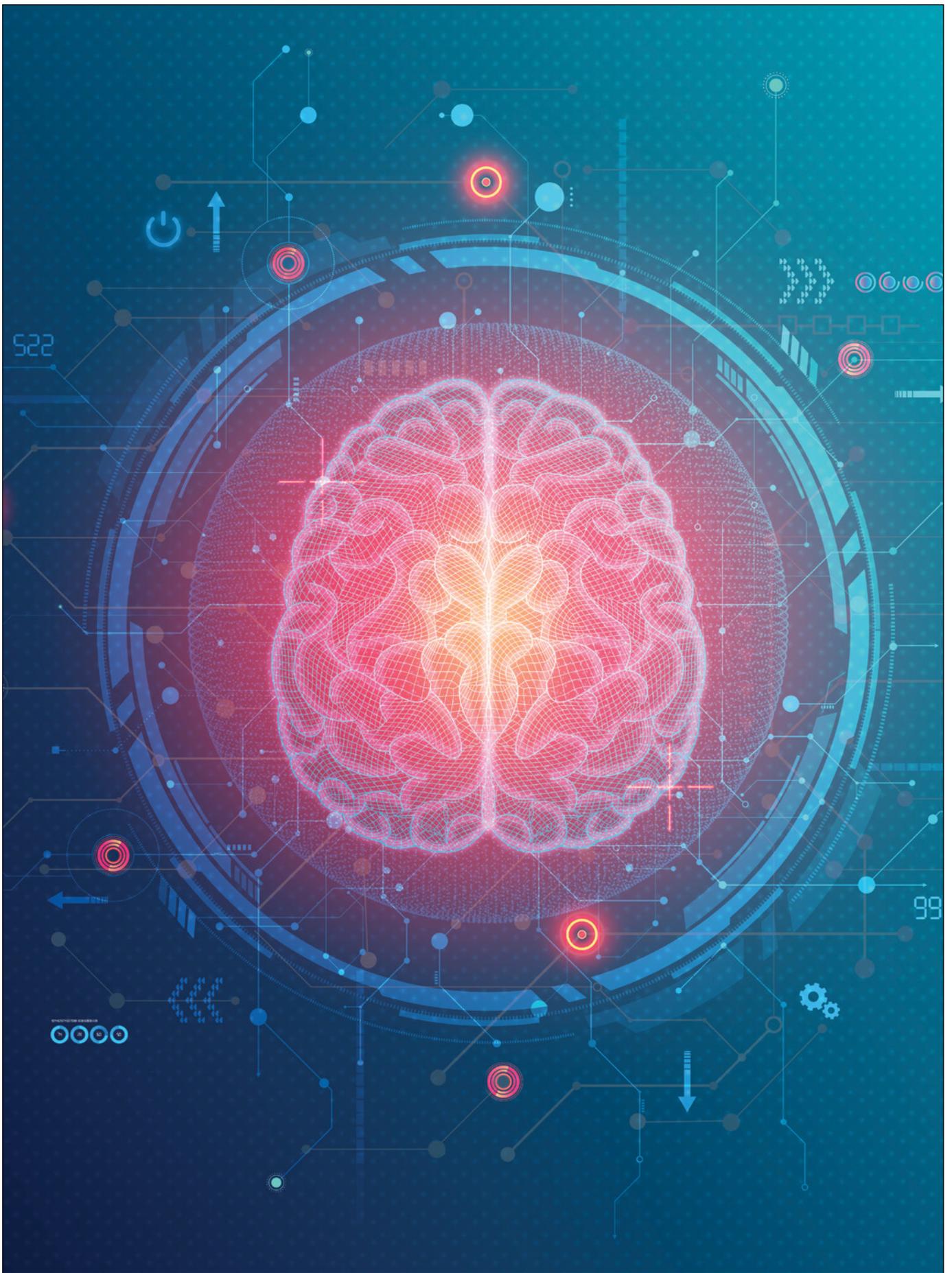STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2026
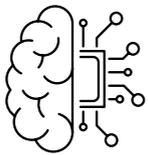
A Report on Ten Key Technologies and Their Policy Implications

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NEUROSCIENCE

KEY TAKEAWAYS

- Advances in human genetics and experimental neuroscience, along with computing and neuroscience theory, have led to some progress in several areas, including understanding and treating addiction and neurodegenerative diseases and designing brain–machine interfaces for restoring vision.

