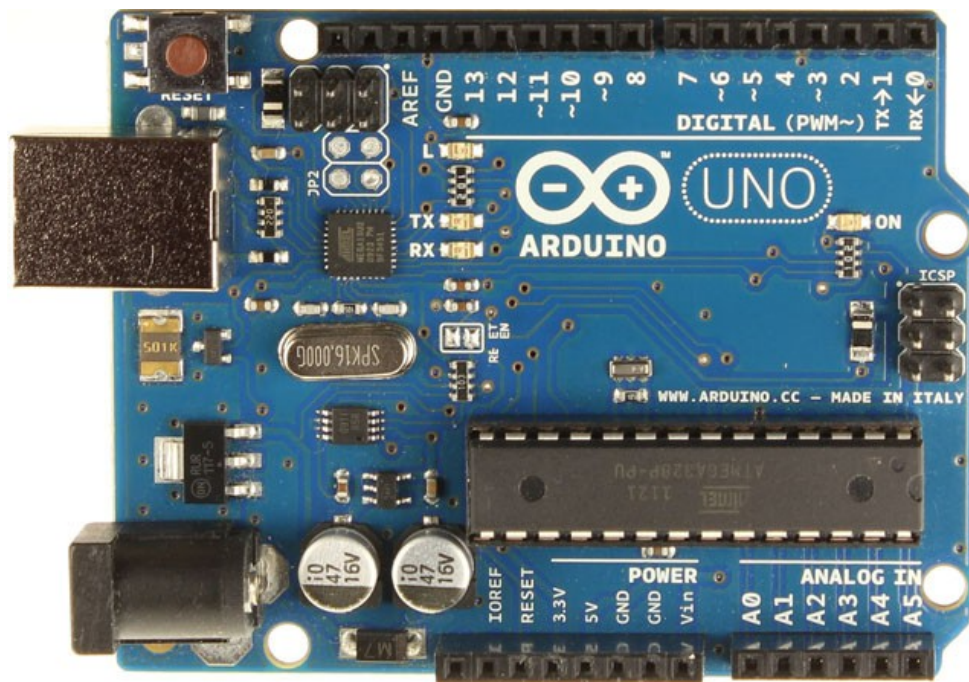


Measuring DC with multimeter

Why do you get this voltage? _____ Could it be because you have switched your probes so the red, which is normally used for the + side of the voltage source, is now reading the – side of the voltage source? _____

Reading Voltages on the Arduino UNO and ESP32

We have just confirmed a 5-volt DC power source, which is available on the Arduino. This 5-volt power source is coming from the USB power source from the computer or the transformer you measured earlier; however, the 17-volt DC first goes through another special part which regulates the voltage down to 5 volts DC. This specialty part is called an LM7805 and is used to create very controlled and clean regulated voltage.

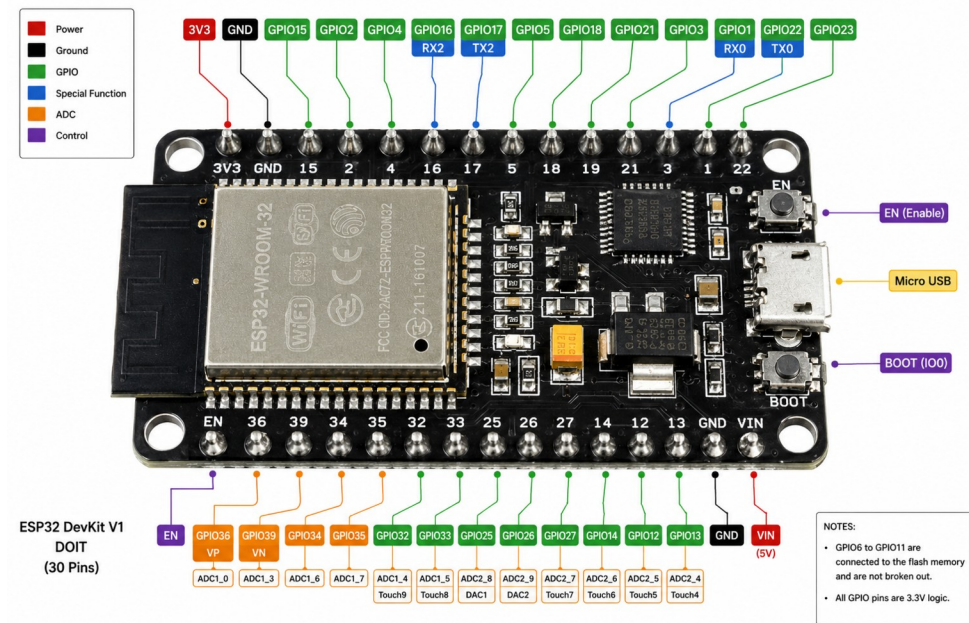


There is also a part called an LM7809 designed to take a higher voltage and regulate it to a clean 9 volts DC, and a 78012 which is designed to take a higher DC voltage and regulate it to a clean 12 volts DC.

It is easy to take a reading of the LM7805 voltage regulating chip, but do this very carefully as if you accidentally short your multimeter probes together while you take voltage measurements you can damage the LM7805 voltage regulator.

This 5-volt regulated source is valuable, as many of the electronic parts we will be using will need an independent power source. Keep in mind that while you can use this power source for driving the Arduino it can also be used to drive other 5-volt DC electronic parts; however, you must not overburden the 7805 power part with too much demand for the voltage, as there must always be enough for the microcontroller.

If you are using an ESP32 instead of the Arduino, its onboard regulator takes the 5 volts DC coming from USB and steps it down further, to 3.3 volts, which is the logic level the ESP32's processor and GPIO pins actually run at. This is an important difference to keep in mind: unlike the Arduino's 5-volt logic, the ESP32 is a 3.3-volt device throughout.



Labeled pinout of a typical ESP32 DevKit V1 (DOIT, 30-pin) development board. Exact pin numbers and layout vary somewhat by manufacturer, but 3V3, GND, and VIN are labeled the same way on nearly every board, and all GPIO pins are 3.3V logic.

Locate the labeled header pins on your board: 3V3 (regulated 3.3 volts out), GND (ground), and VIN (the raw, unregulated voltage coming in from USB, close to 5 volts). Let's take some voltage measurements.

Be very careful not to accidentally short two of the pins together. Hold your hand against the table as you bring your probe tips into contact with the pins to steady your hands.

Set your meter to the 20-volt DC setting. Put your black probe on GND. Now put the red probe on the 3V3 pin. What is the voltage you are reading? _____

What happens when you reverse the probes? _____

What does this tell you? _____ Now put your black probe on GND and your red probe on VIN. What is your reading? _____ How does this compare to the reading you took on the 3V3 pin, and why do you think that is? _____

Activity #3: Measuring AC Voltage

Multimeters are also important tools for measuring AC. It is important to be very careful when measuring AC. If you take precautions, you will be safe.



Set your meter to 500 volts AC.

AC IS DANGEROUS AND CAN KILL. Always be very safe and careful when handling AC voltages and current. Wear rubber shoes and remove metal jewelry that could accidentally contact electrical materials. **Proceed at your own risk.**

Take an extension cord and carefully plug it into a wall socket. Set your multimeter to the AC setting of 500 volts or more. You should always start with your AC setting as high as it will go, which is 500 volts on many multimeters. Carefully, being sure to isolate your hands and fingers from the metal at the tip of your multimeter probes, slip the probes into an extension cord socket as below.



Carefully insert the probe tips into the two long flat areas. You may have to shift them around a bit to make a proper connection. Be careful not to touch the metal probes as you do so.

How much electrical pressure does the AC setting on your meter read? _____ Carefully remove the multimeter probe tips. Now, turn the multimeter setting to AC 200 volts and carefully read the voltage again. (If you are in a country with 220 volts AC 50 Hz then leave your meter on 500 volts AC for this measure.) What is the electrical pressure reading? _____

Notice how it is more accurate than the 500 setting on the multimeter? Why do you think this is the case? _____

Insulators and Dielectrics

Well, we have fully discussed and measured voltages and now we need to consider insulators. [Insulators](#) do not readily conduct electricity.

Some common examples of these are plastic, wax, and air. They do not conduct because they do not have valence electrons to support current flow. However, if given enough electrical pressure, like a high voltage, the insulator will conduct and will pass current. This is called the breakdown voltage, which is when the material can no longer hold back the pressure of voltage.

Insulators are also called [dielectrics](#) because they *resist the passage of current*. Dielectrics literally hold back the pressure of current, as they do not have any charge carriers (electrons) to contribute to current movement through compounds.

A dielectric is a non-conductor.

Air is a perfect example of an insulator conducting, as it allows the high pressure of lightning to pass through the air with the assistance of the moisture of water, as we are aware the Walter De Maria work *The Lightning Field* would permit.

Kapton and Mylar are examples of materials that have dielectric strengths of 7000 volts per mil (a mil is .001 of an inch), but even things like air and glass have dielectric strengths of a lot less — in the 80 to 200 per mil range. Almost any material will conduct if given enough voltage pressure.

Lightning is a great example of this.

While metal is a good conductor and plastic is not a good conductor, we now have a new class of conductive polymers made of plastic. Yes, PLASTIC! From research done at the end of 1979, the researchers [Heeger](#), [MacDiarmid](#), and [Shirakawa](#) were awarded Nobel Laureates in Chemistry for their discovery that plastics could be manipulated to make them electrically conductive. They discovered that they could “dope” plastics with iodine vapor, which enhances the conductivity of polyacetylene, so that electrons could move along the plastic, while conducting. One product that has come out of this is electroluminescent film.

[Dope](#) is where you add some material to another to alter the optical/electrical properties of a semiconductor.

The main lesson here is that charge carriers affect the ability of material to conduct electron flow.

Activity #4: Continuity Test with a Multimeter

In this activity, you will be using the multimeter to do a continuity test on the breadboard by touching the probes to some wire and then to some plastic.

Put your multimeter on the lowest setting of Ohms (Ω) possible. This is 200 ohms on many multimeters. Some meters have a continuity tester that makes a sound, and if this is the case turn your meter to that setting instead of the lowest value of Ohms. We have not yet studied Ohms or Ohm's law, but we will in Chapter 4. For the purposes of today's lesson, focus on using the Ohms setting on your multimeter to measure continuity.



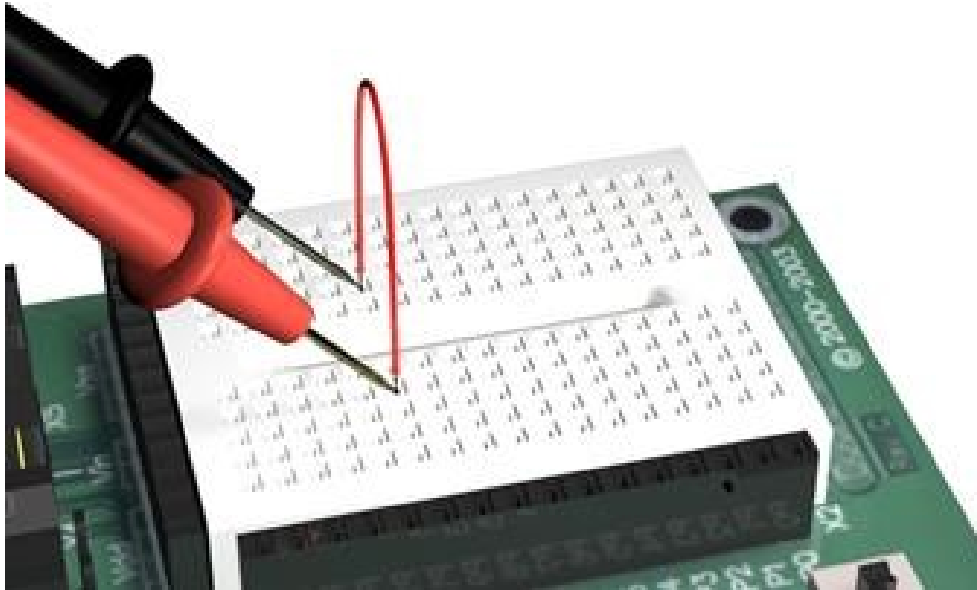
Turn your meter to the Ohm's setting

Ohms are a measure of how much resistance a material presents to the passage of electrons.

2) Notice that when the multimeter probe leads are not touching, your LCD readout gives you a number like one on the left side of the LCD readout.

3) Notice that when you touch the black probe to the red probe tip, at first the meter reads a number that bounces around and then you get a reading like .9, .8, or .6. This means there is an electrical connection between the two points, or that you have what is called a dead-short. It is an indication that indeed you have a good electrical connection between those points.

4) Now put a jumper wire in the breadboard as shown below. Touch the red lead of the multimeter to one side of the wire and the black lead to the other. What reading do you get? _____

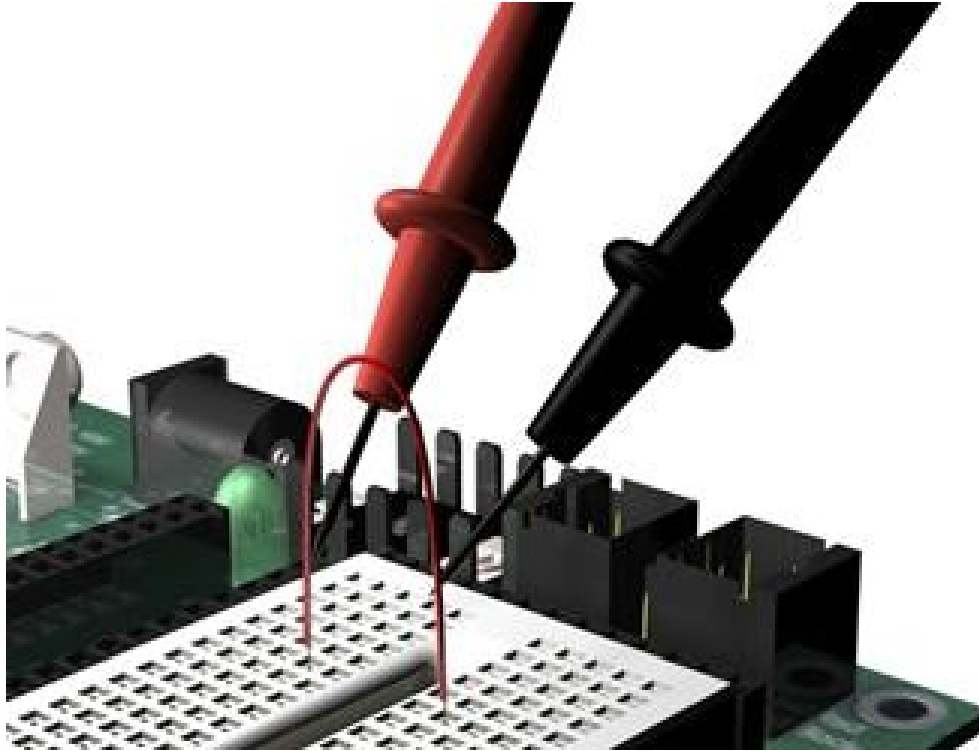


You must push the multimeter and wedge it between the wire and the breadboard.

5) The resistance of .9, .8, .7, or .6 Ohms is the resistance of the wire and it is a very low number because the wire presents little resistance to the passage of the electrons.

This indicates that indeed an electrical connection does exist. You have just confirmed continuity in the wire, or that there is a continuous or good connection.

6) Now grab a piece of wire, and with the same 200Ω setting, touch the leads to the sheathing of the wire. What kind of reading do you get? _____



Measuring the sheathing of the wire for continuity

Why do you get that reading? _____

Checking for continuity is one way of determining why circuits sometimes do not work. It is often because a wire is loose or not making a proper electrical connection, and this can be checked with a continuity test above. The circuit must be powered down or turned off when checking for continuity. Some multimeters have continuity checkers where the multimeter will emit a beeping sound when there is an electrical connection between two points.

Summary

We have learned that metal conducts well because it has [valence electrons](#), which allow the electrons to travel through the metal, while plastics do not, except in specially manufactured plastics designed for this.

With conditioning electronics, transformers convert 115 volts alternating current (AC) into direct current (DC) of varying voltages depending on how they are designed. You have also learned and applied how to read AC voltages and the proper setting for your multimeter, as well that AC is dangerous and needs to be handled safely.

We have learned that the breadboard is an excellent prototyping place to set and test circuits, and used the board to measure DC direct current and how to properly read the polarity of a wall transformer. We learned how to use the multimeter to check for continuity and non-conductance, which is one of the primary ways we will determine why our circuits do and do not work. We have also discussed two contemporary artists who have used voltage: Walter De Maria, who utilized static clouds to direct lightning, and Andrew Neumann, who used the aesthetic of the AC sine wave to question issues of electrical and non-electrical power systems.

References

[1] De Maria, Walter.

[2] Neumann, Andrew: http://www.bitforms.com/statement_neumann.html

[3] Warring, R.H. *Understanding Electronics*.

[4] Coontz, Robert. "The War of the Currents." Exploratorium Quarterly.

[5] Mims, Forrest. *Getting Started in Electronics*.

[6] <http://www.nobel.se/chemistry/laureates/2000/press.html>

Questions

What is continuity? _____

Why is it important to measure continuity when a circuit is not functioning? _____

Why is it important to identify the color of the multimeter probe when measuring for polarity?

How might you imagine using electronic forces to make a work of art? _____

Chapter 4

Resistors, Ohm's Law, and Capacitors

Passive Components: Resistors, Ohm's Law, and Capacitors

"For me, the machine is above all an instrument that permits me to be poetic. If you respect the machine, if you enter into a game with the machine, then perhaps you can make a truly joyous machine — be joyous, I mean free."

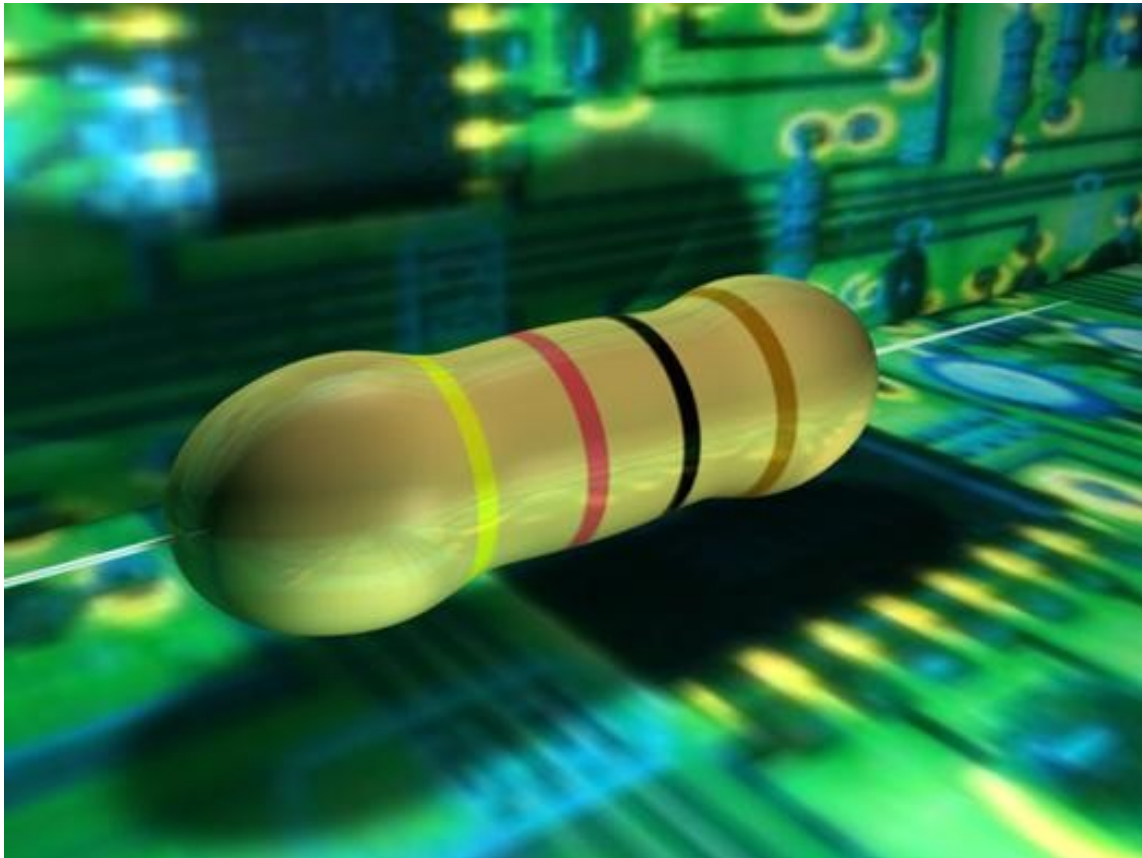
— Jean Tinguely (1925–1991)

Question: Can you limit or vary the number of electrons that pass a point in a given period of time?

Because many electronic devices are sensitive to too much current and voltage, [resistors](#) will be the primary devices you use in limiting the current and voltage flow entering your sensitive electronic parts.



Resistors are devices that are composed of materials that cause an electrical resistance. They are used for current control because they limit the passage of electrons and cut down on voltage pressure.

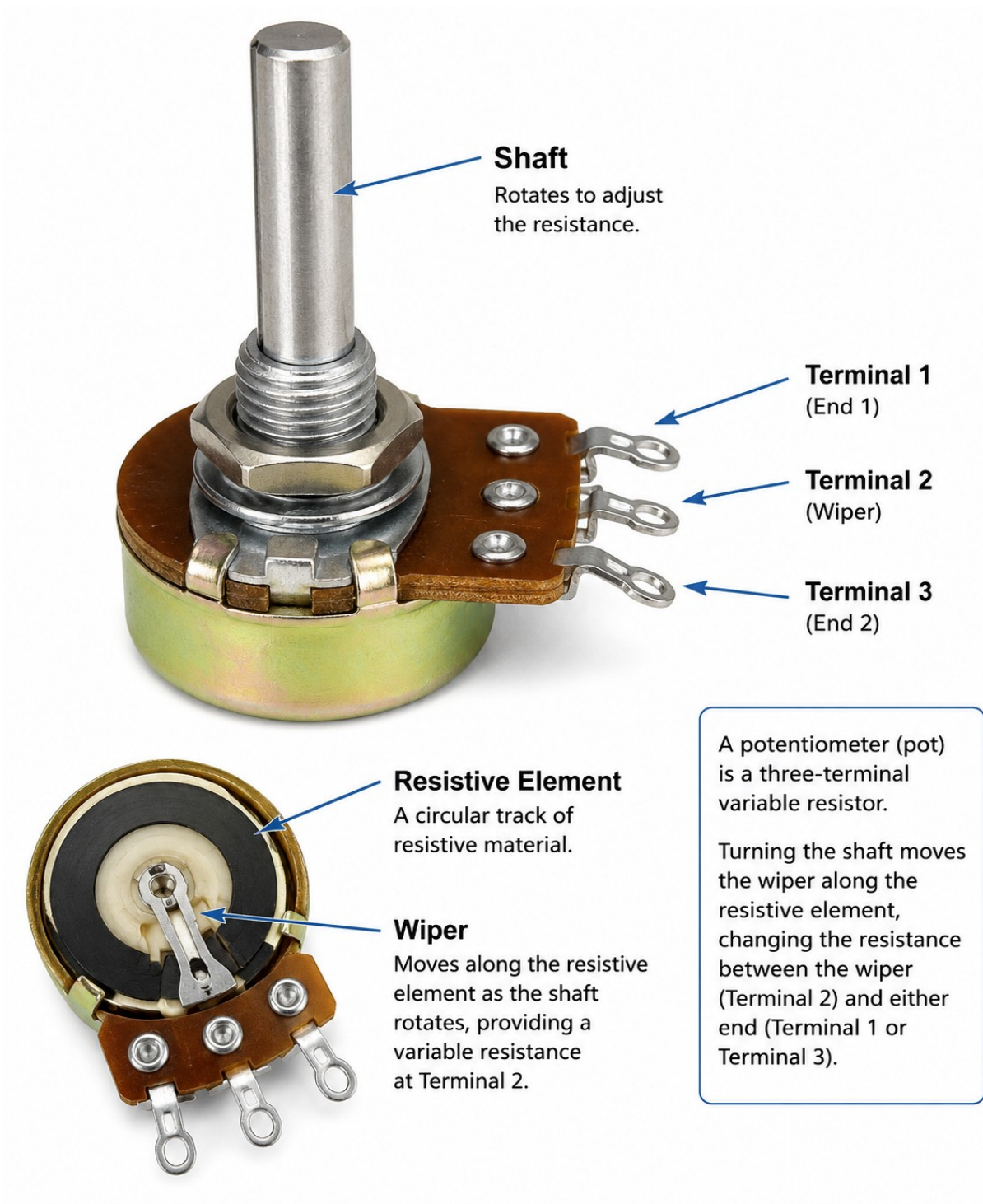


Close-up of a carbon resistor lying on a circuit board. 3D model by Todd Sweptson.

Resistors function by limiting or resisting the flow of electric current. As current passes through a resistor, some of the electrical energy is converted into heat, reducing the amount of current flowing

through the circuit and creating a controlled voltage drop. This allows resistors to protect sensitive electronic components, establish operating voltages, and regulate the amount of current reaching LEDs, sensors, microcontrollers, and many other devices.

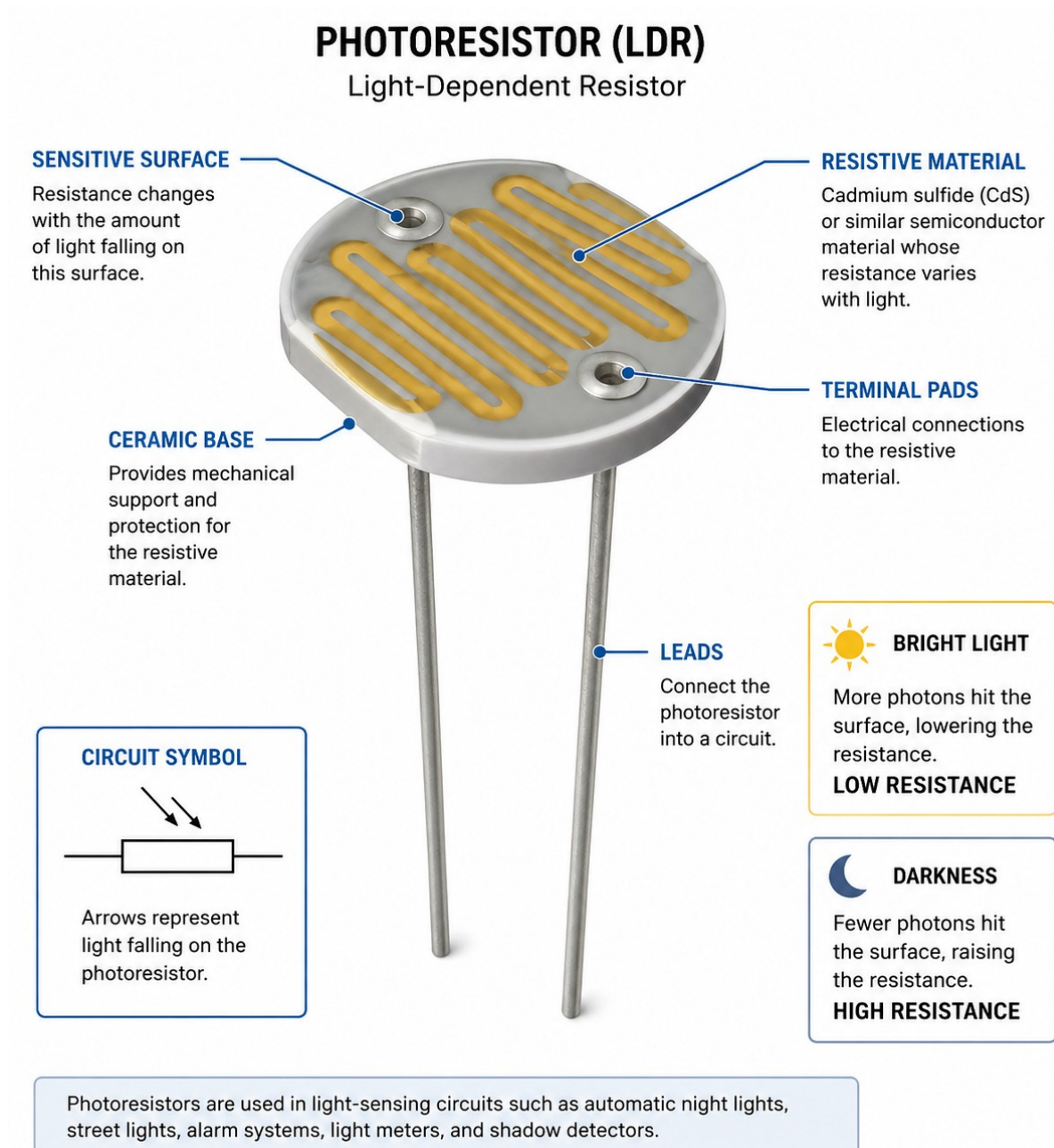
Resistors can have a single fixed value or they can be **variable**. Variable resistors, often called **potentiometers**, allow you to change the resistance by turning a shaft or moving a slider (directly below). As the resistance changes, the amount of current or voltage available to a circuit also changes. Variable resistors are extremely common. Every time you adjust the volume on a stereo, turn a dimmer switch, or move a joystick or control knob, you are changing the electrical signal by varying the resistance. In the case of a stereo, the potentiometer adjusts the audio signal that ultimately controls how much power reaches the speakers—allowing you to pump up the volume or **TURN DOWN THAT NOISE!**



Variable resistor. Here you would hook the middle leg and one of the outside legs into a complete circuit to get the variable resistance.

A **photoresistor**, also called a **light-dependent resistor (LDR)**, changes its resistance according to the amount of light falling on its surface. In bright light its resistance decreases, allowing more current to flow through a circuit. In darkness its resistance increases, reducing the flow of current. Because of this property, photoresistors are commonly used to detect changes in lighting conditions and can trigger circuits when a shadow passes over them. They are often found in automatic night lights, outdoor

security lighting, light meters, solar trackers, and interactive art installations that respond to the presence or movement of people.



A photo resistor changes resistance in relation to the varying light levels it receives.

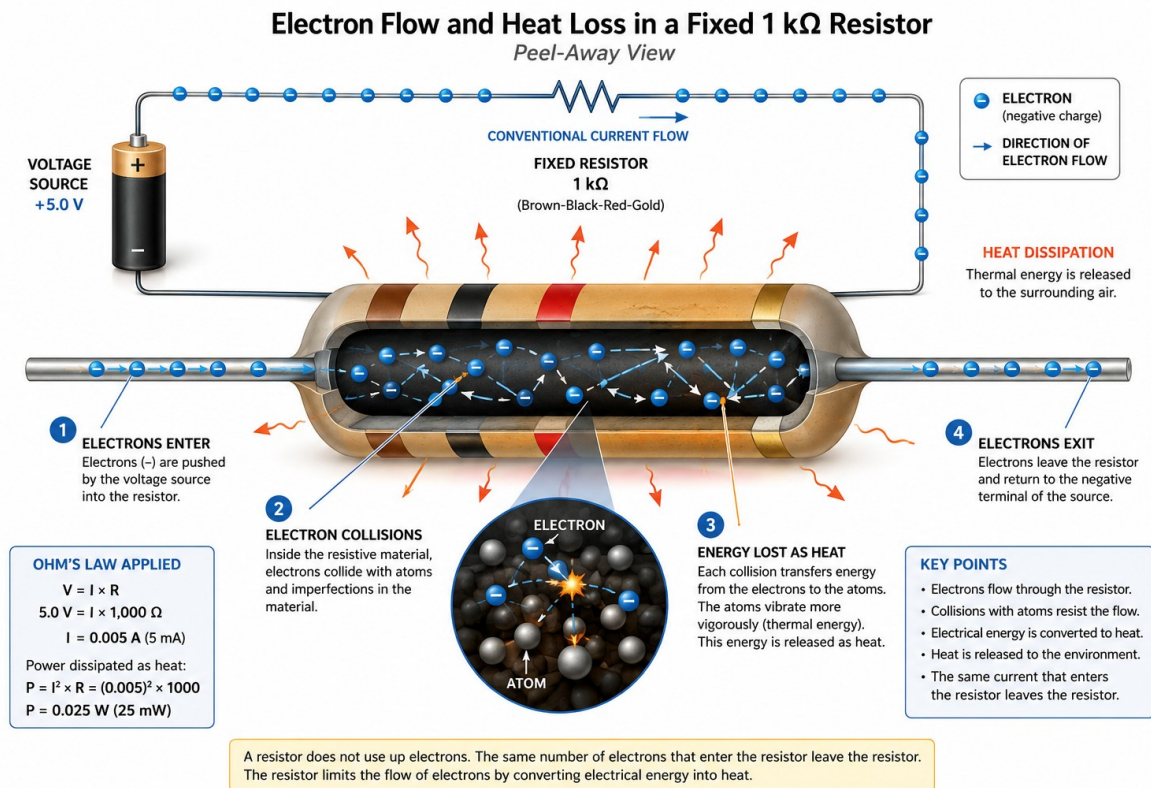
Resistors receive electrical current from a voltage source and function by opposing the flow of that current. Rather than allowing electrons to move freely, the material inside the resistor impedes their motion. The same amount of current enters and leaves the resistor, but energy is lost along the way as heat.

As electrons are pushed through a resistor by the voltage supplied from a battery or power supply, they repeatedly collide with the vibrating atoms and imperfections within the resistive material. These

countless microscopic collisions transfer energy from the moving electrons to the atoms, causing them to vibrate more vigorously. This increased atomic motion is what we experience as **heat**. This is one reason electronic components often become warm during operation and why electronic enclosures frequently include ventilation holes or heat sinks to help dissipate excess heat.

This provides your first important design clue when creating your own electronic projects and inventions. Always make sure your electronic components have adequate airflow or another means of cooling so that heat produced by electrical resistance can escape. Good thermal design greatly improves the reliability and lifespan of electronic circuits.

Many resistors are made from **carbon film**, **metal film**, or **thick-film** materials, while others are constructed from **wire-wound** resistance wire for higher-power applications. Different resistor types are chosen for their ability to dissipate heat, maintain accurate resistance over changing temperatures, tolerate moisture or harsh environments, minimize electrical noise, or handle high-power loads. Selecting the proper resistor is an important part of designing reliable electronic circuits.



In a carbon resistor, you can increase or decrease the resistance by choosing a resistor that increases or decreases the amount of carbon in relation to the glue-like binder. Carbon is the conductive molecule in this material mix.

Even the graphite lead in your 2B pencil is a carbon resistor, and some artists have exploited the resistive qualities of lead pencils in the creation of art. Molecular collisions in the passage of current, be it a human body, a 6B lead pencil, or a resistor, create resistance and therefore heat. The resistor's ability to absorb and disperse heat from all of the molecular collisions is the *wattage rating*.

You must be aware of the wattage rating of resistors as it refers to the current resistors can absorb and be given off as heat. As with wire generally, the thicker a resistor the more electrons you can push through it and the more heat it can withstand.

The most common wattage sizes are 1/8, 1/4, and 1/2 watt. You will be using 1/4-watt resistors for the lessons in this book. There are also 1, 2, and 10-watt resistors and resistors with 10,000 watts for large industrial applications.

Artist's Examples and Resistors

In the installation, Burgoyne has sixteen pieces of 38" x 60" paper, each with a speaker, a sound circuit, and two copper points.



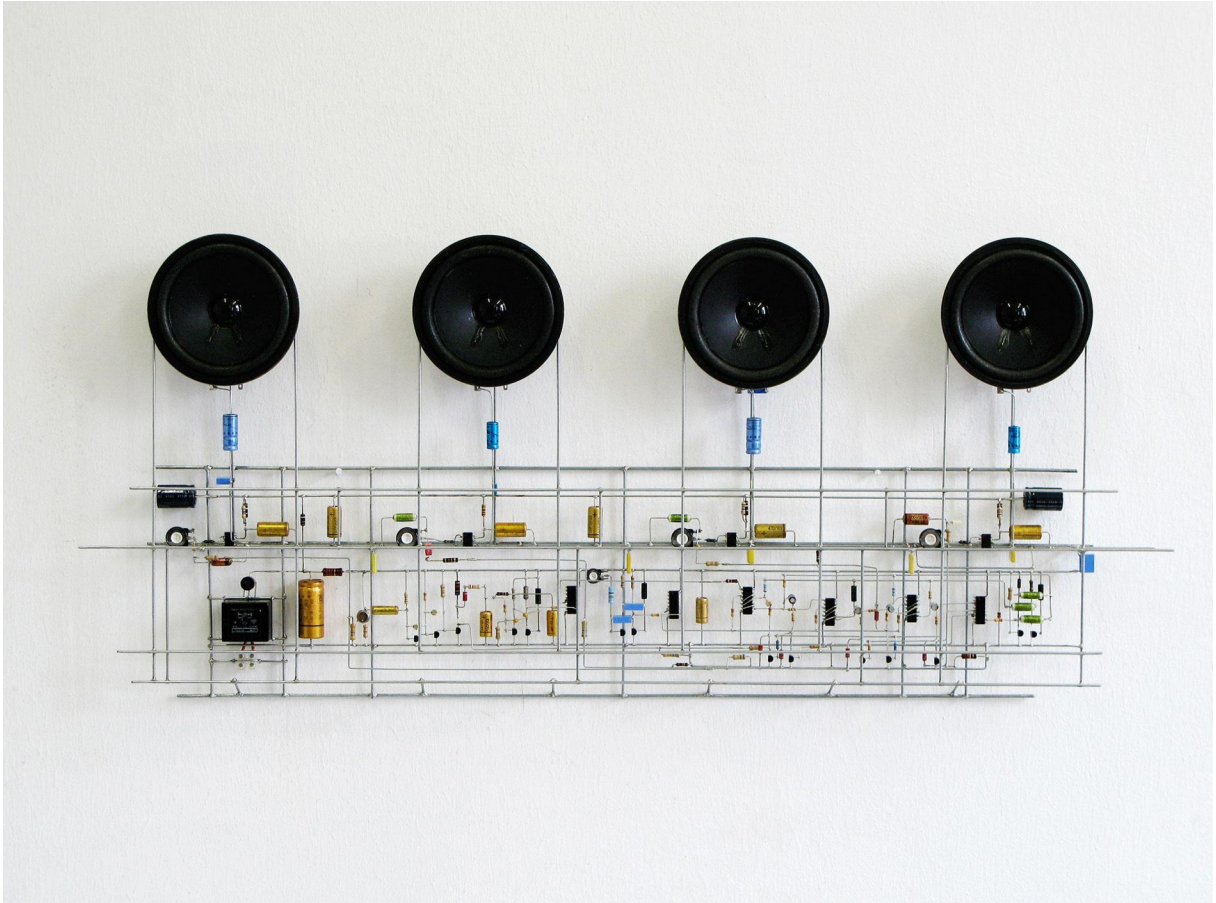
The viewers used lead pencils to connect these copper points, thereby allowing a constantly evolving soundscape. For more complexity, each drawing had both a 6B pencil and an eraser, so the participants could completely manipulate the tonal mix of the room by both drawing and erasing.

This work is particularly significant because it is one of the earliest interactive artworks to use the resistive properties of graphite pencil marks as an active electronic medium rather than merely as a drawing material. Participants literally completed electrical circuits by drawing between copper contacts. Because graphite is resistive rather than perfectly conductive, the length, thickness, pressure, and density of the pencil marks influenced the electrical resistance, allowing the sound circuits to evolve as visitors added or erased graphite.

Peter Vogel (1937–2016) was a German physicist and pioneering media artist whose interactive electronic sculptures transformed exposed circuits into both visual compositions and musical instruments.

Constructed from visible resistors, capacitors, transistors, sensors, and custom electronic circuits, his works responded to viewers' movements by generating sound and light.

Rather than concealing the electronics, Vogel celebrated the beauty of circuitry itself, revealing the invisible processes of electronic communication and making the circuit an integral part of the artwork.





Size vs. wattage rating. Generally the larger the resistor the more current it can handle.

If you apply too much voltage or force too much current through a resistor, it may dissipate more heat than it was designed to handle. As electrons move through the resistive material, countless microscopic collisions transfer electrical energy to the atoms within the resistor, causing them to vibrate more vigorously. If this heat cannot escape quickly enough, the resistor's temperature continues to rise until the materials begin to degrade. An overloaded resistor can become extremely hot, smoke, discolor, or even burn out with a distinctive smell.

Resistors are designed to carry specified amounts of electrical current (**I**), measured in amperes (**A**), while safely dissipating electrical power (**P**) measured in watts (**W**). This electrical energy is converted primarily into heat, although specialized resistors may also be designed to produce light or infrared radiation.

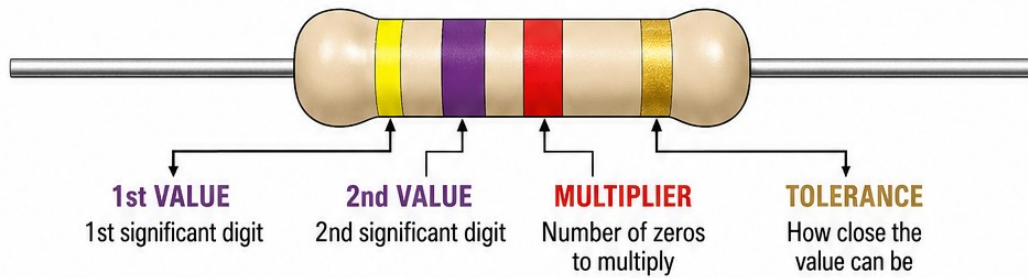
In the image above, notice the different sizes of the resistors. The larger 10-watt and 100-watt resistors have greater thermal mass and much more surface area than smaller resistors, allowing them to dissipate heat more efficiently into the surrounding air. The red 50-watt resistor has a hole through its ceramic body that increases its surface area, improving cooling by allowing heat to be carried away more effectively.

Notice also how the smaller carbon and metal-film resistors increase in wattage rating as their physical size increases—from **1/4 watt** to **1/2 watt**, **1 watt**, and **2 watts**. In general, a larger resistor can dissipate more heat while maintaining a safe operating temperature.

To properly select resistors for your circuits, you will need to understand both how to measure resistance with a multimeter and how to read the resistor color code. The colored bands wrapped

around the resistor indicate its resistance value and tolerance. Each color corresponds to a specific number according to the standard resistor color code chart shown below.

READING RESISTANCE VALUES



EXAMPLE: 4 7 x100 ±5%
 4700 Ω ±5%
 (4.7 kΩ ±5%)

COLOR	VALUE (1st DIGIT)	VALUE (2nd DIGIT)	MULTIPLIER	TOLERANCE
Black	0	0	1	—
Brown	1	1	10	±1%
Red	2	2	100	±2%
Orange	3	3	1K (10 ³)	—
Yellow	4	4	10K (10 ⁴)	—
Green	5	5	100K (10 ⁵)	±0.5%
Blue	6	6	1M (10 ⁶)	±0.25%
Violet	7	7	10M (10 ⁷)	±0.1%
Gray	8	8	100M (10 ⁸)	±0.05%
White	9	9	1000M (10 ⁹)	—
Gold	—	—	1/10 (10 ⁻¹)	±5%
Silver	—	—	1/100 (10 ⁻²)	±10%
None	—	—	—	±20%

- Read from the end opposite the tolerance band (gold or silver).
- The first two bands are the significant digits.
- The third band is the multiplier (number of zeros).
- The fourth band is the tolerance (how much the value can vary).

The quantity of electrical resistance is measured in **ohms**, named after the German physicist **Georg Simon Ohm (1789–1854)**. The unit of resistance is represented by the Greek capital letter **omega (Ω)**.

Resistance describes how strongly a material opposes the flow of electric current. The greater the resistance, the more difficult it is for electrons to move through the material.

For example, if a resistor's color bands indicate a value of **1000 ohms**, we can describe it in several equivalent ways:

- **1000 ohms**
- **1000 Ω**
- **1 kilo-ohm (1 k Ω)**

These all represent exactly the same resistance value. As resistor values become larger, engineers commonly use the SI prefixes **kilo (k)** for thousands, **mega (M)** for millions, and **giga (G)** for billions of ohms. Likewise, very small resistance values may be expressed in **milliohms (m Ω)**, or thousandths of an ohm.

Identifying and Measuring Resistances with Your Multimeter

Grab any resistor from your kit. Look closely at the resistor and notice that the first three colored bands are grouped closer together than the fourth band. The fourth band, which is spaced slightly farther away, is usually **gold**, **silver**, or occasionally another tolerance color such as **brown** or **red**.

Hold the resistor so that the band farthest from the others is on the **right**. This is called the **tolerance band**. The tolerance band tells you how closely the resistor matches its stated value.

For example, if you have a **1 k Ω** resistor with a **gold** tolerance band, the resistor may vary by **$\pm 5\%$** . This means its actual resistance could range from **950 Ω to 1050 Ω** . If the tolerance band is **silver**, the resistor may vary by **$\pm 10\%$** , or from **900 Ω to 1100 Ω** .

The first three color bands determine the resistor's nominal value. For example, **brown**, **black**, and **orange** represent a **10 k Ω (10,000 Ω)** resistor. Refer to the resistor color code chart.

Look at the colored bands on the resistor you selected from your kit and write the colors in the spaces provided.

1st color: _____

2nd color: _____

3rd color: _____

4th color (tolerance band): _____

Now use the resistor color code chart to determine its value. The **first band** represents the first digit, the **second band** represents the second digit, and the **third band** is the multiplier. Together these determine the resistor's nominal resistance.

For example, if the bands are **brown, red, orange, and gold**, the resistor value is:

$$12 \times 1000 = 12,000 \, \Omega = 12 \, \text{k}\Omega \pm 5\%$$

Notice that **12,000 Ω** can also be written as **12 k Ω** , where the prefix **k** means **1,000**.

In the next exercise you will determine a resistor's value in two ways. First, you will use the resistor color code chart to calculate its resistance. Then you will confirm your answer by measuring the resistor directly with your digital multimeter.

You will also use your breadboard—with the power disconnected—as a convenient place to hold the resistor while making your measurements.

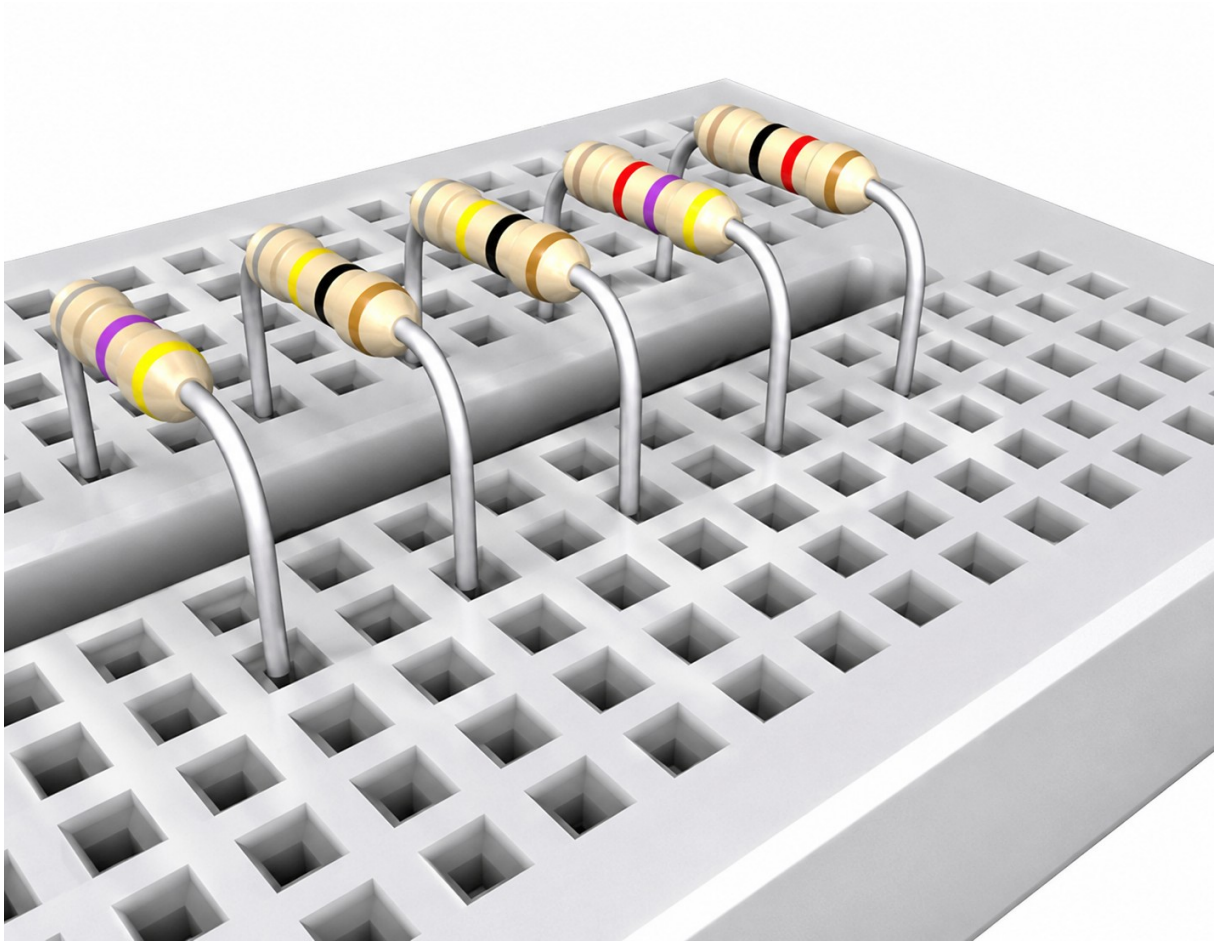
Parts Required

- Five resistors of different values
- A solderless breadboard (or the breadboard supplied with your Arduino or ESP32 kit)
- A digital multimeter capable of measuring resistance (Ω)



Start with the probe set to the highest value of resistance and work your way down to get the most accurate reading.

Take five different resistors from your kit and, one by one, place them on the breadboard as shown below. Notice how they bridge the small valley that exists between the two sides of your white breadboard.



Breadboard with five different values of resistors.

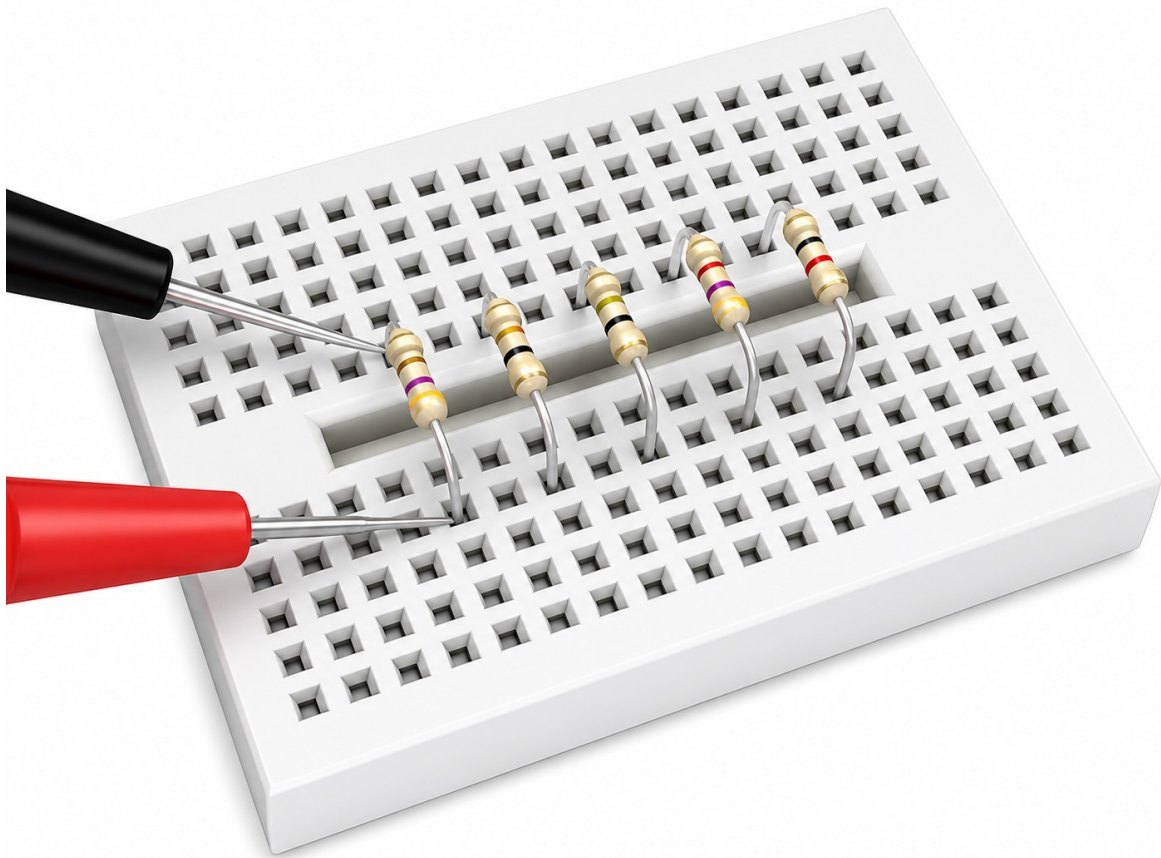
Arrange the resistors on your breadboard so they are easy to identify and so you can comfortably touch each lead with your multimeter probes. Be sure the probes make firm electrical contact with the resistor leads during each measurement.

First, use the resistor color code chart to determine the nominal resistance and tolerance of each resistor. Record your answers in the table below under the **Calculated Value** and **Tolerance** columns (A, B, C, etc.).

Next, set your multimeter to the appropriate **Ω (resistance)** range and measure each resistor. Record the measured resistance in the **Multimeter Reading** column.

Finally, compare the measured value with the value you calculated from the resistor color code. Are the two values the same? If they differ slightly, check whether the measured value falls within the resistor's stated tolerance. For example, a **1 k Ω $\pm$ 5%** resistor should measure between **950 Ω and 1050 Ω** and still be considered within specification.

Test the resistors one by one with your multimeter.



Color chart reading / Multimeter reading

Resistor 1 _____
Resistor 2 _____
Resistor 3 _____
Resistor 4 _____
Resistor 5 _____

Were there different values between what the color codes stated and what your multimeter measured, and if so, why? _____

Measuring Resistances of Random Objects

Now, for the fun of it, try measuring the resistance of a variety of different objects. Compare materials such as plastic, wood, metal doorknobs, aluminum foil, ceramic objects (with and without glaze), graphite pencil marks, tap water, distilled water, plants, fruits, or even damp soil. You may be surprised by the enormous differences in their electrical resistance.

Next, measure your own body's resistance and compare it with the resistance of other people. Human skin is usually a fairly poor conductor, but the measured resistance can vary greatly depending on how dry or moist your skin is, how firmly you hold the probes, and the area of contact.

For another interesting experiment, have one person hold one multimeter probe while a friend holds the other probe. Then hold hands with one another to complete the electrical path. Compare this

measurement with the resistance of a single person. You have just created a **series path** through two people. This is similar to connecting two resistors in series, where the total resistance is approximately the sum of the two individual resistances.

If you have difficulty getting a stable reading, try increasing the contact area by pressing the probes more firmly against your skin or by slightly dampening your fingertips with clean water. **Never perform this experiment if the multimeter is connected to a powered circuit.** The resistance (Ω) setting uses only the meter's small internal battery and is safe for these measurements.

When measuring your own resistance or other high-resistance materials, begin with the highest resistance range (or use an auto-ranging multimeter) and adjust the range as needed to obtain the most accurate reading. Experiment with different objects and compare how conductive or resistive they are.

Safety Note: Always measure resistance with the circuit or object **unpowered**. Never use the resistance (Ω) setting on a live electrical circuit, as this can damage the multimeter and may be hazardous.

Ohm's Law: Voltage, Current, and Resistance Unite

For a moment, think about what resistance looks like from an electron's point of view. Imagine you are an electron being pushed through a circuit by the electrical pressure, or **voltage**, created by a battery or power supply. Along with countless other electrons, you begin drifting through the resistor. As you travel through the mixture of carbon particles and insulating binder, you repeatedly collide with atoms and tiny imperfections within the material. Each collision transfers a little of your energy to the atoms, causing them to vibrate more vigorously. These microscopic vibrations become **heat**. Between collisions, you continue moving through the resistor until you eventually leave it and continue your journey around the circuit.

Now imagine that all of your fellow electrons are being pushed by a battery supplying **9 volts (V)** of electrical pressure. The amount of current (**I**) flowing through the resistor depends on both the applied voltage and the resistor's opposition to that flow. A larger voltage pushes more current through the resistor, while a larger resistance reduces the current.

The German physicist **Georg Simon Ohm (1789–1854)** discovered this fundamental relationship between **voltage**, **current**, and **resistance**, now known as **Ohm's Law**. It states that the current flowing through a conductor is directly proportional to the applied voltage and inversely proportional to the resistance. In practical terms, a potential difference of **one volt** will produce a current of **one ampere** through a resistance of **one ohm**.

Mathematically, Ohm's Law can be written in three equivalent forms:

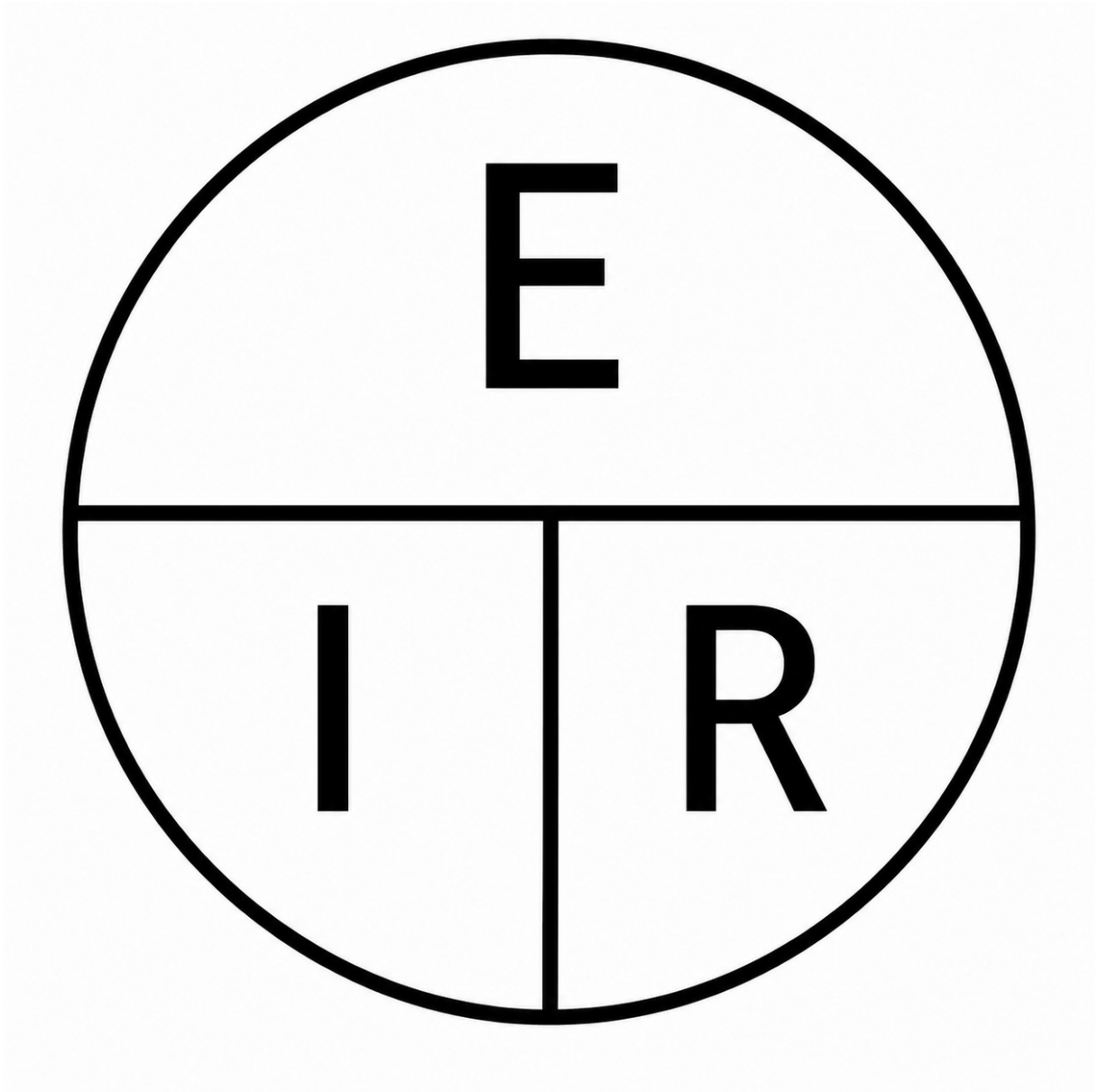
- $I = E \div R$
- $E = I \times R$
- $R = E \div I$

where:

- **I** = current (amperes)
- **E** = voltage (volts)

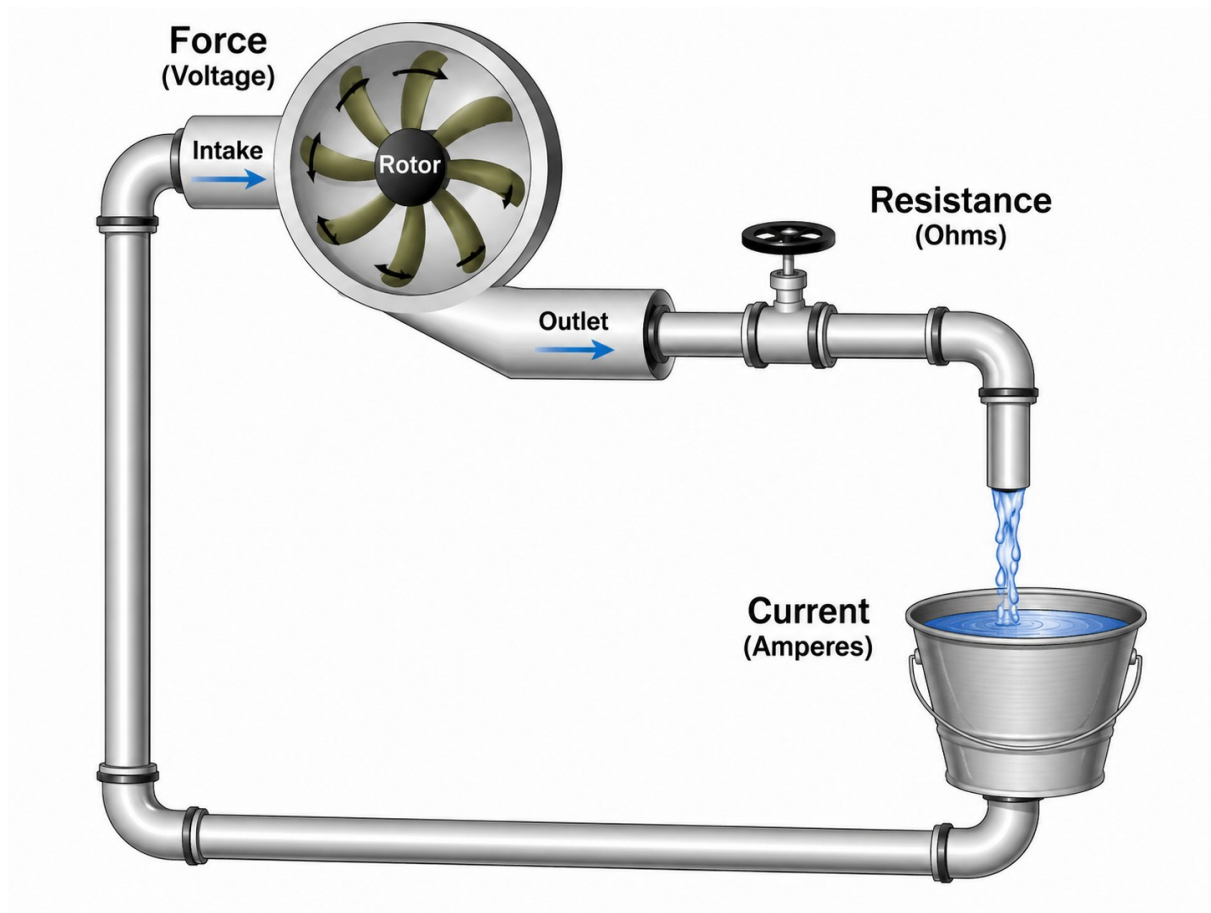
- **R** = resistance (ohms)

The diagram below provides a simple way to remember these relationships. Cover the quantity you want to solve with your finger. The remaining two quantities show the equation needed to calculate the unknown value. For example, if you cover **E**, the remaining symbols show $I \times R$, so $E = I \times R$. If you cover **I**, the remaining symbols show $E \div R$, so $I = E \div R$. Likewise, covering **R** leaves $E \div I$, giving $R = E \div I$.



Ohm's Law

To understand Ohm's law and the relationship between voltage, resistance, and current flow, the water analogy is one way to think about this relationship (directly below).



Visualization of electron flow with a resistor as faucet analogy.

The water flow decreases as the faucet is gradually closed. This is analogous to increasing the resistance in an electrical circuit. A higher-value resistor restricts the flow of current, allowing fewer electrons to pass through a cross-section of the circuit each second. Resistance does not remove electrons from the circuit—it simply opposes their motion. The water analogy also illustrates the relationship between electrical pressure (voltage), resistance, and the resulting current.

Using Ohm's Law, you can calculate the size of resistor needed to protect sensitive electronic components from excessive current. Remember how we described a fuse as a thin wire that melts when too much current flows through it? A resistor helps protect electronic devices by limiting the current and converting some of the electrical energy into heat before it reaches the component.

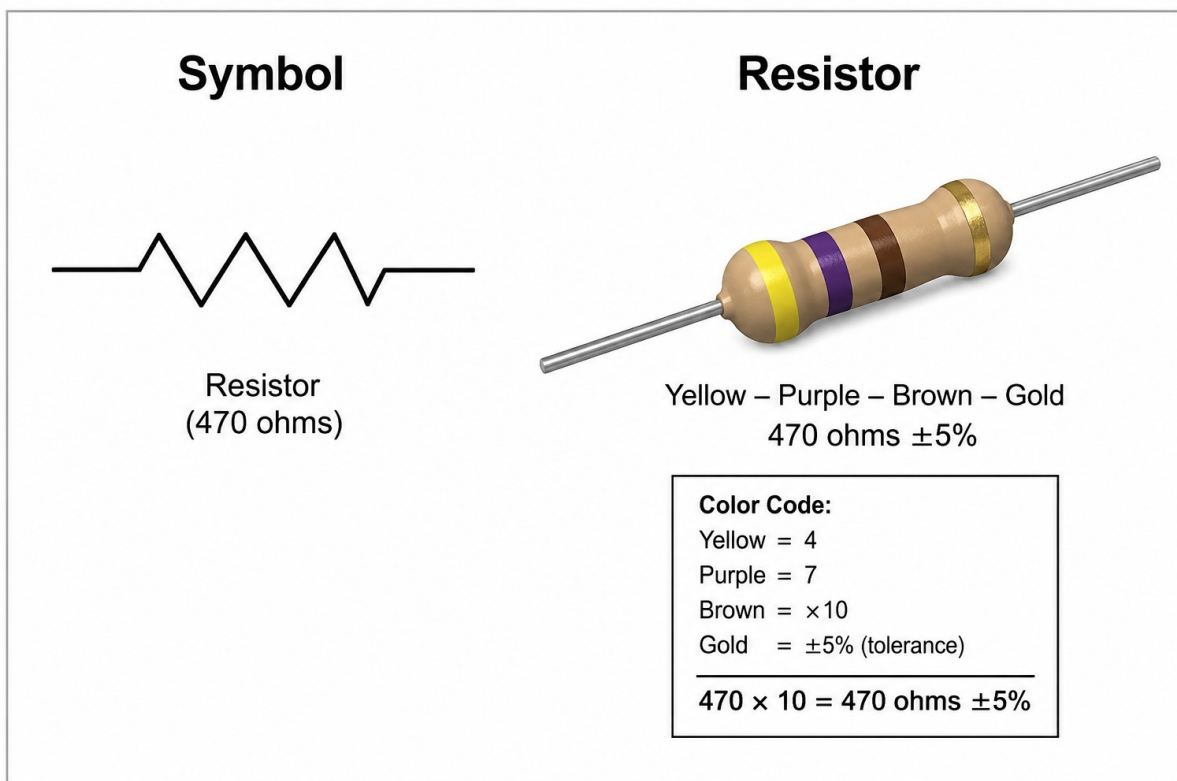
With Ohm's Law, if you know any two values in a circuit, you can always calculate the third using simple algebra. For example, when you purchase an electronic component, its datasheet may specify an operating voltage of **5 volts DC** and a maximum allowable current, often expressed in milliamperes (**mA**).

Using Ohm's Law, you can determine the resistor value needed to allow a **5-volt** power source to safely deliver the proper amount of current to that component. One of the remarkable features of Ohm's Law is that it applies equally well to **DC**, **AC**, and, in many practical situations, **radio-frequency (RF)** circuits.

When working with electronics, it is important to have a common language for communicating circuit designs. As you learn electronics, you will discover thousands of freely available circuit diagrams that can be understood regardless of the language in which they were created. These diagrams, called **schematics**, are maps that show how electronic components are connected. Schematics are constructed from standardized symbols, each representing a different electronic component.

When I first began studying electronics, schematic diagrams seemed intimidating. Eventually I realized that artists and engineers share a similar way of thinking—they both visualize complex relationships and imagine structures in three dimensions. Engineers have simply developed a beautiful symbolic language for representing electronic circuits, and this visual language makes a great deal of sense to artists as well.

For example, the illustration below shows the schematic symbol for a resistor beside a three-dimensional resistor. You might imagine the zigzag line as a winding road that slows traffic, just as a resistor limits the flow of current through a circuit. It can also be thought of as a visual reminder that electrical energy is being converted into heat within the resistor as electrons transfer energy to the vibrating atoms of the resistive material. While the symbol is simply a standardized convention, it provides a memorable way to visualize the role of a resistor in an electronic circuit.



470-ohm resistor: part on right and schematic drawing on left.

Following this paragraph is an example of a schematic that has a resistor, a lamp, and a battery in a complete circuit. We will use this circuit schematic and some changing values to do some Ohm's law calculations.

Ohm's Law Applied

In this lab you will use **Ohm's Law** to calculate the relationships between **voltage**, **current**, and **resistance**.

Parts Required

- Sheet of paper
- Calculator
- Pencil

Look at the circuit shown below. Using Ohm's Law:

- $V = I \times R$
- $I = V \div R$
- $R = V \div I$

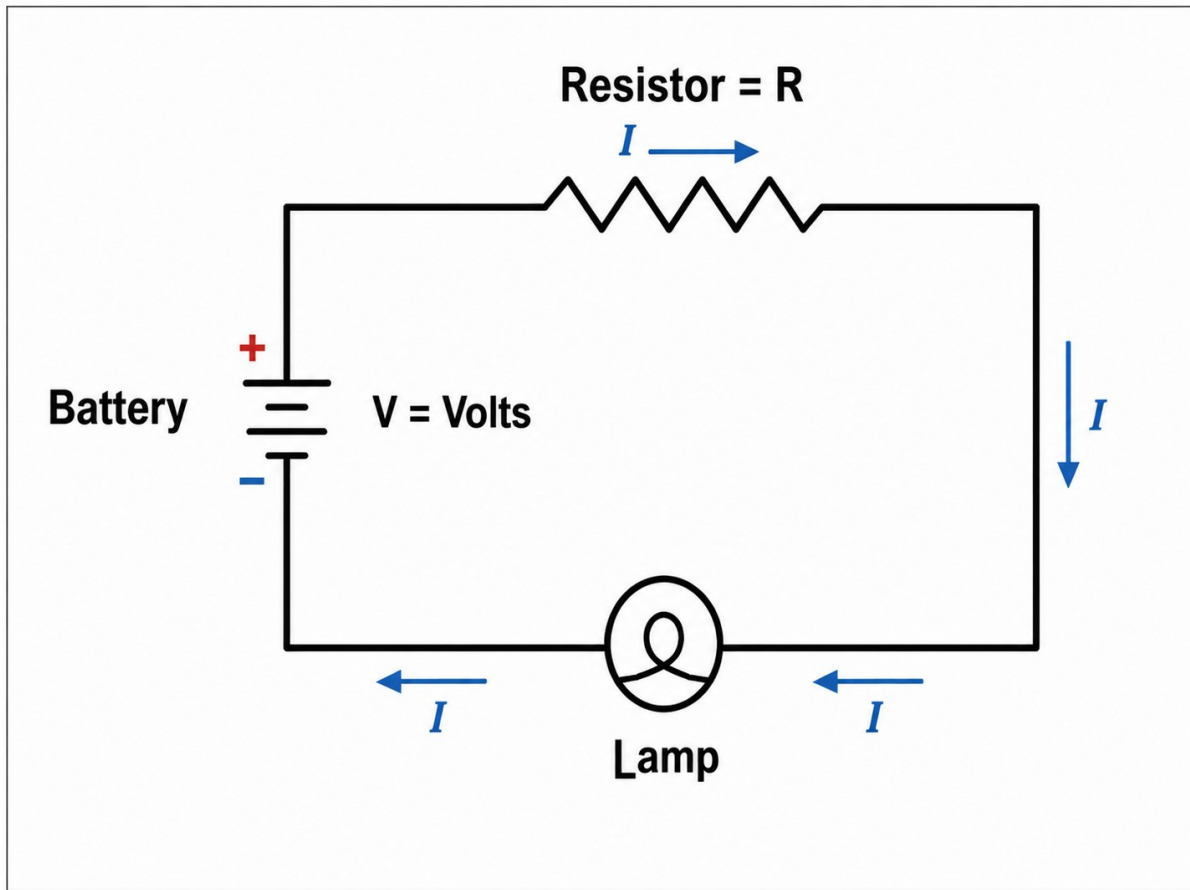
calculate the missing values in each circuit.

Your task is to determine how much current flows through each lamp for the different resistor values shown. A calculator may be helpful during this exercise. If you would like to check your answers, search online for an "**Ohm's Law Calculator**," where you will find many free calculators that solve these relationships instantly.

Study the schematic diagram below. Notice that it represents a complete electrical circuit in which a battery establishes an electrical potential difference (**voltage**) that causes current to flow through the lamp and resistor before returning to the battery.

Notice the schematic symbol for the **battery**, shown as alternating long and short parallel lines. You can imagine these as representing the positive and negative terminals of the battery. Historically, they also recall **Alessandro Volta's** original voltaic pile, which consisted of alternating metal discs separated by pieces of cardboard soaked in brine that produced a steady electrical voltage.

The circle containing a small loop represents the schematic symbol for a **lamp**. The loop suggests the glowing filament found inside a traditional incandescent light bulb. You already know the schematic symbol for a **resistor**—the zigzag line—which represents the component that limits the flow of current through the circuit.



Schematic of battery, resistor and lamp in complete circuit.

If you have a **1 k Ω** resistor connected to a **9 V** source and you want to determine how much current flows through the circuit, use **Ohm's Law**.

Our equations are:

$$V = I \times R$$

$$I = V \div R$$

$$R = V \div I$$

Therefore,

$$I = 9 \div 1000 = 0.009 \text{ A (amperes)}$$

which is the same as **9 mA (milliamperes)**.

Since **1 ampere (A) = 1000 milliamperes (mA)**, you can convert amperes to milliamperes by multiplying by **1000**, or simply moving the decimal point three places to the right.

Now solve the following problems.

`<font face="Courier">R = 10 k $\Omega$ , V = 9 V, I = _____ mA</font>`

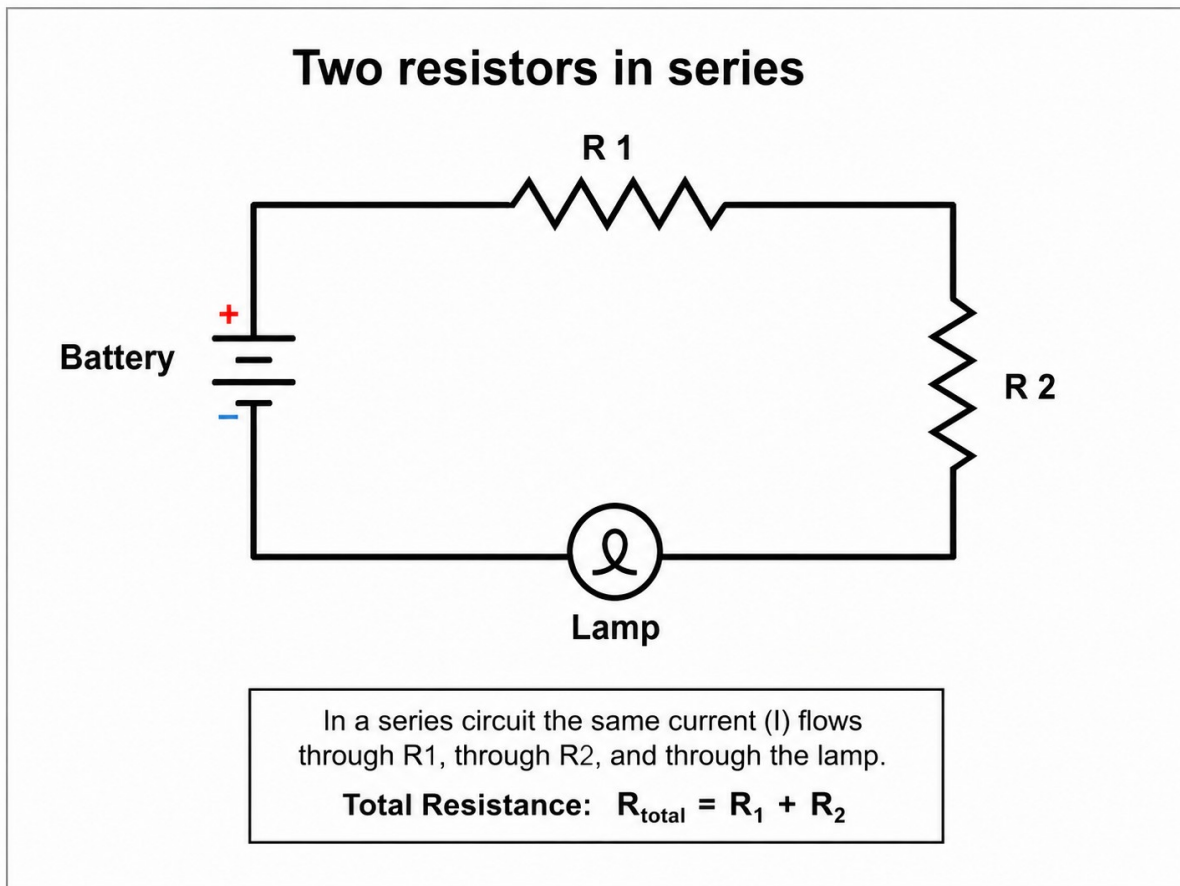
`R = 1000 Ω, V = 5 V, I = _____ A`

`R = 150 Ω, V = 5 V, I = _____ mA`

`R = 12 kΩ, V = 12 V, I = _____ A`

`R = 490 Ω, V = 5 V, I = _____ mA`

As mentioned in a previous experiment, when you joined hands with another person to measure your combined resistance, you created a **series path**. The same principle applies to resistors. You can create new resistance values by connecting resistors **end-to-end** in what is called a **series circuit**.

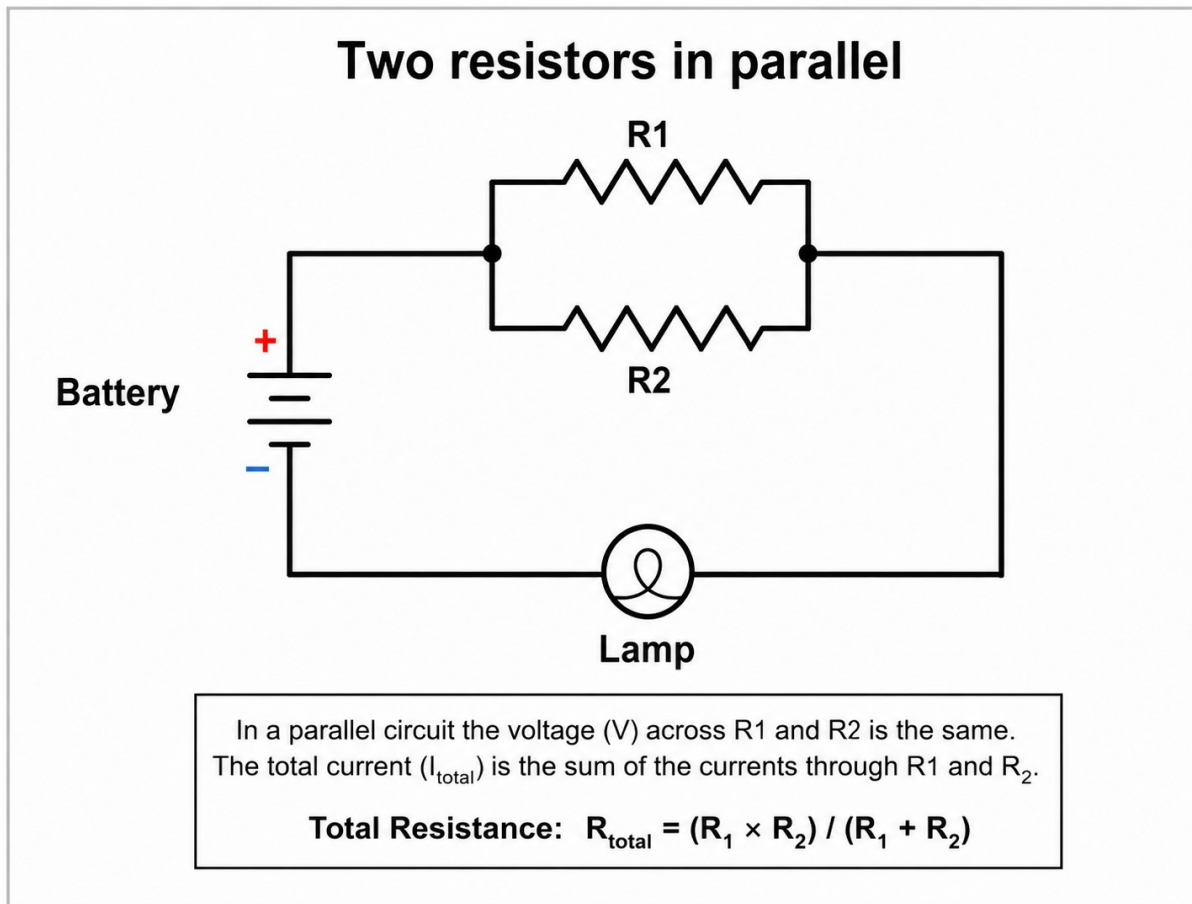


Here is an example of a schematic for a series circuit involving 2 resistors, a lamp and a battery.

You can also customize resistor values by connecting resistors in a **parallel circuit**, shown below. Unlike resistors in series, adding resistors in parallel **decreases** the total resistance because the current has more than one path through the circuit. For **two resistors**, the total resistance can be calculated using the following formula:

$$(R_1 \times R_2) \div (R_1 + R_2) = R_{\text{total}}$$

This allows you to create resistance values that are smaller than either of the individual resistors. Parallel resistor combinations are commonly used when a particular resistance value is not available or when multiple current paths are desired in an electronic circuit.



Schematic of a parallel circuit

Use the white breadboard to create several combinations of resistors connected in parallel. Calculate the total resistance of each combination using the formula directly above, and then use your multimeter to measure the actual resistance. Compare your calculated and measured results. It is often wise to confirm resistor values with a meter because some color bands can be difficult to distinguish and may vary slightly in appearance from one manufacturer to another.

Capacitors: A Quick Storehouse of Electrons

"The function of Art is to disturb. Science reassures."

— George Braque

Question: Are there electronic devices that can temporarily store electrical energy and make it available almost instantly, unlike a battery, which releases energy more gradually?

Capacitors are electronic components designed to store **electrical charge and energy** on two or more closely spaced conducting plates (shown in the image below). They are found in almost every electronic circuit. The plates are separated by a thin insulating material called a **dielectric**. When a voltage is applied, electrons accumulate on one plate while an equal deficiency of electrons develops on the opposite plate, creating an electric field that stores energy. The dielectric prevents the plates from

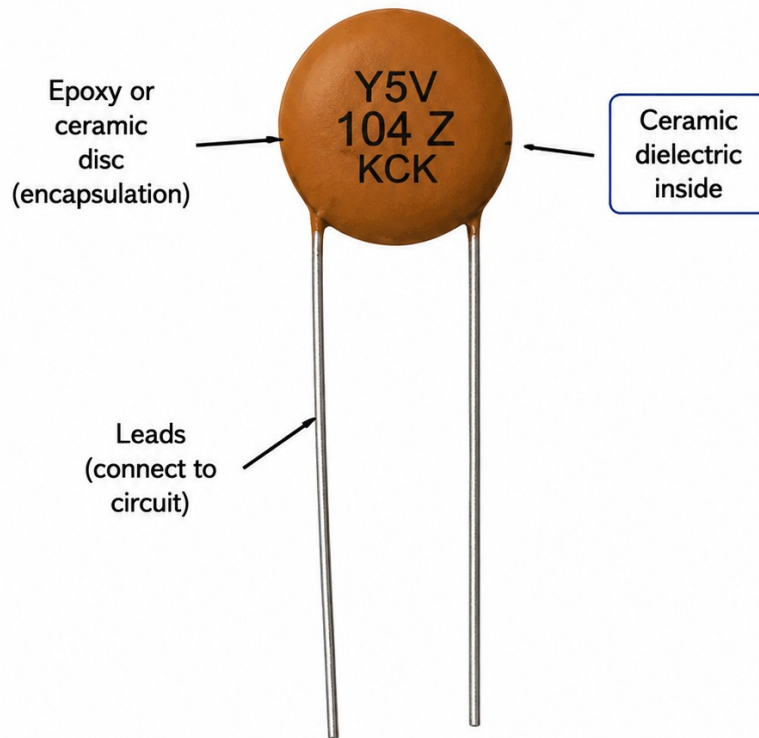
touching or electrically discharging while allowing the capacitor to store a large amount of energy for its size.

The dielectric may be air, as shown below, or materials such as **polyester (Mylar)**, **ceramic**, **glass**, **mica**, **tantalum oxide**, or specialized plastics. Different dielectric materials give capacitors different electrical characteristics, including **capacitance**, **voltage rating**, **stability**, **leakage current**, and performance at different frequencies.

A capacitor is similar to a battery in that it can store **electrical energy**; however, unlike a battery, a capacitor can release its stored energy very rapidly when connected into a circuit. For this reason, capacitors—especially large ones—should always be handled with care, as they may remain charged even after power has been removed.

In a simple capacitor consisting of two conducting plates, the negative terminal of a battery (or other voltage source) pushes electrons onto one plate, while the positive terminal removes electrons from the opposite plate. This creates an electric field between the plates, where the electrical energy is stored. Most practical capacitors contain many closely spaced plates or rolled layers separated by a dielectric. The **surface area** of the plates, the **distance** between them, and the **properties of the dielectric** all determine the amount of capacitance the capacitor can store.

Ceramic Disc Capacitor



Understanding the Markings

- Y5V** = Temperature coefficient
- Capacitance varies from -22% to +82% over the rated temperature range
- 104** = Capacitance value
- First two digits are significant figures
 - Third digit is the multiplier (number of zeros)
- 104** = $10 \times 10^4 \text{ pF} = 100,000 \text{ pF} = 0.1 \text{ }\mu\text{F}$
- Z** = Tolerance
- Z = +80% / -20%
 - Other common codes: J = $\pm 5\%$, K = $\pm 10\%$, M = $\pm 20\%$
- KCK** = Manufacturer / series code
- Identifies the maker and specific product line

$$103 = 10,000 \text{ pF} = 0.01 \text{ }\mu\text{F}$$

$$102 = 1,000 \text{ pF} = 0.001 \text{ }\mu\text{F}$$

$$105 = 1,000,000 \text{ pF} = 1.0 \text{ }\mu\text{F}$$

Symbols:

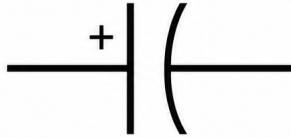
Fixed



A fixed capacitor has a constant capacitance value.

