Ioannis Pavlidis, Ergun Akleman, and Alexander M. Petersen | Multidisciplinary collaborations lead to humanity-helping breakthroughs.

From Polymaths to Cyborgs–Convergence Is Relentless

The first draft of the human genome—a historic map of our species' genetic instruction manual—was completed not by biologists but by a computer science group at the University of California, Santa Cruz. Parsing the complexity of 2.85 billion nucleotides, written across more than 20,000 genes, required technical assistance from and close collaboration with researchers from many disciplines. Ultimately, the Human Genome Project included researchers from engineering, informatics, ethics, physics, biology, and chemistry.

The Human Genome Project is a powerful example of the *convergence* approach in science. In a 2014 report, the National Research Council defined convergence science as the integration of multidisciplinary approaches aiming to address complex questions. For more than half a century, convergent approaches have become increasingly common and impactful in science, prompting some historians of ideas, such as Peter Watson, to identify ongoing convergence as the ultimate scientific trend. Others, including a study panel led by Mihail Roco and William Bainbridge at the National Science Foundation, have proposed that scientific research actually cycles between periods of convergence and divergence, the latter being the fragmentation of science into distinct disciplines.

From the 18th century to the mid-20th century, divergence flourished and highly specialized areas of science were spawned. Then convergence was needed to bring the pieces together to solve problems spanning multiple specialties. This return to convergence, however, has proven challenging. Each specialty has formed its own culture and does not readily welcome change. For example, John Bowlby, the British psychologist who developed attachment theory, experienced ferocious attacks from his fellow psychoanalysts when he attempted to bring a biological perspective to behavioral studies in the post–World War II period.

Convergent approaches have led to breakthroughs with enormous social implications, such as the creation of mRNA vaccines for SARS-CoV-2 and the development of genomic drugs.

Informed by historical and quantitative analysis, our research team takes a more nuanced, comprehensive, and unifying approach to convergence. We deconstruct the definition of convergence into two parts: its *essence* (or aims) and its *methods* (or means to attain those aims). In its essence, convergence strives to provide all-encompassing answers to grand challenges, such as describing the entire human genome or determining how the human brain works. (*See First Person: Hongkui Zeng, pages 208–210.*) In recent years, convergent approaches have led to breakthroughs with enormous social implications, such as the creation of mRNA vaccines for SARS-CoV-2 and the development of genomic drugs. The goals of convergence are consistent with the goals of scientific inquiry itself. But the methods scientists use to tackle big questions have changed and evolved over the course of history. By differentiating between convergence's essence and methods, we replace a static definition of convergence bound to the present historical period with a dynamic one having timeless relevance. In this new framework, science evolution is not a relay with the baton being passed back and forth between convergence and divergence, but a marathon of ever-morphing convergence.

In our conceptualization, divergence is a tactic employed during a specific period—the 1700s, 1800s, and early 1900s—to manage in-depth investigations. Divergent methodologies have brought significant benefits to scientific research, but they have also been seriously undermining the transition back to convergence in recent decades. We believe that, for utilitarian reasons alone, it is likely that divergent methods will eventually be phased out. New methods that can negotiate both the breadth and depth of knowledge will take their place, bringing cultural congruency across the currently splintered scientific community.

QUICK TAKE

The goal of convergence science is to find answers to big questions. The methods of this approach, however, have changed and evolved over the history of Western science.

Using convergent approaches, researchers have made breakthroughs with enormous social implications, such as the development of genomic drugs and mRNA vaccines.

In the 21st century, artificial intelligence may enhance the abilities of researchers whose expertise spans multiple fields as they tackle problems of great depth and breadth.

GSK

The Laboratory for Genomics Research (LGR) explores how gene mutations cause diseases and develops technologies to rapidly accelerate the discovery of new medicines. Genomics as a field is an example of convergence science in action, as it necessarily marries biology and computational science. In the future, labs like LGR could use artificial intelligence and machine learning to guide drug development, solve complex problems, and analyze enormous volumes of data.