- American leadership is essential for establishing and upholding global norms about ethics and human subjects research in neuroscience, but this leadership is slipping with decreased strategic planning and increased foreign investments in the field.

- Popular interest in neuroscience vastly exceeds the current scientific understanding of the brain, giving rise to overhyped claims in the public domain that revolutionary advances are just around the corner.

Overview

Neuroscience is a multidisciplinary field of study that focuses on the components, functions, and dysfunctions of the brain and our nervous system at every level. It reaches from the earliest stages of embryonic development to dysfunctions and degeneration later in life, and its study spans from the individual molecules that shape the functions of a neuron to the complex system dynamics that constitute our thoughts and dictate our behaviors.

The human brain consumes 20 to 25 percent of the body's energy even though it constitutes only a small percentage of a human's body weight, a fact that underscores its outsize importance.[1] The power of the human brain is what has allowed us to become the dominant species on Earth without being the fastest, strongest, or biggest.

The brain is unfathomably complex, containing approximately eighty-six billion neurons[2]—nerve

cells that sense the physical world, transmit information to the brain, process information, and send information from the brain to other parts of the body. A single neuron can make thousands or tens of thousands of connections to other neurons. These connections are called synapses (see figure 6.1).

All of our consciousness and behavior, from the action of stabbing a potato with a fork to contemplating the mysteries of the universe, is underpinned by which neurons connect with one another, the neurotransmitter/receptor pairs involved, the strength of the connections, and the electrical properties of the neurons—as well as by how these various features change over time.

Neurons and synapses function in many ways that are similar to electrical circuits. Indeed, the exploration of the electrical properties of neurons came directly from the same technologies, theories, and equations developed for harnessing electricity. Many pioneering neuroscientists started as electrical engineers and physicists. Just as electrical connectors create a path for electricity to flow through a circuit, neural circuits can be defined by the parallel and recurrent connections between neurons that occur to compute a specific function, such as deciding to move a limb or visually identifying an object. Neurons can also communicate with each other using hormone-like signaling, which is relatively slow but longer lasting compared to fast-acting electric signals. These types of communications underlie mood and behavior states such as sleep/awake and hunger/satiety.

Complete understanding of what each neuron is doing at any given time is currently impossible. Even for a mouse brain, which is much simpler than a human brain, it is still a tremendous effort to characterize individual brain regions despite the availability of powerful techniques that allow us to identify activity in individual neurons or to noninvasively tag cells to respond to light signals.

FIGURE 6.1   Structure of a neuron

Dendrites

Cell body

Axon

Axon terminal

Synapses

Direction of
information flow
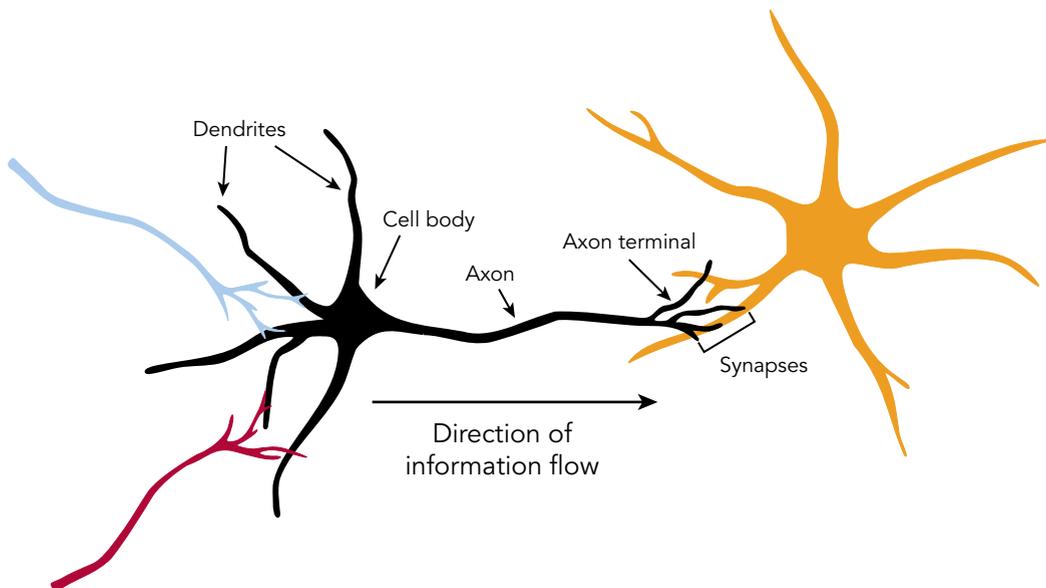
Headlines about mind-reading chip implants are . . . still more the realm of science fiction.

