TEAMS The Engineering Brain

High School Scenario Overviews

2019 TEAMS Competition

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Introduction

The National Academy of Engineers defined fourteen Grand Challenges for Engineering in the 21st century. These challenges bring to light societal issues that are at the heart of our changing world – and pose questions that tomorrow's engineers will answer. One of these Grand Challenges is "Reverse Engineering the Brain."

The brain is a powerful organ that controls functions of the body required for life, including breathing, heartbeat, blood flow, and the central nervous system. The brain controls thinking and action: when you see a dangerous situation, your brain quickly decides the best course of action. In addition, we use our brains to calculate, to follow instructions, to process language, sight, sound and smell. Our brain can examine outside situations full of moving objects and figure their interaction (the basic properties of physics).

Reverse engineering the brain will help us gain an understanding of how the brain works so that engineers can apply that knowledge to information processing and decision making in computers. For example, visual cues provide input to a human brain – engineers may research how an algorithm can be developed to simulate this type of cue for a computer.

Engineers study the brain in a variety of ways including mathematically modeling the function of the brain as neural networks, looking at the biology of the human brain and researching the brain of other organisms.

This TEAMS competition will challenge your team to apply math, science, technology and engineering skills to addressing the challenge of "Reverse Engineering the Brain."

Cognitive Neuroscience

Overview

What is happening inside our brains when we program a computer to solve a complex problem? We know that experts and novices might behave differently, or come up with different solutions to a problem, but does their brain fundamentally think about things in different ways? Scientists and engineers pursue answers to these questions in order to understand how to interpret data important to improving automated solutions.

Cognitive neuroscience is a field that studies data on human behavior and brain activity to understand human cognition (e.g., thinking, planning, decision making). While you might expect biomedical engineers to play important roles in these fields, so do engineers of all kinds. For example, advances in techniques to study the brain involve new types of sensors and signal transformation to filter noise, comprehend data, develop mind-controlled prosthetics that involve robotics and controls; and train the computer to read intentional signals from the brain.

A key part of being an engineer involves learning laws, theories, and formulae from science and mathematics and applying them in a variety of exciting contexts, sometimes using them to solve problems of tomorrow that cannot be imagined in today's world.

How can engineers help?

Engineers are involved in advancing these brain-imaging technologies by improving sensors, developing algorithms to process data, and designing interfaces that help others analyze the data and visualize results. Your team will perform calculations and do some basic interpretation and signal processing to better understand what goes into making sense of this sort of complicated but important data.

Explore More

Mind-controlled prosthetic arm
www.hopkinsmedicine.org/news/media/releases/mind_controlled_prosthetic_arm_moves_individual_fingers_

A Beginner's Guide to Neuroscience
imotions.com/blog/beginners-guide-neuroscience

EEG, MRI, and fMRI
imotions.com/blog/eeg-vs-mri-vs-fmri-differences

science.howstuffworks.com/fmri.htm

EEG (Electroencephalography)
imotions.com/blog/eeg

Functional Near-InfraRed Spectroscopy (fNIRS)
nirx.net/fnirs-and-nirx

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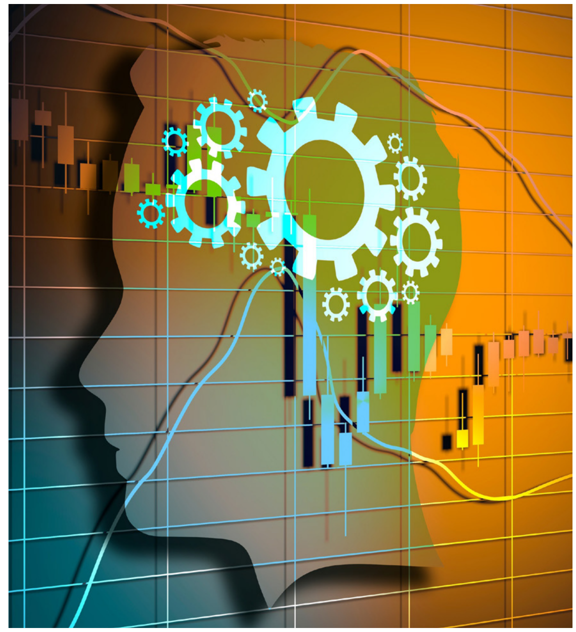
Considering the Brain as Hardware