Used when a specific capacitance is needed.

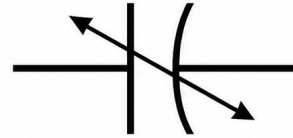
Polarized



A polarized capacitor has positive (+) and negative (–) terminals.

Must be connected with correct polarity in a circuit.

Variable



A variable capacitor allows the capacitance value to be adjusted.

Used in tuning circuits, radios, and other applications.

Note: All capacitor symbols represent two conducting plates separated by a dielectric material. The amount of capacitance depends on plate area, spacing, and the dielectric used.

Various schematic symbols for capacitors: fixed with no polarity, polarized with definite polarity, and variable capacitors.

The **farad (F)** is the unit of capacitance. Because one farad is a very large amount of capacitance for most electronic circuits, capacitors are usually specified in **microfarads (μF)**, which are one-millionth (10^{-6}) of a farad, **nanofarads (nF)**, which are one-billionth (10^{-9}) of a farad, or **picofarads (pF)**, which are one-trillionth (10^{-12}) of a farad.

Capacitors come in a wide variety of shapes and sizes, as well as many different dielectric materials, including **ceramic, polypropylene, electrolytic, polyester (Mylar), polystyrene, polycarbonate, aluminum oxide, mica, PTFE (Teflon), and tantalum oxide.**

Each dielectric material has different electrical properties that affect the capacitor's capacitance, voltage rating, stability, leakage current, temperature performance, and frequency response. **Aluminum electrolytic capacitors** are among the most common types and typically range from about **1 μF to 10,000 μF** or more. They are easily recognized by their small cylindrical "can" shape and are commonly found on power supplies and electronic circuit boards.

Aluminum Electrolytic Capacitor

A common type of polarized capacitor used in power supplies and electronic circuits.

Typical Specifications

- Capacitance:
1 μF to 10,000 μF
(or more)
- Voltage Rating:
6.3 V to 450 V
(or more)
- Temperature Range:
-40°C to +85°C
(or more)



Protective Sleeve

Insulating PVC sleeve protects the capacitor and provides polarity information.

Negative Stripe

The stripe with rectangles indicates the negative (-) lead.

Aluminum Can

Sealed aluminum case contains the dielectric electrolyte and internal constructions.

+
Positive Lead
Longer lead
(usually)

-
Negative Lead
Shorter lead
(usually)

Understanding the Markings (Example: 2200 μF 25V 85°C (M))

- | | |
|-------------------------------------|--|
| 2200μF | = Capacitance value (2200 microfarads) |
| 25V | = Maximum DC working voltage
Do not exceed this voltage. |
| 85°C | = Maximum temperature rating
Capacitor is rated for operation up to 85°C. |
| (M) | = Series / manufacturer code
Identifies the series or manufacturer. |

Important: Electrolytic capacitors are polarized.
Connecting them backwards can cause failure or rupture.



Electrolytic capacitors, like the one on many circuit boards, are generally polarized. You can tell a capacitor is polarized when there are distinct positive and negative sides marked. Metallic capacitor shown second.

You'll find capacitors like these on nearly every microcontroller board, including the **Arduino** and the **ESP32**—typically a few larger electrolytic capacitors for bulk power-supply smoothing, along with numerous small ceramic capacitors located near the voltage regulator, processor, and other integrated circuits to filter electrical noise and stabilize the supply voltage.

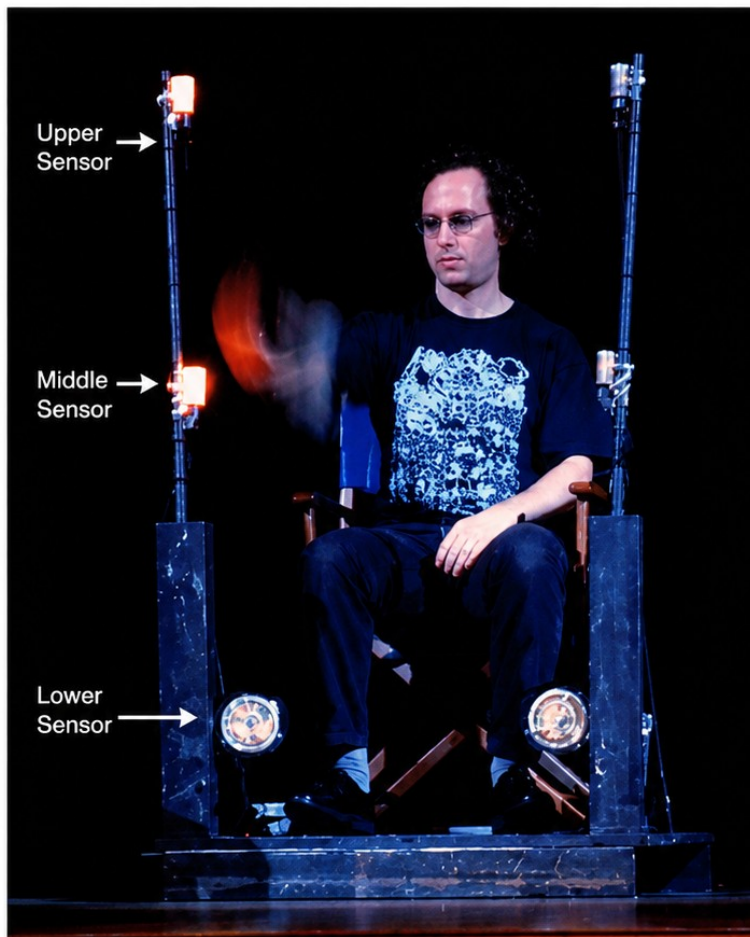
Capacitors and the phenomenon of **capacitance** have been used in art, science, and industry for well over a century. Whenever two conductors are separated by an insulating material, they exhibit some capacitance and can store electrical charge and energy in an electric field, even if the amount is extremely small.

Artist's Applications of Capacitance

The fact that **capacitance** can be measured and used as an input has been explored in many experimental musical instruments and interactive artworks, such as **Todd Machover's Sensor Chair**. Artist **Liz Phillips** has also used capacitive sensing to modulate sound within her immersive sculptural environments. The **Sensor Chair** uses **radio-frequency (RF) capacitive sensing** to detect the movements of the person sitting in the chair. Metal sensing electrodes are housed inside plastic enclosures above and below the participant. These sensors continuously measure subtle changes in the surrounding electric field caused by the body's position and movement. The sensor data are analyzed by software, which determines how different gestures, positions, and movement speeds control the activation, intensity, and spatial characteristics of the sounds produced.

Todd Machover's Sensor Chair

RF (Radio-Frequency) Capacitive Sensing Instrument



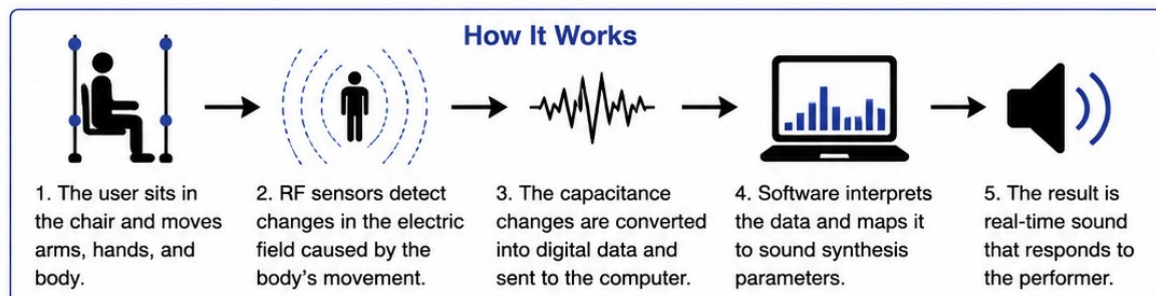
The **Sensor Chair** is an interactive musical instrument that uses RF-field capacitive sensing to detect the body movements of the user.

Metal sensing electrodes are housed in plastic canisters located above and below the participant.

These sensors emit a high-frequency electric field and continuously measure subtle changes in capacitance caused by the body's position, proximity, and movement.

The sensor data is analyzed by software in real time, which maps the movements to musical parameters such as:

- Activation (on/off)
- Intensity (volume, brightness)
- Timbre (sound character)
- Spatialization (location in the sound field)



Key Idea: The human body becomes part of the electrical field. By changing position or movement, the user changes the capacitance between sensors, which becomes music.

Sensor Chair by [Tod Machover](#), in collaboration with Joe Paradiso, 2004.

In discussing his work Todd Machover says: The trick is that we have to be very clever about what aspect of the body movement to measure (you don't want to collect all the data—which would be too much, and not very interesting—but just the relevant data) to indicate what “feeling” the movement has and how to define which movements will produce what music.

Liz Phillips creates immersive soundscapes that are activated by the movements of audience participants as they alter electronic signals controlling synthesizers and other sound-generating devices.

Discussing her work, Phillips says: "I make my work a lot like a painter paints with a wide palette. You mix a little of this and a little of that until you build up the right textures of background and foreground. A lot of what I'm trying to achieve is a dynamic variation that's very much like landscape—like the wind would carve sand dunes."



Sunspots by [Liz Phillips](#), 1982. *Sunspots* is a site-specific sound installation that is tuned to the room in which it's heard. Audience presence and nearness to a copper coiled arch and suspended brass screen determine the combination of sounds.

Selecting Capacitors

Like most electronic components, capacitors should be selected to best meet the requirements of your project.

Whenever you use electronic components, you must pay attention to their **absolute maximum ratings**. These specifications define the maximum voltage, current, temperature, and other operating limits that a component can safely withstand. Exceeding these limits can permanently damage the component or significantly shorten its operating life.

When selecting a capacitor, the most important characteristics are **capacitance value, working voltage, dielectric type, temperature class, physical size, tolerance**, and whether the capacitor is **polarized**.

The capacitance value is measured in **microfarads (μF)**, **nanofarads (nF)**, or **picofarads (pF)**. Capacitors may be connected together in series or parallel to obtain values that are not readily available.

The **working voltage** is the maximum continuous voltage that may be safely applied across the capacitor. If your circuit requires a **35 V** capacitor, it is usually good engineering practice to choose the next higher voltage rating, such as **50 V**, to provide an additional safety margin.

Large capacitors can store enough electrical energy to produce a dangerous or even lethal shock. Always discharge large capacitors safely before handling them, and never assume a capacitor is discharged simply because the power has been turned off.

A friend once told me about accidentally discharging the large capacitor inside the power supply of a cathode-ray tube (CRT) television he was dismantling. The stored energy passed through his body, violently contracting his muscles and throwing him backward across the room. He was fortunate to survive the experience. Handle large capacitors with great respect.

Summary and Resources

In this chapter, you learned how **resistors limit the flow of current** and convert electrical energy into heat. You learned how resistors protect sensitive electronic components by controlling current and reducing the effects of excessive voltage across a circuit. You also learned the difference between **milliamperes (mA)** and **amperes (A)** and became familiar with several new schematic symbols.

You learned how to measure resistance with a digital multimeter and how to determine resistor values using the color code. You also learned one of the most important relationships in electronics—**Ohm's Law**—which you will use repeatedly to calculate voltage, current, resistance, and power while designing safe and reliable electronic circuits. You explored two artists' creative applications of resistance: **Ross Baldwin**, who measures the electrical resistance of the human body to activate his light and glass sculptures, and **Diana Burgoyne**, who uses graphite drawings as variable resistors to create interactive sound environments.

You learned how capacitors store electrical energy in an electric field, how to identify common capacitor types and markings, and how dielectric materials influence their performance. You also explored the work of **Liz Phillips**, who uses capacitive sensing of the human body to shape immersive sound environments, and **Todd Machover**, whose *Brain Opera* employs capacitive sensing to transform human movement into music.

Additional resources:

Mims, Forrest. *Getting Started in Electronics*.

Gibilisco, Stan (Editor in Chief). *Encyclopedia of Electronics*.

Paul Scherz & Simon Monk, *Practical Electronics for Inventors* (4th Edition)

Chapter 5

Semiconductors: Diodes, Transistors, and Integrated Circuits

Active Components, Semiconductors, Integrated Circuits and Artists

“Free of the arbitrary limits of our biological evolution, the children of our minds will be constrained by the physics and logic of the universe.”

— Hans Moravec

Question: Are there materials that are both good conductors and bad conductors, perhaps at different times, in relation to input voltages and current?

Resistors, capacitors, and inductors are considered [passive components](#) because the components do not change in relation to varying voltages and currents.

[Active components](#) are a different class of components because they react and change according to applied signals.

Active components used in electronic circuits are constructed with [semiconductor materials](#) that change according to varying voltages. Semiconductors can allow amplification so a small weak signal can be amplified and turned into a large powerful signal, and they can function as digital and on-off gates.

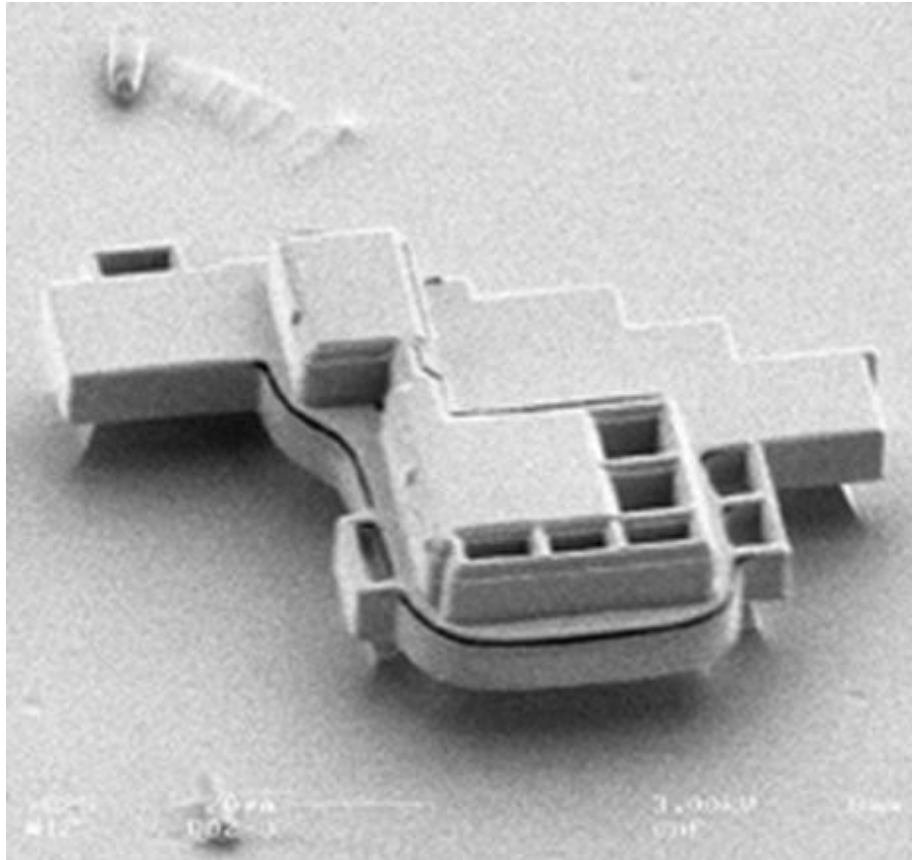
Therefore, at times semiconductors are very good conductors and at other times they are good insulators. This is all controlled by applying voltages to the semiconductor material, and it is why they are called active components.

We have all heard of micro-scale transistor devices constructed using semiconductor **silicon**, and artists/inventors are also inspired by microscale structures and are using silicon to create novel works of nanotechnology art.



Nanotechnology is the science and manipulation of atoms and molecules to build complex structures with exacting specifications at the nanometer scale. One nanometer is about 1/50,000 the width of a human hair or smaller than the wavelength of light.

The artists [Ken Goldberg and Karl Borringer](#) have used microscale silicon as an art material, not for its electronic properties but to make a replica of Frank Lloyd Wright's House on Falling Water.



The Invisible Cantilever by [Karl Borringer and Ken Goldberg](#). 1996. San Francisco, California. A 1/1,000,000th scale version of Frank Lloyd Wright's Fallingwater, invisible to the naked eye, or the width of a human hair.

In Goldberg's recent book *The Robot in the Garden*, he pulled together a series of contributors that discuss the central theme of *telematics* and *telepistemology*. Telepistemology is the study of what we come to know from perception at a distance, which can involve telescopes and microscopes. In the work above, microscopic perception and magnification create questions about our extended senses and how this may influence the nature of what we come to understand about our macro and micro universe.

The media artist Victoria Vesna, UCLA, and James Gimzewski, a nanoscientist at UCSB, are also inspired by the very small, with a twist. Their work *Zero@wavefunction* is a monumental projection installation that allows humans to interact with large-scale projected replicas of molecular-scale nanoparticles.



Zero @ Wave Function by [Victoria Vesna and James Gimzewski](#). 2002. Here, the viewer is manipulating a projected molecule called *Buckminsterfullerene*.

The viewer can interact with these particles by creating a shadow next to the projected nanoparticles and by moving around and changing their shadow. Viewer/participants now have the ability to form, shape, and influence these projected illusory molecules, and this work is telling of the coming nanotech age where scientists and artists will be able to manipulate nanotech materials.

Silicon Semiconductors

Joe Davis has also worked with the very small, and working with researchers at MIT he has created a micro hook made of silicon, which was designed to foster his love of fishing. This hook, however, is designed to hook a paramecium. Joe Davis is a pioneering artist who has done extensive research in bioinformatics and molecular biology and has produced complex genetic databases, which have allowed the production of unique biological art forms.

For this work, Davis collaborated with researchers at MIT, and created a machine where humans can fish for the single-celled protozoan, paramecium.



The nano-hook that was fashioned to hook a paramecium.

Davis was able to use a lockout transformer, a machine that was able to scale up the pull that a paramecium would exert on the hook. This attaches to a marlin fishing rod, which is a full-size surf-casting rod and reel, and theoretically allows the artist to fish for the paramecium.

In fishing for a paramecium, Davis demonstrates that humans can reach into molecular-scale worlds and connect the macro-scale of humans to the scale of a single-celled organism with silicon hooks. Here the work also alludes to the issues of telepresence in probing and “fishing” at the micro scale.

So, how are semiconductors made? Are they unique?

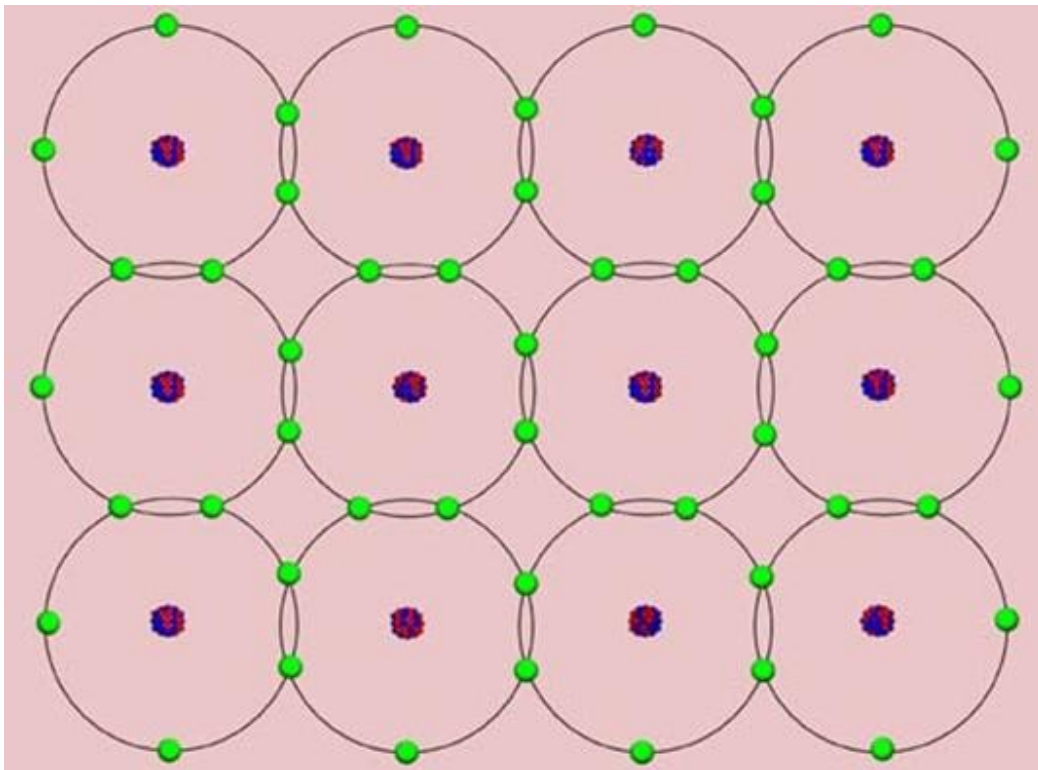
Consider a story by the founder and chairman of Intel, a major producer of microchips, Gordon Moore:

“We needed a substrate for our chip. So we looked at the substrate of the earth itself. It was mostly sand. So we used that. We needed a metal conductor for the wires and switches on the chip. We looked at all the metals in the earth and found aluminum was the most abundant. So we used that. We needed an insulator and we saw that the silicon in the sand mixed with the oxygen in the air to form silicon dioxide — a kind of glass. The perfect insulator to protect the chip. So we used that.”

While silicon is the most prevalent semiconducting material there is a great variety. Sand composes 27% of the earth's crust and is the primary ingredient in silicon. However, it must be refined to allow its atomic structure to be useful and to create that semiconducting state. The atomic structure of silicon gives it the properties of being a good conductor at times and a bad conductor at other times, depending on if valence electrons are available to support current flow.

The reason that silicon in its pure state displays this property is that its atoms have four valence electrons in their outer shell, which allow them to join with their neighbors. In the image below you will see a visual diagram in 2D of a cluster of 12 silicon atoms sharing their 4 valence electrons with atoms next to each other in the crystal lattice. Imagine that the diagram below is a slice through the material to show you how the atoms and their electrons relate.

If you look at the model of the two center atoms, notice how the green electrons circling the nucleus can be a part of these atoms or a part of the other atoms that are surrounding these atoms in the crystal lattice.

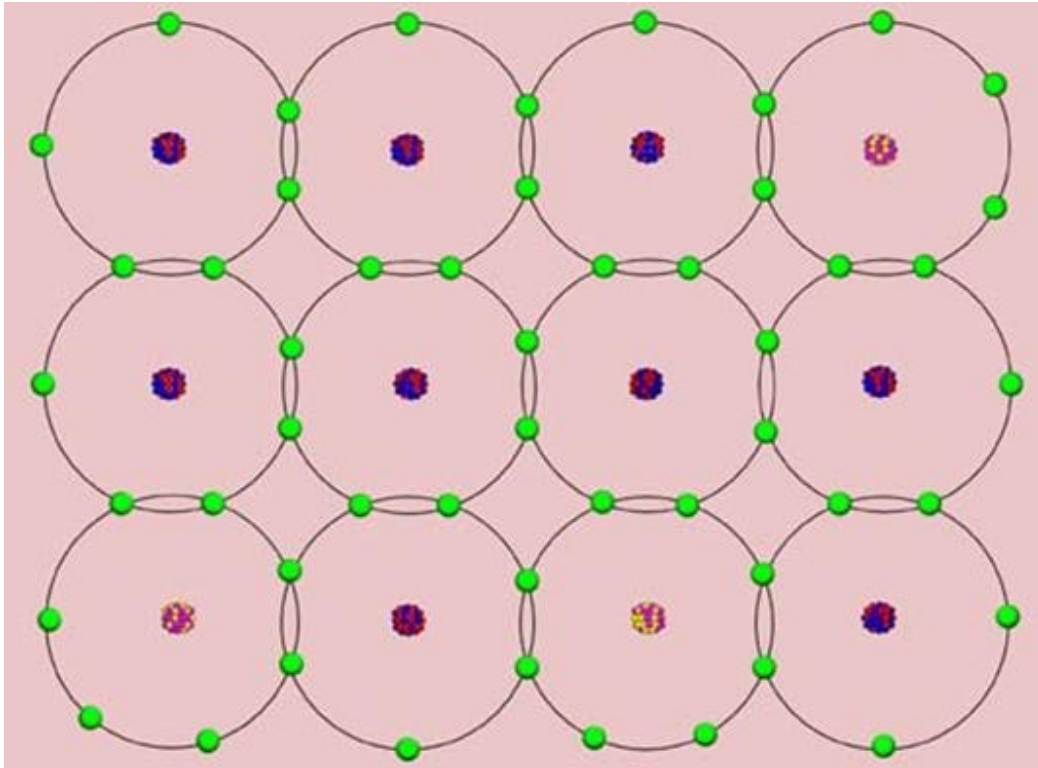


A cluster of 12 silicon atoms.

Adding the elements phosphorus and boron to the mix of silicon can add and subtract available electrons. This is called doping, because a small amount of these elements is added to the crystal and this affects the electrical properties of that silicon crystal.

By adding phosphorus, which has five valence electrons, you end up with an extra electron in the mix. As phosphorus atoms have five valence electrons, the extra electron donated by the phosphorus atom supports current flow. Adding phosphorus creates a crystal lattice of the silicon that at times supports conduction and at other times does not, depending on the voltages which are applied to the material.

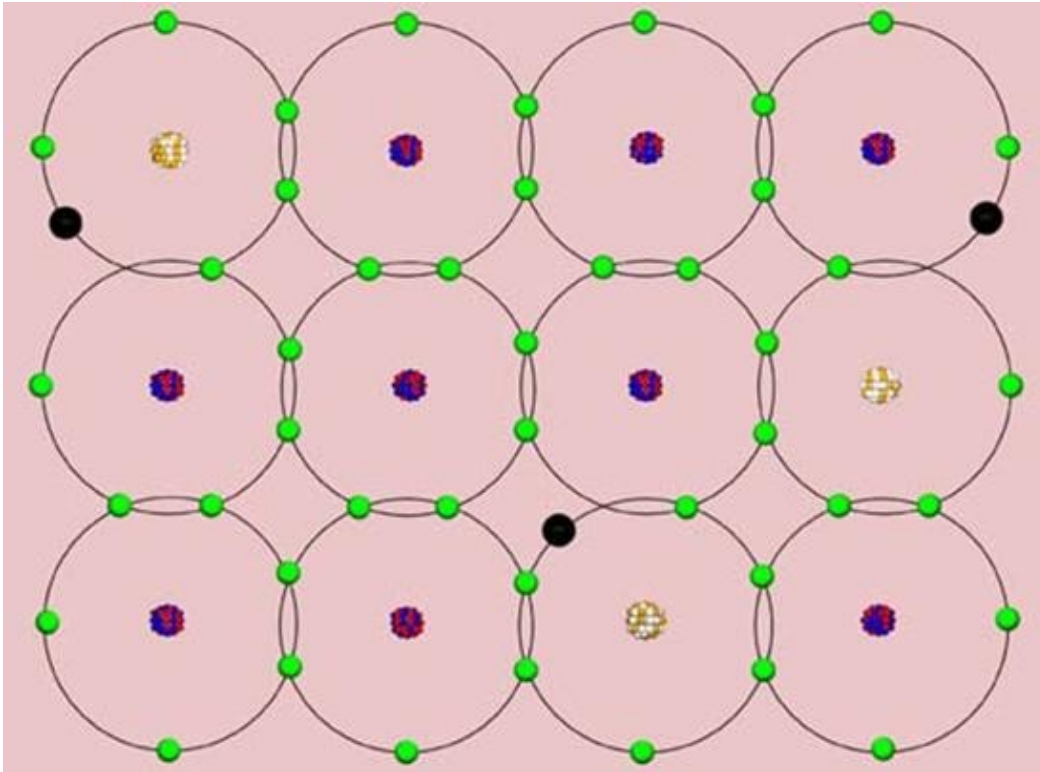
We call this **n-type silicon (negative type silicon)** because the electrons will now outnumber the protons in the silicon mix. Notice in the image below you have a cluster of 12 atoms, 9 silicon atoms (blue and red nucleus) and 3 phosphorus atoms (blue and yellow nucleus), and you will notice the phosphorus atoms each have an extra electron.



Cluster of 12 atoms, 9 silicon atoms and 3 phosphorus atoms, with phosphorus adding the extra electrons.

On the other hand, when you add the element boron to the silicon mix, the three electrons in the outer shell create a material that is short on electrons, or electron deficient.

We call this **p-type (positive-type silicon)** because the protons in the nucleus now outnumber the electrons. Boron creates a vacant electron, which is called a hole. This electron vacancy makes it easy for another electron to fall into the hole. Many visualize the holes as bubbles in water. You can imagine these bubbles (areas of electron deficiency) propagating through a crystal lattice as bubbles floating through water.



A cluster of 9 silicon atoms next to 3 boron atoms, which have an electron deficiency and do not easily support current flow.

Now you can visualize what is happening on a molecular level with electrons moving through semiconducting materials. Semiconducting materials are the backbone of our information culture as we know it, and this ability to manipulate silicon by doping, or adding small amounts of phosphorus and boron, has transformed our culture.

An interesting side note is that the beginnings of life and multicellular animals occurred around the same time that phosphorus became available in the environment. Phosphorus plays a vital role in the biological molecules of DNA (deoxyribonucleic acid) and RNA (ribonucleic acid) and functions as a kind of molecular backbone. It is also an important element in the cell protoplasm and for the functioning of nervous tissue. It is speculated that phosphorus came to the earth via meteorites.

Diodes

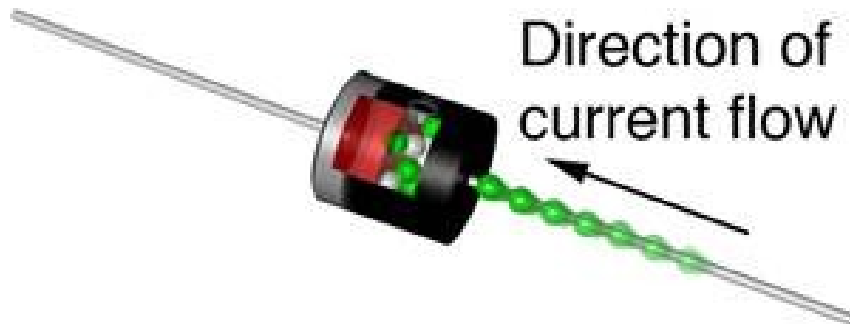
Question: Is there an electronic part that exploits the molecular structure of P and N type silicon and allows AC and DC to flow in only one direction?

The diode can be thought of as a one-way gate for electrons. It allows electron current to flow in one direction and not the other (Zener diodes are an exception to this).

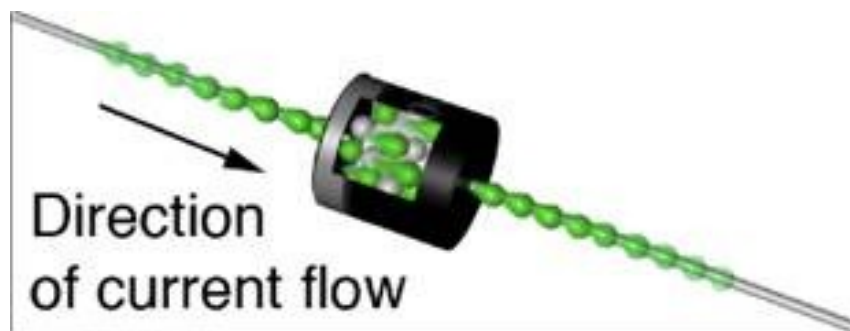
3D model of the diode on the left. The schematic symbol for a diode on the right.

Diodes are often used in voltage conditioning and helping to change AC voltages into DC voltages by removing one direction of current flow from an AC signal. This is called rectification of voltages. They can also be used to drop voltages down to lower voltage levels, and they can be used in motor applications where reverse voltage spikes can potentially damage sensitive parts of your circuit.

A diode is an electronic semiconductor that uses p-type and n-type silicon junctions. That is, the p-type silicon is near the n-type silicon inside a cylindrical package below.



A diode in reverse bias will not conduct (with the exception of Zener diodes).

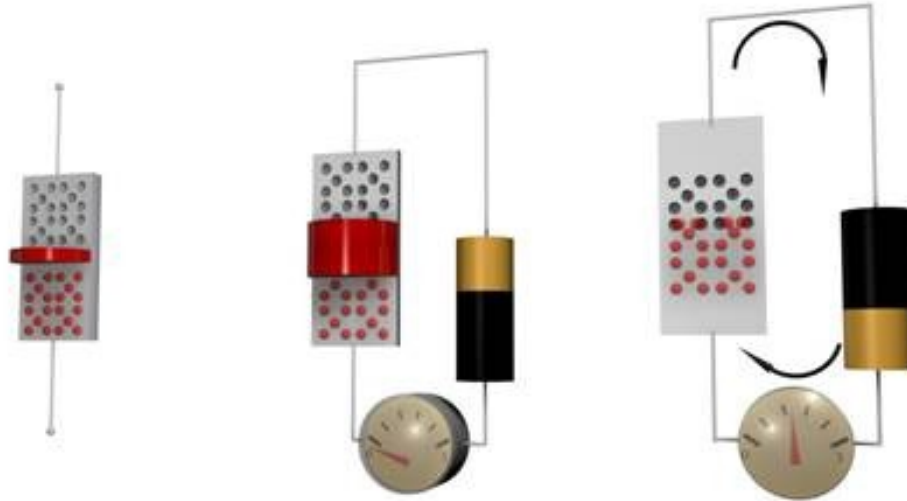


A diode in forward bias will conduct with a voltage drop.

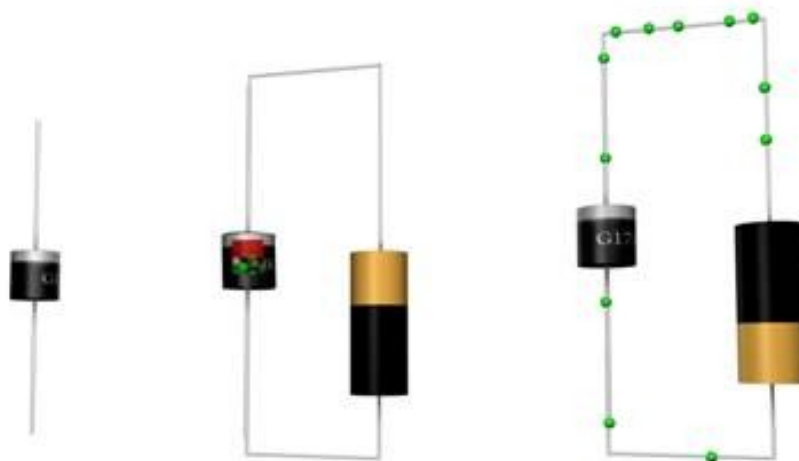
While a diode can act as a one-way valve for electricity, it only conducts if the voltage comes up to about .6 volts. A diode also lowers the voltage slightly. The actual voltage drop changes according to the type of diode. In this case, we will be using a silicon diode, so we can expect the .7v drop. However, Schottky diodes drop the voltage by 0.3v and germanium diodes by only 0.2 volts.

When a semiconductor, such as a diode, is created with p-dope and n-dope materials, there is a tendency for electrons to migrate from the n-zone to the p-zone. There is also a tendency for the holes to migrate from the p-zone to the n-zone.

The effect is a cancellation of charges in the region between the two, and this is called the depletion layer.



The effect of bias on the diode is that in one direction, it conducts, and in the other, it does not.



The effect of bias on the diode is that in one direction, it conducts, and in the other, it does not. Here you can observe the model showing you the voltage drop occurring across the diode.

This depletion layer sets up a potential difference between the two regions, and the device remains in a stable state until an external voltage is applied.

You can generally identify diodes because their part numbers start with the prefix 1N, with common parts being 1N4001, 1N4002, 1N4007, etc., and you can identify them by the single white band near the cathode wire of the diode. In glass diodes, a black band is used to show the cathode.

With diodes, be aware of **IF**, which is the **forward current** moving through the diode. **VF** is the **forward voltage** moving through the diode, and the **PIV**, or **peak inverse voltage**, is the voltage under which the diode will conduct in reverse bias. If the PIV is exceeded you can permanently damage your diode.

These are the **absolute maximum ratings** for the diode, and you must pay attention to these values when you are selecting your parts.

Using the Multimeter to Test a Diode

In this activity, you will learn to build a circuit using a diode and discern the function of a diode.

Parts needed:

Breadboard • 2 diodes • Multimeter with diode tester

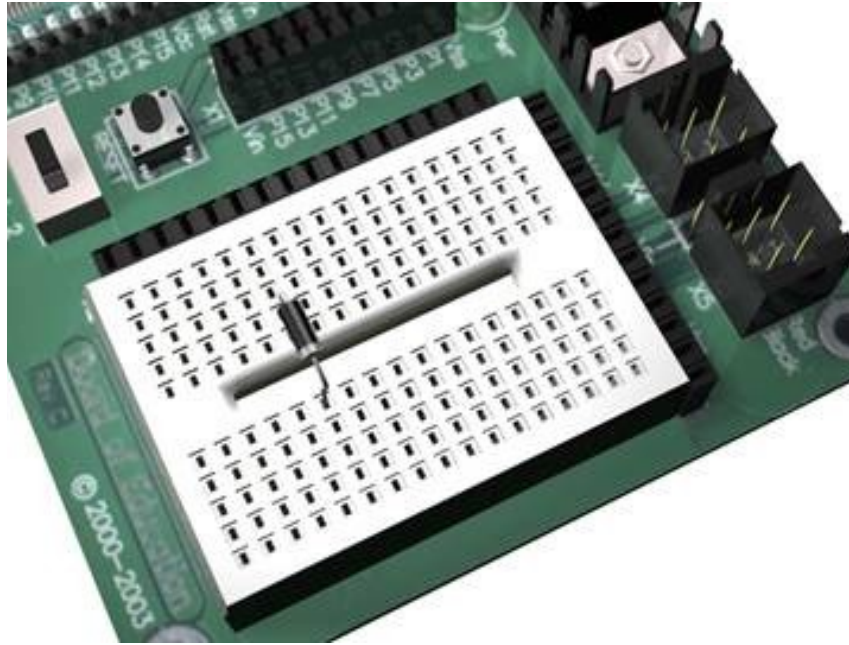
Building the circuit:

Set your meter to the Diode reading area.



Use this setting to measure the bias of the diode.

Place your diode in the board as shown below.



Place the diode in the breadboard like this.

Use your multimeter's diode setting to measure the voltage drop that the diode will create across the circuit. The multimeter provides the voltage necessary to get a reading and functions to tell you what the voltage drop is. If you put your red lead closest to the white band of the diode as below, you will see the number 1, and this is an indication that you have the diode in reverse bias. If you put the black lead closest to the cathode or white band of the diode, then current can flow and you will get a reading. What is the voltage you read? _____ Remember a mV is one thousandth of a volt.

Now put two diodes end to end as you did for creating a series circuit with resistors, and make sure the white bands of the cathode are in the same direction. What is your voltage drop with the two diodes added together? _____

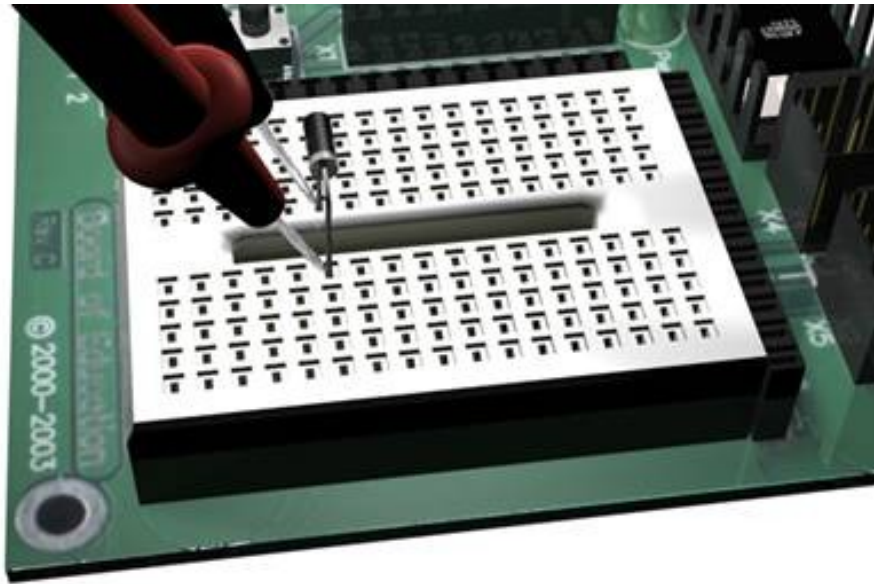


Image of a multimeter in reverse bias, which will produce no current flow on the diode.

Challenge Questions:

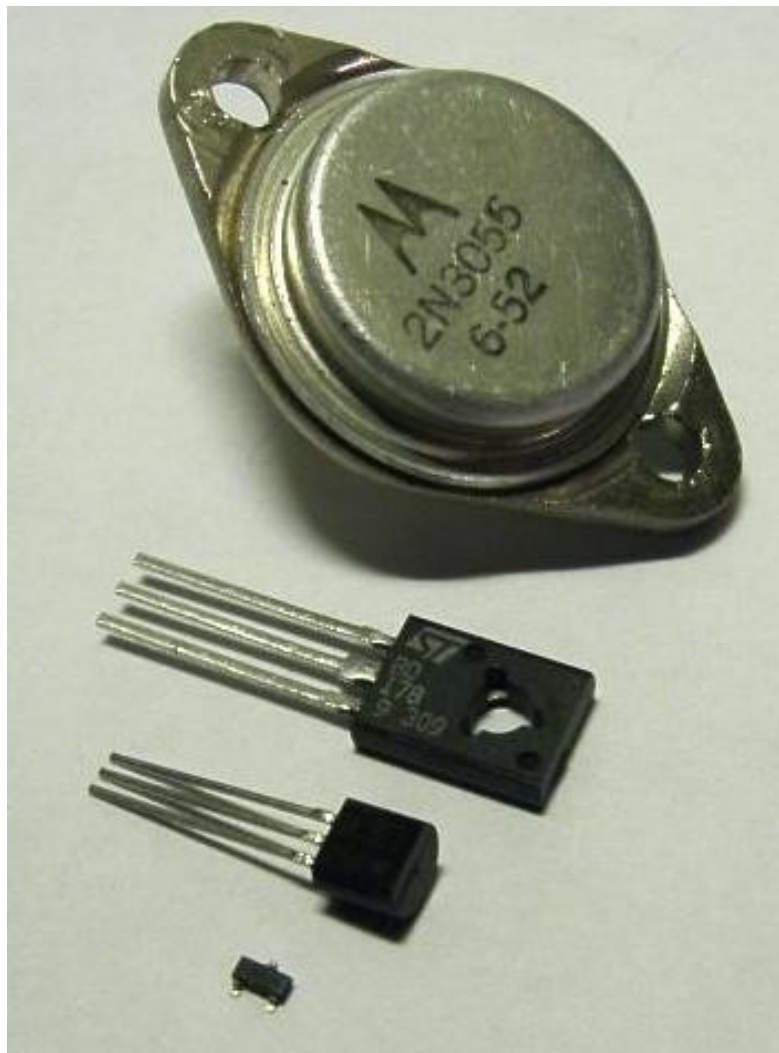
- 1) Name the three most common passive components. _____
- 2) Why are active components called active? _____
- 3) Define a semiconductor. _____
- 4) What is doping? _____
- 5) What are the two kinds of doping in semiconductors? _____
- 6) What kind of semiconductor is formed when you add phosphorus? _____
- 7) What kind of semiconductor is formed when you add boron? _____
- 8) Name three uses for diodes in circuits. _____

Transistors

“As literal and literate culture thus slowly emerged from the oral and material culture, and this cultural memory became ever more closely identified with the library, a curious process of reification and sacralization of the library developed. It was ... taken to be a super-human memory which transcends individual men, which covers over them, and to which they must aspire.”

— Vilém Flusser

[Transistors](#) are semiconductor devices with three leads instead of two, and they allow a small current to control a much larger current. By adding a second junction to a diode, you end up with a three-layer transistor device called either NPN (not-positive, positive and not-positive layers) or PNP, which has two not-positive layers of silicon sandwiching a positive layer of silicon. I call this a silicon sandwich, with NPN having a p-type silicon layer sandwiched between two n-type silicon layers and vice versa for the PNP. In the NPN transistor, the middle layer acts as a gate or faucet, to allow a current to pass when voltages are applied to the middle layer. This means that transistors can be used as digital logic switches and as amplifiers.



Transistors of various sizes and packages.

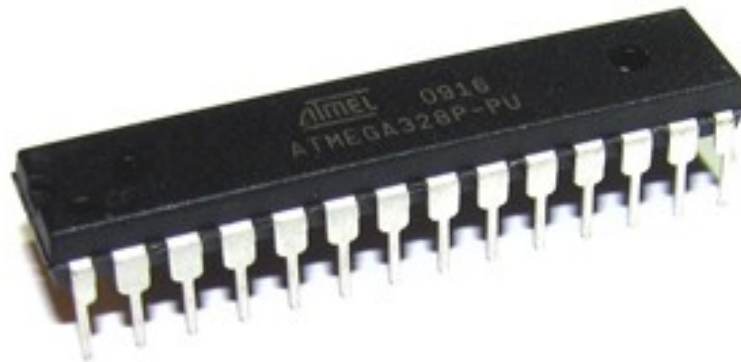
It is important to acknowledge that the transistor welcomed the information age, as we know it. With transistors, portable radios like the Sony TR-55 and the Regency TR1 suddenly became available for the masses, which then had easy and portable access to information and entertainment. The transistor radio certainly fueled the rock and roll music revolution. You can imagine a teen finally free of the constraints of the family's musical tastes and tuned into emotionally charged rock and roll.



[Sony Transistor Radio](#)

Integrated Circuits

During the industrial revolution, humankind made enormous advances in production with the use of mechanical means such as steam and gas-powered motors, which we can think of as an amplification of human muscle. The digital revolution, or information revolution, has made possible the amplification of the human brain. This amplification has created a kind of symbiotic relationship between humans and computers that have permitted more efficient control of the mechanics of the industrial revolution, like the joining of hydraulics with information technology for the creation of robotics.



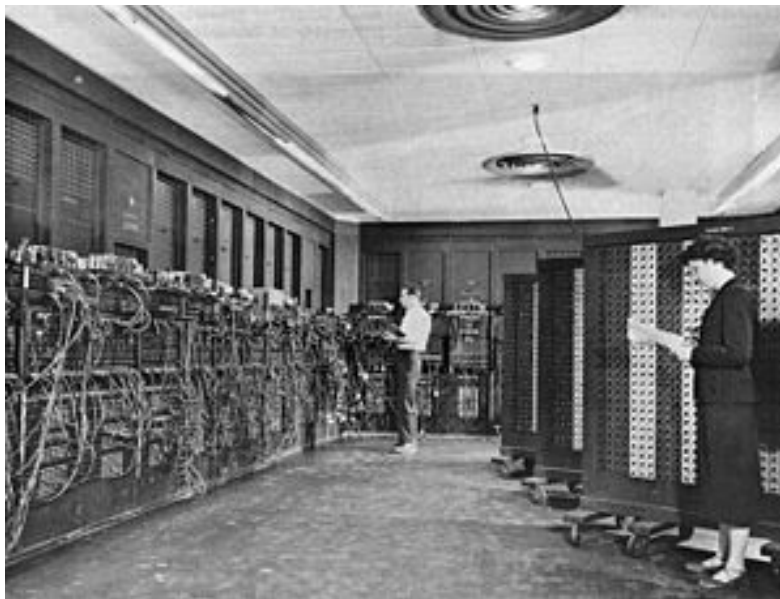
A microchip is an example of an integrated circuit. This is called a DIP, or dual inline package. On the Arduino UNO, an ATmega328 is standard.



Not every integrated circuit ships in a simple DIP package, though. The rectangular metal-can module visible at the left of this ESP32 development board is the ESP32-WROOM-32 module: a small circuit board in itself, with a metal shielding can covering the ESP32 SoC, its SPI flash memory, and supporting components, with a printed antenna trace and castellated edge pads that solder directly onto the carrier board beneath it.

However, more important, integrated circuits have created an attendant increase in the quantity and ease with which information is now available for all, with the deployment of microcomputers and the Internet.

Just think, the first computer, the [ENIAC](#) (Electronic Numerical Integrator and Computer), filled a whole room with tubes and could do a variety of general purpose computing, though it was designed to calculate artillery firing tables. Today, with fast microcomputers we can calculate these trajectories in the background while printing out our papers and generating fractal patterns simultaneously, in the multitasking environments of faster and smaller integrated circuits.



ENIAC Computer

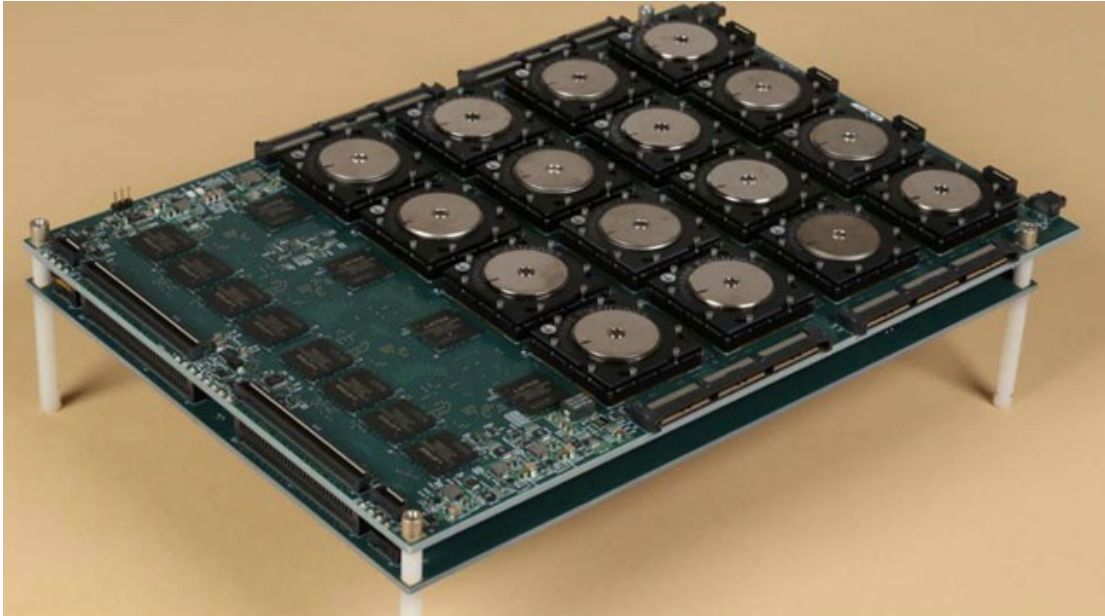
In the manufacture of microchips, there is a law called Moore's law that states that every 18 months we functionally double the number of transistors on a microchip. Gordon Moore made this prediction in 1964, only six years after the invention of the microchip.

Later, Moore went on to co-found the Intel Corporation. Because the doubling of the transistors is not accompanied by an increase in cost, we have seen chip prices falling steadily. In 1985, a dedicated word processor system sold for \$12,000. Today you could purchase a dedicated word processor for \$200, or get a complete desktop system that can run a myriad of software at once for \$500. A single transistor was \$1 in 1968, and today you can purchase roughly 50 million transistors for \$1.

Today processors like the Intel Core Duo have approximately 291 million transistors, or more, on a single chip, and ICs with 500 million are in development. Research into new vertical architectures may change this, as well as the ability of silicon to handle the heat of the electron transfer, which can commonly be at 200°F. New diamond substrates are now being researched that would allow faster chips since normal silicon can only handle a certain amount of heat. Most recently Intel introduced a new

architecture with 14 nm widths called the Broadwell, and the 15-core Xeon Ivy Bridge-EX has 4.3 billion transistors with traces that are 22nm.

DARPA SyNAPSE is a 16-chip board that has 5.4 billion transistors.



DARPA SyNAPSE, 2014

At the current pace, microchips will have many billions of transistors in the not-too-distant future, and Gordon Moore's prediction continues to expand with new vertical architectures. [Transistor counts](#) from Wikipedia.

Integrated Circuits: Fabrication

The contemporary robotics theorist Hans Moravec predicts that we will see computer intelligence arise in the not-too-distant future. He researches the density of the human optic nerve, looks at Moore's law, and predicts that machine intelligence will surpass human intelligence by 2030.

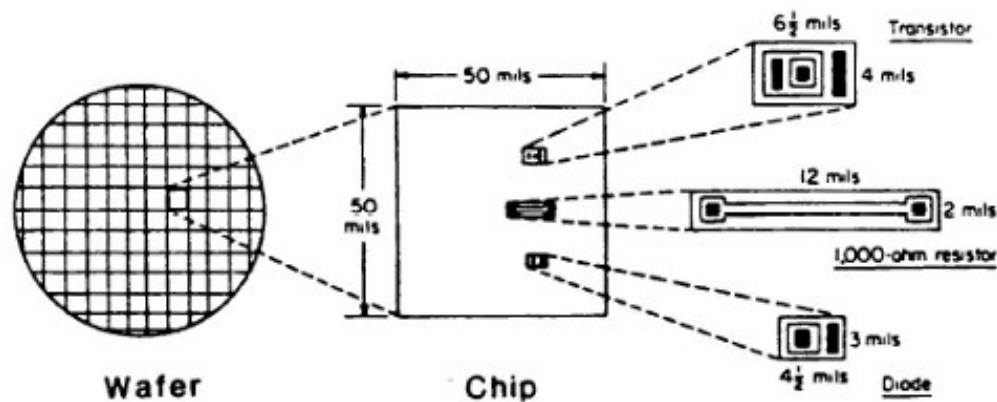
Integrated circuits are the result of physics combined with the modern techniques of engineering and manufacturing. This allows solid-state passive components like resistors and capacitors to be integrated with active components like transistors and diodes into micro-packages that allow the integration of many electrical functions on a single device. These integrated circuits can contain as few as two or three transistors to hundreds of transistors to millions of transistors.

Integrated circuits can be created to amplify or respond to variable voltages, and we call these analog or linear integrated circuits. Examples would be amplifiers, timers, oscillators, and voltage regulators.

Digital or logic integrated circuits respond to just two voltage levels: high 5-volts and low 0-volts. They are called digital because they rely on binary math to allow the chips to utilize and count in base two, as opposed to our base ten system of counting.

They include microprocessors, memory chips, and digital clocks. Many integrated circuits combine both analog and digital functions. These are created by the interconnection of transistors, capacitors, and resistors in a micro-size to form a complex electronic system on a sliver of silicon.

Circuit Details



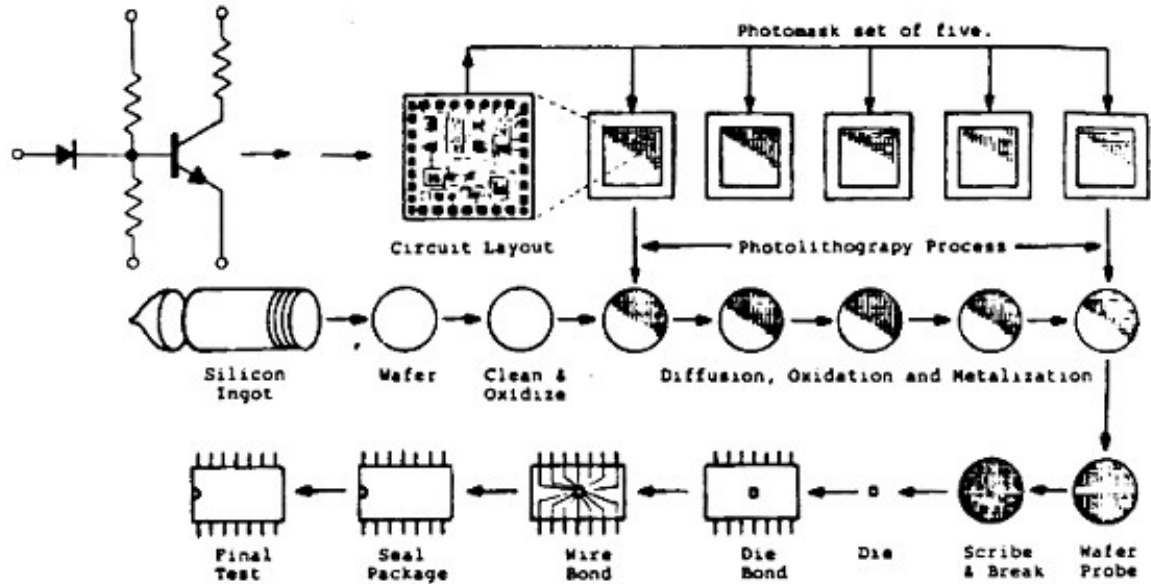
Circuit details in creating a microchip

The fabrication process is based on a series of steps called **mask layers**, which are layered above the silicon and exposed to x-rays. The first process is a layer of silicon dioxide created by exposing the silicon to heat and gases. It grows as rust would grow but more rapidly. After this the silicon wafer is coated with a photoresist, which becomes soluble when exposed to the ultraviolet light used in the process.

The process involves layering, or photolithography, in which a powerful ultraviolet beam is projected through patterned mask layers. The ultraviolet light allows the exposed areas of the chip to become soft,

and this is etched away to leave the traces of the microchip that represent the wires and various parts. The different layers of the microchip involve very different masks, each of which allows components under each other to link up and be connected in the chip.

Manufacturing Sequence



Manufacturing sequence of a chip

Many have seen the masks as art forms in themselves. In 1990 Cara McCarty did a wonderful exhibit at the Museum of Modern Art in NY called *Information Art: Diagramming Microchips*, in which the curator and museum featured the photo masks used in this process of creating microchips.

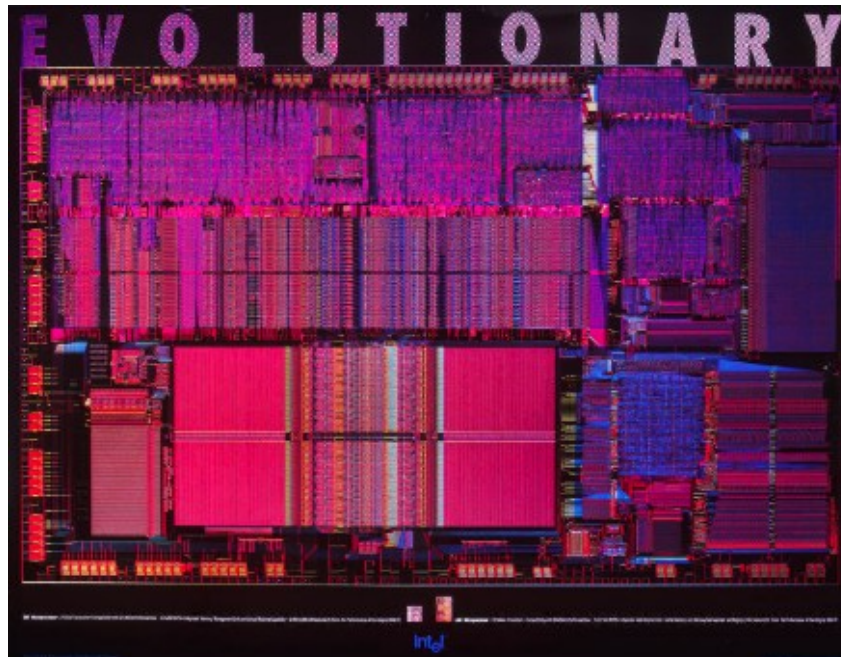
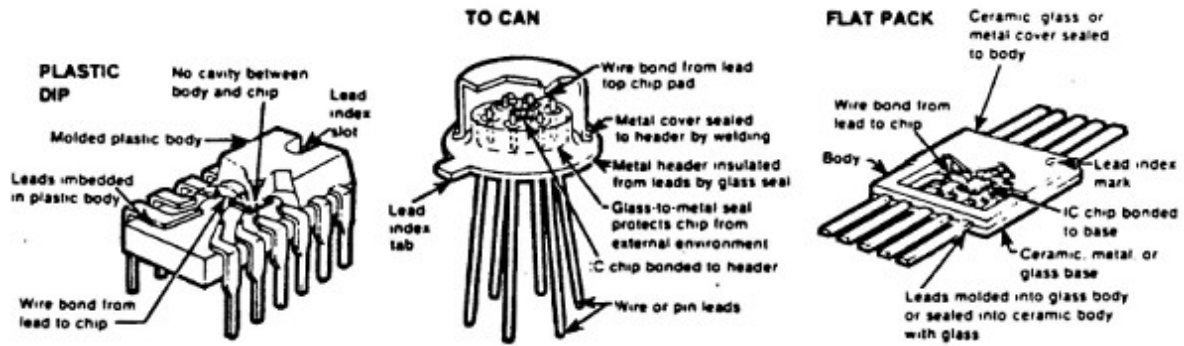


Photo mask for a microchip

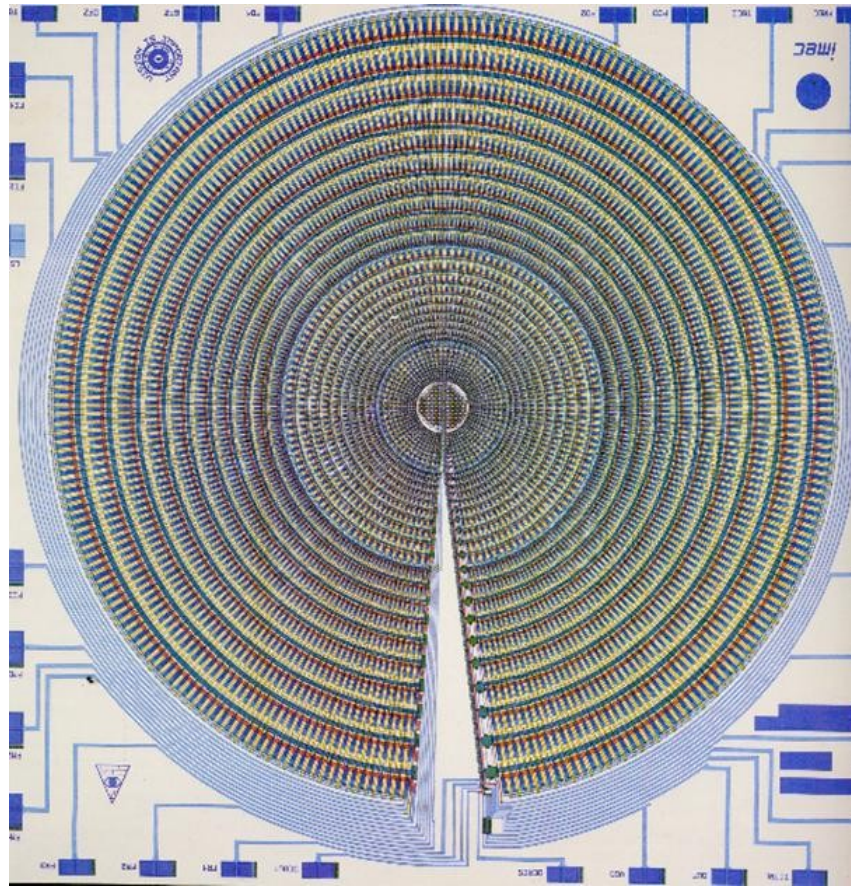
After deposition and lithographic procedures, the layers are processed to “etch” the patterns that, when precisely aligned and combined with those on successive layers, produce the transistors and connections.



Cutaway view of interior of integrated circuits

The types of architectures available in microchips are advancing rapidly, with many experimental designs based on trying to understand biological principles as they may be applied to technological material.

The chip below is an optical sensor artificial eye with foveated vision by Carver Mead, the father of VLSI (Very Large Scale Integration).



Carver Mead photo mask for microchip with foveated vision

Technological Advances

Some researchers are working on microchips that will be driven by object-oriented languages instead of programming with lines of code, and with these, you will manipulate the controllers with on-screen interfaces which permit you to realize complex behaviors that do not require you to be an expert programmer.

Raw chips are part of a new kind of research which can reconfigure their connections so they are optimized to work their fastest for a particular application. In one test, the application results estimate that the program would run ten times faster on the raw chip. Still, these are in early development.

Other recent advances are new chips with multiple core processors, which split the processing into different segments of the microchip, breaking the processing into smaller tasks, though this can cause difficulties for programmers who must adapt their approaches to programming.

A group of scientists in Europe has created a silicon chip designed to mimic human brain function. This chip has 200,000 neurons which are linked by 50 million synaptic connections. The FACETS project is recreating the brain structure in computer form, with transistors, to understand how massively parallel computers can recreate simulations of human brain activity.

Still, it is difficult to imagine when a computer will ever exceed the human animal, in spite of robotics replacing many human functions in factories or for telephone answering systems. When researchers calculate the number of transistors and compare that to the human brain they often fail to account for the human body as an exquisite acquisition tool with trillions upon trillions of neural cells. When robots have bodies that can sense and integrate knowledge about the world around us, and not only be optimized for symbolic languages such as words or numbers, we may have an emergent new species arising around us.

Conceptual readings:

Gimzewski, Jim, and Victoria Vesna. "The Nanomeme Syndrome: Blurring of Fact and Fiction in the Construction of a New Science."

http://vv.arts.ucla.edu/publications/publications/02-03/JV_nano/JV_nano_artF5VG.htm

References:

- [1] Ken Goldberg artist's website: <https://goldberg.berkeley.edu/>
- [2] Goldberg, Ken (Editor). *Robot in the Garden: Telorobotics and Telepistemology in the Age of the Internet*. MIT Press.
- [3] Victoria Vesna, UCLA, and James Gimzewski artists' website: <http://vv.arts.ucla.edu/>
- [4] Gibbs, W. Wayt. "Art as a Form of Life." *Scientific American*, April 2001. viewingspace.com
- [5] Gilder, George. *Microcosm: The Quantum Revolution in Economics and Technology*. Simon and Schuster, 1989, p. 18.
- [6] Scherz, Paul. *Practical Electronics for Inventors*. McGraw-Hill, 2000, p. 127.
- [7] Ibid., pp. 128–129.
- [8] Horgan, John. "In the Beginning..." *Scientific American*, Feb. 1991, pp. 116–125.
- [9] Davis, Joshua. "The New Diamond Age." *Wired*, Issue 11.09, September 2003.
- [10] McCarty, Cara. *Information Art: Diagramming Microchips*.

[11] Ibid.

[12] <http://www.sciam.com/article.cfm?articleID=00040704-9646-1C72-9EB7809EC588F2D7>

[13] Gibbs, W. Wayt. "A Split at the Core." *Scientific American*, p. 96.

[14] Graham-Rowe, Duncan. "Building a Brain on a Silicon Chip." *Technology Review*, MIT, March 25, 2009. <http://www.technologyreview.com/computing/22339/>

Further research resources:

Questlink Chip Center is a great place to research and find chip and data sheets:

<http://www.chipcenter.com/questlink/>

Chapter 6

Microcontroller Platforms: Arduino and the ESP32

“Today, the main option people have for expressing themselves powerfully is through machines.”
— Mark Pauline of Survival Research Laboratories (1987)

The **Arduino UNO** is an extraordinary open source microprocessor that can function as a standalone device using code provided by a massive community of users. If you are developing a single device it functions beautifully and can get you involved in the world of microprocessor control using code to modify things like flashing LEDs, driving motors, driving relays to switch larger currents, or driving sound.

What is spectacular is that the Arduino can also be used in Firmata mode, meaning it can function as an interface device to MAX MSP and Jitter through Maxuino. Maxuino is a collaborative open source project for getting the Cycling '74 software “Max/MSP/Jitter” talking to the i/o elements of any Arduino board. This allows MAX MSP and Jitter to read analog and digital pins, write to digital, run PWM, control servo motors, and listen to i2c sensors. Maxuino can also talk to an Ableton Live device (made with Max for Live) that allows you to communicate with your Arduino-compatible microcontroller from Ableton. You can find video tutorials on how to download the necessary software for both Arduino, downloading Firmata, and testing that your system is talking well to Maxuino and to MAX MSP and Jitter here: <http://www.maxuino.org/>

Once I had gone through the downloading and activation of the Arduino and Firmata testing procedures as referenced in the video tutorials above, Trademark Gunderson wrote a quick patch to allow the necessary pins and functions to automatically reference the Maxuino file so that each time you activate Maxuino you start with this file.

Arduino UNO

The Arduino UNO is a spectacular microcontroller based on the ATmega328 chipset. It has revolutionized open source access to inexpensive microcontrollers. While the Arduino is a tremendous platform and the provided code and IDE (Integrated Development Environment) are wonderful, this book will focus more on using MAX MSP and Jitter through the Arduino, communicating through MAXUINO and Firmata.

Arduino is an open-source physical computing platform based on an i/o board and a development environment that implements the Processing/Wiring language.

Arduino can be used to develop stand-alone interactive objects or can be connected to software on your computer (e.g. Flash, Processing, MaxMSP).

This open-source IDE can be downloaded for free (currently for Mac OS X, Windows, and Linux).

Microcontroller: ATmega328 • Operating Voltage: 5V • Input Voltage (recommended): 7–12V • Input Voltage (limits): 6–20V • Digital I/O Pins: 14 (of which 6 provide PWM output) • Analog Input Pins: 6 • DC Current per I/O Pin: 40 mA • DC Current for 3.3V Pin: 50 mA • Flash Memory: 32 KB (0.5 KB used by bootloader) • SRAM: 2 KB • EEPROM: 1 KB • Clock Speed: 16 MHz

The Arduino UNO can be powered via the USB connection or with an external power supply.

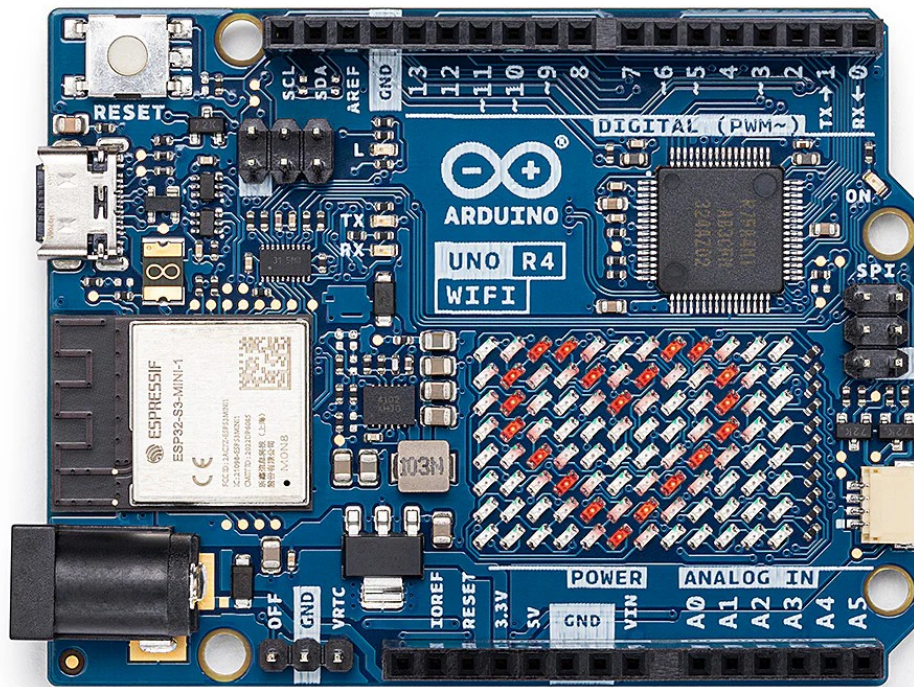
External (non-USB) power can come either from an AC-to-DC adapter (wall wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the power connector. The board can operate on an external supply of 6 to 20 volts.

Each of the 14 digital pins on the Uno can be used as an input or output, using `pinMode()`, `digitalWrite()`, and `digitalRead()` functions. They operate at 5 volts.

The Arduino Uno has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Parts Necessary:

Arduino UNO or other Arduino board • USB programming cable



Arduino UNO R4 WiFi

To start this tutorial make sure your Arduino is not sitting on a metal surface or in accidental connection with wires or leads under the board.

- 1) Plug in the Arduino Uno via the input port. Notice the green LED (surface mount) on the board.
- 2) Notice, as you plug in, another green LED flashes a couple of times at Pin 13 for RX and TX, standing for send and receive, and this is like a handshake between the computer and the Arduino.
- 3) Open up the Arduino IDE after downloading it from <http://arduino.cc/en/Main/Software>.

When you open the software you will find this window.

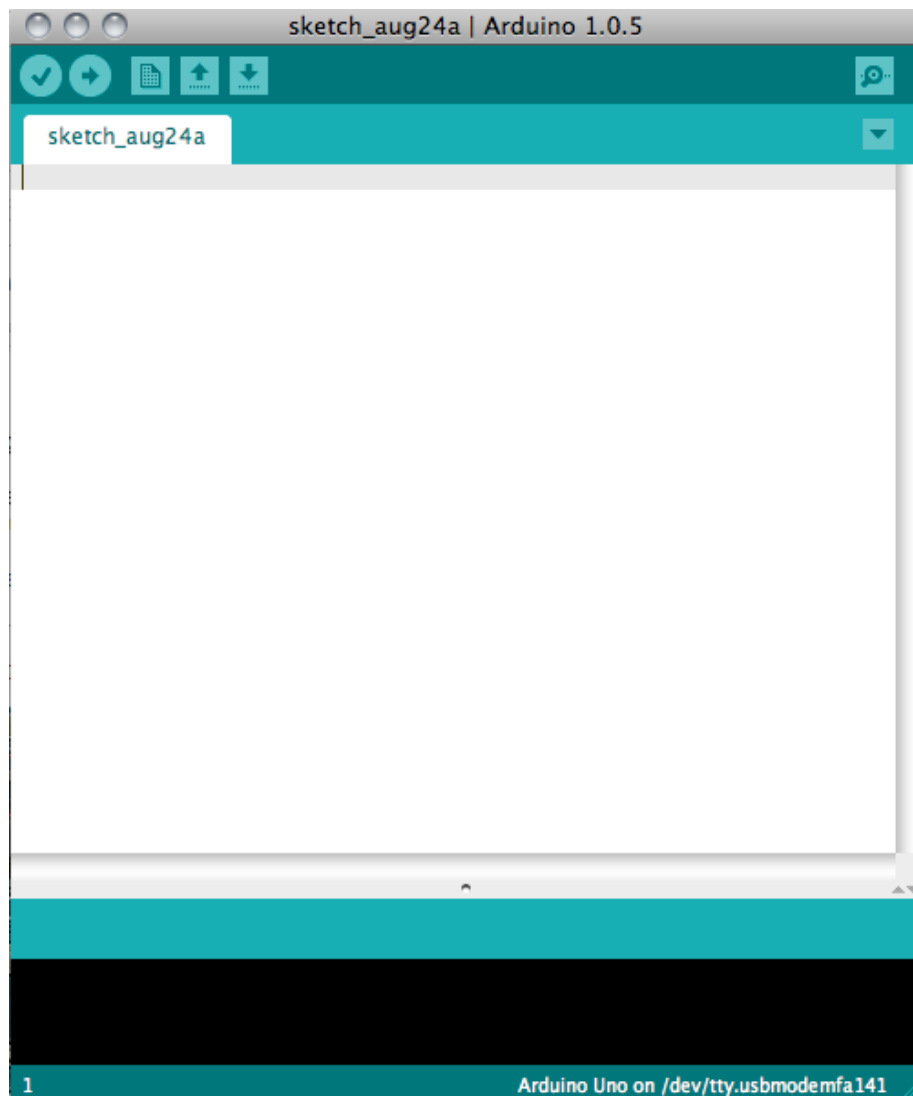
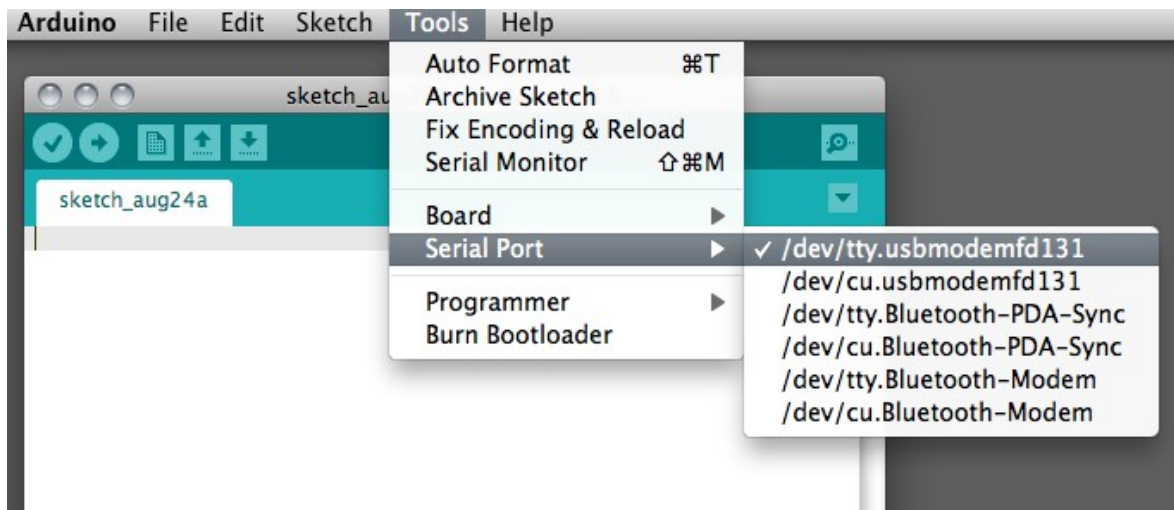


Image of the Arduino IDE

Next you need to select the Arduino UNO or other Arduino product you are using, and then select the proper serial port for communicating with the Arduino.



Selecting the /dev/tty.usbmodemfd131 or other such port. Notice on other computers the number may be different, and the tty. or cu. ports should work fine.

Now navigate to File and Examples and select Blink from the Arduino example code. Now we are ready to try out the Arduino Blink program, so when you select the program you will notice that it appears in the IDE.

 A screenshot of the Arduino IDE showing the 'Blink' program code. The title bar says 'Blink | Arduino 1.0.5'. The toolbar includes icons for checking, uploading, and downloading, along with the text 'Upload Using Programmer'. The code editor shows the following code:


```

/*
  Blink
  Turns on an LED on for one second, then off for one second, repeatedly.

  This example code is in the public domain.
  */

// Pin 13 has an LED connected on most Arduino boards.
// give it a name:
int led = 13;

// the setup routine runs once when you press reset:
void setup() {
  // initialize the digital pin as an output.
  pinMode(led, OUTPUT);
}

// the loop routine runs over and over again forever:
void loop() {
  digitalWrite(led, HIGH); // turn the LED on (HIGH is the voltage level)
  delay(1000);             // wait for a second
  digitalWrite(led, LOW);  // turn the LED off by making the voltage LOW
  delay(1000);             // wait for a second
}
  
```

Blink program in Arduino code

Now it is time to hit download, and you will notice a bar at the bottom of the IDE with progress, and when it says Compiling and then Done, the software is uploaded. Now notice how the little LED at pin 13 is flashing at a given rate of one time per second.

Now, for fun, look into the program above and change the flash rate of the LED to 500 near where it says delay in the program, and you will have changed the rate of the blink to 500 milliseconds.

```
/* Blink — Turns on an LED on for one second, then off for one second, repeatedly. This example code is
in the public domain. */
// Pin 13 has an LED connected on most Arduino boards.
// give it a name:
int led = 13;
// the setup routine runs once when you press reset:
void setup() {
  // initialize the digital pin as an output.
  pinMode(led, OUTPUT);
}
// the loop routine runs over and over again forever:
void loop() {
  digitalWrite(led, HIGH); // turn the LED on (HIGH is the voltage level)
  delay(500); // wait for a second
  digitalWrite(led, LOW); // turn the LED off by making the voltage LOW
  delay(500); // wait for a second
}
```

If we attached an LED to pin 13 with a necessary resistor as detailed in the next chapter, we would be able to change the rate of flashing of the LED with this software loop.

Now disconnect the Arduino UNO from the USB port and you will notice that the Arduino has gone off. What is great is the code is still there. If you have a 9-volt battery adapter, first plug the battery into the adapter and then plug into the power port, and your Arduino will begin the same behavior again, flashing that surface mount LED at whatever rate you programmed it to flash.

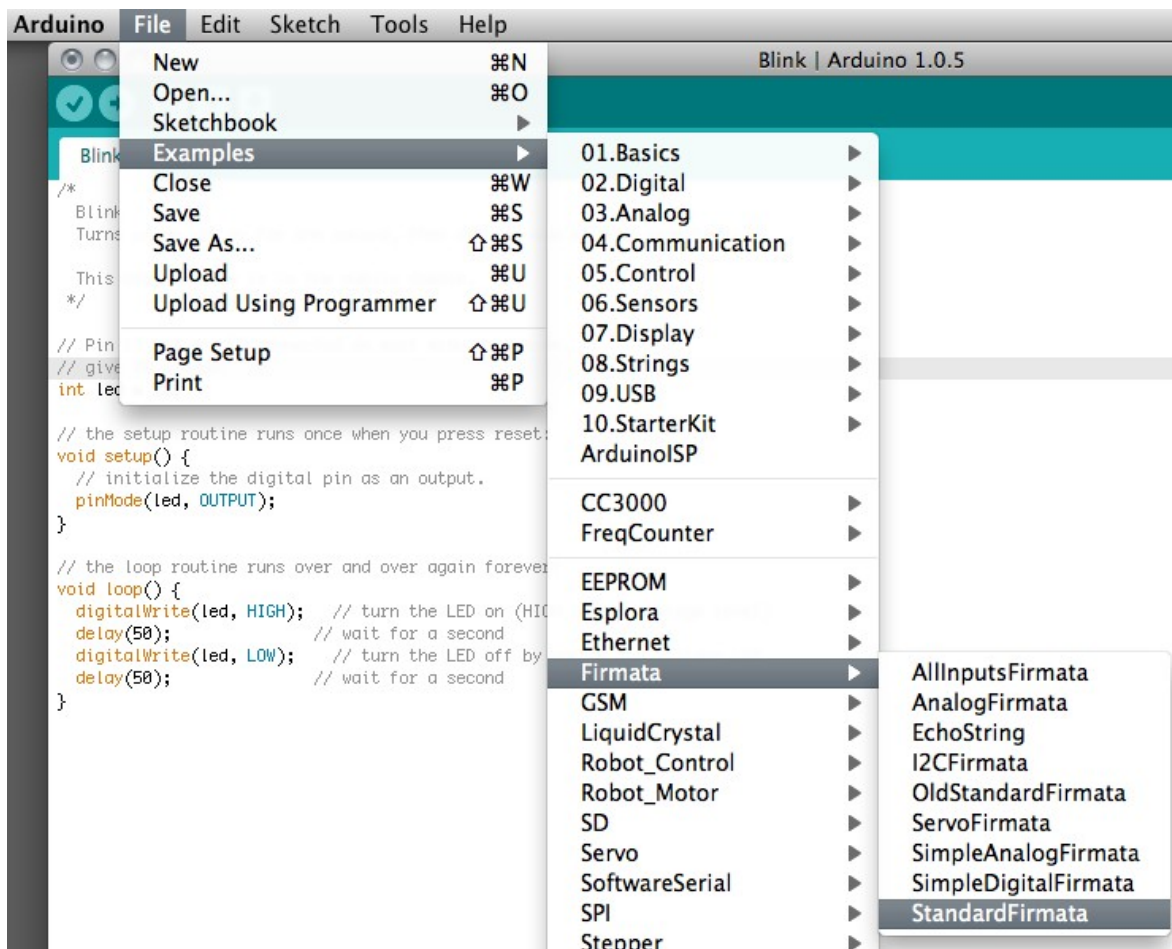
Congratulations, you have now confirmed the Arduino UNO is receiving and able to download code.

Now it is time to explore some other aspects of input and output to the Arduino. Now it is time to download Firmata as we move to have the Arduino communicate with Maxuino and MAX MSP and Jitter.

Arduino UNO with Firmata

Now we will prepare the Arduino UNO to receive another kind of code called **Firmata**, and this will allow us to communicate with MAXUINO and Max MSP and Jitter.

Firmata is a generic protocol for communicating with microcontrollers from software on a host computer. It is intended to work with any host computer software package. Right now there is a matching object in a number of languages. It is easy to add objects for other software to use this protocol. Basically, this firmware establishes a protocol for talking to the Arduino from the host software.



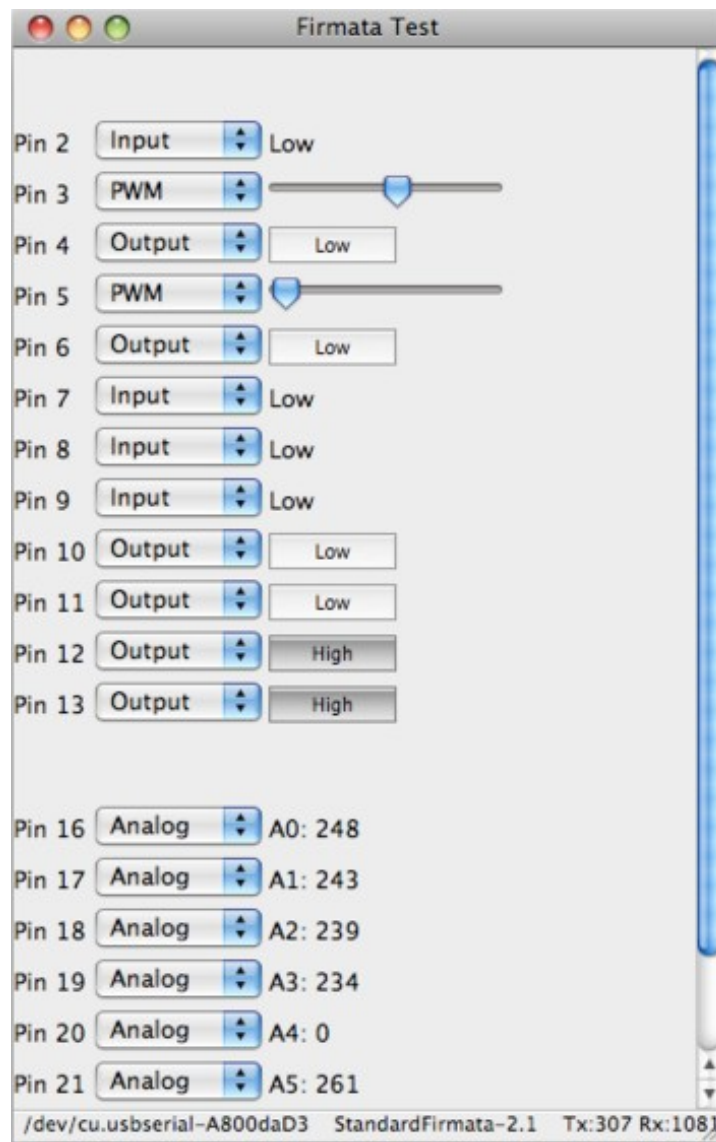
Selecting StandardFirmata

Once the Firmata code is in the window, hit the download arrow again and it will overwrite the Blink code. Now you have set up the Arduino with Standard Firmata, which will allow the Arduino to function as an I/O board with MAXUINO and Max MSP and Jitter.

Now you can move on to section 3 of this chapter to look at the interface of Max MSP and Jitter, and later to Chapter 7 where we will turn on an LED with Max MSP and Jitter. Congratulations.

References: http://www.firmata.org/wiki/Main_Page

This “firmata_test” program works with boards running StandardFirmata version 2.2 or higher on standard baud rate 57600. If you need to test your hardware, this standalone program can access all pins. It runs from a single file (no installation needed), for quick and easy testing!



Standard Firmata test interface

This can be a valuable test program when plugging in a new sensor or device to see if Firmata is properly communicating with the Arduino.

For Mac OS X: http://www.pjrc.com/teensy/firmata_test/firmata_test.dmg

For Windows: http://www.pjrc.com/teensy/firmata_test/firmata_test.exe

Once you download you will get a firmata_test.app, and after clicking on that you will need to select the proper port. Choose /dev/cu.usbmodem131 or similar. It takes a few seconds to activate, though when it does you will get an image like the one above.