Over the past several years, however, it has become clear that individual neurons are almost never responsible for any given behavior or computation; instead, they act in parallel, duplicating some functions and combining to determine thoughts and actions. This neural redundancy makes it easier to infer what is going on in the brain more broadly.

A particular brain region can be considered like a magnificent choir of a thousand voices. Sampling just 1 percent of the singers can provide a pretty good idea of the music the overall choir is producing at any given time. Researchers already have the ability to record from thousands of neurons at a time. This provides useful insight into how a brain functions, even if we don't understand in detail what the other 99 percent of its neurons are doing.

It is important to keep in mind that the pace of neuroscientific discovery is slow and limited by the biological nature and complexity of the nervous system. Year-over-year advances tend to be incremental. Furthermore, the brain's complexity often prevents researchers from fully understanding why even effective treatments for neurological conditions actually work. For example, we know that drugs called selective serotonin reuptake inhibitors block the reabsorption of serotonin into neurons, but neuroscientists do not have a clear explanation for why this helps treat depression. Sometimes, even if a detailed understanding of a treatment's mechanisms is not essential for therapeutic intervention, knowledge of the underlying biology greatly aids in the search for new drugs and therapies.

To gain understanding of how molecules and neurons work, many researchers use simple model organisms like fruit flies and mice to study fundamental questions inexpensively. But the closer research gets toward human application, the more complex, time-consuming, and expensive it becomes. For instance, because neurodegeneration is a slow, progressive disease where day-to-day worsening is minimal, clinical trials often take many years.

Key Developments

This chapter focuses on three research areas in neuroscience that show major promise for concrete applications: brain–machine interfaces (neuroengineering), degeneration and aging (neurohealth), and the science of addiction (neurodiscovery). Most of the economic impacts of neuroscience connect in some way to the healthcare industry and its search for treatments for neurodegenerative disorders (such as Alzheimer's and Parkinson's disease) and neuropsychiatric disorders (addiction, depression, and schizophrenia) and neural prosthesis (brain–machine interfaces to restore limb function and speech).

Neuroengineering and the Development of Brain–Machine Interfaces

A brain–machine interface is a device that maps neural impulses from the brain and translates these signals to computers. The potential applications for mature brain–machine interface technologies are wide-ranging: The augmentation of vision, other senses, and physical mobility; direct mind-to-computer interfacing; and computer-assisted memory recall and cognition are all within the theoretical realms of

possibility. However, headlines about mind-reading chip implants are exaggerated and still more the realm of science fiction. Even with tremendous interest and increasing progress in neuroscience and engineering, the necessary theoretical understanding of how neurocircuits work is still limited to only a few areas of the brain. What's more, the technical problems of safely implanting electrodes have not been solved.

One encouraging example of a brain–machine interface is the recent development of an artificial retina. The retina is the part of the eye that converts light into corresponding electrical signals sent to the brain. People who have certain incurable retinal diseases are blind because the light-detecting cells in their retinas do not work. To restore sight, the Stanford artificial retina project aims to take video images and use electrodes implanted in the eye to simulate the electronic signals in a pattern that a functional retina would normally produce.[3]

The project involves recording spontaneous neural activity to identify cell types and their normal signals, understanding how electrodes activate cells, and stimulating retinal ganglion cells—which collect visual information from photoreceptors in retinas—to represent an image so that this information can be transmitted by the optic nerve to the brain. Solving these technical problems calls for deep knowledge of relevant surgical techniques as well as significant engineering know-how in multiple areas; this includes translating the scientific understanding of the stimulation algorithm used into practical applications, making experimental recordings, and fabricating and packaging the electrode into the device.

