this can give rise to NTE behavior, as it does in $Sm_{0.75}Y_{0.25}S$. The larger $(4f^5)(5d^1)$ configuration gives way to the smaller $(4f^6)$ configuration as temperature increases. There is also an extrinsic mechanism for NTE that is frequently observed in ceramics based on anisotropic particles. Ceramics are generally sintered (fired) at high temperature. On cooling a ceramic with grains that have strongly anisotropic thermal expansion, microcracks usually occur. These can cause expansion of the ceramic body, even if the grain themselves are contracting. On heating such a material, the cracks can close, giving NTE.

For background information *see* COMPOSITE MATERIAL; COORDINATION CHEMISTRY; CRYSTAL STRUCTURE; OXIDE; OXYGEN; STRUCTURAL CHEMISTRY; THERMAL EXPANSION in the McGraw-Hill Encyclopedia of Science & Technology. Arthur W. Sleight

Bibliography. G. D. Barrera et al., Negative thermal expansion, *J. Phys. Condens. Matter*, 17:R217, 2005; J. S. O. Evans, Negative thermal expansion materials, *J. Chem. Soc. Dalton Trans.*, 3317, 1999; A. W. Sleight, Compounds that contract on heating, *Inorg. Chem.*, 37:2854, 1998.

Neuroeconomics

Neuroeconomics is a recent consilient discipline (that is, a discipline that combines the principles of other disciplines to produce a comprehensive analysis) that measures brain activity while experimental subjects make decisions. Because the brains of all animals are "economic," that is, they have limited resources to achieve necessary goals, neuroeconomics experiments are not limited to studies of human beings, but have also employed apes, monkeys, and rodents. Economics is the study of constrained decision making, and it uses both mathematical and statistical models of the decision goals and outcomes without considering the mechanisms leading to decisions. Neuroscience has focused primarily on cataloging mechanisms without considering the purpose of decisions. For this reason, neuroeconomics is a natural combination that draws from the best of, and extends, both fields.

Decisions can be modeled mathematically with three components: a decision maker's preferences, beliefs, and constraints. Such models produce empirically testable predictions. Each of these three factors can be measured using the methods of neuroscience. Many decision models in economics predict choices quite well—for example, individuals purchasing things in competitive markets. In other cases, standard models do not predict behavior well—for instance, as in some models of strategic decisions involving other people.

Neuroeconomists have investigated both individual and social decisions in order to understand the processes behind the models that predict behavior accurately, as well as to improve the models that do not predict behavior well. Because many economic models are specified mathematically and have been studied in both the laboratory and the field, they provide sharp predictions when seeking to find the brain mechanisms involved in decisions.

Utility functions. One of the most fundamental ideas in economics is that a person's preferences are represented by a utility function. Such a function relates an individual's experience with things to that individual's own valuation of those things. Vanilla and chocolate ice cream may cost the same amount, but one buys chocolate because one gets more utility from it. One's consumption of ice cream is constrained, or limited, by a variety of factors, for example, how much money one has. If the price of chocolate ice cream is substantially higher than that of vanilla, one may switch to vanilla. How are such things decided? Direct measurement of brain activity in monkeys has shown that brain cells (neurons) calculate utility. Brain imaging experiments have replicated this work in humans, revealing a network of regions that appear to calculate the value of different choices. Utility calculations draw on both evolutionarily old regions in the midbrain and newer cortical regions on the outer surface of the brain. The older regions appear to get the individual to focus on finding options, while the cortical areas integrate this information with prices to guide the individual toward the "best" choices. "Best" in this case means the choices that were most advantageous for producing progeny over the evolutionary history of *Homo sapiens*. Some of these choices, though, may be maladaptive in the modern environment. An example of a maladaptive choice is the preference for high-fat foods. During the long history of the human species, such foods were rare and were greatly valued for their high caloric content. In today's developed societies, this preference for high-fat foods (and their low cost) is producing high rates of obesity.

Standard utility maximization models also predict that people are risk averse; that is, they typically prefer a sure thing to a risky choice, even if the risky choice has a larger average payoff. Risk aversion has been localized by a number of laboratory analyses to an area of the brain called the anterior insula. This brain region makes you feel queasy when you smell rotten food, and makes your palms sweat when you are riding a roller coaster. Knowing the brain region that causes risk aversion allows scientists to understand why people vary in their responses to risk, as well as to help treat those who are pathologically risk averse or who take excessive risk, like compulsive gamblers.

Game theory. Game theory is a branch of mathematics that describes how to make choices involving other people who are also making decisions. Game theory can describe how best to make chess moves, how to negotiate an employment contract, and how to make myriad other decisions involving other people. Many game theoretic models have choices that are cooperative (sharing benefits) and choices that are selfish (hoarding benefits). Understanding why people choose to cooperate or to be selfish is vitally important because it is not possible to live in a free society unless people choose to behave cooperatively with others most of the time, even when they are not being monitored by the government.