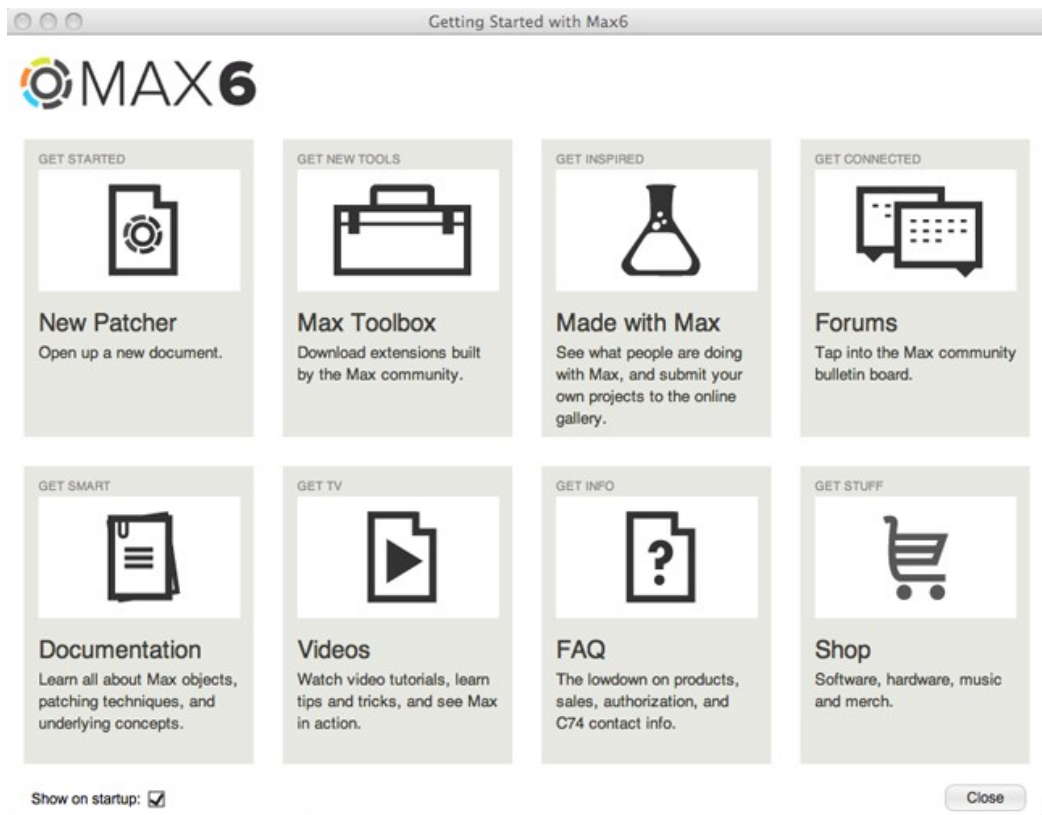
Now when you plug sensors into the Arduino board you should start to see values associated with the sensor — though, of course, they need to be properly wired. This little interface is part of your tool set to determine and help you figure out values coming into sensors.

MAX MSP & Jitter

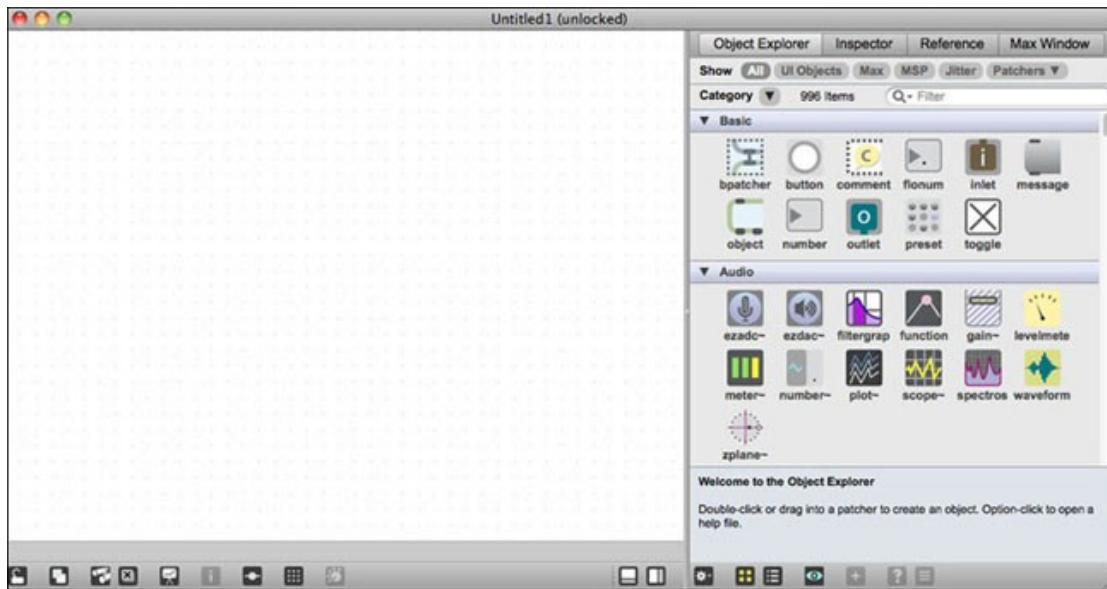
MAX MSP & Jitter allows custom software through the writing of **patches** (which are software subroutines written in MAX MSP) to use as behavioral drivers, to control the inputs and outputs, which can activate sound, video signals, image sequences, and motors. MAX/MSP/JITTER can be downloaded from <http://cycling74.com>

As of the writing of this chapter, MAX MSP 7 is available and students can purchase a one year license for a reasonable price.

From here on out, chapter sections will be identified with Arduino or ESP32 to identify the microcontroller path you have chosen.



To start you must click one time to create a new Patcher.

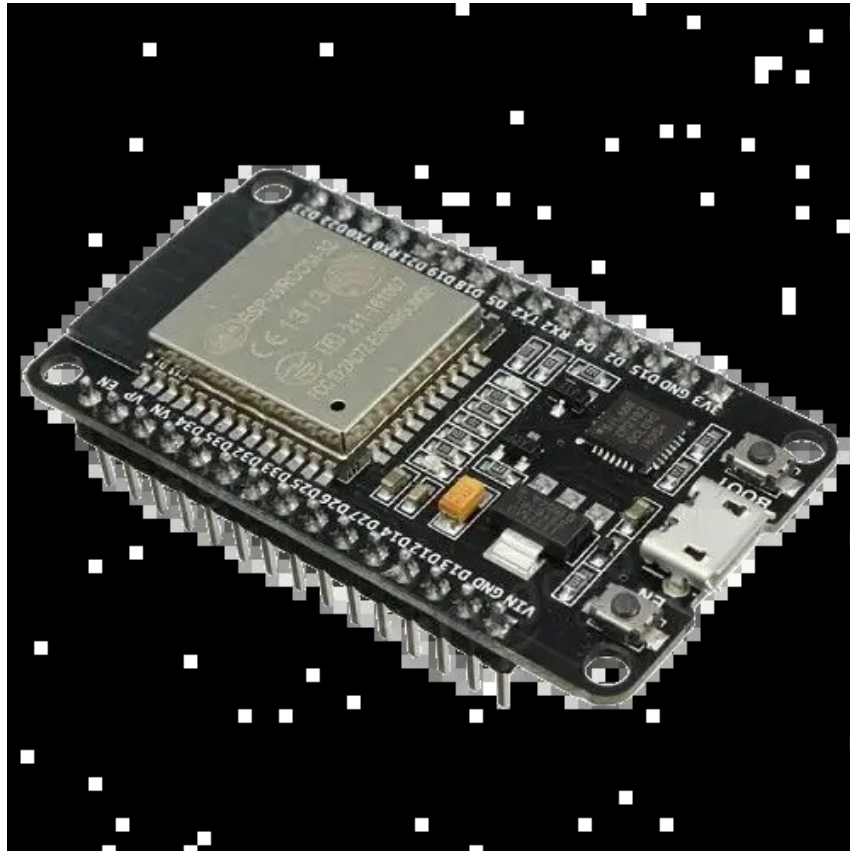


Below is the window where you will be programming and creating behaviors in MAX MSP and Jitter. It looks different than the MAX 5 window in that a new feature is the object explorer of the window, allowing you to explore new objects and code.

MAX MSP lessons on how to use MAX to control the Arduino continue in Chapter 7, where you'll learn about LEDs first. Or, if you would like to skip to lessons on the ESP32, continue with the sections below.

ESP32

The **ESP32** is a low-cost, Wi-Fi and Bluetooth-equipped microcontroller module made by Espressif Systems, and it has become one of the most widely used platforms among hobbyists, artists, and inventors since its release. Where the Arduino UNO gives you a simple, dependable 8-bit microcontroller, the ESP32 adds a dual-core 32-bit processor, wireless networking, and substantially more memory, while remaining fully programmable through the same free Arduino IDE you used in the sections above.



A typical ESP32 development board. The rectangular metal-can module on the left is the ESP32-WROOM-32, which shields the processor, memory, and radio circuitry; its castellated edge pads solder directly onto this carrier development board, which breaks all of its pins out to two long headers along either edge, along with a micro-USB port for power and programming.

Because the ESP32 runs the same Arduino core, `digitalWrite()`, `pinMode()`, and the rest of the code you learned for the Arduino UNO in the sections above all work the same way here — you are learning one language that runs on two different pieces of hardware. This also means the ESP32 can be used with MAX MSP and Jitter through Firmata and Maxuino, exactly as described for the Arduino UNO earlier in this chapter.

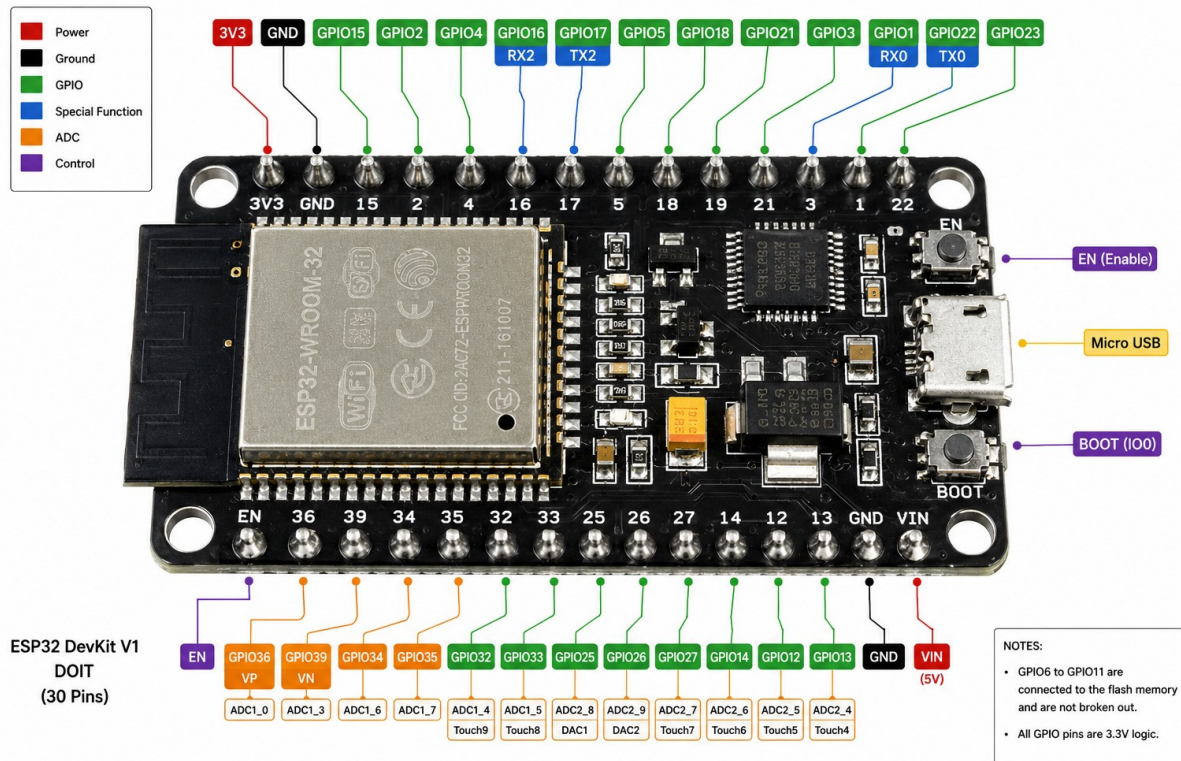


Important: the ESP32's GPIO pins run at 3.3 volts logic, not 5 volts like the Arduino UNO. Never feed 5V directly into a GPIO pin.

The ESP32 also brings capabilities the Arduino UNO simply does not have: built-in Wi-Fi and Bluetooth radios, which mean a project can serve its own web page, respond to a phone app, or talk to other microcontrollers wirelessly, all without any additional hardware. For artists and inventors, this opens up untethered, networked, and remotely triggered installations that would otherwise require bulky external radio modules.

ESP32 Pinout, Power, and GPIO Considerations

Like the Arduino UNO, the ESP32 can be powered over USB, which is also how you will upload your programs to it. It can also be powered from a battery or external supply through its VIN pin (typically 5–12 volts, regulated down onboard) or, on many boards, directly at 3.3 volts through the 3V3 pin.



Labeled pinout of a typical ESP32 DevKit V1 (DOIT, 30-pin) development board. Exact numbering and pin count vary by manufacturer, but most boards break out 25–30 usable GPIO pins along both edges.

A few things are worth knowing before you start wiring the ESP32 into your own circuits:

GPIO numbering isn't sequential around the board. Unlike the Arduino UNO, where digital pins are numbered in order around the board's edge, ESP32 GPIO numbers refer to specific pins on the underlying chip and can appear in almost any order on the board's silkscreen. Always wire according to the GPIO number printed next to the pin, not its physical position.

Some pins are input-only. GPIO 34, 35, 36, and 39 (on the original ESP32) can only be used as inputs; they have no internal pull-up/pull-down resistors and cannot drive an LED or other output.

A few pins are “strapping pins” used during boot. GPIO 0, 2, 5, 12, and 15 influence how the ESP32 boots and can cause upload or boot problems if something is connected to them that pulls them high or low at power-on. For your first projects, it's simplest to avoid these and use GPIO pins like 4, 16, 17, 18, 19, 21, 22, or 23 instead, which is why GPIO 4 was used for the LED lessons in the previous chapter.



A **strapping pin** is a GPIO pin whose voltage level is checked by the chip at the moment it powers on or resets, to decide things like which mode to boot into. Accidentally holding a strapping pin high or low with external wiring can prevent a board from starting up correctly.

None of this makes the ESP32 harder to use than the Arduino UNO — it just means it's worth glancing at the pinout diagram for your specific board before wiring anything new, which is good practice with any microcontroller.

ESP32 with MAX MSP and Jitter via Maxuino

Because the ESP32 uses the same Arduino core as the UNO, it can run the identical StandardFirmata sketch described earlier in this chapter, which means it can talk to MAX MSP and Jitter through Maxuino in exactly the same way.

1) In the Arduino IDE, select your ESP32 board from Tools > Board and the correct port, just as you did for the blink sketch in the previous chapter.

2) Open File > Examples > Firmata > StandardFirmata, and upload it to the ESP32 exactly as you did with the Arduino UNO.

3) Open MaxuinoSimpleStart (or the full Maxuino help patch) as described earlier in this chapter, and select your ESP32's serial port from within the patch.

4) Because ESP32 GPIO numbering does not match the Arduino UNO's pin layout, double-check that the pin number you type into the Maxuino patch matches an actual usable GPIO on your ESP32 board, using the guidance in the previous section.

From here, every technique you learned for driving an LED, reading a sensor, or sequencing outputs with MAX MSP and the Arduino UNO applies directly to the ESP32 as well — the software side of your workflow does not change, only the wiring and pin numbers.

The next chapter puts all of this into practice with hands-on LED lessons for both the Arduino/Maxuino path and the ESP32.

Summary

You have learned to hook up the Arduino or the ESP32 and download code, and you have learned an important method of checking the functionality of your programs.

The next chapter will begin to give you a repertoire of behaviors possible with the Arduino and ESP32 hardware designs that will allow you to expand on this knowledge and begin to build your wildest dreams.

Conceptual reading:

Shanken, Edward A. “The House That Jack Built: Jack Burnham's Concept of ‘Software’ as a Metaphor for Art.” <http://www.duke.edu/~giftwrap/House.html>

Technical reading:

Espressif Systems. *ESP32 Series Datasheet*. Available free from espressif.com, along with the complete ESP32 hardware design guidelines and Arduino core documentation.

Chapter 7

LEDs: Interactive Feedback and Timed Events

Interactive Feedback

“The serious artist is the only person able to encounter technology with impunity just because he is an expert aware of the changes in sense perception.”

— Marshall McLuhan, *Understanding Media* (1964)

Question: How do you create a timed event that is the result of pushing a button?

The ability to work with a microcontroller is exciting, as it will allow you to sequence and control a variety of electronic devices by programming input and output. It means that you can create *interactive* events that function in real time, based on feedback and control from users. Output devices such as light emitting diodes (LEDs) can be activated by a variety of switches that function as input devices.

LEDs are used extensively in the arts and industry for their beauty, their durability, and relatively low cost. Artists/inventors have applied LEDs in imaginative ways, though controlling LEDs also implies that you will be able to control larger things.

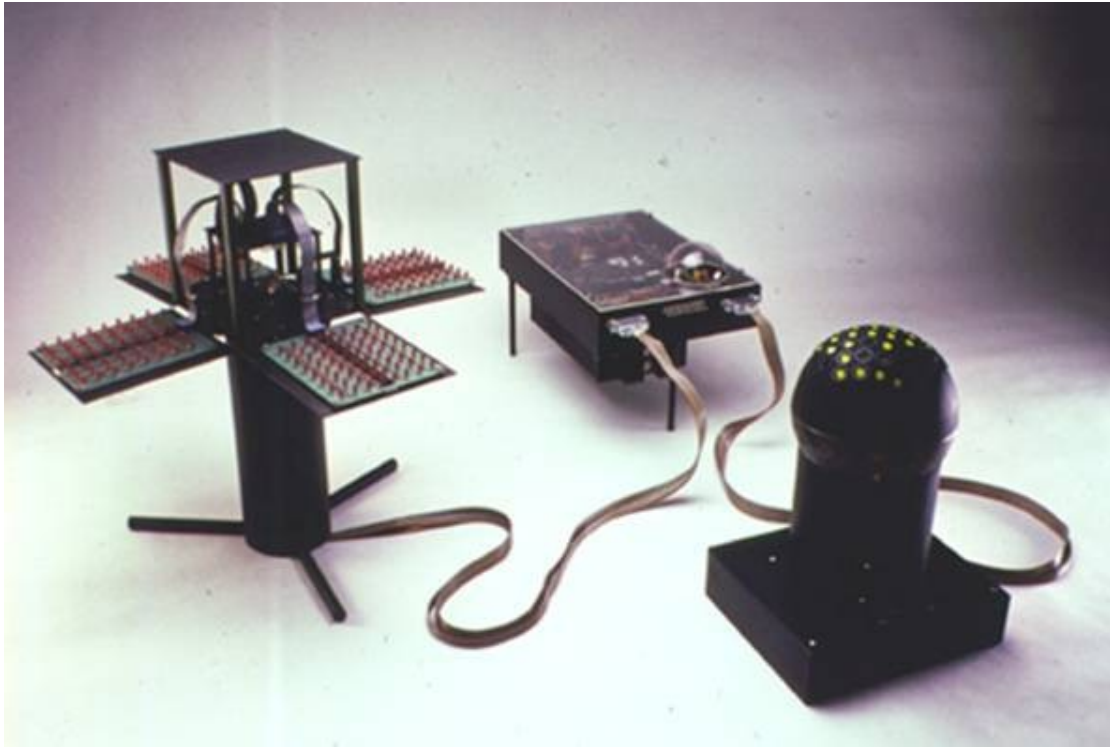
The cognitive scientist and author [Donald Norman](#) said, “Turn signals are the facial expressions of cars,” and likewise, I think we can say that LEDs are the facial expression of computers.

Common LEDs come in red, green, clear, and blue. Sometimes the blue LED and the green and red will appear clear but will, in fact, glow these colors when activated.

When my computer LED flashes off – on, off – on, this feedback shows the internal state of the machine and allows us to know that all is working well. LEDs are being used increasingly in stop lights, car/truck brake lights, as well as mood lighting. The next time you pull up to a stop light, take note: are old incandescent lamps used, or are there bunches of super bright red, green, or yellow LEDs? LEDs are also beneficial because they last longer than incandescent lamps because they are solid-state devices. As you recall, solid-state means they are based on semiconducting materials with no moving parts or filaments to break (as there are in incandescent bulbs). While LEDs are used as indicators of something happening or changing in machines, they can also be used as expressive tools, as you will see from the featured works below.

Artists and inventors have been using LEDs as both indicators of change and as artworks themselves in object-oriented interactive works, textile works, and large-scale installations.

The artist [James Seawright](#), a pioneer in interactive artwork, speaks of new electronic ecologies in his *Houseplant* series. These works open at night in response to the darkness, like digital versions of a moon flower. The arrays of LEDs that James Seawright has integrated with his robotic sculptural forms flash in a random patterning that is akin to the complex patterning that one would associate with a natural system, such as the complexity of a leaf. But here, the leaves or petals are circuit boards of LEDs that reflect the chaos of a natural system in the complex manifestation of the patterning of LEDs being turned off and on. The plants also respond to human presence as a natural plant would and manifest different behaviors based on this interaction. However, unlike natural plants, their response is rapid enough for humans to perceive the changes and understand their impact on the system.



Houseplants series by [James Seawright](#). 1983.

Natural plants also respond to humans and to insects, but very slowly, so their responses are generally imperceptible (except for a Venus flytrap or a mimosa, which are relatively rapid for plants).

The artist [Heidi Kumao](#), interested in wearable computing, has created a custom bra using 180 LEDs with custom electronics and a microphone, which is activated by voice. Heidi Kumao was interested in accentuating a part of the female anatomy which she was aware people were looking at anyway, though instead she decided to humorously invite the eyes and poke fun at social conventions. The louder the voice, the more the LEDs glow, and at maximum volume, the nipple area glows yellow.

Monitor I by [Heidi Kumao](#). Circuit design by Garth Zeglin. 2001.

The LEDs are organized in concentric circles, and the artist has provided a dial to allow you to adjust the sensitivity of the bra. The artist says, “Madonna should have one.”

The artist/engineer Eric Singer works with creating instruments as part of the League of Electronic Musical Urban Robots. He creates and innovates on acoustic instruments that function as synthesizers, though they are played from computers. He is the founder of the LEMUR group, established in 2000.

Artistic Applications of LEDs

The artist [Barbara Layne](#) is working with development of intelligent cloth structures and explores embedding LEDs into clothing. Layne's desire is to have this function to allow wireless transmission and remote communication systems between users/wearers.

The artist [Erwin Redl](#) creates large-scale installations of LEDs in various colors that allow you to reflect on art making in the realm of "digital experience." Redl assembles these installations and incorporates algorithms to create a randomness that is inspired by computer code.

Redl has been investigating the notion of "reverse engineering" by using the visual languages of virtual reality and 3D modeling to create his architectural light installations. Because of the large nature of these works in an architectural space, the viewer must be present to experience the full effect through the perception of space, light, and time.



MATRIX XII (rear view) by Erwin Redl, 2003. LED installation, 120 x 50 x 30 ft (variable). Chinati Foundation, Marfa, TX.

Ellen Grevey is a sculptor concerned with feminist issues and empowering women with her installation works. In the work *Lady Dover* (2001), Ellen has decided to repurpose the traditional clothes iron, classically perceived as a "woman's tool." In this detailed work, she used the LEDs on the back of the RC car as indicators of activity of the robotic duster.



Lady Dover by Ellen Grevey, 2001. Photo by Ellen Grevey.

This humorous work and its interaction allowed a man or woman to dust the floor with the fun of a radio control car. In her own words: "I adopted the iron as a symbol of the heavy, less than pleasurable aspects of the role of 'homemaker.' ... They were essentially relieved of their 'tool' status in favor of that of an object of beauty or entertainment. This piece, Lady Dover, is a homemaker's helper-cum-lapdog. The device, a radio controlled iron-on-wheels, is equipped with a feather duster to clean the road ahead. Operated from a seated position, it dusts and does the ironing. It is the 'perfect pet,' for the modern woman; it comes with its own powder pink dog house with batteries included."

Artistic Applications of LEDs, Continued

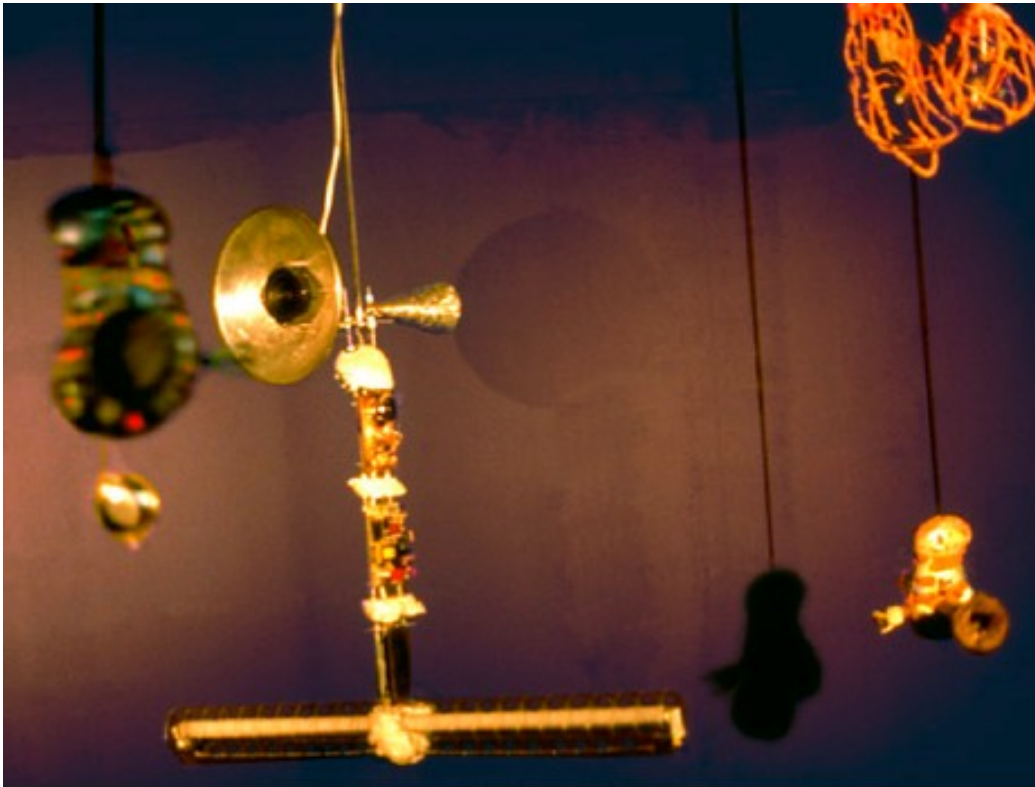
[Amy Youngs'](#) *Engineered for Empathy* was inspired by the creation of transgenic tobacco plants that glow with the genes of fireflies. In the work below, Amy Youngs endowed a cactus with a pulsating glow. However, instead of using bioluminescence, she embedded LEDs in a live cactus. As you approached this work, the electrical charge of your body (capacitance) caused the LEDs to flash more quickly.

According to Amy Youngs: "It is a speculation as to what might be possible in the new plant species in the future. Beyond the creation of visual aesthetics or economically engineered species, I imagine a plant that responds to humans and conveys emotions in ways understandable by us. This cactus is engineered to elicit empathy from humans, presumably so that we will be compelled to take care of it. Its signal to us is a pulsating, glowing heartbeat (LEDs) that speeds up as a person comes near it. If the cactus is touched, its pulsing behavior changes to a frenetic flashing."



Engineered for Empathy by [Amy Youngs](#), 1999, 24" x 19" x 12". The Quantum Research Group.

The *Cyber Squeaks* by [Ken Rinaldo](#) (1989–92), shown below, were a series of electronic sculptures that spoofed the emergence of machine intelligence. In these works, electronics integrated with life-like forms have begun to squeak their first words, in their own language.



Cyber Squeaks in motion at Image du Future, by [Ken Rinaldo](#), 1988–1992.

With photo resistors, transistors, and mercury switches, they responded to human touch and a changing light environment, which induced them to emit emphatic squeaking sounds. In a normal installation of these works, 15–20 of them would be hanging from springs from the ceiling. When touched, triggering a mercury switch, these light-sensitive creatures would squeak on and off. A fluorescent light integrated in the form of one of the *Cyber Squeaks* was turned off and on, and this caused the sound of the other *Cyber Squeaks*, which were light sensitive, to change and become lower in tone as they continued to squeak and burp their sounds.

In these works, LEDs were connected to fiber optics that sprouted from the pieces as thin, glowing hair. When the works were activated by human touch, the LEDs would turn on, causing the fiber optics to glow red and green and later blue.

This disjointed forest of hanging *Cyber Squeaks* analogized the forest of information that we are immersed in. They epitomized life in their collective, chaotic cacophony and are an analog to the complex and dynamic processes that constitute life.

In the sections that follow, we'll build our first LED circuits — first with the Arduino, working through Maxuino, and then with the ESP32.

LED General Information

In order to control many LEDs, you must start with one LED. In this lab, you will be using the Arduino, and then construct your circuit and test it using MAX MSP and Jitter.

This will allow you to turn the LED on and off, and later to turn two LEDs on and off at different rates and for different periods of time. From here you will learn to sequence two LEDs off and on, and then you will use a switch to turn the LEDs off and on, determined by your input of a micro switch.

The circuits you build will all be expanded by your new ability to program different timing of events.

The LED has a long lead (the anode) and a short lead (the cathode). The schematic symbol for a light emitting diode has two small arrows coming out of it, indicating light emission.

The LED is a semiconductor light. It is also a diode, meaning current will travel in only one direction, but unlike other diodes, the LED gives off light in the process of passing electron current. LEDs are available in a variety of colors: red, green, yellow, amber, and blue, and they also come in a variety of brightnesses. Notice the difference in the schematic symbol, with two small arrows coming out indicating it is a light emitting diode and not just a diode.

You can also use LEDs to mix color and can use red, green, and blue to create varieties of RGB color. Now, special RGB LEDs are also available. Because LEDs do not have filaments, they do not burn out as quickly, and they also do not get hot like incandescent bulbs. They are also much less expensive to keep lit because normal filaments lose lots of energy heating the filament.

To flash an LED at a given rate, on-off, on-off, is the seed of all programming, as it indicates your ability to change the value of an output gate on the Arduino. This is exciting, and the first step to being able to control much larger devices like motors, lamps, and actuators of all sorts.

In this exercise, you will be using Ohm's law to identify the proper parts for the project and to calculate the size of resistor you will need. You will then place the parts in the breadboard and program them to turn on and off in sequence, both with the Arduino and MAX MSP and Jitter talking through MAXUINO.

An LED has two terminals, one called the anode and the other the cathode. The longer lead is the anode, but the best way to test them is to carefully look for the flat mark at the bottom of the LED. On some LEDs it is difficult to see the flat area, or it may not be apparent, so you must use all clues.

Because the LED is a semiconductor, and we know that it is sensitive to too much current, we need to know what the absolute maximum ratings are on this part before we hook it up to the circuit.

We also need to know what the absolute maximum ratings are for the microprocessor, and we will address this in Chapter 8 in more detail.

The LEDs we are using do not want to see any more than 20 mA, or .02 amps, maximum, so you will need to use a resistor to limit the current.



You must never exceed the absolute maximum ratings on any parts, or you risk the parts and maybe your Arduino.

Here you will get to use Ohm's law to calculate what the proper resistor would need to be in order to have the LED glow brightly and safely.

Ohm's law should be repeated for each and every part that you interface to your Arduino microcontroller, because the controller has delicate components.

1) Use Ohm's law to calculate the resistor you need, because your LED can take no more than 20 mA. 20 mA is the same as .020 amps. The voltage of 5 volts is a given, coming from your Arduino.

2) Ohm's law is $V = I \times R$, where R is the resistance (measured in ohms), V is the voltage (volts), and I is current (amps). We have 5 volts and want to solve for R, or resistance, so $5v = .020A \times R$, or $5/.020 = R$, or 250 ohms.

3) However, because we are concerned with the ability to drive many LEDs at one time for this lesson, we are wise to use a 470 ohm resistor. This will allow us to turn on many LEDs, on and off, using the total of 50 mA we can source (provide) from the Arduino. Remember, when driving more than one LED you need a resistor for each LED and line out from the Arduino.

4) It is okay to use a larger value but not a smaller value. Using the larger value will only mean the LED will glow a little less brightly, but the circuit and flashing will still work. A smaller value will allow too much current and possibly damage your Arduino, so use your multimeter to confirm the resistor values.

5) Identify the part using the color codes, which should be yellow, violet, and brown.

6) Set your multimeter to the Ohm's setting. As instructed in Chapter 3, use your meter to measure the resistor and confirm that you have the correct resistor for this circuit.

MAXUINO

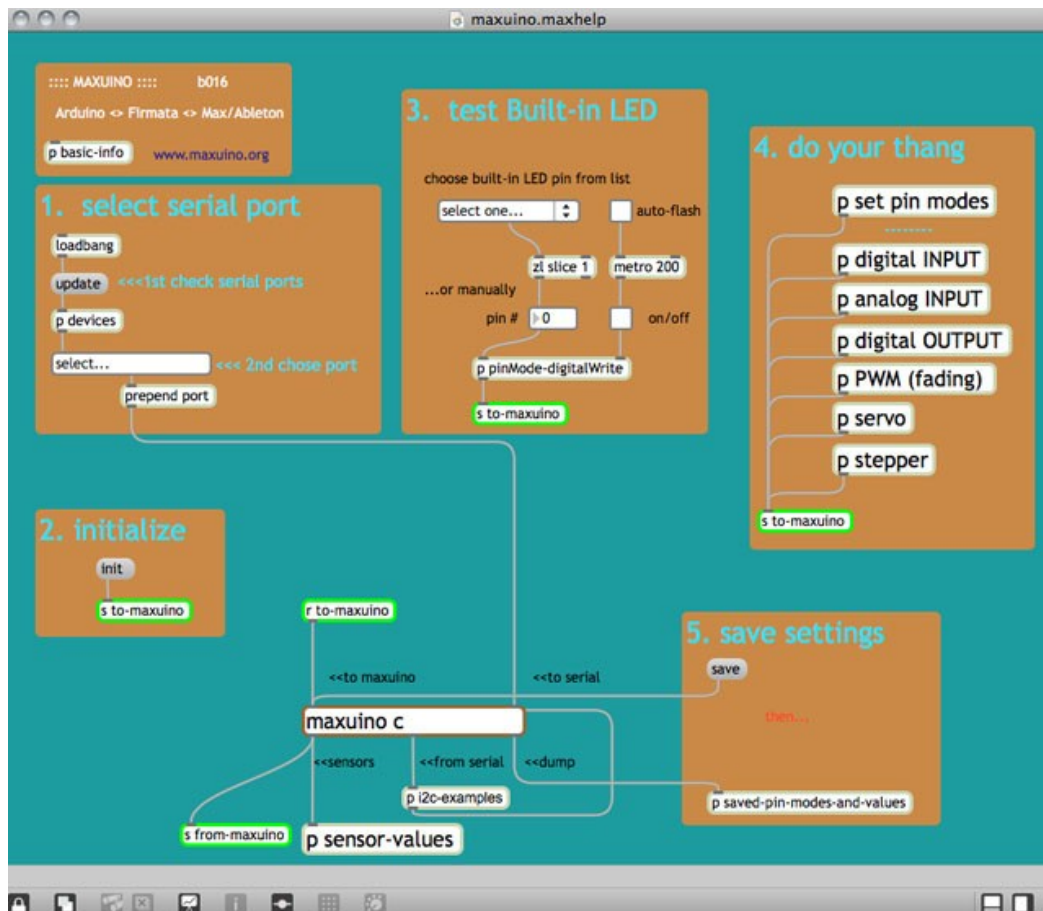
In this section, we will replicate code that is part of MAXUINO and then use that code to abstract and further develop the input and output capabilities of the Arduino running through Maxuino.

In order for the code below to work, you must first follow the excellent tutorials located on the Maxuino site and download the code, a text program created by Chris Coleman and Ali Momeni:

<http://www.maxuino.org/> — [maxuino b017](#) (March 24, 2014).

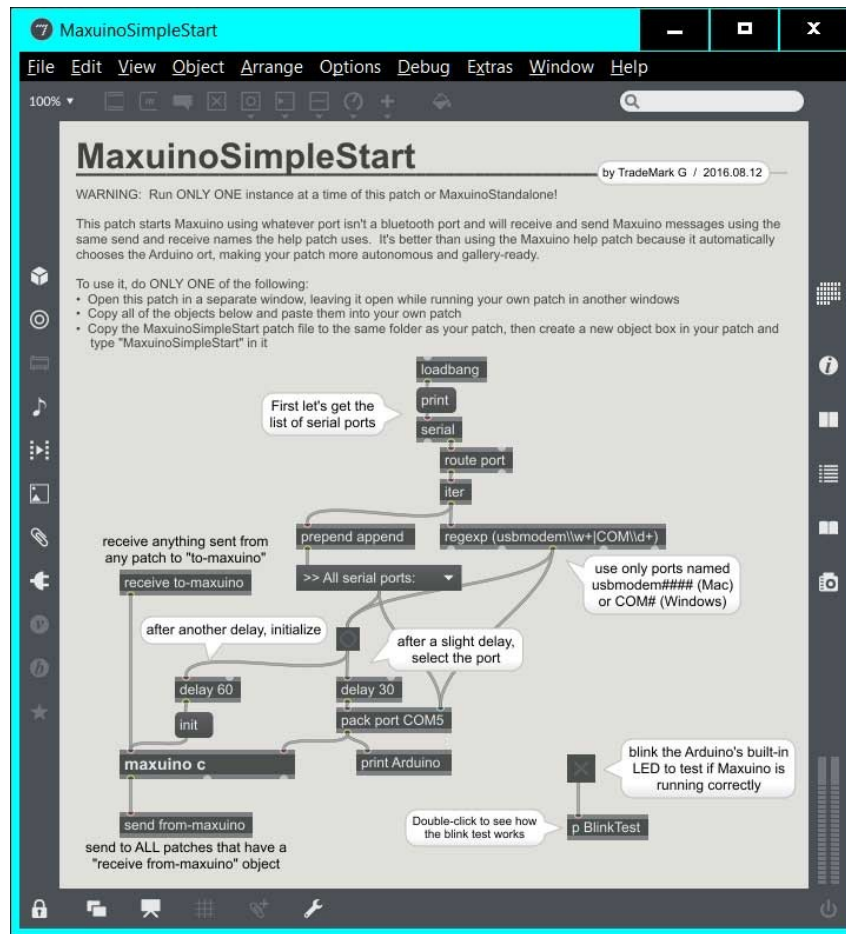
The tutorials are excellent video tutorials for downloading the Maxuino help patch and adding a search path within Max MSP and Jitter. The externals are best placed in a Max folder in the documents folder in your system: <http://www.maxuino.org/video>

When you do all of this in the correct fashion you will end up with a fantastic Maxuino patch that allows you to set pins to input and output and drive motors, as well as receive signals from sensors, etc. You will end up with a MAXUINO help patch that looks like this.



Copyright Chris Coleman and Ali Momeni

As this is a wonderful patch, we are grateful to Chris and Ali. Still, we wanted to try to make the startup a bit more automated, so Trademark Gunderson scripted a patch to allow you to have a simple start before using Maxuino and Max MSP and Jitter through Firmata and the Arduino.

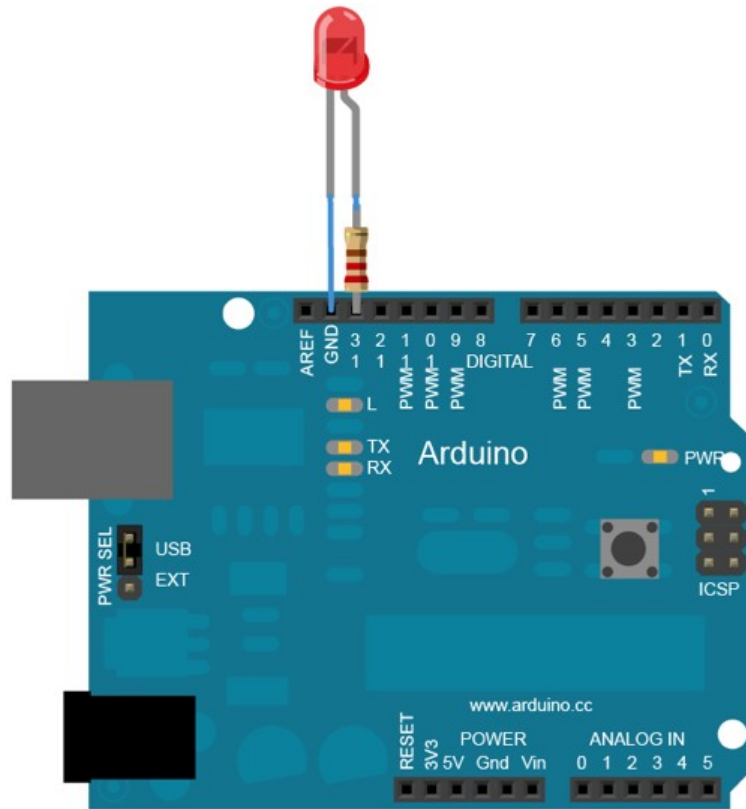


MaxuinoSimpleStart (Max/MSP and Jitter patch) by TradeMark Gunderson. Copyright Ken Rinaldo.

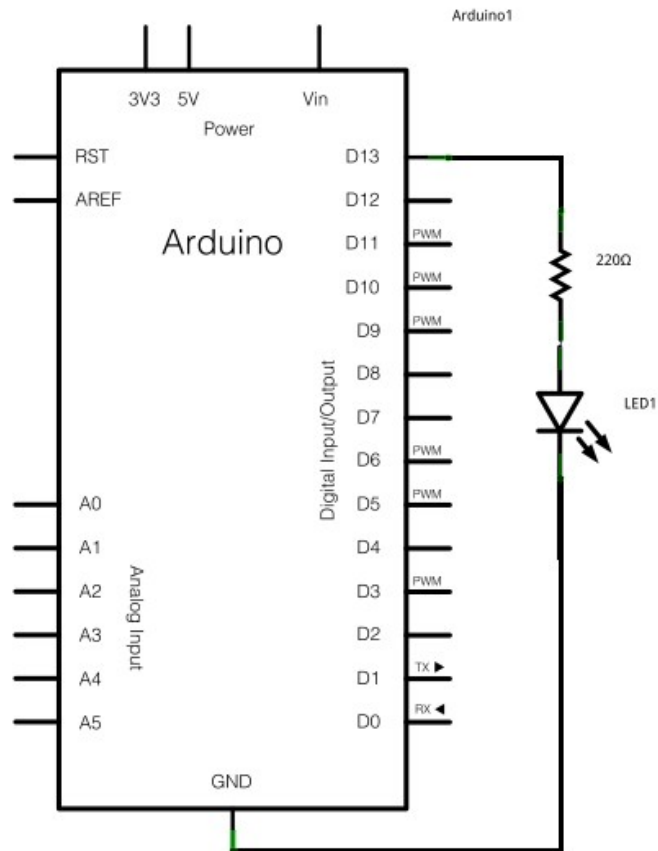
Arduino/Maxuino: Driving an LED High and Low

In this section, we will explore the most basic code to drive an LED high and low, interfacing through Arduino and then Maxuino, using MAX MSP and Jitter 6.

Below is the basic circuit design and schematic.



Showing the LED with 220 ohm resistor going into pin 13. (CC from Arduino website.)



Schematic of LED going from the ground on the Arduino UNO to pin 13.

Using the Arduino to Blink an LED High and Low

/* Blink — Turns on an LED on for one second, then off for one second, repeatedly. Most Arduinos have an on-board LED you can control. On the Uno and Leonardo, it is attached to digital pin 13. If you're unsure what pin the on-board LED is connected to on your Arduino model, check the documentation at <http://www.arduino.cc>. This example code is in the public domain. Modified 8 May 2014 by Scott Fitzgerald. */

// the setup function runs once when you press reset or power the board

```
void setup() {
```

```
  // initialize digital pin 13 as an output.
```

```
  pinMode(13, OUTPUT);
```

```
}
```

// the loop function runs over and over again forever

```
void loop() {
```

```
  digitalWrite(13, HIGH); // turn the LED on (HIGH is the voltage level)
```

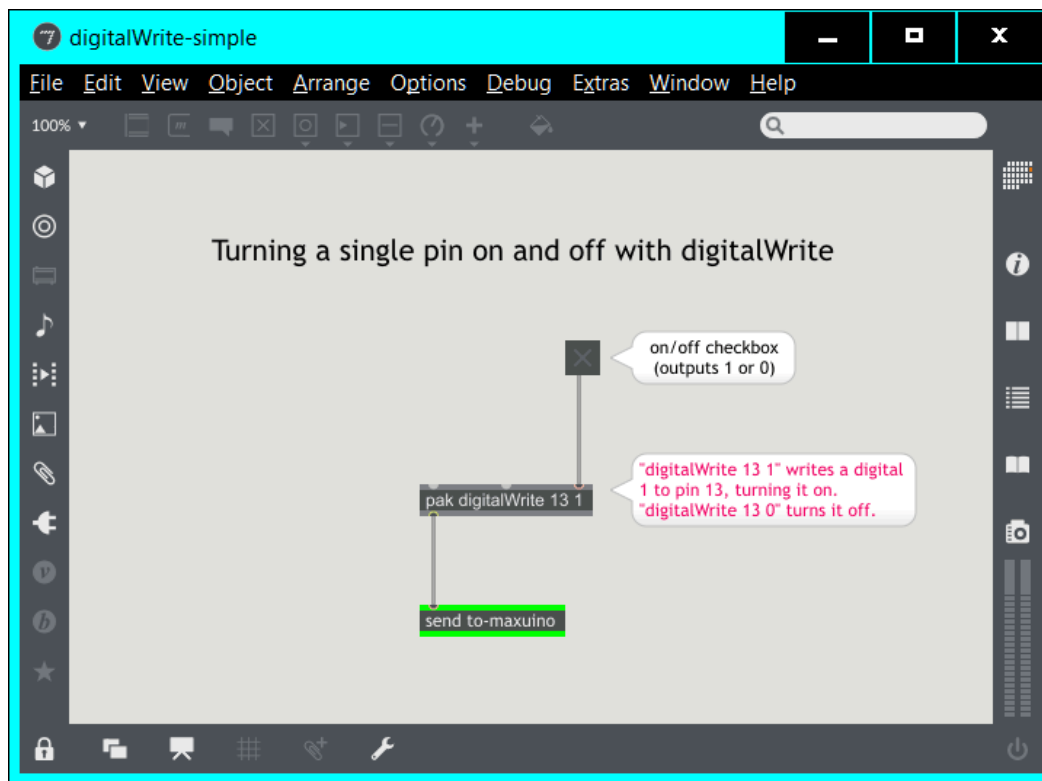
```
  delay(1000); // wait for a second
```

```
  digitalWrite(13, LOW); // turn the LED off by making the voltage LOW
```

```
  delay(1000); // wait for a second
```

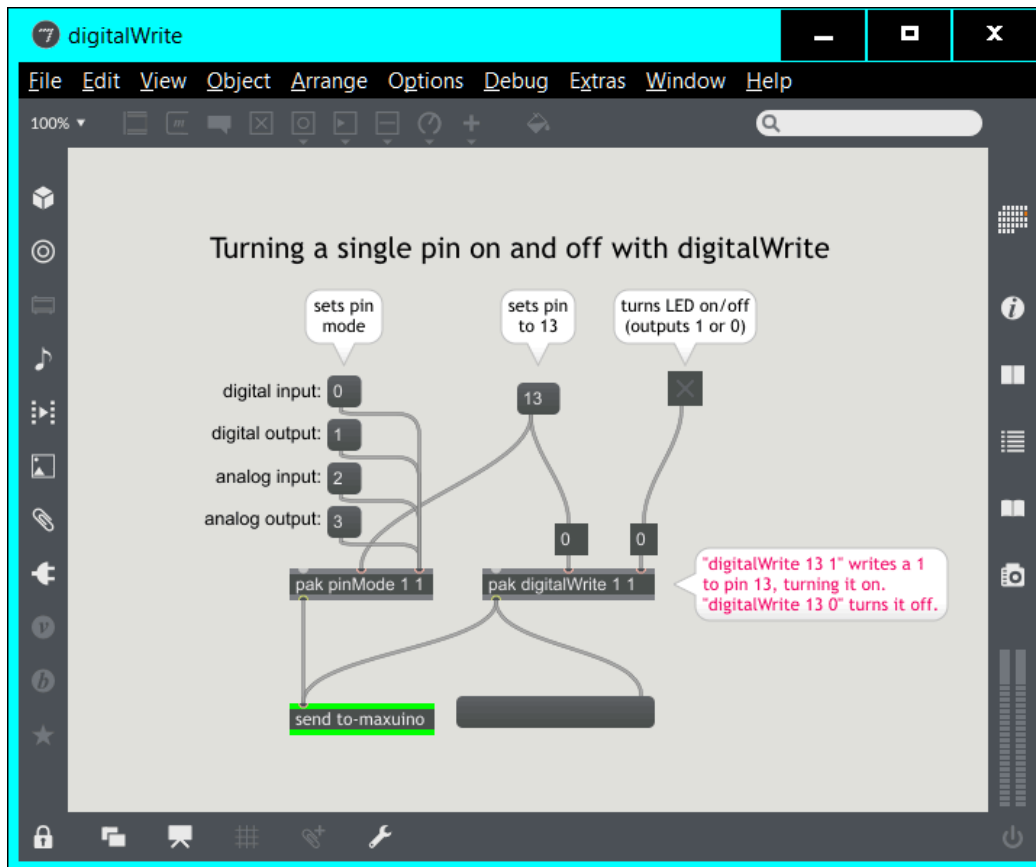
```
}
```

To build this circuit, make sure your LED is aligned properly with the anode and cathode in the correct direction. You should use a 220 ohm resistor, though you can also use a 1K ohm resistor if you do not have a smaller one.



digitalwrite-simple (Max/MSP patch). Copyright Ken Rinaldo.

With this patch you must specify the pin number to function on the Arduino, and you must also activate the pin. We are going to use the code (pak digitalWrite 1 1) where the first 1 is updated by the clicking of the message 13. By clicking the 13 you replace the 1 with 13. If you want to activate a different pin, simply change that number by unlocking the patch and writing a new number.



digitalwrite (Max/MSP patch). Copyright Ken Rinaldo.

Maxuino/Arduino: Driving an LED High and Low at Different Rates

Blinking an LED Without Delay

`/* Blink without Delay — Turns on and off a light emitting diode (LED) connected to a digital pin, without using the delay() function. This means that other code can run at the same time without being interrupted by the LED code. The circuit: LED attached from pin 13 to ground. Note: on most Arduinos, there is already an LED on the board that's attached to pin 13, so no hardware is needed for this example. Created 2005 by David A. Mellis, modified 8 Feb 2010 by Paul Stoffregen, modified 11 Nov 2013 by Scott Fitzgerald. This example code is in the public domain.`

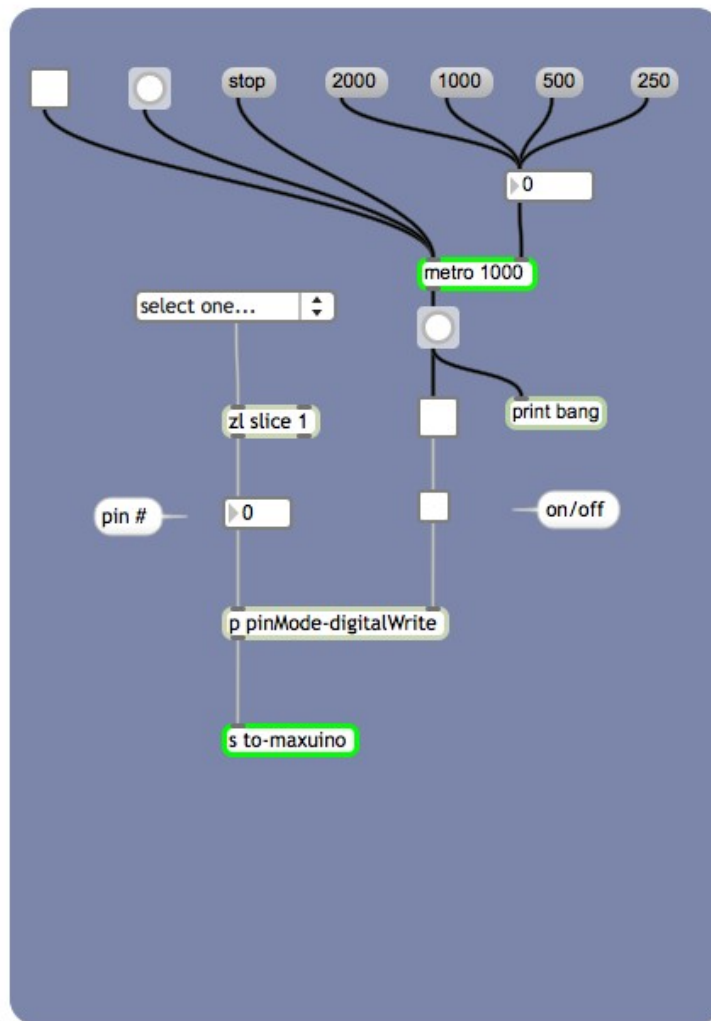
```
http://www.arduino.cc/en/Tutorial/BlinkWithoutDelay */
// constants won't change. Used here to set a pin number:
const int ledPin = 13; // the number of the LED pin
// Variables will change:
int ledState = LOW; // ledState used to set the LED
// Generally, you should use "unsigned long" for variables that hold time
// The value will quickly become too large for an int to store
unsigned long previousMillis = 0; // will store last time LED was updated
// constants won't change:
const long interval = 1000; // interval at which to blink (milliseconds)

void setup() {
  // set the digital pin as output:
  pinMode(ledPin, OUTPUT);
}

void loop() {
  // here is where you'd put code that needs to be running all the time.
  // check to see if it's time to blink the LED; that is, if the
  // difference between the current time and last time you blinked
  // the LED is bigger than the interval at which you want to
  // blink the LED.
  unsigned long currentMillis = millis();
  if (currentMillis - previousMillis >= interval) {
    // save the last time you blinked the LED
    previousMillis = currentMillis;
    // if the LED is off turn it on and vice-versa:
    if (ledState == LOW) {
      ledState = HIGH;
    } else {
      ledState = LOW;
    }
    // set the LED with the ledState of the variable:
    digitalWrite(ledPin, ledState);
  }
}
```


You can use the message capability in Max MSP and Jitter to drive an LED high and low. By selecting different messages you can change the rate of the LED, and you can also start and stop the LED. Notice that you need to select the device you are using (Arduino UNO) and specify the pin number. The `pinMode-digitalWrite` code is sent via a patchcord to the `s to maxuino` object. Keep in mind you need to have the `MaxuinoSimpleStart` program open at the same time in order for this to work.

Digital output from a single pin that you select and using messages to stop, create a 2 second and 1 second and 1/2 and 1/4 second pause or flash rate



MAX MSP lessons continue in Chapter 8.

ESP32: Introduction and Wiring One LED

The **ESP32** is a low-cost microcontroller module with built-in Wi-Fi and Bluetooth, dual-core processing, and enough onboard memory to run substantially more complex programs than the classic Arduino UNO. Development boards run about \$5–\$10 and are widely available. Like the Arduino, the ESP32 is programmed through the free Arduino IDE (once you add ESP32 board support), so the `digitalWrite/pinMode` style of code you learned in the Arduino/Maxuino sections above carries over directly.

Setting up the Arduino IDE for ESP32: In the Arduino IDE, go to Preferences and add this URL to “Additional Boards Manager URLs”: https://raw.githubusercontent.com/espressif/arduino-esp32/gh-pages/package_esp32_index.json. Then open Tools > Board > Boards Manager, search “esp32,” and install the package by Espressif Systems. Once installed, select your specific board (e.g. “ESP32 Dev Module”) from the Tools > Board menu, and select the correct serial port, just as you did with the Arduino UNO.

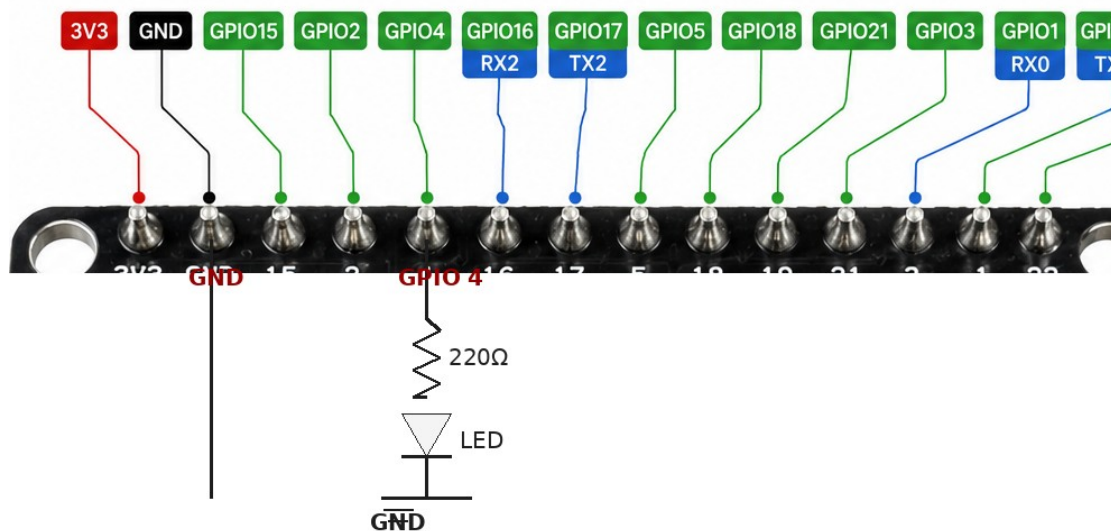


Important: the ESP32's GPIO pins operate at 3.3 volts logic, not 5 volts like the Arduino UNO. Never feed 5V directly into a GPIO pin, or you risk permanently damaging the board.

Because the ESP32 runs its logic at 3.3V instead of 5V, we should recalculate our LED resistor with Ohm's law, exactly as we did for the Arduino UNO in the LED General Information section. With a 20 mA (.020A) maximum LED current and 3.3 volts available: $R = V/I = 3.3/.020 = 165$ ohms minimum. As before, it's safer to round up rather than down, so a 220–330 ohm resistor is the standard choice, and it is what we will use here.

Parts Necessary:

ESP32 development board • USB cable • breadboard • 1 LED • 1 – 220 ohm resistor • jumper wires



LED and resistor wired from an ESP32 GPIO pin to ground. As with the Arduino, current flows from GPIO 4, through the resistor, through the LED (anode to cathode), and to ground.

Build the circuit as shown, then enter the following sketch. Note that it is essentially identical in structure to the Arduino UNO blink sketch from earlier in this chapter — only the pin number changes.

```
/* ESP32 Blink — Turns an LED on for one second, then off for one second, repeatedly. */  
const int ledPin = 4; // GPIO 4  
void setup() {  
  pinMode(ledPin, OUTPUT);  
}  
void loop() {  
  digitalWrite(ledPin, HIGH); // turn the LED on  
  delay(1000); // wait one second  
  digitalWrite(ledPin, LOW); // turn the LED off  
  delay(1000); // wait one second  
}
```

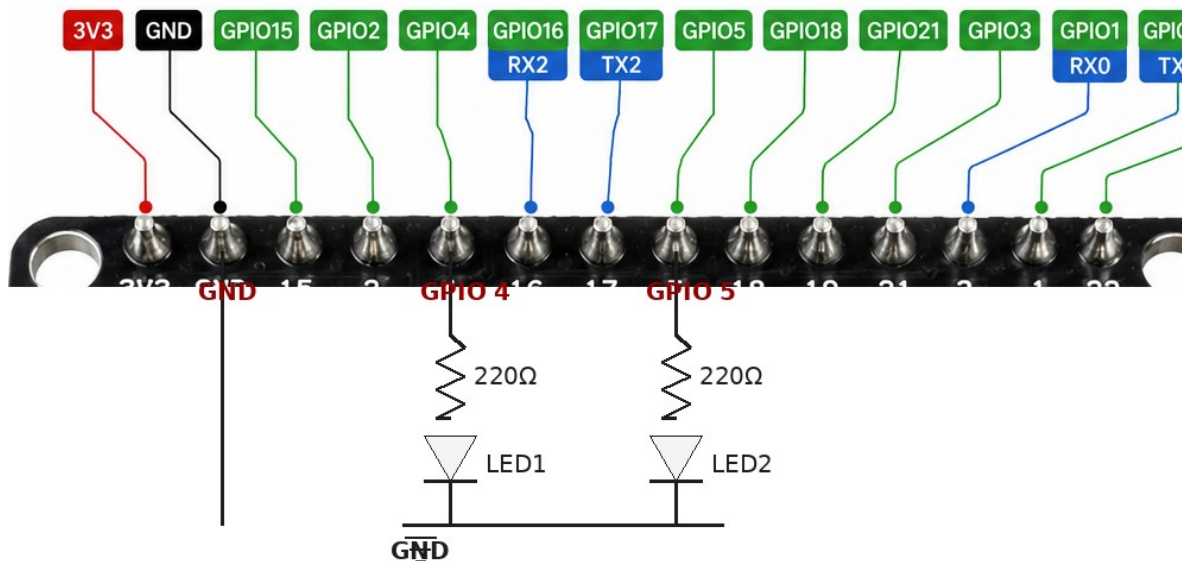
Select your board and port from the Tools menu, hit upload, and confirm the LED blinks once per second, exactly as the Arduino UNO's did earlier in this chapter. Congratulations — you've confirmed your ESP32 is wired and programmed correctly.

ESP32: Two LEDs at Different Rates

Now let's extend the circuit to two independent LEDs blinking at different rates. This mirrors the “blink without delay” lesson from the Arduino/Maxuino sections earlier in this chapter: instead of calling `delay()`, which pauses the entire program, we track elapsed time for each LED separately using `millis()`. This lets both LEDs blink at their own independent rates simultaneously, and it is also the foundation for handling any number of inputs and outputs at once as your projects grow more complex.

Parts Necessary:

ESP32 development board • breadboard • 2 LEDs • 2 – 220 ohm resistors • jumper wires



Two LEDs, each with its own 220 ohm resistor, wired to separate GPIO pins.

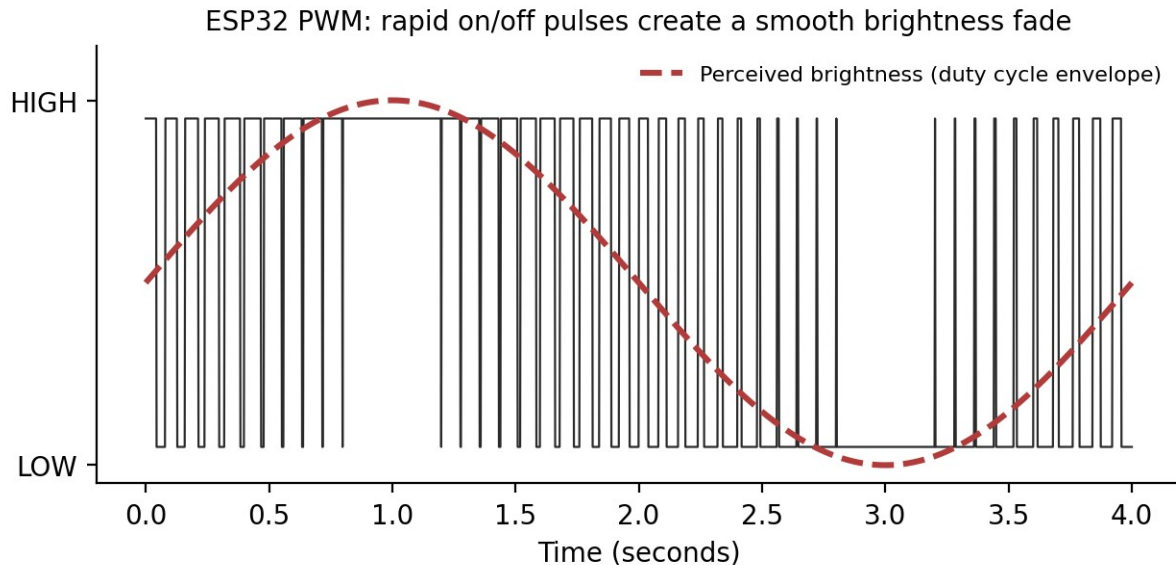
```
/* Two LEDs blinking at independent rates, without using delay() */
const int led1Pin = 4;
const int led2Pin = 5;
int led1State = LOW;
int led2State = LOW;
unsigned long previousMillis1 = 0;
unsigned long previousMillis2 = 0;
const long interval1 = 500; // LED 1 blinks every half second
const long interval2 = 1300; // LED 2 blinks every 1.3 seconds
void setup() {
  pinMode(led1Pin, OUTPUT);
  pinMode(led2Pin, OUTPUT);
}
void loop() {
  unsigned long currentMillis = millis();
  if (currentMillis - previousMillis1 >= interval1) {
```

```
previousMillis1 = currentMillis;
led1State = !led1State;
digitalWrite(led1Pin, led1State);
}
if (currentMillis - previousMillis2 >= interval2) {
  previousMillis2 = currentMillis;
  led2State = !led2State;
  digitalWrite(led2Pin, led2State);
}
}
```

Try changing interval1 and interval2 to different values and notice how the two LEDs drift in and out of sync with each other — a simple example of the kind of independent, overlapping timing that becomes essential once you're driving motors, sensors, and lights all in the same program.

ESP32: PWM and Timed Patterns

So far we've only turned LEDs fully on or fully off. The ESP32 also has dedicated hardware for **PWM (Pulse Width Modulation)**, which lets you control brightness (or motor speed, or servo position) rather than a simple on/off state. PWM works by switching the pin on and off very rapidly — thousands of times a second — and varying the proportion of time it spends HIGH versus LOW (the *duty cycle*). Because the switching happens faster than the eye (or a motor) can respond, the LED appears to dim smoothly rather than flicker.



A short burst of HIGH pulses within each cycle (thin black trace) creates a perceived brightness level (dashed red envelope) — more time HIGH within each cycle means a brighter LED.



Duty cycle is the percentage of time a PWM signal spends HIGH during one on/off cycle. 0% is fully off, 100% is fully on, and values in between produce intermediate brightness or speed.

The Arduino-ESP32 core provides a simple `ledcAttach()/ledcWrite()` PWM API. The sketch below creates a slow “breathing” LED that fades up and down continuously — a nice visual replacement for the fixed on/off timing of a simple metronome-style trigger, and a good building block for later chapters on motors and dimmable lighting.

```
/* ESP32 breathing LED using hardware PWM */
const int ledPin = 4;
const int pwmFreq = 5000; // 5 kHz PWM frequency
const int pwmResolution = 8; // 8-bit resolution: values 0-255
void setup() {
  ledcAttach(ledPin, pwmFreq, pwmResolution);
}
void loop() {
```



```
// fade up
for (int duty = 0; duty <= 255; duty++) {
  ledcWrite(ledPin, duty);
  delay(8);
}
// fade down
for (int duty = 255; duty >= 0; duty--) {
  ledcWrite(ledPin, duty);
  delay(8);
}
}
```

(Note: older versions of the ESP32 Arduino core use a slightly different API — `ledcSetup(channel, freq, resolution)` followed by `ledcAttachPin(pin, channel)` and `ledcWrite(channel, duty)`. If `ledcAttach()` is not recognized, update your ESP32 board package to the latest version in the Boards Manager, or use the channel-based calls instead.)

ESP32: Lighting an LED with a Switch

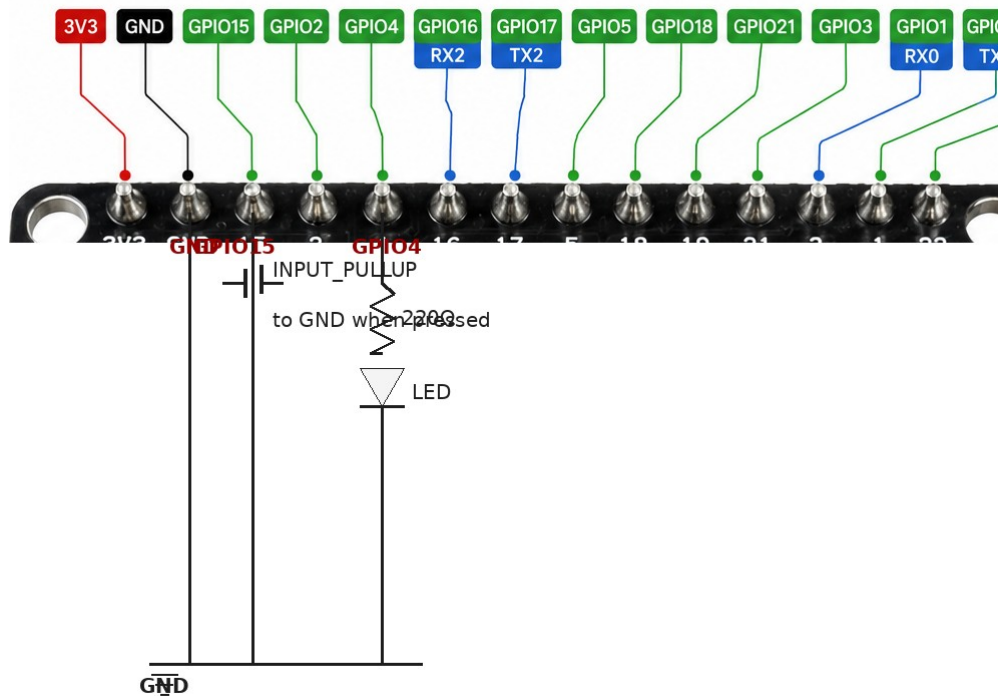
In this section you will use a pushbutton switch to turn an LED on and off — the same goal as the switch-controlled lesson used for other microcontroller platforms, but here we'll take advantage of a convenience built into the ESP32: an internal pull-up resistor you can enable directly in software, so no external pull-up or pull-down resistor is required for the switch itself (you'll still need one for the LED).



A **pull-up resistor** holds an input pin at a known HIGH voltage when a switch is open, so the pin reads a clean, predictable LOW only when the switch is pressed and connects the pin to ground. Without a pull-up, an unconnected input pin can "float" and read randomly.

Parts Necessary:

ESP32 development board • breadboard • 1 pushbutton switch (normally open) • 1 LED • 1 – 220 ohm resistor • jumper wires



The switch connects GPIO 15 to ground when pressed. With the internal pull-up enabled in software, GPIO 15 reads HIGH when the button is not pressed and LOW when it is. The LED circuit on GPIO 4 is wired exactly as in the earlier single-LED lesson.

Wire the switch between GPIO 15 and ground, and the LED (with its 220 ohm resistor) between GPIO 4 and ground, as shown above. Then enter the sketch below.

```
/* Turn an LED on while a button is held down, using the ESP32's internal pull-up */  
const int buttonPin = 15;  
const int ledPin = 4;  
void setup() {  
  pinMode(buttonPin, INPUT_PULLUP); // enable internal pull-up on this pin  
  pinMode(ledPin, OUTPUT);  
}  
void loop() {  
  int buttonState = digitalRead(buttonPin);  
  // buttonState is LOW when the button is pressed (pulled to ground)  
  if (buttonState == LOW) {  
    digitalWrite(ledPin, HIGH);  
  } else {  
    digitalWrite(ledPin, LOW);  
  }  
}
```

Notice the logic here is inverted from what you might first expect: because the pull-up holds the pin HIGH by default, a LOW reading is what indicates the button *is* pressed. This is an extremely common pattern in microcontroller programming, and it's worth taking a moment to make sure you understand why, since you'll see it again throughout the rest of this book.

Upload the sketch, press the button, and confirm the LED lights up only while the button is held down.

Summary

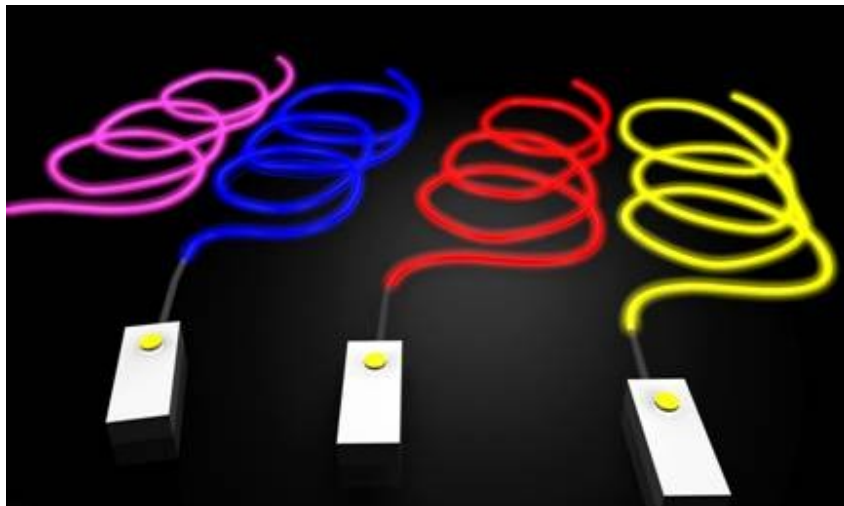
LEDs are easy to control using HIGH and LOW commands, and timing is easy to control using delay or timed intervals in your code. These code examples will be visited repeatedly and will come in useful in future programs, so save all your programs as you create them.

Future

Development of a new class of LEDs is moving to devices called OLEDs, which stands for organic LEDs. This new class of LEDs will prove to be brighter and more flexible. They will be able to be as thin as paper and will consume less power, and they are easier to manufacture. In the future, we will see these in consumer products such as large-scale TVs and as projection screens that you can roll up like paper.

What art applications can you imagine? Can you use them in clothing, wallpaper, or to have your whole sculpture glow as if neon?

Electroluminescent wire is a wire that appears to be like a mini neon tube but is flexible. The artist Marjorie Franklin has been weaving jewelry with these electroluminescent wires.



Other possible lighting sources are small neon tubes, which will run on a 9-volt battery. Light sheet is a cuttable lighting source which is about twice the thickness of paper and when turned on emits a blue or green glow.

Small incandescent bulbs in 5, 9, or 12 volts are possible, but be careful not to try to power these or the electroluminescent wires directly from your microcontroller, as they need more power than the outputs of your board can provide. However, there is a circuit later in this book that will allow you to control these additional devices utilizing transistors.

Conceptual reading:

Burnham, Jack. "Systems Esthetics." Reprinted from *Artforum* (September 1968).

Krueger, Myron. *Artificial Reality*.

Huhtamo, Erkki. "The Seven Misunderstandings of Interactive Art."

References:

- [1] Norman, Donald. *The Design of Everyday Things*.
- [2] Seawright, James. *Houseplants* series.
- [3] Kumao, Heidi. *Monitor I*, 2001. Bra, 180 LEDs.
- [4] Redl, Erwin. *MATRIX XII*. <http://www.paramedia.net/portfolio/gallery.htm>
- [5] Grevey, Ellen. *Lady Dover*, 2001. Information and images supplied by the artist.
- [6] Youngs, Amy. *Engineered for Empathy*. Artist website: <http://accad.osu.edu/~ayoungs>
- [7] Rinaldo, Ken. Artist website: <http://accad.osu.edu/~rinaldo/>
- [8] Howard, Webster E. "Better Displays with Organic Films." *Scientific American*, p. 78.

Electronic or Electrical Debugging

There are rules of thumb when trying to figure out why something does not function. The primary philosophy is to break the problem down and isolate what does work from what does not work.

Ross Baldwin jokes, *"If it ain't broke, fix it until it is..."* but seriously, you must be deliberate and careful in tracing down where the problems lie.

Is it plugged in? Is it turned on? Check that power and ground are getting to each part of your circuit that needs it.



Be careful when using multimeter leads not to accidentally short out your probe tip to other parts or the other probe tip.

Are power and ground reversed? Are all connections you think are correct actually correct? (Use your continuity test with your multimeter to determine that all connections are allowing signals and voltage to get through.) I have built circuits multiple times to get them right, and this is very much a part of this practice.

Are all components placed on the board with proper polarity? Check polarities again (capacitors, LEDs, diodes). Use layout schematics and check off what you have placed on the board. Are all components within the proper ranges and voltages? Try changing out a component with an identical component and see if this works. Is there a short on the board? Do you get a reading between power and ground?

Good practices to prevent the above from happening when constructing your project:

When constructing a board, use sockets for chips and other parts that may be damaged and need to be changed out.

Review the manufacturer's data sheets, and when you order parts be sure to ask if they have specification sheets on the product that they can send, though most are available for free as PDF downloads at questlink.com. File these away when done with the project or keep an electronic copy.

Use a .1 μ F capacitor from the power supply of operational amplifiers to ground.

Use a .1 μ F tantalum capacitor in each digital chip across power and ground pins.

Test all components before installing on boards, i.e. measuring resistors.

Use existing circuits as building blocks, as both models and actual circuits.

Avoid placing heat-sensitive components near components that get hot.

Leave room for necessary heat sinks.

All leads that carry household current must be insulated.

Circuits in which current flow is suddenly switched off or on may emit radio frequency radiation that can cause interference in nearby radios, TVs, and other circuits.

Use stranded wire for all connections that are not fixed in position (battery clip leads, etc.). Use solid wire for fixed connections.

Use connectors with gold instead of copper or tin for long-term removable connectors.

Insulate exposed component leads mounted close to other exposed leads or hardware.

The input and output sections of high gain amplifiers should be physically isolated from one another. Inductance between output and input may cause output to be fed back into input.

Chapter 8

Controlling Arrays of LEDs and Analog Input

The Persistence of Vision

“Art is not theoretical; it needs to be experienced rather than interpreted.”

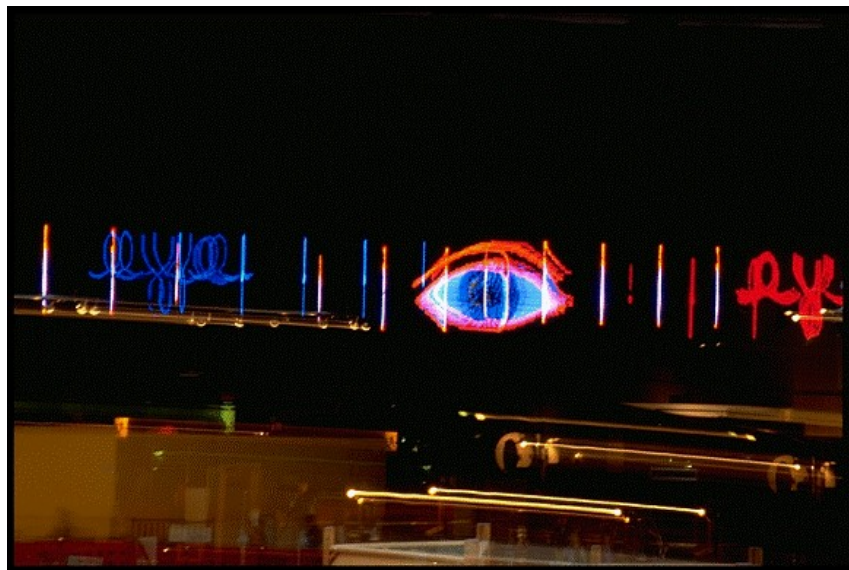
— Jack Dollhausen

Question: Can I control eight pins or sixteen pins at one time and have them function as both inputs and outputs?

Controlling an Array of LEDs with Binary and Software Loops

The ability to turn sequences of LEDs on and off can be powerful. You can create some illusive effects with light and control the ON and OFF state of multiple pins at one time. Understanding how to control the states of multiple pins at one time is an important building block that leads to digital control of many electronic devices simultaneously, both AC and DC.

The artist and inventor Bill Bell employs an optical effect called *persistence of vision* to create images with flashing LEDs. In this process, the images left on the eye as it scans a straight row of LEDs creates pictures and text, such as the word “eye” and a pictograph of the eye.



Triple Eye Lightstick by artist [Bill Bell](#). “Persistence of vision”, Lily Rodriguez, © Exploratorium. The same optical effect that allows us to see moving images in movies is coupled with another effect — saccadic, or rapid eye movement — to reveal the seemingly hidden images.

The LEDs in Bell's Lightstick works blink 5,000 times per second—a frequency that is barely detectable to the human eye and yet the images are revealed for roughly one tenth of a second. As you stand still and move your head back and forth looking at the vertical row of LEDs, the images are left on your eye.

The artist [Jim Campbell](#) has used this technique with his Ambiguous Icons (2000–2004) series, which have human figures moving in time, through arrays of LEDs. Jim Campbell programs arrays of single and multicolor LEDs, and your eyes and brain visually integrate their separate flashings into a coherent image of a human form walking. The image is constructed in your mind's eye based on the flashing and movement of the image.

Light Bulb Works by [Jim Campbell](#). 2001–2008. One artist who has been particularly successful at using the subtlety of LEDs is Jim Campbell. He uses LEDs to suggest human form moving in space as a kind of cinematic experience.

This creates a wonderful marriage between what we see and the ability of our perceptual system to resolve information and create a coherent structure. Jim Campbell's work demonstrates collaboration between the perceptual system of the eye and our expectations and knowledge about the world, and in this process, we construct reality. In Jim Campbell's words, "Ambiguous Icons explore the relationship between information and meaning, in the context of reduced or compressed levels of information."

Persistence of vision is one major theme that can be explored in technologically based art, as it is directly related to establishment and evolution of pattern.

[Dan Paluska, Jessica Banks, and jackbackrack](#) have created a work called *The Fotron 2000*—2003, a robotic sketch artist that uses an LED light to create quick gestural sketches on long exposure Polaroid film. The robot moves quickly and captures the viewer's image in what appears to be a persistence of vision image, but the image is recorded to the film.



Fotron2000 (FOE-tron-too-THAU-zin) by [Dan Paluska, Jessica Banks, Jackbackrack](#). 2003.

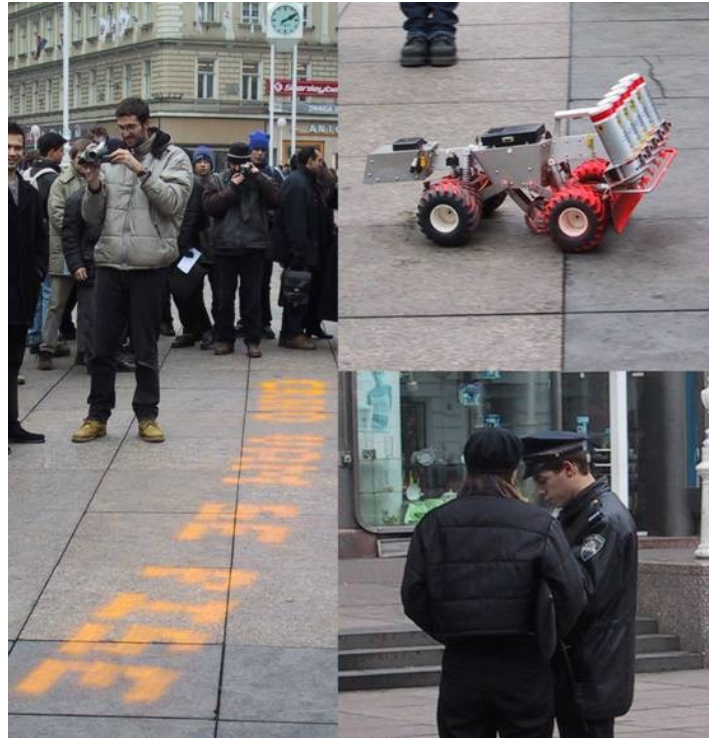
In this work, the artists were interested in the robot precision and automated processes in making drawings that they could not realize themselves and to utilize the technology in powerful but also impractical ways. The artists joke that *The Fotron2000* "brings good things to light."

Artistic Applications of LEDs

The [GraffitiWriter](#) is an example of controlling nozzles of spray paint cans in time as if they were LEDs, and the spray creates text left on the street. The remote-controlled robot GraffitiWriter sprays sometimes-subversive texts on streets and public squares. Instead of activating LEDs, the artist is activating transistors that are switching solenoids on and off. Solenoids are linear motors that push a rod forward. They can be used to allow the opening and closing of a valve. Chapter 11 teaches you how to create and program a circuit that can switch solenoids.



GraffitiWriter in action from [Institute for Applied Autonomy](#), 1998.



GraffitiWriter in action from [Institute for Applied Autonomy](#), 1998.

The Institute for Applied Autonomy created the Robotic GraffitiWriter to fulfill a need for a teleoperated and portable platform that could operate beyond the line of sight of the authorities to disseminate unsanctioned content in the urban environment, and is part of a movement for the creation of *contestational robotics*.

In this work, the messages are submitted by Internet users to the Institute for Applied Autonomy and are then applied by means of remote-controlled spray-paint cans to the surfaces that the robot rolls over.

The artist [Jenny Holzer](#) is well known for her contradictory texts with LED signs. She has conceived and implemented site-specific installations, such as her transformation of the Solomon R. Guggenheim Museum in New York.



Work by [Jenny Holzer](#), from Art Basel. Photo by ImageMD, copyright owned by ImageMD.

The texts function as declarations and truisms, and many are fused with architecture and sculptural form. The methods of controlling many LEDs can also be applied to devices called seven segment displays, which can allow you to create text works on square arrays of LEDs.

Another artist who has used persistence of vision in his work is Jack Dolhousen with *Just To See It*. Jim Jenkins used LEDs in multiples in his work *The Little Chair*, which is a school chair that is spun by a motor while an array of timed LEDs uses persistence of vision to spell out “Sit Still”.

Ohm's Law Applied to Multiple Pins (Arduino)

In this lesson you will use Ohm's law to calculate the values of the resistors you will need to protect the microprocessor as you power eight LEDs, instead of one and two LEDs, as in Chapter 7.

You will then build the circuit using a new part called a bar resistor and program the output pins to create sequences of on and off states for the eight LEDs. You will be using binary to write high and low commands directly to the pins. After this, you will add a micro switch to the circuit and program the circuit to allow different sequences to be manifested in relation to pressing or not pressing your input switch.



Source is the amount of current available to drive a device from the Arduino UNO.



Sink is the amount of current the pin can absorb before damage is done.

While each individual pin of the Arduino can **source** 40 mA, exceeding either the source or sink current can damage the tiny wires on the interior of the microcontroller. There are also limits to how much current multiple pins can source and sink at the same time. Pins 13 through 10 should not exceed 100 mA source total, so a series of pins has specific source capabilities that must be acknowledged in your design.

Using Ohm's law, calculate what size resistor you would need to limit the Arduino to source only 100 mA total for all eight output pins. Remember, Ohm's law states $V = I \times R$, or voltage = current times resistance. We already know that we have 5 volts DC available on the Arduino.

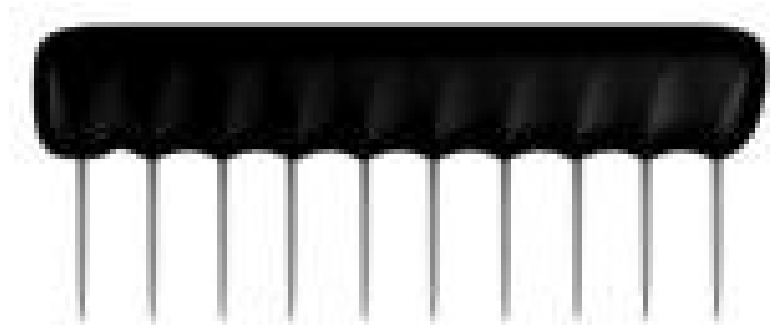
Solving for resistance: we first need to convert mA into amps by moving the decimal place three spaces to the left. So, 100 mA = .1 A. Now, divide .1 A by 4; this gives us .025 A per pin available from the Arduino device when driving four pins simultaneously. Plug these values into Ohm's law to get the resistor value needed at each: solving for resistance gives you a value of 200 ohms per LED.

Now that you have figured out your resistor value you are ready to build the circuit. You will be using a new part called the bar resistor, with 9 resistors inside one single unit. You can use a 200 ohm bar resistor, or a resistor with a larger ohm rating such as a 1000 ohm resistor, to know that you will not damage your Arduino.