The artificial retina project is the most mature brain–machine interface to date in terms of its ability to "read" and "write" information. The retina, a part of the central nervous system, is well suited as an experimental environment because its stimuli (light) is experimentally controllable and can be captured by a digital camera. It is the best-understood neural circuit, and the theory of its function has developed to the point where much of retinal processing can be modeled. Compared to complex cognitive processes like learning and memory—where even the inputs aren't fully understood—the task of reconstructing vision is more achievable, albeit still challenging.

Other brain–machine interfaces are currently being developed, though they are less mature or less ambitious than the artificial retina project. Some of these decode brain activity without controlling a neural signal. For instance, one interface can translate brain activity in areas controlling motor functions into signals that can then be sent to an artificial prosthetic limb. Here, feeding high-dimensional patterns of recorded neural activity into an artificial intelligence (AI) algorithm can make it possible to control an artificial limb without requiring direct control of neural functions—a form of control that remains beyond our current scientific understanding.

These demonstrations hint at the prospect of other brain–machine interfaces in the future, such as computer-assisted memory recall, even if the full suite of potential applications is still unclear. The scope and feasibility of these applications will be determined by advances in neuroscientific theory and by technical solutions to engineering problems such as how to safely and accurately insert probes into deep-layer tissues.

Neurohealth and Neurodegeneration

Neurodegeneration is a major challenge as humans live longer. Alzheimer's disease is of particular concern. In the United States alone, the annual cost of treating it is projected to grow from $305 billion in 2020 to $1 trillion by 2050.[4] Diseases like Alzheimer's and Parkinson's surge in frequency with age; while just 5 percent of 65- to 74-year-olds have Alzheimer's, this rises to 33 percent for those over 85 (see figure 6.2).[5] As modern medicine and society enable longer lifespans, the human body and brain remain maladapted to maintaining nervous system function for decades past childbearing age.

Alzheimer's disease is characterized by the accumulation of two different proteins—amyloid beta and tau—into toxic aggregates. Amyloid beta accumulates outside of neurons, induces cellular stress, and in turn may cause tau to build up inside the neurons. As the brain regions where tau accumulates are those most cognitively impacted, a reasonable consensus exists that tau is the more direct cause of the neural death responsible for dementia.

However, despite what is known about neurodegenerative diseases such as Alzheimer's, no drugs can reverse the associated memory loss. Tau remains harder to target therapeutically, and the recently approved drugs target amyloid beta. While these amyloid drugs are very effective in eliminating the amyloid plaques from patient brains, they only modestly slow disease progression. One factor that can improve the outcomes of future clinical trials is to select early-stage patients whose neurons have not yet died, as re-creating memories after neurons have died is not believed to be possible. Efforts are being made to develop techniques for early diagnosis for more effective intervention.

Another form of neurodegeneration results from traumatic brain injury (TBI), which can manifest itself in a range of complex symptoms and pathologies.[6] Traumatic impact to brain systems can affect cognitive and behavioral functions in ways that lead to long-term and severe psychiatric conditions requiring specialized care. This is particularly evident in the current surge of athletic and military brain injuries that exhibit predominantly psychiatric symptoms. A person's past medical and psychiatric records, as well as any coexisting conditions, play a vital role in diagnosis and treatment. TBI offers insights into other neuropsychiatric disorders and can pave the way for innovative concepts in neurodegenerative disease.