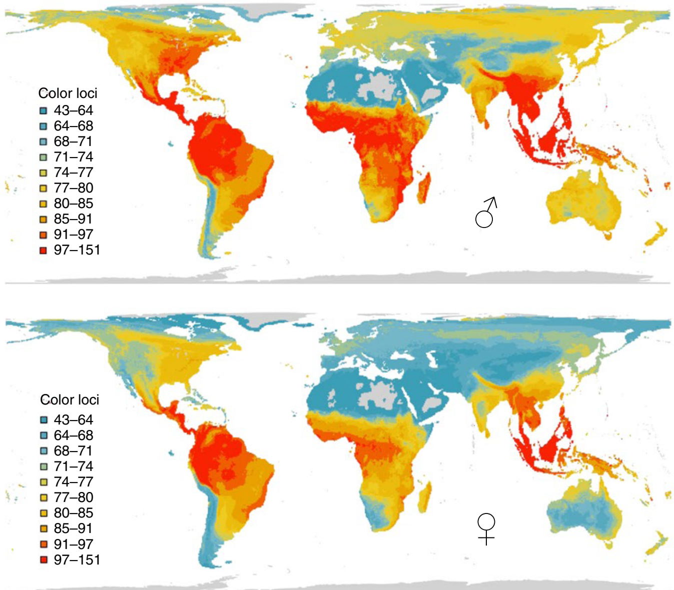
Ancient Natural Philosophy

Long before the rise of the scientific method, convergence was the traditional mode of inquiry. For ancient natural philosophers, the goals of intellectual inquiry were not so different from the overarching goals of modern science. They viewed their studies as a holistic effort to explain nature—an approach that intimately tied protoscience to convergence. If we consider the famously polymathic Aristotle to have been a representative example of these early scholars, they practiced what they preached. Aristotle studied subjects in physics, biology, and many other areas of scientific inquiry, synthesizing a sophisticated worldview based on his diverse knowledge. He was also the father of logic, providing early scientists with a deductive method for drawing inferences. Aristotelian philosophy was a remarkable showcase of convergence, the impact of which lasted well into the Renaissance. Although many of Aristotle's specific findings were later proved incorrect, his philosophical system demonstrated the lasting value of a convergent approach to science in which holistic explanations reign supreme.

For nearly 2,000 years in the Western world, convergence was pursued solely within the minds of scholars. Exceptional individuals such as Aristotle, Leonardo da Vinci, and Galileo were largely responsible for holding science's evolving convergent state, in much the same way that the mythical Atlas held up the heavens and sky. Science was still nascent, its body of knowledge growing but still manageable for singular scholars. Instruments were limited, so the amount of data collected and analyzed was limited as well. In many cases, data were nonexistent; for instance, the natural philosopher Democritus correctly deduced the atomic nature of matter purely through thought processes.

Explosion of Data and Disciplines

The state of scientific inquiry changed radically during the Industrial Revolution in the 18th and 19th centuries. New instruments such as aneroid barometers, sextants, and theodolites allowed for precise measurements in meteorology, naval navigation, and surveying, respectively. Such abundant and reliable measurements produced ever-increasing amounts of data begging for analysis. New and more rapid forms of communication, such as scientific journals, gave rise to thriving knowledge networks. During this period, Western science and the economy were linked in a positive reinforcement loop: Scientific advances brought economic growth, which in turn brought further scientific advances. For all these reasons, the body of scientific knowledge and its underpinnings mushroomed in short order, rendering expansive, individual polymathic inquiries like those of Aristotle practically impossible. An era of specialization dawned in science, in which scholars focused on in-depth investigations, trying to make the most of their new informational powers. As a result, many disparate scientific disciplines, including chemistry, biology,



Reprinted by permission from Springer Nature

Thomas Marent/Minden Pictures

By using artificial intelligence to collate and analyze photographs of more than 4,500 passerine birds, researcher Christopher R. Cooney from the University of Sheffield and his colleagues were able to validate a long-standing theory that the plumage of birds in the tropics (such as the multicolored tanager from Colombia on the right) is more colorful than the plumage of birds from temperate regions. The maps (*left*) show global mean color loci scores—a measure of color variation in the plumage of a particular bird—for males (*top*) and females (*bottom*). This analysis is an early example of what the authors call *cyborg team convergence* in action.

and civil and mechanical engineering, were established and institutionalized.

Upon closer examination, however, science's attraction to convergence never really withered; what changed during this period is that convergence emerged from within, rather than across, disciplines. For example, Darwin's theory of evolution in biology—an all-encompassing causal account of living organisms—inspired generalized theories of complex system evolution in other disciplines, such as social science and economics.

