The foundation of deep-tech innovation

What is deep-tech innovation and why we should care?

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The Industrial Revolution stands as the most pivotal event in human history since the advent of agriculture. Numerous technological breakthroughs preceded this transformative area, but none of them could elicit the unprecedented growth that has materialized since the 19th century. It was the introduction of inventions such as the steam engine and vaccines that suddenly propelled economic growth and life expectancy, which continues to this day. Global GDP per capita had an average growth rate of around 10 percent per century between the 9th and 18th centuries but experienced an expansion of 250 percent in the 19th century, followed by an impressive growth of 850 percent in the 20th. Likewise, life expectancy in Europe witnessed a remarkable surge, rising from a preindustrial average of 35 years to 43 by 1900, and reaching 70 at the end of the 20th century.

But then, why did the technological inventions of the pre-industrial era fail to trigger a similar exponential growth? What set the technical progress of the 19th century apart from earlier innovations? Undoubtedly, inventions like the water wheel, gunpowder, and the mechanization of printing, which all emerged before the Industrial Revolution, also significantly improved productivity and had profound social impacts. The crucial distinction lies in the fact that the technologies of the 19th century were firmly rooted in science. For the first time in history, humanity delved into what we now refer to as deep-tech innovation, marking a transformative shift in the way technological advancements were approached.

Deep-Tech: reframing innovation

In a recent experiment, researchers demonstrated the remarkable ability of individuals to optimize the design of a wheel – a fundamental technological advance in human history. Teams of participants were tasked with enhancing the performance of a simple wheel that descended a ramp by adjusting the placement of weights on its spokes. As time passed, the design of the wheel continually improved, eventually achieving a remarkable level of performance exceeding 70 percent of its maximum potential. Despite their accomplishments, however, participants struggled to articulate the fundamental reasons behind the success of their design. Their achievements were solely based on a process of trial and error, guided by the outcomes of their previous attempts.

This cumulative process of improvements provided insights into the development of pre-industrial technologies and explained how even preliterate societies could create sophisticated tools. This approach, sometimes described as "local search" by scholars of innovation, involved altering various aspects of a technology or combining existing technologies until a desired outcome was achieved. As a result, innovators possessed the knowledge to make their technology function, yet lacked a deep understanding of why it worked. The solutions, albeit effective, were low-tech, as they built upon limited fundamental insights.

However, the advent of scientific thinking, sparked by Newton's scientific revolution, gave rise to a new paradigm. It provided inventors with scientific representations of how the world operated, which acted as invaluable mental maps for exploring the uncharted territories of novel technologies. These scientific representations guided the inventors' thinking, enabling them to run thought experiments and extend the boundaries of their imagination.

Deep-tech innovation was born

Deep-tech innovation is the practice of harnessing the most recent advancements in scientific understanding to create technologies that were previously inconceivable. This science-based approach to innovation has two notable benefits. First, it reduces the search space by focusing on technologies that are most likely to work, limiting the need for trials and errors. Second, it fosters the conception of technologies that has never been explored before, allowing for a more far-reaching search process compared to the local search for low-tech innovations.

The achievements of the Wright Brothers greatly exemplify the contrast between these low-tech and deep-tech approaches. In 1903, on the beach of Kitty Hawk, North Carolina, the brothers successfully flew the world's first motor-operated airplane.

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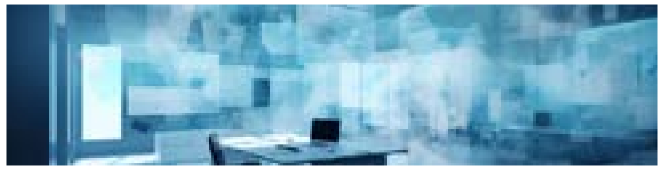
While their rivals fervently engaged in trial and error, launching prototypes off ramps and even by catapults, the Wright Brothers embraced aerodynamics as their guiding principle. They leveraged this new science to envision a revolutionary propeller uniquely designed for compressible air, unlike boat propellers tailored for incompressible water. Science effectively helped them identify the most promising designs, avoiding the need to test countless and inferior alternatives. This deep-tech approach moved humanity from the Wright Brothers' first flight to the Apollo program within just sixty years. Trial and error alone could never have achieved such astounding successes in such a short timeframe.

The demarcation between low tech and deep tech, however, evolves constantly. As new scientific discoveries unlock possibilities for novel deep-tech innovations, the once groundbreaking science that underpinned yesterday's inventions gradually becomes standardized. This fosters low-tech innovation, which leverages established scientific knowledge and combines existing technologies.



Risk profiles

Still, most technological advancements to this day stem from low tech. Even the iPhone, which Steve Jobs once described as a "widescreen iPod with touch controls," was built on the recombination of preexisting technologies. The touch screen, for instance, was patented in 1969 by a British engineer and the first human-controlled multi-touch device was created at the University of Toronto in 1982. This is because combining established technologies carries less risk compared to venturing into cutting-edge scientific discoveries.