FIGURE 6.2   Alzheimer's disease surges in frequency with age
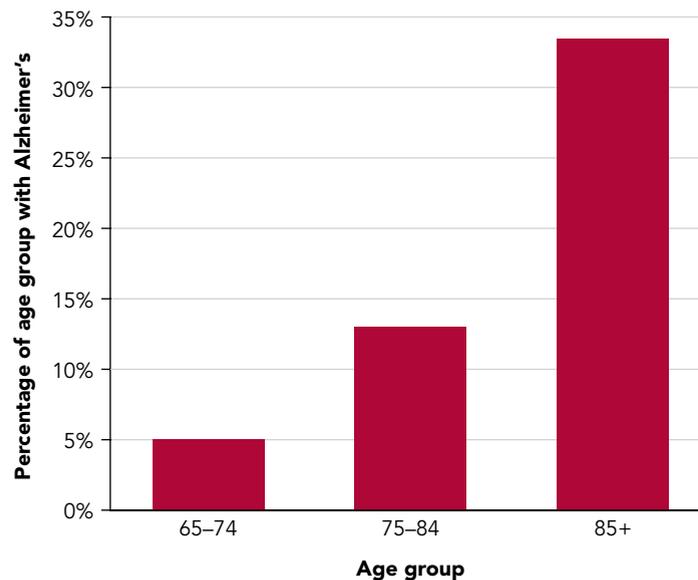
Source: Data from "2023 Alzheimer's Disease Facts and Figures," *Alzheimer's & Dementia* 19, no. 4 (April 2023): 1598–1695, https://doi.org/10.1002/alz.13016

Neurodiscovery and the Science of Addiction

Researchers are working to understand the neural bases of addiction and chronic pain while collaborating with psychiatrists and policymakers to address the opioid epidemic.[7] Estimates of the economic costs of that epidemic range from $100 billion to $1 trillion a year when the loss of potential lifetime earnings of overdose victims is included.[8] Additional economic losses occur due to depletion of the labor force and the billions spent on the criminal justice system and healthcare related to addiction.[9] Beyond economics, there are the significant emotional costs to individuals experiencing addiction and their families and friends. Death also takes its toll: The number of opioid deaths in the United States rose from 21,000 in 2010 to 83,000 in 2022,[10] placing deaths from opioid overdoses at the same level as those caused by diabetes and Alzheimer's.[11] Overdose deaths from opioids fell by 38 percent between the end of 2023 and the end of the following year,[12] but it is unclear if that trend will continue.

Many of the most impactful changes for dealing with the societal problems arising from addiction come from public policy interventions and societal shifts, such as raising taxes on tobacco or changing physicians' prescribing practices for addictive substances such as opioids (see figure 6.3). Nevertheless, neuroscience has a potentially important role to play in addressing addiction. For example, a nonaddictive painkiller drug as effective as current-generation opioids could be transformative.[13]

Another approach is to leverage neuroscience to identify and target brain states that reinforce addiction or make it more likely. Consider the problem of relapse in tackling addiction. Scientists have found that the brain mechanisms leading to an initial opioid addiction differ significantly from those that trigger a relapse. It turns out that opioid receptors are found in neural circuits related to the desire for social interaction. Stanford neuroscientists have recently identified a circuit that is responsible for the onset of aversion to social interactions during recovery.[14] Such an aversion is a significant challenge to recovery because social interactions are often key to helping an individual cope with the vulnerabilities associated with the recovery process. The finding suggests it may be possible to develop drugs that inhibit social aversion during withdrawal, thereby assisting patients in seeking help or companionship from friends, families, recovery programs, and doctors.

The Nature of Neuroscience Applications

Contrasting work on artificial retinas with that on the science of neurodegeneration and addiction illustrates the two primary aspects of neuroscience applications: (1) a scientific aspect that focuses on identifying relevant brain circuits and understanding how these function and compute; and (2) an engineering aspect that is focused on how to safely use devices to stimulate the relevant brain circuits to create the desired responses.

FIGURE 6.3   Opioids prescribed by physicians

Source: iStock.com / Johnrob

As previously noted, there is much about the brain's anatomy, physiology, and chemistry that is still not well understood, and addressing the theoretical issues in neuroscience is almost exclusively the purview of academia rather than of industry. There are industrial research programs that tackle basic biological questions in neuroscience, but these are tied to solving problems with a profit motive—usually the development of new drugs.

Once the basic science has been developed and a research area approaches an economically viable application, industry does a much better job of developing it. Consequently, helping to smooth the friction of moving a project from academia to industry is crucial to overcoming roadblocks in development. Incubators and accelerators can help transition the findings of basic research to applications by aiding in high-throughput screening—the use of automated equipment to rapidly test samples—and in prototyping. With viable prototypes, new companies can be created or licenses granted to existing companies to produce a final product. Such activities are critical in facilitating the integration of well-understood scientific theory and technical engineering into final applications.