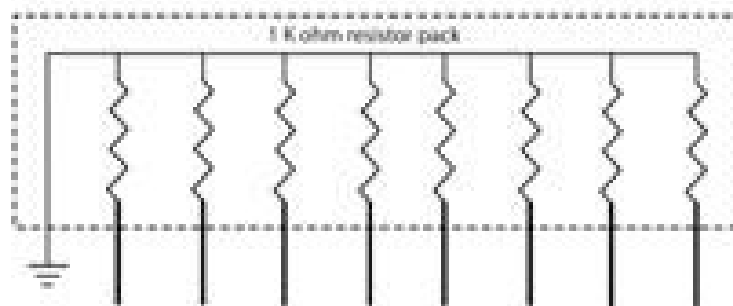
Introducing a New Part

Single In-Line Package (SIP) resistor networks are packs of 8 or 9 resistors or more in a single unit with 10 pins. One of the pins is the common pin that is shared by all the resistors. As with other resistors, SIP resistor networks also have maximum ratings for how much mA they can absorb as heat. The one provided in the kit is a 1/4 W resistor pack. This is a valuable part because it can reduce the chance of

accidental short circuits on your board by reducing the number of parts and wires exposed to other parts.



Bar resistor



Bar resistor schematic symbol

Parts Required

Arduino UNO • 4 220 ohm resistors, or a bar resistor

Max MSP and Jitter Data Spaces

There are many other ways of interacting with data besides switches and sensors. Max MSP and Jitter is quite good at taking data and allowing artists to use that data to give feedback about the world or the universe surrounding us.

New media artist [Trademark Gunderson](#) is perhaps one of the best Max MSP programmers I know and has created a visually, conceptually and sonically wonderful body of work.

Maxuino/Arduino Controlling Many LEDs

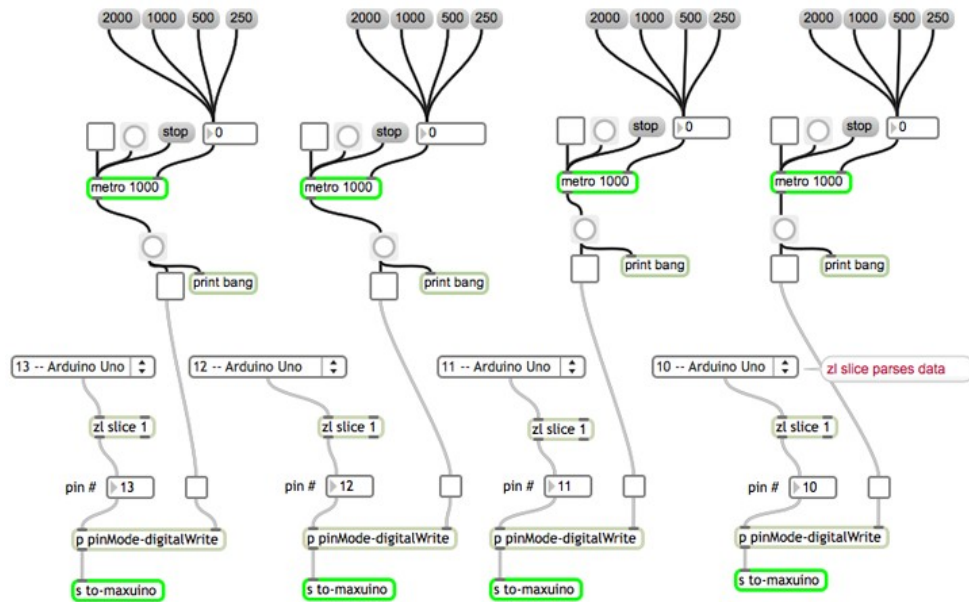
You can control many LEDs at different rates dynamically by using Max MSP code to write to each pin, or with Arduino code that drives a row/column LED matrix directly.

Arduino Method of Driving an LED Matrix High/Low

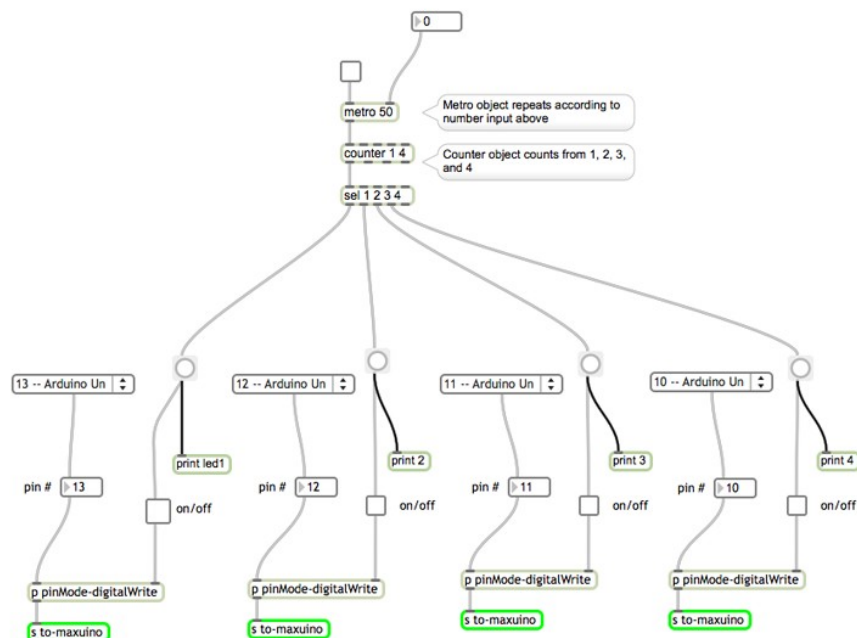
```
const int row1 = 2; // the number of the row pin
const int row2 = 3;
const int row3 = 4;
const int row4 = 5;
const int row5 = 17;
const int row6 = 16;
const int row7 = 15;
const int row8 = 14;
// the pins to control the columns
const int col1 = 6;
const int col2 = 7;
const int col3 = 8;
const int col4 = 9;
const int col5 = 10;
const int col6 = 11;
const int col7 = 12;
const int col8 = 13;
void setup() {
  int i = 0;
  for (i = 2; i < 18; i++) {
    pinMode(i, OUTPUT);
  }
  for (i = 2; i < 18; i++) {
    digitalWrite(i, LOW);
  }
}
void loop() {
  // row 1, col 1 of the LED matrix turn on
  digitalWrite(row1, HIGH);
  digitalWrite(col1, LOW);
  delay(1000);
  // turn off all
  for (int i = 2; i < 18; i++) {
    digitalWrite(i, LOW);
  }
  delay(1000);
}
```

You can also have LEDs play in sequence on the Arduino running through Maxuino. In this code, as all the LEDs are controlled by a single metro box, you can control their speed by increasing the numbers in the number box.

Controlling MANY LEDS at different rates



Notice that you will need to choose the pin number to output to on the Arduino UNO.



Maxuino/Arduino Dimming an LED

Using one of the analog output pins you can also dim an LED and change the brightness dynamically. It must be a pin on the Arduino that has the capability for analog output, such as pins 11, 10, 9, 6, 5, and 3 on the Arduino UNO. The frequency output is at approximately 980Hz and is a PWM (pulse width modulation) signal, so this technique can also be used to control motors, as you will see in later chapters.

Using the Arduino IDE to Dim an LED on Pin 9

/ Fading — This example shows how to fade an LED using the analogWrite() function. The circuit: LED attached from digital pin 9 to ground. Created 1 Nov 2008 by David A. Mellis, modified 30 Aug 2011 by Tom Igoe. This example code is in the public domain. */*

```
int ledPin = 9; // LED connected to digital pin 9
void setup() {
  // nothing happens in setup
}
void loop() {
  // fade in from min to max in increments of 5 points:
  for (int fadeValue = 0; fadeValue <= 255; fadeValue += 5) {
    analogWrite(ledPin, fadeValue);
    delay(30); // wait to see the dimming effect
  }
  // fade out from max to min in increments of 5 points:
  for (int fadeValue = 255; fadeValue >= 0; fadeValue -= 5) {
    analogWrite(ledPin, fadeValue);
    delay(30);
  }
}
```

Remember, in order to use the Max MSP patch below, you will need to have the MaxuinoSimpleStart program open.

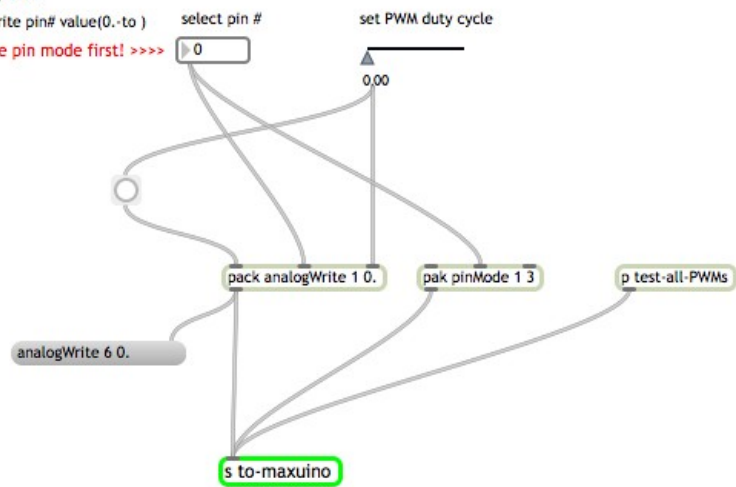
PWM (fake Analog Output)

use pin mode 2 allows you set the duty-cycle of a pulse-width-modulation (PWM) signal (used for fading/varying speed/etc).

this uses the arduino's hardware PWMs so the pin you use MUST be PWM capable
message: "analogWrite"

format: analogWrite pin# value(0..to)

set the pin mode first! >>>>



Maxuino/Arduino High Brightness LED

A high brightness LED can be powered from the Arduino as well, using analog output signals. This unit is a 3W LED module with a color temperature of white 6000–6500K.

Forward Current: 700mA • Luminous flux: White 180–200LM (lumens) • Forward Voltage: 3.3–3.6 V • Reverse voltage: 5V • Viewing angle: 180 degrees • Working temperature: -20–60 degrees • Storage temperature: -20–60 degrees • Brightness attenuation: 3% after 5000 hours • Life: 50,000 hours



High brightness LED

Notice the glowing yellow in this LED. That is phosphorus, which makes the LED even brighter as the lumens come from the current adding electrons in the process.

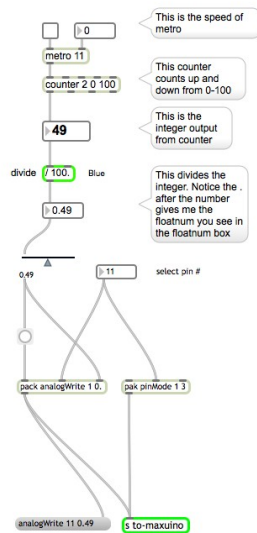
The Max MSP patch below can adjust the brightness.

High Brightness LED White

180~210 lumens 6000-7000 kelvin

This led is very bright and can output with an analog signal

- pin to GND,
+ pin to digital or analog output
Middle pin to 3.3-5V +



Maxuino/Arduino RGB LEDs

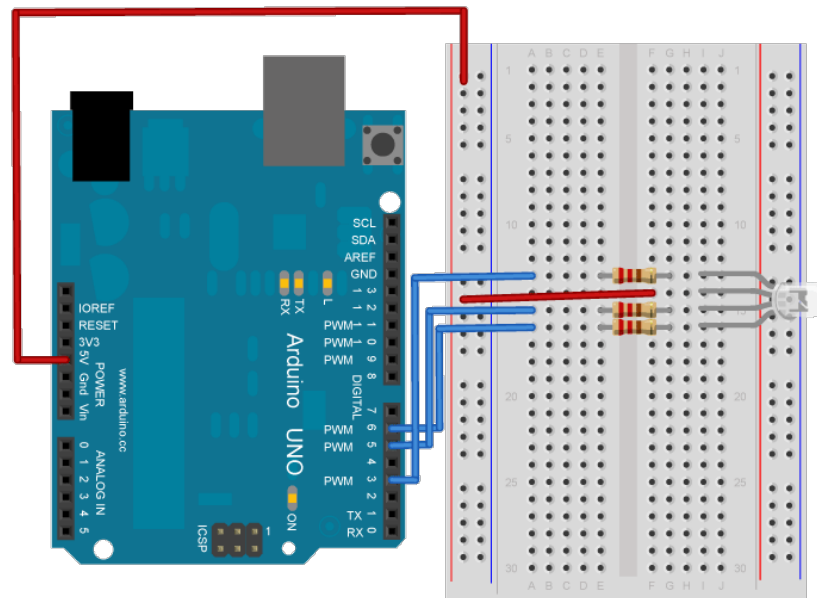
"If you want to find some secrets of the universe think in terms of energy, frequency, and vibration."

— Nicola Tesla

RGB LEDs are exciting devices where you can mix red, green, and blue light in a single package to create an infinite number of colors. They are quite beautiful and can add some real pizzazz to a work.

Building the Circuit

Parts: Arduino UNO • RGB LED • 3 × 220 ohm resistors



© 2014 Arduino. Using the Arduino IDE to control an RGB LED.

```
#define GREEN 3
#define BLUE 5
#define RED 6
#define delayTime 20
void setup() {
  pinMode(GREEN, OUTPUT);
  pinMode(BLUE, OUTPUT);
  pinMode(RED, OUTPUT);
  digitalWrite(GREEN, HIGH);
  digitalWrite(BLUE, HIGH);
  digitalWrite(RED, HIGH);
}
int redVal;
int blueVal;
int greenVal;
```

```

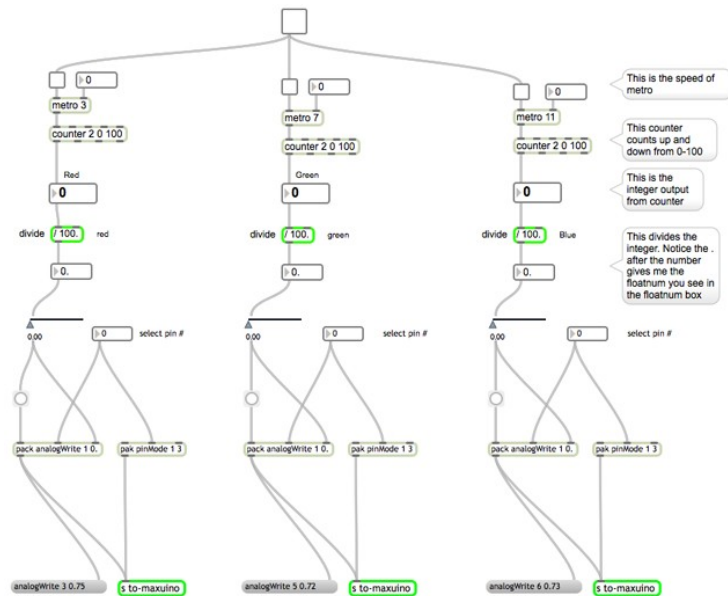
void loop() {
  int redVal = 255;
  int blueVal = 0;
  int greenVal = 0;
  for (int i = 0; i < 255; i += 1) {
    greenVal += 1;
    redVal -= 1;
    analogWrite(GREEN, 255 - greenVal);
    analogWrite(RED, 255 - redVal);
    delay(delayTime);
  }
  redVal = 0; blueVal = 0; greenVal = 255;
  for (int i = 0; i < 255; i += 1) {
    blueVal += 1;
    greenVal -= 1;
    analogWrite(BLUE, 255 - blueVal);
    analogWrite(GREEN, 255 - greenVal);
    delay(delayTime);
  }
  redVal = 0; blueVal = 255; greenVal = 0;
  for (int i = 0; i < 255; i += 1) {
    redVal += 1;
    blueVal -= 1;
    analogWrite(RED, 255 - redVal);
    analogWrite(BLUE, 255 - blueVal);
    delay(delayTime);
  }
}

```

Notice that the V+ line for the RGB LED should be indicated on the package. Also notice that PWM-capable pins are the only ones that can be used for the patch below.

RGB LEDs

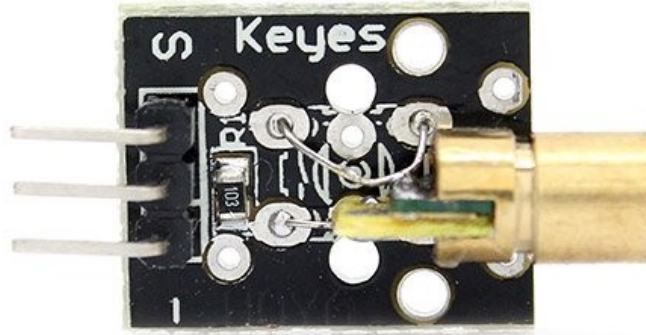
An RGB LED is essentially 3 LEDs (red, green, and blue) packed into one. Each color can be individually controlled, but we see all three colors combined. The result: any color of the rainbow.



© 2014 Ken Rinaldo.

As you wire up your RGB LEDs, keep in mind that some may require a common ground vs. a common V+ rail to function.

Maxuino/Arduino Laser Output



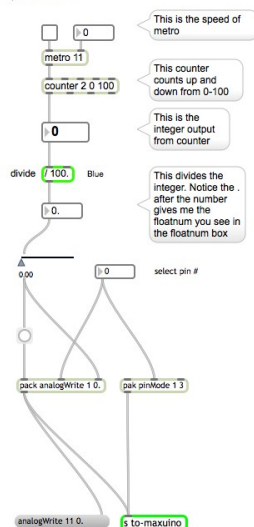
Keyes Laser Module (650NM)

Code for driving brightness. You may need a resistor on the input to the laser if you are driving it at a full 5 volts.

Laser Module for Arduino KY-008

This laser can be used to create a breakbeam or can also be used to send codes to a light receiver. It is a 650 NM laser. Do not look directly into ANY Laser.

- pin to GND.
- pin to digital or analog output.
Middle pin to 3.3-5V +



Code to drive laser module brightness high and varying low

Maxuino/Arduino Input with Digital Switch

Here is some code on how to use a switch in Maxuino (Arduino controlled by Max MSP and Jitter). You can search the Arduino website for the switch schematic if you need a wiring reference.

Simple pushbutton switch digital Input

An easy way to detect humans is with a simple digital input. Think how the finger connected to the brain is going to know it made connection. How might you dress up your switch. Should it be soft with fur? Should it have a light to draw the eye and therefore the hand in?

Notice that many switches have NO normally open configurations or NC normally closed configurations and you must determine which one you have.

Also note that generally we use a 10K ohm resistor in the circuit

REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port.

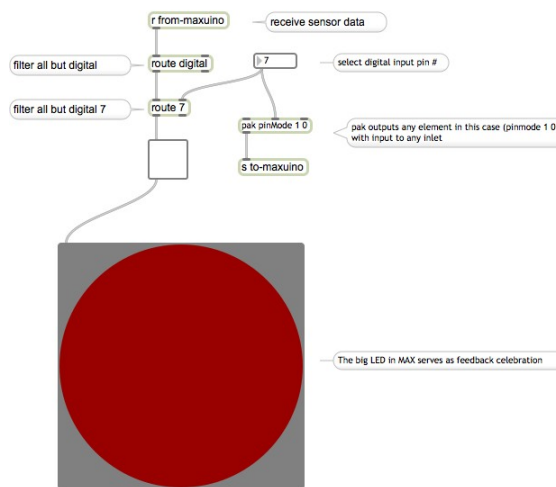
Connections to Arduino:
pin7: detection (0 = off, 1 = on) to Arduino 7 which functions as a digital input pin
G: Ground
+5: Arduino 5V

[Click for detailed project page](#)

max launchbrowser <http://arduino.cc/en/tutorial/button>

[Click for switch info](#)

max launchbrowser
http://www.mediafire.com/index.php?uploadfrom=com_casita&view=vertical&docid=19%3Achapter-17&id=154%3A&idterm=21



Max MSP Jitter code with Maxuino and Arduino

Maxuino/Arduino Input Control to Output Control of LED

Here you can make an input with a switch turn on and off an LED. This is the beginning of an interactive action.

Using the Arduino IDE to Activate an LED with a Switch or Button

/ Button — Turns on and off a light emitting diode (LED) connected to digital pin 13, when pressing a pushbutton attached to pin 2. The circuit: LED attached from pin 13 to ground; pushbutton attached to pin 2 from +5V; 10K resistor attached to pin 2 from ground. Note: on most Arduinos there is already an LED on the board attached to pin 13. created 2005 by DojoDave <<http://www.0j0.org>>, modified 30 Aug 2011 by Tom Igoe. This example code is in the public domain.*

*<http://www.arduino.cc/en/Tutorial/Button> */*

```
const int buttonPin = 2; // the number of the pushbutton pin
```

```
const int ledPin = 13; // the number of the LED pin
```

```
int buttonState = 0; // variable for reading the pushbutton status
```

```
void setup() {
```

```
  pinMode(ledPin, OUTPUT);
```

```
  pinMode(buttonPin, INPUT);
```

```
}
```

```
void loop() {
```

```
  buttonState = digitalRead(buttonPin);
```

```
  if (buttonState == HIGH) {
```

```
    digitalWrite(ledPin, HIGH);
```

```
  } else {
```

```
    digitalWrite(ledPin, LOW);
```

```
  }
```

```
}
```

Simple pushbutton switch LED activate

In this tutorial you will use a digital switch to activate an LED output.

Notice that many switches have NO normally open configurations or NC normally closed configurations and you must determine which one you have.

Also note that generally we use a 10K ohm resistor in the circuit.

REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port.

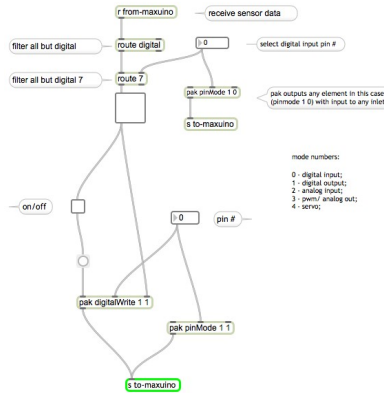
Connections to Arduino:
pin7: detection (0 = off, 1 = on) to Arduino 7 which functions as a digital input pin
G: Ground
+V: Arduino 5V

[Click for detailed project page](#)

[View source for maxuino: Simple pushbutton switch](#)

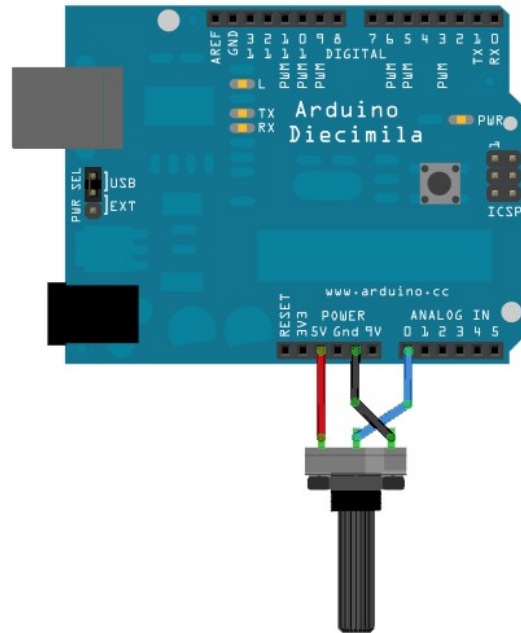
[Click for switch info](#)

[View source for maxuino: Simple pushbutton switch](#)
[View source for maxuino: Simple pushbutton switch](#)
[View source for maxuino: Simple pushbutton switch](#)
[View source for maxuino: Simple pushbutton switch](#)
[View source for maxuino: Simple pushbutton switch](#)

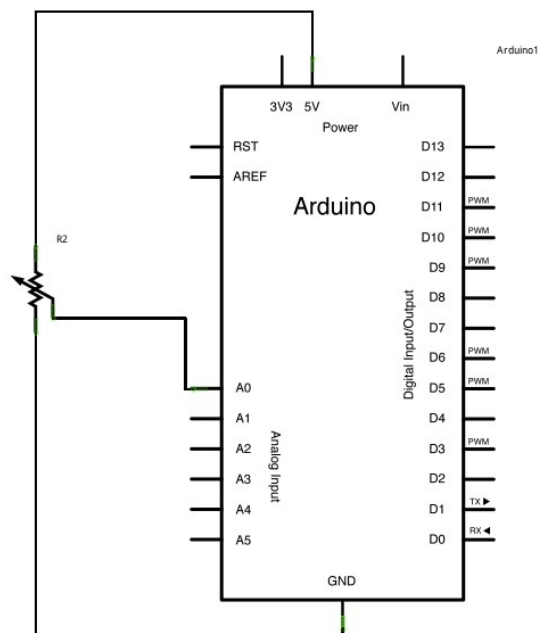


Maxuino/Arduino Analog Input with Potentiometer

You can also create an input into your Arduino UNO reading analog voltages, though of course here you must use the analog input pins. On the Arduino UNO, those are pins A0, A1, A2, A3, A4, and A5, or numerically in order pins 14, 15, 16, 17, 18, and 19.



CC Arduino design for a potentiometer with the Arduino UNO.



CC Arduino schematic design for a potentiometer with the Arduino UNO.

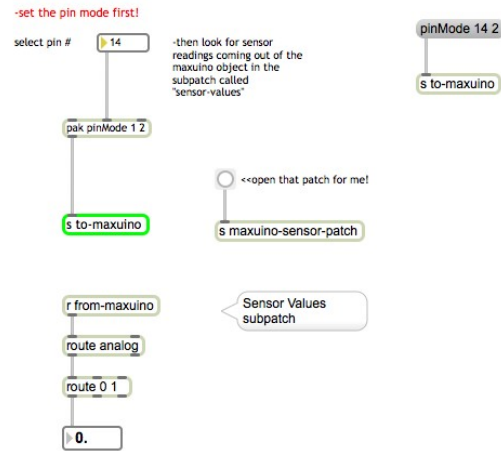
The code for the analog input looks like this.

Analog Input

use pin mode 2 to use a pin as an analog input, good for continuous sensors like faders, accels, gyro's...

the pin you use MUST be analog-input-compatible!

Arduino analog pin numbering starts with the pin after the highest number digital pin: an Arduino UNO has 13 digital pins, so analog 0 to 5 are pins 14 to 19; an Arduino Mega has 53 digital pins, so analogs 0 to 15 are pins 54 through 69



Copyright Ken Rinaldo.

Maxuino Analog Input to LED Dim Output

You can also use a potentiometer or other variable resistor to change the brightness of an LED.

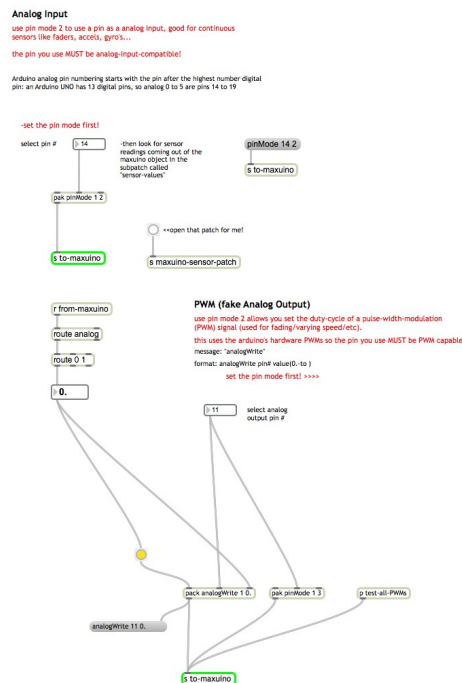
Using the Arduino IDE and a potentiometer to read an analog voltage and display that on the serial monitor:

```
/* ReadAnalogVoltage — Reads an analog input on pin 0, converts it to voltage, and prints the result to
the serial monitor. The graphical representation is available using serial plotter (Tools > Serial Plotter
menu). Attach the center pin of a potentiometer to pin A0, and the outside pins to +5V and ground. This
example code is in the public domain. */
```

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  int sensorValue = analogRead(A0);
  // Convert the analog reading (0 - 1023) to a voltage (0 - 5V):
  float voltage = sensorValue * (5.0 / 1023.0);
  Serial.println(voltage);
}
```

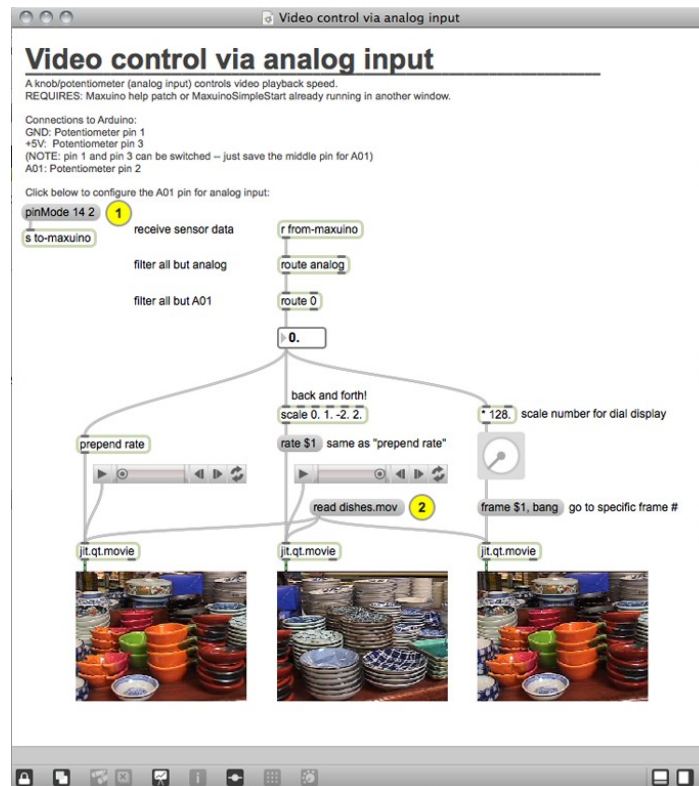
Using Max MSP and Jitter to read and display output to an LED:



Analog Input to Video Output

There are many ways of controlling video in Max MSP and Jitter, and one really great way is using a potentiometer or other analog input voltage. Perhaps a variable resistor or a bend sensor, for example? Before you start this lesson, review and become familiar with the Max MSP and Jitter *Movie Playback* tutorial, an introduction to video playback. That will give you a real sense of the possibilities of how you can tie this lesson to physical input.

The patch below allows you to use footage that is commonly a part of the basic tutorials in Max to attach a potentiometer to input pin 14 (A0) on the Arduino UNO and use that to control video playback. Remember, your easy-start patch needs to be open for this to work.



You will notice a number of elements here. The first thing you must do is assert the (PinMode 14 2) in the patch to set up the A0 pin. After you have done this, you should have control over the potentiometer in Max, and when you turn the pot you should notice the dial turning clockwise and counterclockwise with your potentiometer attached to the Arduino.

Now click on the code to read the QuickTime movie file, and you will notice a number of possibilities: 1) the first, to the lower left, allows you to use the potentiometer to change just the rate; 2) the middle one allows you to scale potentiometer data in such a way that you can change the speed and direction of the video; and 3) the lower right one allows you to use the dial as if you are going to a specific frame in the video, to scrub through the video footage with the potentiometer dial.

Maxuino/Arduino Input from a Joystick

The joystick is a great controller for controlling two potentiometers at one time.

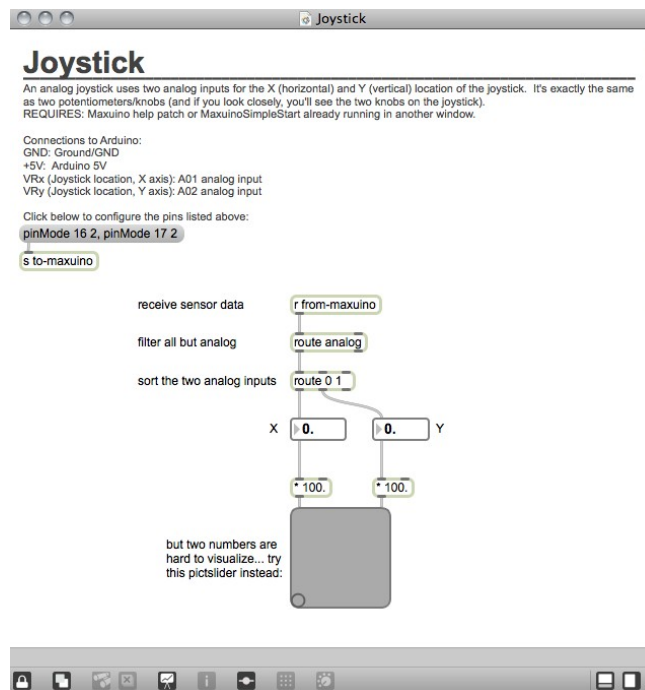
/ Read Joystick — Reads two analog pins that are supposed to be connected to a joystick made of two potentiometers. We send three bytes back to the computer: one header and two with data assigned to bytes, taking the form Jxy, where x and y are integers sent in ASCII. */*

```
int ledPin = 13;
int joyPin1 = 0; // slider variable connected to analog pin 0
int joyPin2 = 1; // slider variable connected to analog pin 1
int value1 = 0;
int value2 = 0;
void setup() {
  pinMode(ledPin, OUTPUT);
  Serial.begin(9600);
}
int treatValue(int data) {
  return (data * 9 / 1024) + 48;
}
void loop() {
  value1 = analogRead(joyPin1);
  // this small pause is needed between reading analog pins
  delay(100);
  value2 = analogRead(joyPin2);
  digitalWrite(ledPin, HIGH);
  delay(value1);
  digitalWrite(ledPin, LOW);
  delay(value2);
  Serial.print('J');
  Serial.print(treatValue(value1));
  Serial.println(treatValue(value2));
}
```

Here again, you must use analog input pins in order for the circuit to work properly. In this case, the joystick came from a kit created by KEYES sensors.



Keysight 023 joystick sensor. Not actual size.



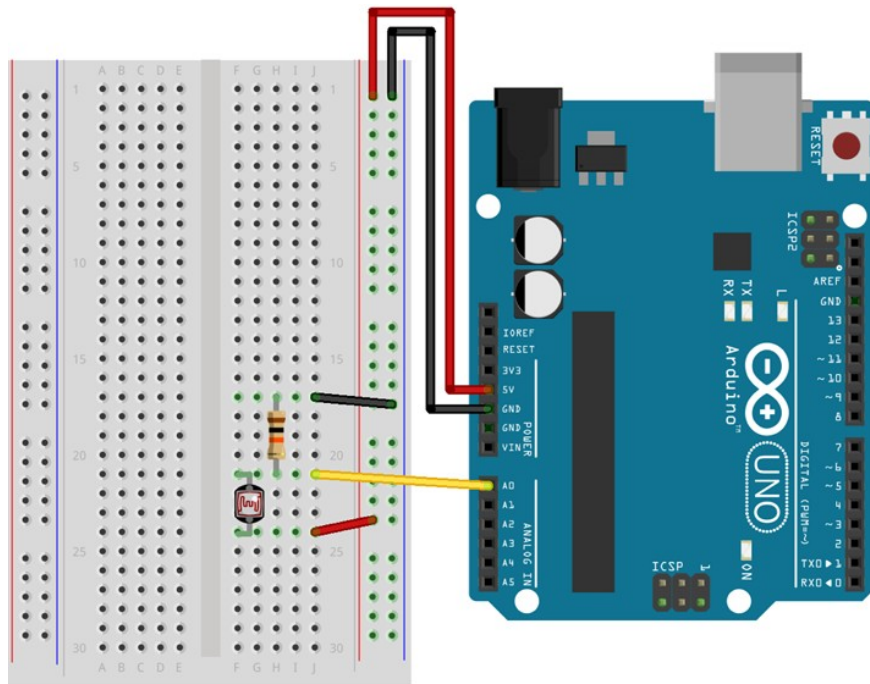
Copyright Ken Rinaldo.

Maxuino/Arduino Input with a Photo Resistor

You can also use a photoresistor as an input device in analog mode with the Arduino running Max MSP and Jitter through Maxuino.

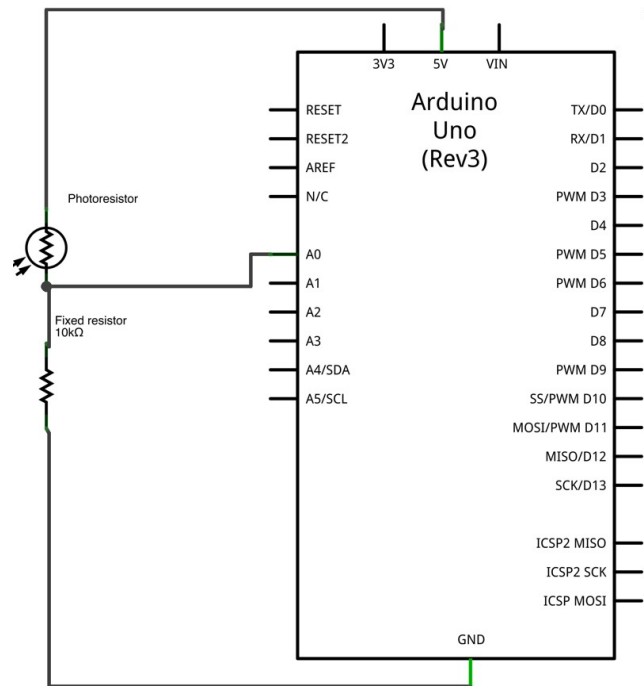
Parts necessary:

10K ohm resistor • Arduino UNO • Connector wires • Photocell (variable resistor)



CC Arduino.com diagram of photoresistor and Arduino UNO.

Schematic



CC Arduino.com diagram of photoresistor and Arduino UNO.

The code for the analog input for the photoresistor is the same as that for the potentiometer.

MAX MSP lessons continue in Chapter 9.

Summary

In this chapter, you have learned about some unusual applications of LEDs that reference our perceptual system in the works of Jim Campbell and Bill Bell. You have also seen LEDs utilized as devices for the creation of sketches, as with the work of Dan Paluska, Jessica Banks, and jackbackrack, and you have seen the applications of driving LEDs abstracted into the notion that binary outputs can also drive solenoids for controlling valves to spray paint politically contentious messages, as with the *GraffitiWriter* by the Institute of Applied Autonomy. You have also seen that control of the code for arrays of LEDs will allow you to drive seven segment displays. These displays are the basis of emotionally active socio-political messages, as with the works of the contemporary artist Jenny Holzer.

While artists and inventors should have good use for this binary technique in driving lights on and off in sequence, the real excitement is being able to control much larger AC or DC devices in the same fashion. With Maxuino/Arduino, the Metro object working with `pinMode-digitalWrite` lets you address individual pins, or many pins in sequence, when you use the Metro object in association with the counter object and the sel object.

Questions & Exercises

Why is it important to be able to control an LED? _____

Do LEDs prevent voltage from moving in one direction but not the other? _____

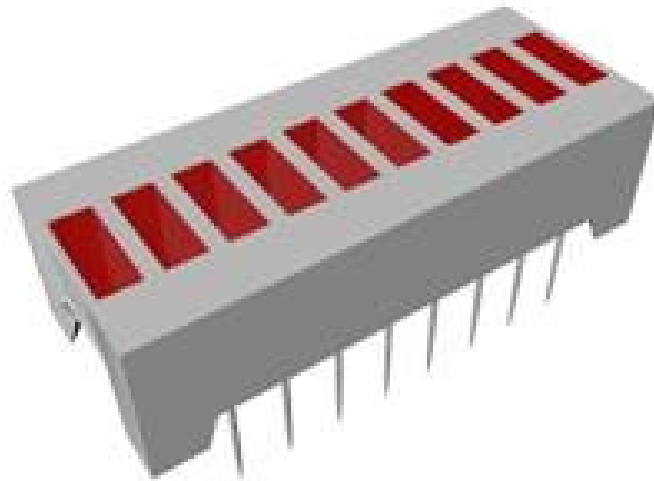
Exercises

What kind of artwork would you envision that might have LEDs as an element?

Can you imagine an application for an LED which has not yet been thought of?

Other Devices & References

There are also solid state [LED bar graphs](#) with 8 and 10 LEDs molded in solid plastic, which you can use to create LED chase patterns or to test code. These will work with the bar resistor as well.



LED Bar Graph

Further Investigation

[The History of the Interface in Interactive Art](#), Söke Dinkla

Article on Contestational Robots: [Institute for Applied Autonomy — Wikipedia](#)
Robot Builder's Sourcebook, McGraw-Hill

References:

- [1] Waldman, Jonathan. "Faster than the Blink of an Eye."
<http://elixir.bu.edu/apr3003/hotspot/photonics.htm>
- [2] Campbell, Jim. Artist's website: <http://www.jimcampbell.tv/>
- [3] Paluska, Dan, Jessica Banks, and jackbackrack. Fotron2000 artist website.
- [4] [Institute for Applied Autonomy — Wikipedia](#)
- [5] Holzer, Jenny. Image compliments of ImageMD.

Chapter 9

Solid-State Relays and Infrared Sensors

Solid-State Relays, Passive Infrared Sensors, and Software Loops

“The aim of art is to represent not the outward appearance of things, but their inward significance.”
— Aristotle

Question: Are there methods to control AC voltages in relation to varying sensor inputs?

Controlling an array of LEDs creates many possibilities, but the greater excitement comes in knowing that you can sequence and control almost any AC or DC device with the Arduino or ESP32, or your microcontroller's logic-level control, connected to a solid-state relay (SSR). Devices such as AC and DC motors, high-brightness lamps, neon sculptures and signs, refrigerators, and virtually any high voltage device can now come under the delicate and precise electronic control possible with your microcontroller. You can even interface the Arduino to the web.

The SSR is interfaced to the microcontroller and programmed to function in either a repetitive fashion or a chaotic one. Both repetitive and chaotic programming modes can be activated by a variety of sensors, such as the infrared sensor in this lesson.



A **solid-state relay (SSR)** is a device that allows you to use a small DC voltage to switch a much larger AC voltage.

The artist David Foster is interested in Firefly communication as well as carnivorous plants such as Venus Fly Traps that eat insects, so he has created an electromechanical hybrid that alludes to these living entities.

Photuris muscipula by David Foster, 2003. Photo by Scott Shelton.

This work engages a critical look at biological research and the implications of working with **transgenics**. Foster's works are metaphorical and meticulous sculptural constructions composed of steel, glass, and control electronics.



Transgenics is the art/science of taking a gene from one animal or plant and splicing it into another plant or animal. The artist Joe Davis has been working in this field and creating wonderfully original work.

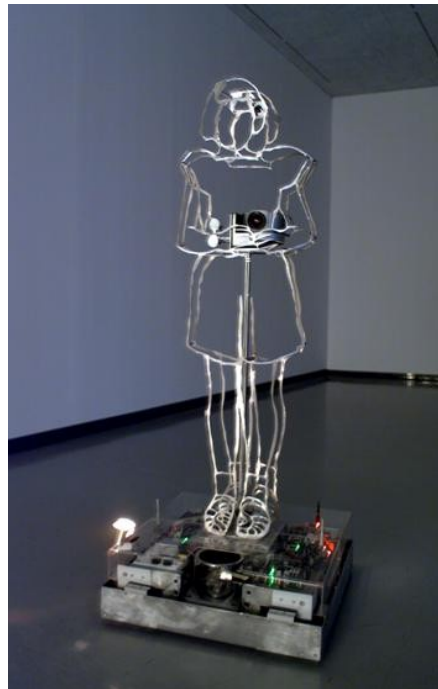
In this sculpture, Foster used **passive infrared sensors (PIR)** to sense the presence of the participant. As the viewer approaches the work, the infrared sensor triggers a sequence of behaviors, and the light under the glass dome flashes on and off rapidly while the stainless steel petals of this techno-electro-hybrid subtly open.



Passive infrared sensors (PIR) measure a quantity of infrared light and look for changes in that signal. They are best used on a stable platform. These are the kind of sensors that activate the AC lights on people's porches when you pass by.

Foster programmed this work so that each time the sensor is triggered, a new behavior comes forth from a repertoire of pre-programmed but seemingly random responses. He also used an SSR to switch the AC lights on and off rapidly, and a powerful 12-volt DC gear head motor to open and close the steel petals.

The artist Reva Stone has been working with interactive installations, robotics, and responsive 3D environments for 15 years. Her installations explore the technological augmentation of the human body.



Carnevale 3.0 by [Reva Stone](#) with technical assistance by Dave Sandeman. 2000–2002.

The work *Carnevale 3.0* is an autonomous robot that is a surrogate of the artist as a young girl.

This robot uses **active infrared sensors**, which are suitable for moving platforms. The sensor system detects people and then triggers an onboard microcomputer to capture images with a mini digital video camera mounted on a cut aluminum form. The video functions as a form of memory for the surrogate, and the captured images are then combined with previously stored images, which are projected outward from the metal body through a small video projector. This process of automated video capture, mixing, and playback addresses the idea of memory and stored knowledge.



Active infrared sensors work well on moving platforms as well as stable platforms. They send out beams of infrared light that, when reflected by living or nonliving objects, trigger the sensor.

Additionally, *Carnevale 3.0* carries images from each of its venues to the next, building a database of “lived experience” in which the captured video images become stored memories of past captured events. For Reva Stone, the work investigates the relationship between somatic ways of knowing through the body and the ways in which bodily experience is merging with new technologies.

In talking about this work, Reva Stone says: “As a mediator of experience, this fleshless entity has the ability to exhibit human behavior by generating responsive movements, processing information, and accessing memory. Recollection, physicality and sentience become mutable entities.”

Artist's Applications of Solid State + Electromagnetic Relays

"Blogged" by [Bill Shackelford](#) uses a web interface in an interactive installation, creating a one-day, net-event concerned with the concept of being 'blogged'. The more hits that the site gets, the more the big red balloon inflates.



Blogged by [Bill Shackelford](#). 2007.

Blogged counts a visit for each unique IP address and URL referral combination to his web page. The visits are logged into Bill Shackelford's MySQL database, and this determines the length of time the air compressor is activated. If there are 20 visits to the website, then this activates the compressor for 20 seconds.



Blogged by [Bill Shackelford](#). 2007.

The microcontroller was interfaced with a Netburner network adapter, which receives the running time from the database, and this switches the air compressor on using a solid state relay to fill the red balloon.

This work creates a cathartic visual metaphor for being noticed on the WWW and relates a big red balloon to the notion of ego swelling with this attention. The work is a clever use of multiple platforms to realize a conceptually driven work of art that has a local performative element and a distant activation element, as visitors to the site were able to watch the balloon inflate with a web cam focused on the balloon.

The artist [Cesar Martinez](#) has created a series of works that use solid state relays and computer timers to turn the works on and off to switch the AC blowers. In the process, Martinez creates poetic works which allude to human love, friendship, and competition.

Lo otro en si mismo (The other in itself) by [Cesar Martinez](#), 2002.



Me quieres o no me quieres, (You want to me or you do not want to me) by [Cesar Martinez](#), 2002.



Me quieres o no me quieres, (You want to me or you do not want to me) by [Cesar Martinez](#), 2002.

The works are constructed of latex rubber with hot air blowers to inflate the works over time. Martinez uses the human figure in various positions to get at powerful emotions, and as the figures inflate and deflate they seem to capture and convey emotion.

The artist Carl Bailey has created a techno-rhythmic sculpture called *Patterned Behavior* (2003), which looks for people's body heat with three PIR sensors that trigger low-frequency percussive themes juxtaposed with different sound accents, meters, and varying tempos.



Patterned Behavior by Carl Bailey (2003). Photo by Amy Youngs.

The amplified sounds are high and shrill at times and more melodic and rhythmic at other times. AC bulbs that flash on and off in patterned, rhythmic, and contrapuntal relation to the sound created accompany these sounds.

Carl Bailey used multiple SSRs to turn nine AC lamps on and off in relation to his custom programming. Carl also used a rewired dumpster-dive stereo amp, which amplified the signal coming directly from the output of his microcontroller. The code used included a pulse-out routine, which allowed the artist to create a complex sound work. The Plexiglas box, which housed and exposed the wiring, also allowed shadows cast by the lights to project the tangle of wires onto the walls of the installation, and in this process created complex visuals to complement the abstract musical elements.

Bailey's work also employed the same PIR sensors that are part of this lesson. He used three PIRs to allow different preprogrammed sequences to come forth based on the chance interaction of the viewer/listener with the sculpture.

Maxuino/Arduino Solid State Relay

In this lesson, you will first learn to use the SSR to flash an AC bulb on and off using your Arduino UNO (or ESP32). You will then employ a 5-volt PIR sensor to activate the bulb into varying flashing behaviors. You will use a **Metro** object in MAX MSP and Jitter for the Arduino.

Solid State Relay (SSR): Controlling AC Voltages

With the SSR, you can use a 5-volt DC voltage at 20 mA to control a 120-volt AC circuit. Now the power of sequencing begins to come to “light”. You can sequence, control, and switch most voltages as long as you select the right SSR for the job. SSRs, like their electromagnetic cousins, need a certain control voltage and amperage in order to switch much larger voltages. SSRs are available to match most controlling voltages, and they function with the logic level (0–5 volts) available with most microprocessors.

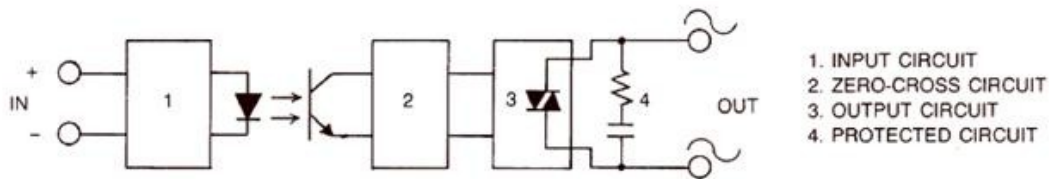


Kyotto Solid State Relay. Control pins are 1 and 2 and require 3–32 volts. Switched output pins are 3 and 4. The maximum rating for these pins is 2 amps at any voltage between 24 and 280 volts AC.

One major benefit of using SSRs is that they do not create electromagnetic noise, because they use optical photo couplers to switch the signals on. This allows high speed and high-frequency switching, but if you require very high-speed SSR switching, be sure to seek out the data sheet and specifications of the part you choose.

Because SSRs have no mechanical parts, they will last longer than electromechanical relays. Using light as a switching agent does not create the noise associated with electromechanical relays. This is a benefit, as the electromagnetic noise created with electromagnetic relays can cause noise in the circuits.

Inside each SSR are an LED, which creates light, and a light receiver, looking for that light. When the light inside the SSR turns on, the receiver also turns on, and this allows you to use light to switch the device on and off. This isolates the larger voltage you are switching from the much smaller voltage necessary to turn the small LED on inside the SSR. This method also protects the microprocessor from the electromagnetic field that surrounds most relays.



Kyoto KB20C02A. In this diagram, number 1 is the circuit that turns the LED inside the plastic case on. The + goes to the signal from your Arduino UNO pin 13. The area at 4 shows a sine wave; this refers to the AC signal.

There are many different mounting possibilities for SSRs, depending on the physical package needs, the voltage, and the current switching capabilities you require. Jameco Inc. has a nice selection of small pictures that may help decode the many mounting and form factors that exist for SSRs. You can also do a web search for the part and often find what you are looking for. The important thing is to select the proper SSR from the start. SSRs, like many devices, also have absolute maximum ratings; pay strict attention to this fact.

The main considerations when selecting an SSR are: 1) how much voltage and amperage does your microprocessor provide for switching on and off, and 2) what are the maximum voltages and amperage you will be switching? Is it going to switch AC or DC, and how many volts can it switch?

For example: if you need to switch 200 volts AC at 30 amps, then make sure the SSR you choose is rated in excess of 200 volts AC, and that it can also handle the 30 amps. The Arduino can source (provide) up to 40 mA output per pin, so if you purchase other SSRs, be aware of **the required switching volts** and **amps** to allow the circuit to function, and **ALWAYS** confirm these voltages before purchasing future SSRs.

Manufacturers often publish **data sheets** about their parts on the web as PDF documents. Most electronic catalogs also publish **absolute maximum ratings** in their catalogs.



Data sheets are technical specification sheets that list ratings such as absolute maximum voltage and amperage for the part.

Building the Circuit

To build the circuit, first unplug all the previous circuits you have been prototyping on your breadboard.

The SSR in your kit comes with a power cord and extension cord outlet already soldered. Look for the red wire into pin 1 on your microcontroller. The blue wire goes into ground.



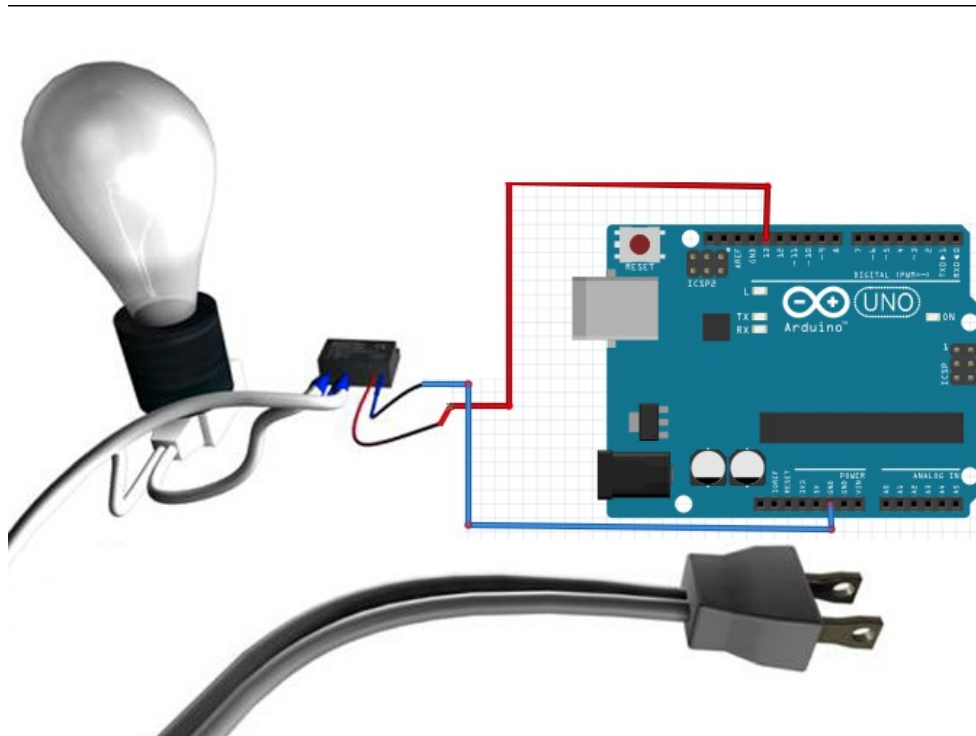
Warning! AC can KILL you. Handle AC with care and be around to celebrate your inventions. Always unplug and turn off any circuitry you are working on. Double check that you have the AC extension cord unplugged when you are screwing in your AC bulb and building and programming this activity.

Parts Required

One solid-state relay with extension cord soldered in line with the SSR. Parts supplier Jameco's part number is 176698CG and the manufacturer's part number is (KYOTO) KB20C06A-R. One AC socket with plug soldered in line and attached. Your local hardware store is the best source for a 100-watt AC bulb. Keep in mind that as bulbs are now changing from filament-based incandescent to LED and fluorescent bulbs, the ability to switch them off and on quickly is limited and can damage the circuit and bulb.

To create this project using the Arduino, you can use the same pinout and lesson plan described in activating an LED out of pin number 13. The circuit design for the Arduino UNO should work just fine.

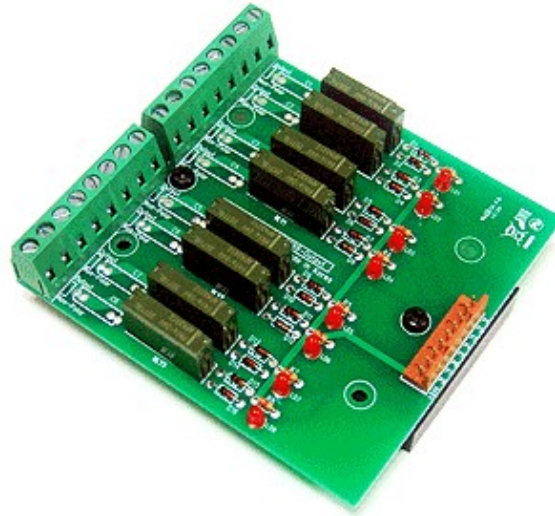
If you look carefully at the SSR, you can see the extension cord, and you can see that the device is just acting as an LED switch to allow the AC to be activated and turn the light bulb on. Of course, the AC cord is providing the power for the bulb, and the Arduino is providing power for the LED inside the solid state relay.



Solid-state relay with light socket and light bulb

You can also purchase relatively inexpensive solid state relay boards that can be driven directly off the Arduino UNO, such as one from Comfile Inc. Keep in mind that with a board like this you would then

have to dedicate 8 output lines to drive 8 loads; however, you can still use just 1 or 2, or as many as 8, of these SSRs if you need for your application.



Relay 8 Board — 5A MATSUSHITA PA Relay — DIN-Rail Attachable. User manual can be found online at comfiletech.com.

You can use an array to control the sequence of the SSR:

```
/* Arrays — Demonstrates the use of an array to hold pin numbers in order to iterate over the pins in a
sequence. Lights multiple LEDs in sequence, then in reverse. Unlike the For Loop tutorial, where the pins
have to be contiguous, here the pins can be in any random order. The circuit: LEDs from pins 2 through 7
to ground. created 2006 by David A. Mellis, modified 30 Aug 2011 by Tom Igoe. This example code is in
the public domain. http://www.arduino.cc/en/Tutorial/Array */
int timer = 100; // The higher the number, the slower the timing.
int ledPins[] = {
  2, 7, 4, 6, 5, 3
}; // an array of pin numbers to which LEDs are attached
int pinCount = 6; // the number of pins (i.e. the length of the array)
void setup() {
  // the array elements are numbered from 0 to (pinCount - 1).
  // use a for loop to initialize each pin as an output:
  for (int thisPin = 0; thisPin < pinCount; thisPin++) {
    pinMode(ledPins[thisPin], OUTPUT);
  }
}
void loop() {
  // loop from the lowest pin to the highest:
  for (int thisPin = 0; thisPin < pinCount; thisPin++) {
```



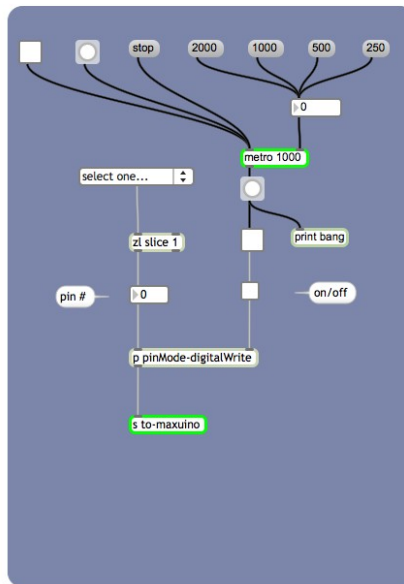
```

digitalWrite(ledPins[thisPin], HIGH);
delay(timer);
digitalWrite(ledPins[thisPin], LOW);
}
// loop from the highest pin to the lowest:
for (int thisPin = pinCount - 1; thisPin >= 0; thisPin--) {
  digitalWrite(ledPins[thisPin], HIGH);
  delay(timer);
  digitalWrite(ledPins[thisPin], LOW);
}
}

```

Using MAX MSP and Jitter to control an SSR: code for running the SSR is going to be the same as running an LED. Remember to use the MaxuinoSimpleStart patch covered in Chapter 6.

Digital output from a single pin that you select and using messages to stop, create a 2 second and 1 second and 1/2 and 1/4 second pause or flash rate



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Maxuino/Arduino Passive Infrared Sensor

A wonderful pyroelectric sensor device that detects motion by measuring changes in the infrared (heat) levels emitted by surrounding objects is the PIR sensor. It can be used for sensing out to a distance of 30 feet down to a few feet. The PIR (passive infrared sensor) is best used on a platform or artworks that are not moving, as it senses by imaging infrared light emitted, and when it detects a change in infrared quanta, it switches high at 5 volts.

They are robust and easy to use, though they can also switch off and on quickly, so sometimes software filtering is a good idea.

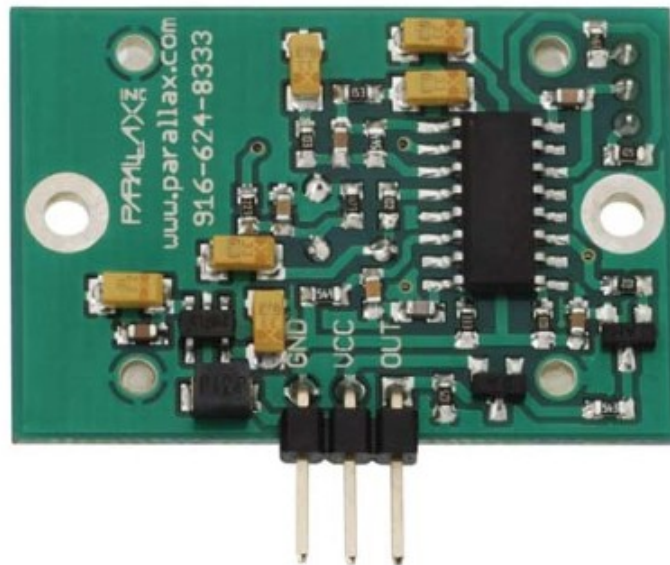
They have a longer detection range, selectable by an on-board jumper, and a wider supply voltage that can range from 3 to 6 VDC.

The PIR Motion Sensor — Features:

Detect a person up to 30 ft. away, or up to 15 ft. away in reduced sensitivity mode • Jumper selects normal operation or reduced sensitivity • Source current up to 12 mA @ 3 V, 23 mA @ 5 V • Mounting holes for 2-56 sized screws • 3-pin SIP header ready for breadboard or through-hole projects

You can find the PDF data sheet [here](#).

PIR sensor



Notice pins (GND, VCC, and OUT). VCC goes to Voltage + and OUT to the signal input.

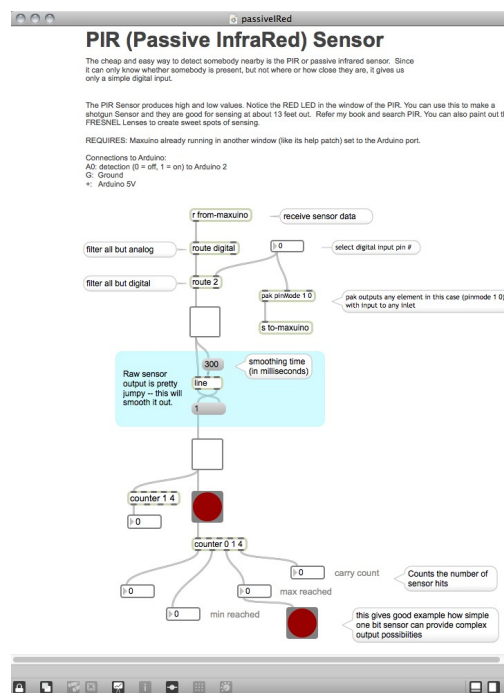
You would attach this sensor exactly as if you were attaching an input switch to your Arduino UNO microcontroller, and therefore you can use the Button code provided in the Arduino Examples below.

/* Button — Turns on and off a light emitting diode (LED) connected to digital pin 13, when pressing a pushbutton attached to pin 2. The circuit: LED attached from pin 13 to ground; pushbutton attached to

pin 2 from +5V; 10K resistor attached to pin 2 from ground. created 2005 by DojoDave
<<http://www.0j0.org>>, modified 30 Aug 2011 by Tom Igoe. This example code is in the public domain.

```
*/  
const int buttonPin = 2;  
const int ledPin = 13;  
int buttonState = 0;  
void setup() {  
  pinMode(ledPin, OUTPUT);  
  pinMode(buttonPin, INPUT);  
}  
void loop() {  
  buttonState = digitalRead(buttonPin);  
  if (buttonState == HIGH) {  
    digitalWrite(ledPin, HIGH);  
  } else {  
    digitalWrite(ledPin, LOW);  
  }  
}
```

Maxuino code for driving a PIR on the Arduino UNO:



Copyright Ken Rinaldo.

Instructions on Modifying Hardware to Make a Shotgun PIR Sensor

You can change the area of sensing that the PIR can see by modifying the PIR with a thin tube or by painting portions of the Fresnel lens.

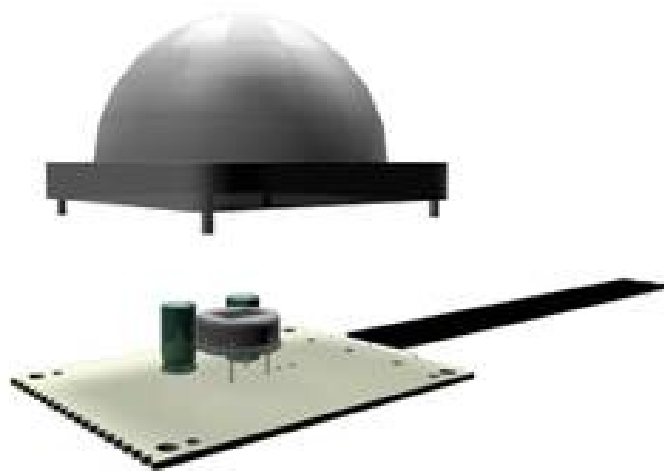
Modifying the PIR Sensor

In this activity, you will turn the PIR sensor into a shotgun sensor. The PIR, with the Fresnel lens, allows you to mount this sensor on the ceiling and see in a full 360-degree area. However, what if you wanted to sense in only a 180-degree area? Well, one trick is to paint out portions of the Fresnel lens to create mini sweet spots where the sensor can see vs. where the sensor cannot see. For example, in order to allow it to see only 180 degrees, you would paint out half of the sensor. I recommend white acrylic paint for this, and make sure it is thick enough to block the infrared heat from your infrared sources. You can also change the sensor into a shotgun sensor by putting a piece of brass tubing 3/4 inch long over the heat sensor.

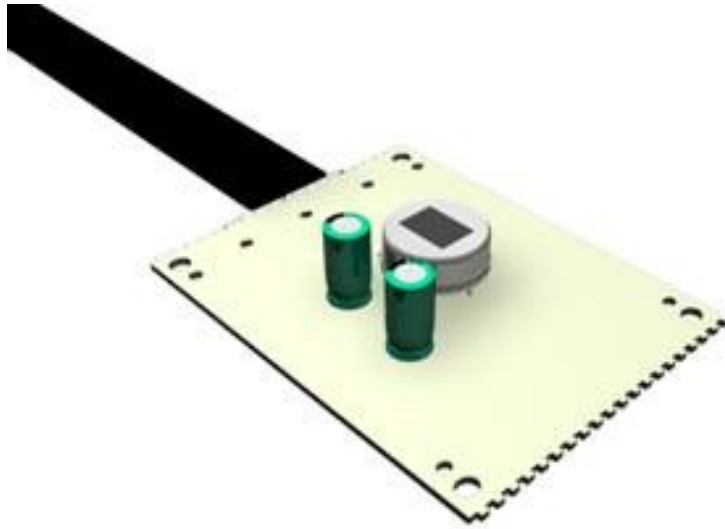
Parts Necessary

One PIR sensor and one small brass tube (step tubing). These sensors can be purchased from Amazon, which now stocks many more electronic parts than in the past.

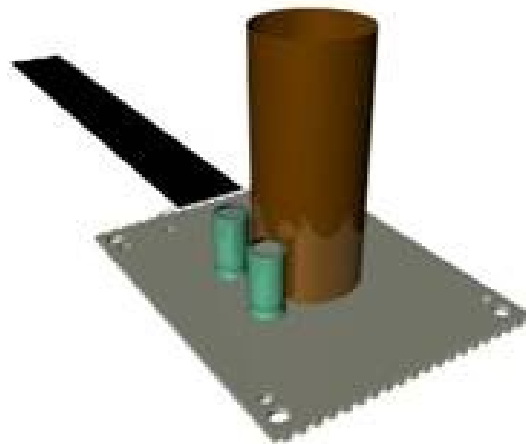
Carefully remove the Fresnel cap that is covering the sensor. You will notice a round can-shaped form with a rectangular window. Notice, as well, the capacitors on each side.



Fresnel lens coming off the PIR sensor. Model by Jessica Miller.



PIR sensor revealing heat sensor and two capacitors. Model by Jessica Miller.



PIR sensor with a small tube one inch long cut to fit over the cover of the sensor. It must slip over the sensor can; be careful not to use glue here, as it can creep onto the sensing window of the PIR sensor.

In order to see how the Fresnel lens sees light, try this experiment:

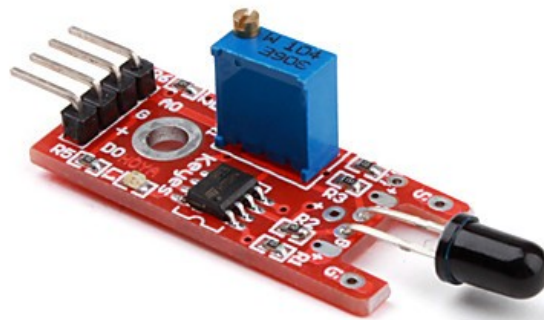
Take the Fresnel lens, put it over your eye, and turn your head while looking at a light source. Notice how the light jumps from one window to the next in the lens? When the lens is attached to the sensor, this is how it is imaging infrared heat onto the can-shaped pyroelectric sensor inside. Place the small tubing that came with your kit over the top of the sensor. Now run the program entered above and

notice how the sensor will only sense in a narrow beam where your tube sensor is pointed. Remember to give the sensor 25–40 seconds to warm up.

Maxuino/Arduino Flame Sensor

A flame sensor can be used to sense a flame and is a high sensitivity IR receiver.

Extremely sensitive to wavelengths between 760–1100nm • Power supply indicator lamp • Comparator output indicator lamp • AO, real-time thermistor voltage signal output • DO, high/low electric level signal output • Analog quantity output • Threshold rollover electric level output • Threshold adjusted by potentiometer • Detection angle range: about 60 degrees • Power supply: 0–15 V DC • Hole inner diameter: approx. 3mm • Size (L x W): approx. 36 x 16mm



Flame Sensor

Arduino Code for Flame Sensor