Overview

Brains, and extended neurological systems as a whole, are some of the least understood organs in many species. However, while their core functionality and the processes by which they produce consciousness remain a mystery, key aspects of their structure are becoming increasingly clear. From vision replacement or augmentation prosthetics—to prosthetics designed to reduce the frequency of seizures—there is increasing research into devices designed to interface directly with the brain.

When engineers design hardware for—or around—brains, they must consider a number of factors including interface method, operational speeds, and translation between digital and analog signals. Analyzing and understanding the functionality of the brain from an engineering standpoint also involves understanding how the nature of the brain translates into more traditional terms, with respect to processing power, speed, energy usage, etc. We need to understand how machines need to interface with a brain and how the brain can be interpreted as a machine, or as a mechanistic component.

How can engineers help?

Your team must work to explore and establish the necessary design parameters for using a brain to accomplish tasks that normally would be handled by conventional electronics. In addition, your team will determine the needs of a specific application and consider how well a biological brain could meet those needs.

Explore More

Does thinking burn calories?
www.scientificamerican.com/article/thinking-hard-calories

Conductivity of nerve cells
sciencing.com/conductivity-nerve-cells-central-nervous-system-22283.html

EEG, MRI, and fMRI
www.pubnub.com/blog/how-fast-is-realtime-human-perception-and-technology

www.extremetech.com/extreme/218403-critical-flicker-fusion-test-can-measure-the-brains-processing-speed

www.newscientist.com/article/dn9633-calculating-the-speed-of-sight

Could you charge an iPhone with the electrical energy from your brain?
gizmodo.com/could-you-charge-an-iphone-with-the-electricity-in-your-1722569935

Using Decision Trees to Inform the Engineering Process

Overview

Everyone makes decisions on a daily basis—from selecting what to wear to choosing the right financial investment. Our human brains are hard-wired to make these decisions primarily based on instinct, intuition or a "gut feeling." Such wiring is the result of human evolution, as our stone-aged ancestors relied on their intuition to seek cover from an incoming storm, escape a predator, or decide where and how to start hunting. At that time, a faulty decision could lead to death; hence, only the "good" decision-makers survived and were more likely to procreate.

However, while these intuitions once helped us survive, they can sometimes lead us to make flawed decisions. We tend to select the things that seem more attractive, without realizing they could be harmful. For example, we appreciate fast food when we are hungry because it "solves" the current problem and we may be deceived into thinking that fast food is healthy. Decisions based on intuition are biased toward the things we like, or we believe we like.

This phenomenon also can be observed through our preferred social network. We handpick the posts we like; we click "like" to the posts that are related to what we believe in. In response, the social network's algorithm shows us more posts related to the ones we liked before, and the system continues to show us more posts in which we are inclined to believe. In the end, our intuition deceived us into thinking what we believe in, must be true (regardless of whether we have any evidence of support.)

Engineers and scientists can help overcome such biased intuitions by using proper technology tools to discover how the brain makes decisions. A systematic process of decision-making aims to increase the likelihood of achieving the best possible outcome and reduce the possibility of the worst outcome. Such processes are repetitive, yet reliable, insuring that regardless of the outcome, the best possible decision was made with the information known at the moment.

How can engineers help?

Your team will explore and apply the algorithms necessary for using tools of decision making, including decision trees, to make engineering decisions.

"We all make decisions every day, but few of us think about how we do it."