Over the Horizon

Molecular and Genetic Atlases of the Brain

Recent technological advances are transforming neuroscience, enabling scientists to create "bottom-up" maps of the brain at the molecular and genetic level rather than starting from high-level neuroanatomy and behavior (see figure 6.4). These new brain atlases integrate detailed maps of neuronal wiring that show where different genes are activated in the brain and also highlight electrical recordings from different brain regions, allowing scientists to compare differences between healthy and diseased

FIGURE 6.4   A rat hippocampus
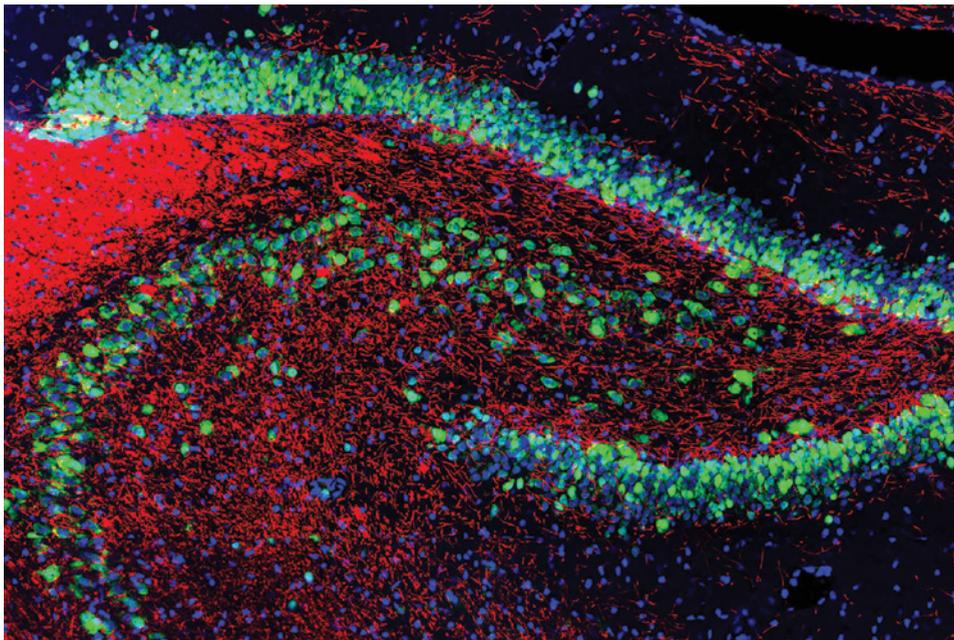
Source: Gerry Shaw, Wikimedia Commons, 2015, CC BY-SA 3.0

brains. These atlases have already revealed key insights into the genetic mechanisms of Alzheimer's and Parkinson's disease.[15] Understanding the genetic mechanisms behind these diseases could enable the development of rationally designed therapeutics to strengthen brain resilience. (Rational drug design refers to understanding the specific biological target of a disease, such as a protein, and then designing a molecule that precisely fits and interacts with it.)

Over the past decade and a half, we have advanced from mapping individual cells to creating atlases of 100 million cells in a single scientific study,[16] thus accelerating scientific discovery (see figure 6.5).

Beyond facilitating insights into Alzheimer's and Parkinson's, brain atlases have the potential to become foundational "molecular observatories" for neuroscience, providing a shared resource for academic and industry researchers to chart new

hypotheses and therapeutic targets for a broad range of neurological diseases. Coupled with substantial decreases in the cost of DNA sequencing (in some cases by several orders of magnitude), gene synthesis, and computing capabilities, these new molecular and genetic approaches to studying the brain have been enabled by the National Institutes of Health (NIH) Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative.