```
/* fade2 — This program is similar to the fade sketch; however, the brightness of the LED is
proportional to the intensity of the IR source on the phototransistor. */
int ledPin = 9; // the PWM pin that the LED is connected to
int photoCktVinPin = A5; // analog input pin used for phototransistor circuit Vin
int brightness = 0; // map value between phototransistor input and LED output
const int backgroundIROffset = 20; // helps remove some background IR sources
void setup() {
  pinMode(ledPin, OUTPUT);
}
void loop() {
  // read in the phototransistor circuit Vout level
  brightness = analogRead(photoCktVinPin) + backgroundIROffset;
  // map value to LED brightness scale
  brightness = map(brightness, 0, 1023, 255, 0);
  // set PWM value for LED source
  analogWrite(ledPin, brightness);
}
```


Flame Sensor

The Flame Sensor produces....

REQUIRES: Maxuino help patch or MaxuinoSimpleStart already running in another window.

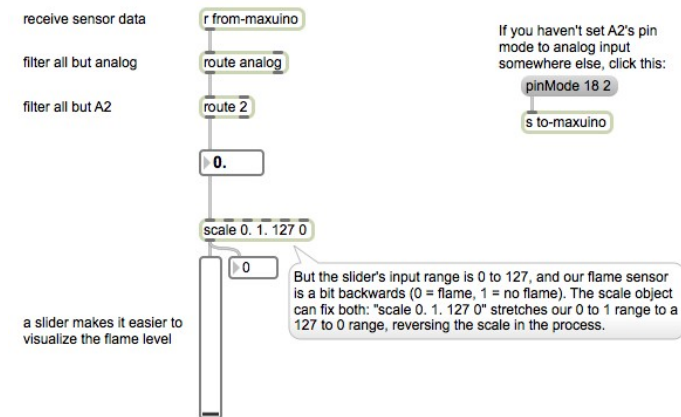
Connections to Arduino:

A0: Flame detection (0 = flame, 1 = no flame) to Arduino A2

G: Ground

+: Arduino 5V

D0: Unused



MAX MSP lessons continue in Chapter 10.

IO-204 IO Bridge: Web Connected/Activated Microcontroller

A really neat board that I have seen demonstrated by Amy Youngs is the IO-204 [IO Bridge](#). The board connects to the web and creates a network connection, DHCP transaction, starts DNS resolution, looks for a gateway, and authenticates the connection.

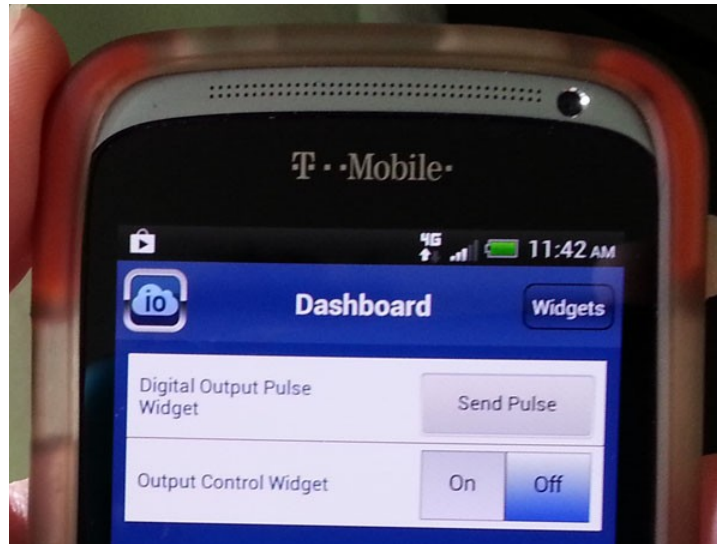
The IO-204 bridge can be networked with a 10/100/1000 DHCP wired Ethernet network. It has four I and O channels of analog/digital input and digital output pins.

Amy Youngs used this to attach to her Museum for Insects for a web-activated and viewed cricket world. In this case, she used a small relay, though not a solid state relay — the relay she used was a 5-volt [reed relay from Radio Shack](#).



Four channels: Analog Input, Digital Output, Digital Input. Power: 5 VDC, 500 mA. The board has a nice tutorials section.

Using a phone to control the relay board from the IO Bridge. Using digital output from the board, Amy Youngs hooked up a Radio Shack reed relay and drove a 3-volt output to drive a servo motor attached to an artificial cricket.



With this input and output board controlled via the phone, you were able to control both the turning of the cricket as well as switch miniature spotlights off and on in the museum. You can learn more about the project [here](#).



Museum for Insects by Amy Youngs. Installation of interior works by Ken Rinaldo.

For the first exhibition, Amy Youngs invited the author to populate the museum with rapid prototyping works such as the Rodeo Cricket in the foreground, the legs mobile, and the cricket jungle jim to the right side. You can see what the installation looked like in the first exhibition [here](#).

Amy also used a webcam so people from afar could peer into the Museum for Insects from anywhere on the WWW, as well as from their mobile phones.



Photo of cricket in process in Amy Youngs' work.

Summary & Conceptual Readings

In this chapter, you have used a 5-volt DC voltage PIR sensor to control a solid-state relay that switched an AC voltage on and off. Given the proper SSR, you will now be able to switch high voltage motors, lamps, and other AC devices with the Arduino, ESP32, and other microcontrollers.

Remember to always check data sheets to confirm that the parts you select will work with what you are switching. You have applied a passive infrared sensor while learning about the way the PIR sensor images on the sensor window and how you can manipulate this by either painting out the Fresnel lens or by using a small tube to limit the sensing area. You have also learned that a simple one-bit PIR sensor can still provide rich interaction based on certain counting subroutines that will allow your program to conditionally branch to new locations in your program.

You have learned about a variety of projects where artist inventors have used electromagnetic and solid state relays. In David Foster's and Carl Bailey's work, solid-state relays were used to activate AC lamps rapidly, and passive infrared sensors triggered both. In Reva Stone's work, active infrared sensors activated electromagnetic relays, and in Nell Tenhaaf's work, passive infrared sensors were used to advance video sequences. In Bill Shackelford's work, he used a microcontroller interfaced to the WWW as input to a solid state relay as output to inflate a large balloon. In Cesar Martinez's work, the simple action of powerful AC blowers can activate emotionally moving figurative forms.

Further Investigation

Many electronic kit suppliers carry relay boards that have multiple SSRs onboard. For example, the neon artist Michael Hayden controls much of his neon utilizing solid state relays designed to switch the primary of the transformer.

Many suppliers also carry kits with electromagnetic relays onboard. Some of the larger suppliers are: a1parts.com (Canada) and electronics123.com (USA).

Conceptual Readings

"Resurrecting the Technological Past: An Introduction to the Archaeology of Media Art," Erkki Huhtamo: http://www.ntticc.or.jp/pub/ic_mag/ic014/huhtamo/huhtamo_e.html

"Seeking Deeper Contact: Interactive Art as Metacommentary," by Erkki Huhtamo: <http://www.kenfeingold.com/seekingdeeper.html>

Chapter 10

Mobility: Servo Motors and Positional Control

Mobility: Servo Motors and Positional Control

"You're walking and you don't always realize it, but you're always falling. With each step you fall forward slightly and then you catch yourself from falling. Over and over you're falling and then catching yourself from falling. This is how you can be walking and falling at the same time."

— Laurie Anderson

Question: Are there positional motors that can be easily controlled by a microprocessor?

Mobility

Humans seem to take their mobility for granted. From our youngest years, we instinctively learn to grasp objects and we begin to distinguish our own bodies from the external world. Without a thought, we reach out, grab objects, and begin to manipulate and shape the world around us.

[Gunther von Hagens](#) has invented a plastination system that allows you to see the amazing distributed nature of the muscular and vascular systems of the human body. He uses actual human bodies and plasticizes them, a process that coats and preserves the tissue. The techniques used and the poses Professor von Hagens selects have many of these scientific works residing comfortably in the realm of art.

Humans have evolved complex neurological and musculoskeletal systems that allow us to take action quickly and fluidly. Not to say that our conscious actions are always intelligent, but our cells have another kind of intelligence.

The distribution of oxygen and nutrients to the heart, as well as to the leg muscles that allow us to walk, have been relegated to the **autonomic nervous system**. For walking (or falling), our legs do not need to receive step-by-step instructions, though certainly as infants, our cells need to learn to walk.



The **autonomic nervous system** controls involuntary muscle movements in the body.

The evolution of the neuromuscular system for mobility, as well as distribution of oxygen and nutrients through our vascular systems, has allowed humans to focus on higher thoughts while our autonomic nervous system buzzes along in the background.

The science of *biomorphic engineering* allows researchers to understand, model, and mimic animal locomotion, adaptation, learning, and perception. These lessons are then utilized in technological systems.

Artists and engineers have been working for a long time to understand and mimic these living system models, and figurative art from our earliest human ancestors could be thought of as a formal variant of biomorphic engineering research. A relatively new variant is *behavioral mimesis*. Behavioral mimesis is the study of animal behavior and the symbolic representation of it in art and literature.

Some robots utilize microprocessors and actuators to mimic these animal perceptions and actions. Some of these systems learn to adapt to their environments utilizing artificial life techniques, such as the Autotelematic Spider Bots (2006) by the author.

Other formal variants of machine nervous systems can be seen in work like Tim Hawkinson's *Organ* (1977). In this work, a deconstructed organ reveals the wires remaining after all the supporting material and keys were removed. It created a wonderful analog of a biological nervous system.

The contemporary artist [Bill Vorn](#) has created an interactive sculpture installation entitled *STÈLE 01*. The installation utilizes artificial life concepts and is composed of many systems and subsystems working in parallel. When heat sensors that sense humans activate the work, an anthropomorphic robotic form stands up while covering its face with its hands. Video imagery of human death is projected on the mosaic of Stèle's body, which at times reflects the images onto the audience and at times receives the image on the revolving plates (mini screens) that constitute the body. Mortuary steles from Père Lachaise's Cemetery in Paris inspired *STÈLE 01*, and the work is designed to evoke a "dichotomy between the real and the virtual, life and death, movement and inertia, men and machines."



STèle 01 by Bill Vorn. 2002. Montreal, Canada.

In this installation, Vorn used 32 microcontrollers to control very accurate positional motors called stepper motors. Stepper motors have multiple coils, which makes them extremely accurate, and can turn a full 360° continuously in either direction, as well as stop instantly.

Stepper motors differ from the servo motors you will be learning to use later in this chapter because they lack an internal position encoder, which is an integral part of servos. The encoder enables you to send a simple signal from your microcontroller to rotate the servo to a specific position. Servos are not as accurate as stepper motors, though for their size they have a lot of torque.

Artist's Inventor Applications of Servo Motors

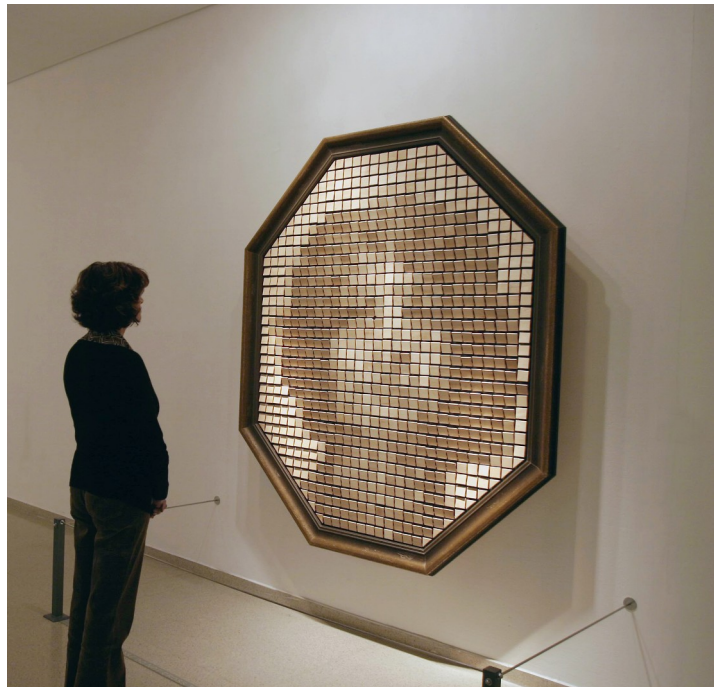
In Jen Hall's work *Acupuncture for Temporal Fruit*, twelve bell jars covering tomatoes are suspended from the ceiling. When a sonar sensor is triggered by human presence, acupuncture needles pierce the delicate red tomatoes under the glass. The needles are pushed forward using servo motors, which receive signals from a microcontroller.

Acupuncture for Temporal Fruit by Jen Hall, engineering by Kyle Jarger. 1999.

After being pierced, the tomatoes leak, shrivel, and grow delicate molds around the wounds. Hall says about the work, “they are slaves to a repetition and compulsion.” For Hall, this work is a metaphor for the issues surrounding our medical system, technology, and ethics.

In this installation, the artist has re-contextualized the acupuncture needle (an instrument of healing) into a sinister weapon. While the machines appear clean and clinical and carry the language of the “rational sciences”, the piercing action alludes to torture, pain, and death, and the viewer/participant becomes complicit in causing the needles to hurt these passive objects. The tomatoes also serve as metaphors for the delicate human body.

The contemporary artist Daniel Rozin created a wooden “mirror” that recreates the face of the viewer using hundreds of servo motors to micro-position small pieces of wood. The motors work in concert with a camera and a computer that reads the average light levels of the image. It is then able to move the wooden pieces toward and away from a light source.



Wooden Mirror by Daniel Rozin. 1999. 61" x 70" x 8".

This positioning creates light and dark pixelated images of what the camera sees. The sound of the wooden pieces being moved into position is an important component of this work.

The designers Amanda Parks and Hayes Raffle from the Tangible Media Group at the MIT Media Lab have invented a set of 3D building blocks that use servo motors in a unique fashion. Instead of programming the motors to move, they invented a toy that allows you to construct your own Topobo creature and then program the work simply by moving the individual blocks. As you move the blocks, pulses of the motor are fed back to a microprocessor, and this movement is then stored as pulses that are replayed to the servo motors in the sequence that they were originally moved.



Topobo by Amanda Parks and Hayes Raffle. 2003.



Topobo by Amanda Parks and Hayes Raffle. 2003.

This clever interface allows users to realize complex behavioral manifestations for Topobo while not having to enter software code.

Artist's Inventor Applications of Servo Motors, Continued

[Jeremy Boyle](#)'s *Gravity* (2002) is a video piece consisting of a small LCD screen mounted to a small motor. A motor rotates an LCD screen in semicircular arcs, first clockwise and then reverse to counterclockwise.



Gravity by [Jeremy Boyle](#). 2002. 4h x 6 x 2 1/2 inches.

Playing on the LCD screen is a video of the horizon line of the water tilting from left to right. Boyle created this by rotating the video camera left to right when the video was made. The motor moves accurately under the control of a microcontroller, and its resulting movement cancels the tilt in the horizon line of the video, thus leaving the surface of the water to always remain horizontal. The two images show the video and motor at different moments of equal though opposite rotation.



Gravity by [Jeremy Boyle](#). 2002. 4h x 6 x 2 1/2 inches.

Artist Jessica Miller created an experimental musical sculpture entitled *Aquasiter*. The work used five servo motors, a special servo motor controller, and an active infrared sensor. When the viewer placed their hand underneath the work, they were able to control the movement of the individual servo motors as they struck the glass elements filled with water.



Aquasiter by Jessica Miller, 2002. Photo Amy Youngs.

By filling the glasses with varying amounts of water, Miller was able to allow different pitches of sound to exist, and the interaction prompted the participants to compose their own sound sequences.

Miller's piece is part of a large community of artist/inventors creating experimental make-your-own/play-your-own musical instruments. The sculptural qualities and interactive aspects of this sound piece were an important part of its success.

A key resource for anyone interested in creating experimental musical instruments is Bart Hopkin's *Musical Instrument Design*.

Servomotors

Those who have played with radio control cars or planes might be familiar with servo motors.

They are used in the special effects industry, and they are popular with artists, puppeteers, and inventors for their ease of use in the creation of interactive sculpture, inventions, and environments. Servomotors are motors that can be easily positioned because they possess a simplified feedback mechanism that allows them to have a sense of their rotational location in space. They consist of a plastic case, DC motor, output shaft bearing, potentiometer, electronics, and a gear train. There are varieties of servos with metal gears and some with plastic gears, and, of course, the metal gear servos will last longer and be more robust.



Servomotor

The intelligence of a servo motor is the feedback from the potentiometer, which allows the microcontroller to tell the motor where to go with a command. The motor will go to that position and stay there as long as that position command exists and is asserted by your microprocessor.



Servo motor deconstructed, showing the potentiometer and gears. The pot is the encoder for the motor.

The common servo motor will rotate from 0–180°, and using the microcontroller you can turn it rapidly in either direction, as well as step degree-by-degree. Servos use a voltage in the range of 4–6 volts. To make a servo hold its position, a pulse must be sent to instruct it to stay in that desired spot.

You communicate the angle that the servo rotates to by the *duration of the pulse* that is sent to the servo control circuit from your microcontroller.

In robotics, this is called **pulse width modulation**. A servo motor needs a stream of pulses in order to move. Every 20 ms, a pulse between 1 and 2 ms in length is sent to the servo. The length of the pulse allows the motor to turn to exact locations in relation to the width of this pulse. If the servo receives a pulse that is 1 ms in length, it will rotate to one extreme, and as the pulse width increases to 2 ms in length, it will move toward the other extreme.

For example, a 1.5 ms pulse causes the motor to turn to a 90° position. When the pulse is shorter than 1.5 ms, the control circuit will turn the shaft toward the 0° position. When the length of the pulse is longer than 1.5 ms, it communicates to the control circuitry to turn the shaft toward the 180° position.

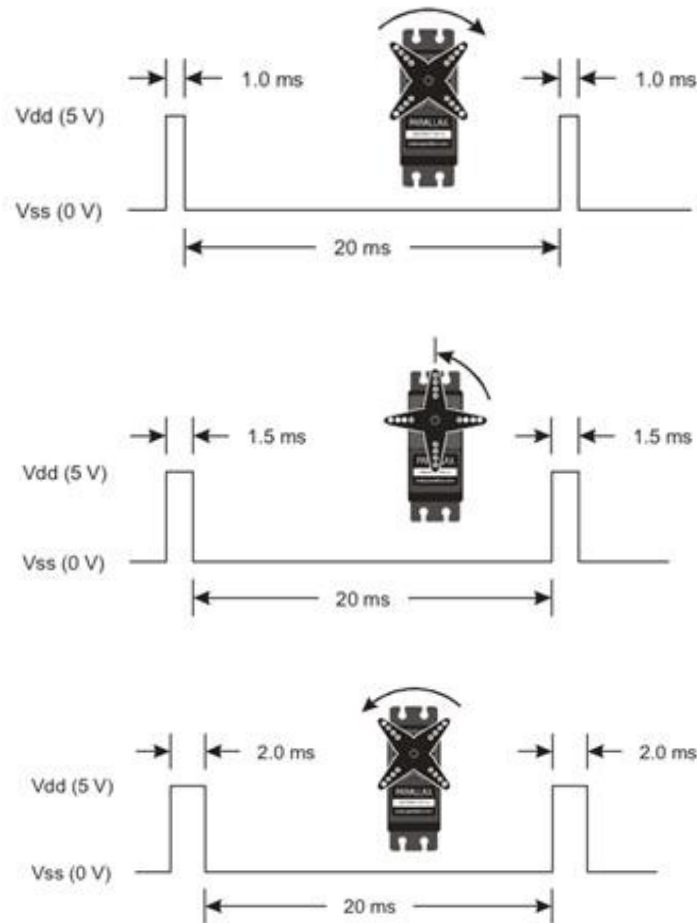


Pulse Width Modulation (PWM) is the process of changing the width of a pulse so it can control a device looking for that coded pulse.

On the Arduino and ESP32, you do not need to generate this precisely timed pulse train by hand — the Servo library takes care of it for you, letting you simply write an angle in degrees (as you'll see in the next section). Under the hood, the library is still generating exactly this kind of pulse; understanding the

underlying pulse-width relationship is what lets you debug a misbehaving servo or work with one that doesn't have a friendly software library available.

You can also purchase servos that have been modified to turn 360° in either direction, and these are used extensively in smaller mobile robotic platforms.



Servomotor. The pulse duration is proportional to the angle of the output shaft.

Servos are marvelous because they have high torque for their low cost. The more torque you get in a servo, generally the price will go up. It is also very easy to control many servos at the same time, as there are also dedicated servo motor controllers, which allow you to control up to 16 servo motors from a single microprocessor, or you can connect multiple servo controllers together to allow control of 32 servo motors.

Using a dedicated servo motor controller could be roughly analogous to the autonomic nervous system, in that these servo controllers can function in the background.

Maxuino/Arduino Controlling a Servo Motor

You can control a servo motor very easily with Maxuino running on your Arduino, or directly on an ESP32. You attach the servo motor exactly the same way as you would for controlling the motor directly from the Arduino IDE.

`/* Sweep — by BARRAGAN <http://barraganstudio.com>. This example code is in the public domain.
modified 8 Nov 2013 by Scott Fitzgerald. */`

`#include <Servo.h>`

`Servo myservo; // create servo object to control a servo`

`// twelve servo objects can be created on most boards`

`int pos = 0; // variable to store the servo position`

`void setup() {`

`myservo.attach(9); // attaches the servo on pin 9 to the servo object`

`}`

`void loop() {`

`for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees`

`// in steps of 1 degree`

`myservo.write(pos); // tell servo to go to position in variable 'pos'`

`delay(15); // waits 15ms for the servo to reach the position`

`}`

`for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees`

`myservo.write(pos);`

`delay(15);`

`}`

`}`

While the servo motor can be controlled very nicely from the Arduino IDE, it can also be controlled by Max MSP and Jitter talking to the Arduino through Maxuino.

On the ESP32, the same Servo library and the same write()-in-degrees approach works, though you should confirm which GPIO pins on your specific board support the PWM channels the library needs before wiring your servo's signal line.

Copyright Ken Rinaldo.

MAX MSP lessons continue in Chapter 11.

Summary & References

In this chapter, you have come to realize that the control of a biological system is dependent on a number of intelligent and self-functioning subsystems to allow life to exist as we experience it. The works of Gunther von Hagens serve to illustrate and demonstrate this complex interaction of multiple subsystems of living system functionality through his method of plastination. In the work of Bill Vorn's *Stèle 01*, you have seen how the application of hundreds of servo motors can control and permit an immersive and projected environment. In the work of Jen Hall, you have seen servos used to delicately position needles to challenge notions of tenderness and care. In Daniel Rozin's *Wooden Mirror* (1999), you can see how servos can be applied to making new kinds of reflections mediated through light and motor. In the work of Amanda Parks and Hayes Raffle, the motor was used both to program and activate their creatures, and in the work of Jessica Miller, the servo motor is used to make an interactive sound work.

Further Conceptual Reading

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- [5] Amanda Parks and Hayes Raffle, *Topobo* (2003).
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- [7] Miller, Jessica. Artist's collection; photo compliments of Amy Youngs.

Chapter 11

Sound: Aural Environments and Sonic Invention

Aural Environments

“There is no such thing as an empty space or an empty time. There is always something to see, something to hear. In fact, try as we may to make a silence, we cannot.”

— John Cage (1912–1992), avant-garde composer

Question: Is there a method of adding emotion and voice to works of art and invention?

Humans have been using sound in rituals and performances long before written history. The San Bushmen in the Kalahari region in southern Africa are some of Africa's oldest inhabitants, having lived in the region for 25,000 years.

The San people are nomadic hunter/gatherers and they make their own instruments. They tie the wet skin of a Springbok's thigh over the mouth of a pot and use a sinew to hold it in place, which allows them to pull the surface of the drum tight. They create rattles from the Springboks' ears and tie these to their feet for dancing. For the San people, music and drumming rituals are a part of life and provide a place for dance, ritual, and celebration.

Sound connects to a primordial element of the human animal that reaches back before language. In the contemporary world of media art, sound has become an important component and is used as feedback in devices, as a central element in installations, or as a platform for experimentation with new forms of instruments and in sculptural and sound narratives. There is now a very large community of experimental sound artists, as well as those creating unique instruments. In this chapter, we will look at a few of the artists exploring the field and then move into some lessons on how to apply and control sound. In the closing of this chapter, other resources will be explored.

[John Cage](#) (1912–92) is well known for his experimental music, particularly the piece 4'33", where the performer walks onto the stage and is silent for four minutes and thirty-three seconds, allowing the listeners to hear the ambient sounds of the room and perhaps meditate on their own personal states. Cage is also known to modify instruments to change their pitch and timbre. He has performed songs on a piano with erasers, nuts, and bolts placed on the strings in order to change the sound into something completely different. He was the precursor to a host of conceptual artists who would think more about the ambient and experimental possibilities for reconfiguring the notion of sound and its relation to music and installation.

In [Nigel Helyer](#)'s work *Ariel*, eight laser-cut acrylic forms have digital Theremin circuits with amplifiers and speakers. Each form acts as an antenna and senses human proximity, varying the sound accordingly.



ARIEL by Nigel Helyer. 2003. In recounting his childhood, Nigel Helyer says: “My childhood village contained two significant buildings, significant not for their formal qualities—they were both simple cottages—but because one had been the home of Halley, the astronomer, and the other the home of William Blake, the poet. Without being conscious of the fact, I grew up in a cosmos in which the arts and science were intertwined; it has marked my endeavors ever since.”

These creatures were inspired by marine life, particularly the primitive and microscopic Radiolarians, the fossil forms of which are found in abundance in the crust of the Earth. Each object responds individually to viewers as they approach, but they also operate as a “swarm” through a form of electromagnetic coupling, producing clouds of audio “turbulence” as a visitor approaches the installation.

[Maywa Denki](#) is an art company that was formed in 1993 by Nobumichi Tosa and his brother Masamichi. Since the formation of their company, the two have created unconventional artworks that they refer to as “products” and installations and performances they refer to as “product demonstrations”. Maywa Denki describes their activities over the past eleven years as “The Nonsense Machines”, which aptly describes their Dadaistic approach to art-making, commenting on Japanese corporations and industry in much the same way Duchamp commented on Western industry.



Singing Robots Betty and Clara by Nobumichi Tosa. Prix Ars Electronica 2003. Photo Sabine Starmayr. Fishbone-shaped xylophone, which lights a bulb for each key you hit with 100V electric sticks. Equipped with a circuit breaker.

Nobumichi has attained true pop star status in Japan with his development of new types of musical instruments and his absurd music constructions, whereby mechanical instruments are played by electromagnets and motors. Maywa Denki was the name of his father's company, and Nobumichi is known for wearing the typical blue-collar working uniform worn in Japanese electric stores. Maywa Denki mass produces and sells small, affordable robots, ironically supporting the artist while making subversive comments about ubiquitous Japanese corporations and industry.

Artist's Sound Installations

[Paul DeMarinis](#) has been working with electronic composition and experimental musical processes since 1971. He has created performance works, computer installations, and sound works, and many of his works are inspired by historical inventions.

DeMarinis's recent work involves speech, which is processed and synthesized through computers. One series of DeMarinis's works uses lasers, optics, and computers to create new sounds by laser-scanning old gramophone records, wax cylinders, and holograms, and amplifying the light-modulated sounds.



RainDance Source by Paul DeMarinis. Photo Sabine Starmayr. Ars Electronica, 1998.

In the work *Raindance*, which I had the pleasure of viewing at Ars Electronica in 2001, twenty streams of water are modulated by proprietary electronic nozzles that respond to audio signals. The raindrops fall on the umbrellas provided for the visitors, who can stand under them and hear the water spray out the sound of the Blue Danube Waltz, an appropriate piece for the Austrian venue. The umbrellas actually act as speakers, and the tactile quality of the sound as it enters both your ear and hands is spectacular.

Rebecca Horn's art career spans over 30 years, in which she has worked in performance, installation, conceptual works, and feature-length films. Her work engages the intersection between the body and the machine, and she transforms and recontextualizes simple objects into new pieces, many with subtle sexual allusion.

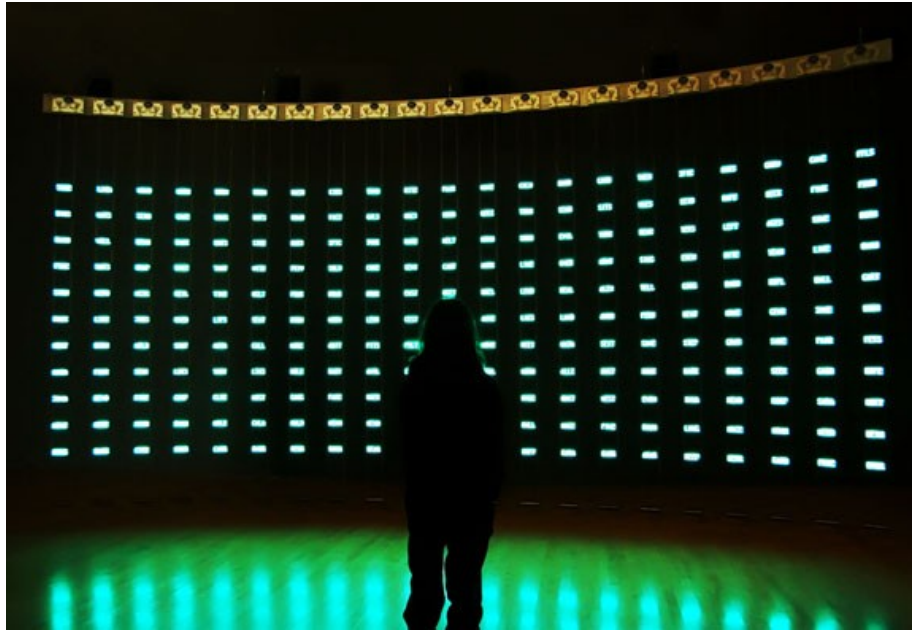


Bee's Planetary Map by [Rebecca Horn](#). 1998. Photo copyright Cynthia at Flickr.

Rebecca Horn has used the body as one of her main sources of inspiration and points of departure. For an extended period of time, she was confined to bed, which inspired her body extensions, sculptural prostheses, and, in some cases, cocoon-like garments that extend and constrict the body while also creating delicate appendages.

[Ben Rubin](#) and [Mark Hansen](#) have created a work called *Listening Post*, an installation that grabs text fragments from thousands of Internet chat rooms and bulletin boards. Using statistical analysis, the averages of the chat room texts are taken and collapsed into simple lines that are sung or read by a voice synthesizer and displayed across more than two hundred LED screens.

The work cycles through four movements with different arrangements of visual, aural, and musical elements. The work is very successful in dissociating the chat room communication from the conventional reception of the computer screen and instead placing it in a deeply moving sound space.



Listening Post by Ben Rubin and Mark Hansen. Photo by Fenchurch on Flickr.

Listening Post is a powerful visual and aural environment that speaks to the ubiquity and immediacy of the virtually thousands of chat rooms and bulletin boards it monitors. All the messages that appear in this installation are acquired and broadcast seconds before they would appear in a chat room and become reflections of the global communication of the web that is all around us. The statistical aspects of finding and collapsing the words and minds of hundreds of speakers is a poetic expression that makes reference to Roy Ascott's notion of a noetic network, or group consciousness, of the web.

Max MSP and Jitter Data Spaces and Sound

There are many other ways of interacting with data besides switches and sensors. Max MSP and Jitter is quite good at taking data and allowing artists to use that data to give feedback about the world, or universe, surrounding us.

New media artist [Nathaniel Hartman](#) has created a visually and sonically complex light work that is activated by pulsar data. The piece examines the timing of 96 rotating pulsars and displays this data as light and sound.



Extraterrestrial Origins of Pulsating Stars (2013) by Nathaniel Hartman.

LEDs inside tubes function as abstracted screen displays of either single stars as a pulsing wave or clusters of stars, which creates a cacophony of visual and sonic noise. The brightness of the tubes also varies with the stars' relative distance from Earth, which can give the viewer a sense of the distance of the pulsar.



Extraterrestrial Origins of Pulsating Stars (2013) by Nathaniel Hartman.

This installation creates a visceral, sensory experience for the audience with radiation to sound, sound to light, light to sensation as feedback about the nature of celestial pulsars.

Amplification Environments

Intra-terrestrial Soundings, by [Amy Youngs](#), is an installation that offers human participants an opportunity to tune into bodily experiences and vibrations made by tiny, soil-dwelling beings. Humans continue to be interested in detecting signals of extraterrestrial life in outer space but have overlooked the intra-terrestrial signals of life, such as worms and insects that sustain our own terrestrial existence. This highly amplified environment allows humans a chance to appreciate these extraordinary life forms through sound and infrared video.



Intra-terrestrial Soundings by [Amy Youngs](#), 2004. Artist/theorist Shannon Bell feels the vibration of the worms.

Human participants enter a gallery containing a worm box covered in soft artificial fur, wired to a chaise longue covered in vinyl. The participant/viewer, who sits or lies down on the chaise, experiences vibrations of the live sounds of the worm box, which are highly amplified and directed into eight speakers embedded in the chaise. Human participants are able to spatially locate the activity inside the worm box based on the location of the speakers just underneath them.



Intra-terrestrial Soundings by [Amy Youngs](#), 2004.

The viewers are able to “feel” the vibrations of the worms and other insects in the box, who are going about their regular activities of eating, moving, and making fertilizer.

An infrared camera inside the dark container feeds live, projected images onto the ceiling to provide viewers with visual confirmation of the life inside. Hopefully, this experience will give the viewer/participant a different sense of the life inside the earth, one that goes beyond the scientific and instead approaches something more akin to fellowship, communion, or appreciation.

Spatial and Sculptural Sound

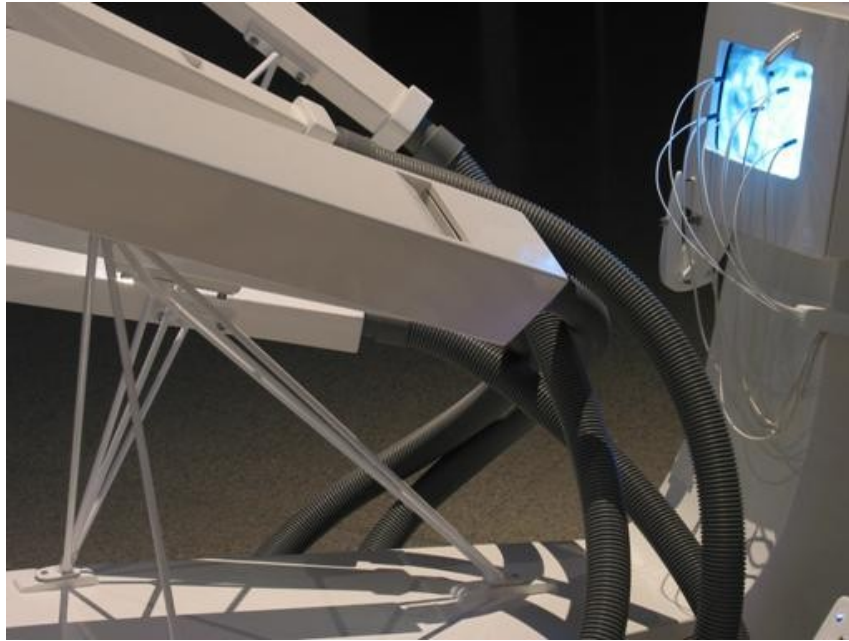
Spatial Sounds (100dB at 100km/h) is an interactive audio installation created by [Marnix de Nijs](#) and [Edwin van der Heide](#). This powerful and intimidating motor-powered installation consists of a rotating arm with a speaker mounted on one end and a counterweight on the other. When a person enters the room, the machine senses it, and the visitor can hear the engine slowly revving up, then swinging towards them at 100km/h in order to blast sounds at them at 100dB. At the same time, the installation is made more chaotic by a randomly flashing strobe light. The visitor is both drawn to the piece and repelled from it by its deadly swinging and deafening sounds, which are as intense as a freight train and eerily contorted by the Doppler effect.



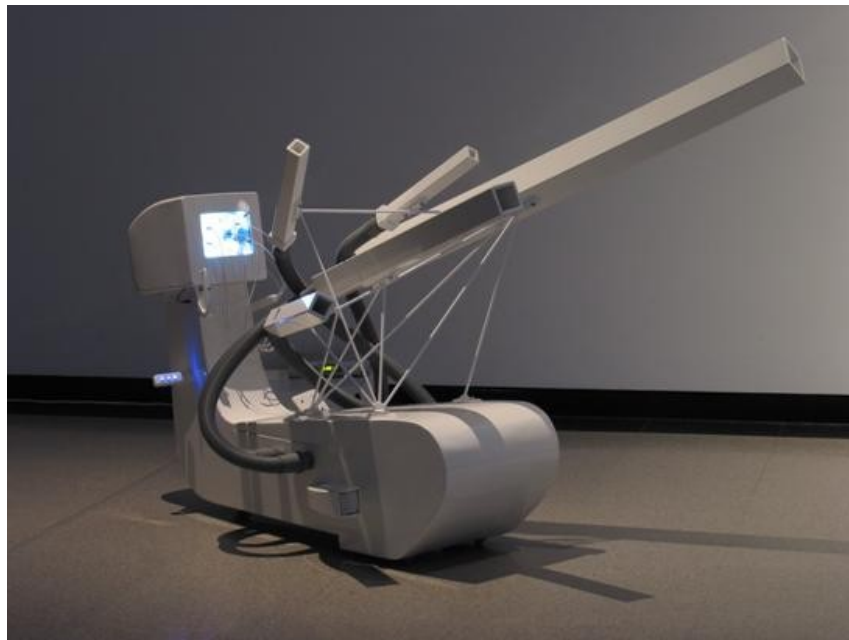
Spatial Sounds by Marnix de Nijs and Edwin van der Heide. Ars Electronica, 2000–2001.

As the machine slows down and the shock wears off, the viewer feels tangibly connected to the machine with the memory of their chest rumbling from the vibration of the heavy sounds.

[Bjoern Schuelke](#) has created an organ that uses photo resistors hooked up to the surface of a TV screen to sense light and trigger the organ to play. As the photo resistors are exposed to different content on the screen, they are activated or not activated, which causes relays to switch fan motors on and off and blow air through the pipes. The sound of the organ is mixed naturally with the sound coming from the TV, which creates a very humorous collage of sounds and pokes fun at the dramatic content you see streaming through the TV tube.



Orgamat by [Bjoern Schuelke](#). 2003, 170 x 90 x 120cm.



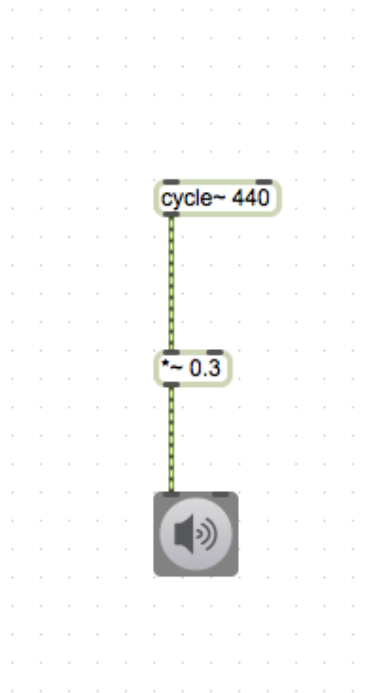
Orgamat by [Bjoern Schuelke](#). 2003, 170 x 90 x 120cm.

The work is constructed with white fiberglass over plywood, and an important component of the work is a large couch (not shown), built in the same style as the organ, and a TV remote that allows the viewer to switch the channel and therefore change the sound that will be created by the piece.

Max MSP and Jitter: Basic Tones with cycle~

With Max MSP and Jitter, you can generate tones quite easily with a few simple objects such as the cycle~ object, *~ (multiplier object), and the ezdac~ object. Random can also add some fun, as you will discover.

Create the patch below. This includes the sinusoidal cycle function placed in a function object with the tilde ~, telling Max to generate a tone, and the 440 frequency itself, which will be 440 Hz per second.



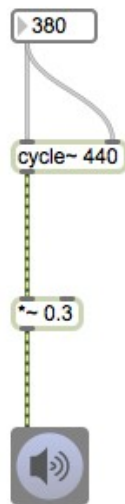
Notice how the patch cords are striped to indicate the signal coming through?

Now be sure to activate the tone by choosing this from the options menu and choose Audio Status to get the controls over the ezdac~ object. Activate the audio, choose your proper driver selection, and you should hear audio.

Now let's create a simple synthesizer.

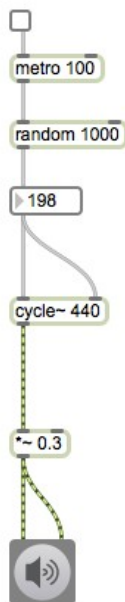
Take this same patch and add a number box above the cycle~ 440 object, and attach both to the inlets of the cycle~ object; you can then change the tone.

Now change the number box and notice how the tones change. Can you create many tones at one time? What happens if you attach a patch cord from the *~ 0.3 object to the second inlet of the ezdac~ to the right? Attaching the second outlet to the inlet of the ezdac~ allows you to get stereo output.



Now for fun let's add a random object and a bang to change the random object. Notice that it will choose frequencies that are beyond your ability to hear, below certain really low tones? Use random 1000 to skew the number toward the high end, and also add a button to create a bang.

Pretty fun to create a dynamic synthesizer that is randomly oriented. Can you think of a way to automate that process? What about a metronomic device or function? Let's try that. Add a toggle and a metro 100 to keep the pace going.



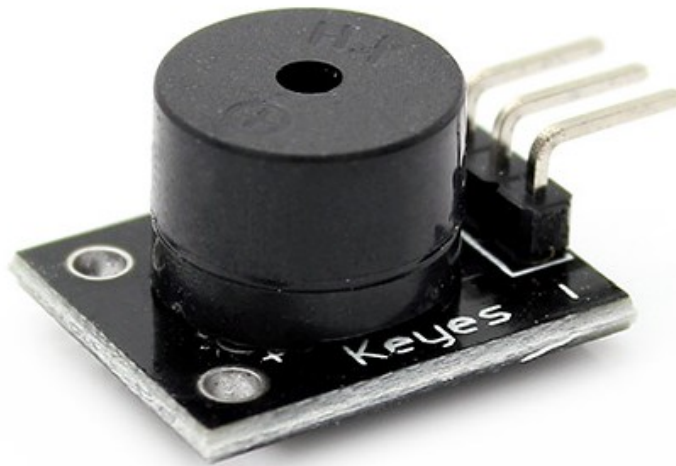
Now try to add another random function to your random code and duplicate this across a number of patches. You are ready for your auto-generative sound premiere.

How might you attach this to physical switches, or the real world of touch, to the world of sound?

Maxuino/Arduino Buzzer (Keyes 006)

Not nearly as sophisticated, though a good beginning with Maxuino and sound, is the Keyes 006 buzzer, which is suitable for making warning sounds. They are used in alarm systems, though at screaming decibels. This one will be more quiet with the Arduino UNO driving an analog voltage.

If you want to replicate the more complex sound in the previous patch, you can use an amplified speaker or the speaker directly from your computer, as opposed to this limited-range piezo speaker.



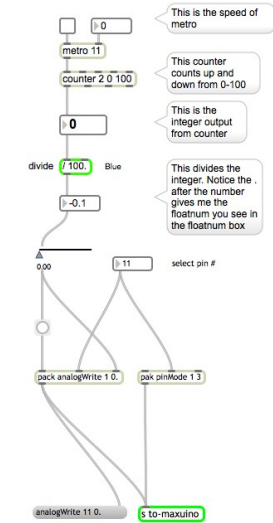
Keyes 006 Buzzer

Notice how, when you use the slider in the patch below, the tone does not change much, though the volume does change.

Buzzer module KY-006 / 8550 transistor

This buzzer can output sound though not a high fidelity as it has limited range.IT is suitable for PC, printer, car audio systems

- pin to GND,
a pin to digital or analog output
Middle pin to 3.3-5V +



Analog output for buzzer to change volume. Copyright Ken Rinaldo.

Max MSP Jitter, Kinect & Bodysynth

Artists have been defining, hacking, and creating interfaces since the beginning of musical instrument design, and there is a strong international acoustic and experimental musical instrument design movement. As with acoustic instruments, artists are also experimenting with high tech material and processes and help to define and redefine the interface. The artist [Trademark Gunderson](#) is known for hacking Wiimote controllers with his *Thimbletron*.

Trademark Gunderson, a musician and founder of the band The Evolution Control Committee, is a culture jammer, equipment designer, software designer, and is known for his copyright-challenging stance, using found sounds to construct sonic and culture jamming mashups.



Trademark Gunderson with the Thimbletron system for composing live digital sound.

Later in this chapter, Trademark shares some MAX MSP code on making a Kinect-based Theremin.

The artist/musician [Pamela Z](#) has performed using a BodySynth™, a MIDI controller that uses electrode sensors to translate her physical movements into sound and image installations. Pamela Z is a composer/performer and audio artist who works with voice, electronic processes, and sampled sound. Her performances are layered with sound that is operatic bel canto at times, mixed dynamically with experimental vocals.



Pamela Z by Lori Eanes, 1998.

She uses digital delay devices with found percussion sounds, along with digitally sampled sounds that are triggered with the BodySynth, which takes analog input from electrode sensors she wears on her skin, and this generates MIDI signals, which trigger the sounds.



Pamela Z, photograph by Donald Swearingen. 2003.

The BodySynth was designed by Ed Severinghaus and allows gesture and performative action to trigger and combine Pamela Z's sound fusions, resulting in spiritually charged and organically activated performance installations.

Kinect with the Macintosh

There are also wonderful ways to work with MAX MSP in order to create generative sound. One of the masters in this regard is composer and artist of real-time composition Karlheinz Essl, who has created a significant software library for algorithmic composition.



Professor Essl presenting his ideas and software to a class.

His patches and externals for Max/MSP offer the possibility to experiment with serial procedures, permutations, and controlled randomness. Most of his patches are focused on straightforward processing of data, and using these objects makes this kind of composition more fun. Professor Essl has provided many functions for algorithmic composition, and therefore artists, composers, and sound hackers can concentrate on play in the making of composition versus more complex programming tasks.

Trademark Gunderson recently completed a [Kinect Turntable hack](#) video. Below is the work at the *Extract Exhibition*, an Art & Technology exhibition, 2013.

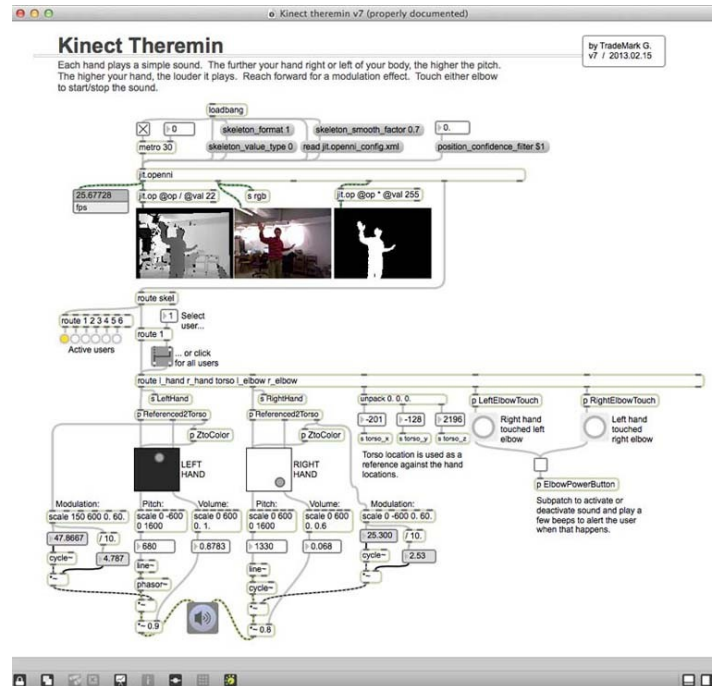


Trademark Gunderson's *Object Turntable* at its premiere. Photo Amy Youngs.

Below is a hack software instrument created by Trademark Gunderson using the Xbox Kinect sensor to create a Kinect Theremin.

Russian inventor [Léon Theremin](#) created one of the first electronic musical instruments in 1919, and it is played by hovering one's hands near two antennas without touching them.

Trademark's Kinect Theremin modernizes the concept using the Microsoft Xbox Kinect sensor, a video game controller which can track a user's movements in three-dimensional space.



Like the original theremin, the player of the Kinect Theremin hovers their hands to make music, and both the Kinect sensor and the original theremin offer control and accuracy. With the Kinect Theremin, each hand controls a different pitch. Raising one's hand higher or lower makes the sound's volume higher or lower. Waving one's hand left or right from the body changes the sound's pitch/frequency. Reaching one's hand forward or back also adds an effect on the sound.

Finally, the Kinect allows the "power switch" to start and stop everything to be placed on one's elbow — touch an elbow, the sound stops; touch it again, and the sound restarts.

The Kinect Theremin operates via **joint tracking**, where the various joints of the body are tracked through three-dimensional space. Locations for left and right hands, elbows, feet, and so on are detected by the Kinect sensor and reported back as X, Y, and Z locations. By simply assigning each axis (X, Y, or Z) to control a different aspect of the sound (volume, pitch, or effect), a simple but expressive virtual musical instrument is created.

At the time of development, Kinect hacking was in its infancy, so the project began using one joint tracking system called Synapse, but eventually this was upgraded to use jit.opennn, a solution native to the Max/MSP programming environment used for this project. While Synapse has the advantage of easy

installation and flexibility of use beyond MaxMSP, jit.openni is a MaxMSP external, meaning that it is used only within the MaxMSP environment, but ultimately jit.openni proved more reliable than Synapse.

The patch begins by initializing jit.openni with various messages ("skeleton_format 1", etc.). If it finds the Kinect and all is well, a few seconds after the patch loads you should see images from the Kinect appear in the three windows just beneath the jit.openni object. Once a human figure ("user") is identified, they become one of the "active users". Normally only one user makes sound at a time, unless the "click for all users" switch is active.

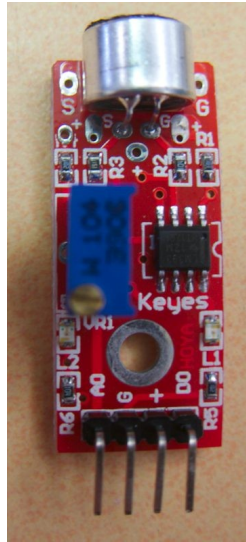
Joint data is routed for both hands (l_hand and r_hand), the torso, and both elbows (l_elbow and r_elbow). Indicator windows for the left and right hands show the hand's position in reference to the person's torso or body, i.e. the center of the body is the "zero point" where there is no sound. The data is then scaled appropriately to control pitch, volume, and modulation settings, which are finally synthesized into sound. The entire sound stops and starts when an elbow is touched, or more specifically, when the calculated distance between one elbow and the opposite hand is small enough that they must have touched.

Maxuino/Arduino Sound Input

While a piezo speaker can be an output or an input device, you can also use a more traditional microphone that can be attached to your Arduino and can act as a sound-based controller, where either an analog or digital input into the Arduino UNO (or ESP32) can trigger an event or device.

The microphone sound sensor module KY-038 is one such example.

1) AO – Analog input • 2) G – Ground (GND) • 3) + – 5-volt power • 4) DO – Digital input



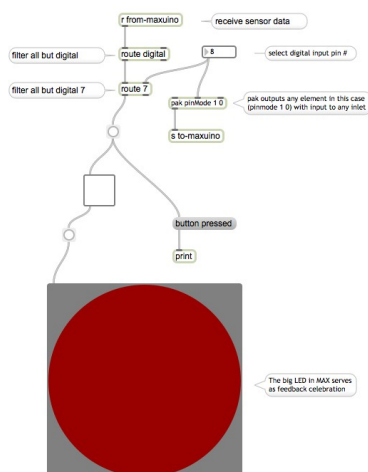
Not actual size (enlarged).

Volume switch digital Input

One way to detect humans is with a simple digital input using volume. This sensor seems to really want to see LOUD sounds in order to trigger the LED onscreen.

REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port.

Connections to Arduino:
pin8: detection (0 = off, 1 = on) to Arduino 8 which functions as a digital input pin
G: Ground
+: Arduino 5V



MAX MSP lessons continue in Chapter 12.

Digital Sound Memory, MIDI, Reed Relay

You can also add digital sound to your projects by using ISD chips, which are a bit expensive, though for lower fidelity and a quick method to add sound, you can use RadioShack's mini solid-state sound memory that stores up to 20 seconds of sound (product number 276-1323).

Another option is to purchase a small MP3 player and hack into that. The nice thing about hacking into an MP3 player is the sound fidelity is quite good and the memory is solid state.



20-second sound memory.

This product comes with a microphone and speaker built in, though you can use your computer to output sound and download the sound into these solid-state sound memories from most sound editing software. You can also hack and activate MP3 players by using a relay to activate play buttons for higher fidelity.

You would have to: 1) test the unit and see how it works; 2) then remove the speaker and attach a sound jack compatible with your computer and wire it into your computer; 3) when you hit the record button on the digital sound memory unit, also hit play on your computer, and the sounds will be downloaded into the digital sound memory (be careful to turn the record-out volume really low here); 4) then unwire the jack, or get a female-to-female jack that allows you to attach this sound memory to a pair of powered computer speakers. You will be surprised at how loud it can get, and also that the fidelity is not too bad.

You can then attach the switch of the sound memory and use the Arduino, ESP32, or other microprocessor to activate the sound. You can use a small relay like a [RadioShack 5VDC/1A SPST](#) reed relay to open and close the rewired activating switch. This compact 5VDC/1A SPST reed relay has a fast response, small size, and low cost, making it a good choice for robotics, computer interfacing, and projects that require several relays. Maximum switching power of 10 (watt/VA); maximum switching voltage of 60 VDC, 120 VAC; maximum switching current of 0.5 A; maximum initial contact resistance of 150m ohms.



RadioShack 5VDC/1A SPST #275-232.

These relays can also be used to switch on and off MP3 players that are wired to play a song continuously. This allows sound to be activated only when someone is in the room. What makes these small relays so convenient is that they run directly off the microcontroller's output pins.

Interfacing to MIDI

You can also send MIDI data directly from an Arduino or ESP32 by wiring a standard 5-pin DIN MIDI connector to one of the board's serial transmit pins and sending data at MIDI's standard 31,250 baud rate: connect the microcontroller's serial TX pin to pin 5 of the MIDI connector through a 220 ohm resistor, connect another 220 ohm resistor from the microcontroller's 5V (or 3.3V, with an appropriate resistor value) to pin 4 of the MIDI connector, and connect pin 2 of the MIDI connector to ground.

On the Arduino, this is as simple as calling `Serial.begin(31250)` and then using `Serial.write()` to send standard MIDI note-on and note-off byte sequences; the same approach works on the ESP32's hardware serial ports. Many hobbyists also now bypass the DIN connector entirely and use USB-MIDI or Bluetooth LE MIDI libraries, which let the Arduino or ESP32 appear directly as a MIDI device to your computer or MAX MSP and Jitter, without any additional wiring at all.

Summary & References

In this chapter, you have learned that the area of sound is a vast and ancient method of celebration and joy, which connects to a primordial aspect of all human animals. It can create emotion and offer feedback in your invention, even if not used for emotionally expressive possibilities.

You have learned about many artists and inventors who use sound both as a primary approach to their work and as a component in larger installations. In the work of Nigel Helyer, capacitance is used to allow many works to respond and create an aural field. In the work of Maywa Denki, sound is explored as a way of creating performative works and new sound inventions. In the work of Paul DeMarinis, sound is explored in new contexts by using custom circuits and methods of modulating sound into jets of water. The installation work of Rebecca Horn explores the intersection between the body and the machine through sound. In the work of Ben Rubin and Mark Hansen, aural environments are created and performed through statistical analysis of chat rooms, finding form in a large-scale sound installation. Bjoern Schuelke realized large sculptural and humorous works, many concerned with issues of surveillance, and Amy Youngs works to amplify and create appreciation for worms through her sonic environment *Intra-terrestrial Soundings*.

In this chapter, you have further explored methods of adding emotion to your works using a piezo speaker, and you have further reviewed other methods of manipulating sound through other devices like amplifiers and MIDI signals.

Further Investigation

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Chapter 12

DC Motors, Darlington Transistors, and Stepper Motors

DC Gearhead Motor, Darlington Transistor, and PWM with a Passive Infrared Sensor

"I generally think of motors, lamps, circuits, etc., as they are used in my sculptures as having little interest in themselves; it is the way they are integrated into a functioning system that strikes me as the essential application of contemporary technology."

— James Seawright

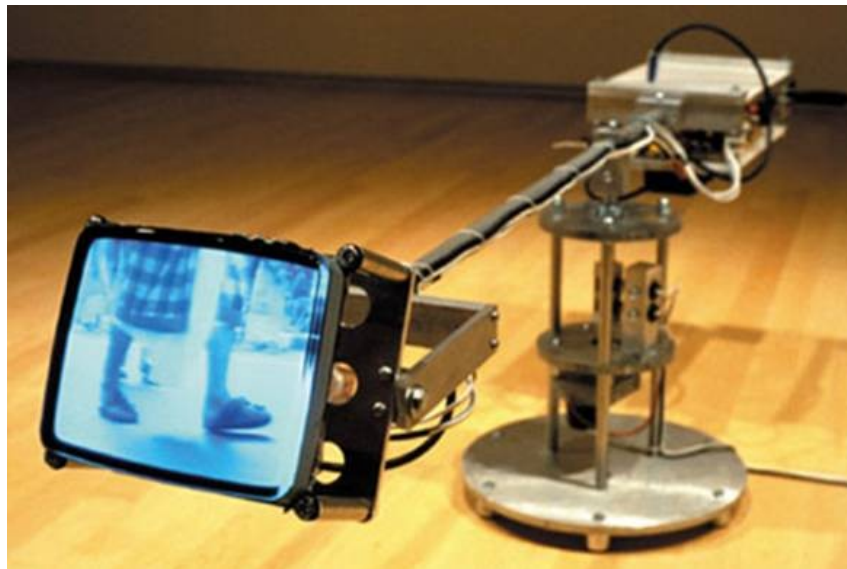
Question: How can I add motion to my projects?

DC motors and sensor feedback loops are the muscles and brains of industry, and they provide artists and inventors with a variety of unique and sometimes counter-intuitive applications for motors.

[Moholy-Nagy](#) (1895–1946) created the film *Light Display Machine: Black, White, Grey* (1932) to integrate film media and create a play of light in space. He used a rotating kaleidoscope that could project patterns of light, color, and shadow. Nagy was so excited about the work that he said: "The mobile was so startling in its coordinated motions and space articulations of light and shadow sequences that I almost believed in magic."

Jean Tinguely (1925–1991), working with Billy Kluver, created *Homage to NY* (1960), a machine designed to commit mechanical suicide at MoMA, New York. Fragments of scrap metal, motors, paint bombs, bottles of chemical stink, bicycle wheels, and a piano were part of the sculpture's self-destructive performance.

The contemporary artists [Jeff Carter and Susan Giles](#) have been collaborating for years on electronic and interactive works. In this work, the artists captured video footage of people walking in Indonesia and reanimated that act of walking by spinning the video monitor at about the same speed that the pedestrians walked.



Footage by [Jeff Carter and Susan Giles](#). 2000. Vedanta Gallery, Chicago.

This work utilized a powerful motor and a Darlington transistor, such as you will be using in this lesson. The monitor's orbit and the focus on the feet make the simple act of walking seem both mundane and fascinating.

The contemporary media artist [Fernando Orellana](#) has constructed drawing machines that are simultaneously chaotic and constrained in their motions. *Drawing Machine 3.14159* (2001) explores the possibility of giving machines the ability to create artwork without human interference or input. The artist has expressed his desire that the work produced be equal in quality and complexity to human-made artwork. A microcontroller drives a DC motor and counterbalanced pens, which make intermittent contact with the paper. The drawing paths and pressure are the results of the kinematics of the mobile that holds the pen. However, the input from viewers' voices that activate the motors allows a complex and random drawing that could never be repeated twice. The code and schematic for Fernando's work are at the end of this chapter.



The Unstoppable Hum by [Sabrina Raaf](#). 1999.

[Sabrina Raaf](#) created *The Unstoppable Hum* (2002), an installation work that acknowledges the ceaseless hum and random noise found in the human body. The building the sculpture inhabits provides a metaphor for the body.

With this installation, Raaf has connected a whole series of sensors and numerous microprocessors to monitor, amplify, and reflect the building's vibrations and ceaseless hum.

All buildings are like living systems, and as the artist says, "A sometimes subtle, sometimes deafening, but ever present hum extends from our walls, our refrigerators, our computers, and our whole electronically infused late 20th century living/working environment. There is a secondary set of hums, which we experience when we place our hands over our ears. This is the hum of our own blood rushing, the strange high frequency in our ears, and the vibrations of our voice boxes." In this work, contact microphones and microprocessors "listen to" elements such as telephones, vibrating ventilation pipes, human footsteps, and automatic doors. This outputs to fans blowing into the necks of individual glass bottles, which emit sensually dissonant musical tones and phrases. Micro video cameras also monitor and play back images of inhabitants of the space, which are distorted by a thin flesh-like membrane that

stretches over the LCD screen that plays back the images. Raaf used power-driving transistors to activate the motors in this work, similar to the ones you will be learning to use in this chapter.

The contemporary artist Jane Prophet uses motor controllers and devices called linear actuators to activate a milled aluminum sculpture in Birmingham, UK.



Jane Prophet, *(Trans)Plant*, 2008.

(Trans)Plant (2008) is a mechanical and kinetic artwork at a very large scale. This self-assembling sculpture is inspired by the structure of cow parsley (*Anthriscus sylvestris*), a native British plant. The artist writes, “In the past children used its hollow, furrowed stems as peashooters,” and this plant is quite common in the UK.

Increasing the scale of this everyday plant gives it an unexpected emphasis, and it becomes surprisingly grandiose. The jointed sculpture is made from milled aluminum blocks and tubes. The work is activated throughout the day as the branching structures rise from a collapsed state; they snap into the organic form you see in the photo above.

(Trans)Plant changes and morphs as it assembles itself into a three-dimensional form. At the touch of a button, the installation moves and its branches collapse and droop, until it is activated again.

Artist's Applications of DC Motors

The artist [Bjoern Schuelke](#) has created a work that also listens and watches, and surveillance issues are one major theme that Schuelke explores in many of his works.



Planet Space Rover by [Bjoern Schuelke](#), 2004. Height 290 cm, working diameter 300 cm.

Planet Space Rover is an autonomous observation system built for the garden. It uses fast-turning DC motors, which are powered by a solar energy system, and the motors spin propellers which create enough force to allow the sculpture to turn slowly in its quest to observe others. Additional components are kinetic camera arms, a monitor that occasionally shows the viewer the surveillance system, a long-wave scanner, and a sound detector, which listens to humans who approach the work.

The artist/inventor [Julien Maire](#) has been creating emotionally moving cinematography for many years. He uses small DC motors in a unique way that allows him to bring motion into moving visual and sound montages. His work *Demi Pas* is about a day in the life of the artist and features a series of inventive slides that are inserted into a custom-made projector along with a rich soundtrack that helps to develop the narrative of the work.





Demi Pas by [Julien Maire](#). 1995–1998. The slide on the left allows the hand to move back and forth, and the shadow of the artist is superimposed into the scene. A PIC BASIC chip-programming platform was used to control the motors.

Julien Maire used a laser-cutting device to fashion the slide-like inserts, which he then placed in a fantastic and imaginative custom-built projector. As the work is performed, the artist lifts the slides from his tray and places them in the projector, one by one. These works are modern visitations on the ancient art of montage and shadow play.

[Gregory Barsamian](#) is an artist who explores persistence of vision by using motors and specifically timed strobe lights to visually morph spinning objects from one shape to another.



Putti (Helicopter Morphs into Angel) by [Gregory Barsamian](#). 1991.

The lights are timed to create a cinematic experience, and the illusion of one object morphing into another is spectacular. This cinematic effect allows a helicopter to seemingly morph into cherubim (angels). This work suggests a relationship between the religious iconography of flying saviors, angels,

and our contemporary technological saviors, helicopters. Here, the human wings and body morph into the fuselage and propeller.

The sound installation artist [Shawn Decker](#) uses motors and steel to fashion new sound environments. These pieces explore rhythmic patterns that are derived and inspired from natural processes.

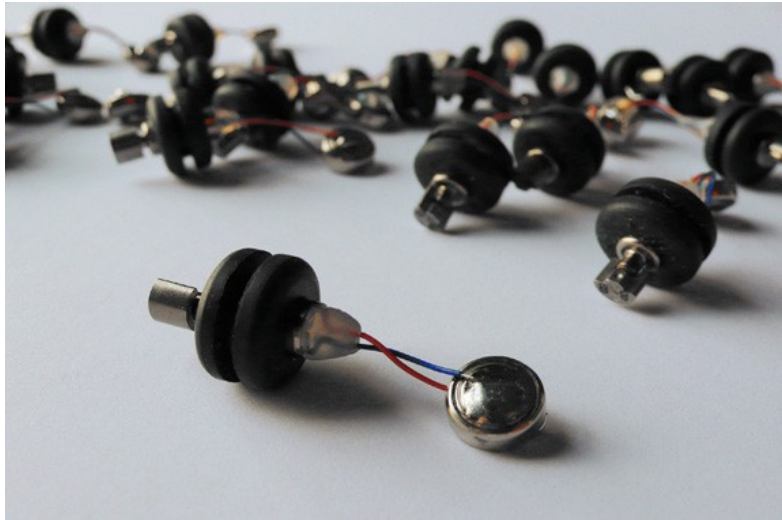


Scratch Studies by [Shawn Decker](#). 2000. Block Museum, Northwestern University.

These natural processes are simulated algorithmically within a microcontroller that sends pulses to the motor, which creates a seductive, arrhythmic, and ambient scratching sound environment.

Decker's computer algorithms investigate various natural patterns ranging from highly ordered to sporadic and disorganized. The patterns are based on processes as diverse as Brownian motion (the movement of particles in fluids), bird song rhythms and migratory patterns, and statistical studies of large populations.

The artist team PE Lang Zimoun has used many motors, all running simultaneously, to create complex and alluring sound and motion installations.



Untitled by PE Lang Zimoun. Size variable.



Untitled by PE Lang Zimoun. Size variable.

DC Gearhead Motor & Darlington Transistor

In this lesson, you will be learning to use a DC gearhead motor, a power transistor, a diode, and a resistor in a complete circuit that controls the speed of the motor. Using software code, you will learn to instruct your microcontroller to turn the motor off and on fast enough to act as a motor speed control. After programming the motor to move, you will use the same circuit with a PIR sensor to activate the motor in response to your infrared heat signature.

DC Gearhead Motor

The DC gearhead motor is one of the best ways to create motion in your work. You can utilize the circular abilities of a DC motor to spin a gear or object. You can also use motors with cams to turn a circular motion into a linear motion.

DC gearhead motors consist of two parts: a fast-turning motor and a speed-reducing gearbox attached to the shaft in front of the motor. This gears the motor down so the shaft will turn much slower. It also significantly increases the torque that the motor can provide.



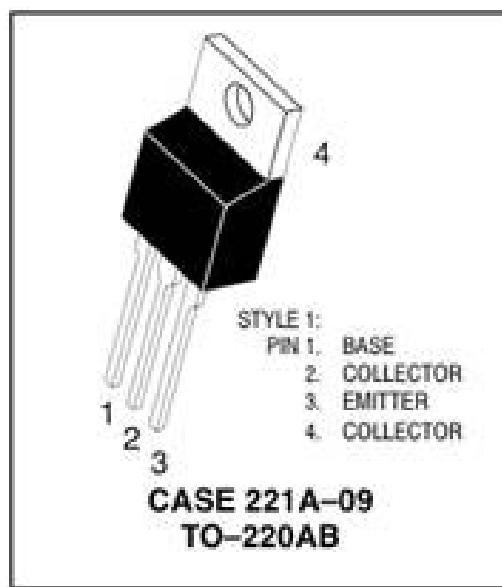
Common DC gearhead motor. The motor is the smaller circumference element at the bottom, and the gearbox is closest to the shaft.

Common DC motor voltages are 1.5–12 volts, but there are 24-volt models, as well as up to 1000s of volts also available. Generally, the larger the motor, the more current it will consume in running. It is important to think about the power source for the motor. 1.5–24-volt power supplies are quite common, but as they exceed 24 volts, the cost of power supplies increases, and therefore it is sometimes best to stay in the 1.5–24-volt range.

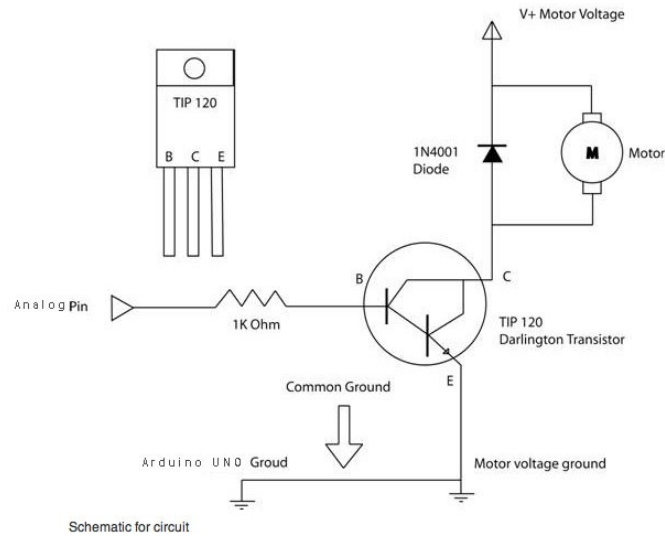
Darlington Transistor

The Darlington transistor (TIP 120) is designed as a medium power-switching transistor and can be used to switch a motor on and off. As discussed in Chapter 5, the transistor can use a small current to switch and amplify a much larger current. Transistors, like most semiconducting parts, have absolute maximum ratings. The controlling pin on the transistor, or base, is sensitive to too much current, so you must have a 1k ohm resistor coming from the output pin of your microcontroller into the TIP 120. The maximum voltage that the TIP 120 can switch is 60 volts DC at 8 amps when pulsing and 5 amps when not pulsing.

This transistor, coupled with a motor power supply, will allow you to run DC motors and empower you to activate many other devices like solenoids (linear motors) and other inductive loads like more powerful relays. Other common Darlington transistors are the TIP 122, which can switch 100 volts, and the TIP 121, which can switch up to 80 volts DC. The pin arrangements of these three transistors are identical.



TIP Darlington Power Transistor. Copyright Ken Rinaldo.



DC Motor Control (Darlington transistor) or Solenoid control

Motors require more power than a microprocessor board (such as Arduino) can output, but you can use a power transistor to amplify the output to much, MUCH more power by connecting all to an external power supply.

When hooking to an external power supply you will need to have a power supply rated for the motor. You are wanting to power. So a 12 volt rated motor at 5 amps needs to have that kind of a powerful power supply vs a small motor only requiring a few 100s of MA.

In order to also move the motor with the more powerful supply you must use a transistor capable of handling that extra powerful current. Often we use a Darlington transistor and each transistor connects to a single analog output which can control both the direction and speed of DC motors through Maxduino and MAX MSP and Jitar.

REQUIRES: Maxduino help patch or MaxduinoImpediant already running in another window.

Connection to Arduino: 1k ohm resistor, A01 analog input
 V+ to 12 volt or voltage the motor is rated for (you can sometimes use less though not more voltage)
 Ground of power supply to the ground of motor (GND)

*** Remember Common Ground back to 5V ground of Arduino Board***

Click below to configure the pin listed above:

- [Click for schematic web page](#)
[Click for schematic web page](#)
[Connect to webpage](#)
- pinMode 6 3

Set the pin number for output and connect this to the Maxduino Patch

send the pin to the maxduino patch
- Control the speed of the motor

show value of floating point number

write to analog pin 6

send the pin to the maxduino patch

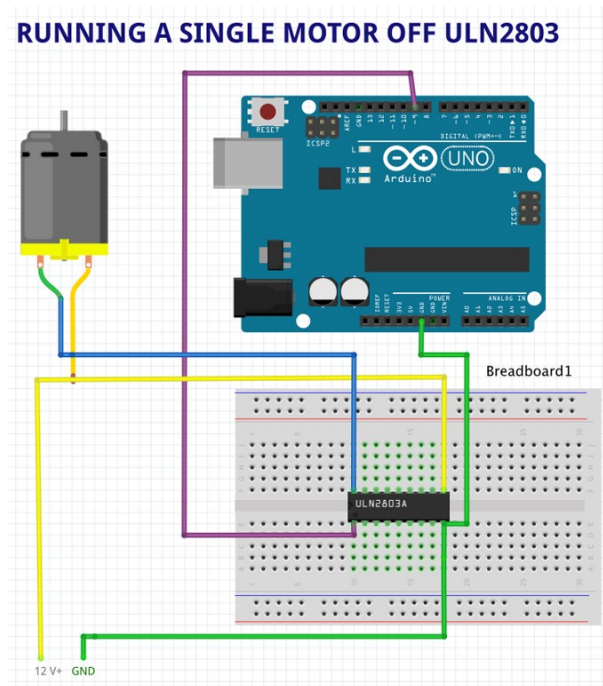
Copyright Ken Rinaldo.

Maxuino/Arduino DC Motor Drive with a ULN2803

Another great Darlington device is the ULN2803, which is 8 Darlington transistors on a chip, allowing you to drive many DC motors or solenoids at one time.

8 Darlington arrays in an 18-pin DIP package, part number ULN2803A, is ideal for running relays and high-power devices up to 500mA and up to 50V.

You can purchase this from Sparkfun for as little as \$1.95 at the time of this writing. Here is the [datasheet on the ULN2803](#). While you can run many motors, you can also run a single motor off of one ULN2803. This chip is convenient because you can bypass the protection diode in the design, as it is built in.



Copyright Ken Rinaldo.

The code to drive this motor would be the same as using the TIP 120 or TIP 122, though without the protection diode, which is built into the ULN2803.

DC Motrr with ULN2803 (unlocked)

DC Motor Control (ULN2803) & Solenoid control

Motors require more power than a microprocessor board (such as Arduino) can output, but you can use a power transistor to amplify the output to much, MUCH more power by connecting all to an external power supply.

When hooking to an external power supply you will need to have a power supply rated for the motor you are wanting to power. So a 12 volt rated motor at 5 amps needs to have that kind of a powerful power supply vs a small motor only requiring a few 100s of mA.

In order to also move the motor with the more powerful supply you must use a transistor capable of handling that extra powerful current and the ULN2803 may be just the perfect part.

REQUIRES: Maxuino help patch or MaxuinoSimpleStart already running in another window.

Connection to Arduino: pin 6 analog output on Arduino
V+ to 12 volt or voltage the motor is rated for (you can sometimes use less though not more voltage)
Ground of power supply to the ground of motor (GND)

*** Remember Common Ground back to the ground of Arduino Board***

Click below to configure the pin listed above:

1

pinMode 6 3

Set the pin number for output and connect this to the Maxuino Patch

send the pin to the maxuino patch

6 to maxuino

2

Control the speed of the motor

show value of floating point number

write to analog pin 6

send the pin to the maxuino patch

0.

prepend analogWrite 6

6 to maxuino

Copyright Ken Rinaldo.

Maxuino/Arduino ULN2003 Stepper Motor

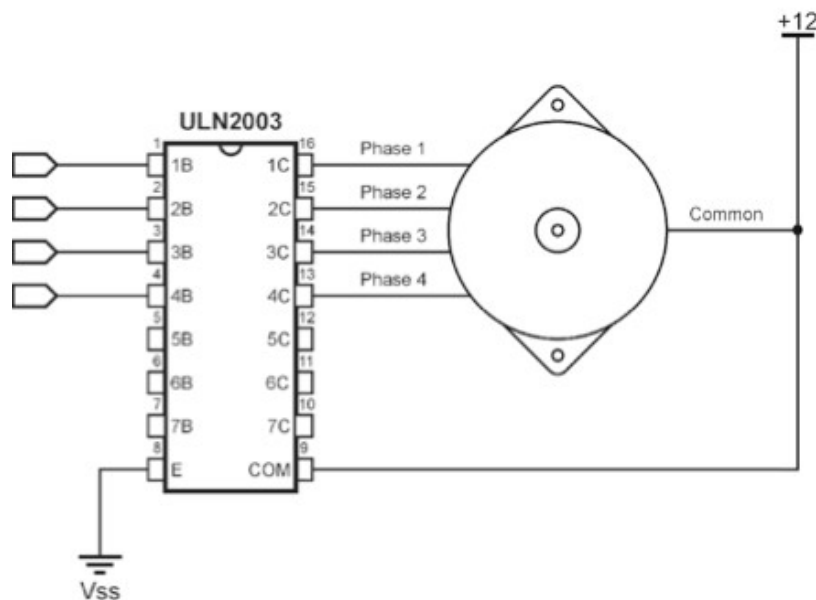
Another motor that is quite nice to use for accurate positioning is a stepper motor. Steppers have many discrete coils that allow them to step through the motor coils, and you can use a counter subroutine to move the steppers in step.

This could allow you to count the number of steps to turn the motor one time, for example. With a motor that steps 1.8° , you would need 200 steps to go one full revolution.

Since the motors are accurate, you can also tell them to go 50 steps, for example, and that would be $1/4$ of a 360-degree turn. The challenge with steppers is that they have no feedback, and if you are holding the motor and it does not turn while the code is advancing and telling it to turn, the motor or the program may not know it has not turned.

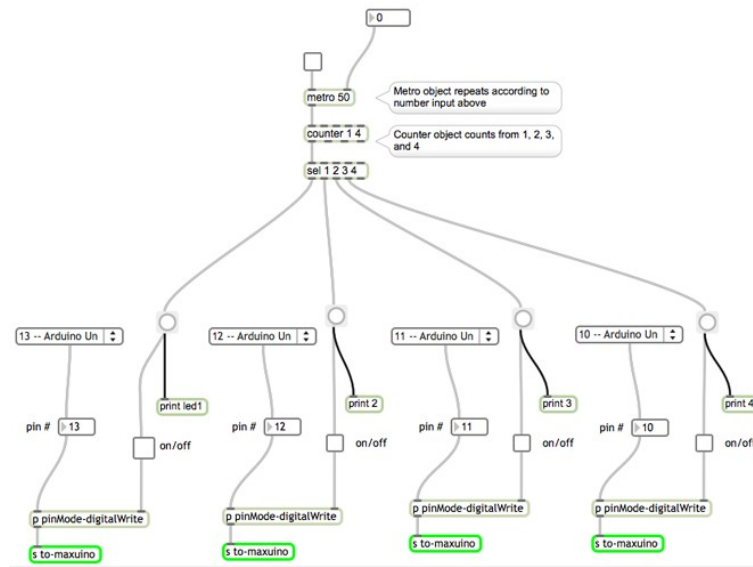
Notice that the part number used here is for a ULN2003 versus a ULN2803; either part will work, though pay attention to the extra pins on the ULN2803 and account for them in your design if that is what you are using.

Also note that the supply voltage is 12 volts and the GND rail is also tied to that power supply. It is important to tie that GND back to the GND rail of the Arduino you use to create the stepping code for this stepper motor.



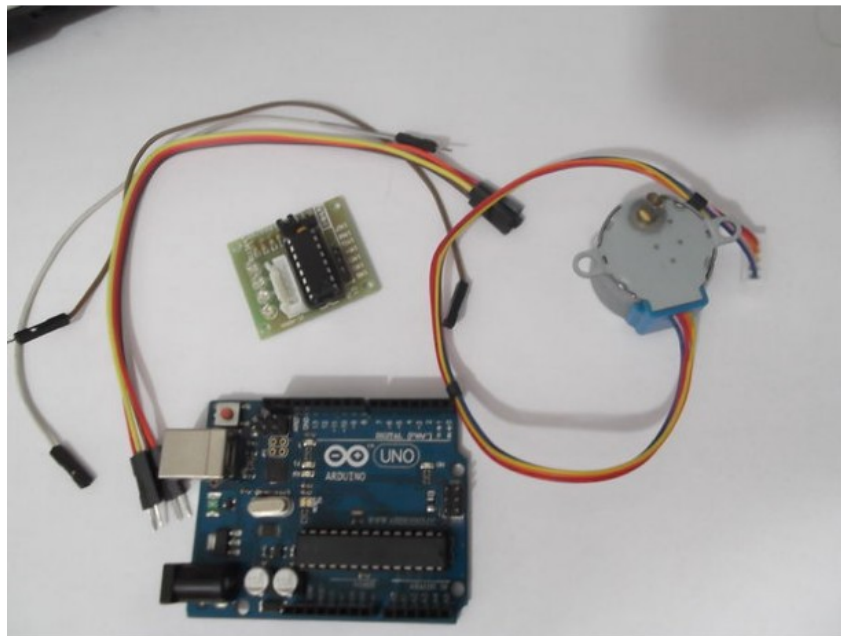
Code to drive the stepper motor using Maxuino.

DRIVING A ULN2003 CHIP IN SEQUENCE



Copyright Ken Rinaldo.

You can purchase stepper motors from [Sparkfun](#) or [Pololu](#), or small ones that run at 5 volts. The Stepper Motor 28BYJ-48 is inexpensive and relatively easy to control with the Arduino IDE directly. There is a nice tutorial on [Instructables](#) on how to use these motors, and they can be purchased online from Amazon for amazingly low prices.



MAX MSP lessons continue in Chapter 13.

This motor can also be controlled with the Arduino code directly, below. By manipulating the `delay(2000)`, `Direction=!Direction`, and `steps_left=4095` values, you can change the rotation amount and pause between rotations.

```

/* make BYJ-48 step motor rotating clockwise and counter clockwise — project tutorial see
http://osoyoo.com/?p=201 */
#define IN1 8
#define IN2 9
#define IN3 10
#define IN4 11
int Steps = 0;
boolean Direction = true;
unsigned long last_time;
unsigned long currentMillis;
int steps_left = 4095;
long time;
void setup() {
  Serial.begin(115200);
  pinMode(IN1, OUTPUT);
  pinMode(IN2, OUTPUT);
  pinMode(IN3, OUTPUT);
  pinMode(IN4, OUTPUT);
  // BYJ48 Stepper Motor
}
void loop() {
  while (steps_left > 0) {
    currentMillis = micros();
    if (currentMillis - last_time >= 1000) {
      stepper(1);
      time = time + micros() - last_time;
      last_time = micros();
      steps_left--;
    }
  }
  Serial.println(time);
  Serial.println("Wait...!");
  delay(2000);
  Direction = !Direction;
  steps_left = 4095;
}
void stepper(int xw) {
  for (int x = 0; x < xw; x++) {
    switch (Steps) {
      case 0: digitalWrite(IN1, LOW); digitalWrite(IN2, LOW); digitalWrite(IN3, LOW); digitalWrite(IN4, HIGH); break;
      case 1: digitalWrite(IN1, LOW); digitalWrite(IN2, LOW); digitalWrite(IN3, HIGH); digitalWrite(IN4, HIGH); break;
      case 2: digitalWrite(IN1, LOW); digitalWrite(IN2, LOW); digitalWrite(IN3, HIGH); digitalWrite(IN4, LOW); break;
      case 3: digitalWrite(IN1, LOW); digitalWrite(IN2, HIGH); digitalWrite(IN3, HIGH); digitalWrite(IN4, LOW); break;
    }
  }
}

```

```

    case 4: digitalWrite(IN1, LOW); digitalWrite(IN2, HIGH); digitalWrite(IN3, LOW); digitalWrite(IN4,
LOW); break;
    case 5: digitalWrite(IN1, HIGH); digitalWrite(IN2, HIGH); digitalWrite(IN3, LOW); digitalWrite(IN4,
LOW); break;
    case 6: digitalWrite(IN1, HIGH); digitalWrite(IN2, LOW); digitalWrite(IN3, LOW); digitalWrite(IN4,
LOW); break;
    case 7: digitalWrite(IN1, HIGH); digitalWrite(IN2, LOW); digitalWrite(IN3, LOW); digitalWrite(IN4,
HIGH); break;
    default: digitalWrite(IN1, LOW); digitalWrite(IN2, LOW); digitalWrite(IN3, LOW); digitalWrite(IN4,
LOW); break;
}
SetDirection();
}
}
void SetDirection() {
    if (Direction == 1) { Steps++; }
    if (Direction == 0) { Steps--; }
    if (Steps > 7) { Steps = 0; }
    if (Steps < 0) { Steps = 7; }
}