Unfortunately, many game theoretic models do not predict behavior very accurately. For example, consider a set of choices known as the "Ultimatum Game." Suppose you were given $100 and asked to propose some split of it to another person in a different room. No communication with this person is allowed, and you will never meet him or her. The other person knows that you were given $100 and that you have to propose a split of the money. Here's the catch: if the other person accepts your proposal, you are both paid the money; but if your proposal is rejected, you both get nothing. What would you do? Standard game theoretic models predict that any offer, no matter how small, will be accepted, since some money is always preferable to nothing. However, in most developed countries, offers of $20 or less are nearly always rejected. Neuroeconomics experiments have shown why. Stingy offers produce strong activation in the interior insula, suggesting that low offers are rejected because people are disgusted by them. Human brains have evolved for social interactions, and it was typically better to lose some resources to punish a stingy person than to build a reputation for being exploitable. On the other hand, why would anyone ever make an offer in the Ultimatum Game that is generous, that is, larger than needed to be accepted? Neuroeconomists thought that empathy toward others might drive people to be generous. They tested this by giving people more of a brain chemical called oxytocin that increases empathic behaviors. Infusing oxytocin into people's brains using a nasal spray increased generosity to a stranger in the Ultimatum Game by 80%. This shows that people cooperate with them because they emotionally identify with them and do not want to hurt them.

Trust. The role of oxytocin in decisions to trust a stranger with one's money has also been studied by neuroeconomists. Any transaction that occurs over time, like a financial investment, has a degree of trust embedded in it since there are no perfectly enforceable contracts. Indeed, the general level of trust among people in a country is among the strongest predictors of which countries will have rising standards of living: high-trust countries see rapid increases in incomes. But, an open question is: Why would you ever trust a stranger with your hard-earned money? If someone shows that he or she trusts you by investing money with you, neuroeconomics studies have found that the receiver's brain releases oxytocin. In addition, the more oxytocin released by people's brains, the more they returned some of the invested money (which typically earns a large return) to the trustee. This is surprising because, in these experiments, there is no obligation to return any money at all. To prove that brains use oxytocin to help determine whom to trust, neuroeconomists have infused oxytocin into the human brain. When this is done, more than twice as many people show maximal trust in a stranger by sending that stranger all their money.

The neuroeconomists' findings on generosity and trust present a conundrum for traditional economics: trustworthy people (typically more than 90% of people studied) could have kept all the money they controlled for themselves. Instead, these people freely chose to return often a large proportion of the money to the person who initially trusted them. Why? Recent brain imaging experiments have shown that monetary transfers to another person indicating trust activate regions in the brain that reinforce behaviors by making them pleasurable. This brain reward circuit prominently uses the neurotransmitter dopamine. Because humans are social creatures, our brains have evolved to make cooperative behaviors, including trust, rewarding. Brain imaging studies have shown that even donating money to charity appears to activate brain regions associated with empathy (through oxytocin) and reward (through dopamine). These studies also reveal the importance of emotions when making economic decisions.

Punishment. What happens when someone betrays your trust? If you are like most people, you don't like this at all, and you want to let the other person know it. When people are given the chance to spend some of their own money to punish another person for betrayal, they readily do so. Costly punishment occurs even if the individuals involved will not interact with each other again. This has been called moralistic punishment. Physiologically, when one is betrayed, testosterone, a hormone associated with aggression, spikes. The act of punishment also activates dopaminergic reward regions of the brain. Individuals punish because they are angry, and they find it rewarding to punish betrayers—even at a cost to themselves. The threat of punishment is an important mechanism that sustains cooperative behaviors, even among those who might consider being selfish.

Outlook. Rather than the classical view of humans as "*homo economicus*" (purely rational and self-interested), research in neuroeconomics suggests that humans could more appropriately be called "*homo reciprocans*"—reciprocating creatures who are influenced by emotion. These early but important neuroeconomics studies indicate that the human brain is wired to evaluate the utility of options and to extract economic value from social interactions. While neuroeconomics is a new field, it holds the promise to improve the ability to understand one's own choices, to better predict the choices of friends and customers, and to guide government policy. Neuroeconomics studies also allow scientists to help those who make poor choices, including criminals, those with psychiatric disorders, and those under extreme stress, such as soldiers.