The Atom, the Moon, and the Genome

Around the middle of the 20th century, the arc of convergence bent in a new direction. Science had grown so big that individual scholars could not traverse its breadth the way their ancient predecessors had done, so researchers from different disciplines began to work together in teams to solve complex challenges. In this era, convergence would not take place within the minds of polymaths like Aristotle or emerge semi-disguised from within disciplines such as systems evolution; rather, it would be forged in multidisciplinary teams. The Manhattan Project in the 1940s was a stunning demonstration of the power of this approach, ushering humanity into the nuclear age. Similarly, in the 1960s NASA's Apollo space program leveraged multidisciplinary team convergence to send humans to the Moon. And as the 20th century was ending, multidisciplinary team convergence in the Human Genome Project marked the beginning of the genomic era. In 60 short years, multidisciplinary team convergence advanced humanity far beyond what thousands of years of prior scientific progress had achieved.

Multidisciplinary team convergence worked well in 20th-century "Big Science" projects because it was directly and effectively managed by government institutions.

In all these "Big Science" projects, multidisciplinary team convergence worked well because it was directly and effectively managed by government institutions, such as the military, NASA, and the National Institutes of Health (NIH). The NIH, for example, not only successfully completed the Human Genome Project, but did so under budget. The project also marked the beginning of a more inclusive era in science, as more female scientists joined the team. Thus the Human Genome Project demonstrated that multidisciplinary team convergence had some capacity for equity, which may have been aided by the more progressive times and by the appeal that convergent research holds for female scientists—who are often drawn to more nascent fields that are less established and, therefore, less exclusionary, according to researchers Diana Rhoten of the Social Science Research Council and Stephanie Pfirman of Barnard College.

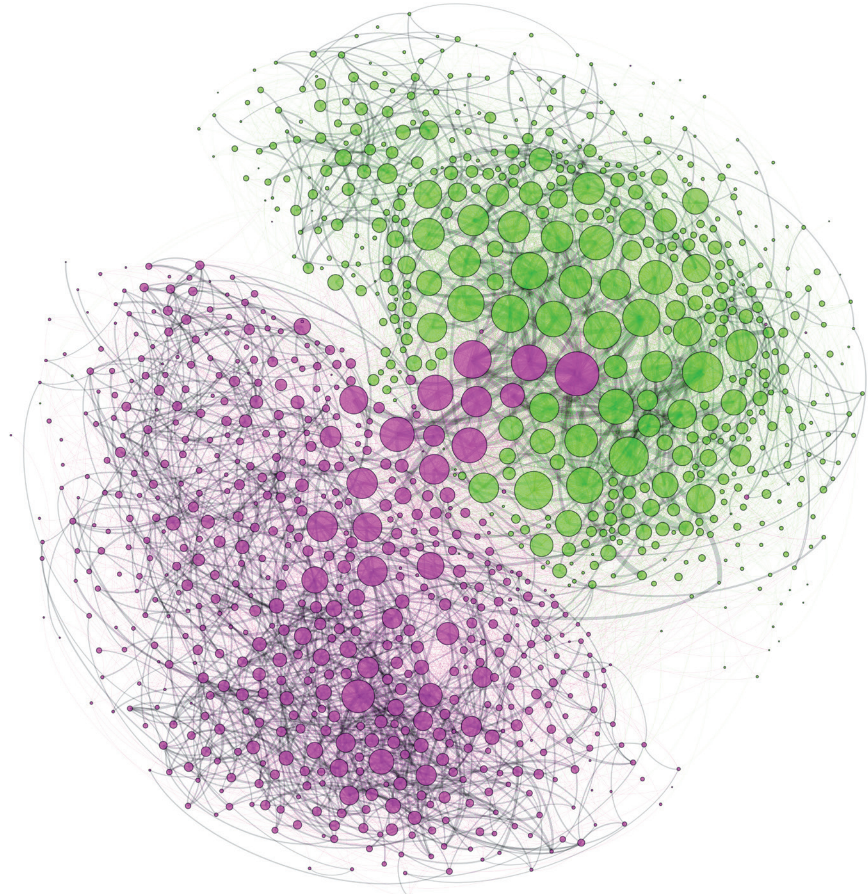
Open Software and the Brain

At the start of the 21st century, the wheels of change started spinning yet again. At the end of the 1990s, large government agencies such as the NIH and NASA started putting more emphasis on funding multidisciplinary teams and using public-private partnerships to drive scientific inquiry. Self-organized, multidisciplinary teams of scientists now competed to win small and midsize grants from funding agencies, such as the National Science Foundation (NSF) and the NIH. The agencies also started issuing solicitations on convergent themes such as the nexus of computing and health and the nexus of computing and behavioral sciences.

