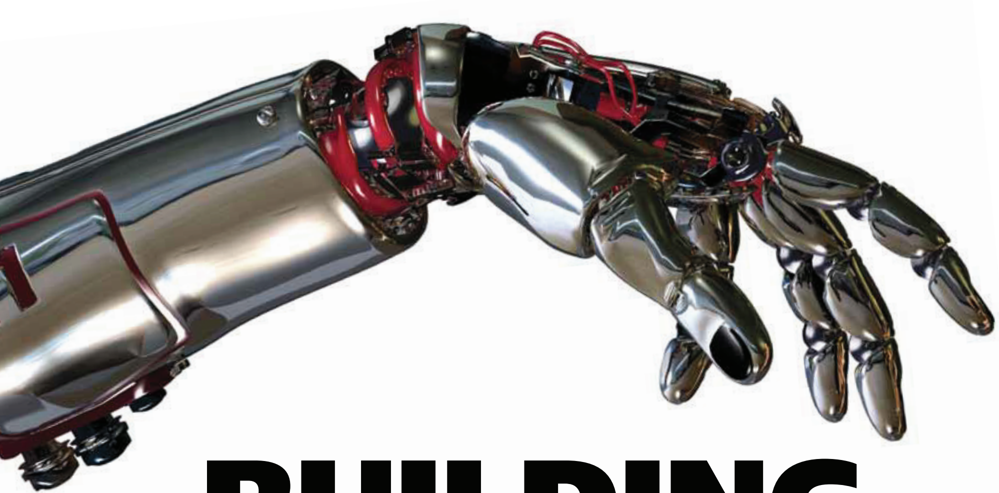


BUILDING SMARTER MACHINES

Engineers have made impressive strides in creating artificial intelligence systems, autonomous vehicles and robots, and smart electronics. But these systems still lag far behind what living organisms can accomplish. No vehicle can navigate its environment the way a rat can, or fly easily in a crowd like a swarm of bats. No device can learn, remember, or interpret information like a human brain—or even like the brain of a small mammal or insect.

Now, a growing movement at Boston University and beyond is bringing together the disciplines of biology, computer science, and engineering to dramatically advance the state of engineered systems and push the boundaries of what human designs can do. The goal: to learn from biology to make smarter machines.

1 Machines That Can Multitask

IMAGINE A WORLD in which each person could only perform one task. One excels at sensing other people's facial expressions, another can assist in a specific kind of surgery, and another can recognize and avoid objects. No one can adapt and learn the tasks that other people know. Despite the hype that's surrounded artificial intelligence over the years—the promise that robots and computers could do all the things humans and other animals do—artificial systems are more like this scenario of vastly limited abilities.

Designing a robot that can sense, learn, make decisions, *and* move on its own is the ambitious goal of a project led by Massimiliano Versace, head of the Neuromorphics Lab, which is part of the multi-institution Center of Excellence for Learning in Education, Science & Technology (CELEST), funded by the National Science Foundation and hosted at Boston University. Most robots, he explains, are designed for one particular problem.

"We're not interested in special-purpose intelligence," says Versace. The group's leading project, Modular Neural Exploring Traveling Agent (MoNETA)—co-funded by Hewlett-Packard (HP) and CELEST—is a comprehensive software program referred to as a "brain on a chip." MoNETA, as Versace and his team envision it, would eventually be an autonomous robot that can sense its surroundings, identify important information, and use that information to make decisions and perform tasks. The group's research was recently published in *IEEE Spectrum* as the cover article, written by team member Ben Chandler.

The Neuromorphics Lab is developing brain models—biologically inspired algorithms that mimic the way brains work—and, in collaboration with HP, the operating system that will run on the chip. The hardware is based on an innovative type of electrical component only a few atoms wide, called a memristor. Versace explains that this technology will enable more lifelike intelligence by processing information faster and more efficiently, similar to how neurons in the brain work. Memristors are used to

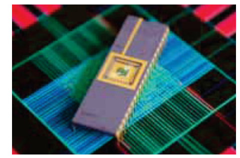
Massimiliano Versace

simulate the billions of synapses found in biological brains. With respect to current technology, they allow hardware designers to build chips with unprecedented density and to operate at very low power, critical design requirements for the brain of a free-moving machine.

This is a tall order, so the lab is breaking down aspects of behavior and tackling them one piece at a time, creating computer models and programming simple robots to simulate ways the brain can learn and adapt. For instance, Anatoli Gorchetchnikov, research assistant professor of cognitive and neural systems, is creating computer algorithms that simulate how a rat can learn to find its way to a platform in a pool of water. Schuyler Eldridge, a PhD student in electrical and computer engineering, is working on programs for decision-making processes based on visual information, while Sean Patrick, a PhD student in cognitive and neural systems, is using knowledge about how the brain operates to enable robots to think as flexibly as animals do.

The long-term goal is to create an artificial intelligence that can think for itself, Versace says. "There is no a priori knowledge; they have to adapt and learn in the way they interact with the environment."