—Ronald Howard & Ali Abbas

Explore More

Introduction to Steps of the Decision-making Process
online.csp.edu/blog/business/decision-making-process

Introduction to how to Build Decision Trees for decision-making
www.decision-making-solutions.com/decision-making-tree.html

Decision-making Process Using Decision Trees
www.mindtools.com/dectree.html

hbr.org/1964/07/decision-trees-for-decision-making

Introduction to Probability from Khan Academy and CNYU
www.khanacademy.org/partner-content/wi-phi/wiphi-critical-thinking/wiphi-fundamentals/v/bayes-theorem

Engineering the Invertebrate Brain

Overview

Scientists have spent hundreds of years trying to comprehend the human brain in order to better understand human behavior and disease. With the recent advent of more advanced imaging methods and chemical staining techniques, we now know more about the brain than ever before. While the basic structure and function of the human brain is taught in almost all basic biology courses, that of the invertebrate brain is not nearly as widely known and can appear extremely different both in structure and function.

For all organisms, the brain is only a portion of the nervous system, which functions to receive and transmit signals throughout the entire body. These signals mediate both voluntary and involuntary information and behaviors for the organism. For example, muscle movement, hearing, sight, and smell are processed by the nervous system, as are the circulation of blood, breathing, and the maintenance of internal body pressure.

Generally, the number of neurons in the brain are considered to correlate with the ability and intelligence of an organism. While human brains can have billions of neurons, invertebrates generally have fewer cells than those of even the smallest vertebrates, sometimes as few as 300 nerve cells altogether. However, invertebrates experience the same survival dilemmas to overcome, live in highly organized communities, and can communicate effectively between each other. They exhibit highly diverse behavior despite their much smaller nervous systems and, sometimes, lack of an overall brain.

How can engineers better understand the invertebrate brain in order to more fully comprehend how other organisms interact with, and survive, in our shared world?

Invertebrates far outnumber the number and diversity of vertebrates, yet engineers, do not always consider them when trying to study the nervous system. Your team will use a variety of tools in order to understand and measure various aspects of some different invertebrate nervous systems, including how this might affect behaviors, interactions, and sensing of their environment.

Explore More

Invertebrate Brain, Vertebrate Brain, Human Brain, Brain Stem, etc.
science.jrank.org/pages/1016/Brain.html

science.jrank.org/pages/1009/Brain-Invertebrate-brain.html

Invertebrate Nervous Systems, Thomas Matheson
pdfs.semanticscholar.org/098e/c8214c08ca39098d8033932e1749c8fa2284.pdf

Vertebrate vs. Invertebrate Neural Circuits
www.cell.com/current-biology/pdf/S0960-9822(13)00634-9.pdf

Brains—Invertebrate Nervous Systems
guides.library.harvard.edu/fas/Brains/inverts

Mathematizing the Human Mind

Overview

Reverse engineering the brain is a significant grand challenge for engineers. Deconstructing the human mind to model its functions to develop realistic artificial intelligence and solve problems, is valuable in a variety of sectors, from speech-to-text recognition to automation. Emerging in the late 1940s, D.O. Hebb developed an idea for the mathematical representation of "learning" based on neural plasticity, which is the ability of the brain to change over one's lifetime.

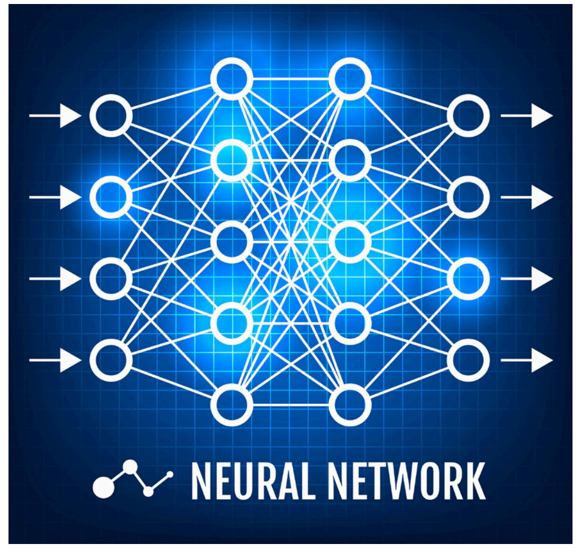
The initial computational models of Farley and Clark in 1954 and Rosenblatt in 1958 provided the first steps toward the simulation of learning, but the development of Werbos's algorithm of "backpropagation" in 1975 generated more interest in the learning models because of their ability to solve previously intractable problems. Now, the learning models are known as "artificial neural networks."