Currently, it costs about $2 million to $4 million to create atlases with 100 million cells.[17] However, if the aforementioned technological trends continue with federal funding, routine atlassing of the human and the mouse brain at a cost below $10,000 could be possible in the next ten years. Continued investment in these foundational technologies and datasets has the promise to accelerate both fundamental research and translational drug discovery (i.e., the process of moving biomedical knowledge from

FIGURE 6.5 There has been an exponential increase in the size of cellular atlases over the past sixteen years

Growth of Cell Atlases Over Time
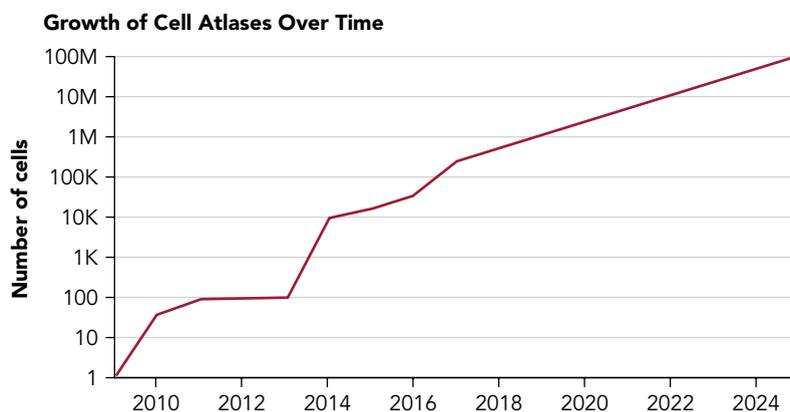
Source: See Valentine Svensson, Roser Vento-Tormo, and Sarah A Teichmann, "Exponential Scaling of Single-Cell RNA-Seq in the Past Decade," *Nature Protocols* 13, no. 4 (2018): 599–604, https://doi.org/10.1038/nprot.2017.149; and Jesse Zhang et al.,"Tahoe-100M: A Giga-Scale Single-Cell Perturbation Atlas for Context-Dependent Gene Function and Cellular Modeling" bioRxiv 2025.02.20.639398, doi: https://doi.org/10.1101/2025.02.20.639398

the laboratory to patient care and public health for developing new, effective, and accessible therapies for diseases).

Organoid Models of Human Brain Development and Disease

Developing new treatments for neurological diseases requires an understanding of underlying disease mechanisms and an ethical way to test potential therapies. Since testing new therapeutics in humans poses ethical challenges, scientists must first use model organisms, such as mice, to conduct experiments. However, several neurodegenerative diseases, such as Alzheimer's, are specific to humans and poorly replicated in other species. Organoid models serve as a promising alternative, enabling human-specific disease research without direct experimentation on patients.

Organoid models, or organoids, are three-dimensional cellular structures that self-assemble under specific culture conditions to replicate key aspects of human tissue.[18] Stem cells are derived from individual patients: Their cells—often skin cells—are harvested and then reprogrammed into stem cells, which are then differentiated into the desired cell type (e.g., neurons) that makes up an organoid. These organoids can then be studied in a dish to better understand the biology of a disease or to screen potential therapies that can slow a disease's progression. One of the most promising features of organoid models is that they can be personalized to individual patients. This offers unique advantages in several areas, such as, for example, better understanding and treatment of rare diseases.

Scientists can also transplant organoids into xenografted mice—genetically immunocompromised rodents with integrated human cells—to study disease processes in vivo. This is often done to explore how environmental conditions affect neurodegenerative diseases (e.g., how physical activity influences the progression of amyotrophic lateral sclerosis, also

known as Lou Gehrig's disease).[19] Such exploration cannot be done in a dish.

Recent guidance from the US Food and Drug Administration has recommended reducing the use of mice in drug testing,[20] opening the door for new approaches, such as organoid models and xenografted mice, to prove therapeutic safety and efficacy. However, there are not yet clear legal and ethical standards for research involving xenografted mice. This is an area where collective discussions between scientists can help to provide greater clarity. While using organoids is becoming a very useful way to study human cells in a dish, it remains an artificial system and is unlikely to replace the role of mice in the understanding of neuroscience and beyond.

Alzheimer's Disease Detection and Treatment

The potential for early detection prior to the onset of cognitive impairment is higher than it has ever been before. Current-generation diagnostic tools now include the ability to cheaply test for biomarkers from blood plasma paired with more accurate but expensive spinal taps and positron emission tomography (PET), which scans for toxic tau and amyloid buildup. A rollout of mass blood-plasma screening, along with confirmation using more expensive tests, might mean the anti-amyloid drugs could be applied before cell death and clinical symptoms manifest themselves, possibly increasing their effectiveness.