At the same time, the internet was globalizing and democratizing knowledge access, as ubiquitous sensing and computing flooded the world with data, and artificial intelligence (AI) allowed researchers to use that data in new ways. Crucially, a wave of open-source scientific software bestowed tremendous powers on the average researcher. For example, psychologists could now use open programming scripts featuring sophisticated machine learning algorithms to analyze behavioral data, and even contribute to the development of such scripts through cross-disciplinary training.

Now, for the first time in a long time, it has become feasible for any intelligent, curious person to play Aristotle and comb through ideas from many disparate fields, thanks to online educational materials for everything and everyone, the proliferation of open data sets, and the abundance of ready-to-use expertise, packaged in freely available open software modules. With these "black boxes," scientists can know the inputs, outputs, and best-use cases, but do not need to know the intricate internal algorithmic details. This is a prime example of modern convergent approaches facilitating both investigational breadth and depth, where the depth is provided by the open software. As these tactics proliferate, the practice of convergence science is becoming more personal and decentralized. The combination of open data and packaged expertise in the form of these software modules encourages scientists to expand beyond their disciplinary boundaries, gradually becoming polymaths to the point that they start producing their own open software and data, perpetuating the process.

We call this emerging form of decentralized, discipline-fluid research *polymathic team convergence*. Polymathic team convergence is close to, but distinct from, what we call multidisciplinary team convergence, in which researchers from different disciplines work together on collaborative projects but stay in their respective, narrow disciplinary lanes. In polymathic teams, individual researchers carry multiple disciplines in their own heads. On a polymathic team convergent project on human behavior, for example, there would be no pure computer scientists or psychologists; instead, each of the researchers on the team would have mixed expertise and be capable of working across the computational and psychological aspects of the project.



Courtesy of Alexander Petersen & Ioannis Pavlidis

This graphic representation of multidisciplinary convergence depicts the research collaboration network of about 1,000 scholars sampled from U.S. computer science departments (*magenta*) and biology departments (*green*) in 2015. Links represent collaborations, and node size is proportional to a scholar's centrality within this network. The cross-disciplinary bridge formed by computing scholars extending into the biology domain represents the genomics nexus, where computer scientists and their surrounding biology collaborators are forming a new convergent culture.

In our research, we've found strong evidence that, in parallel with multidisciplinary team convergence, polymathic team convergence gained traction in brain research during the 2010s. During that period, governments around the world began setting up initiatives to map and understand the functioning of the human brain using cross-discipline research approaches. In this context, multidisciplinary teams made great strides; for example, a neurally controlled robotic arm for people with tetraplegia was developed by Leigh Hochberg and colleagues in 2012. This robotic arm opened the door to mind-controlled prosthetics that stand to transform the lives of millions of people who are disabled. The technology is currently undergoing clinical trials, one of which—the BrainGate2 trial at Massachusetts General Hospital—is scheduled to conclude in 2026.

Polymathic teams also expanded significantly and published important work during this time. In brain science during the 2010s, the annual growth and citation impact of polymathic team publications outpaced that of single discipline team publications by 3 percent and 6 percent, respectively. This polymathic team trend is exemplified in the field of transcriptomics. Transcriptomes reflect differences in gene expression between different cells and can reveal molecular organization in the brain and other organs. The key to understanding neurodegenerative diseases lies in this molecular organization. Although transcriptomes hold exceptional promise for brain science, they represent complex biological entities and are notoriously difficult to reconstruct computationally. Accordingly, polymathic teams that traverse biology and computing (for example, Manfred G. Grabherr and colleagues from the Broad Institute) have excelled in the development of transcriptomic methods that have already impacted research into brain disorders such as Alzheimer's disease.

We expect the growth and impact of polymathic team convergence to accelerate during the 2020s, with this approach eventually becoming the dominant form of convergence. Our prediction is based on favorable underlying conditions. Presently, a new generation of researchers is being trained through a wave of convergence grants, such as the Bridge2AI grants from NIH, which aim to connect biomedical and computer sciences. These young researchers are also afforded the tools of open science, which facilitate mastery of multiple disciplines. As these researchers mature, so too will polymathic team convergence.