Team Versace's laptop-guided robot successfully navigates around objects, thanks to new hardware that mimics the brain's ability to adapt to its surroundings.



Versace jokes that his son, Gabriel, top, "is a great example of a general-purpose learning machine."

The chip technology developed by the Neuromorphics Lab, above, is highly dense and operates on low power—two essential qualities for making smart and efficient robots.

The Long Way Home

2

THE TASK OF NAVIGATING from one place to another is one that even simple life forms can easily accomplish, but computer scientists have long struggled to design robots that can navigate with anything close to the efficiency of a rat hunting for food, since it's very hard to get a robot to find its way around in a cluttered and changing environment. For a rat foraging in an alleyway, however, the ability to remember its route and come home quickly is key to its survival.

A new collaborative project aims to use what we know about the street smarts of rats to help robots find their way. Funded by a grant from the U.S. Office of Naval Research, the project is being led by Michael Hasselmo, a professor in psychology and neuroscience, and associate director of the Center for Memory & Brain (CMB). He has spent years studying the navigational system in rats' brains that allows them to remember their previous experiences in time and space.

Michael Hasselmo

The mammalian brain, it turns out, has developed a very efficient system for spatial memory, using specialized "grid cells" located in the brain's entorhinal cortex. By monitoring their activity with electrodes, scientists have found that grid cells are constantly active as an animal navigates its environment, and the specific pattern of cell activation is repeated when a rat returns to a place it's been before. Moreover, the cells activate in an organized way—some maintain their response as the animal moves several meters, others change their activity over just a few inches. Hasselmo explains that such a system makes sense because we remember spaces in different scales: sometimes we need to remember the layout of neighborhoods in a city, and other times we need to remember the layout of cubicles in an office building.

Recent work in his lab, led by graduate student Mark Brandon, suggests that these patterns arise from the interference of rhythmic oscillations in the electrical activity of brain cells. An ongoing collaboration with psychology, neuroscience, and CMB professors Howard Eichenbaum and Chantal Stern—who also directs the Cognitive Neuroimaging Laboratory—as well as researchers at MIT, the University of Texas at Austin, and University College London, will investigate whether a similar principle can be encoded in software to help robots remember their routes and positions as they move around. Hasselmo explains that robots usually represent space point by point, in a very detailed way. "It's more efficient to talk about space on different scales," he says, and breaking spaces up into a hierarchy of rooms, buildings, and neighborhoods "would make a robot better at communicating with humans about where it's been."

The Math Behind Vision

SCIENTISTS HAVE LONG KNOWN that the brain uses shortcuts to glean information from the senses. In vision, for instance, we don't need to see all the nuances of an object to recognize it. A simple, shaky line drawing of an apple or a house is instantly recognizable as the object depicted. In 1980, the late David Marr, then a professor in MIT's Artificial Intelligence Laboratory, attempted to explain this phenomenon using a theory of visual processing known as edge detection.

Marr postulated that humans determine information about images by finding edges, that is, lines of contrast that delineate one object from another adjacent one. A line drawing thus represents what the brain is already doing—outlining the world using edges separating discrete objects.

Being aware of this shortcut has made it possible for scientists to better understand vision, and for computer scientists to simulate visual perception through edge detection algorithms. One of Marr's most trenchant observations was that different edges appear at different visual length scales. Looking at an aerial view of a city, for instance, different structures come into view at different heights, from the gross outlines of neighborhoods to the fine borders of individual yards. Or consider the way that different edges emerge when you blur an image to different degrees. Marr made a conjecture: that by locating only a picture's edges at various levels of blurring—what are called multiscale edges—it would be possible to reverse-engineer mathematically this so-called edge information and reconstruct the full original visual image.

This principle has been used extensively in computer science for practical applications like facial recognition and image processing, and has informed neuroscience research on vision in humans and other animals. But Marr's conjecture also set up a fundamental problem for mathematicians: his approach made practical sense, but could his conjecture be proven mathematically?

"People grabbed onto this as a mathematical conjecture," says Mark Kon, professor of mathematics and statistics at BU. Several scholars attempted to tackle the problem, and a team of mathematicians even succeeded in showing the conjecture false for images that were infinite in size, but no one could prove or disprove the conjecture for real images, which have finite boundaries.

Kon's research deals with statistics and applied mathematics, so he has long been interested in questions that connect to problems in the real world, particularly when teaching students. Several years ago, while discussing Marr's problem in one of his classes, Kon came upon the idea of using a mathematical tool known as multipole expansions, which are used to describe electromagnetic and gravitational fields in physics, to solve Marr's problem. He assigned the task of investigating the idea to Ben Allen, then a PhD student at BU and now a postdoctoral fellow at Harvard University. Together they produced a mathematical proof of Marr's conjecture for finite images, which is under review at *Annals of Mathematics*, three decades after the conjecture was first put forth.

Their work also offers proof of the kind of flourishing and productive conversations that can take place between biology, computer science, and pure mathematics. In proving the conjecture behind a practical vision tool like multiscale edge analysis, Kon says, "We've put the icing on the cake."

Mark Kon