For background information *see* BRAIN; COGNITION; DECISION ANALYSIS; DECISION THEORY; DOPAMINE; GAME THEORY; INFORMATION PROCESSING (PSYCHOLOGY); INSTRUMENTAL CONDITIONING; LEARNING MECHANISMS; MEDICAL IMAGING; NEUROBIOLOGY in the McGraw-Hill Encyclopedia of Science & Technology. Paul J. Zak

Bibliography. C. F. Camerer and E. Fehr, When does "economic man" dominate social behavior?, *Science*,

311:47–52, 2006; C. F. Camerer, G. Loewenstein, and D. Prelec, Neuroeconomics: how neuroscience can inform economics, *J. Econ. Lit.*, 43:9–64, 2005; M. Kosfeld et al., Oxytocin increases trust in humans, *Nature*, 435(2):673–676, 2005; P. J. Zak, Neuroeconomics, *Philos. T. Roy. Soc. B*, 359:1737–1748, 2004; P. J. Zak, The neurobiology of trust, *Sci. Amer.*, pp. 88–95, June 2008.

Neuromorphic and biomorphic engineering systems

Many biological systems, from the molecular scale to the macroscale and from the body to the brain, display remarkable efficiency and robustness. For example, a single mammalian cell, approximately 10 micrometers in size, performs complex biochemical signal processing on its mechanical and chemical input signals with highly noisy and imprecise parts, using approximately 1 picowatt (10^{-12} W) of power. Such signal processing enables the cell to sense and amplify minute changes in the concentrations of specific molecules amid a background of confoundingly similar molecules, to harvest and metabolize energy contained in molecules in its environment, to detoxify poisonous molecules, to sense if it has been infected by a virus, to communicate with other cells in its neighborhood, to move, to maintain its structure, to regulate its growth in response to signals in its surroundings, to speed up chemical reactions via sophisticated enzymes, and to replicate itself when it is appropriate to do so. The approximately 20,000-node gene-protein and protein-protein molecular network within a cell makes even the most advanced nano-engineering of today look crude and primitive.

The brain is made of approximately 22×10^9 neurons that form a densely connected network of approximately 240×10^{12} synaptic connections. This network performs approximately 10^{15} synaptic operations per second at approximately 14 W of power, several orders of magnitude more energy efficient than the most advanced computers. The brain can perform real-time, reliable, complex tasks with unreliable and noisy devices. It uses remarkably compact hardware built with a rich array of biochemical and biophysical devices and is architected with a 3D interconnect technology that allows three orders of magnitude more connectivity than the most advanced engineering systems of today. The brain is adaptive and plastic with rapid learning and generalization capabilities that outperform the most sophisticated machine-learning algorithms.

Can we learn from nature to build better engineering systems that are equally impressive, robust, and efficient? The goal of neuromorphic engineering, a term coined by Carver Mead, is to take inspiration from neurobiological architectures to build better engineering systems, "morphing" them with insight from their natural neurobiological domains to be useful in artificial engineering domains. More generally, we can define a biomorphic system as one that takes inspiration from any architecture in biology, for example, the architecture of cells, to create a morphed version that is useful in an engineering context. Thus, airplanes are biomorphic architectures that are inspired by the winged flight of birds. A neuromorphic silicon cochlea or silicon retina is inspired by the architecture of the ear or the eye and performs highly parallel nonlinear filtering, gain control, and compressive computations on an audio or image input respectively.

Relation of engineering to biological systems. Biomorphic solutions have sometimes been reinvented by engineers without their even knowing that they are biomorphic or that they already exist in nature: The use of chirp signals for accurate range sensing in radars was invented by engineers around World War II, but bats had already been using ultrasonic chirps for range sensing in their biosonar systems for millions of years. Positive-feedback circuits were invented about 100 years ago but have been present in sodium ion channels for more than 100 million years. Thus, knowledge of systems in nature can provide useful ideas for engineering. Several biomorphic architectures, such as machine-learning and pattern-recognition systems inspired by the operation of neurons in the brain, are already widely used in artificial systems.

In biomorphic systems, it is important to keep the insightful "baby" and throw out the cluttering "bathwater" details. Certain architectures in biology may be accidents of evolution, may be more suited to the constraints of a biological organism, and may serve or may have served a purpose that we do not yet understand. Consequently, their relevance to a different engineering context where the constraints are different may be questionable. Birds are not airplanes and airplanes are not birds, although the study of one can shed insight into the study of the other. Hence, it is important to evaluate a biomorphic engineering system by traditional engineering metrics to insightfully understand where value can be added.

Types of biomorphic systems. From an engineering point of view, where do biomorphic systems add value? They clearly have the potential to shine in the following kinds of systems:

1. Ultralow-power and highly energy efficient sensing, actuating, and information-processing systems.
2. Signal processing and pattern-recognition systems that need to operate in noisy environments and over a wide dynamic range of inputs.
3. Robust and efficient computation with noisy and unpredictable devices.
4. Systems with feedback, adaptation, and learning at multiple spatial and temporal scales.
5. Systems that integrate technologies from diverse domains.
6. Self-repairing systems.
7. Self-assembling systems.
8. Energy-harvesting systems.
9. Robotic systems.

Features of biomorphic systems. How do biomorphic systems appear to accomplish these feats?