Cyborg Science

If we were to make a bold prediction about where convergence will go in the mid-21st century, we would bet that polymathic teams will be enhanced with AI, a development we call *cyborg team convergence*. We believe AI will accelerate convergence by enhancing ideation and solve the breadth–depth conundrum in research by combining and comparing collections of data far too big for an unaided human mind to handle. In terms of ideation, major advances are often the product of scientific novelty, arising from atypical combinations conceived by talented scholars. AI excels in combinatorial analysis, provided the combined elements have been properly encoded. For instance, in a recent publication, Vahe Tshitoyan and colleagues at the University of California, Berkeley, presented an AI system that predicts novel material combinations worth investigating for their thermoelectric properties. Novel thermoelectric materials can be applied in highly efficient cooling and energy scavenging, thus making significant contributions to sustainable energy solutions. Importantly, this work is an early example of AI intervention in the discovery process, which thus far has depended exclusively on human talent, experience, and luck. Luck is what AI interventions promise to replace, while enhancing talent and partly making up for experience.

AI will also be indispensable in allowing teams to investigate problems of great depth and breadth. A glimpse of the vast possibilities is offered by a recent publication by Christopher Cooney and colleagues from the University of Sheffield in England. Cooney's team used AI to analyze thousands of digitized bird images from a museum collection to prove that birds are more colorful closer to the equator, thereby validating a long-standing evolutionary theory that plumage colorfulness is greater in tropical regions. Charles Darwin and Alfred Russel Wallace spent decades in the 19th century documenting the same finding, but only anecdotally. In essence, Cooney's team was able to negotiate a broad problem's considerable depth thanks to a machine partnership.

We envision researcher–machine partnerships in which AI will help researchers find novel and insightful ways to combine topics, and to dig deeply into data archives that would otherwise be overwhelming. For instance, brain–machine interfaces, such as those being developed by the company Neuralink, would allow researchers to connect with AI engines, enhancing the researchers' ability to analyze voluminous human behavior data, scan the ever-expanding scientific literature, and in general perform currently challenging or impossible tasks. Assuming the open data and open software trends continue, such human–machine partnerships stand to benefit scientific productivity because they can provide a head start to convergent teams at large.

Ultimately, convergence matters because it is extremely effective at supporting science in its inexorable progress toward making the world a better place.

Through history, convergence has evolved to accommodate the ever-changing state of scientific inquiry. It started as a solitary, expansive endeavor by polymathic scholars. When this became untenable, convergence attempted to provide total answers from within scientific disciplines even while divergence appeared to be the dominant form of inquiry. Eventually, convergence assumed its modern form by attempting to integrate within multidisciplinary teams. Currently, polymathic team convergence is emerging, increasingly supported by technology, and is a process that may ultimately lead to cyborg team convergence.

Convergence keeps enhancing science's efficiency and impact by joining together many different strands of knowledge and insight. The names of the research team members who gave us the mRNA vaccines or genomic drugs may not be household names like Aristotle and Leonardo da Vinci, but their impact on society is massive. Ultimately, convergence matters because it is extremely effective at supporting science in its inexorable progress toward making the world a better place. Convergence is science's destiny.

Bibliography

National Research Council. 2014. Convergence: Facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond. Washington, DC: The National Academies Press.

Pavlidis, I., A. M. Petersen, and I. Semendeferi. 2014. Together we stand. *Nature Physics* 10:700–702.

Petersen, A. M., D. Majeti, K. Kwon, M. E. Ahmed, and I. Pavlidis. 2018. Cross-disciplinary evolution of the genomics revolution. *Science Advances* 4:eaat4211.

Petersen, A. M., M. E. Ahmed, and I. Pavlidis. 2021. Grand challenges and emergent modes of convergence science. *Humanities and Social Sciences Communications* 8:1–15.

Tshitoyan, V., et al. 2019. Unsupervised word embeddings capture latent knowledge from materials science literature. *Nature* 571:95–98.

Woelfle, M., P. Olliaro, and M. H. Todd. 2011. Open science is a research accelerator. *Nature Chemistry* 3:745–748.

Wuchty, S., B. F. Jones, and B. Uzzi. 2007. The increasing dominance of teams in production of knowledge. *Science* 316:1036–1039.

Ioannis Pavlidis is the Eckhard-Pfeiffer Distinguished Professor of Computer Science at the University of Houston. He is a polymathic researcher with background in computing, psychology, and engineering. Ergun Akleman is a professor in the departments of visualization and of computer science and engineering at Texas A&M University. He is a pioneer of visual storytelling in science and has published extensively in various areas of computer graphics research. Alexander M. Petersen is an associate professor in the Department of Management of Complex Systems at the University of California, Merced—an example of the nascent institutionalization of convergence in the academe. Twitter for Pavlidis: @ipavlidis