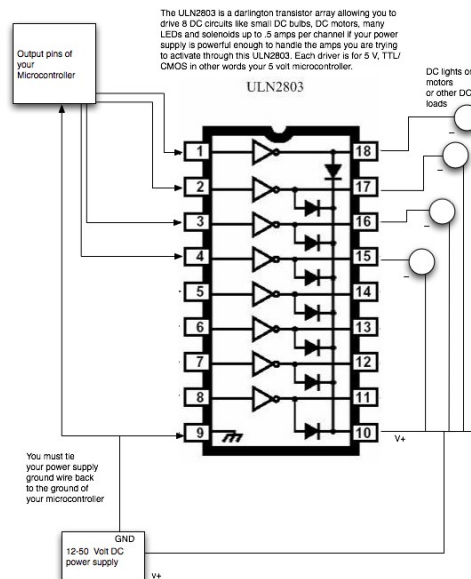
```


Stepper Motors, MAX MSP, and Darlington Transistors

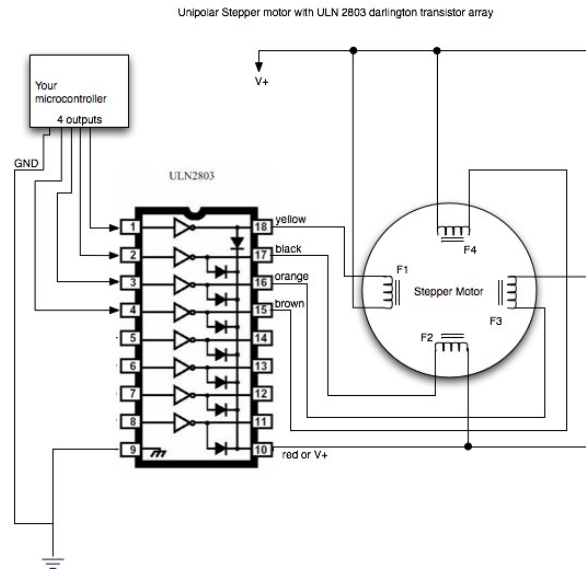
There is an array of other DC parts that you can drive with the circuit designs above, such as solenoids, many LEDs at one time, and electromagnetic relays, to name a few. The primary characteristic you need to look at is whether the TIP chip can handle the current and voltage you are switching. Always get and read data sheets on the part you have, to make sure you are not exceeding maximum voltages and amperage.

The TIP 120, 121, and 122 are also available in a DIP (Dual Inline Package) called the ULN2803A or the UDN2981A chip, which has eight transistors in a single DIP package. These 8-channel source drivers are valuable and easy to use for interfacing between 5-volt TTL (Transistor-Transistor Logic) and high-current loads, and they can be driven off of many different control platforms, including the Arduino and ESP32 examples you built earlier in this chapter.

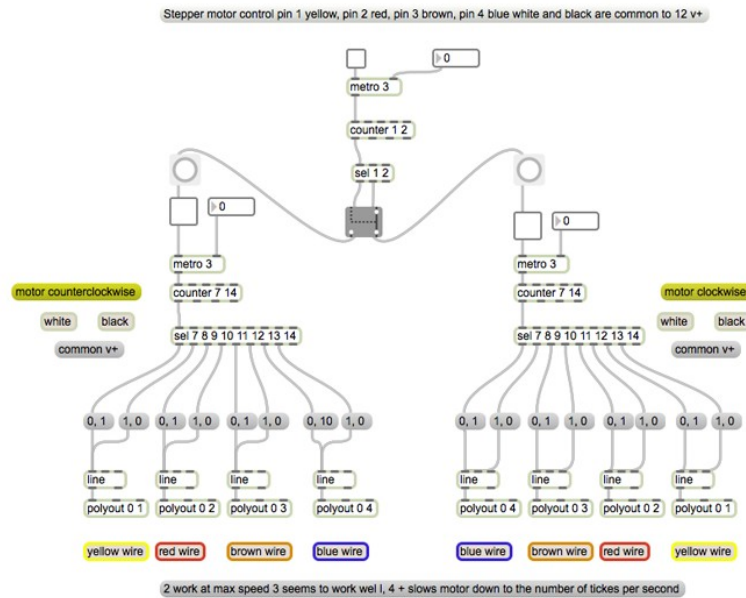
Here is a diagram showing how you would use the ULN2803 to control a stepper motor in two directions.



This is how you would use the same ULN2803 to control a 5-wire unipolar stepper motor.



Here is a MAX MSP patch to drive a 6-wire stepper motor, with black and white connected to positive 12 volts DC.



Solenoids are linear actuators, and the metal pins that go into the electromagnetic coils will move about 1/4 to 1/2 inch. To increase these distances, you can use a levering action. These loads can include solenoids, lamps, relays, stepper or servo motors, and LEDs.



3D model of a solenoid.



3D model of a solenoid.

In this chapter, you have learned that DC gearhead motors are important devices for driving kinetic objects and activating interactive installations. In the work of Jeff Carter and Susan Giles, they employed a device called a brush system to allow power to come into a continually spinning CRT screen revealing video footage.

References and Additional Readings

- [1] Packer, Randall. *Multimedia: From Wagner to Virtual Reality* (2001).
- [2] Jeff Carter and Susan Giles, artists' website: http://www.spencerbrownstonegallery.com/Past%20Shows/Carter_Giles2003.html
- [3] Fernando Orellana, artist's website: <http://www.fernandoorellana.com/>
- [4] Sabrina Raaf, artist's website: <http://www.raaf.org/>

- [5] Bjoern Schuelke, artist's website: <http://www.schuelke.org/>
[6] Julien Maire, artist's website.
[7] Gregory Barsamian, artist's website.

Chapter 13

H-Bridges, Soldering, and Autonomous Robotics

Artist's Applications of H-Bridges

The contemporary artist [Sabrina Raaf](#) has created a work that is intertwined with another environmental aspect: the breath of viewers in the room. *Translator II: Grower* is a small aluminum robotic vehicle that slowly navigates the periphery of a room, hugging the walls while sniffing every few seconds for the carbon dioxide (CO₂) levels in the air.

The carbon dioxide is proportional to the number of people in the room, and this induces the robot to draw varying heights of “grasses” on the walls in green ink.



Translator II: Grower by [Sabrina Raaf](#). 2004–2006. Photo by Sabrina Raaf.

When *Grower* completes a line, it advances along the wall a quarter of an inch and then stops to take another sniff. At the end of the exhibition, the walls are covered with green lines that resemble a field of grass, and the installation becomes a map of the number of participants (breath) in the installation.

Sabrina Raaf used an H-bridge motor control circuit and a CO₂ sensor interfaced with multiple microcontrollers to allow the robot to sense and navigate. The work alludes to the coming symbiosis of human, machine, and environment.

Augmented Fish Reality by [Ken Rinaldo](#) (2004) gives a group of Siamese fighting fish control of the location and placement of their fishbowl. These five rolling robotic fish tanks are intertwined, and the Siamese fighting fish use intelligent hardware and software to control the movement of their bowls. Siamese fighting fish have excellent vision that allows them to see for great distances outside the water. They can also see color and seem to like yellow.

This design uses four Swanson sensors, which are short-range (one foot) active infrared sensors around each bowl, integrated with a microcontroller that allows the fish to move forward and backward and turn the bowls. The work also uses the exact DC gearhead motor you will be using in this lab, along with

the same H-bridge motor control. By swimming to the edge of the bowl, the fish activate motorized wheels that move the robots in that direction. Micro video cameras are located within two of the tanks and project the fishes' point of view on the walls of the installation.



Augmented Fish Reality by [Ken Rinaldo](#). 2004. Photo by Ars Electronica, Otto Saxinger.

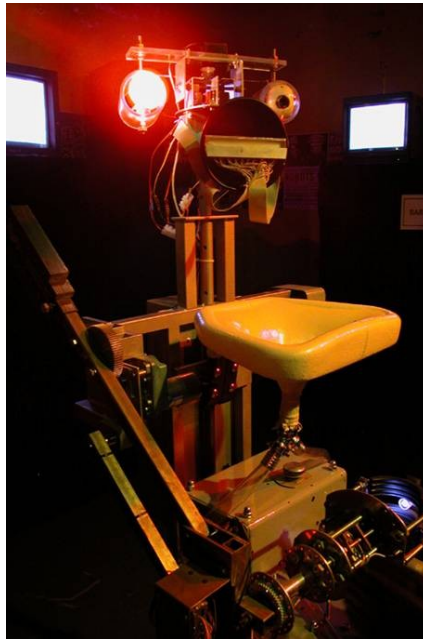
From the most recent research on fish intelligence, published in the journal *Fish and Fisheries* by biologists at the Universities of Edinburgh, St Andrews, and Leeds, edited by Culum Brown at the University of Edinburgh, there are now revisions about fish intelligence, which is much greater than formerly thought. Fish are now regarded as “steeped in social intelligence” and, the report says, “pursuing Machiavellian strategies of manipulation, punishment and reconciliation” while also displaying “cultural” traditions and cooperating to watch for predators and obtain food.



Augmented Fish Reality by [Ken Rinaldo](#). 2004. A close-up of Siamese fighting fish.

It is said that fish monitor the social prestige of other fish and track the relationships of other fish in their environment. It is now widely supported that fish use tools and build nests, as well as exhibit “impressive long-term memories.” Fish have the ability to mentally map their environments (called a cognitive map) to find food, create relationships with each other, and avoid predators.

In speculating what makes a robot conscious, the researchers at the [Humanoid Robotics Laboratory](#) (HRL) work on the creation of artificial humanoid machines, but with a twist. Researchers and engineers at the HRL believe that they have narrowed the gap between the ideal autonomous robots envisioned by science as it is modeled by human beings. Their robot manifests a behavior we normally associate with humans: the desire for inebriation. The *Bar Bot* is designed to survive in a bar by asking people for money in order to buy itself a beer.



Barbot by [Humanoid Robotics Laboratory](#). 2003.

When you approach the work, machine vision tracks your gaze and activates a voice synthesizer that asks you to buy it a beer. A custom micro control system with limit switches senses the weight of the beer in the robot's hand, slowly lifts the beer, and pours it into its gullet.

While robotics science attempts to build robots as human-like as possible, the science tends to overlook a distinguishing human characteristic: selfishness and the pursuit of self-interest. HRL has engineered selfishness into the *Bar Bot*, as its only goal is to satisfy its thirst for more beer, and therefore it may be the most humanoid robot ever built. Burp!

In the next lessons, you will first learn to solder wire. Then, you can proceed to solder an H-bridge motor control board and complete this lesson by programming your board to control a single DC gearhead motor.

Practice Using a Soldering Iron & Introducing the L298 H-Bridge Motor Driver

Parts required:

1 soldering iron (25–35 watts is okay, with a fine soldering tip) • 1 roll of standard rosin-core solder (.032-inch diameter) • wires that have been stripped for multiple practices • 1 pair of wire strippers



Warning! Solder is POISONOUS and must be handled with care. Never put this in your mouth, and always wash your hands carefully after handling it. Also, make sure not to leave solder around the house where children may have contact with the lead, which is a neurotoxin.



A standard 25-watt soldering iron is adequate for soldering solid-state parts, but make sure you get a fine tip for those extra-fine parts. A temperature-controlled soldering iron is better, as it allows you to control the amount of heat that gets to the part.



Common wire cutters and strippers. These are also very common and can strip wires more by the gauge.

Plug the soldering iron in and make sure the iron is hot enough to melt the solder, but not too hot to damage the part. Have a wet sponge or wet paper towel available to wipe down the black oxidation that can build up on the soldering iron. The black carbon buildup will prevent the proper heat transfer to your part, and the moist sponge will help remove this and spread a thin layer of solder on the tip of the iron.

You can also use a fine piece of 200 grit sandpaper to lightly sand down the tip of the iron to remove unwanted black carbon buildup.



Warning! The soldering iron gets very hot and you must use this with caution. Do not touch the tip to any part of your skin under any circumstances. Also, make sure not to let the iron contact the power cord, as this can melt the plastic sheathing and cause a short.

The rule of thumb when soldering electronic parts is to leave the iron on the part (with good contact being made) for as long as you need to get the wire hot enough to melt the solder... but no longer. Remember that while wire is not too sensitive to heat, other electronic parts, especially semiconductor parts like transistors and microchips, are much more sensitive.

Practice by stripping two wires and twisting the two ends of the wires together so that they will remain connected. Make sure you have a good mechanical connection between the two wires.



Make sure the iron touches both wires for proper heat transfer.

Bring the iron in contact with the wire, and after about 1–2 seconds max, feed the solder into the wire. You must always heat the part for a short time first and then feed the solder into the area between the wire and the iron. The solder should appear to be absorbed into the wire; this is a sign that you have a good connection.

After you solder the wire, wipe your iron tip on a moist sponge to spread a thin layer of solder around the tip. This thin layer of solder allows proper heat transfer to the part you want to join.

Practice this procedure on at least 4–5 pairs of wire until you feel comfortable with the process, first heating the wire with the iron and then feeding the solder into the hot connection.

Introducing the L298 H-Bridge Motor Driver

In Chapter 10, a gearhead motor called a servo motor was capable of rotation from 0–180°. Using the Arduino's Servo library, you were able to accurately position the motor degree-by-degree, or swing from one rotation to the next.

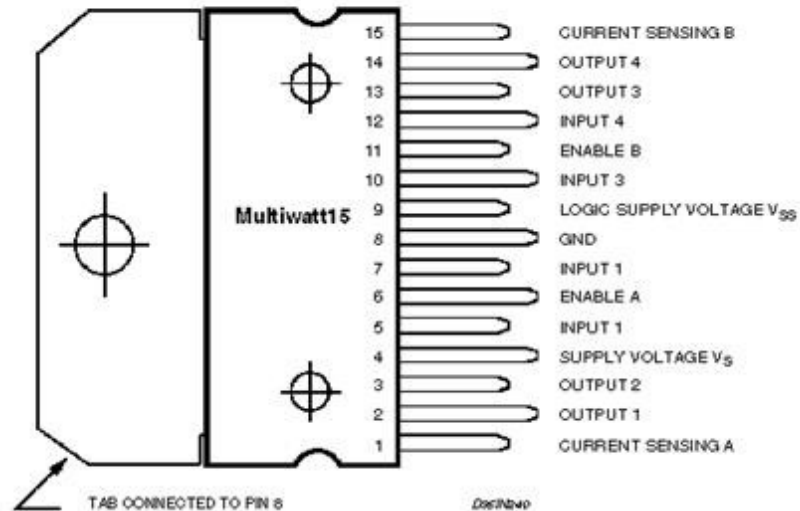
In Chapter 12, you learned how to control the DC gearhead motor you will use in this lesson, and you varied the rotation from full stop to full speed and everything in between utilizing PWM, but the ability to go to an exact position, as with the servo, was not possible with this circuit/motor and software control.

In this chapter, you will learn how to use DC gearhead motors in association with a special device called an H-bridge. The H-bridge allows you to change the direction of the voltage going to the motor, which means that you can change the direction of the motor dynamically. The use of an H-bridge opens up many possibilities in the control of robotic devices.

The L298 is a specialized solid-state H-bridge that allows you to control the direction of motors with the microprocessor of your choice. The L298 that you will be using in this lesson is a versatile H-bridge controller that is capable of running two DC motors simultaneously — forward and backward.

This H-bridge has two input pins that allow you to stop one or two motors by sending the voltage of those pins to ground, which instantly disables the PWM output that is driving the motor.

The L298 motor driver is electrically isolated from the microcontroller, enabling it to handle a continuous current of two amps per motor and short surges of peak amperage as high as three amps. The motors that can be controlled by an H-bridge use between 6–35 volts DC.



Pinout of the L298 motor-driving H-bridge.

Autonomy: H-Bridge Motor Control with PWM

“Only a machine can appreciate a sonnet written by another machine.”

— Alan Turing

Question: How can I control the direction and speed of two DC motors?

The neurophysiologist Dr. [Grey Walter](#) (1910–1977) explored theta and delta waves using an electroencephalogram (EEG) that amplified brain waves produced by the brain in light and deep sleep. In the 1940s, Walter did early research on autonomous robots at the Burden Neurological Institute in the process of modeling human brain function. He studied reflex behaviors to test his theory that complex behavior can arise from the interconnections of neural circuitry. In this research, he created “Elsie” and “Elmer”, two robot “tortoises” that showed very complex behaviors in navigating their environments using a phototube eye and two amplifiers equivalent to two neurons. These transistors drove relays that activated the steering and driving of the motors.

Walter's research was influential in the birth of the field of cybernetics, which was documented in his book *The Living Brain* (1953). Grey's research would influence researchers like [Rodney Brooks](#) of MIT, who observed that insects with relatively few neurons could display very complex social behaviors and navigate their environments with great skill. Brooks was interested in using simple rules to create complex and **emergent behaviors**, which he termed “subsumption architecture”, and created a series of insect-like robots that are very successful in navigating complex environments. These systems are capable of taking the unknown and responding intelligently.



Subsumption architecture allowed a system to emerge into complex behavior while relying on a series of sensors running independently.



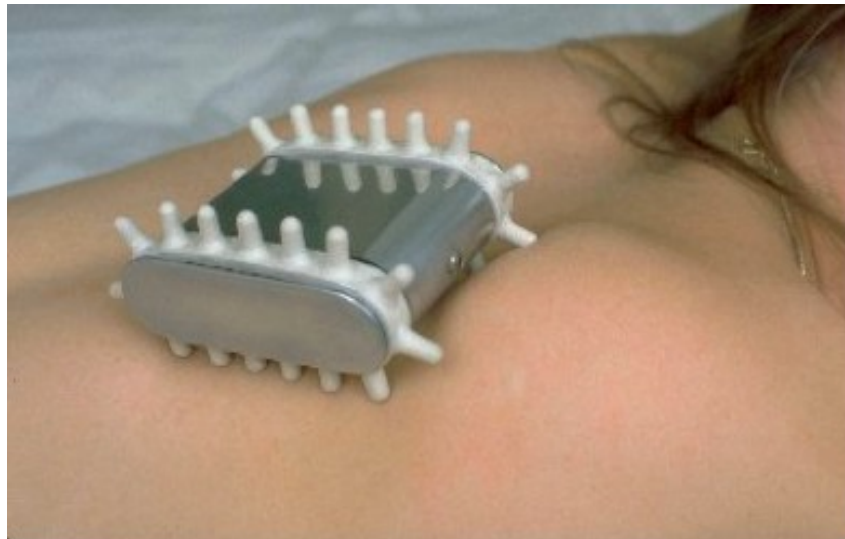
Emergent behavior results from the interaction of an agent within a dynamic environment. Here, behavioral patterns are not programmed in, but rather result from the system components interacting with the environment.

These sensor networks would trigger various subsuming behaviors like attraction and repulsion. For example, if a limit switch were not triggered, then the robot could move forward based on a heat sensor. Therefore, we could say the limit switch subsumed the heat sensor.

The writer [Valentino Braitenberg](#) describes a series of thought experiments in the book *Vehicles: Experiments in Synthetic Psychology*. Braitenberg describes how simple internal structures can give rise to unexpected and complex behavior, and he speculates that humans might ascribe love, aggression, foresight, and even optimism to these vehicles because they don't realize the underlying principles that make them behave the way they do. In other words, meaning is opportunistic.

Braitenberg sees this as proof of what he calls the “law of uphill analysis and downhill invention,” which states that it is more challenging to guess the internal structures necessary to generate complex robot behaviors than it is to create structures that can actually exhibit such behaviors.

What if these vehicles moved across the body instead of the floor? The artists/inventors [Erwin Driessens and Maria Verstappen](#) created an autonomous robot called *Tickle* (2000–04). *Tickle* is a small robot that rolls on the body to generate pleasant, tickling sensations. It has two motors that power tiny rubber feet for a good grip on the skin. When it senses a slope that is too steep, it will steer away, until a safe level is found.



Tickle by [Maria Verstappen and Erwin Driessens](#). 2000–2004.

Tickle's behavior is hardwired to avoid steep edges, and therefore the body as an environment becomes a kind of dynamic programming for the work, shaped by the individual bodies. This allows *Tickle* to manifest different behaviors in relation to the body it is exploring. Two high-torque, 5-volt mini motors drive treads that are silicone rubber caterpillar tracks designed to stick to the body.

Petit Mal (1992–95), by the artist/theorist [Simon Penny](#), is an autonomous robot that explores architectural as well as human space as it rolls through its environment on two bicycle wheels. Penny used multiple sensors and programming that activated motors attached to the bicycle wheels to create a sense that intelligence is present, though the intelligence is neither “anthropomorphic nor zoomorphic”.

Penny thinks of this intelligence as unique to its electronic and physical nature. In Penny's words, “An autonomous robotic artwork marks out a territory quite novel with respect to traditional artistic endeavors, as we have no canon of autonomous interactive aesthetics.”



Petit Mal by [Simon Penny](#). 1992–1995. Centre Georges Pompidou.

In this work, Penny used microcontrollers, programming, an H-bridge (an integrated circuit that controls the speed and direction of motors) with two high-torque DC motors, and ultrasonic sensors for sensing walls and humans to help control and move this reactive and interactive work.

The overall system emerges with its architectural and human environment and permits autonomous, sensory-based navigation.

Penny envisioned the *Petit Mal* system as an embodied intelligence, where the programming that is not pre-specified is allowed to emerge from the bottom up as the hardware interacts with its environment.

Accelerometers are employed as minimal sensory input and still allow complex behavioral manifestations.



Petit Mal by [Simon Penny](#). 1992–1995. Centre Georges Pompidou.

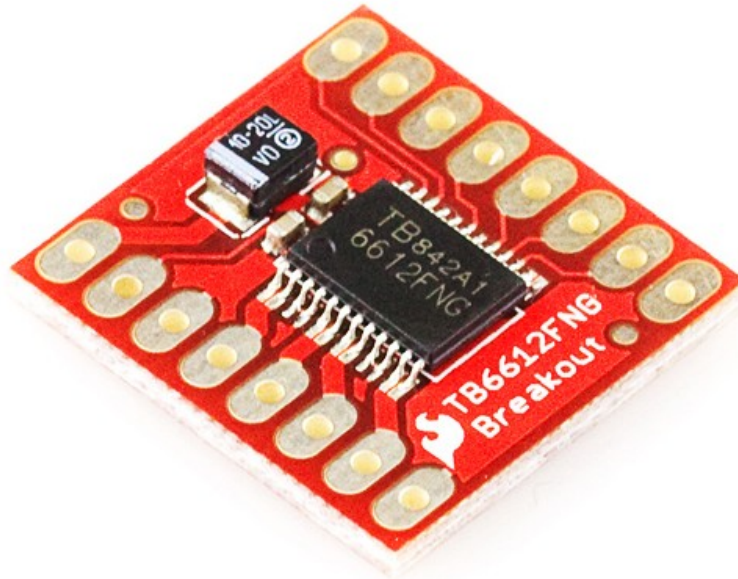


Accelerometers are used for measuring the effects of acceleration or gravitational forces. They come in many varieties, and many animals' biological systems have cellular structures with pendulum-like weights that can measure and give the neural circuitry a sense of gravitational pull or acceleration.

Maxuino/Arduino Motor with the H-Bridge, MAX MSP

In this lesson, you will use the Maxuino interface, Arduino UNO board, and MAX MSP and Jitter to drive a motor. H-bridges are wonderful electronic control boards that allow you to ramp motors up and down in speed as well as reverse their direction dynamically.

Code to control a DC gearhead motor with Maxuino/Arduino UNO and a 1 amp H-bridge.



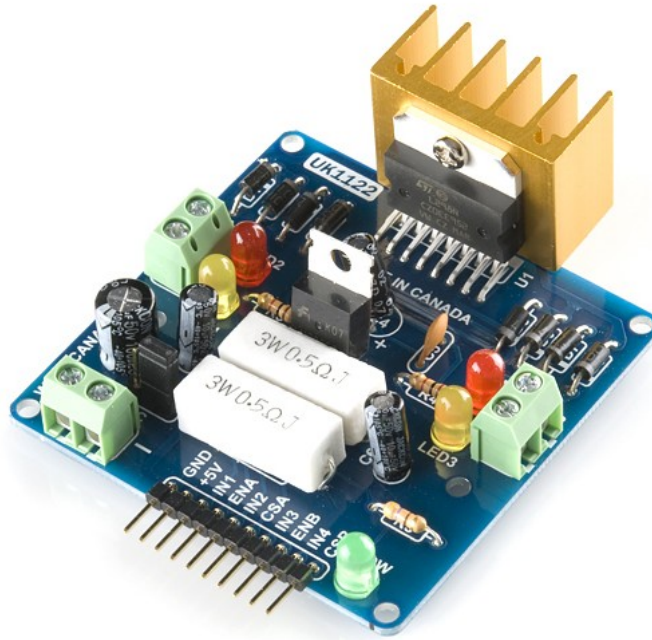
Enlarged H-bridge image from [Sparkfun](#).

The H-bridge motor control board used in this demonstration was a prebuilt unit and can handle peak loads up to 1 amp. The TB6612FNG motor driver controls up to two DC motors at varying speeds based on PWM.

Two input signals (IN1 and IN2) can be used to control the motor in one of four function modes: CW, CCW, short-brake, and stop. The two motor outputs (A and B) can be separately controlled; the speed of each motor is controlled via a PWM input signal with a frequency up to 100kHz.

The STBY pin should be pulled high to take the motor out of standby mode.

For a more powerful H-bridge to drive larger motors that require more amps, the [L298 H-bridge board](#) is recommended, and the lesson that follows shows how to solder one like it together, though keep in mind that while the chipset is the L298, the pins may be different on the Sparkfun product.



L298 Motor H-Bridge available from [Sparkfun](https://www.sparkfun.com/products/1122).

Features:

Motor supply: 6 to 35 VDC • Control logic: standard TTL logic level • Output power: up to 2 amps each • Current sense outputs • Onboard power resistors provided for current limiting • Enable and direction control pins • External diode bridge provided for output • Heatsink for IC • Power-on LED indicator • 4 direction LED indicators

There are also many popular boards that fit directly on top of your Arduino, such as the Qunqi L298 Motor Drive Shield, which can be purchased from Amazon.

These boards are called shields, and they match the header pins on the Arduino to make connections quite easy. Be sure to check which outputs you are using from your Arduino, and keep in mind they require an external power supply to provide the necessary voltage to both the motors and the shield.



The L293D is a monolithic integrated, high-voltage, high-current, 4-channel driver. Basically, this means that using this chip you can use DC motors and power supplies of up to 12 volts. The H-bridge is typically an electrical circuit that enables a voltage to be applied across a load in either direction to an output, e.g. a motor. That's some pretty big motors, and the chip can supply a maximum current of 600mA per channel; the L293D chip is also a type of H-bridge. It can drive 4 DC motors, or 2 stepper motors, or 2 servos.

Maxuino/Arduino Encoder Input

In this section we will look at how to use a position encoder from Keyes. The MAX MSP code for this section is contributed by contemporary artist [Jessica Ann](#).

While many motors are excellent at responding to digital or PWM signals in order to allow a motor to go in either direction, we often desire some form of feedback to also confirm that what we told the motor to do with our microprocessor was how it responded. There are other uses for the encoder as well, for example as a way to advance video in MAX MSP and Jitter.

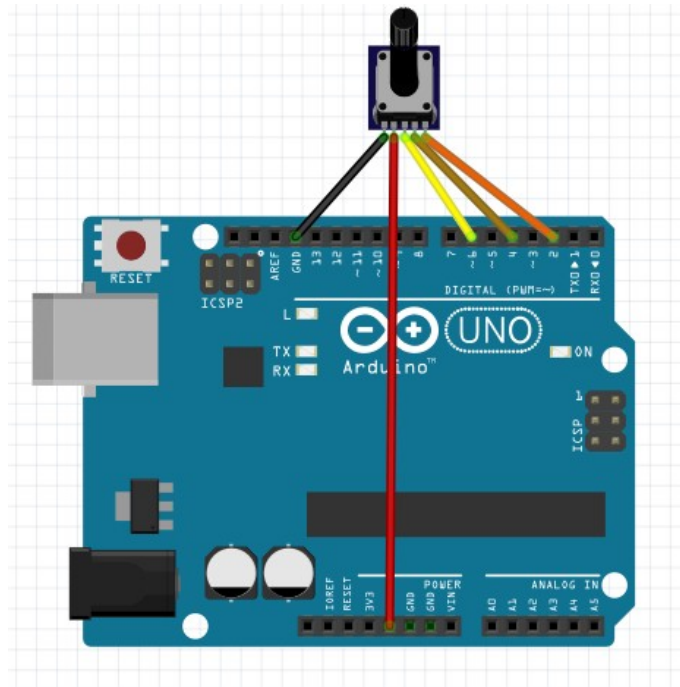
In this tutorial we will look at some code that allows you to determine the direction the encoder is turning, and use that information to make intelligent decisions in MAX MSP and Jitter.



Keyes Rotary Encoder

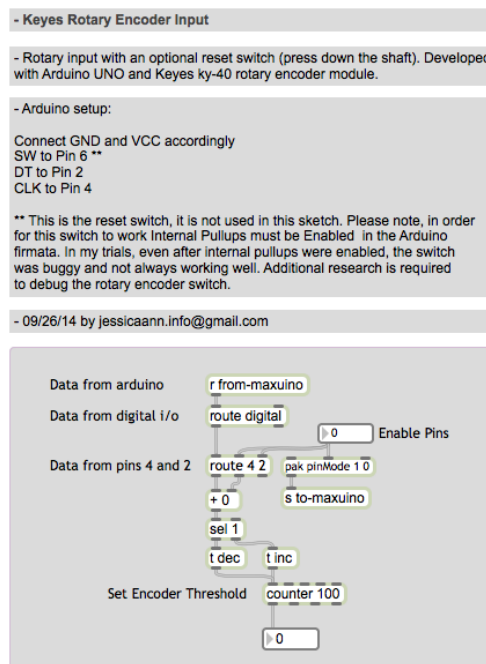
It is important to notice that with this prebuilt encoder there are already 10K ohm resistors soldered to the board, so if you use another encoder, do further research to make sure you are properly protecting your microprocessor.

To attach the KEYES rotary encoder module for Arduino, here is a simple schematic.



Arduino sketch for wiring to the Arduino UNO.

Here is the Max MSP and Jitter code for driving the encoder and getting useful input.



Patch by Jessica Ann.

MAX MSP lessons continue in Chapter 14.

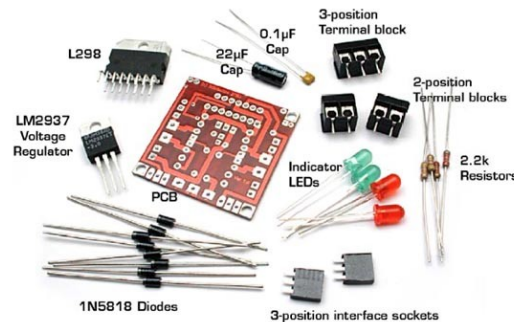
Soldering the Parts into the H-Bridge Board

In this activity, you will be assembling the H-bridge board and soldering the project. In order to solder, you will need to be very careful not to let your soldering iron sit for too long on the semiconductor parts, as these are sensitive to too much heat. You must get in and out immediately with your iron. This will assure you that you have not burned out the semiconductor part. Naturally, some parts are able to absorb more heat than others, but the best practice is to get the soldering joint done as fast as you can.

Generally, a semiconductor is more sensitive to excessive soldering heat than parts like resistors or wire, which can absorb more heat without damage.

Parts Required

- 1 - Red printed circuit board (PCB).
- 1 - L298 motor driver chip
- 1 - LM2937 voltage regulator chip
- 1 - 22 μ F capacitor
- 1 - 0.1 μ F capacitor
- 1 - 3-position terminal block
- 2 - 2-position terminal block
- 2 - 47k Enable pull-up resistors (Yellow / Violet / Orange / Gold)
- 2 - 2.2k LED current limit resistors - (Red / Red / Red / Gold)
- 2 - Red LEDs
- 2 - Green LEDs
- 8 - 1N5818 Schottky EMF-protection Diodes
- 2 - 3-position interface socket strips

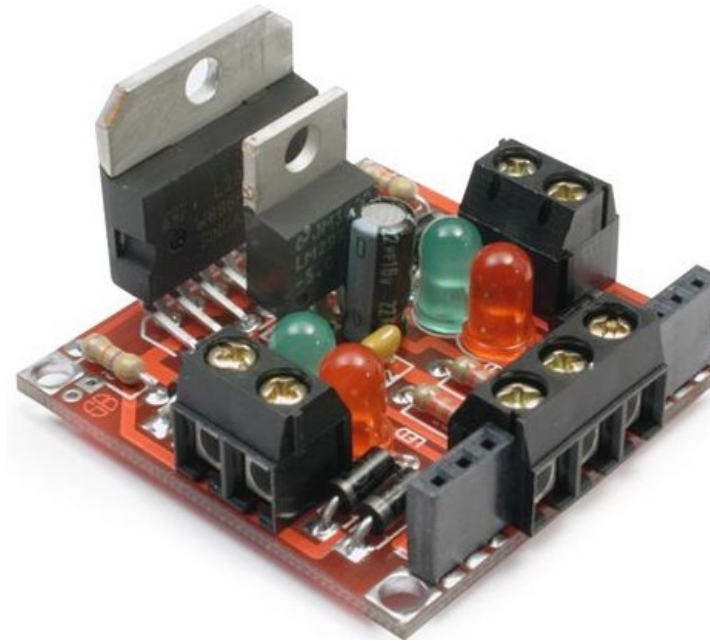


The white silkscreen printing on the circuit board allows you to understand where each component goes.

Soldering the Parts

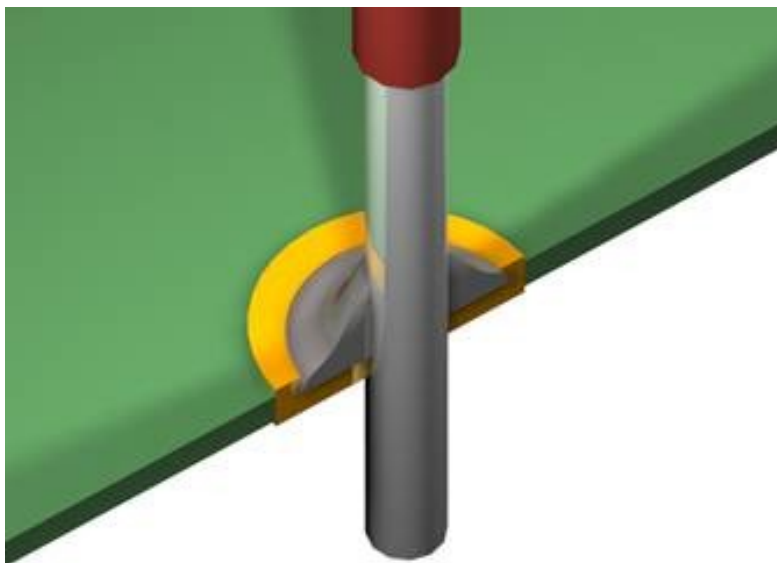
Plug in the soldering iron and let it warm up. Look carefully at the tip of the soldering iron and confirm that it is not black or discolored. It should appear to be a silvery color with no black on the tip. If there is black on the tip, then you must clean this with some fine grit sandpaper and “tin” the tip of the soldering iron by melting a thin coat of solder onto it.

Another challenge with soldering is a cold solder joint (one in which an electrical connection has not actually been made, though it might look like it is) that prevents the current from traveling from the wire to the solder and then into the electronic part.

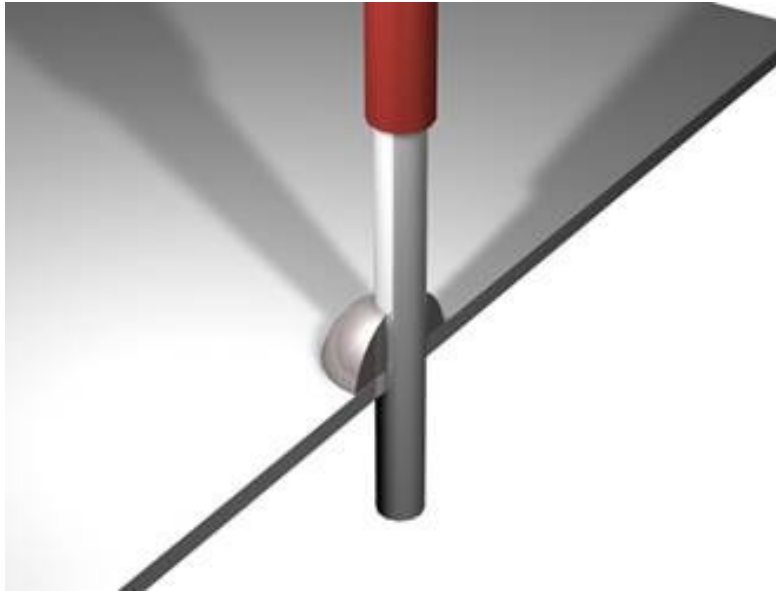


Another version of an H-bridge that will work with the code provided. This can be purchased from [Hobby Engineering](#) or other online sources. Another source is [Sparkfun](#).

A good PDF construction guide to this driver can be found at [SolarBotics](#) in Canada.



Enlarged. This is a cross-section of the printed circuit board that shows a warm solder joint. Notice how the solder wicks into the copper traces, and then pull your iron away fast.



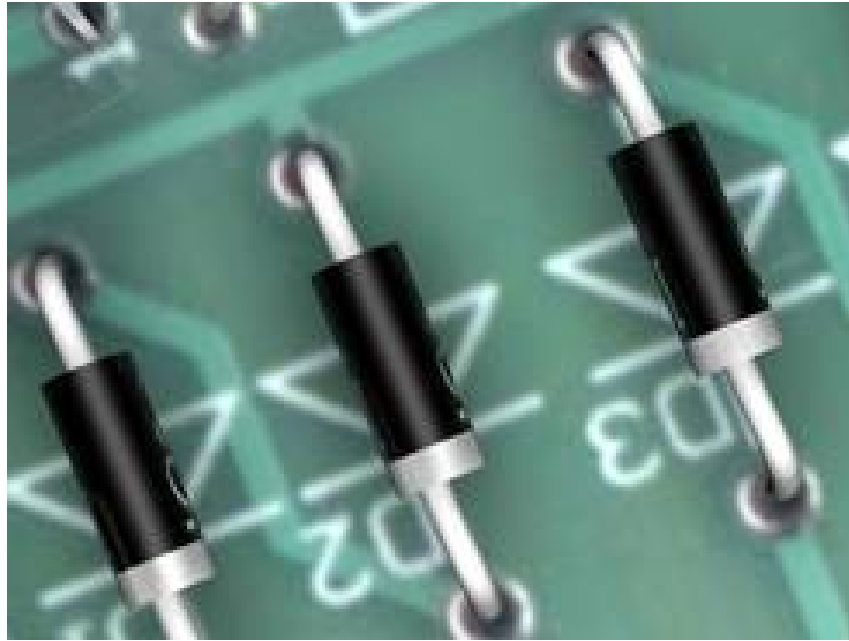
Enlarged. Image of a cold solder joint. This may look like it is connected, but there may not be an electrical connection. You can use your multimeter to do a continuity test to determine if a connection does exist, but it is easier to solder well from the start.

Start with placing the resistors in the board. Notice the board above, supplied by Hobby Engineering and Sparkfun, uses similar parts to the lesson below. If you can see the silkscreen, then you are putting the resistors on the right side.

Once all the resistors are placed, turn the board over and begin by placing the tip of the iron so it makes contact with the pad of the printed circuit board and the resistor lead. Then feed a small amount of solder in. Once you have soldered the resistors, cut the excess lengths of resistor wire off the backside as close to the board as possible without damaging the surface traces. Use your wire cutter for this process.

As you solder the parts, be careful not to create any solder pools (unintended connections between the copper traces on the back of the board) between pins. Use this opportunity, working with resistors that are not likely to be damaged by the heat of the soldering iron, to practice doing your solder connections. It is a good idea to have a magnifier nearby to check that all your soldering joints are up to standard.

Turn your attention to fitting the diodes into the board. Make sure to place each diode so the white/grayish ring (the cathode end) is closest to the white silkscreen line of the diode symbol. You may need small needle-nose pliers, as sometimes the holes are a bit tight.



Close-up of the diodes in the board.

Now turn the board over and solder the diodes into the board one by one. Again, practice your soldering skills, but be more careful with the diodes, not letting the pins get too hot for too long. Semiconductors, as we know, can be heat sensitive.

Clip all the wires one at a time on the back of the board.

Next, place the 78L05 +5V voltage regulator in the board. This part looks like a transistor, but it is in fact an integrated circuit in a transistor package. Make sure the orientation of the 78L05 is aligned to the silkscreen mask.

Solder the transistor and clip the leads. Now place the capacitors into the board. These are non-polarized, so do not worry about orientation. They are $0.01\mu\text{F}$ tantalum capacitors, and they suppress transient voltages that could cause the L298 to malfunction.

Carefully place the L298 chip into the board. Check that all the pins are fully through the holes and not touching in any way.



L298 H-bridge.

Solder the L298 pin by pin. Watch that solder pools do not accidentally connect pins that should not be connected. Always inspect the board before and after to see if some pins have accidentally been connected. If they have, you can use a bit of solder braid to lift the solder off the board, or you can use a device called a solder sucker that will suck up the solder you do not want.



Solder sucker (smaller than actual size) by Jessica Miller.

Now, grab the motor power supply that you will be soldering to the board. Plug it into the wall and make sure the V+ and ground leads are separated.

Summary and Other Motor Control Possibilities

In this chapter, you have learned about methods and theories about autonomy, beginning to think about your microcontroller as an executive controller that ties multiple parts together. You have also learned how to properly solder and attach heat-sensitive parts to a circuit board. As you can see, the L298 is a powerful H-bridge that can control one or two DC motors from a few volts DC up to 60 volts DC.

Other Motor Control Possibilities

Beyond the L298 and TB6612FNG boards covered in this chapter, the Arduino and ESP32 ecosystems offer a wide range of other motor controller options worth knowing about as your projects grow more ambitious.

The Adafruit Motor/Stepper/Servo Shield stacks directly onto an Arduino and can independently drive up to 4 DC motors, 2 stepper motors, or 2 servos, using the same TB6612FNG-style driver chips discussed earlier in this chapter, controlled through a simple Arduino library.

The DRV8833 and DRV8871 breakout boards from Adafruit and Pololu are small, inexpensive dual H-bridge drivers that are a popular modern successor to the L298 for smaller robots, offering lower minimum voltage requirements and less wasted heat.

For larger, higher-current motors, Pololu's Simple Motor Controllers and the Sabertooth line of motor controllers from Dimension Engineering accept simple serial, PWM, or analog signals from an Arduino or ESP32 and can independently drive one or two motors at speeds and currents well beyond what a bare L298 can handle, which is especially useful for mobile robotics platforms with drive wheels.

For stepper motors specifically, dedicated stepper driver chips like the A4988 and DRV8825 (commonly found on 3D printer and CNC controller boards) provide microstepping for smoother, quieter, and more precise motion than the ULN2003/ULN2803 approach shown earlier in this chapter, at the cost of needing a slightly higher supply voltage.

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- [2] Braitenberg, Valentino. *Vehicles: Experiments in Synthetic Psychology*. MIT Press, Cambridge, MA, 1984.
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Chapter 14

Materiality: Conceptualizing and Designing Your Project

Materiality: Conceptualizing and Designing Your Project

“Always design a thing by considering its next larger context — a chair in a room, a room in a house, a house in an environment, an environment in a city plan.”

— Eero Saarinen

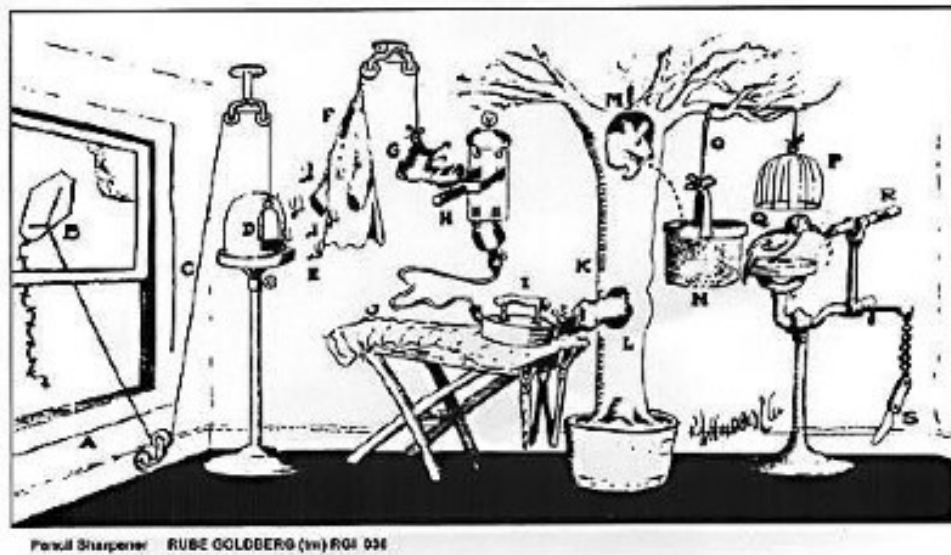
Begin designing your work by thinking about your primary interests. If your project involves your interests, it will already involve something you have the expertise and emotional excitement with. For example, if you are interested in communication between humans and animals, a work that involves these elements and issues is much more likely to be driven by your intellectual excitement with the ideas surrounding trans-species communication.

It is wise to start projects by researching the area to develop ideas, seek knowledge, and determine what already exists. Broad research in advance of your project will prevent those who do not know history from repeating it. Your research may include the media arts broadly through books and journals, which are recommended researching and reading tools. Look at and read scientific journals that have the latest developments in particular areas of expertise to become knowledgeable in that field. In both online and printed publications, you will find much inspiration and contextual information to further develop your ideas. Of course, the web is a great place for hyperlinked reading and is excellent for promoting particular kinds of search oriented to the different ways you choose to search. It is wise to use Google Alerts, for example, to have readings sent to you each day. Do cross-associated Google searches to find conflation-based logic.

In this research phase, you will also discover processes that you should become familiar with, and the lingo/terminology of the area of expertise that is important. Professionals working in the field will be far more willing to engage you and your ideas, and perhaps even offer help, if you can speak their language.

I used to read science fiction for inspiration, though recently the developments in science and art have been so spectacular and strange that fiction is no longer my greatest inspiration. Just reading publications like *Scientific American*, *Wired*, and the *New Scientist*, I discover interesting and engaging research that stimulates the imagination.

Sometimes, asking strange questions or posing thought experiments can allow you to find some imaginative and wild ideas. The artist [Rube Goldberg](#), for example, was known for asking wacky questions and receiving equally wacky answers that would inspire drawings. Goldberg gets his think-tank working and evolves the simplified pencil-sharpener. He also became well known for his humorous inventions, which critique a society overly consumed with solving problems with technological inventions. His parodies on sharpening a pencil, shown below, seem especially more relevant in our complex, technologically mediated environments.



Simplified Pencil Sharpener by [Rube Goldberg](#). Open window (A) and fly kite (B). String (C) lifts small door (D) allowing moths (E) to escape and eat red flannel shirt (F). As the weight of the shirt becomes less, shoe (G) steps on the switch (H), which heats electric iron (I) and burns a hole in pants (J). Smoke (K) enters the hole in the tree (L), smoking out opossum (M), which jumps into the basket (N), pulling rope (O) and lifting cage (P), allowing woodpecker (Q) to chew wood from a pencil (R), exposing lead. Emergency knife (S) is always handy in case the opossum or the woodpecker gets sick and can't work.

As you conceptualize your project, try to think about your unique perspective in relation to your ideas, and think about how you can best communicate your idea to your audience.

Remember the wise words of the media artist Laurie Anderson: "One of my jobs as an artist is to make contact with the audience, and it has to be immediate. They don't come back later to look at the details in the background."

Try to be as original as possible. With art and invention, original ideas and ways of seeing will have a lasting impact. Ask unique questions, and unique answers may follow. Trust your ability to ask these questions.

Try to work to see from the perspective of another thing or person. The artist [Hachiya Kazuhiko](#) did a work that allowed one to see from the perspective of the other. The *Inter DisCommunication Machine* (1993/2002) allows you to see through the eyes of another person when you wear these machines.



Inter DisCommunication Machine by Hachiya Kazuhiko, 1993/2002. Photo: Kurokawa Mikio.

This forcibly puts you in the other's place and, in the process, obscures the border between the identities of two people. It also allows you to consider modes of observation beyond the self.

Delivering on all these possible ways of thinking about making new art begs the question: what might some approaches be to make a new work? Well, in making art and invention you will need to engage both your creative and engineering minds within the self.

Engineer consultant David Goldberg has a systemic approach to creating and thinking about ways of engineering things, and since artists and engineers often share the same engineering aptitudes, you will have to engage both sides of your brain. His philosophy is well captured in the graphic below from a TEDx talk he gave.

7 Missing Basics of Engineering

1. Asking questions (Socrates 101)
2. Labeling patterns in data (Aristotle 101)
3. Modeling conceptually (Hume 101)
4. Decomposing (Descartes 101)
5. Experimenting (Locke 101)
6. Visualizing/ideating (Da Vinci 101)
7. Communicating (Newman 101)

Artist Examples

Wise questions are: can you offer a critical perspective on the existence or operation of an object or social institution? Certainly, you have strong opinions on many things, and as an artist/inventor, you can exercise your new expressive possibilities in the process of defining and perhaps critiquing culture. Making good art and invention can often arise from opinions or unique observations, which we may wish to communicate to our audience.

Memes are like our genes and can have a powerful impact on culture and offer a lasting change in society. Genes will allow you to live for 100 years if you are lucky, but your memes, or ideas, are timeless if well thought out and profound.



A **meme** is a unit of information that replicates from brains or printed matter, such as books and electronic media, and is passed down to other brains or electronic media. A meme is a unit of cultural evolution, which is self-propagating and analogous to the gene. This term was created by Richard Dawkins in the book *The Selfish Gene*.

Think of the idea of 3D **perspective** that the Italian sculptor and architect Filippo Brunelleschi was able to refine, and how this transformed the artworks that followed, and the new ways of seeing and creating the illusion of three dimensions in a two-dimensional space.



Perspective is one part of the visual perception of space that is related to the point of view from which it is perceived, and is a way of creating three-dimensional images on a two-dimensional surface.

Think also about the relation of the tools and the ideas that are related to those tools. Are your tools limiting your thoughts? Might another tool allow you to better express your idea, or should you dismiss tools until your ideas are well developed?

I am of the opinion that the idea should precede the tool, but one can also approach work that is more tool-driven, or the concept and the tool can be approached simultaneously. Either way, avoid work that is just about the inherent capabilities of tools. Flashing a lamp or LED may demonstrate technical capability, but does it offer anything new?

Think about the *morphology*, or the structure and form, of the work in relation to its behavior in the piece or installation. Imagine existing systems as a model for the work. If you can, imagine a pet or animal you have observed, and think for a moment about the relation between the physical aspects of the project and the behavioral aspects of it.

A work that engages conceptual thinking, where ideas have preceded technology, is “*Spamtrap*” by [Bill Shackelford](#). This interactive installation prints, shreds, and blacklists spam email. The idea here determined the technology the artist used to solve the conceptual question, which was: can I create a robot that automatically collects, traps, and shreds spam?



Spamtrap by [Bill Shackelford](#). 2006. Photo compliments of Bill Shackelford.

In this installation, Shackelford has created email addresses to lure the spam and has set the installation to print and shred each email as it arrives, providing a catharsis for those of us inundated with spam.

The installation is also feeding spam blacklists on the web with information gathered from all the received spam. In turn, it helps to feed spam-filtering systems across the web that are working to reduce the amount of spam we all receive.

In this work, the artist used a “Pentium II computer connected to a wireless network, personal printer, personal shredder, aluminum rails, Spamtrap email addresses, automatic printing software, email client software, antivirus software, and a SpamCop user account.” The paper is recycled after the spam email has been shredded.

Sketches to Conceptualize and Organize

You can evolve your ideas and design in successive drawings and visualizations, which will save you important time and materials in the end. At first, though, do not worry about refining your drawings, and just let your imagination and hand wander. The conceptualization stage is not the stage to be self-critical — save this for later in the process. If you can use a 3D program to visualize your idea, you will already be far ahead in this process, but 3D visualizations can also slow you down, so it is best to rely on paper and pencil in the early stages.

When you have settled on an idea to pursue, then think of looking at your idea with a magnifier. Magnify each point of your project and make detailed drawings of how things are connected, powered, disconnected, what material they are made of, and the compatibility of each material in relation to the other. Work to smaller, more detailed sketches until the design is complete. A design, however, is never complete until the project is complete, and even after this, you may need to consider that the work could be just a prototype of a later, more refined work. I would recommend using Illustrator and Photoshop to work out details, and *keep a sketchbook of your ideas*.

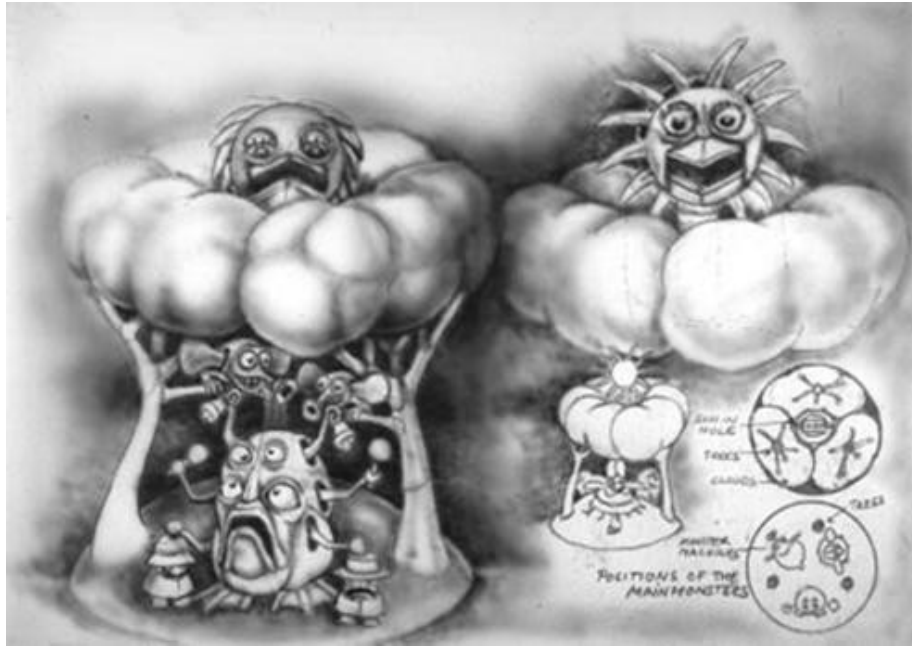
There is an important relationship between the drawings and the way the work evolves both conceptually and actually. During the process, you should begin to create drawings that are more about the overall look, and other drawings for indications of electronic systems and how they are integrated. By doing these early plans, you will be able to eliminate many possible formal, mechanical, and electronic paths that may not work.

Once you have finished your visualization stage, you should ask artistic friends what they think. Ask them if your concept works with the way the piece looks. Can you state your concept in one paragraph or less?

This is a sign that the work is consumable and will be easily understood. If you must go on and on about your work, then perhaps the idea is not yet fully worked out, or perhaps it just takes a long description? Ask your peers to comment, but ultimately, you must trust the uniqueness of your artistic vision and be willing to take the psychic risk.

When someone asked Picasso how he made so much great work, he said he made a lot and threw out the bad ones. As an artist/inventor, you must accept this as part of the process, and you should expect failed attempts before you will be completely satisfied. Edison invented the light bulb, but not before creating thousands of light bulbs that did not function. Learn from your mistakes and evolve your ideas and approaches.

The group [Dead Chickens](#) always does extensive drawings before committing their works to material. They work with rubber muscles, which allow their works to move. Here the drawings are artworks themselves.



Drawings by [Hannes Heiner](#).



Dead Chickens Group. 2004. Lille, France. Julie Loi, Hannes Heiner, Bodo Albrand, Ole Rocholl (in the JM from his backside), Nils Peters. Photo by Henryk Weiffenbach.

I recommend making paper and cardboard mock-ups before committing metal and expensive materials to your design. It is easier to work stiff cardboard and test mechanical ideas, and you can use them as templates to commit your design to more permanent materials.

Artist's Examples

The media artist Kate Jones has created a work, *Manifest Destiny* (2001), that uses material and motion to communicate greater concerns about the relation of one culture to another. She used the songs of the Wood Thrush (*Hylocichla mustelina*) and the Hermit Thrush (*Catharus guttatus*) to allude to larger social concerns about manifest destiny. The Wood Thrush is more common in Eastern North American forests and the Hermit Thrush in forests in Western North America. The Wood Thrush is the dominant bird here and is slowly expanding its territory across North America, often pushing the Hermit Thrush out of its native territory.

Manifest Destiny by Kate Jones. 2001. Photos by Amy Youngs.

These interspecies territory wars become a metaphor for the larger issues of the displacement of Native Americans as European settlers encroached on Indian land. The artist selected the wagon wheel carefully to suggest the notion of manifest destiny, and both turkeys and thrushes are sacred to Native Americans.

The bird song of the less aggressive Hermit Thrush plays when the wheel is still, and as the song of the more aggressive Wood Thrush comes forth, the wheel slowly speeds up, allowing the natural lift of the feathers to raise them in the air. The stones on the underside of the work allude to Native American rituals.

For Jones, this work was an evolution of ideas to find materials and sounds that would communicate her message with subtlety. As with natural systems, your artwork will evolve and change as you come to understand what you are trying to say, and you should welcome and expect the evolution of your idea, as well as how your idea is communicated in form and action.

The work will evolve, and you should allow time to think about the special capabilities that a microprocessor can provide. Activated or interactive objects, where input and programmed output to some installation, device, or mechanical object unify the control system with your custom program and concept, is your concern here.

Emphasis on the concept. Look for elegant materials that will help to express your ideas by playing with existing cultural dialogues, which surround and are associated with those materials. Think about how the form will change and modify the work.



Homo indicium by [Yianni Yessios](#). 2004. His work stimulated issues of information privacy, identity theft, and the collecting or mining of information, and even hinted at DNA cloning issues due to the collection of hair from participants. He used a bar code scanner to allow viewers access to the data on each sample.

The robotic theorist Hans Moravec says, “And true creative work is shaped more by upwelling from the deep than by overt procedure.” Look to your ideas.

Try to think about the sensual aspects of the material world and how this has an impact on you and your emotions on a daily basis. Why does the flower excite your nose? Why do we enjoy petting a dog? Think about the sensation of meeting a new animal for the first time and not being sure if the pet is friendly or not. Think about how the sensation of meeting the animal and petting the animal involves tactility and time.

Artist's Examples, Continued

The artist [Ann Hamilton](#) is very successful at using sensual and process-oriented materials in large-scale, site-specific installations. She combines sound, movement, smell, and often living things into large, metaphorical works that are evocative and subtle, but all have underlying and powerful meanings.



Myein by [Ann Hamilton](#). 1999. Venice Biennale.

Hamilton often conceals the mechanical controls of her works to allow the material complexity to come through.

For this piece, the artist worked with engineers to create walls that sifted red pigment down the sides and onto the floor below. There was an intimate and site-specific play between the bleeding walls and the Jeffersonian building, a type of architecture tied to democracy, but also to the emotional pain of slavery. The walls were covered with large Braille dots, which captured the pigment that trickled down, and in the process the Braille dots were stained with the red-blood powder.

[Todd Slaughter](#) has explored materiality in many of his sculpture works, such as *Beyond the Gate of the Animal Kingdom*, in which he used denture material to construct cats and impregnated teeth in the works. In the large-scale installation *Landscape Hats*, he has used paprika, which filled the space with the smell and intensity of this spice.

[Paul Kos](#), a conceptual artist recognized as a pioneer in video, installation, and performance, has always had a sensual, creative, and strong materiality in his work. In the work *The Sound of Ice Melting* (1970), Kos put seven microphones next to two blocks of ice to record the melting. In the work *Guadalupe Bell* (1989), made of bronze, steel, phosphorescent pigments, and a strobe light, the viewer could pull a large rope hanging from a bell, and the sound would activate a strobe light, which would allow an image of the Virgin Mary to appear. The image of Mary was painted in phosphorescent paint, so immediately after the

bell rings you can see her, but she soon fades from sight. Many of Kos's works involve play and interaction.

Kos says: "I have always been intrigued by materials and the way their indigenous characteristics have a certain poetry... I like the poetry of materials... the way ice behaves or the way cheese behaves or the way a chair behaves."



The Sound of Ice Melting, 1970. Two twenty-five-pound blocks of ice, boom microphone stands, microphones, speakers.
Installation view: Museum of Contemporary Art, San Francisco, 1970. © 1970 Paul Kos.

Xan Palay is an installation artist who has also engaged the use of material and form in her installation at the Aronoff Center for the Arts (2004), in which she coated a plane in black feathers. The dark feathers and the orientation of the plane (pointed down) are foreboding and become a metaphor of chance, disaster, and loss of loved ones.



How Nature Works, "Here We Go" by Xan Palay. 2004. Aronoff Center for the Arts.

As humans, we tend to favor the vision system, but also think about how your project may involve the senses of sound, touch, and smell. You could design something that engages the full spectrum of senses available to the human animal. Think about the daily experiences you have and the logic of your involvement, both emotionally and sensorially. This will provide many clues for you to pursue your ideas.

Artist's Examples and Rough Sketches

If you are having trouble thinking of an idea, then refer to Brian Eno and Peter Schmidt's strategies for brainstorming and creating questions that may inspire your ideas. You can Google the phrase "Oblique Strategies + Brian Eno," and if you have a seed of an idea, then apply their interrogative methods to nurture your idea. The artist Jim Campbell has a formula for creating computer art, which can be found on his artist website. Campbell sees the computer as an input interpreter and envisions various kinds of input and output in this animated web page.



Yellow Suit by [Kenji Yanobe](#). 1992. 91 x 120 x 120 inches. Photo by argyle-street.

Furthermore, as you think about your project, invention, or installation, think about whether you would like to work alone or in a group. If you choose a group, think carefully about the skills that each member brings to the table and make sure the capabilities are balanced. What can your local community bring to your project? What resources are out there in your community environment that will bring knowledge and approaches to your art/invention idea?

Think about whether you want a temporary or permanent piece, continuous or intermittent piece, autonomous or operator-activated piece or installation. Would you like a gallery to be able to construct the work (plug and play), or will you have to travel to construct the work each time?

The success of your artwork will rest on these factors:

- 1) Available time.
- 2) Cost of materials.
- 3) Materials availability — how long to get materials. Most often overlooked. Order early and confirm the time that your materials will be available. Are there alternative sources? Do you trust that your sources are going to come through?
- 4) The people necessary to realize the project and their availability.

- 5) The learning curves necessary to learn the new material.
- 6) Are the tools available for the project?

If you are pursuing this text in a class, you should present your idea to the class in an approval brainstorming committee that will make suggestions as to possible problems and solutions and the aesthetic merits of the work.

Caveats: KISS principle (keep it simple, and stupid). Use existing systems rather than reinventing a mechanism.

Rough Sketches

Make three rough sketches of your idea without editing or concern for how you will make the ideas work. Just let your imagination wander and think about your interests here. Be far out and crazy, and do not self-edit at this stage.

The Relation of Description to the Development of the Work

Now use language to describe your idea to a group of no more than three people. Ask them which ideas they think are the best and why. Ask them if they have some possible solutions to any problems there might be. Can they suggest solutions and means of finding them?

Ask the group if they are familiar with any artists or inventors who have done something like this before.

Research these artists online and in the library. Do not skimp on this step. Do a search online in the patent office: uspto.gov. Try to really dig into this aspect of the subject, as it will inform how you later think and write about your project.

Refinement

Take the suggestions of your peers, classmates, or artist friends, and if their notions ring true, incorporate these into your project design, but at this time start to think about how the project will be constructed.

Pay attention to which *materials* you will want to use. What are the *implications* or *cultural languages* of that material?

Even if you do not like the ideas your peers put forth, give their thoughts and questions careful consideration, as their knowledge may have bearing on your work, and they may be seeing something that you are not. Remember, though, this is your work, and you can take it in whichever direction you feel is correct.

Now make more refined drawings; many of them. Treat your original drawings as rough sketches from which to base your more refined drawings.

Act as if you are taking a magnifying glass and looking at each point in your invention/artwork, and sketch out the details. Mundane things, like how deep the screw needs to go in order to properly grab plywood. Or will you use glue as opposed to screws to make connections, and will this be strong enough in the user environment? What are the mechanical linkages you expect to create, and will you have the proper strong materials to transfer the turning of a motor shaft, for instance, to a lever or cam? The work will always break at its weakest point, and I cannot tell you how many works I have seen broken because artist/inventors do not use mechanical shaft couplers. Even epoxy or super glue, which is very strong for certain connections, should not be used to make mechanical connections.

Parts Required

What are the parts you will need? This is often the most difficult part of the project, as finding the right part is challenging and can take a very long time. I have found myself wandering the aisles of home improvement stores for hours, as well as doing extensive online searches. Do not underestimate this stage if you are under deadline. Start immediately to look for parts that represent real, workable solutions, and test these parts in mock-ups of the project.

Often overlooked is what kind of wire you will use. Choose the wire that is dictated by the user environment first, and by the aesthetics second. If you need wire to bend multiple times, think about how the fatigue of bending the copper will cause it to break over time.



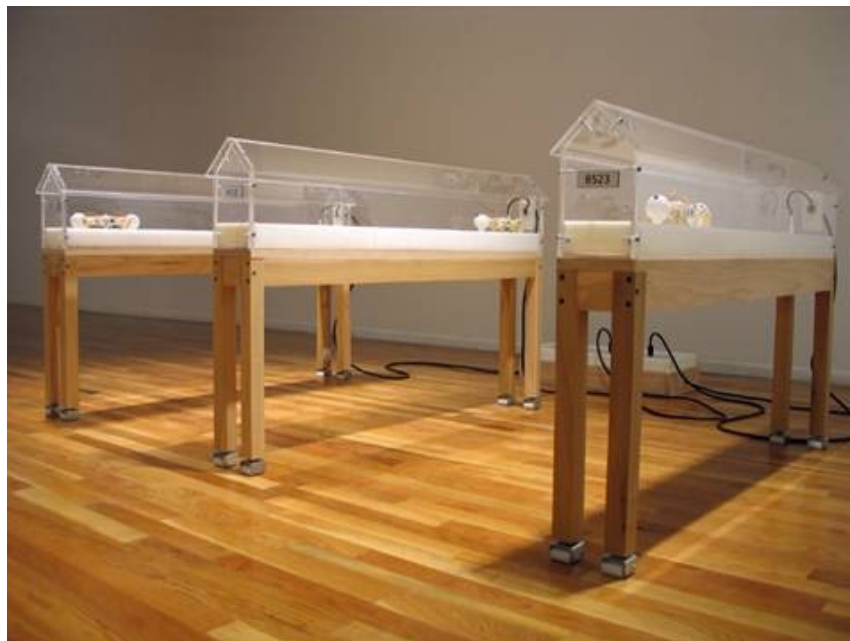
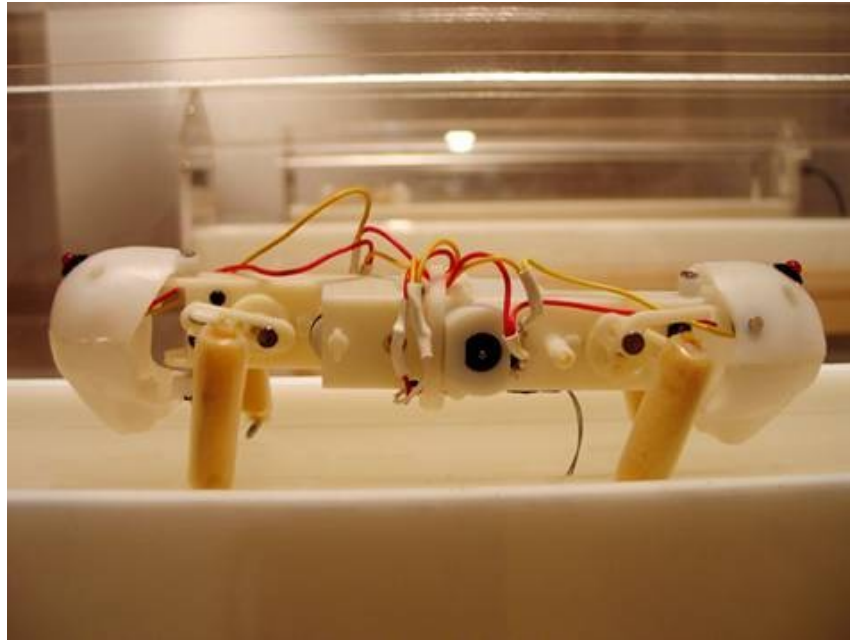
Image of wire and conductors.

What are the skills you will need to acquire in order to complete this project? How long do you have to get these skills? What existing parts can you utilize in your project that may already exist and will not challenge your idea?

This last question is the most important, as it reflects the primary approach I recommend, which is to use pre-existing kits or products to realize your project. It is not necessary to fabricate everything from scratch, and it is often best to use existing circuits and subsystems of other systems to realize your idea.

At the art school The Crucible in Oakland, California, the media artist Bruce Cannon teaches a course in toy hacking — taking apart and utilizing toys to create unique new pieces and inventions. Once you take the skin off many common toys, you will find a myriad of sensors and electromechanical linkages that will seem very inexpensive because of the production economies of scale that occur in toy production. Sensors like micro switches, roller balls in cages, mercury switches (less common because they are very toxic), infrared sensors, photo resistors, etc., and motion activators like mini solenoids, servo motors, mini cams and levers, and small DC motors both with and without gearboxes. There are online communities dedicated to hacking toys like Furby, and hacking Mark Tilden's BIO Bugs.

The media artist [Fernando Orellana](#) used this approach in his work *8520 S.W. 27th Pl.* (2004), which is an installation about our pointlessness and never-ending decision-making processes. In the artist's words: "choosing between left or right, brown shoes or black shoes, K-mart or Wal-mart." The work is constructed of rewired and reworked dancing hamster toys.



8520 S.W. 27th Pl. by [Fernando Orellana](#). 2004. Photo by Mindy McDaniel.

In the installation, eight double-headed robotic hamsters live in identical houses that are narrow and transparent. The houses are plugged into individual monitoring stations and are numbered with a unique numerical address. The robotic rodents have the ability to run about in their houses, but in only two directions. This becomes a witty commentary about the nature of decision making itself. Orellana used infrared sensors to monitor the activity outside the houses; this information is gathered and processed through a microcontroller, and from this observation the rodents decide which new direction to run in. The work is akin to our mental decision process, in that the sensor system permits external forces to influence each new movement the robot makes.

Before you begin to construct the final project, consider these questions: Are the means and materials by which you have chosen to express your idea appropriate to the idea? Do you have enough technical skills to realize your ideas, and if not, is there time available to learn the skills? Can you find collaborators or technical people to contribute to your project? Are they reliable? Are you good at getting others involved and acknowledging them in the process?

Design Issues

- 1) Have you left a place for heat to escape from your hot electronics?
- 2) Can children or unsuspecting adults accidentally get a shock from your project?
- 3) Can it hurt someone? Be very careful at this stage, as we live in a litigious culture and lawsuits are very unpleasant and expensive.

Additional Readings and References

As you take your project from concept to completion, it is worth returning to some of the foundational thinking on creativity, design process, and materiality referenced throughout this chapter. A few starting points for further reading:

Eno, Brian, and Peter Schmidt. *Oblique Strategies*. A deck of prompt cards designed to help artists and musicians break creative deadlocks by reframing a problem from an unexpected angle.

Petroski, Henry. *The Evolution of Useful Things*. Vintage Books. A study of how everyday designed objects, from paper clips to forks, evolve through iterative failure and refinement.

Norman, Donald A. *The Design of Everyday Things*. A foundational text on how form, material, and feedback communicate an object's use to the people who encounter it.

Csikszentmihalyi, Mihaly. *Creativity: Flow and the Psychology of Discovery and Invention*. HarperCollins. Explores the conditions, including deep research and immersion in a field, that tend to produce creative breakthroughs.

The [United States Patent and Trademark Office](#) full-text and image search remains one of the best free resources for researching prior art and related inventions before committing to a final design direction.

Chapter 15

Mechanics, Building Techniques, and Fasteners

Mechanics, Building Techniques, and Fasteners

“One of the new realms of practice and exploration offered by these tools is interactivity. We are beginning to shape a new aesthetic language.”

— Simon Penny

The mechanical elements you will bring into your project are often overlooked until the very end, but they should be considered in parallel with the electronic and electromechanical aspects of your creation. At all times, you will need to consider what the environment will be in which your work will exist and what kind of usage it will receive.

[Theo Jansen](#), a physicist turned artist, explores the kinematics and mechanics of wind-driven sculptures designed to grab sand from the seaside and continually build up the coast of the Netherlands. They are designed to walk like giant millipedes along the seaside, and when one of these sculptures reaches the water and collects some sand, a wind-activated mechanism switches the direction of the walking, and it walks the sand back to the dune and drops it. Then it switches direction again and walks back down to the seaside for another scoop. This is a poetic work of sculpture, and the artist has a wish for the machine to mesh with the ecology, walking and picking up sand to maintain and manage the Dutch coastline.



Strandbeest by [Theo Jansen](#). 2007.

In designing these works, Jansen uses artificial life to evolve his walking morphologies. The machines are first visualized using a computer program that tests the **kinematics** and the relationship of one bendable angle and joint to another. Jansen then translates these designs into sculptures to test his virtual designs in the physical world.



Kinematics are the dynamics of motion, without consideration of mass and force, and also describe stiff and rigid bodies and interconnecting linkages and joints.

The rhythmic patterns of the walking are visually exciting, and Jansen's desire to harness the wind to power these machines makes an important ecological statement. These creatures create a structural coupling between machine, wind, land, and sea. The creatures are like primitive life forms that do not exist without the environment they are designed to inhabit.

The works are constructed with nested electrical conduit, connected with cable ties. The sails, which oscillate and harness the wind, are thin films made of polystyrene. Jansen's mechanical walking mechanisms, with all the elements moving in sequence, create a visually stunning experience.

One important consideration of design was how they would walk on wet sand near the seaside versus walking on dry sand near the dune. Special pads allow the creatures to walk on the sand. Seawater is salty and corrosive, so the plastic selected to construct the works needed to be salt and water resistant.

Most importantly, Jansen evolved many designs, and in the process of testing, he discovered the successful designs. He also has a whole graveyard of designs that are paths on the evolutionary tree that died off, and other evolutionary paths that became the evolved progenitors of his next designs. Engineers and artists can evolve successful designs through trial, error, modification, and testing until success is discovered.

With your work, you must test your works in the environment where they will reside, and if possible the testing should be extensive.

When thinking about the mechanics of your work, think about how robust the work needs to be. How long would you like your work to function? Will there be someone to maintain and oil parts? Does it have parts that are subject to wear, like pull-string mechanics or certain kinds of motors with brushes? Will it move intermittently or continually? Will it be a warm, hot, or very cold environment, or will there be environmental extremes like water or corrosives? Will there be dust and dirt in the environment, and how might this affect your piece? Will there be water or corrosive materials or smoke, or have you selected materials that are not compatible, such as galvanized screws and aluminum? Will children, adults, or animals use it? How can you create a work that will last?

Clearly, certain materials are more robust than other materials for making mechanical transmissions. Whenever possible, use metal, plastic, and hard woods to create final mechanisms, though also consider what will really last given punishing user environments. For mechanical transmissions, use [bearings](#) and oil-impregnated sleeves whenever possible to reduce friction and wear and tear. VXB Inc. has a nice variety of bearings.

Do your initial tests of your mechanism in cardboard and paper to determine physical and simple mechanical relationships, as you will be able to solve many mechanical problems before committing to more expensive material. Begin with paper or a cardboard box and an X-Acto knife, and cut out circular cams, linkages, rocker arms, levers, etc., to determine the relationships of one mechanism to another and to determine the kinematics. You can often use push pins and larger cardboard surfaces to see that all the mechanisms do what you expect and move as you desire. You can often use the paper or cardboard as a template when cutting the metal or wood later on.

Cardboard and paper are a great way to create 3D maquettes of the piece or installation you wish to construct. 3D design software is an excellent method to visualize how a mechanism or installation will mesh with your concept.

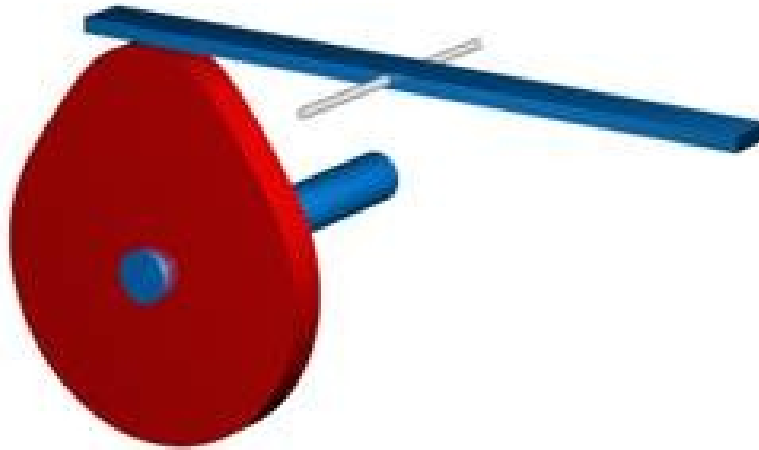
Levers, Cams, and Shafts

Lever

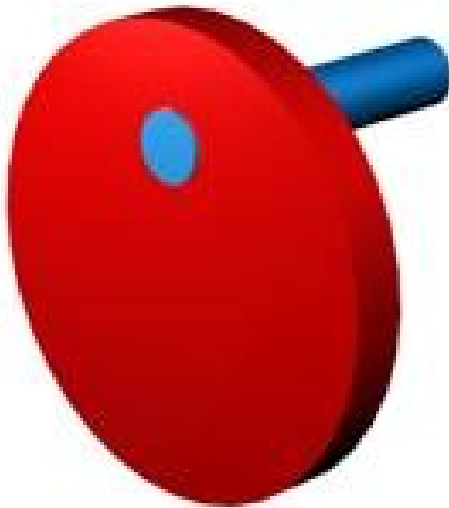
A lever is a great device for using a small force to lift or move a larger weight. It rotates in an arc around the fulcrum, which is the point at which the lever pivots. A hole puncher and a pair of scissors are both types of levers. Levers are used in many mechanisms to translate the rotary motion of a cam into an up-down or linear motion, or to amplify a small distance into a greater distance.

Cams and Shafts

Cams change a rotary motion into a linear motion that follows the shape of the cam. Cams can have a variety of shapes, or profiles, which determine which way the follower will move. One example is the pear-shaped cam, which can be seen below. Imagine this pear-shaped cam lifting up or pushing down on a lever. It has a profile that will keep the rocker arm, or follower, motionless for about half the cycle, and then the wheel makes it rise and fall.



Pear-shaped cam on a rotating shaft with smooth rise and falling edges with a blue lever follower.



An eccentric cam with a smooth rise and fall, as the shaft is off center.

[Paula Gaetano Adi](#) has used cams to create her sculpture *The Desiring Machine*, in which milk moves along tubes and is collected in her waterproof dress.

Circular (eccentric) cams with followers can be used to create a series of slow motions that allow slats to rise and fall in sequence.

[Jeff Carter](#) has created a series of works that create complex wave-like patterns as DC gearhead motors spin, causing the plywood slats to rise and fall in synchronicity as if they were waves on the ocean.

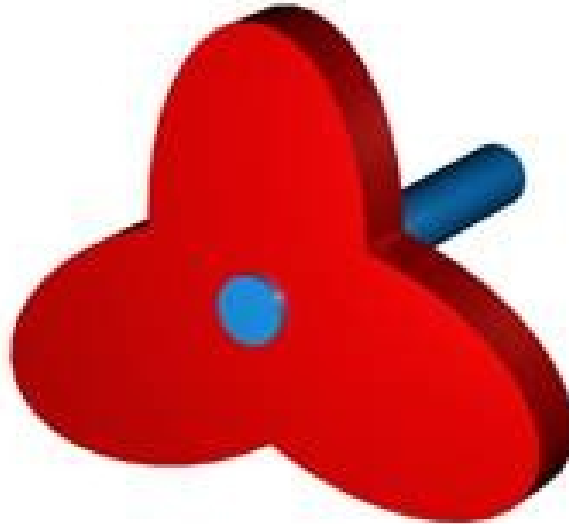


A Vague Sensation of Paradise by Jeff Carter. 2002. 43 x 41 x 26 in.

A series of circular eccentric cams and plywood followers made this piece function and appear to create the motion of ocean waves. The work is peaceful and very well crafted, and the use of the plywood for the wave material and the shipping crate alludes to ocean, travel, and distance, and creates a unified aesthetic of meaning and material. This piece has a rare materials sensibility found in the best artwork of this category.

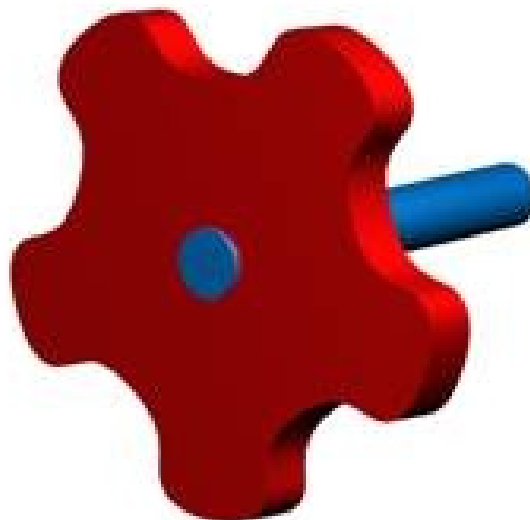
Cams and Linkages

The cam below would trigger a movement of three valleys and peaks per rotation. As the roller surface goes along the edge of this three-lobed cam from peak to valley, there is a quick change of direction in the follower arm, which may also create a noise.

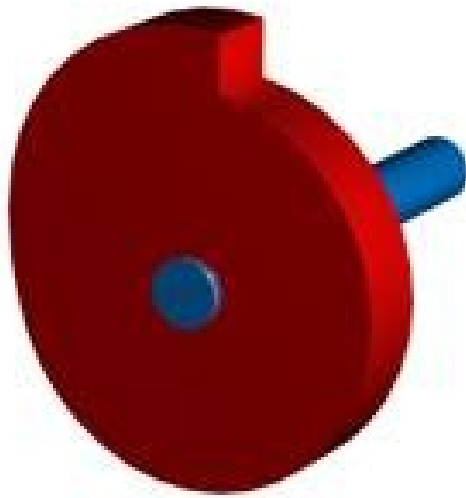


Three-lobed cam.

The cam below would move the follower up and down five times per rotation.



5-lobed cam.



Snail or drop cam.

A snail (or drop) cam (above) has a slow rise and then a sudden drop. This is a one-event-per-turn cam with a slow buildup to the peak and a rapidly decreasing edge. This cam has one direction only, which is counterclockwise. You can think of this mechanism as a sound-generating device with acoustics that are based on the physics of the materials you select.

In the image below, the turning snail cam moves a rod with a shoulder bolt at the tip.



Snail cam and a vertical follower with a roller shoulder bolt at the end that makes contact with the spinning cam.

A shoulder bolt creates a rolling surface, so the follower arm will be able to roll against the cam with ease.



Shoulder bolt used to create a rolling surface on rods or other objects coming into contact with the spinning cam.

Linkages

Linkages are connections that can be levers (but aren't always) and function to transfer motion from one component to another. The distance that the arm travels is determined by the size of the crank.

The **crank slider** (below) is a type of linkage composed of three main components: the *crank* is the rotating circular disc, the *slider* slides inside the slot or tube, and the *pushrod* connects the slider to the crank.

The pushrod traces a curved line as a mirror of the circulating crank. By changing the length of the slider or the diameter of the crank, you can change the shape of the circular line being traced.



Crank slider.

Cranks, Drives, and Gearing

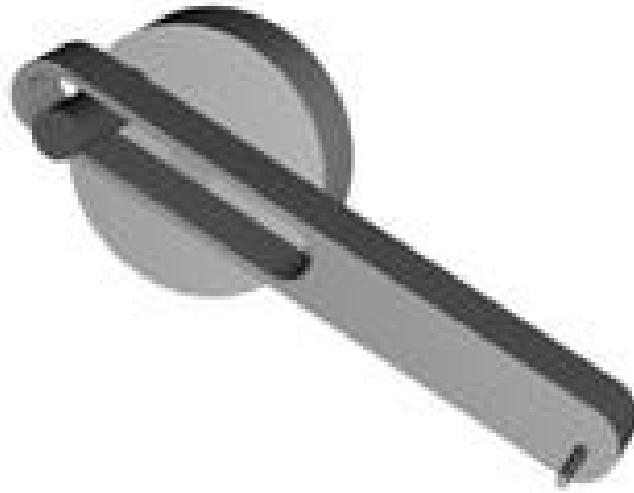
This **bell crank** converts a circular motion to a side-to-side linear motion. The bell crank can also be used to change an up-and-down linear motion to a side-to-side linear motion if there is no circular wheel driving the crank. The origin of the name “bell crank” came about because the mechanism was originally used to ring a servant's bell.



Bell crank.

By increasing or decreasing the size of the arms and linkage, you can pronounce the leverage available at each point. Notice the circular motion will push and pull on the linkage, and notice the pivot and resting or constraining points for parts of this mechanism.

This crank allows the cam to push and pull the lever; however, you would need to use a rolling surface like a piece of step tubing. Step tubing is metal tubes that are nested inside other metal tubes. They can be used in creating bearing-like linkages.



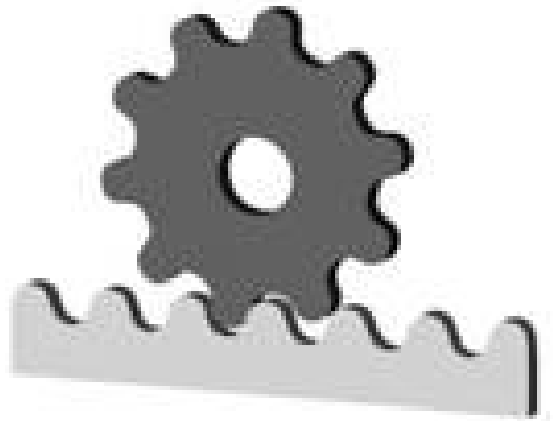
Crank.

The **crank** converts a rotary motion to a back-and-forth motion. The size of the turning wheel and the distance of the wheel from the center of the shaft will alter the reciprocating action.

Drives and Gearing

Gears are important simple machines that function in many ways in mechanical devices, but they are most commonly used to give small motors more torque. Gear reduction makes it possible for a small, fast motor attached to a small gear to turn a larger gear, therefore slowing down the speed of the spinning motion and increasing the torque. Gears can also adjust the direction of rotation and change the type of motion.

In a rack and pinion gear, the toothed straight gear meshes with the toothed round gear. This makes it possible to change a linear motion into a circular motion, and vice versa.



Rack and pinion gear.

Gears have teeth in order to prevent slippage and to ensure that the axes are always synchronized. The teeth also make it easy to find the exact gear ratios, which are determined by the circumference of the gears. Different gear ratios make it possible for gears to spin at different rates. For instance, if there are two gears spinning together and one gear is twice as big as the other, the gear ratio would be 2:1, and the larger gear would spin at half the speed of the smaller gear. You can easily find a gear ratio by counting the number of teeth in each gear and dividing.

The gears below have a 1:1 ratio, but one gear will spin in one direction and the other in the opposite direction.



1:1 ratio gear.

These gears have a 2:1 ratio, and the smaller gear spins twice as quickly as the larger gear.



2:1 ratio gear.

Chains, Sprockets, Belt Drives, Worm Gear, Pulleys

Artists like [Tim Hawkinson](#) and [Arthur Ganson](#) have done works that use gearing and the idea of the gear as an aesthetic.

Chain and Sprocket

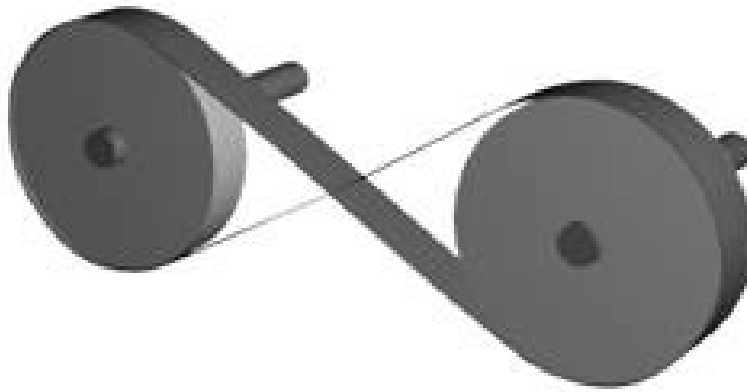
This is a positive drive because the drive sprocket will not slip as it drives the secondary sprocket. This is an important consideration if your mechanism cannot slip at all costs. Small chains and sprockets that can be screwed to a motor shaft are available from Small Parts Inc.



3D model of a chain and sprocket.

Belt Drive

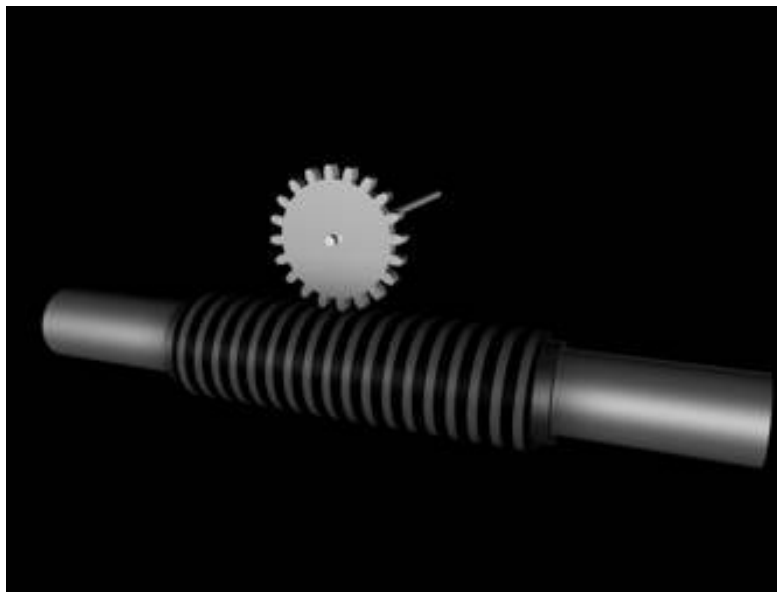
With this configuration, a connection is made between two shafts, causing one shaft to turn the other shaft in the opposite direction. This is a friction drive, and if the tension of the belt is not accurate, one wheel can slip while the other wheel turns. You can place another wheel on the belt to adjust the tension of the wheel.



Belt drive.

Worm Gear

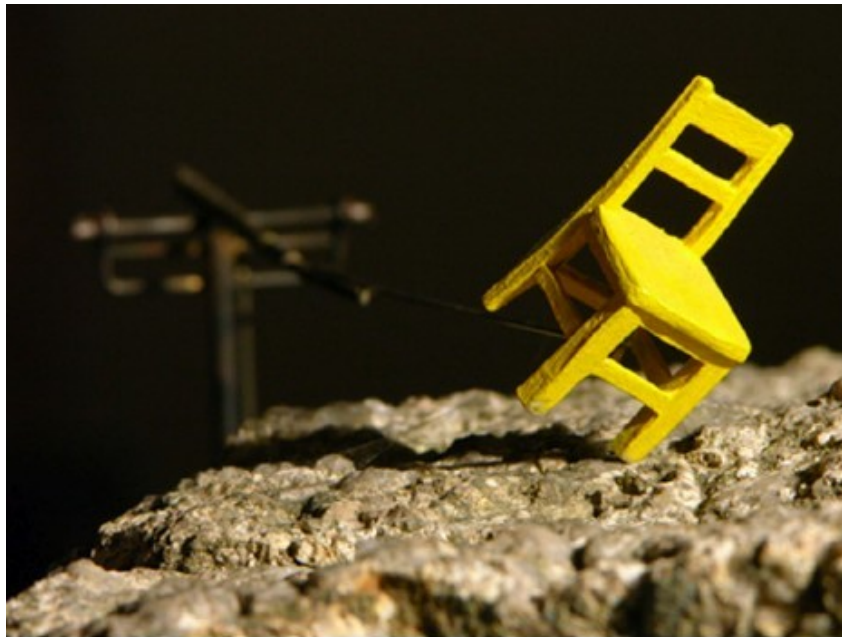
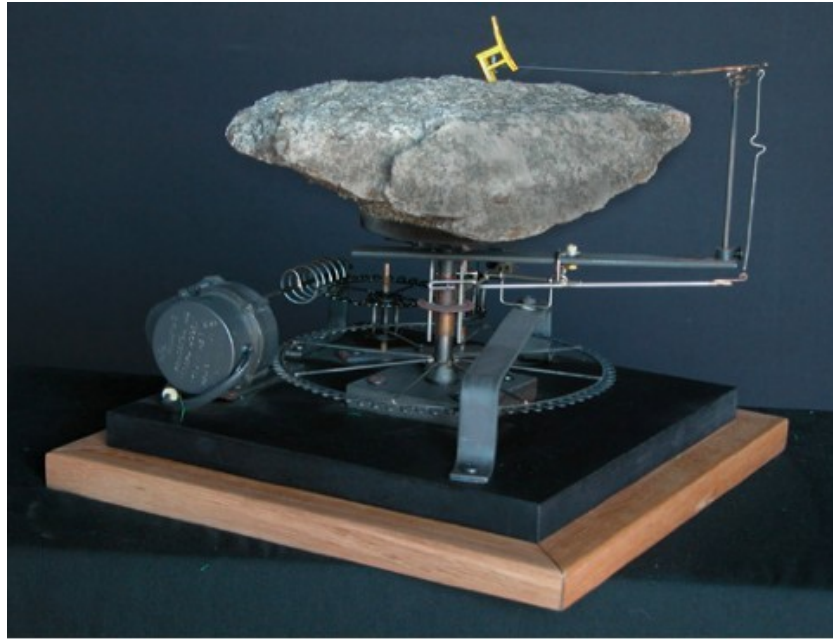
Worm gears are important mechanisms for large gear reductions. They have a property that no other gear has: the worm can turn the gear, but the gear cannot turn the worm. This makes for a great braking mechanism when the motor is not turning.



Worm gear.

[Arthur Ganson](#) works with complex and often handmade mechanisms and is a cross between an engineer and a choreographer. His works vary from highly complex machines that allow a chair to dance through the air, as with *Machine with Chair*, to another work where the chair seems to spontaneously fly apart, entitled *Cory's Yellow Chair*. Other works revel in the beauty of the mechanisms, such as the work *Small Tower of 6 Gears*, which uses a worm gear to turn all the other gears in a tower of gears.

In the work *Thinking Chair*, Ganson is using a worm gear to allow a yellow chair to walk around a stone, as if to try and find a place to settle down.

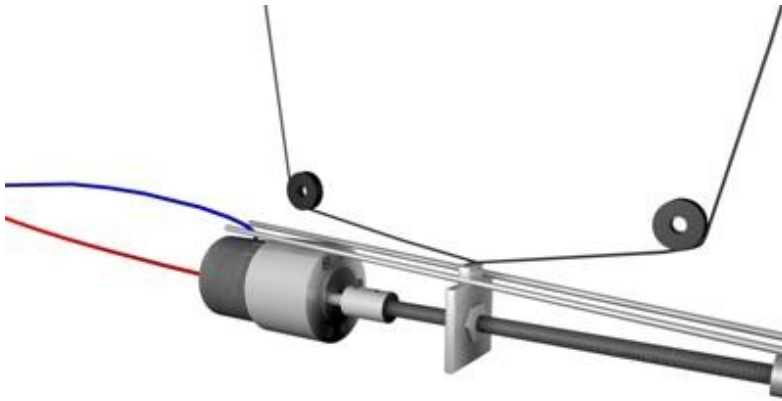


Thinking Chair by [Arthur Ganson](#), 2009.

You can also drive a plate back and forth using a threaded rod (below). This device, connected to a fast-spinning motor, can be an effective way of creating pull-string mechanics by attaching a wire or flexible cable to the moving elements.

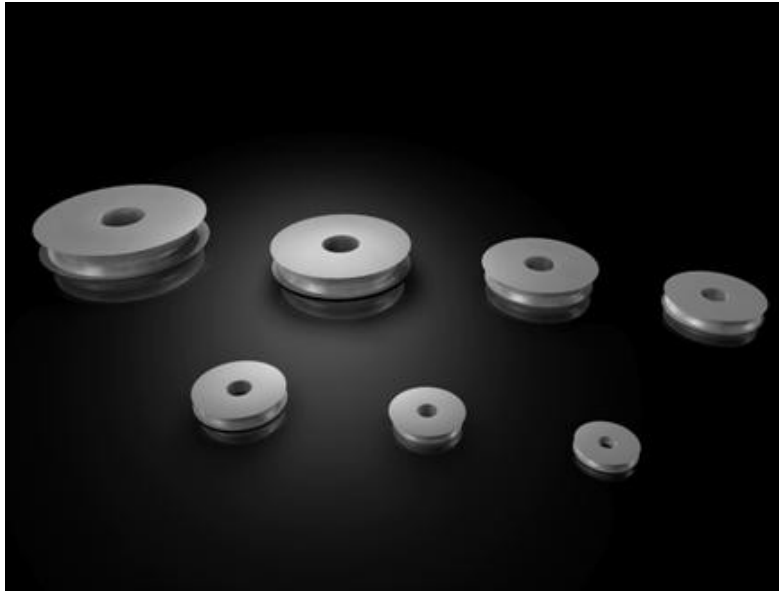


The plate moves up and down the threaded rod attached to a DC gearhead motor.



A cable or wire can be attached to the moving plate to create pull-string mechanics.

A pulley is a wheel with a groove for a rope or cable to run through. It can be used to reduce the force needed to move an object and also reverses the direction of the force needed to lift the object. The amount of work needed to lift the object remains the same when using a pulley, but the magnitude of the force is decreased because it is spread over a longer distance. Using more than one pulley will make the distance (the rope) longer and less force will be needed to lift the object, yet the workload will remain the same because more pulling of the longer rope will be necessary to lift the object to the same height. There are a number of different pulleys available.



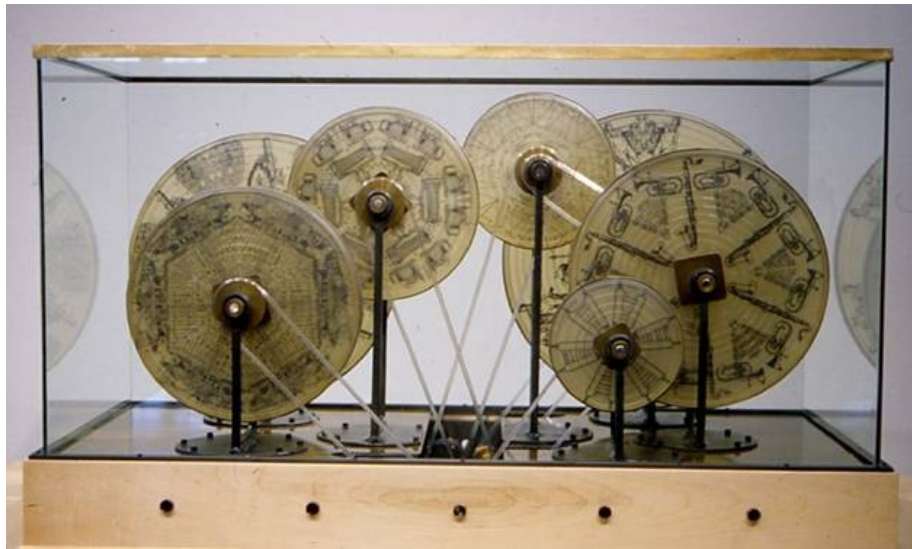
Pulleys.

You can find pulleys at Small Parts Incorporated or Grainger, and they are available in nylon, delrin plastic, or with a bearing surface that has very little friction. Pulleys can also be used to spin and rotate objects when combined with belts.

Artist's Applications and Bearings

The artist [Isabel Farnsworth](#) created a sculpture commission titled *Sharpening Device: Stones of Knowledge* out of resin, bronze, brass, wood, glass, and motors.

In this work, the resin wheels turn in different directions slowly with a pulley and belt system driven by two motors. This metaphoric piece combines the symbol of the grindstone and patterned images on the glass to relate branches of knowledge.



Sharpening Device: Stones of Knowledge by Isabel Farnsworth. 2002. 30 x 48 x 24 in. A public artwork commissioned by the Berea Public Library in Berea, OH.



Sharpening Device: Stones of Knowledge by Isabel Farnsworth. 2002. 30 x 48 x 24 in. Detail of drive mechanism.



Bearings with notched pulleys.

Bearings reduce the friction of moving or spinning components because things that roll naturally have a lot less friction than things that slide. There are several types of bearings, but ball bearings are the most common. These consist of two concentric, smooth, metal rings sandwiching a row of metal balls. The balls “bear” the load of the spinning component, such as a wheel around a shaft, and allow it to spin smoothly without a lot of wear. The outer ring transfers the load to the balls, which then transfer the load to the inner ring. The balls only make contact with small points on the surface of the rings, which allows a smooth spinning motion, but also lessens the area for bearing a load and makes the balls subject to squishing if they are overloaded.

Bearings are subject to two kinds of loading, radial and thrust, and depending on the application, they may see just one of these or a combination of both. Bearings in electric motors and pulleys see only radial loading, which comes from the tension in the belt that connects two bearings together. The bearings in a spinning stool would receive thrust loading from a person sitting and spinning, and a good example of the combination of both kinds of loading is a car wheel, which sees thrust loading from cornering and radial loading from the weight of the car.

Roller bearings use cylinders instead of balls, which increases the surface area where the roller touches the ring, and therefore increases the strength of the bearing and allows it to receive much greater radial loads. Needle bearings are roller bearings with very small-diameter cylinders that can be used in tight places.

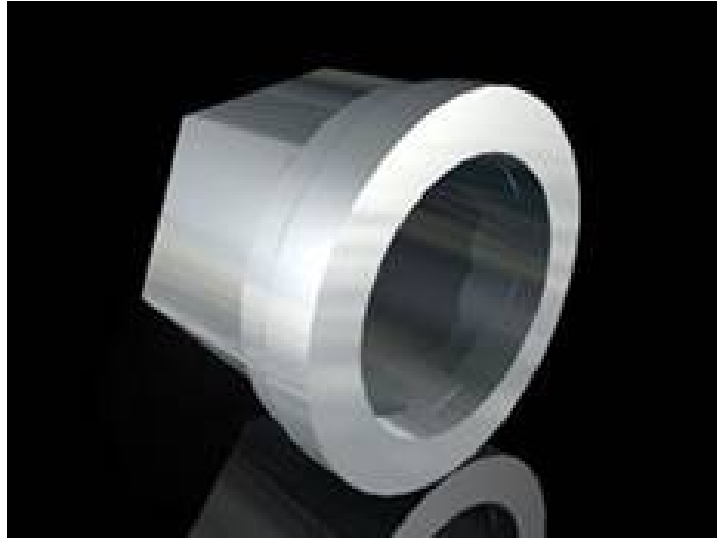


Ball bearings.

Bushings, which are also referred to as dry bearings, have no moving parts. Bushings serve the same basic purpose as bearings and are made of “self-lubricating” metal or plastic, a material that is impregnated with oil. Bushings are less expensive and lighter weight than bearings and can be used for low-friction applications.

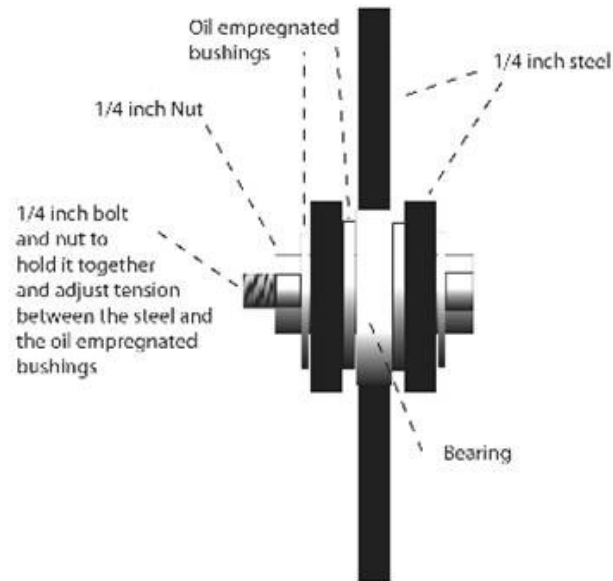
Oil-Impregnated Bushings and Universal Joints

Oil-impregnated bushings can also be washer-like devices that allow you to create a lubricated surface between two metal surfaces. They are generally used in a low-speed environment, i.e., you would not want to use these bushings as a bearing in a fast-turning object.



Bushings.

Below is an example drawing of oil-impregnated bushings used with metal surfaces.



Standby Deliver consists of steel plates attached to activating motors that face each other and move back and forth. Underneath is a lit glass sugar molecule. Visitors have access to chewing gum that they can chew and stick to the plates, which will stretch out long colorful strings of the sticky substance. The round junctions where each of the mechanisms meet have a bearing and oil-impregnated bushing to help reduce wear and tear over time.





Standby Deliver by [Ken Rinaldo](#), 2000.

After many cycles of the plates' back-and-forth motion, the glass sugar molecule is coated with the colorful goo.

Look for bearings and bushings from these and other online sources and catalogues: Canadian Bearings Ltd., Go Kart Supply, and Mendelson's Liquidation Outlet.

Universal Joint

Universal joints are used to transfer a circular motion in one plane to a circular motion in another plane.



Universal joint.

Springs, Monofilament, and Trick Kite String

Springs are wonderful devices that can store and release energy, act as shocks, and return objects back to a starting place. However, it can sometimes be difficult to find just the right spring with the proper springiness. You can order custom springs with exacting specifications, but you must order them in bulk (which can be expensive) and far in advance, because it might take the manufacturer some time to make them. Springs are available in steel and plastic, and a good source is your local hardware store or the larger home builder stores.



Compression and torsion springs.

Torsion Springs

Torsion springs are used to hold levers open or closed, and you are probably most familiar with torsion springs from doors that automatically swing shut after you enter. These types of springs would be located at the point of the hinge.



Varieties of springs.

Compression Springs

Compression springs are used to provide cushioning in systems or to push on an object that needs to have something engaged. The shocks in your car or on railroad cars are compression springs. The pogo stick you probably hopped on as a child has a compression spring.



Springs.

Below is a 3D render of how to use a spring to create a universal joint. You simply drill into the two ends of a piece of one-inch basswood and insert the ends of a spring into each hole. The stiffness of the spring can be adjusted to create different characteristics in the bendable joint. Control or sensor wires can be run through the center of the spring and can extend through your sculpture. Be aware that where wires come through the spring near the end, there are sharp edges that can wear the sheathing away from the wire.



Universal joint.

This same method can be used to create some pull-string mechanics, whereby pulling on one string in relation to the others will cause the spring to flex. This method was the basis for the joints of *Autopoiesis* (Chapter 1).



Universal joints with monofilament to bend.

Trick Kite String

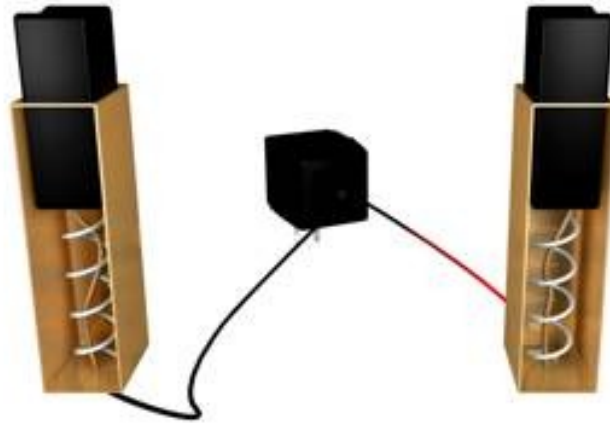
Trick kite string is a monofilament (a single, untwisted, continuous strand of manmade fiber) and is an excellent choice for making pull-string mechanics, as it stretches very little over time, though it is quite expensive.

Fishing Line

Fishing line is another great choice for any pull-string mechanics. Parts for fishing rods can also be used as guides, though they tend to be expensive, but you can also use Teflon tubing or wood. Fishing line comes in a variety of strengths, and its drawback is that it stretches more easily.

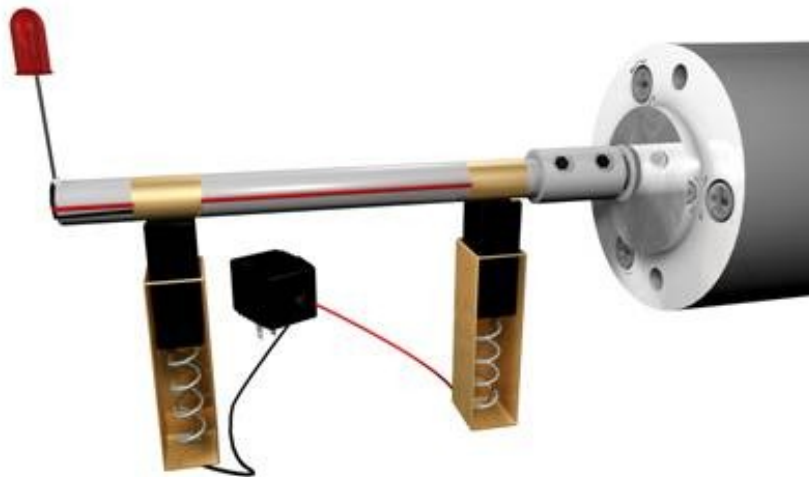
Power in Spinning Objects: Graphite Brushes

Carbon graphite brushes can be used to bring power into rotating shafts or surfaces. This is how power normally comes into the spinning coils of DC motors. Carbon brushes you would normally purchase for a car alternator are available from auto stores. You can also find them if you Google the phrase “commutator brushes”.



It takes two carbon brushes, one on each lead of the power supply, to transfer power to a surface.

You can bring carbon brushes into contact with rotating metal surfaces in order to electrify them while they turn.



In this image, carbon brushes are used to light an LED attached to a rotating shaft.

Step Tubing

Telescoping tubes or step tubing are valuable nested tubes that can be used for creating slippery surfaces. With a little oil on the interior of these tubes, they can be used for creating bearing-like surfaces for levers and devices.



Telescoping step tubing.

The smaller diameter tubes can be cut near the edge of a table. If you are careful, you can use a matt knife and roll the tube, allowing the blade to circumscribe a circle around the tube.

After cutting the tube, you must deburr the metal. You can use a utility knife or, depending on the size of the tube you are deburring, a scissor tip pushed down into the opening can bend the lip of the metal outward. You can also purchase a deburring tool with a narrow blade that can be used on aluminum, brass, steel, and cast iron.



Square step tubing.

You can also use Dremel tools to cut the tubing, and a cutoff wheel is a good method, though goggles are a must. The square step tubing is available in a variety of sizes at your local hobby shop. You can also order this tubing in a variety of materials and thicknesses from Small Parts Inc.

You can silver solder this material. Dremel tools can be used to cut the tubing. You must heat up the metal evenly, and before heating, use some flux; Harris Safety-Silv works well to etch the metal and allow the solder to wick into the metal.

It helps to sand the metal where there are joints, and as you heat it, be careful not to let it get too hot. You can hold the work on a brick to allow the metal to be on the material. Tweezers are indispensable for placing the small bits of silver solder.

Construction Materials and Fasteners

There is a vast variety of construction methods and materials, and each has its own associations for the viewer and benefits and drawbacks. Here are just a few possibilities.

Plywood and wood in general make excellent construction material for robots, environments, or inventions, as it is relatively inexpensive and readily available. It is easy to cut using common tools like jigsaws, but it can be heavy and may not be appropriate for a mobile platform unless you are using very heavy-duty motors. It accepts paint well, and it is easy to modify after working by using common Phillips head sheetrock screws or wood screws to attach, and wood putty to fill. You can upholster plywood with materials of all varieties. It is easy to work with plywood, but the right angles that most commonly result may not communicate what you are working to communicate to your audience.

Fiberglass is an excellent material for strong and biomorphic forms and can be painted with car paint for very smooth finishes. It can be done over plywood, as with Bondo, though the drawbacks are that the dust from sanding is quite toxic, so check MSDS sheets and use with respirators and caution.



Superclub by [Bjoern Schuelke](#), 2002. 80 x 110 x 140 cm. An automated scratching machine that results in wonderfully musical machine scratching through viewer participation. If the visitor approaches, LEDs light on the work, and then a theremin steers the turntable and the electronics interact with dynamic sound and movement. The systems react to small changes in their surroundings, where a small draft or a single observer may influence the work through reading the capacitance of the viewer/participant.

Welding can produce large open space frames or can allow you to create very strong support structures for other materials.

TIG welding is expensive and requires specialized equipment, though you can TIG aluminum and steel with clean and refined beads and joints. **MIG welding** is less expensive and easier to master, though the welding material splatters and can require cleanup with grinders and metal files. Both TIG and MIG

welding require ventilated spaces to work, though you can pick up inexpensive MIG welders from most home stores like Lowe's and Home Depot.

Plaster is an often-overlooked material, and you can realize many wonderful forms by creating structures of wood or steel and covering them in chicken wire. You can push and pull the chicken wire, which I call tuning. You can then use saran wrap and wrap the plastic around the form. A fun technique is to use an adjustable spray mister and a sifter, and by gently sifting plaster onto surfaces like plastic wrap around forms and then spraying the surface of the sifted plaster with water, you can achieve a shell that you can then paint with acrylic paints. Plaster bandage is also an excellent material, and you can use the technique above with fiber, or consider scrim, to give it strength.

The work below, called *Watcher*, was about the power of ambient TV light. The work is constructed with plaster and pipes as an interior superstructure, with rewired TVs and metalized paint on the exterior of the form to reflect the ambient TV light, creating a glowing quality.



Watcher by [Ken Rinaldo](#), 1988.

Glass, Plexiglass, Aluminum, Sheet Metal, and Fasteners

Glass and Plexiglas are popular with artists working with electronics, as the translucency allows you to enjoy the beauty of the electronic parts, and these parts become texture in robotic art, installation, and invention. Glass is excellent as it is a dielectric and will not conduct. The drawbacks are that glass is fragile, and you must either have access to a hot shop or find a commercial glass-blowing facility. Few schools have access to glass-blowing facilities. Borosilicate glass is another option, otherwise known as lamp-working glass, and it is stronger and can be continually worked before the final annealing process.

An exotic and increasingly less expensive material that can be finished with a completely clear finish like glass is rapid prototyping, and we are seeing many artists adopting rapid prototyping materials and integrating these with electronic form.

[John Marshall](#) and [Cezanne Charles](#) have created a sound work where they used SLS to create a form designed to house electronics that were custom designed to fit.

BAB & L by John Marshall and Cezanne Charles (Root of Two), 2001. Dayton, Ohio.

Aluminum is the natural material for electronic and robotic installation, as it is soft and relatively inexpensive and readily available. The low weight of aluminum relative to its strength is very high, and it is easy to drill and tap. There are also a large variety of extruded aluminum parts available from most hobby shops as well as online. Generally, you can choose a 6061 aluminum, which is strong and better for structural works, and where finish is more important than strength, a 6063 aluminum would be a good choice.

Aluminum can also be easily laser cut with an industrial laser cutter in your town, though you will have to check with your local shop to see what thickness they can cut. Water jets are also a possibility for cutting aluminum and can cut massively wide or very thin pieces of aluminum.

Aluminum can also be easily powder coated to protect the metal from oxidation over time or to add custom colors. Powder coating is a process of dipping your aluminum or other parts in a bath of dry powder, and then the powder is baked on to create a smooth, hard surface.

A good source for aluminum stock is [Onlinemetals.com](#). For projects like *Augmented Fish Reality*, I have been able to cut .25 inch aluminum with a Bystronic laser cooled with a cloud of nitrogen. Since aluminum is so soft and will go molten after it is cut, it needs to be cooled quickly.

Carbon Fiber is another option for building lightweight and strong structures, and it also has a high tensile strength and low thermal expansion, so it may be appropriate where heat and cold converge. A good source for these materials is [Midwest Products Inc](#). Carbon fiber works well with epoxies and seems to also glue well with cyanoacrylates. It is difficult to cut with any but the sharpest saws; I have been using a steel-cutting hand saw to carefully saw through rods.

Sheet metal is easily cut with shears and can also be bent, though this material can really cut your hands unless you wear gloves and use files to sand down rough edges.

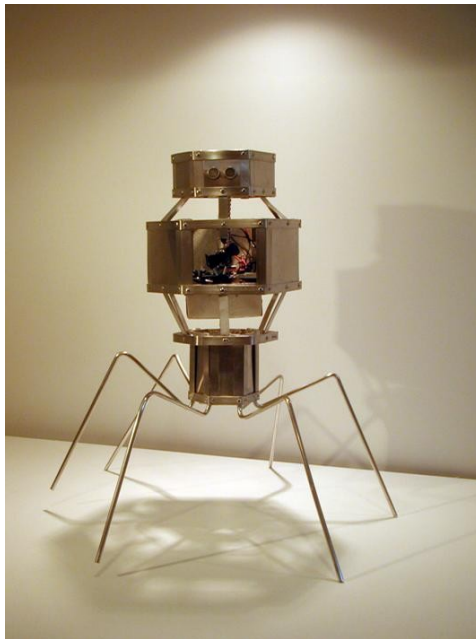
Robotics can be constructed with a variety of fasteners; however, reusable fasteners such as nuts, bolts, and screws may be a better choice than glues and adhesives, which are difficult to disassemble for repair and upkeep.

Another good way is to use rivets, but it is not easily reversible. The artist Michael Hyatt created a work constructed with flat stock aluminum that was 1/8 inch thick by 3/4 inch wide and fastened it with rivets. He used a vise to bend this standard aluminum stock and then drilled out the appropriately sized holes before using a rivet gun to fasten it all together. Before committing to the method and materials, Michael Hyatt modeled the work in 3D.



Viral Toxoid by Michael Hyatt. 3D model. 2005.

In this work, Hyatt used an ultrasonic sensor to sense people, which triggered a bubble blower to blow bubbles onto the viewer.



Viral Toxoid by Michael Hyatt. 2005.



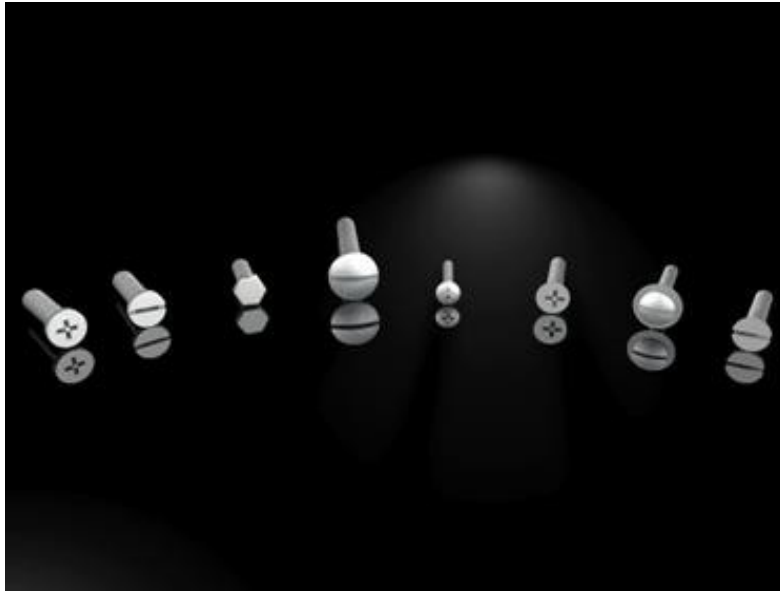
Rivets.

The most common fastener for robot construction is the machine screw, which is like a regular household screw without the tapered end. Machine screws are meant to be secured with a nut and can differ by size and number of threads per inch, head type, and driver type.

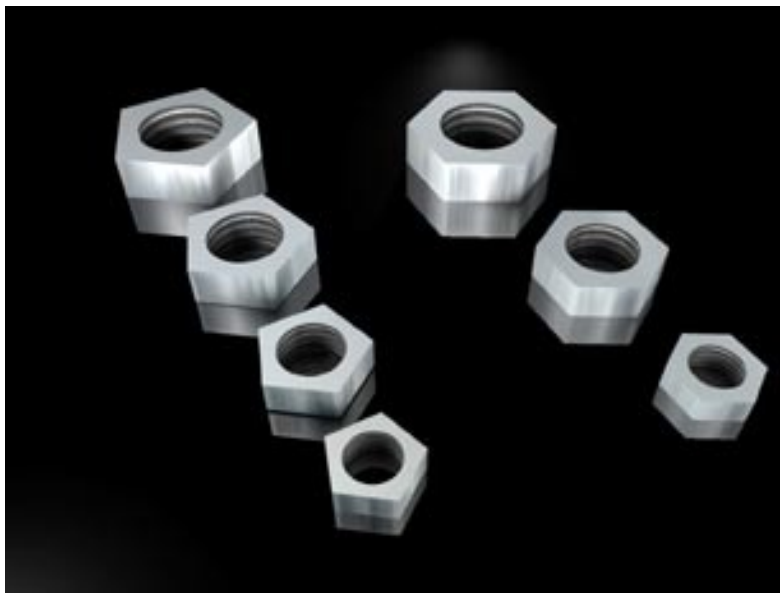
The head type refers to the shape of the head of the screw, such as pan, flat head, round, oval, Fillister, and truss. The driver type refers to the tool that needs to be used to drive the screw. Phillips and slotted are the most common types, and hex, Torx, and Pozidrive are other options.

The well-outfitted shop should have a good supply of 6/32, 8/32, and 10/32 stainless steel nuts and screws.

Machine screws are held in place with nuts. Six-sided hex nuts and wing nuts are some of the most common, but there are also nuts that dig into soft material called blind nuts, self-locking nuts with nylon inserts, and many other varieties.



Array of screws.



Five-sided and six-sided hex nuts.

Washers are also used with screws and nuts to help spread the tension of the screw and nut across a larger surface area. Lock washers are flat washers with teeth and prevent the nut from loosening itself from the screw.



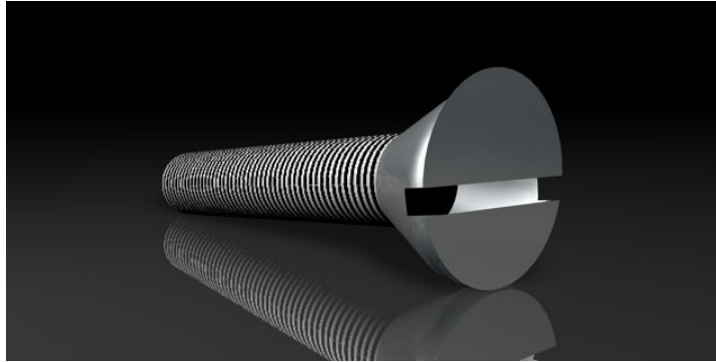
Washers.

Standard fasteners are zinc-plated steel, but screws, nuts, and washers are also made from a variety of other materials. Steel fasteners can also be found with a black-oxide finish or hot-dipped galvanized finish for use where water corrosion might occur. Stainless steel's resistance to rusting and corrosion makes it a good choice for any work that might be exposed to the elements. Brass is an attractive choice used mainly for its looks. Another attractive option is colored zinc-coated fasteners that can be found in green, yellow, and other colors.

If weight is a concern, nylon is much lighter than brass or steel, and aluminum is a great choice when weight is a concern but metal is desired. It is also the choice material if working with an aluminum structure, as steel will eventually corrode aluminum framing.

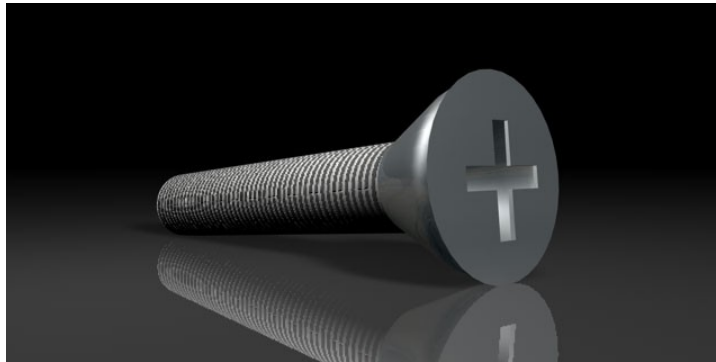
Machine Screw Types

Slotted flat head — Used for basic fastening and has a low-torque drive because the screwdriver might slip out of the slot. Good for countersinking below the surface of the material. Often you will need a countersink bit to drill countersunk holes into material to create a chamfer.



Slotted flat head.

Phillips — This cross-point drive is great for higher torque because the driver will not slip, but it is susceptible to being easily stripped out if the wrong size driver is used.



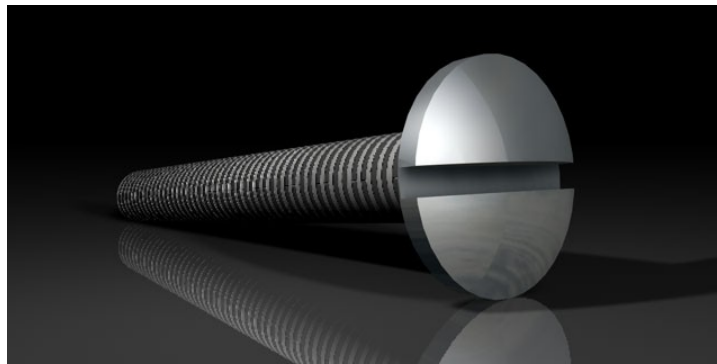
Phillips head.

Hex, Torx, and Pozidrive — These fasteners require a specific type and size of driving tool. The advantage is less stripping, but the disadvantage is that you must have the exact tool for the job.



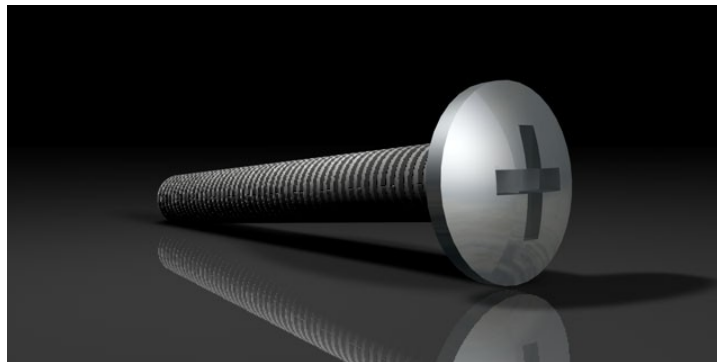
Varieties of hex screws.

Pan — This is a good basic fastener, but the shallow head might cause slippage with the driver. Drawbacks or benefits are that the pan head can protrude above the material being connected.



Pan head screw.

Round — The taller head makes this fastener good for less driver slippage and higher-torque applications. You can use a slotted or Phillips screwdriver to drive some of these.



Round head Phillips.

Countersunk — This fastener, also called a flat head, is used when the head must be flush with the surface of the project, and requires a countersunk hole.

Fillister — This fastener has a super deep head for extra torque.

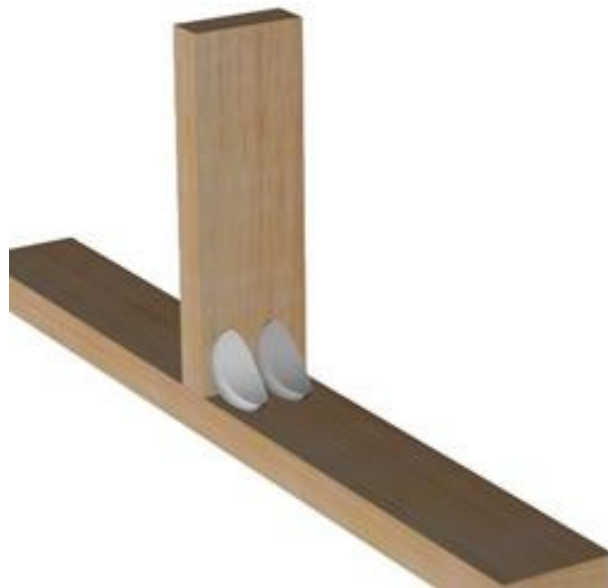
Glues

Cyanoacrylate, otherwise known as superglue, is an important glue for making quick and strong connections in porous materials. You can use cyanoacrylate to glue bits of balsa and/or basswood together for building lasting artworks and inventions. The work *Autopoiesis* in Chapter 1 was glued together with cyanoacrylate and baking soda.

Hobby shops in your town are the best source of cyanoacrylate. Stay away from small tubes of this stuff found in your local market, because it needs to be fresh in order to work properly. You can get this glue in different speeds of curing and thicknesses, but I am partial to the thin variety used with baking soda.

Be careful with this stuff, as it is very easy to stick your fingers together, as well as get this in your eye. Never bring your hands near your face or eyes when using it. Use in a well-ventilated room.

I like to use baking powder because it is common and safe.



Example of baking powder laid against basswood and then a small drop of cyanoacrylate to glue it into place.

Wood glue is an excellent glue for fastening all sorts of wood products. It is runny but will allow you to have very strong bonds.

E6000 is one of my favorite glues, as it will stick almost anything to anything else, such as fabric to glass and wood to wood. It creates a very strong bond that will be difficult to break, and it maintains a bit of flexibility, so it is fine in environments that have some vibration. You definitely need ventilation when using this glue, as the fumes are toxic. Fabric stores are good places to find this glue. Another strong glue comparable to E6000 is Gorilla Glue, available at most hardware stores.

Epoxies are important glues for all forms of extremely strong glue joints.

Generally, the longer the glue cures, the more strength it will have, and therefore, five-minute epoxy is excellent for quick points of attachment but not as strong as glues that dry for 48 hours.

The PC 7, 11, and 12 epoxies have fiber in the mix and are extremely strong, but require some cleanup for clean-looking junctions.

There is also a silver conductive epoxy, which can be used for repairing traces or creating traces on a board or other surfaces; however, you cannot solder to this epoxy, or it will melt.

Hand Tools

It is important to have a set of hand tools, and below are the recommended tools for pursuing projects, in addition to other power tools.

Soft metals such as aluminum can be easily threaded yourself with a die and tap. A die and die wrench are used to create threads on an outer surface, such as a rod.



Die wrench and die.



Dies in back row, die wrench in center, tap wrench in lower left, and taps in lower right.

A tap tool is used to create a thread in a drilled hole in metal. While it is much easier to drill and tap soft metals, use of the proper cutting oil will permit you to drill and tap steel. A good guide for this is *Constructing Robot Bases* by Gordon McComb.



Taps.



Tap wrench.

Common pliers are important tools for constructing and deconstructing machines. They can come in handy as bending tools if a vise is not available.



Pliers.

Needle nose pliers are important for making finer connections and for holding with precision or getting into tight spots. It is recommended that you have a host of these needle nose pliers.



Needle nose pliers.

Hammers are important for a number of reasons and are fantastic for making quick, temporary, or permanent structures and installations constructed of wood. As you look for hammers, be aware of the head smoothness, as some hammers have rough heads and can mar softer woods like pine, so a finish hammer may be a better purchase.



Hammer.

Matt knives are valuable for a number of reasons. They can be used with metal rulers for cutting cardboard or paper, plastic, or for cutting thin balsa and basswood.



Utility knife.

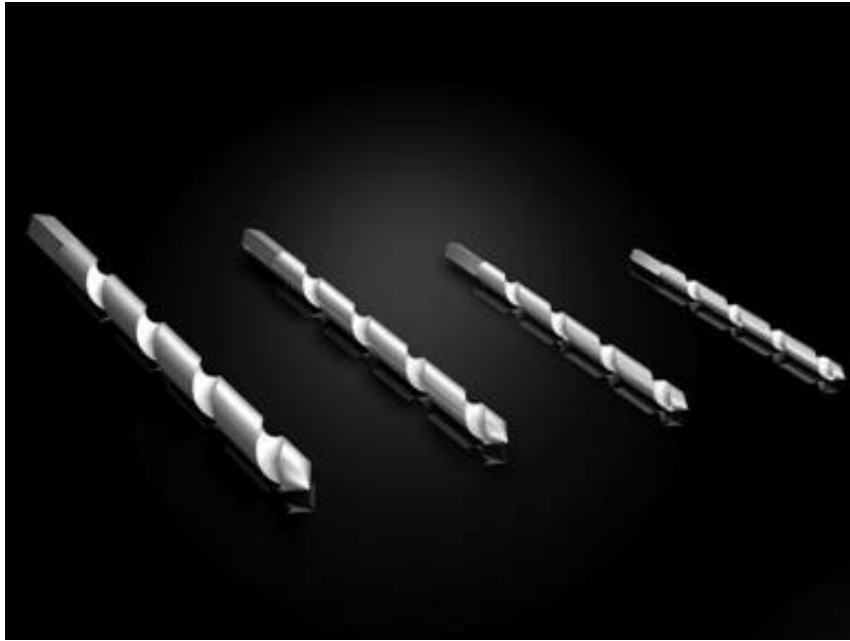
Power Tools

A hand drill is an important tool for working on installations and robots, and drills with AC cords, as well as cordless drills, are now readily available for surprisingly little money. They can be used both for manufacturing your project and as drive motors in a project.



AC drill.

Drill bits come in a variety of sizes and quality. Generally, when purchasing drill bits for your manufacturing stage, be sure you are getting the right bits for the job. For drilling steel, make sure to purchase carborundum or hardened carbon drill bits. For drilling concrete or stone, be sure to use masonry bits or tungsten carbide bits. For wood, a good set of wood drill bits will suffice, though a lip and spur drill will allow you to drill in such a way as to remove the bits of wood more efficiently. Lip and spur drills can also function well in soft plastic.



Twist drill bits.

Additional Resources

Bickford, John H. 1972. *Mechanisms for Intermittent Motion*. New York: Industrial Press Inc.
Brown, Henry T. 1868. *Five Hundred and Seven Mechanical Movements*. New York: Brown & Seward.
Chironis, Nicholas P. 1965. *Mechanisms, Linkages, and Mechanical Controls*. New York: McGraw-Hill.
Lyson, Captain Burr. 1944. *Elements of Mechanics*. New York: E. P. Dutton & Co.
McComb, Gordon. 2004. *Robot DNA Series: Constructing Robot Bases*. New York: McGraw-Hill.
McComb, Gordon. 2003. *Robot Builder's Sourcebook*. New York: McGraw-Hill.
Cabaret of Mechanical Theatre, understanding movement and making automata, by Keith Newstead.
Good resource on automata: <http://www.phm.gov.au/hsc/aibo/origins.htm>

Sources of Parts:

Small Parts Incorporated

Chapter 16

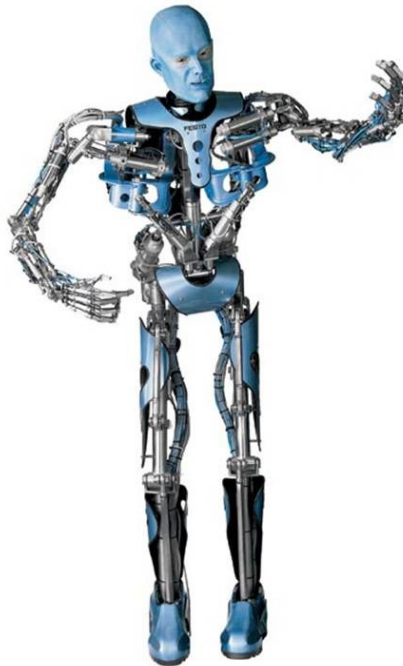
Motors and Muscles: Solenoids, Steppers, Servos, and Pneumatics

Motors and Muscles

“The function of Art is to disturb. Science reassures.”

— George Braque

The choice of using a motor or an artificial muscle to make something move in a certain way can be a complicated task and requires testing and research. Though, motorized aspects can also be important elements that give your robotic interactive work of art or invention motion and a life-like quality. The motor and muscle aspects of your project need to come together in parallel with the mechanical and electronic control system.



Festo Rubber Muscle Robot, image compliments of Festo Corporation.

The kind of motor or muscles you choose will determine much about the electronics you choose, as well as how you integrate these into a functioning project both mechanically and aesthetically. One of the more challenging aspects of using electromechanical and motorized elements is finding just the right part.

A great resource for seeing what parts are out there is Thomas Register at thomasnet.com. This site lists many industrial companies worldwide and has an excellent index, which will help you search for the products you need by part type, brand name, and company name.

DC Gearhead Motor

DC gearhead motors are very common, but when selecting a motor, try to find one that is close to the maximum speed you will need.

For example, if you want a mobile platform to move at five revolutions per minute, try to find a motor that is close to this speed, as the gear ratios will allow for enough torque to drive your platform. If you

were to select a 100 or 300-rpm motor, you would likely not have enough torque to drive the motor, as the power is reduced using PWM or variable voltages.

Think also about the voltage and amperage necessary to drive the motor. Will it be on a platform that is battery powered, or will you be driving the motor with a power supply and an AC-to-DC converter?

If you are going to use batteries, look for a low-current motor and go for the highest quality motor at the lowest cost.

3–12 volt DC motors are recommended simply because it is easier to find power supplies for these than, for instance, a 90 VDC motor. There are many sources of surplus motors, though remember that if you purchase a surplus motor for your work of art or invention, you may not be able to get this motor again if it fails.

Good surplus houses are Herbach and Rademan, 73.com, All Electronics, and Goldmine Electronics. Good sources for new motors are Solarbotics, Robotstore, and Grainger.



Nominal voltage is the motor's input voltage that is applied to move the motor under normal use. The published ratings of the motor from specification sheets define how the nominal voltage is related to the torque, speed, and amperage consumption during use.

You can use less voltage on DC motors, which will allow them to spin slower, as you learned in Chapter 12. PWM is a way to provide less voltage over time, but do not exceed the maximum voltage ratings. Torque is also related to the voltage, and the motor will have the rated torque at its maximum voltage. However, it will not have the same torque at a lower voltage, so consider this in your design.



Torque refers to the power of the motor in creating force. The motor's torque will be listed in a specification sheet that you should request or find online for each motor you use. The torque will be rated at the nominal voltage.

Operating current is the amount of current used by the motor. **Stall current** is the current the motor draws when you stop (stall) the output shaft (if you can). Stalling a motor is very hard on the motor and can burn open the motor windings and ruin the motor. If you want to test for stall current, grab the output shaft with your hand or a pair of pliers (only if the motor is not too powerful) while measuring the current drawn. Remember, some motors turn so fast and are so powerful that they can hurt your hand and arm, so do not test the current with this method if this is the case.

As the motor approaches stall, the current usage will climb. Refer to Chapters 12 and 13 for control of DC motors. A good source of used DC motors is C & H, and for new ones try Grainger and Jameco. Micromo makes some of the top-of-the-line motors in the business, though they tend to be expensive and more industry-oriented.

When thinking about using the motor to transfer the rotation of the shaft to a cam, mechanism, gear, or lever, the closer an object is to the shaft center, the more drive torque is available, and levers farther

from the motor will have less torque available. Motors are rated according to ounces per inch. A lever one inch out from the center of the shaft of a motor that is rated at one ounce can lift one ounce, or 28 grams. If a motor is rated at 16-ounce-inches, a lever one inch from the shaft will lift one pound.

Speed refers to the motor's rotational speed in revolutions per minute (RPM). The speed will vary with varying voltages and the load you place on the motor.

The *gear ratio* of the motor is the amount or degree of gearing of the motor up or down. This only counts for gear motors. If the motor has a gear ratio of 30:1, every 30 revolutions of the main motor will turn the output shaft one time. The higher the revolutions of the main motor in relation to the output shaft, the more torque you will have and the more powerful the motor will be. Incidentally, this also translates into more noise from the motor.

In order to connect a lever, piece of metal, or piece of wood to the motor shaft, you will need a shaft arbor (below) with an insert to clamp onto the shaft. The hex nuts that are placed into the motor arbor must be screwed down tight to the flat surface of the motor shaft, so they engage and hold the motor shaft tightly to the arbor. A good source for these is Grainger, item #6L105.

Another good source is McMaster-Carr; search for "shaft coupling" and you will find many options. Another key search phrase on McMaster-Carr is "arbor attachment for electric motors," and generally the motor shafts are 1/4 inch on many DC gearhead motors; however, they also have sizes in 3/8, 1/2 inch, etc., for larger shafts on AC and DC motors.



Hex bolt.



Shaft arbor.

Hex wrenches are commonly found at most hardware stores and are an important tool when working with motors, as generally you will need one of these to work with the arbors on motor shafts. A very high-torque hex bolt has no slot and needs to be tightened with a hex wrench.



Hex wrenches.

DC Gearhead Motor, Solenoids, Linear Actuators



DC gearhead motor.

For smaller applications where precise and small motors are necessary, you can use micro motors. Some of these can be controlled with voltages as low as 1.5 volts DC.



DC gearhead motor. Image compliments of Solarbotics Ltd.



GM gearbox with auto-center spring. Image compliments of Solarbotics Ltd.

Pager motors with mini gearboxes are also available from Solarbotics.



GM geared pager motor. Image compliments of Solarbotics Ltd.

12-VDC Continuous Tubular Solenoids and Linear Actuators

Solenoids are linear motors activated in the same way you would activate a regular motor. They consist of coils of wire in which you insert a metal pin. When the power is activated, the coils create a magnetic field, and this pulls the pin down. The closer the pin is to the magnetic field, the more pull strength you will get.

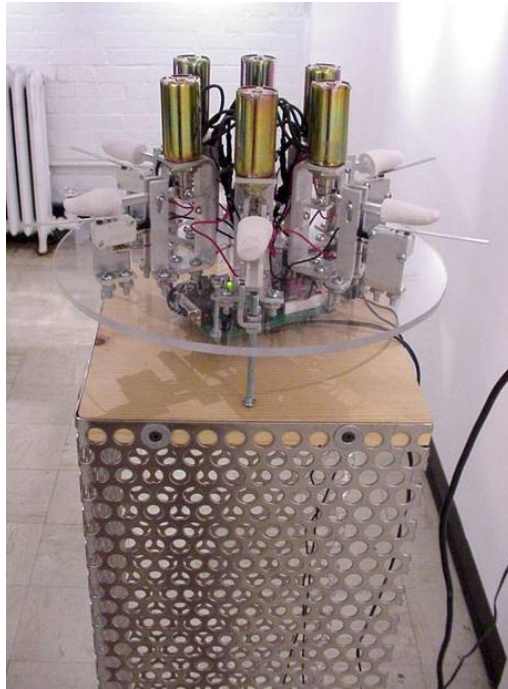


Common solenoid in a square package. Notice the holes and slot on the silver plunger, which attaches to the device or lever.

You can use a power-driving Darlington transistor such as the TIP 122, discussed in Chapter 9, or you can drive many of these devices using a ULN2803A Darlington transistor array.

Some solenoids come with springs, which hold the metal pin above the magnetic coils, and other solenoids come without springs, which you must supply in order to pull the coil up with a spring. There are push/pull solenoids that go in one direction and then the other. Continuous tubular push/pull solenoids at 12VDC are common and can be found at Jameco.com. Their life expectancy varies, so always check the data sheets.

Jesse Hemminger created a sound sculpture concerned with the continuity of family. He created molds of each family member, casting their fingers in plaster and inserting aluminum inside each cast plaster finger.



Proximal Actuator by [Jesse Hemminger](#). 2001. Photo Amy Youngs.

The fingers and aluminum levers were attached to solenoids, and as you pressed a limit switch near the fingers, they would click down in complex and evolving rhythmic patterns.



Rotary solenoid.

There are also “rotary” solenoids, which rotate roughly 45 degrees when the electromagnetic coils are activated.

You can also activate air-powered muscles with solenoids if you use pneumatic solenoids. A good source of used solenoids is C & H Surplus, though suppliers like LL Electronics and Jameco carry a selection of standard solenoids.

If you want more activation with longer reach, you can use a linear actuator. The actuators can have quite a bit of force, with some powerful enough to lift 400 pounds. The one below can actuate out to 30 inches with a force of 40 pounds.



Linear actuator.

Tubular actuators are nice looking and clean, and well suited for art and design applications where the actuator is going to be seen. They can run on 12-volt DC current and work great with the H-bridges discussed in Chapter 13. Pay attention to the amperage used, as it comes under load. The one above can extend out to 30 inches.

You can also get brackets to attach to each end of the linear actuator below. A good source for linear actuators is Fircelli Automations.



Linear actuator holding bracket.

Stepper Motors

Stepper motors have multiple coils, which can be activated separately to step the motor through specific sequences. They are accurate positional motors, and therefore the microcontroller counts through a sequence and the motor can proceed through that sequence. Stepper motors are the ideal motors for creating XY positioning tables, such as the one Shawn Brixey and Richard Reinhart used in their collaborative project *Chimera Obscura*. *Chimera Obscura* is a network-based, telerobotic artwork that was inspired by anxieties and eugenic fantasies surrounding contemporary genetics research.



Chimera Obscura by [Shawn Brixey](#) and [Richard Reinhart](#), 2002.

This collaborative project creates a discourse on human evolution, which arises out of interest and concern with the Human Genome Project.

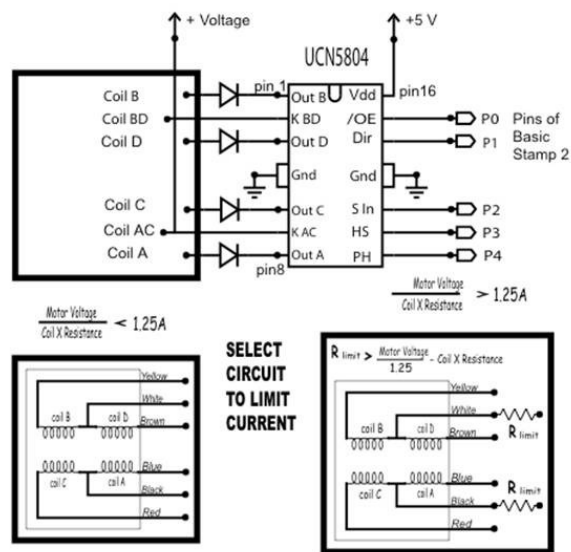
Stepper motors are the motors you will generally find in common commercial printers that drive belts on linear bearings. They can be controlled with special stepper-driving chips. You can use the ULN2803, a series of Darlington transistors in a DIP array, which can function as a power motor driver, and step the motor through its sequences using your microcontroller.

A better way to drive a unipolar stepper motor is to use a special function chip. The UCN5804 and the newer Allegro SLA7060M through SLA7062M unipolar stepper-motor translator/driver chips allow you to take the signal from the microprocessor and, with either a high or a low pulse, control the speed of the motor and the direction. This specialty chip also has a half-step function to provide more accuracy of stepping forward or back. The UCN5804 stepper driver can replace many other parts in this simple 16-pin DIP package. The driver handles motors up to 35V at 1.25A.

Stepper motors are relatively easy to use once you have determined your coils, and they become much easier to use with a specialty stepper-driving chip.



Stepper motor.



Schematic for driving a stepper motor.

Stepper Control Code

Below is Arduino code for driving a UCN5804-style unipolar stepper driver chip through its four control lines: EN (enable, active low), DIR (direction), HALF (half-step versus full-step), and PHASE (one-phase versus two-phase drive). The code cycles the motor through clockwise and counterclockwise motion in one-phase, two-phase, and half-step modes, one after another, in the same sequence as the original lesson.