Neural networks were intriguing to the scientific community, but the method fell to the wayside at the time, because computing power was not mature enough yet to solve massive problems. As computational power grew, researchers were able to find more complex patterns which the artificial neural networks could predict in a reasonable runtime. The ability of the networks to discern patterns has been useful for several applications such as handwriting recognition (translating handwritten documents into typed documents).

Considering the loose interpretation of the biological processes occurring in the brain during learning, the power of the networks potentially foreshadows our capacity to capture our biology in the future more effectively.

How can engineers help?

Your team will learn about the basics of a neural network and design one to solve a simple pattern recognition problem. You will consider the effect of different parameters in the creation of the neural network, such as the thresholds and weights, on the axons connecting the neurons.



Explore More

Overview of ANNs
www.digitaltrends.com/cool-tech/what-is-an-artificial-neural-network

Deeper into "learning"
becominghuman.ai/making-a-simple-neural-network-2ea1de81ec20

Neural Network
bit.ly/TinkerNeuralNetwork

Math of Neural Networks
neuralnetworksanddeeplearning.com/chap1.html

History, Current Uses, and Controversy
gizmodo.com/youre-using-neural-networks-every-day-online-heres-h-1711616296

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The Brain as a Computer: Measuring Activity

Overview

A computer can be thought of as any device or system that receives and processes information, stores data, and generates responses to the information it has received. In this sense, the brain acts as a computer for the human body by receiving, processing, and storing information from our various senses (such as sight, touch, smell, etc.) and by generating responses to that information (such as movement or new thoughts). Understanding how our body's computer works is important for improving current treatment options for various neurological disorders or injuries; designing better treatment and rehabilitation plans for stroke patients; and even in improving the design of controlled prostheses and other devices.

Engineers and scientists work in a variety of settings that enable them to improve our understanding of the brain. In particular, engineers play a vital role in improving measurement techniques and analyses of recorded brain activity through devices such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG). Studying the recorded brain activity as a result of various stimuli can help to "decode" brain activity by determining localized functionality of various regions of the brain and can lead to discoveries of new connections among those localized regions.

Although there have been great improvements in the last century related to measuring neural signals and "decoding" or understanding the brain, there are still significant challenges and limitations related to measuring brain activity with highly accurate spatial and temporal resolution.

How can engineers help?

Using EEG equipment, a scientist or engineer can measure neural activity with a temporal resolution of roughly 0.05 seconds; however, these measurements have, at best, a spatial resolution of roughly 10 mm. Conversely, scientists or engineers can use fMRI to measure neural activity with a spatial resolution of roughly 1 mm, but a temporal resolution of, at best, 1–2 seconds. Your engineering team will work to determine which measurements must be made to gather information on neural activity and how that data can be applied to better understanding the inner workings of the brain.

Explore More

fMRI Overview
www.ndcn.ox.ac.uk/divisions/fmrib/what-is-fmri/introduction-to-fmri

EEG Overview
www.myvmc.com/investigations/electroencephalogram-eeg

Review of Brain-Computer Interfaces (benefits/limitations of fMRI, EEG, etc.)
www.ncbi.nlm.nih.gov/pmc/articles/PMC3304110

Regions of the Brain and their Functions
www.mayfieldclinic.com/pe-anatbrain.htm

gallantlab.org/huth2016

Working Memory
www.cell.com/neuron/pdf/S0896-6273(15)00777-1.pdf

Physics of MRI and Induction
onlinelibrary.wiley.com/doi/pdf/10.1002/jmri.25761

www.simplyphysics.com/page2_3.html

Brain Connectivity
www.scholarpedia.org/article/Brain_connectivity

Traffic Engineering

Overview

The human brain controls everything we do—from basic functions needed to survive, to navigating through traffic. Traffic has a significant impact on everyday life. From the moment we leave our homes, we are interacting with transportation systems designed with different users in mind, and these designs are not trivial. Everyone wants to get where they are going faster, but we also prioritize safety when using the road as drivers, passengers, pedestrians, cyclists, or others.