Neuroscience and AI

As understanding of the mathematics of our neural computations increases, these computational models may have direct relevance to AI. In particular, machine learning requires vast training datasets. By contrast, humans can learn languages with a small fraction of the training data that AI models require (for more discussion of this point, please refer to chapter 1, on artificial intelligence). A better understanding of the mathematical principles that define how human

brains compute may therefore improve AI. The melding of neuroscience theory and AI is a topic of increasing interest under the umbrella of Stanford's Wu Tsai Neurosciences Institute.[21]

Policy Issues

Disconnect Between Public Interest and Capability

The brain is perhaps the least understood, yet most important, organ in the human body. Demand for neuroscience research advances and applications—including understanding brain circuitry, developing new drugs, treating diseases and disorders, and creating brain–machine interfaces—is therefore expected to continue to grow considerably over the coming years. The Society for Neuroscience's annual meeting draws close to thirty thousand attendees.[22]

Science fiction and fantastical headlines fuel beliefs that mind-reading technology, brains controlled by computers, and other dystopias are imminent. In reality, work to comprehend the brain's staggering complexity remains in its early stages. Most advances involve incremental progress, expanding

our theoretical foundations rather than producing revolutionary leaps to futuristic applications. This vast gap between public expectations and scientific reality creates an environment ripe for exploitation. Impatience for solutions to pressing medical problems like dementia and mental illness leaves many open to dubious proclamations or pseudoscience.

The Impact of Cognitive and Behavioral Neuroscience on Law

Cognitive and behavioral neuroscience, which studies the biological basis of thoughts and actions, has broad implications for public policy. For example, a basic aspect of criminal law is the nature and extent of an individual's responsibility for a criminal act. Under a 2005 US Supreme Court ruling, minors under eighteen years of age cannot be subject to the death penalty for crimes they have committed, because adolescent brains are not fully developed, which puts minors at higher risk of impulsive, irrational thoughts and behaviors.[23]

Funding Cuts to Transformative Neuroscience

Over the past decade, much of the work outlined in this chapter was funded by the BRAIN Initiative.

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Starting in 2014, this initiative aims to be the equivalent of the Human Genome Project for the human brain. Research from the BRAIN Initiative has helped neuroscience generate advances that aid specifically in translating science to medicine. In 2024, however, the initiative's budget was cut by 40 percent, from $680 million to $402 million. The decline was due to a combination of reduced funding from the NIH and through the 21st Century Cures Act. Funding through that legislation fell by an additional $81 million in 2025.[24] Without additional financial support through the NIH, neuroscience research in the United States and the country's ability to tackle some of the most societally impactful diseases will decline.

Foreign Collaboration

Human expertise will continue to be the primary driver of future advances in neuroscience, and success will continue to depend on the United States being the best place for international scientists to train, conduct research, and use their own expertise to teach the next generation of scientists. Against this backdrop, the apparent targeting of US scientists with personal and professional links to China raises concerns,[25] and the United States only loses if these scientists leave and move their labs to China.

Another concern is intellectual property protection. Nearly 80 percent of US biotech companies currently outsource research to Chinese biotechnology firms, such as WuXi AppTec, which offer lower labor costs and benefit from an expanding domestic scientific workforce.[26] Future US leadership in biotechnology will require carefully managing intellectual property risk;[27] increasing investment in technologies that improve scientific productivity in the United States; funding fundamental neuroscience research; and retaining the top US-trained, foreign-born scientists as part of the US scientific workforce.

Ethical Frameworks

Neuroscience research naturally raises many ethical concerns that merit careful, ongoing discussion and monitoring. Chief among these is research on human subjects, which is governed by several existing frameworks and regulations that guide neuroscience studies in American academia today. Ethical guidelines for scientific research are usually national, not international. Some countries might allow particular types of brain research and drugs, while others might not; for example, a nation might permit experimentation on prisoners or on ethnic minorities. Managing differences in state research regimes will be critical to harnessing the power of international collaboration.

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