```
/* Stepper driver control via UCN5804-style chip — cycles through CW/CCW, one-phase, two-phase, and
half-step motion. Adapted for Arduino from original PBASIC lesson coding by Ross Baldwin. */
const int EN = 2; // enables the driver chip when LOW
const int DIR = 3; // controls the motor direction
const int STEPIN = 4; // sends pulses to drive the motor
const int HALF = 5; // controls half or full steps
const int PHASE = 6; // controls phase information
void setup() {
  pinMode(EN, OUTPUT);
  pinMode(DIR, OUTPUT);
  pinMode(STEPIN, OUTPUT);
  pinMode(HALF, OUTPUT);
  pinMode(PHASE, OUTPUT);
}
void loop() {
  stepMotor(LOW, LOW, HIGH); // clockwise, one phase
  stepMotor(HIGH, LOW, HIGH); // counterclockwise, one phase
  stepMotor(LOW, LOW, LOW); // clockwise, two phase
  stepMotor(HIGH, LOW, LOW); // counterclockwise, two phase
  stepMotor(LOW, HIGH, LOW); // clockwise, half step
  stepMotor(HIGH, HIGH, LOW); // counterclockwise, half step
}
// direction: LOW = clockwise, HIGH = counterclockwise
// half: LOW = full steps, HIGH = half steps
// phase: HIGH = one phase, LOW = two phase
void stepMotor(int direction, int half, int phase) {
  digitalWrite(EN, LOW); // enable the driver chip to control the motor
  digitalWrite(DIR, direction);
  digitalWrite(HALF, half);
  digitalWrite(PHASE, phase);
  for (int x = 1; x <= 100; x++) {
    digitalWrite(STEPIN, LOW);
    digitalWrite(STEPIN, HIGH); // creates a pulse on STEPIN
    delay(1); // brief high pulse
    digitalWrite(STEPIN, LOW);
    delay(2); // pause between pulses
  }
}
```

```
digitalWrite(EN, HIGH); // disable the driver chip's control of the motor  
}
```

As with the original lesson, this same approach works equally well on an ESP32, substituting whichever GPIO pins are convenient on your board for EN, DIR, STEPIN, HALF, and PHASE.

Original coding by Ross Baldwin.

DC Servo Motor, Muscle Wire, Pneumatics, and Rubber Muscles

Servo motors are wonderful motors that can provide a high level of torque and precise control. Servo motors can rotate in both directions, generally from 0 degrees to 180 degrees, though they can also be purchased with a more limited range of rotation, such as 60 degrees or 90 degrees. They can also be modified for continuous rotation, though you can purchase them pre-modified for continuous rotation. A DC servo motor's shaft is positioned by sending a coded signal. As the signal to the motor varies, the shaft rotates to a new position. For their size, servo motors are quite powerful.

When searching for a DC servo motor, you must consider the weight of the motor, the torque of the motor rated in ounce-inches, the shaft speed, the voltage, maximum current, and the life or number of rotations it will withstand.

Current refers to the max current that can activate the motor without overheating the motor coils. Torque is the rotational power of the motor under continuous conditions where the shaft is under load.



3D model of a servo motor.

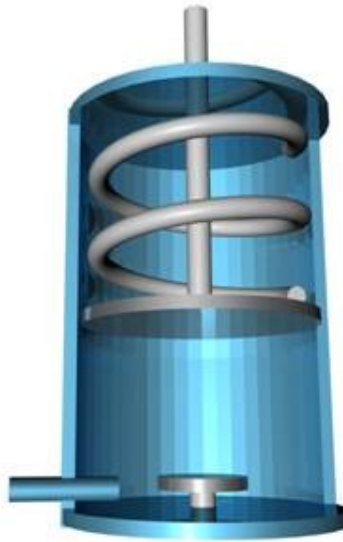
Muscle Wire

Nitinol is an alloy wire material that expands when given electricity and contracts when it does not receive the electricity. It is effective for moving applications but not so good where the speed of the system is critical, though it can move relatively quickly. When muscle wire is activated, you can move it back into position faster by pulling it back with another muscle wire, or you can use a spring. The wire will consume more current based on its width.

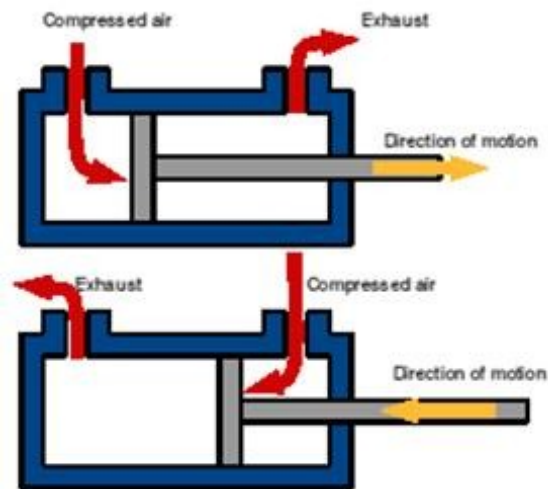
Pneumatics

Pneumatics use compressed air to move and control linear actuated valves. Compressed air can drive linear piston cylinders as well as drills, automatic doors, and hammer drills.

The cylinders can convert compressed air into motion, and a piston is pushed by the compressed air. One type of cylinder is a single-acting cylinder (below), which has one air outlet.



Single-acting cylinder.



Double-acting linear actuated valves have two connections to outlets.

Rubber Muscles

The Festo rubber muscle robot that started this chapter is a beautiful figurative sculpture. [Festo](#) is a large company that specializes in rubber muscles, and artists like [Stelarc](#) have used these to create large walking robots.

The artist David Foster has constructed his own pneumatic rubber muscles and has given us the recipe below.



David Foster's homemade pneumatic rubber muscle.

Note these parts are not part of the kit you received but can be obtained from the sources in the next section.

This homemade muscle will contract by 20% at 75 PSI. Cut Manosil rubber tubing 10% shorter than polyester sleeving. Insert hose barbs into the ends of the rubber tubing.



Rubber tubing below polyester sleeving.

Slide the rubber tubing with hose barbs through the polyester sleeving. Move hose clamps over the hose barbs and crimp. Add necessary hardware. Fabricate and attach fasteners.



Tubing inside polyester sleeve.

Rubber Muscle Parts

Minimatic hardware and valves from clippard.com:

11752 (1/8" hose barb, 10/32 male)

15002-3 (10/32 T)

15004 (10/32 coupling)

11755 (10/32 screw plug)

15006-1 (10/32 to 1/8" NPT adapter)

5000-1 or 1A (small and large hose clamps)

EV-3-12 (12V NC valve, 5–10 milliseconds @ 105 PSI response)

Manosil® silicone rubber is available at vwrsp.com.

Polyester sleeving is available at alphawire.com.

Chapter 17

Interface: Sensors and Resources

Interface: Sensors and Resources

“The responsive environment has been presented as the basis for a new aesthetic medium based on real-time interaction between men and machines.”

— Myron Krueger

Question: What other input possibilities are available for my microprocessor?

The common cockroach is equipped with thousands of tiny sensory hairs on its legs and abdomen, making it one of nature's fastest escape artists. These hairs detect the slightest changes in air movement, allowing the insect to react before a predator can strike. As Dr. Hananel Davidowitz of the NEC Research Institute in Princeton, New Jersey, remarked, *“the jet-propelled bug thinks with its behind.”*

The cockroach senses approaching danger using two small appendages at the rear of its body called **cerci**. Air currents bending the sensory hairs on the cerci activate a network of **14 giant interneurons** that relay the information directly to the legs. Because this rapid escape pathway bypasses much of the brain's processing, the cockroach can begin running almost instantly. In addition to the cerci, each leg is covered with tens of thousands of sensitive hairs that respond to touch and vibration, providing an additional early-warning system that makes the cockroach remarkably difficult to catch.



The end of a cockroach leg from the video *Squish* by [Catherine Chalmers](#), 2003.

Herein lies one of the greatest challenges of interactive electronics: integrating many sensors while efficiently collecting, processing, and managing the data they generate. The sensors you choose become the **eyes, ears, nose, and skin** of your invention or artwork, allowing it to perceive and respond to its

environment. As your projects grow in complexity, you'll need to consider not only how to process information from multiple sensors, but also practical issues such as wiring, power distribution, signal When selecting sensors for your project, first decide what type of information you want to measure. Do you simply need to know whether something is **on or off**, such as whether a button has been pressed or a door has opened? If so, a **digital sensor** is usually the best choice because it produces only two states: **HIGH** or **LOW** (on or off). On the other hand, if you want to measure something that changes continuously—such as light intensity, temperature, sound level, pressure, or distance—you will typically use an **analog sensor**.

If you choose an **analog sensor**, its continuously changing signal must be converted into digital data that a microcontroller can understand. This is the job of an **analog-to-digital converter (ADC)**. Fortunately, most modern microcontrollers, including the **Arduino** and **ESP32**, have built-in ADCs, making it easy to connect analog sensors directly.

While sensors provide the input to your microcontroller, it is your **program** that transforms those signals into meaningful interactions. The same sensor can produce very different behaviors depending on how you write your software. An excellent resource for learning about sensors, programming, and project ideas is the **Arduino Project Hub**, which contains hundreds of examples and tutorials.

For example, a simple pushbutton can do much more than turn something on or off. The first press might start a motor, the second could change its speed, and the third might stop it altogether. By keeping track of previous events and combining information from multiple sensors, your program can create rich, responsive, and engaging behaviors.

Choosing the right sensor begins with understanding **what you want to sense**. Are you detecting people, animals, plants, or changes in the environment? How quickly must your system respond? Some applications require only a few measurements each second, while others—such as tracking movement or sound—may require hundreds or even thousands of samples per second.

You should also consider the environment in which the sensor will operate. Will it be used indoors or outdoors? Is it exposed to moisture, dust, vibration, or extreme temperatures? Will people interact with it directly through touch, or should it detect their presence without physical contact? Some sensors are designed specifically for measuring motion, distance, force, light, sound, or magnetic fields, while others combine several sensing capabilities into a single device.

Finally, think about the **human experience**. A familiar interface, such as a wall switch or pushbutton, feels natural because most people have used one throughout their lives. Yet even these simple devices had to be learned at some point. Successful interactive systems build on familiar experiences while introducing new possibilities in intuitive ways.

Artist **Perry Hoberman** has been particularly successful at creating interactive installations that invite people to explore through simple, familiar actions. His work demonstrates that compelling interaction often depends less on complex technology than on carefully designing the relationship between people, sensors, and responsive behavior.



Faraday's Garden by [Perry Hoberman](#). 1990–1999.

As crowds stream through this landscape of appliance nostalgia, their footsteps, conversations, and movements combine to create a rich acoustic tapestry, transforming the installation into a living social environment.



Faraday's Garden by [Perry Hoberman](#). 1990–1999.

The nostalgic beauty of these Goodwill treasures pays homage to **Michael Faraday**, whose pioneering work on electromagnetism led to the development of the AC motor that powers most of these appliances to whirl, chop, and spin. Together, these familiar machines create a rich and immersive sonic environment. The interface for the installation is equally simple and intuitive: pressure-sensitive floor mats activate the appliances as visitors walk through the space. This direct relationship between movement and sound creates an immediate sense of cause and effect, making the interaction effortless, engaging, and highly effective.

One of **Anicka Yi's** most significant interactive works is *In Love With The World* (2021), commissioned for the Turbine Hall at Tate Modern. Rather than creating robots that perform predetermined movements, Yi imagined an ecosystem of airborne organisms she called "**aerobes**." Inspired by jellyfish, spores, mushrooms, and microscopic marine organisms, these helium-filled autonomous sculptures drifted through the enormous gallery as though they were living creatures inhabiting a new atmospheric biosphere. The installation asks viewers to imagine a future in which machines evolve alongside biological organisms instead of simply serving humans.

Unlike conventional drones that follow fixed flight paths, the aerobes exhibited individual and collective behaviors. Two principal "species" occupied the hall:

- **Xenojellies** – translucent, tentacled aerobes that explored the space more actively.
- **Planulae** – fuzzy, cilia-covered forms that tended to remain lower in the environment and behaved more conservatively.

Together they created the impression of an artificial ecosystem rather than a collection of independent robots.

Sensors and sensing technologies

Yi and her collaborators—including engineers from Sitara Systems—have described the sensing system in broad terms. The installation incorporated several forms of environmental sensing:

- **Overhead electronic tracking sensors** monitored the positions of the aerobes throughout the Turbine Hall.
- **Human-presence sensing** allowed the aerobes to respond to visitors, maintaining comfortable distances while exhibiting apparent curiosity toward human activity.
- **Heat sensing** enabled the aerobes to detect the warmth of nearby people, causing them to drift toward visitors without making contact.
- **Proximity and collision-avoidance sensing** prevented aerobes from striking one another or the architecture while maintaining fluid, lifelike movement.
- **Localization sensors** allowed the aerobes to navigate back to a maintenance station for battery replacement before returning to the exhibition space.
- **Artificial life software** coordinated these sensor inputs, producing emergent group behaviors rather than scripted choreography. Each aerobe continually adjusted its actions based on the state of the larger ecosystem.

The project is particularly notable because the sensors were not used merely to trigger responses. Instead, they continuously informed an artificial-life simulation that determined how each organism behaved within the larger population. This approach resembles biological systems, where individuals respond to local environmental conditions while producing complex collective behaviors.

Scent as an environmental sensor

Yi also extended the concept of sensing beyond electronics. Throughout the exhibition she created **changing scent environments** that evolved weekly, referencing different historical periods associated with the former Bankside Power Station and surrounding neighborhood. While the aerobes themselves were influenced primarily through their software ecosystem, the installation encouraged viewers to consider smell as another form of environmental intelligence alongside vision and motion.

Why the work is significant



In Love With The World demonstrates a shift away from traditional interactive art, in which visitors directly activate artworks through buttons or motion sensors. Instead, humans become just one element within a much larger ecological system. The aerobes respond to people, architecture, airflow, and one another, creating an installation whose behavior continuously changes over time.

Yi's work suggests that future robotic systems may be less like tools and more like independent species coexisting with humans in shared environments.



Artist [Ian Haig](#) is also fascinated by interfaces, but in *Excelsior 3000* he pushes the concept to humorous and provocative extremes. Toilets are, in many ways, a form of **cyborg technology**—devices that extend and augment the human body.

In *Excelsior 3000*, Haig playfully reimagines our relationship with this everyday object, satirizing the growing market for increasingly sophisticated, high-tech toilets while inviting viewers to reconsider the boundary between the human body and the technologies it depends upon.

Haig has created an interactive toilet that, in effect, becomes an extension of the human digestive system, blurring the boundary between the body and technology while transforming an ordinary household fixture into an interactive experience.

Maxuino/Arduino Photo Resistors

Photoresistors, also called **light-dependent resistors (LDRs)**, are variable resistors whose electrical resistance changes according to the amount of light falling on their surface. As the light level increases, the resistance decreases, allowing more current to flow. In darkness, the resistance rises significantly. This simple property makes photoresistors an inexpensive and effective way to measure changes in ambient light.

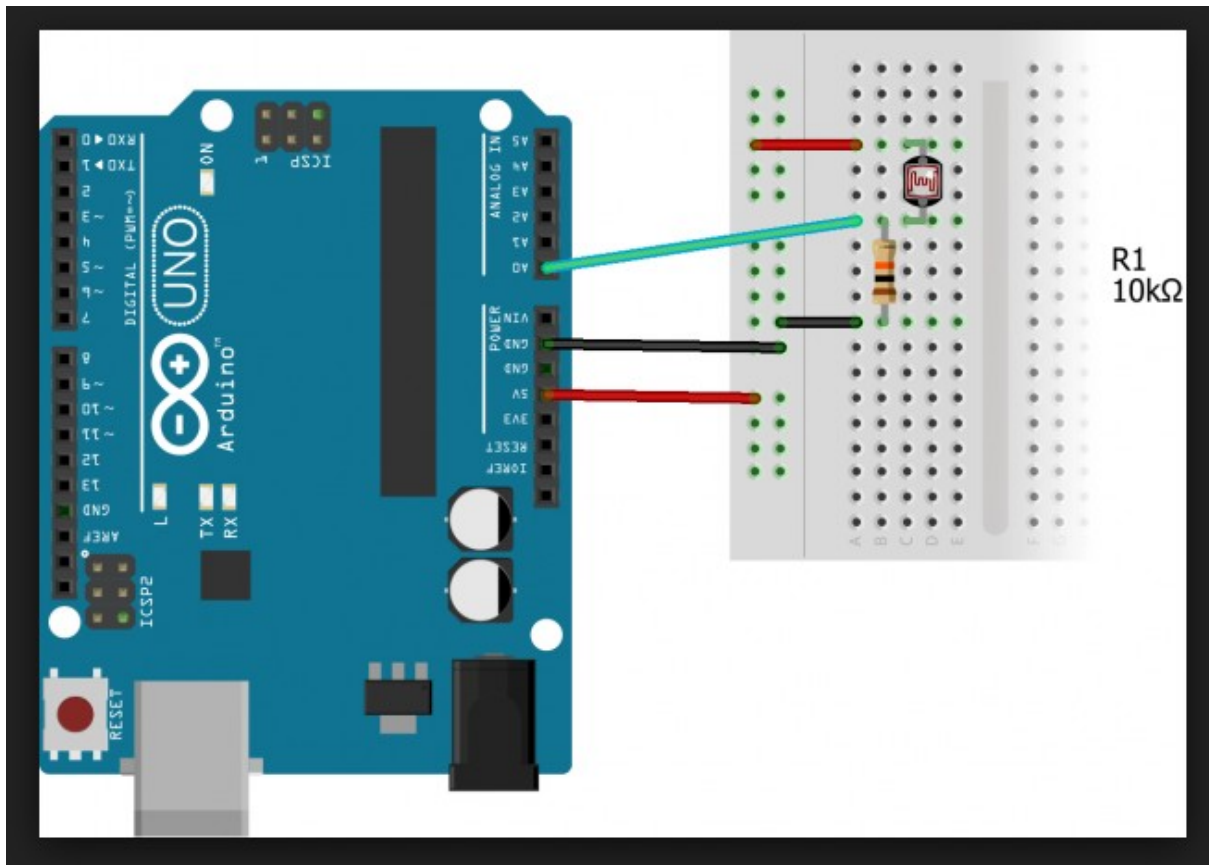
Photoresistors respond to the number of **photons** striking their light-sensitive material and are most sensitive to visible light in the **500–600 nanometer (nm)** wavelength range, which corresponds to the green-yellow portion of the spectrum where the human eye is also most sensitive. Although they are slower than photodiodes or phototransistors, they are ideal for many interactive projects where rapid response is not required.

A photoresistor can be made more directional by placing it inside a small tube or short piece of black plastic tubing. This blocks light arriving from the sides and limits its field of view, making the sensor more responsive to shadows or light coming from a particular direction. This simple technique is useful for applications such as tracking a moving light source, detecting a hand passing over the sensor, or reducing the influence of ambient room lighting.

Because a photoresistor produces a changing resistance rather than a voltage, it is typically connected in a **voltage divider** circuit with a fixed resistor. The junction between the two resistors produces a variable voltage that changes with light intensity. This voltage is then connected to one of the **analog input pins** of an Arduino, ESP32, or other microcontroller, where the built-in analog-to-digital converter (ADC) converts the signal into a numerical value that your program can interpret.

Photoresistors are commonly used in projects that automatically turn lights on at dusk, adjust display brightness, detect shadows, follow a flashlight beam, measure ambient lighting, or create interactive artworks that respond to changes in illumination. Their low cost, simple wiring, and ease of programming make them one of the most popular sensors for beginning electronics students.

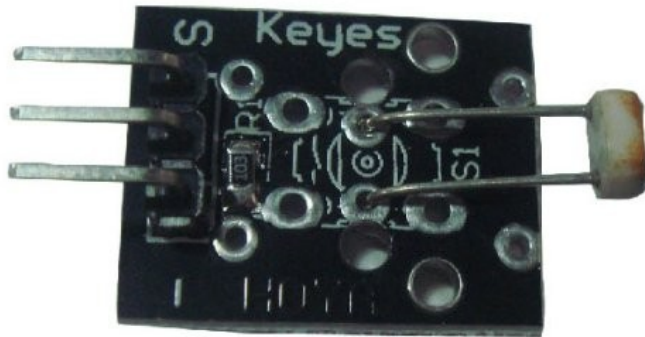
Typical Circuit: Connect one lead of the photoresistor to **5 V** (or **3.3 V** for an ESP32), the other lead to an analog input pin, and connect a **10 k Ω resistor** from that analog pin to **ground**. This forms the voltage divider needed to produce a voltage that varies with the amount of light reaching the sensor.



If you did not want to build your own, some sensors come with the 10K ohm resistor already part of the board.

Keyes KY-018 Photosensitive Resistance Sensor Module for Arduino

As with all photosensors, they can be used for wide-pan sensing to sense shadows. We see them in solar garden lights, lawn detectors, clocks, musical gift boxes, mini night lights, light-switching toys, as well as a variety of light control applications. Working voltage: 5V. PCB size: 1.5 x 1.9 cm.



Keyes photoresistor module.

The code for the analog input for the photo resistor is the same as that for the potentiometer.

DHT11 Temperature / Humidity Keyes KY-015 Module

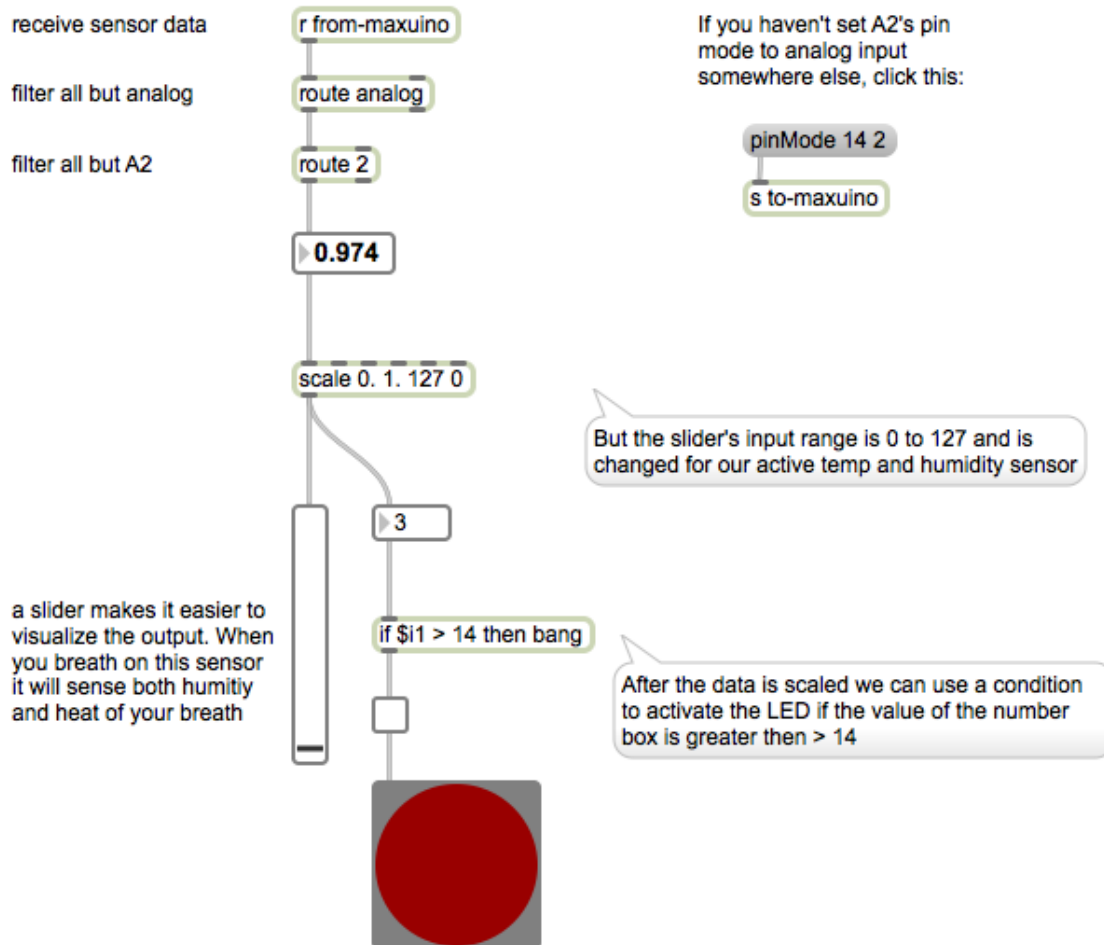
REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port. Make sure you also activate the analog input pin selector in this case pin number A0 or pin 14 are the same pin. (Lower right hand area analog input pins)

Connections to Arduino:

A0: Remember pins A0-A5 or pins 14-19

G: Ground

+: Arduino 5V



Copyright Ken Rinaldo.

Maxuino/Arduino Active Infrared

Active infrared (IR) distance sensors are among the most useful sensors for mobile robots and interactive installations because they contain both an **infrared emitter** and a **receiver** in a single package. Unlike passive infrared (PIR) sensors, which detect changes in heat emitted by people or

animals, active IR sensors illuminate the environment with invisible infrared light and measure the reflected signal to determine whether an object is present and, in many cases, how far away it is.

Many active IR sensors modulate their infrared LED at approximately **38–40 kHz**. By transmitting a rapidly pulsed infrared signal and looking only for reflections at that same frequency, the sensor can reject most ambient light from sunlight and room lighting. This modulation greatly improves reliability, allowing the sensor to operate in a wide variety of lighting conditions.

Several different types of active infrared sensors are available. Some simply detect whether an object is present within a fixed range, while others measure the actual distance to an object. Distance-measuring sensors generally use **optical triangulation**, projecting a narrow beam of infrared light onto an object and measuring where the reflected beam strikes a position-sensitive detector (PSD). As the object moves closer or farther away, the angle of the reflected beam changes, producing an analog voltage that corresponds to distance. Because the measurement is based on geometry rather than reflected light intensity alone, these sensors are more accurate than simple reflective IR detectors and are relatively insensitive to the color or brightness of the target.

One of the most popular sensors for robotics and interactive art is the **Sharp GP2Y0A02YK0F** infrared distance sensor. This sensor measures distances from approximately **20 cm to 150 cm (8 to 60 inches)** and produces a continuously varying **analog output voltage** that can be read directly by an Arduino or ESP32 analog input. It operates from a **5-volt supply**, updates approximately every **39 milliseconds**, and contains all of the optics and signal processing electronics within a compact package. Because of its wide range, reliability, and ease of use, it has become a standard sensor for obstacle avoidance, autonomous navigation, interactive sculptures, and kinetic artworks.

The shorter-range **Sharp GP2Y0A21YK0F** is equally popular for tabletop robots and installations, measuring distances from **10 cm to 80 cm**, while other members of the Sharp GP2Y0 family cover ranges from only a few centimeters to more than a meter. Selecting the appropriate model depends on the working distance required by your project.

Because these sensors produce an **analog voltage**, they require only three connections:

- **5 V**
- **Ground**
- **Analog Output**

The analog output is connected directly to one of the analog input pins on an Arduino or ESP32, where the built-in analog-to-digital converter (ADC) converts the voltage into a numerical value. Your software can then translate this value into an approximate distance using a calibration table or mathematical equation. Since the voltage-distance relationship is **nonlinear**, calibration produces more accurate measurements than assuming a simple linear relationship.

Active infrared sensors are excellent for:

- Obstacle avoidance in mobile robots
- Detecting approaching visitors in interactive artworks
- Measuring hand position for touch-free interfaces
- Autonomous navigation

- Interactive musical instruments
- Kinetic sculptures that respond to viewer proximity

One limitation is that they perform best with solid, opaque objects. Highly reflective, transparent, or very dark surfaces can reduce measurement accuracy, although they generally remain more reliable than simple reflective infrared sensors.

For new designs, Sharp/Socle Technology continues to manufacture these sensors, and they are readily available through DigiKey:

- **Sharp GP2Y0A02YK0F** (20–150 cm analog distance sensor)
- **Manufacturer:** Sharp/Socle Technology
- **Available from:** [DigiKey](#) (or search for **GP2Y0A02YK0F** if inventory varies)

These sensors remain an excellent choice for education because they require minimal circuitry while providing robust, real-time distance measurements.



Active Infrared Sensor (2YA02 Sharp Sensor)

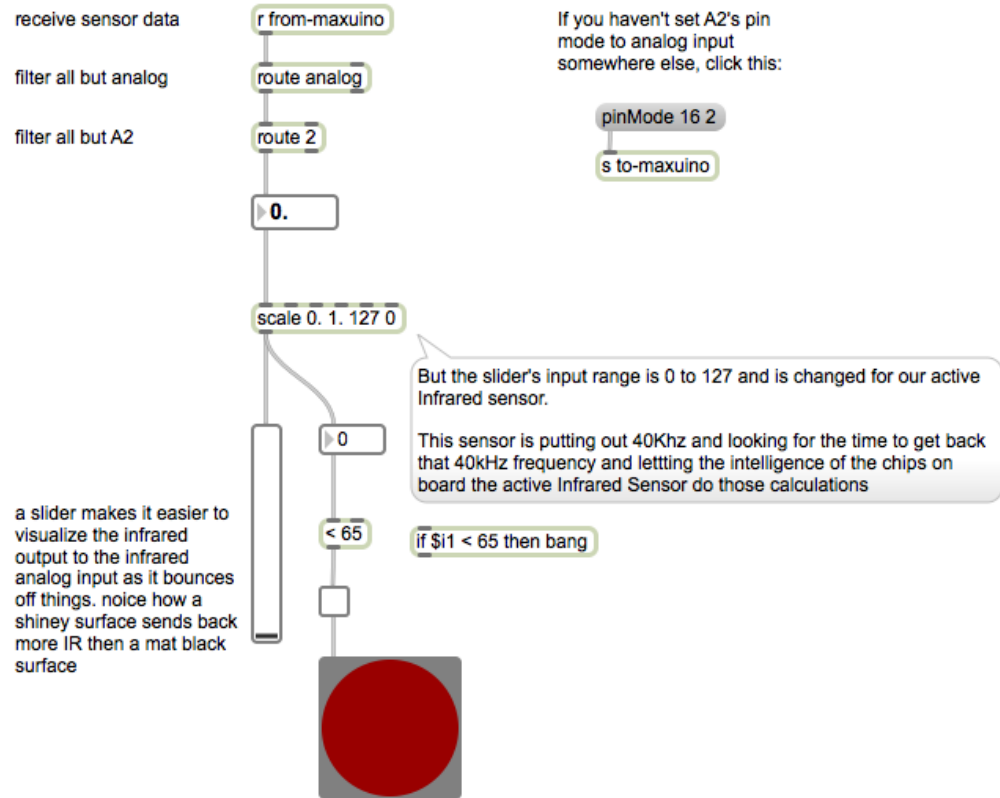
REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port. Make sure you also activate the analog input pin selector in this case pin number A2 or pin 16 are the same pin. (Lower right hand area analog input pins)

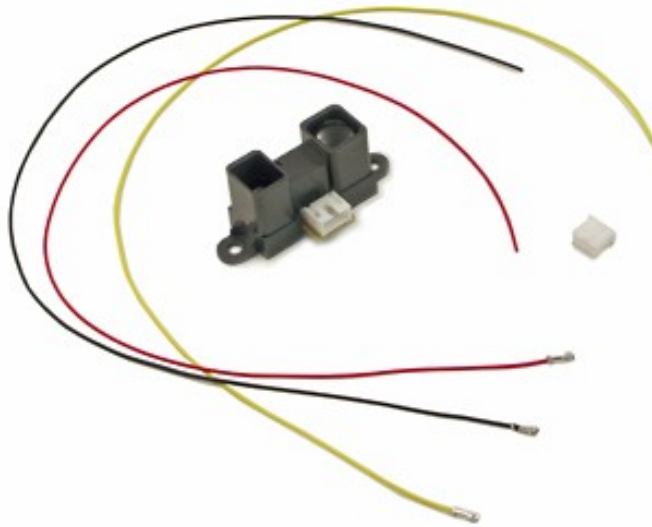
Connections to Arduino:

A0: Remember pins A0-A5 or pins 14-19

G: Ground

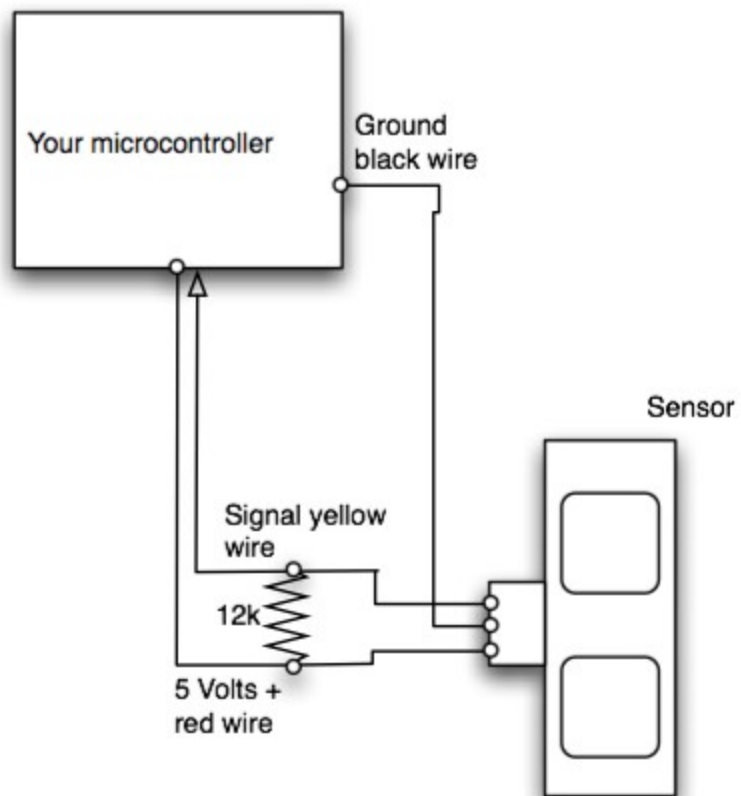
+: Arduino 5V





Using optical triangulation, the **GP2Y0A02YK0F** above measures distances from approximately **20 cm to 150 cm (8-60 inches)**, making it well suited for longer-range obstacle detection and interactive sensing applications.

Circuit layout for Sharp GP2Y0D02YK



Maxuino/Arduino Force and Bend Sensors

Force Sensors

Force-sensitive resistors (FSRs) measure the amount of force or pressure applied to their sensing surface. One of the most widely used FSRs is the **FlexiForce™ A201**, manufactured by **Tekscan**. These thin, flexible, piezoresistive sensors change their electrical resistance as force is applied. With little or no pressure, the sensor has a very high resistance. As the applied force increases, the resistance decreases, producing a signal that can be measured by an Arduino, ESP32, or other microcontroller using a simple voltage divider circuit.

The FlexiForce A201 is only **0.008 inches (0.2 mm)** thick, making it easy to embed beneath surfaces, fabrics, or flexible materials without significantly changing their appearance or feel. At one end of the sensor is a **three-pin connector** for interfacing with electronics, while the opposite end contains a **0.375-inch (9.5 mm) diameter circular sensing area** that acts as the force transducer. The sensor itself remains flexible, allowing it to conform to curved surfaces while maintaining reliable force measurements.

Unlike a pushbutton that simply reports **on** or **off**, a force sensor provides **continuous analog data**. This allows your program to distinguish between a light touch, a firm press, and a heavy load. The sensor can therefore become an expressive interface rather than a simple switch.

FlexiForce sensors are commonly used in:

- Interactive sculptures and installations
- Electronic musical instruments
- Robotic grippers
- Wearable electronics
- Smart textiles
- Medical and rehabilitation devices
- Pressure mapping and human-computer interfaces

To interface the sensor with an Arduino or ESP32, the FlexiForce is typically connected as one half of a **voltage divider** using a fixed resistor. The junction between the resistor and the sensor is connected to one of the microcontroller's analog input pins. The built-in analog-to-digital converter (ADC) converts the changing voltage into a numerical value that your software can interpret. Because the resistance changes nonlinearly with force, applications requiring accurate force measurements should be calibrated using known weights or forces.

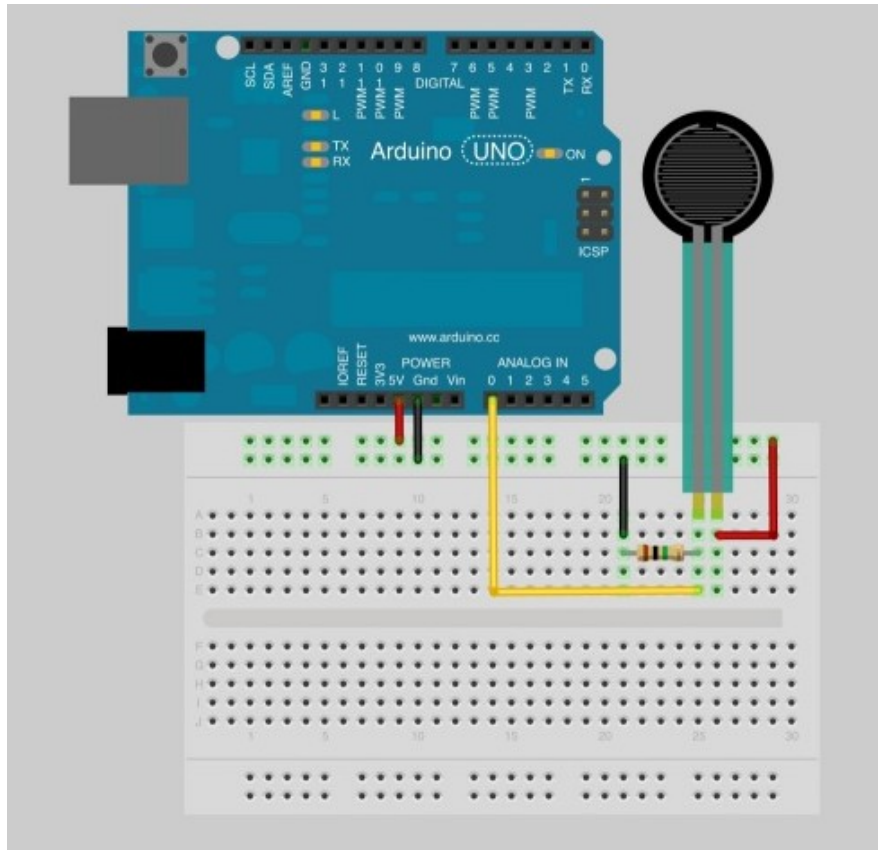
For most interactive art projects, however, precise force measurement is unnecessary. Instead, the sensor provides an intuitive way for users to control sound, light, video, or robotic movement through variations in pressure. A gentle touch might trigger one response, while increasing pressure can continuously alter brightness, motor speed, musical pitch, or other behaviors, creating a much richer interaction than a simple pushbutton.



Pressure sensor.

The FlexiForce sensor produces a continuously varying **analog voltage** that can be read directly by the built-in **analog-to-digital converter (ADC)** on an Arduino UNO, ESP32, or most modern microcontrollers. Depending on the model and calibration circuit, the sensor typically outputs a voltage proportional to the applied force (for example, approximately **0–4.2 V** over its operating range). To interface the sensor with an Arduino UNO, connect it as one half of a **voltage divider** using a **10 k Ω resistor**, as shown in the schematic below. The junction between the sensor and the resistor is connected to one of the Arduino's analog input pins, where the ADC converts the changing voltage into a digital value that your program can process. By calibrating the sensor with known weights, you can estimate the force being applied or simply use the readings to create expressive, pressure-sensitive interactions.

Note: The Arduino UNO uses a **10-bit ADC**, producing readings from **0–1023**, while the ESP32 typically provides a **12-bit ADC**, producing values from **0–4095**, giving higher measurement resolution. Both microcontrollers can read the FlexiForce sensor using the same voltage-divider circuit.



Maxuino/Arduino Temperature/Moisture Sensor

Temperature and Humidity Sensors

The **Keyes KY-015** module is an inexpensive temperature and humidity sensor commonly used in educational electronics projects. It is based on the **DHT11** digital temperature and humidity sensor and combines a humidity-sensing element with a temperature sensor and a small onboard microcontroller that performs calibration and signal processing. Rather than producing an analog voltage, the module outputs a **digital data stream**, allowing it to communicate directly with an Arduino, ESP32, or other microcontroller using a single data pin.

The DHT11 measures **relative humidity** using a **resistive polymer humidity sensor**, whose electrical resistance changes as moisture in the surrounding air is absorbed or released. Temperature is measured using an **NTC (Negative Temperature Coefficient) thermistor**, a resistor whose resistance decreases as temperature increases. An integrated 8-bit microcontroller inside the sensor converts these measurements into calibrated digital values and transmits them over a proprietary single-wire communication protocol. Because the sensor performs the analog-to-digital conversion internally, it is relatively immune to electrical noise and requires only one digital input pin on the microcontroller.

The DHT11 is designed for applications where moderate accuracy is sufficient. It measures temperatures from approximately **0°C to 50°C (32°F to 122°F)** with an accuracy of about **±2°C**, and relative humidity from **20% to 90% RH** with an accuracy of approximately **±5% RH**. The sensor

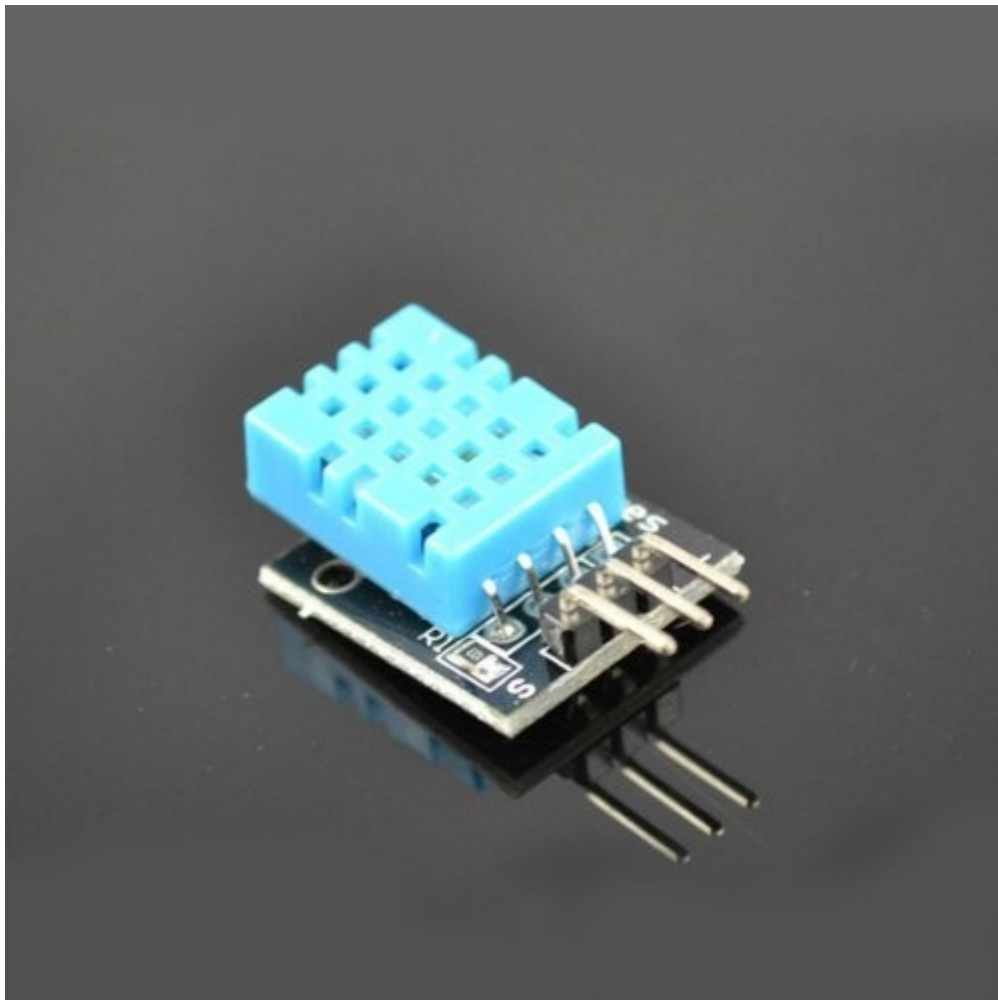
updates about **once per second**, making it suitable for monitoring environmental conditions but not for rapidly changing measurements.

Temperature and humidity sensors are frequently used in interactive installations, greenhouses, environmental monitoring, weather stations, terrariums, museum displays, and artworks that respond to changing atmospheric conditions. For example, an installation might gradually alter lighting, sound, or robotic movement as humidity rises, or respond differently as the ambient temperature changes throughout the day.

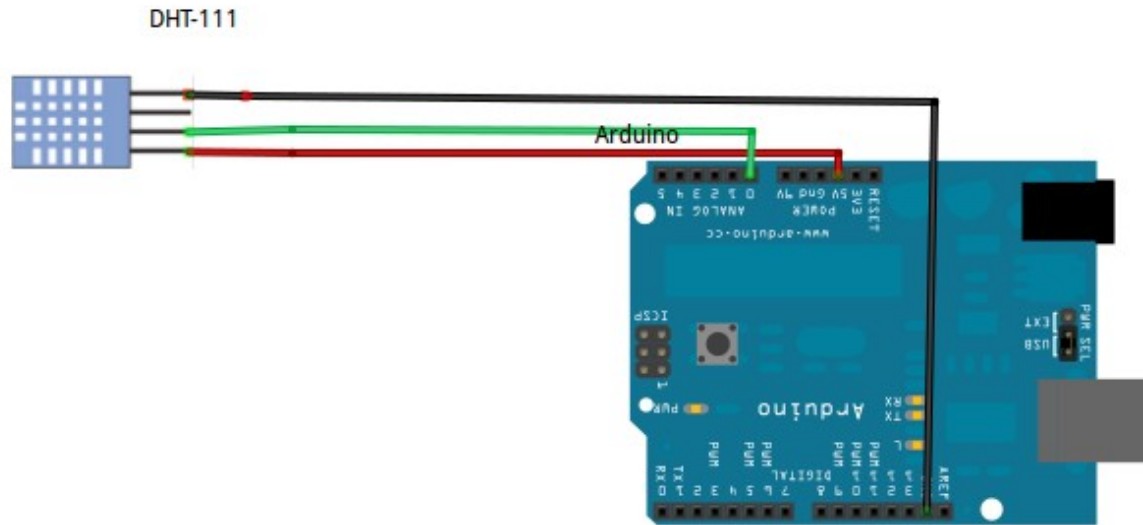
The **DHT22 (AM2302)** or **Sensirion SHT31/SHT40** sensors offer a significantly higher accuracy, wider operating ranges, and faster response times.

Sources

- **Adafruit DHT11, DHT22, and AM2302 Guide** (excellent wiring and programming examples):
<https://learn.adafruit.com/dht>



Keyes 015 sensor.



Hookup of the Keyes 015 sensor to the Arduino. Notice that one pin is not used, though on the sensor board by Keyes it is not attached to one of the three pins you see in this diagram.

Maxuino/Arduino Tilt, Limit Switches, Magnetic Reed

Switches

Switches are among the simplest and most reliable sensors used in interactive electronics. Although they provide only two states—**on** or **off**—they remain one of the most effective ways for people to communicate with an interactive system. Nearly everyone understands how to press a button, flip a switch, or activate a lever, making switches an intuitive interface that requires little or no explanation.

While switches are technically simple, they need not feel mechanical or uninspiring. The physical design of a switch strongly influences how people approach and interact with an artwork or device. Large arcade buttons, illuminated pushbuttons, foot pedals, toggle switches, or oversized industrial controls each communicate different expectations and invite different kinds of interaction. Choosing the appropriate switch is therefore not simply an engineering decision but also an aesthetic and conceptual one.

Robust **illuminated pushbuttons**, such as those commonly used in arcade machines and pinball games, are particularly well suited to interactive installations. These switches contain bright LEDs beneath translucent caps, allowing them to glow even in dim exhibition spaces. The illumination naturally attracts visitors, encouraging them to touch, press, and explore the interface without requiring written instructions. The satisfying tactile "click" and visual feedback also reinforce the participant's actions, making the interaction feel more responsive and engaging.

Many suppliers of arcade and pinball components offer durable pushbuttons designed to withstand hundreds of thousands—or even millions—of actuations. Their rugged construction makes them an excellent choice for museum installations, where reliability is essential and visitors of all ages may interact with the work continuously for months.

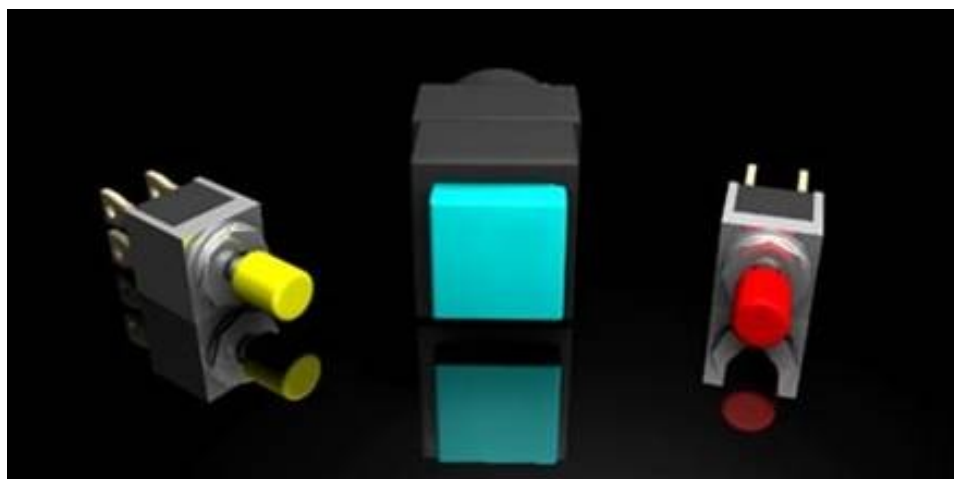
When selecting a switch, however, consider not only its function but also its **cultural associations**. Every interface carries a history. A polished chrome arcade button may evoke video games and playful competition, while an industrial emergency stop button suggests urgency or danger. A vintage toggle switch may recall laboratory equipment or early aviation controls. These associations become part of the meaning of an artwork or interactive object and can either reinforce or distract from your intended experience. As designers, we should remain aware that interface materials are never entirely neutral—they bring with them expectations, memories, and cultural narratives.

The illuminated switches shown below are an excellent example of this principle. Their glowing interiors immediately attract the eye and invite touch, particularly in darkened galleries or theatrical environments. Beyond improving visibility, the colored illumination adds energy and theatricality to the installation, transforming a simple electrical component into an inviting interactive element that encourages exploration. By carefully selecting the size, color, illumination, and tactile feel of a switch, you can shape not only how people operate your system, but also how they emotionally experience it.



Illuminated pushbutton switches.

Pushbutton switches can be normally open (NO) or normally closed (NC) and are generally spring loaded so that they will be deactivated after they are pushed. A good source for switches is Digikey.



Pushbutton switches.

Here is some code on how to use a switch in Maxuino (Arduino controlled by Max MSP and Jitter).

Simple pushbutton switch digital Input

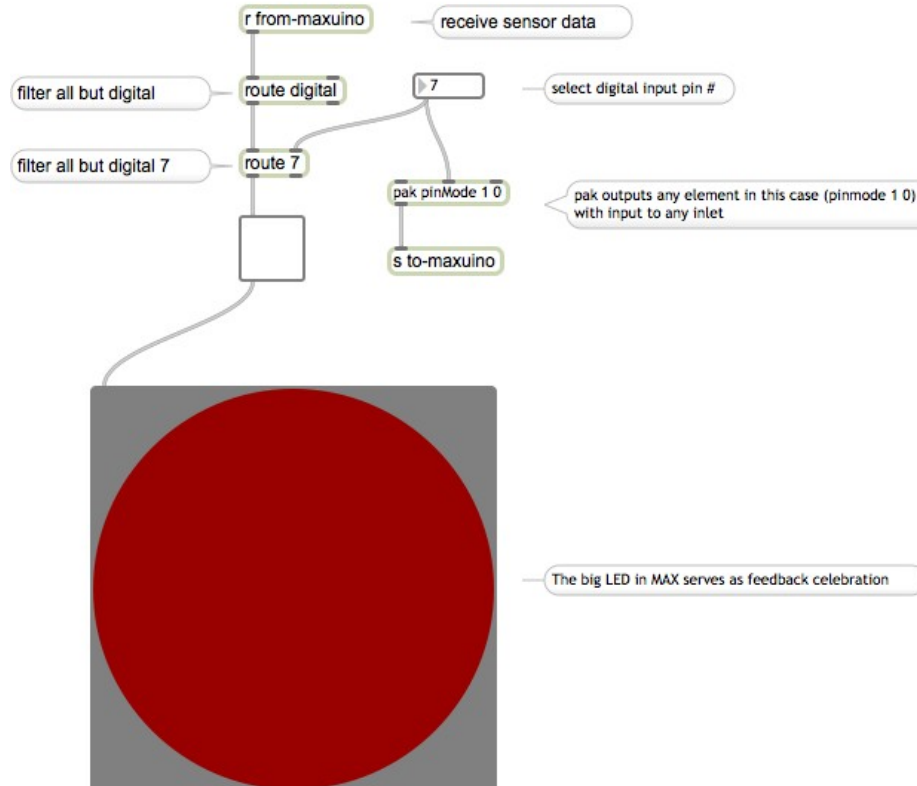
An easy way to detect humans is with a simple digital input. Think how the finger connected to the brain is going to know it made connection. How might you dress up your switch. Should it be soft with fur? Should it have a light to draw the eye and therefore the hand in?

Notice that many switches have NO normally open configurations or NC normally closed configurations and you must determine which one you have.

Also note that generally we use a 10K ohm resistor in the circuit

REQUIRES: Maxuino already running in another window (like its help patch) set to the Arduino port.

Connections to Arduino:
pin7: detection (0 = off, 1 = on) to Arduino 7 which functions as a digital input pin
G: Ground
+: Arduino 5V



Max MSP Jitter code with Maxuino and Arduino.

Limit Switches

Limit switches are rugged, spring-loaded mechanical switches used to detect the presence or position of a moving object. They are commonly employed as **end-of-travel safety devices** in machines, robots, CNC equipment, and automated systems. When a moving mechanism reaches a predetermined position, it presses the switch's lever or roller actuator, causing the electrical contacts to change state. This signal

can immediately stop a motor, reverse its direction, trigger another action, or notify a microcontroller that a travel limit has been reached.

In motorized systems, limit switches provide an important layer of protection. For example, if a linear actuator, robotic arm, or sliding mechanism travels too far, a limit switch can disconnect the motor driver or send a signal to the microcontroller, preventing damage to gears, belts, motors, or the structure itself. They are frequently used in industrial automation, elevators, garage door openers, 3D printers, and CNC machines because of their reliability and long service life.

Limit switches are also valuable in **mobile robotics**. Mounted on the front, sides, or rear of a robot, they function as **bump sensors**. When the robot makes contact with a wall, obstacle, or another object, the switch is activated, allowing the robot to stop, reverse, or choose a new direction.

Although newer robots often employ non-contact sensors such as LiDAR or ultrasonic range finders, mechanical bump switches remain popular because they are inexpensive, extremely reliable, and provide an unambiguous indication that physical contact has occurred.

Most limit switches are available with different actuator styles, including **lever arms, roller levers, whiskers, plungers, and hinged actuators**, allowing them to be adapted to many different mechanical designs. Their robust construction and long operating life—often rated for **millions of switching cycles**—make them ideal for interactive installations and robotic projects that will be used repeatedly by the public.

Recommended Supplier

A reliable source for educational and professional projects is **Omron**, whose **D2F Series** miniature limit switches are widely used in robotic art and industrial equipment.

- **Manufacturer:** Omron
- **Series:** D2F Miniature Basic Switches
- **Supplier:** DigiKey
- **Typical Applications:** Robot bump sensors, end-of-travel detection, machine safety interlocks, CNC machines, and interactive kinetic sculptures.

Omron limit switches are known for their durability, consistent performance, and long mechanical life, making them an excellent choice for interactive art installations where dependable operation is essential.



Limit switch.

A good source for limit switches is Jameco.

Tilt sensors detect changes in orientation and provide a simple way for an electronic system to determine whether an object has been tilted, tipped, or inverted. They are commonly used in robotics, security systems, toys, handheld devices, and interactive artworks where movement or orientation triggers an event.

Traditional tilt sensors contain either a small **rolling metal ball** or, in older designs, a drop of **liquid mercury** sealed inside a capsule. As the sensor tilts, the ball moves under gravity and bridges two electrical contacts, completing the circuit. Today, **ball-type tilt switches** are preferred because they are inexpensive, reliable, and avoid the environmental concerns associated with mercury.

Tilt sensors operate like simple **on/off switches** and connect easily to the digital input pins of an Arduino, ESP32, or other microcontroller. One drawback is that the internal contacts may "bounce" briefly as the ball settles, producing several rapid electrical pulses instead of a single clean transition.

To prevent false triggering, programmers use **debouncing**, which filters out these unwanted transitions. This is commonly done in software by introducing a short delay after a state change is detected or by using the `millis()` function or a debounce library to ignore rapid repeated signals.

Although modern **accelerometers and IMUs** provide much more precise orientation data, mechanical tilt switches remain popular because they are inexpensive, rugged, require almost no power, and are extremely easy to interface.

Recommended Supplier

- **Adafruit Industries** – Ball Tilt Sensor Switches for Arduino and ESP32 projects.