Whether driving to the store, walking on the sidewalk with friends, riding a bike to school, or taking public transportation in a city—the design of these systems impacts and anticipates human behavior. In this way, traffic engineering intersects with the study of the human brain and behavior. For example, adjusting the timing of stoplights can influence how many drivers decide to enter the intersection during the yellow caution light. Or, widening roads might result in drivers feeling more comfortable going faster. People also may react to obstacles at different rates depending on how distracted they are in their vehicle. There is a need to consider the brain and human behavior in the design of traffic systems.

How can engineers help?

Traffic engineers consider the physical design of the road and how cars move through these confines, all while making safety a top priority. Your team will utilize established rules of thumb and formulas that model human behavior around traffic systems to make predictions about the consequences of driver behavior and optimize the design of traffic systems.

Explore More

What is Traffic Engineering?
www.azdot.gov/business/engineering-and-construction/traffic/faq

Institute of Transportation Engineers
www.ite.org

State Transportation Websites
www.fhwa.dot.gov/about/webstate.cfm

Uniform Traffic Control Devices for Streets and Highways
mutcd.fhwa.dot.gov

Predicting Human Behavior to Improve Transportation Systems
www.cmu.edu/cee/news/news-archive/2015/2015-predicting-human-behavior-to-improve-transportation-systems.html

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Probability and Uncertainty in Design

Overview

The engineering brain is used to design solutions to problems, typically, with the creation of a new physical device or process. The solution is expected to function in a certain manner and under certain conditions. For example, the purpose of a bridge is to provide efficient transportation across difficult terrain such as rivers or valleys. One characteristic of any engineering design is that it is bound by criteria such as weight, size, capacity, operating environment and, cost. The various constraints required of solutions are often contradictory. The constraints on a bridge may be the capacity of the bridge to carry certain loads and its flow capacity. The criteria for an interstate bridge and a pedestrian bridge would be very different. A pedestrian bridge could be built to the level of an interstate bridge, but it would be too costly and therefore a poor design.

When designing, both criteria and solutions need to be quantified. The engineer is never certain of the answer to these questions since there is never 100% certainty in the answer to any quantifiable question.

The engineer will rely on engineering standards and experience to estimate the values, but will never be sure that the maximum flow capacity is, for instance, 20,000 vehicles per day. There is uncertainty, and with uncertainty there is always the possibility of failure. With perhaps 80,000 vehicles per day using the bridge, it causes the bridge to fail by weakening to an unacceptable level or perhaps even catastrophic failure. With failure always a possibility, that probability must be quantified to determine at what point failure is acceptable.

Engineers are tasked with providing design solutions that with maximum efficiency, meet the needs of society. Large uncertainty in design elements can lead to overdesigned solutions that are costlier in material, time, pollution, cost, and other critical factors. Constantly, engineers are exploring new materials and methods and applying them in new ways to create increasingly efficient designs that solve problems at an acceptable level of success. These efficiencies free scarce resources such as material and money for use in other societal needs.

How can engineers help?

Your team will be tasked to find levels of probability graphically and through the use of statistical tools and methods. These calculations and estimations form the basis for many engineering designs.

Explore More

Determining Acceptable Failure of Safety Equipment in Vehicles
www.nytimes.com/2011/02/17/business/economy/17regulation.html

Taking Lessons from What Went Wrong
www.nytimes.com/2010/07/20/science/20lesson.html

United States Office of Energy Efficiency and Renewable Energy
energy.gov/eere/office-energy-efficiency-renewable-energy

NASA: Risk, Failure Probability, and Failure Rate
kscddms.ksc.nasa.gov/Reliability/Documents/170505_Risk_Failure_Probability_and_Failure_Rate.pdf

Flood Risk Probability
training.fema.gov/hiedu/docs/fmc/chapter%204%20-%20flood%20risk%20assessment.pdf

Reliability at General Electric
www.ge.com/en/company/companyinfo/quality/whatis.htm