```
/* Tilt Sensor Sketch: LED connected to the ledPin will stay on until the tilt sensor is turned sideways or upside down. */  
int ledPin = 8;  
int tiltSensePin = A5;  
void setup() {  
  pinMode(ledPin, OUTPUT); // set ledPin to output mode  
}
```

```

void loop() {
  // read in voltage to 10-bit ADC value: 0 to 1023
  int tiltSense = analogRead(tiltSensePin);
  if (tiltSense > 512) { // at least 1/2 of Vcc: no tilt
    digitalWrite(ledPin, HIGH); // turn on LED
  } else {
    digitalWrite(ledPin, LOW); // turn off LED
  }
}

```

Reed switches are magnetic sensors consisting of two thin metal reeds sealed inside a small glass tube. When a magnet is brought close to the switch, the reeds become magnetized, touch one another, and complete the circuit. When the magnet is removed, the reeds separate and the circuit opens.

Reed switches work best with **strong neodymium (rare-earth) magnets** and provide a simple, reliable method of detecting position without physical contact. They are commonly used in door and window security sensors, robotics, and interactive installations to detect the movement or location of objects.

Because they behave like ordinary switches, reed switches connect directly to the digital input pins of an Arduino, ESP32, or other microcontroller using a pull-up or pull-down resistor. Their simplicity, low cost, and long operating life make them an excellent choice for non-contact position sensing.

Recommended Supplier

Standex Electronics (formerly Meder Electronic) manufactures a wide variety of reed switches and magnetic sensors, available through **DigiKey** and other major electronics distributors.



Reed magnetic switches.

Rotary Encoders

A **rotary encoder** converts the rotation of a shaft into a series of digital pulses that a microcontroller can count. Unlike a potentiometer, which has a limited range of motion and produces an analog voltage, a rotary encoder can rotate continuously in either direction. By monitoring two digital output signals (**CLK** and **DT**), an Arduino or ESP32 can determine both the **direction** and the **amount** of rotation. Many encoders, including the popular **KY-040**, also include a built-in **pushbutton switch** activated by pressing the knob.

The **KY-040 Rotary Encoder Module** is widely used in Arduino and ESP32 projects because it is inexpensive and easy to connect. It requires five connections: **VCC**, **GND**, **CLK**, **DT**, and **SW** (pushbutton). Rotary encoders are commonly used for menu navigation, volume controls, tuning interfaces, robotic controls, and interactive artworks where a user adjusts values or selects options.

Recommended Supplier

The **KY-040 Rotary Encoder Module** is available from **SparkFun**, **Adafruit**, **DFRobot**, and **DigiKey** (EC11-compatible rotary encoders), making it an excellent choice for educational and interactive electronics projects.



Keyes 040 encoder.

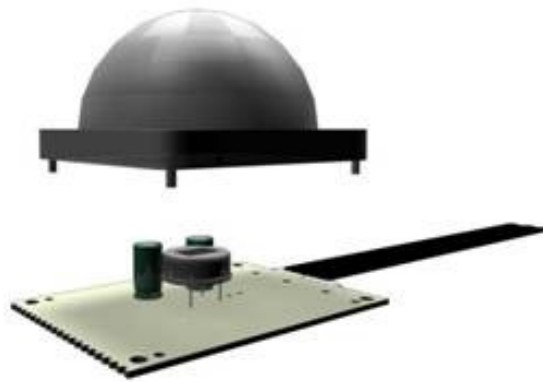
Maxuino/Arduino Ultrasonic Sensor

PIR Infrared Sensor

Passive Infrared (PIR) Sensors

Passive infrared (PIR) sensors detect the motion of warm objects, such as people and animals, by sensing changes in the infrared energy naturally emitted by their bodies. Unlike active infrared sensors, PIR sensors do **not** emit any light or radiation of their own. Instead, they continuously monitor the infrared energy in their field of view and generate a signal whenever they detect a significant change.

PIR sensors are commonly used in **interactive artworks, security lighting, burglar alarms, automatic doors and energy-saving lighting systems**. A familiar example is the outdoor porch light that automatically turns on when someone walks nearby. Most PIR modules operate from **3.3 to 5 volts** and connect directly to an Arduino, ESP32, or other microcontroller using a single digital output pin, making them simple to interface.



PIR with the lens off.

Most artists use PIR sensors to detect motion over distances ranging from **a few inches to approximately 20 feet (6 meters)**, depending on the model and lens. They are inexpensive, reliable, and consume very little power, although they typically require a short warm-up period after power is first applied and respond more slowly than many other motion sensors.

PIR sensors are **not well suited for moving robots or mobile platforms** (unless is it still for a bit) because they detect changes in infrared energy across their field of view. If the sensor itself is moving, it continually perceives changes in the background, making it difficult to distinguish between its own motion and the movement of other objects.

Most PIR sensors use a **Fresnel lens** to divide their field of view into multiple sensing zones. By modifying or masking portions of the lens, you can narrow the detection area or create specific "sweet spots" where motion will trigger the sensor. For even narrower detection, the sensor can be mounted inside a tube or enclosure to limit its field of view, allowing it to function as a more directional motion detector.

Recommended Supplier

PIR sensor modules are widely available from **Adafruit**, **SparkFun**, **DFRobot**, and **DigiKey**, making them an inexpensive and dependable choice for robotics, home automation, and interactive electronics projects.

The **Sharp GP2Y0D02YK0F** is a compact **active infrared proximity sensor** that emits a pulse-modulated beam of infrared light and uses **optical triangulation** to detect nearby objects. Unlike analog distance sensors that continuously report the distance to a target, the GP2Y0D02YK0F provides a simple **digital (one-bit) output**, indicating whether an object is within its detection range. This makes it ideal for applications that require fast, reliable triggering rather than precise distance measurements.

The sensor detects objects between approximately **5 cm and 80 cm (2–32 inches)** and connects easily to an Arduino, ESP32, or other microcontroller using a single digital input pin. Because it produces only a HIGH or LOW signal, it requires very little processing time, making it an excellent choice for activating motors, lights, sound, or other interactive events when a participant approaches an installation. Its fast response, compact size, and immunity to most ambient lighting conditions have made it a popular sensor for robotics, interactive art, and obstacle detection.



GP2Y0D02YK.

Recommended Supplier

The **Sharp GP2Y0D02YK0F** is available from **DigiKey**, along with datasheets and application information, making it an excellent choice for educational, robotics, and interactive electronics projects.

Sharp GP2Y0A710K0F Long-Range Infrared Distance Sensor

The **Sharp GP2Y0A710K0F** is a **long-range active infrared distance sensor** that uses pulse-modulated infrared light and **optical triangulation** to measure the distance to nearby objects. It can detect objects from approximately **100 cm to 550 cm (40–216 inches)**, making it well suited for interactive installations where visitors can be detected several meters before they reach the artwork.

Unlike the digital **GP2Y0D02YK0F**, the GP2Y0A710K0F produces a **continuously varying analog voltage** that corresponds to the measured distance. This allows your program to create multiple interactive behaviors as people approach—for example, gradually increasing sound, changing lighting, altering projected imagery, or activating robotic movements based on a visitor's distance from the installation.

Because the sensor produces analog distance measurements, the microcontroller must periodically sample and process its output. While this places a slightly greater computational load on the processor than a simple digital proximity sensor, it is easily handled by modern microcontrollers such as the

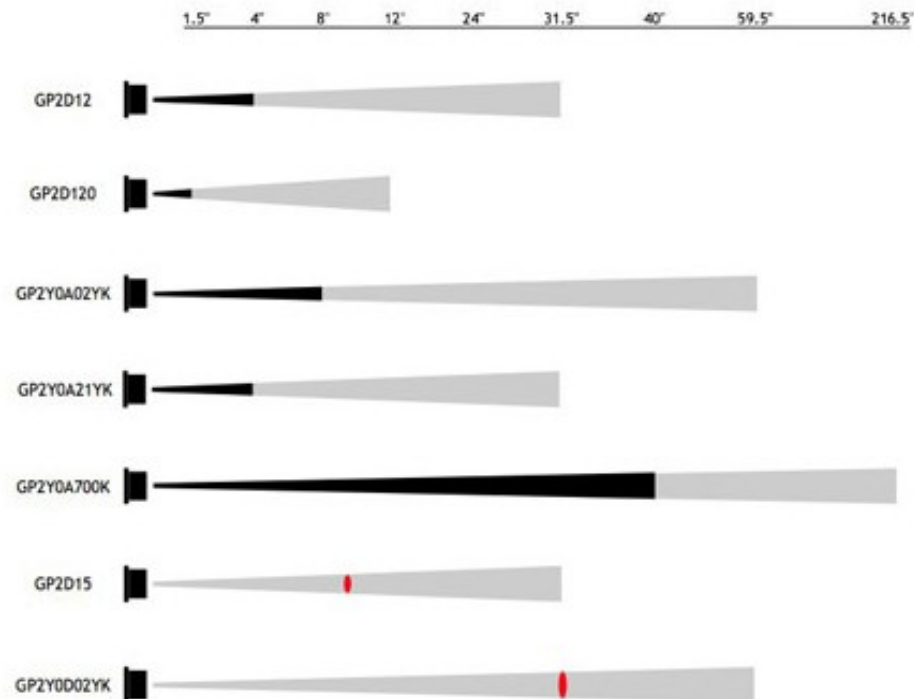
Arduino UNO and ESP32. If your project only needs to know whether someone is present or absent, a digital proximity sensor such as the **GP2Y0D02YK0F** may be a simpler choice.

Recommended Supplier

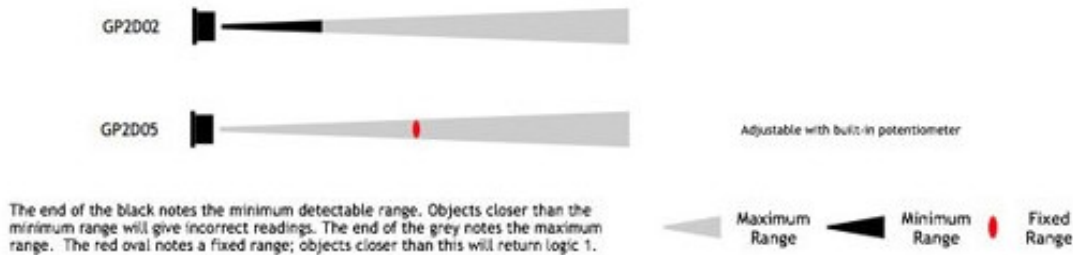
The **Sharp GP2Y0A710K0F** is available from **DigiKey**, **Pololu**, and **SparkFun**, all of which provide datasheets and example circuits for Arduino and ESP32 projects.



GP2Y0A700K.



The following detectors are discontinued, and are included here for historical reference:



This chart from Acroname indicates which sensor to choose for a variety of distances.

QTI Sensor Infrared Transmitter/Receiver Module

A **reflective infrared (IR) sensor** combines an infrared LED and a matching phototransistor in a single package. The LED emits invisible infrared light, and the phototransistor measures the amount of light reflected back from a nearby object. Light-colored or reflective surfaces return more light than dark surfaces, allowing the sensor to distinguish between black and white objects as well as different shades of gray.

Reflective IR sensors are inexpensive, fast, and easy to interface with a microcontroller. They are widely used in **line-following robots**, **edge detection**, **object detection**, **wheel encoders**, and **position sensing**. Because the sensor measures reflected light rather than requiring an object to break a beam, it is ideal for detecting markings or changes in surface color.

Many reflective IR sensors can operate as either a **digital sensor**, detecting the presence or absence of an object, or as an **analog sensor**, measuring how much light is reflected. This analog capability allows

the sensor to distinguish between different shades of gray, making it useful for following printed lines or reading patterns.

Today, a widely available sensor the **onsemi QRE1113GR**, which offers high performance in a compact package.



QTI sensor.

The **onsemi QRE1113GR** is an excellent general-purpose reflective infrared sensor for Arduino, ESP32, Raspberry Pi, and other microcontroller projects.

- **Manufacturer:** onsemi
- **Manufacturer Part Number:** QRE1113GR
- **DigiKey Part Number:** QRE1113GRCT-ND (Cut Tape)
- **Output:** Analog phototransistor
- **Sensing Distance:** Approximately **1–10 mm**, depending on the reflectivity of the target
- **Operating Temperature:** -40°C to $+85^{\circ}\text{C}$
- **Package:** Compact surface-mount device

Although the QRE1113GR is a surface-mount component, it is widely used on inexpensive breakout boards and robot sensor modules. It provides excellent sensitivity and is supported by numerous Arduino and ESP32 software examples, making it an outstanding choice for educational projects and robotics.

Ultrasonic Distance Sensor

Ultrasonic sensors work by bouncing a 40 kHz frequency sound off objects and waiting for the return pulse-modulated frequency. They can communicate with your microcontroller directly, providing a series of numbers created in relation to the distance from the object being sensed. This sensor functions by transmitting ultrasonic chirps and measuring the time it takes to “hear” the chirp echo back.

Output from the sensor is a variable-width pulse, which will vary in proportion to the distance to the object or person being sensed. A wool sweater and a piece of felt will absorb more sound than a piece of plywood, for instance, so the sensing distance will vary based on the material or object being looked for, as well as its physical size.



Ultrasonic sensor.

Ultrasonic Distance Sensors

An **ultrasonic sensor** measures the distance to an object by using high-frequency sound waves, much like the way a bat navigates in the dark. The sensor sends out a short burst of ultrasonic sound—typically **40 kHz**, well above the range of human hearing—and then listens for the echo reflected from a nearby object. By measuring how long it takes for the echo to return, the microcontroller can calculate the distance to the object.

Ultrasonic sensors are inexpensive, accurate, and easy to use. Most can measure distances from about **2 cm (0.8 in.) to 4 m (13 ft.)** with an accuracy of approximately **3 mm**. They are widely used in robotics for obstacle avoidance, object detection, parking sensors, liquid-level measurement, and interactive installations.

Most ultrasonic modules require only **two digital I/O pins** on a microcontroller: one pin sends a **trigger** pulse, and the second receives the **echo** signal. In addition, the sensor requires only **5 V power and ground**, making it easy to connect to an Arduino or similar microcontroller.

Bats also use ultrasonic sound for navigation, although their hearing is extraordinarily sensitive. Some species can detect echoes so accurately that they can fly through openings only a few centimeters wide or avoid obstacles as thin as a strand of thread.

Recommended Sensor

For Arduino and ESP32 projects, one of the best choices is the **HC-SR04 Ultrasonic Distance Sensor**, which has become the standard educational ultrasonic sensor.

- **Manufacturer:** SparkFun Electronics
- **Manufacturer Part Number:** 15569
- **DigiKey Part Number:** 1568-15569-ND
- **Operating Voltage:** 5 V
- **Measuring Range:** 2 cm to 4 m
- **Ultrasonic Frequency:** 40 kHz
- **Typical Accuracy:** ± 3 mm
- **Interface:** Trigger and Echo digital signals

The HC-SR04 is inexpensive, reliable, and supported by hundreds of Arduino and ESP32 example programs, making it an excellent choice for beginning and intermediate robotics and sensing projects.

Max MSP Jitter Kinect Animation

Creating an interactive animation using Max MSP Jitter and video playback files.



Interactive Animation by Caleb Shuey, Art & Technology Exhibition, Autumn 2013. Interaction is directed by skeletal recognition.

Using FFAST

In creating an interactive animation, you begin by defining your “key” variables using FFAST code. These variables will allow you to create distinct paths for the animation, such as up, left, and right.

This will allow you to write FFAST code such as the one below:

```
# mappings from input events to output events
# format: event_name threshold output_type event
left_arm_out 10 key_press s
right_arm_across 15 key_press s
right_arm_out 10 key_press d
left_arm_across 15 key_press d
left_arm_up 10 key_press f
right_arm_up 10 key_press f
```

This code allows for both right- and left-hand usage. When either the right or left hand moves to the designated distance past the corresponding shoulder, the assigned keystroke will be performed. In this case, if the right hand moves ten inches above the right shoulder, the “f” key will be pressed.

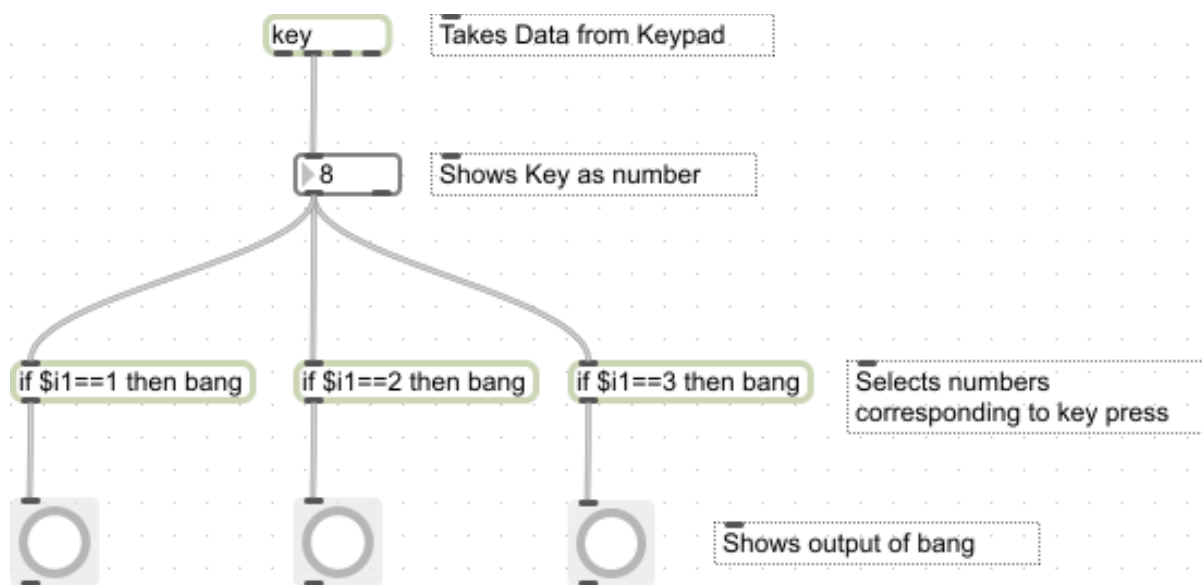
Max MSP Jitter Code

From here we need to code a Max file. If you have written your FAAST code using “s,” “d,” and “f,” it will be easier to write the Max code.

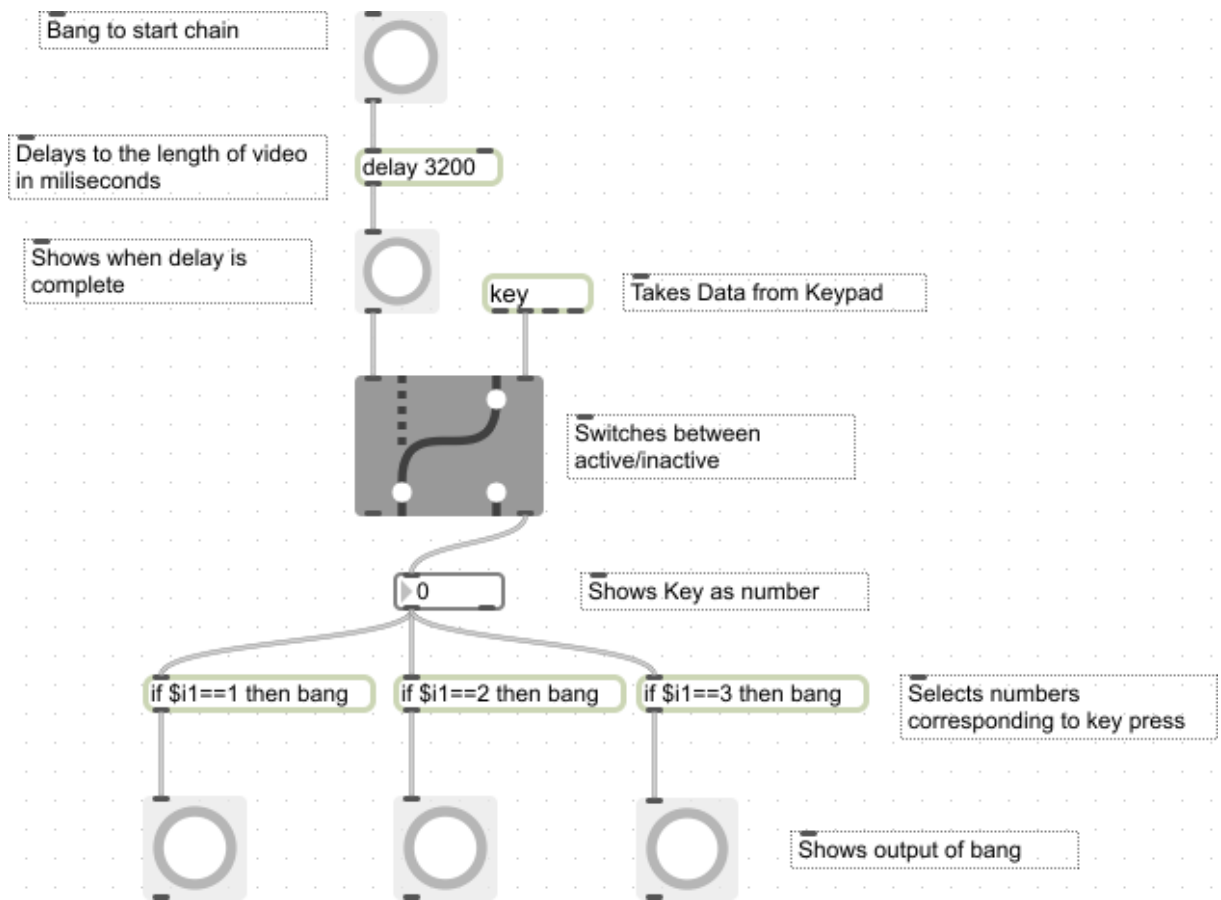
First, create a “key” object and an integer box. Each port of the key object has a different way the keyboard is numbered and arranged. Connect the key object to the integer box using the second port from the left; this will make s=1, d=2, and f=3. Other settings can be confusing and hard to figure out which key is which.

Create “if-then” statements for the three choices and connect them to buttons.

Test your code: lock the patcher and test your keys, making sure that they light up the buttons and correspond to the proper key.



To view the movie you wish to import, you can choose to see it in the patcher or in a new window. To create a video to view in the patcher window, create a jit.pwindow attached to a jit.qt.movie. To view the video in its own video window, attach a jit.window to the jit.qt.movie (you can use both at the same time if you wish). Remember, both of these methods require a metro to play the movie. If you don't want the video playing constantly, you will also need to add a system to stop the metro, such as a delay object.



To produce a project that has more than one video, you can create multiple patchers connected to each other. If you choose to do this, you can then add in other things such as “loadbangs,” “closebangs,” or, in this example, “active” objects to control when videos do and do not play. To continue elaborating your code and project, you can write more specific code. One possibility would be to write code for the use of multiple screens, such as numerous projectors or TVs. With customization, you can create a project that loops, has multiple endings, or is directed to a particular audience.

Temperature Sensors

DS2760 Thermocouple Temperature Sensor

Thermocouples are temperature sensors that take advantage of an interesting physical phenomenon discovered in 1821 by [Thomas Seebeck](#). By placing two dissimilar metals together in a junction, Seebeck noticed that a potential difference (voltage) was present across the two different metals, which varied proportionally along with the temperature.



DS2760 thermocouple kit.

The variable voltage output of a thermocouple enables it to be used for highly accurate temperature measurements over a wide range of temperatures. Unfortunately, for us artists and inventors, the output voltage from a thermocouple is very small, in the range of a few microvolts or less, so it cannot be directly sent to your microcontroller for measurement. However, Dallas/Maxim has created the DS2760, a microchip used to precisely monitor the voltage from a lithium-ion battery, which is also implemented to measure thermocouple output voltages. This sensor is available on the web at hvwtech.com. HVW provides the Thermocouple Kit DS2760, which includes the DS2760 soldered onto a board, along with three different types of thermocouple elements.

The DS2760 has many features which make it a logical choice for thermocoupling applications: one-wire output to your microcontroller for data, a large measurement range (0°C to 127°C), and a low 2–90 milliamp power draw. This part does require a lengthy program to convert the signal from the DS2760 to real-world temperature numbers. You can find sample code at HVW Tech.

LM34 Temperature Probe

The LM34 temperature probe provides a linear voltage output proportional to the temperature. This small, three-pin probe is easy to use because its output voltage can convert into useful Fahrenheit data, unlike thermocouples, which provide output based on the Kelvin scale. Unlike digital sensors (SHT45,

DS18B20, etc.), the LM34 outputs a voltage that is directly proportional to temperature. Temperature probes are valuable devices for sensing heat and cold changes over time.



LM34 temperature probe. +32 to +212°F, -40 to +230°F, -50 to +300°F.

All-in-One Temperature Sensor

If you want a temperature sensor that is easy to use and doesn't require many extra electronic components, the **DS1620+ Digital Thermometer** is a good option. This small 8-pin chip can work either as a **digital thermometer** or as a **programmable thermostat**.

In **thermometer mode**, the DS1620+ measures temperatures from **-67°F to 257°F** and sends the temperature as a digital value that your microcontroller can read. The sensor uses a binary number format called **two's complement** to represent both positive and negative temperatures. If you're unfamiliar with this format, don't worry—sample programs are available, and you'll learn more about it later.

In **thermostat mode**, the DS1620+ can operate on its own. You first connect it to your microcontroller to program the high and low temperature limits. After that, it can be left to monitor the temperature independently. If the temperature rises above or falls below the limits you set, the chip automatically sends an output signal that can be used to turn another device on or off.



DS1620+

Hardware interface: the DS1620+ interfaces with controllers through a three-wire connection, consisting of a data input/output line (DQ), a synchronizing clock line (CLK), and a reset/select line (RST).

Measuring Humidity

Until fairly recently, measuring humidity was surprisingly difficult. Earlier humidity sensors often required additional electronic components, such as analog-to-digital converters, operational amplifiers (op-amps), or oscillator circuits. They also needed careful calibration, temperature compensation, and complex calculations to determine values such as dew point. Even with all this extra circuitry, many sensors responded slowly and produced only modest accuracy.

Fortunately, modern digital humidity sensors have made the process much simpler. The **Sensirion SHT71** and **SHT75** are high-quality digital sensors that measure both **humidity and temperature** in a single device. The two models share the same pinout, operating voltage, communication protocol, and package. Their primary difference is accuracy—the **SHT75** provides slightly more precise measurements than the **SHT71**.

The SHT7x sensors communicate directly with a microcontroller using just **two signal wires**, making them easy to integrate into your projects. They also consume very little power (typically **30 μ W**), require no additional external components, respond quickly, and are inexpensive. These features have made the SHT7x family a popular choice for environmental monitoring, weather stations, terrariums, greenhouses, and robotics.



Humidity sensor.

Electronic Switches, Hall Effect Sensors, Break Beam, Capacitance, Piezo

Electromagnetic Relays

An **electromagnetic relay** allows a low-voltage signal from a microcontroller to safely switch a much higher voltage or current. The relay electrically isolates the low-voltage control circuit from the higher-power circuit, helping to protect your microcontroller.

When the relay is turned off, however, the coil inside it generates a brief voltage spike called **back EMF (electromotive force)**. This spike can damage a microcontroller if it is not properly protected. To prevent this, a **diode** is connected across the relay coil to safely absorb the voltage spike.

Because electromagnetic relays use a coil to create a magnetic field, they require more current than many other switching devices and can produce a small amount of electrical noise when they switch on or off.

A **solid-state relay (SSR)**, discussed in Chapter 9, has no moving parts. It can often be controlled directly by a microcontroller, switches silently, uses very little power, and does not generate the electrical noise associated with electromagnetic relays.

The relay shown below is an **electromagnetic relay**. When its coil is energized, a magnetic field pulls a metal switch into place, allowing one circuit to control another. Since most microcontrollers cannot supply enough current to drive a relay coil directly, a **transistor**, such as a TIP Darlington transistor, is commonly used between the microcontroller and the relay to provide the required current.



Electromagnetic relay. As a coil creates a magnetic field, it pulls a switch down.

Some very small relays, called **reed relays**, can sometimes be connected directly to a microcontroller if the microcontroller pin can supply enough current to activate the relay. For example, these could be driven directly by some microcontrollers.

SPST stands for **Single Pole, Single Throw**, meaning the relay controls **one switch that opens or closes a single circuit**. Larger relays usually require a transistor to provide the additional current needed to operate the relay. Digikey has them from Omron. I like that they can fit in a breadboard for prototyping.



Reed relay.

Hall effect sensors detect magnetic fields. Some work like simple digital switches—they turn **on** when a magnet is nearby and **off** when it moves away. Others, called **linear (or ratiometric) Hall effect sensors**, can measure changes in magnetic field strength very accurately.

One of the biggest advantages of Hall effect sensors is that they **do not require physical contact**. Because there are no moving parts touching each other, they experience very little wear and can operate reliably for many years.

Hall effect sensors are commonly used for:

- Contactless switches
- Detecting the position of objects
- Measuring the speed of rotating gears or wheels
- Determining the direction of movement

Manufacturers such as **Allegro MicroSystems** and **Xensor** offer a wide variety of Hall effect sensors. Their websites provide datasheets and technical information, although the sensors are usually purchased through electronics distributors rather than directly from the manufacturer.



Hall effect sensor.

Break-Beam Sensors

A **break-beam sensor** detects when an object passes between a light source and a receiver. One device continuously sends an invisible beam of infrared light to a matching receiver. When a person or object blocks the beam, the receiver detects the interruption and sends a signal to the microcontroller.

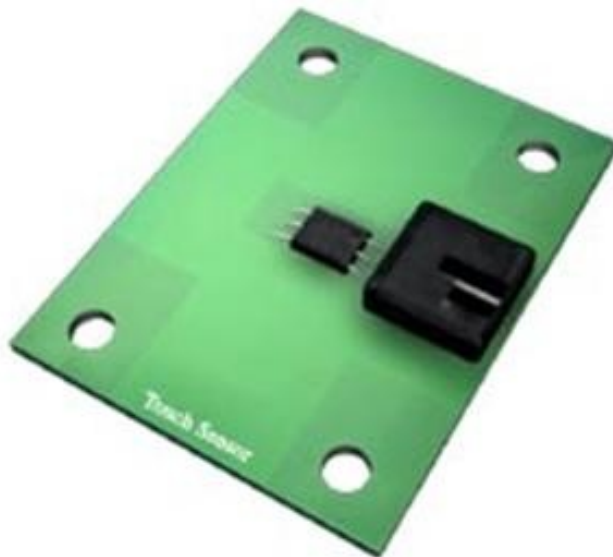
Because the transmitter and receiver are designed to work together, it is best to purchase a **matched pair**. These sensors are simple to use, reliable, inexpensive, and are commonly used for object detection, counting, security systems, and robotics.

A good modern choice available from DigiKey is the **TT Electronics OPB100Z**. This pre-wired infrared break-beam sensor has a sensing distance of up to **12 inches (30 cm)** and is easy to interface with an Arduino, ESP32, or other microcontroller.



Matched infrared receiver and diode

Capacitive touch switches are switches that are solid state with no moving parts and are often capacitive, used for sensing touch or other conductive materials. A good source for these is HVW Tech. This is an analog sensor, so in order to use this with a microcontroller that lacks a built-in analog-to-digital converter, you would need to use one separately.

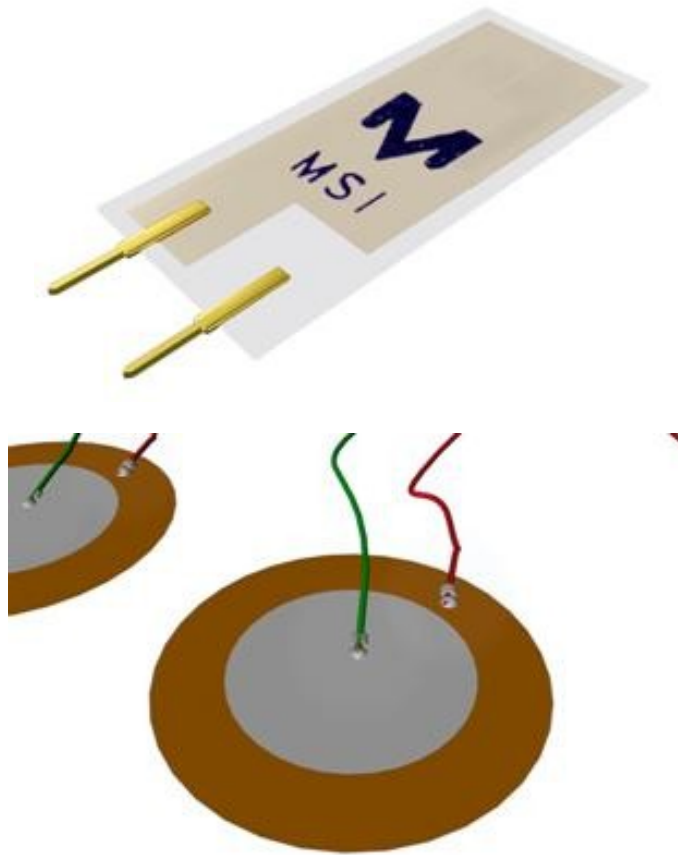


Board dimensions: 3.0 cm x 3.8 cm.

Piezo pickups are great ways to sense minute vibrations propagating through materials. Amplified guitars often use piezoelectric pickups; however, when you purchase these from music stores, they are very pricey and set to pick up the frequencies they are designed to work optimally within.

When purchasing, make sure you have a good sense of the frequency you are trying to amplify or sense, and then purchase at that frequency. A good source for piezo products is Digikey, American Piezo, MSI USA Inc., and Sparkler Ceramics.

For an excellent application note and some entertaining examples of how to use them, search for the sound artist [Richard Lerman](#) and piezo pickups, and you will see how he amplified a spider web to make a wind harp. Richard Lerman has used these sensors extensively.



Piezo disks.

Future Developments

Nanotechnology will play a major role in the future development of sensors and their interfaces to computers. One can imagine ultra-small nanotech surfaces that are mini linear actuators, which can create pressure on the body and receive electrical signals from muscle activation. The pressure waves that are created with these nano devices could allow us to have more immersive experiences as the multisensors provide input to computers and create feedback to the computer.

[Takao Someya](#) and his research team at the University of Tokyo have created pressure sensors that have a high degree of sensor density. They have created a sensor array with 16 sensors per square centimeter that will permit robots to have an artificial skin and use this to have better tactile feedback.



Sensor Matrix by [Takao Someya](#). 2004. University of Tokyo.

The “skin” is constructed of rubber and organic transistors, which allow sensing and conduction. These sensor arrays could be used in the future to monitor the heart and breathing rate of hospital patients, or they could be embedded into carpets to distinguish family members by the rhythm of their walk, thereby adjusting the lighting in the room. This artificial skin may allow for more domestic robots that are sensitive to their human-habited environments.

References

[1] Dr. Hananel Davidowitz of the NEC Research Institute in Princeton, NJ, says, "the jet-propelled bug thinks with its behind."

[2] Mery, Fernand. *Animal Languages*. Saxon House, p. 3.

[3] The end of a cockroach leg by Catherine Chalmers, image from catherinechalmers.com

Further Reading

Fraden, Jacob. *Handbook of Modern Sensors: Physics, Designs, and Applications*. 2nd ed. New York: Springer Verlag, 1996.

A great deal of practical sensor project ideas and concise code fragments can also be found on the Arduino Project Hub referenced earlier in this chapter.

Chapter 18

Resources: Artists, Organizations, and Publications

Artists, Scientists, Researchers, Inventors, Theorists

“Traditional narratives are being restructured. As a result, people feel a greater need to personally participate in the discovery of values that affect and order their lives, to dissolve the division that separates them from control, freedom...”

— Lynn Hershman Leeson

The fields of art & technology, entertainment engineering, media arts, and dance & technology are immensely connected via the web. Fantastic print and web publications, and hundreds of museums and organizations support media artists and inventors by providing show space, technical support, and monetary support.

One of the best ways to get to know the field of digital art, theory, interactive sculpture, and installation is to explore the websites of those working at the intersections of the arts and technology.

The names and websites listed below are from artists/inventors who have situated themselves more around physical computing, though you will find links to conceptual artists, installation artists, video artists, virtual artists, dance & technology artists, sound artists, theorists, scientists, and researchers who have figured prominently in the field of digital and interactive art, installation, and invention.

All listings were correct at time of original publication. Where a link had gone dead, it has been updated where a current site could be found, or replaced with a general search reference for that name.

A

[Laurie Anderson](#) — performance, new media, robotics, sound, storytelling.
[Stuart Anderson](#) — bipedal robots, robotics, engineering, locomotion, art.
[Lois Andison](#) — kinetic sculpture, body, automation, mechanics, installation.
[Peter Anders](#) — architecture, cyberspace, virtual environments, design, education.
[Suzanne Anker](#) — bio art, genetics, microscopy, sculpture, education.
[Dr. Irina Aristarkhova](#) — feminism, technology, embodiment, aesthetics, posthumanism.
[Roy Ascott](#) — telematic art, cybernetics, consciousness, interactivity, theory.
[Alice Aycock](#) — kinetic sculpture, mythology, architecture, engineering, installation.

B

[Ingrid Bachmann](#) — interactive installation textiles.
[Jack Backrack](#) — spatial computing.
[Nick Baginsky](#) — sculpture robots and autonomous systems utilizing neural network programming.
Steve Baker — theorist, the postmodern animal.
[Gregory Barsamian](#) — animated sculpture, stroboscopic effects.
[Laura Beloff](#) — performance and installation environments.
[Maurice Benayoun](#) — new media artist and theorist working with virtual reality.
[Joanna Berzowska](#) — responsive clothing, wearable technology.
[Carrie Bodle](#) — installations surrounding history, memory, and social dialogue.
[Marc Bohlen](#) — robotics installation and social commentary.
[David Bowen](#) — kinetic, robotic, interactive, sculptural works controlled by data, insects, satellites.
[Edward Boyden](#) — Synthetic Neurobiology Group at MIT.
[Cynthia Breazeal](#) — animated robotic characters, Personal Robotics Group at MIT.
[Shawn Brixey](#) — biotechnology as hybrid strategies for computational expression.
[Jonah Brucker-Cohen](#) — custom interfaces for the web.
[Leah Buechley](#) — High-Low Tech research group, MIT; e-textiles and LilyPad Arduino.
[Lee Bul](#) — intimacy, gender, technology, class, and race.
[Chris Burden](#) — conceptual artist working with science and technology.
[Annick Bureau](#) — new media art critic and theorist.

C

[France Cadet](#) — robotics, a-life, autonomy.
[Mariela Cádiz](#) — electronic image, body, memory, video, identity.
[Alexander Calder](#) — mobiles and stables.
[Jim Campbell](#) — interactive video and projection installations.
[Rejane Cantoni](#) — interactive virtual reality environments.
[Janet Cardiff](#) — sound artist, narratives.
[Rachel Clarke](#) — digital and traditional media in drawings, video, and installation.
[Kent Clelland](#) — interactive composition.
[Seth Cluett](#) — architectural sound and light installation.
[Malcolm Cochran](#) — public sculpture, installation, video.
[Harold Cohen](#) — a-life robotic painter.
[Celestino Soddu & Enrica Colabella](#) — Generative Design Lab.
[Brooks Coleman](#) — interactive robotics sculpture.
[Chris Coleman](#) — interactive sculpture and co-author of Maxuino.
[Luc Courchesne](#) — experimental video installations

[Jody Culkin](#) — physical computing.

[Merce Cunningham](#) — pioneer dance and technology choreographer.

D

[Ernestine Daubner](#) — art historian, educator, cultural theorist.

[Charlotte Davies](#) — artist focused on virtual environments.

[Joe Davis](#) — bioart and installation art

[Donald Day](#) — street plastic.

[Dead Chickens](#) — mechanical creatures.

[Joseph DeLappe](#) — installation, fetishism, interaction.

[Wim Delvoye](#) — digestive system simulation.

[Paul DeMarinis](#) — sound and computer installations, interactive electronic inventions.

[Maywa Denki](#) — theatrical robotics and experimental music.

[Peter Dittmer](#) — language-based computer interaction.

[Ricardo Dominguez](#) — hacktivist and performer.

[Alan Dorin](#) — generative artwork.

[Tony Dove](#) — interactive video.

[Richie Kuhaup & Geoffrey Drake-Brockman \(Australia\)](#) — digital mirror, figuration.

[Rob Duarte](#) — conceptually and politically based installation and physical computing.

[Kitsou Dubois](#) — experimental environment of altered gravity conditions.

[John Dunn](#) — artist, musician, and software designer.

E

[Doug Easterly](#) — conceptually based robotic and interactive works.

[David Eckard](#) — performance and kinetic sculpture.

[Electronic Disturbance Theatre](#) — developed the practice of electronic civil disobedience.

[Sharon Engelstein](#) — massive inflatable forms and sculpture.

[Karlheinz Essl](#) — Austrian composer, performer, improviser, media artist.

[Takehito Etani](#) — sculpture and installations involving process and extended vision.

F

[Isabel Farnsworth](#) — kinetic sculpture installation.

[Jurgen Faust](#) — video installation.

[Jeff Feddersen](#) — new musical instruments.

[Ken Feingold](#) — robotic artificially intelligent talking heads and installations.

[Gene Felice](#) — contemporary conceptual artist working with fabrication technologies.

[Jorge La Ferla](#) — video artist, theoretician, writer, curator.

[Mary Flanagan](#) — networked and computer-based works, gaming technology.

[Monika Fleischmann](#) — identity change in media culture.

[Dario Floreano](#) — research into intelligent robotics and software inspired by biological principles of self-organization.

[Larnie Fox](#) — kinetic sculpture, windmills, ornithopters.

[Amy Franceschini](#) — futurist group employing technology.

[Masaki Fujihata](#) — interactive telematic video installations.

[Noriyuki Fujimura](#) — field between interactive art and public space.

G

Naum Gabo — pioneer of constructivism.

[Ulrike Gabriel](#) — immersion, robotics, virtual spaces.

[Cyprien Gaillard](#) — ruins, entropy, architecture, archaeology, landscape.
[Philip Galanter](#) — allegories of the genome.
[Arthur Ganson](#) — kinetic sculpture, poetic mechanics.
[Christy Georg](#) — kinetic sound sculpture and performances.
[Steve Gerberich](#) — mechanical sculpture.
[Nicholas Gessler](#) — synthetic anthropology.
[Carol Gigliotti](#) — writer and artist working with multimedia, genetic technology, and living creatures.
[Brian Goggin](#) — poetic site-specific works involving time and light.
[Ken Goldberg](#) — telematic performances, robotic sculpture.
[Andy Gracie](#) — robotic installations that involve living systems, wet biology.
[Jennifer Gradecki](#) — artist working with a practice based on dataveillance.
[Ken Gregory](#) — new hybrid soundscapes.
[Matthias Groebel](#) — robot-assisted paintings involving cultural memory.
[Trademark Gunderson \(Mark Gunderson\)](#) — interactive art and performance works.
[Brian Gustafson](#) — empathy through interactive devices.
Steven Gutierrez — robotics, autonomy, environmental concerns.
Patrick Gyger — author & director, Maison d'Ailleurs Museum of Science Fiction.

H

Hans Haacke — pioneer of critiques of social institutions, kinetics, and process.
[Ian Haig](#) — fleshbot, unique and hilarious interfaces, cynical.
[Jennifer Hall](#) — interactive robotic installations, biological works, installation.
[David Halsell](#) — interactive installations concerned with body and biology.
[Ann Hamilton](#) — site-specific installation, sound works.
[Donna Haraway](#) — feminist theory, cyborg manifesto, technoscience.
[Hilary Harp](#) — kinetic sculpture.
[Georg Hartung](#) — kinetic art installation.
[Mona Hatoum](#) — sculpture, installation, video.
[Tim Hawkinson](#) — large-scale sound installations.
[Michael Hayden](#) — architectonic-scaled sculptures in light.
[Katherine Hayles](#) — research into virtual bodies in cybernetics, literature, and informatics.
[Barney Haynes](#) — symbiont, co-dependency, interactive installation.
[Jean-Pierre Hebert \(1939–2021\)](#) — algorithmic art, robotics.
[Matt Heckert](#) — mechanical sound orchestras and menacing machines.
[Agnes Hegedus](#) — interactive installation.
[Nigel Helyer](#) — immersive sculpture and sound art.
[Jesse Hemminger](#) — interactive sculpture/video.
[Paulo Henrique](#) — communications technologies and dance.
[Hugh Herr](#) — Biomechatronics Group at MIT; computer-controlled prosthetics.
[Garnet Hertz](#) — reanimating insects/telematics, theory.
[Craig Hickman](#) — physical computing.
[Cesar A. Hidalgo](#) — Macro Connections Lab at MIT.
[Christoph Hildebrand](#) — neon installations.
[Gary Hill](#) — pioneering video installation.
[Michael Hirschner](#) — wind-powered kinetic sculpture.
[Marla Hlady](#) — sound and kinetic works.

[Rania Ho](#) — mobile robotic kitchen appliances.
[Perry Hoberman](#) — installation artist defining unique and humorous interfaces.
[Erik Hobijn](#) — techno parasites.
[Carsten Holler](#) —
[Tiffany Holmes](#) — large-scale interactive installations.
[Henry Holtzman](#) — Information Ecology group at MIT.
[Jenny Holzer](#) — language-based installations involving LEDs and other mediums.
[Rebecca Horn](#) — large-scale conceptually based kinetic and sound works.
[Shih Chieh Huang \(Taiwan\)](#) — inflatable technological gardens from reworked appliances.
[Catherine B  chard & Sabin Hudon](#) — sculpture, audio art, new media.
[Human Product](#) — psychomorphic mutant theatre.
[Tim Hunkin](#) — automata and kinetic sculpture.

I

[Tom Igoe](#) — design for human-machine interfaces, networked art.
[Edward Ihnatowicz \(1926–1988\)](#) — creator of the Senster interactive robot.
[Ian Ingram](#) — a Lamettrian Geppettoist, tickworks and tockworks.
[Troy Innocent](#) — a-life works, generative art.
[Institute for Applied Autonomy](#) —
[Milena Iossifova](#) — sonic-video installations.
[Hiroshi Ishii](#) — Tangible Media Group, MIT.
[Joi Ito](#) — global technology policy; Internet as a way of transforming society, MIT.
[Toshio Iwai](#) — experimental animation and projections.

J

[Will Jackson](#) — kinetic and interactive sculpture with much humor.
[Joseph M. Jacobson](#) — Molecular Machines Group, MIT.
[Jim Jenkins](#) — kinetic sculptor and editor of *Motion Motion: Kinetic Art*.
[Pamela Jennings](#) — explores issues of identity and otherness.
[Natalie Jeremijenko](#) — biotech installations/mechatronics.
[Franz John](#) — large-scale sound and web-based installation dealing with earth processes.
[Daniel Jolliffe](#) — conceptually based synthesis of sculptural practice and electronic technologies.
[Paul Ramirez Jonas](#) — automaton sound sculpture.
[Simone Jones](#) — kinetic sculpture.
[Francois Junod](#) — automata, robotics, kinetics; rightful heir to Jacques Droz.
[Gary Justis](#) — kinetic sculpture and installation.

K

[Eduardo Kac](#) — telematics, biological art, robotics, and conceptual installations.
[Ned Kahn](#) — kinetic and interactive works that capture natural processes.
[Sepandar Kamvar](#) — social computing and information management, MIT.
[Istvan Kantor](#) — action-based media.
[Hachiya Kazuhiko](#) — telematic and web works, immersion.
[Zerek Kempf](#) — sculptural interactive works inspired by situationist art.
[Sean Kerr \(New Zealand\)](#) — new media web, sound, film, video, and installation.
Martin Kersels — interactive, electronic sculpture installation, sound works.
Robert Kinoshita — designer of Robby the Robot and the Robot B-9 from *Lost in Space*.
[Yves Amu Klein](#) — interactive robotics utilizing neural networks for control.

Tammy Knipp — mixed-media collage.
Milton Komisar — light sculpture as music.
Piotr Kowalski — architect, mathematician, bio-physicist, town-planner.
Myron Krueger — pioneer of artificial reality to examine relationships between people and machines.
[Heidi Kumao](#) — cinema machines for intimate installations.
[Machiko Kusahara](#) — media artist and theorist, Japan.
[Daniela Kutschat](#) — interactive virtual reality works.
[Ryota Kuwakubo](#) —

L

[Manuel De Landa](#) — philosophical essays on non-linear dynamics, artificial intelligence, self-organization, and artificial life.
[Diane Landry](#) — multidisciplinary sound and kinetic works.
[Sean Langlais](#) — sound sculptor.
[Eve Andree Laramée](#) — installation, sculpture, performance about art, science, nature.
[Ken Larson](#) — responsive urban houses and ubiquitous technology, MIT.
[Chris Larson](#) — kinetics, installations.
[John Lathram](#) — interactive installation, relation of virtual to physical.
[Brenda Laurel](#) — computer interface design/theatre.
[Shawn Lawson](#) — real-time animation and video compositing.
[Barbara Layne](#) — wearable computing.
[Vincent Leclerc](#) — wearable instruments.
[Lynn Hershman Leeson](#) — conceptually based installations, film, early interactive digital prints.
[George Legrady](#) — conceptual artist working with language.
[Dante Leonelli](#) — large-scale light works interactive with the environment.
[Richard Lerman \(1944–2025\)](#) — sound artist and installations.
[Simon Lewandowski](#) — electronics kits to talk to dead people.
[Jen Lewin](#) — boundaries relationship, physical/analog & digital.
[Matt Lewis](#) — artist/researcher, artificial life, animation, interaction, ACCAD OSU.
[Patrick Lichty](#) — conceptually based artist, writer, and activist.
[Henry Lieberman](#) — software agents and AI, MIT.
[Anne Lilly](#) — kinetic sculptor.
[Andrew Lippman](#) — viral spaces and digital life, MIT; scalable real-time networks.
[Philomene Longpre](#) — interactive video and installations, robotics.
[Margot Lovejoy \(1930–2019\)](#) — installation artist/author.
[Bernie Lubell](#) — kinetics and interactive installation.
Kristin Lucas — humorous spoofs on high technology.
Diane Ludin — converging the body and information.
[Len Lye](#) — kinetic sculpture.

M

[Tod Machover](#) — robotic opera, development of unique musical instruments, MIT.
[Chico MacMurtrie](#) — large-scale robotic installation often involving sound.
[Mark Madel](#) — participatory electronic sculpture.
[Pattie Maes](#) — Fluid Interfaces Group, MIT.
[Frank Malina](#) — kinetic painting.
[Steve Mann](#) — cyborg research.

[Guy Marsden](#) — audio electronic sculpture and kinetics, engineering services, green tech.

[John Marshall](#) — rapid-prototyped sound works at the intersection of design, art, and RP technologies.

[Michael Mateas](#) — art and artificial intelligence.

[Jean-Marc Matos](#) — live multimedia performances integrating technology into dance.

[Jon McCormack](#) — generative modeling for electronic media environments.

[Jennifer and Kevin McCoy](#) — sound works, structures of thought through repetition.

[Rosmarie McGoldrick](#) — the animal gaze.

[Turi McKinley](#) — interactive installation, mobiles.

[Marta de Menezes](#) — visionary bio-based and genetic installations.

[Feng Mengbo](#) — interactive virtual worlds utilizing game engines.

[Agnes Meyer-Brandis](#) —

[Christa Sommerer & Laurent Mignonneau](#) — a-life installation.

[Daniel Miller](#) — interactive systems, kinetic sculpture.

[Marvin L. Minsky](#) — AI and machine common-sense reasoning, MIT.

[Bonnie Mitchell](#) — interactive, electronic, audio/visual installations and environments, animation.

[Michael Mittelman](#) — interactive video installation.

[Laszlo Moholy-Nagy](#) — former director, New Bauhaus; early kinetic works.

[Ali Momeni](#) — art, engineering, design; co-author of Maxuino.

[Hans Moravec](#) — theorist on the emergence of machine and robotic intelligence rivaling human intelligence.

[Leonel Moura](#) — painting robots, architecture, bio-based art forms.

[Muntadas](#) — web art pioneer.

N

[Gunalan Nadarajan](#) — theorist/curator/artist, educator, robotics.
[Michael Naimark](#) — cinematography, interactive systems, immersive projection.
[Joseph Nechvatal](#) — artificial life virus code, computer-robotic assisted paintings.
[Nicholas Negroponte](#) — founder/chair, One Laptop per Child; co-founder, MIT Media Lab.
Shirin Neshat — video installation.
[Andrew Neumann](#) — electronic sculpture, LCD works dealing with electric and metaphorical power.
[Keith Newstead](#) — humorous mechanical and kinetic sculpture, automata.
[Liz Nofziger](#) — site-specific mixed media installations.
[Sally Jane Norman](#) — dance and technology, cultural theory, a-life.

O

[Dan O'Sullivan](#) — connection between virtual and physical spaces.
[Michael Oliveri](#) —
[Berenice Olmedo](#) — prosthetics, embodiment, disability, biopolitics, kinetic sculpture.
[Fernando Orellana](#) — interactive sculpture and installations.
[Santiago Ortiz](#) — language, life, interaction research.
[Ed Osborn](#) — sound installation.
[Tony Oursler](#) — video installation.
[Neri Oxman](#) — Mediated Matter Group, MIT; nature as model.
[Hiromi Ozaki \(Sputniko!\)](#) — imaginative alternative futures, MIT.

P

[Randall Packer](#) — artist and author.
[Nam June Paik \(1932–2006\)](#) — pioneer in robotic art and video sculpture.
[Garth Paine](#) — sound works, installation artist.
[Maria Palazzi](#) — animation researcher and artist/designer, ACCAD OSU.
[Jim Pallas](#) — objects of desire, inflatable, interactive sculptures.
[Gabor Papp](#) — software art.
[Joseph A. Paradiso](#) — Responsive Environments Group, MIT.
[Peter Patchen](#) — electronic installation.
[Nancy Patterson](#) — electronic media artworks.
[Mark Pauline](#) — destructive and violent robotics with a message of self-expression.
[Richard Pell](#) — contestational robotics.
[Simon Penny](#) — interactive and robotic installations, theory, unique interfaces.
[Sandy Pentland](#) — Human Dynamics Laboratory director, MIT.
[Rosalind W. Picard](#) — Affective Computing Group, MIT.
[Patricia Piccinini](#) — new media technology and biological form.
[Carl Pisaturo](#) — robotic actors.
[Andrea Polli](#) — experimental interface, eye tracking, music installation.
[Corey Poole](#) — electronic and interactive sculpture.
[Jane Prophet](#) — site-specific installation, artificial life, theory.

Q

[Liu Zhi Qiang](#) — computer vision and machine intelligence.

R

[Sabrina Raaf](#) — robotic installation with sound and tactility.
[Kit Galloway & Sherrie Rabinowitz \(1950–2013\)](#) — telematic art, video environments.

[Melinda Rackham](#) — video installation, virtuality; artist, writer, curator.
[Brittany Ransom](#) — new media artist probing animal, human, and environmental relations.
[Ramesh Raskar](#) — Camera Culture Research Group, MIT.
[Alan Rath](#) — robotic and video sculpture.
[Casey Reas](#) — algorithmic work, Processing co-author with Ben Fry.
[Erwin Redl](#) — large-scale LED architectural installations.
[Michael Rees](#) — digital sculpture, rapid prototyping, installation.
[Douglas Repetto](#) — sound works, installation.
[Mitchel Resnick](#) — Lifelong Kindergarten Group, MIT.
[George Rhoads](#) — audio kinetic sculptures.
[Owain Rich](#) — environmental sound works.
[Katherine Richards](#) — web-integrated art.
[Martin Riches](#) — talking machines based on research into voice and vocal cords.
[Ken Rinaldo](#) — new media artist working with sculptural robotic installation, biorobots, green technology, transpecies communication, and animation.
[Christian Ristow](#) — extreme robotics.
[Don Ritter](#) — new media artist and designer working with interactive installation and body motion.
[Roger Quinn & Roy Ritzmann](#) — biorobots inspired by insects.
[Jocelyn Robert](#) — sound and video environments.
[Robotlab \(Matthias Gommel, Martina Haitz, Jan Zappe\)](#) — robot DJ, robot sketch, industrial robots.
[Marcel.li Antunez Roca](#) — performance engaging technology.
[Michael Rodemer](#) — interactive environments, neon, cast objects.
[Hector Rodriguez](#) — media artist, algorithmic approaches to moving image.
[Bryan Rogers \(1941–2013\)](#) — conceptual and electronic sculpture installations.
[David Rokeby](#) — sound and video installation, image recognition.
Willy Le Maitre & Eric Rosenzweig — a-life generative video sculpture.
[Philip Ross](#) — biological and electronic symbionts.
[Ryan Ross](#) — interactive sculptures, light installation, interactivity.
[James Rouvelle](#) — experimental sound artist.
[Deb Roy](#) — language, games, and social dynamics at the intersection of AI and cognitive psychology, MIT.
[Daniel Rozin](#) — wooden mirror that reflects the viewer.
[Ben Rubin](#) — sound designer and multimedia artist.
[Teri Rueb](#) — embodied interaction.
[Jessica Rylan](#) — analog sound generation and experimentation.

S

[Ryan Sabine](#) — interactive works.
[Mariano Sardon](#) — new media, Argentina.
[Joachim Sauter \(1959–2021\)](#) — interactive digital media and design.
Julia Scher — surveillance in the cyber-sphere.
[Christian Schiess \(d. 2024\)](#) — neon works.
[Thecla Schiphorst](#) — wearable computing, dance, media art.
[Chris Schmandt](#) — Speech and Mobility Group, MIT.
[Nicolas Schoffer](#) — CYSP 1 (Cybernetic Spatiodynamic Sculpture).
[Bjoern Schuelke](#) — interactive works often dealing with surveillance issues.
[Andy Schuessler \(1955–2005\)](#) — electro-mechanical assemblage.

[Victoria Scott](#) — digitally controlled mechanical installations and sculptures.

[Jill Scott](#) — interactive media, wearable computing, hybrid environments, and artificial intelligence.

[Bill Seaman](#) — large-scale interactive projection environments concerned with language.

[James Seawright \(1936–2022\)](#) — pioneer in interactive electronic installation, sculpture.

[Seemen](#) — audience-directly-controlled robotics and kinetic art.

[Bill Shackelford](#) — conceptually driven networked robotics.

[Gregory Shakar](#) — sculptural combinations of electric light and arcing electricity.

[Edward A. Shanken](#) — theorist/writer/art historian specializing in art and technology.

[Bruce Shapiro](#) — robotic egg painter and plasma cutter, XY table for sculpture.

[Norah Zuniga Shaw](#) — dance and technology.

[Jeffrey Shaw](#) — pioneered interactivity and virtuality in his art installations.

[Sudarshan Shetty \(India\)](#) — conceptually based electronic installation.

[Sheri Simons](#) — large-scale interactive and kinetic installations.

[Karl Sims](#) — a-life works, virtual spaces.

[Eric Singer](#) — engineer/artist; musical, robotic, and performative works.

[Sandy Skoglund](#) — interactive large-scale tableaux installations.

[Todd Slaughter](#) — site-specific installation and kinetic sculpture, materiality, rapid prototyping.

[Kevin Slavin](#) — Playful Systems Group, MIT; gaming and integrated digital media.

[Joel Slayton](#) — telepresent surveillance.

[Martin Smith & Matt Smith](#) — automata and kinetic art.

[Scott Snibbe](#) — interactive sculpture.

[Laetitia Sonami](#) — custom-made instruments.

[Paul Spooner](#) — figurative mechanical sculpture.

[David Stairs](#) — designer/philanthropist surrounding altruistic issues.

[Jennifer Steinkamp](#) — immersive interactive projection installations.

[Matthew Steinke](#) — kinetics, robotics.

[Stelarc](#) — extends the concept of the body and its relationship with technology through human/machine interfaces.

[Gefried Stocker](#) — media artist, curator, Ars Electronica.

[Michael Sturtz](#) — interactive kinetic sculpture.

[Yongjian Su](#) — sound, insects, installation, interactive works, Beijing, China.

[Subrosa](#) — cyberfeminist cell of cultural researchers.

Ashok Sukumaran (India) — telematics, kinetic, electronic installation.

[Survival Research Labs](#) — destruction, mayhem, obtainium technology.

[Jenna Sutela](#) — living sculptures, biology, computation, language, sound.

T

[Keiko Takahashi](#) — interactive sound drawing machines.

[Takis](#) — pioneer of kinetics and electromagnetic installation.

[Jeff Talman](#) — soundspace installation.

Julie Taymor — theater sets, kinetic costuming, puppetry.

[Paul Thomas](#) — sonic spaces, web interaction.

[K.D. Thornton](#) — installation.

[Marc Thorpe \(1946–2023\)](#) — robot wars, design, and kinetic sculpture.

[David Tinapple](#) — installation-based works.

[Jean Tinguely](#) — pioneer of kinetic sculpture.

[William Tomlinson](#) — ethical autonomous creatures.

[Troika Ranch](#) — digital dance theater company.

[Joan Truckenbrod](#) — interactive installation inspired by aspects of nature.

[Wen-Ying Tsai \(1928–2013\)](#) — cybernetic sculpture.

[Norman Tuck](#) — kinetic, interactive sculpture.

U

[Ullanta](#) — performance robots, theatre, and dance.

[Camille Utterback](#) — interactive video installations.

V

[Val Valgardson](#) — kinetic sculptures involving various media.

[Paul Vanouse](#) — interactive works that critique institutionalization and corporatization.

Francisco Varela — biologist, research into the organization of living systems; Autopoiesis theory with Humberto Maturana.

[Steina Vasulka & Woody Vasulka](#) — electro/opto/mechanical environments; light art, video, sound art, installation.

[Mari Velonaki](#) — robotic installation.

[Barry L. Vercoe](#) — emeritus head, Music, Mind and Machine Group, MIT.

[Roman Verostko](#) — generative algorithmic prints.

[Bill Verplank](#) —

[Erwin Driessens and Maria Verstappen](#) —

[Victoria Vesna](#) — communication technologies and collective behavior.

Paul Virilio — theorist working with the social implications of new technologies.

[Stephen Vitiello](#) — soundscapes that alter perception.

[Bill Vorn](#) — theatrical interactive environmental robotics.

W

[Tamas Waliczky](#) — new media artist and computer animator.

Grey Walter — neurophysiologist pioneering research in mobile autonomous robots.

[Julian Weaver](#) — sound works installation.

[David Webber](#) — robotic sound sculpture, video and interactive works.

[Peter Weibel](#) — artist, exhibition curator, art and medium theoretician.

[Grahame Weinbren](#) — interactive cinema.

[Michael Weisert](#) — robotics, sound, and video working with medical issues.

[Norman White](#) — interactive sculpture in the form of robots.

[Gail Wight](#) — conceptual interplay between biology and art.

[Stephen Wilson \(1944–2011\)](#) — conceptually driven interactive works and author.

[Greg Witt](#) — kinetics, robotics installation.

[Ryan Wolfe](#) — interactive sculptures and designs.

[James Woodfill](#) — sonic sculpture.

[Nancy Worthington](#) — kinetics, interaction, comedy.

[Adrianne Wortzel](#) — theatrical robotics.

Nanette Wylde — language-based works, haiku.

Y

[Hiro Yamagata](#) — laser light installation.

[Kenji Yanobe](#) — large-scale figurative sculptural installations.

[Mariela Yeregui](#) — robotics and new media, Argentina.

[Yianni Yessios](#) — interactive installation.

[Ip Yuk Yiu](#) — experimental filmmaker and media artist.

[Chang Young-hae \(Korea\)](#) — new media artist.

[Amy Youngs](#) — complex relationship between technology and concepts of nature and self.

Z

[Joe Zane](#) — video LCD sculpture and installation.

[Carlos Zapata](#) — figurative mechanical sculpture.

Adam Zaretsky — bio-based art installations.

[Garth Zeglin](#) — researcher on robotics and education.

[Ethan Zuckerman](#) — Center for Civic Media, MIT.

[Ricardo Miranda Zuniga](#) — tactical public intervention.

[Janet Zweig](#) — kinetic sculpture.

Organizations, Festivals and Exhibitions

Below is a list of organizations from around the world, many of which are focused on the intersection of the arts and technology. Many others are contemporary arts centers, which are supportive and show this kind of work as part of their programming. Some of these museums are large organizations; some are small and poorly funded. Before contacting any of these arts organizations, do your research.

If you should choose to submit your works, read their requirements carefully and consider how to best frame your pursuits in light of their conceptual concerns. If you are submitting video art or documentation, CD-ROMs, or DVDs, be sure you are sending the proper formats for that country. In many cities, there are media conversion services that will translate your NTSC video to the PAL format used in Japan and parts of Europe, for instance.

Organizations Supporting Art and Technological Works

[24 Hour Art](#) (Australia), now the Northern Centre for Contemporary Art — government-funded art space; innovative, experimental, contemporary art.

[ACMI, Australian Centre for the Moving Image](#), Melbourne, Australia — exhibitions, education, productions, and events centered around the moving image.

[AIL, Artists in Labs](#), Zurich, Switzerland — coalition between AIL and the Swiss Science Laboratories encouraging art and science residencies.

[ANAT, Australian Network for Art and Technology](#), Adelaide, Australia — skill training, artist residency, conference and workshop fund.

[Ars Electronica Center](#), Linz, Austria — international media art and cutting-edge technologies; festival, museum, research, futurelab.

[Art Center Nabi](#), Seoul, Korea — creative center for new media art; research, exhibitions, education, artist support.

[Artspace](#) (Australia) — pushes the boundaries of experimental art practice and critical theory.

[Art Laboratory Berlin](#) — art and science laboratory/gallery in Berlin, founded by Regine Rapp and Chris de Lutz.

[ASCI, Art & Science Collaborations](#) (USA) — artists inspired by science and technology.

[Associacao Cultural Videobrasil](#), Sao Paulo, Brazil — electronic art of Brazil, Latin America, and beyond; festival, screenings, seminars.

[Bang](#) (South Africa) — gallery providing a platform for contemporary artists.

[The Banner Art Collective](#) (USA) — creates, collects, and distributes net art.

[BEK, Bergen Center for Electronic Arts](#) (Norway) — resources for artists in art and technology; media lab, workshops, presentations.

[Blackout](#) (Australia) — features Australian Indigenous new media arts practitioners.

[BNML, Banff New Media Institute](#), Banff, Canada — collaborative research center for scientists, social scientists, and artists (now part of Banff Centre for Arts and Creativity's history).

[C-Level](#) (USA) — cooperative public and private lab sharing physical, social, and technological resources.

[C3 Center for Culture and Communication](#), Budapest, Hungary — research and development of innovative art, science, and communications.

[Cartodigital](#) (Mexico) — solutions to communication problems affecting Latin America in the technological age.

[CELL](#) (Holland) — initiates interdisciplinary projects within media, art, and culture.

[CAiiA-Star](#), University of Wales College Newport (CAiiA) and University of Plymouth (Star), UK — world-wide research community for interactive arts and science technology, now continuing as the Planetary Collegium.

[Canon Artlab](#), Tokyo, Japan — experimental laboratory of media art through collaboration of artists and computer engineers.

[CIAC](#) (Canada) — Centre international d'art contemporain de Montreal; visual arts exhibitions and events.

[Contemporary Arts Organizations of Australia](#) — development and support of contemporary art practice in Australia.

[Centro Multimedia](#), Mexico City, Mexico — documentation of Mexican art with the assistance of new media.

[CRAC, Creative Room for Art and Computing](#), Stockholm, Sweden — digital media workshop for dialogue between art and technology, active primarily in the 1990s-2000s.

[Cultivamos Cultura](#) — residency in Sao Luis, Portugal, focused on bio-based applications in the arts.

[DA2, Digital Art Development Agency](#), Bristol, UK — explored understanding of the world through digital art; the organization dissolved in 2010.

[Daniel Langlois Foundation for Art, Science, and Technology](#), Montreal, Canada — combines arts and sciences with the help of technology.

[DATA, Dublin Art and Technology Association](#), Dublin, Ireland — promotes and exhibits art and technology.

[dLux Media Arts](#), Sydney, Australia — development and discussion of innovative film, video, new media, and sound arts.

[Digital Talkies](#) (India) — India's first digital film festival, held in 2001, founded by Shekhar Kapoor.

[EAI, Electronic Arts Intermix](#), New York, NY — leading resource for artists' videos and new media.

[Electronic Music Foundation](#) (USA) — creative community of electronic musicians and artists; its educational programs continue today as EMF Institute.

[Eryk Salvaggio Museum of Modern Living](#) — everyday objects discovered, created, or discarded as side effects of the human condition.

[Electrohype](#), Malmo, Sweden — promoted computer-based art in Sweden and the Nordic countries through biennials from 2000 to 2010, now inactive.

[Experimenta](#), Melbourne, Australia — convergence of interactive technologies, multimedia, digital music, and virtual reality.

[Experimental Art Foundation](#) (Australia) — encouraged new approaches to the visual arts; merged into ACE Open in 2017.

[Eyebeam](#), New York, NY — access, education, and support for students and artists in art and technology.

[FACT, Foundation for Art & Creative Technology](#), Liverpool, UK — support and exhibition of film, video, and new media projects.

[Fournos, Center for the Art and the New Technologies](#), Athens, Greece — research and production of 21st-century digital culture.

[Hull Time Based Arts](#), Hull, UK — artist-led organization producing and exhibiting time-based arts.

[IAMAS, Institute for \(and International Academy of\) Advanced Media Art and Sciences](#), Ogaki, Japan.

[ICC, NTT InterCommunication Center](#), Tokyo, Japan — dialogue between technology and the arts.

[ICECA, Initiative for Cultural Exchange and Computer Arts](#), Chiang Mai, Thailand — ran a New Media Art Festival in the early 2000s.

[ICA](#) (England) — Institute of Contemporary Arts.

[IFA](#) (Germany) — supports local and foreign new media artists with services and funding.

[INM, Institut fur Neue Medien](#), Frankfurt am Main, Germany — cutting-edge new media projects and theoretical research.

[InterAccess, Electronic Media Arts Centre](#), Toronto, Canada — intersection of culture and technology.

[Interactive Institute](#), Stockholm, Sweden — innovation-oriented research in digital media, now RISE Interactive.

[ISEA, Inter-Society for the Electronic Arts](#), now ISEA International, headquartered at the University for the Creative Arts, UK.

[Kuda](#) (Montenegro) — non-profit organization of artists, theorists, media activists, and researchers.

[Leonardo Observatory for the Arts and Techno-Sciences](#) (France) — studies and research in arts related to techno-science.

[LMCC](#) (USA) — funding, career support, and audience development.

[Location One](#), New York, NY — new media art and cross-discipline collaborations; founded 1997, now closed.

[Moving Image Centre](#) (New Zealand) — promotion of creative media arts in New Zealand.

[Media Lab Madrid](#), Spain, now Medialab Matadero.

[Metro Screen](#) (Australia) — video, television, and multimedia resource centre; founded 1981, closed 2015 due to funding cuts.

[M-cult, Centre for New Media Culture](#), Helsinki, Finland.

[Netherlands Media Art Institute, Montevideo/Time Based Arts](#), Amsterdam, Netherlands.

[New Media Scotland](#), Edinburgh, UK.

[New Radio and Performing Arts Inc.](#) — experimental work for radio, sound arts, and net art; founded 1981, dissolved 2017.

[Public Netbase t0, Institute for New Culture Technologies](#), Vienna, Austria — active 1994–2006, funding withdrawn by the City of Vienna; related work continues at the World-Information Institute.

[Performance Space](#) (Australia) — centre for contemporary performative arts.

[Perth Institute of Contemporary Arts](#) (Australia).

[QPIX](#) (Australia) — film, television, and new media; closed in 2014 after Screen Queensland withdrew funding.

[Rhizome, the New Media Art Resource](#), New York, NY.

[RIXC, The Centre for New Media Culture](#), Riga, Latvia.

[Sarai](#) (India) — research, practice, and conversation about contemporary media and urban constellations.

[SAT, Society for Arts and Technology](#), Montreal, Canada.

[Screen Development Australia](#) (Australia) — a network of state-based screen resource organizations (including Metro Screen and QPIX), most of which have since closed or been absorbed into state screen agencies.

[Soundtoys](#) (England) — artists researching sound, audio, and video.

[STEIM, the Studio for Electro-Instrumental Music](#), Amsterdam, Netherlands, closed in 2020 after over 50 years of operation.

[Studio XX](#), Montreal, Canada — media arts and multimedia resource centre for women.

[TATE Galleries](#) (England) — supports new media and net art.

[The Institute of Modern Art](#) (Australia).

[trAce](#) (England), Nottingham Trent University — online writing community, active 1995–2005, now archived.

[The Arts Catalyst, the Science Art Agency](#), now based in Sheffield, UK.

[V2 , Institute for the Unstable Media](#), Rotterdam, Netherlands.

[Videotage](#), Hong Kong, China.

[Waag Society for Old and New Media](#), Amsterdam, Netherlands, now simply "Waag."

[Wexner Center for the Arts](#) (USA).

[YCAM, Yamaguchi Center for Arts and Media](#), Yamaguchi, Japan.

[Yaitya Makkitura](#) (Australia) — Indigenous membership-based screen culture organization, Adelaide.
[ZKM, Center for Art and Media](#), Karlsruhe, Germany.

Festivals and Exhibitions

[AIM, Art In Motion](#), University of Southern California, Los Angeles, CA; annual; time-based media.

[ART IN OUTPUT](#), Eindhoven University of Technology, Netherlands; biennial; art & technology.

[Ars Electronica](#), Linz, Austria; annual; presentation and development of electronic art.

[Art Futura](#), Spain; annual; digital technologies and new media.

[Art Outsiders](#), Paris, France; art, technology, and biology.

[Avanto](#), Helsinki, Finland; annual; experimental music and moving images.

[Banquete ACTS](#), Madrid, Spain; art, science, technology, and society.

[BEAP](#), Perth, Australia; biennial; electronic art.

[Boston Cyber Arts Festival](#), Boston, MA; biennial, ran 1999–2011, organization continues as a year-round gallery.

[COSIGN](#) (England) — cross-disciplinary event on meaning created by and through the computer.

[Ciberart Bilbao](#), Bilbao, Spain; new technologies, art, and communication; festival ran through 2004.

[D-Motion](#), Halle, Germany; annual; interactive media.

[DAF, Digital Art Festival Tokyo](#), Tokyo, Japan; ran annually through at least 2008, tied to NHK's Digital Stadium program.

[DEAF, Dutch Electronic Art Festival](#), Rotterdam, Netherlands; biennial; electronic art; ran 1994–2014.

[Electrofringe](#), Newcastle, Australia; ran as part of This Is Not Art, which wrapped up operations in 2024 after 25+ years.

[Elektra Festival](#), Montreal, Canada; annual; electronic music, digital imagery, robotics.

[EMAF](#), Osnabruck, Germany; annual; media art.

[EXIT](#), Creteil, France; annual; culture and new technologies.

[Festival VIA](#), Maubeuge, France and Mons, Belgium; renamed SuperVIA in 2019, then iTAK from 2022 onward; still organized by the same venue.

[Festival Garage](#), Stralsund, Germany; annual.

[Festival VAE](#), Lima, Peru; annual; video and electronic art.

[FILE, Festival Internacional de Linguagem Eletronica](#), Sao Paulo, Brazil; annual.

[Futuresonic](#), Manchester, UK; electronic music and media arts; renamed FutureEverything in 2010, closed in 2026 after 31 years.

[interactivA](#), Yucatan, Mexico; biennial; new media.

[International Festival of Electronic Art 404](#), Rosario City, Argentina.

[ISEA, International Symposium on Electronic Arts](#), nomadic; annual (now organized by ISEA International).

[Japan Media Arts Festival](#), Tokyo, Japan; ran annually 1997–2022.

[LA Freewaves](#), Los Angeles, CA; annual.

[MAAP, Multimedia Art Asia Pacific](#); annual.

[Machinista](#), Perm, Russia; art, technology, and AI.

[Metapod](#), Birmingham, UK; digital arts media; the organizing company dissolved in 2010.

[MIMAF, Microwave International Media Art Festival](#), Hong Kong, China; annual.

[Montreal International Festival of New Cinema New Media](#), Montreal, Canada; annual.

[MUTEK](#), Montreal, Canada; annual; music, sound, new technologies.

[New Forms Festival](#), Vancouver, Canada; annual.

[Pixxelpoint](#), Nova Gorica, Slovenia; annual; computer art.

[Siggraph Art Show](#), various USA locations; annual.

[**Sonar**](#), Barcelona, Spain; annual; cutting-edge music and multimedia arts.

[**Stuttgarter Filmwinter, Festival for Expanded Media**](#), Stuttgart, Germany; annual.

[**Subtle Technologies**](#), Toronto, Canada; annual; art and science.

[**The First International New Media Arts Exhibition and Symposium**](#), Beijing, China.

[**Transmediale**](#), Berlin, Germany; annual; media art.

[**Version**](#), Chicago, IL; ran annually into the mid-2010s, organized by the Public Media Institute.

[**Videobrasil International Electronic Art Festival**](#), Sao Paulo, Brazil; biennial.

[**Villette Numerique**](#), Paris, France; new media art festival held 2002–2004.

[**Viper Basel**](#), Basel, Switzerland; annual; film, video, and new media; ran 1982–2006 (originally in Lucerne, moved to Basel in 1999).

[**WRO**](#), Wroclaw, Poland; biennial; new media art.

Publications

Journals, Magazines, and Online Publications

[Antennae](#), The Journal of Nature in Visual Culture.

[Artthrob](#) (South Africa), contemporary visual arts publication.

[Chair et Metal](#) (France), e-magazine on new media art.

[E-Art Asean](#) (Malaysia), e-journal on internet advancement and creative collaborations across Southeast Asia.

[C-Theory](#) (Canada), journal of theory, technology, and culture, published 1976–2017, now archived at the University of Victoria.

[Digital Art Source](#), articles, reviews, forums, links, and displays of new media and digital art.

[The Journal of Aesthetics and Protest](#), art, activism, and cultural/political representation.

[Pop Matters](#), cultural criticism.

[Design Research News](#), free newsletter covering design events, articles, and competitions.

[Fine Art Forum](#), art and technology news.

[POL Oxygen](#) (Australia), magazine on art, design, and architecture.

[Leonardo](#), journal supporting the convergence of media at the intersection of art and technology.

[Rhizome](#), online publications.

[RealTime](#) (Australia), covering visual arts, dance, music, new media, installation, and performance art.

[Switch Magazine](#).

[The Thing](#).

[Net Culture](#) (Greece), e-zine on digital culture.

[New Media Notes](#) (Ireland), newsletter and resource for artists working with new media.

[Teknokultura](#) (Puerto Rico), e-journal discussion forum on technoculture.

Books and Reading Resources: Technical & Theoretical

Shanken, Edward. *Art and Electronic Media*.

McComb, Gordon. *Robot Builder's Sourcebook*.

Turrell, James. *James Turrell: Eclipse*.

De Landa, Manuel. *War in the Age of Intelligent Machines*.

Ascott, Roy (ed.). *Reframing Consciousness*.

Manovich, Lev. *The Language of New Media*.

Stocker, Gerfried, and Christine Schopf (eds.). *Life Science*.

Gelernter, David. *Machine Beauty: Elegance and the Heart of Technology*.

de Menezes, Marta. *Retrato Proteico*.

de Menezes, Marta. *Decon*.

Rath, Alan. *Alan Rath Robotics*.

Hegedus, Agnes. *Interactive Works*.

Stafford, Barbara Maria, and Frances Terpak. *Devices of Wonder: From the World in a Box to Images on a Screen*.

Ascott, Roy. *Telematic Embrace: Visionary Theories of Art, Technology, and Consciousness*. Edited by Edward A. Shanken.

Virilio, Paul. *The Art of the Motor*. Translated by Julie Rose.

Druckrey, Tim (ed.). *Electronic Culture: Technology and Visual Representation*.

Packer, Randall, and Ken Jordan (eds.). *Multimedia: From Wagner to Virtual Reality*.

Druckrey, Timothy (ed.). *Ars Electronica: Facing the Future*.

Benjamin, Walter. *Illuminations*. Edited by Hannah Arendt, translated by Harry Zohn.

Tofts, Darren. *Parallax: Essays on Art, Culture and Technology*.

Rush, Michael. *New Media in Late 20th-Century Art*.

Heidegger, Martin. *The Question Concerning Technology and Other Essays*. Translated by William Lovitt.

Rutsky, R.L. *High Techne: Art and Technology from the Machine Aesthetic to the Posthuman*.

Francastel, Pierre. *Art and Technology in the Nineteenth and Twentieth Centuries*. Translated by Randall Cherry.

Fortunati, Leopoldina, James E. Katz, and Raimonda Riccini (eds.). *Mediating the Human Body: Technology, Communication, and Fashion*.

Houston, Joe (curator). *Post-Digital Painting*.

Maeda, John. *Maeda@Media*. Foreword by Nicholas Negroponte.

Cook, Sarah (ed.). *Curating New Media: Third Baltic International Seminar 2001*.

Rees, A.L. *A History of Experimental Film and Video*.

Barthes, Roland. *Camera Lucida: Reflections on Photography*. Translated by Richard Howard.

Keen, Melanie (ed.). *Frequencies: Investigations into Culture, History and Technology*.

Gleizes, Albert. *Art and Religion, Art and Science, Art and Production*. Translated by Peter Brooke.

Update 2.0: Medien Kunst Aktuell aus Deutschland.

Cadava, Eduardo. *Words of Light: Theses on the Photography of History*.

Leonardo Almanac: International Resources in Art, Science and Technology.

Leonardo Magazine (back issues).

Douglass, and Davis. *Art and the Future*. Praeger.

Bryson, Norman. *Vision as a Mediated Experience*.

Virilio, Paul. *Vision and Technology*.

Shannon, Claude. *Information Theory: Signal & Noise*.

Benjamin, Walter. *The Work of Art in the Age of Mechanical Reproduction*.

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