Arguably, studies suggest that less than 10 percent of failed startups attribute their downfall to product-related issues, while approximately 75 percent cite market failure or flawed business models. Jobs's genius was not in generating technological breakthroughs but in identifying unmet market needs and formulating effective strategies to address them, as demonstrated by the App Store ecosystem for the iPhone. Fundamentally, low-tech innovation faces market uncertainties, not insurmountable technical problems.

The risk profile of deep techs could not be more opposite. While market fit is also crucial for these ventures, it entails less uncertainty compared to low-tech endeavors. For instance, only 5 percent of newly approved drugs fail because of a lack of market needs or poor strategic management.

This stems from the very nature of deep-tech innovation, which seeks to harness scientific breakthroughs. The more foundational the breakthrough is, the more pervasive the resulting technology becomes, with much greater potential to tackle unresolved and highly impactful issues. The possible applications of quantum computing, for example, span domains like cybersecurity, drug discovery, and advanced AI.

But because these scientific findings sit at the frontier between the known and the unknown, deep techs also face massive technological risks. The path to attaining a mature quantum computing technology is still highly uncertain, with a projected timeline stretching beyond a decade. Also, over 90 percent of new drugs fail the clinical trials required for approval — and this percentage increases substantially when considering drugs that do not even progress to trials. These technological risks are further compounded by the fact that scientific research demands substantial capital investments for highly specialized infrastructure, costly raw materials, and a proficient workforce.

This difference in risk profiles can actually be measured with patents, a legal intellectual property which protects the innovations of inventors. Recent research shows that patents building directly on scientific publications are significantly more valuable on the market than patents in the same technology which are more disconnected from science. This is also for economic reasons: once technical risk is overcome – and if market demand is proven – deep-tech startups have stronger defensibility from competition, thanks to technology barriers. But the study further shows that science-based patents are riskier, with a much higher probability of yielding low or no value to their owners.

Because it relies on science and faces significant technical risk, deep-tech innovation requires a distinct set of strategies and managerial approaches. Tackling deep-tech problems with a low-tech mindset can actually be economically and socially very damaging. The story of medical-testing startup Theranos provides a tragic testament to this.

Misframing deep tech

Elizabeth Holmes founded Theranos in 2003 when she was nineteen years old, with the promise of disrupting the diagnostic industry. Her vision was to introduce a groundbreaking technology that could rapidly and accurately perform tests using a single drop of blood, at a fraction of the cost of conventional methods. Over the span of a decade, the company attracted high-profile investors, such as Rupert Murdoch and Henry Kissinger, and reached a valuation of over $9 billion. However, in November 2022, Holmes was convicted of criminal fraud and sentenced to 11 years in prison.

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As it turned out, Theranos' technology was grossly inaccurate, leading to the misdiagnosis of thousands of patients.

And yet, Elizabeth Holmes had adhered to the playbook of successful Silicon Valley tech startups to the letter. Following in the footsteps of Steve Jobs, Bill Gates, and Mark Zuckerberg, she dropped out of college to launch her own company. She embraced Jobs's management style, including his fixation on secrecy. She envisioned her blood-analysis device as the "iPod of healthcare" and, after visiting an Apple Store, was inspired to collaborate with retail chains such as Walgreens and Safeway to bring it to the public.

Perhaps most crucially, Holmes adopted a strategy that had proven very effective for several tech giants, including Microsoft and Oracle: promoting an imperfect product, at times with excessive hype, to secure funding and feedback for improvement. Jobs himself famously faked the iPhone's functionality during its 2007 launch, where the device appeared to work flawlessly despite being plagued by bugs that caused frequent crashes and memory issues. In the same vein, Holmes faked demonstrations of Theranos' technology and relied instead on third-party equipment to produce many of its tests.

Launching an imperfect product early to collect advanced information from the market, while demonstrating the potential of a technology, is a very efficient approach to innovate. This method has since been formalized by the lean startup movement, which promotes putting a "minimum viable product" in front of real customers as early as possible to test and iterate different versions of the product until it fits the market. The strategy is a well-articulated implementation of low tech's trial-and-error approach to de-risk a market.

But the main source of uncertainty that Holmes was facing was not the market. It was the technology itself. Holmes was working on the assumption that, sooner or later, her blood-testing device would properly work and thus applied a fast-iterating, lean-startup approach to its development. Such a low-tech strategy, however, was never meant to de-risk a science-based technology that did not yet exist. Still, Holmes ostracized the scientists who warned her and instead turned to a former software company's executive, who had no training in biological sciences, to run Theranos' operations. In the end, no one in the leadership of Theranos had proper scientific training.

Ultimately, Holmes's fundamental error was in conflating technology startups with deep-tech entrepreneurship. The two pursuits demand fundamentally different mindsets, and her failure to grasp this crucial distinction proved to be her ultimate undoing.

Decoupling

Translating scientific breakthroughs from the research labs and into practical applications opens unforeseen and at times catastrophic consequences. This is due to the inherent nature of scientific research, which resides at the frontier between the known and the unknown. A striking example can be traced back to the 1890s, when Marie and Pierre Curie delved into the uncharted territory of radioactivity, unaware of its inherent dangers. Their research notes from that era retain such high levels of radioactivity that scholars seeking to study them today are required to sign a risk waiver.

For this reason, deep-tech ventures cannot simply release an untested technology directly in the market to gather early insights from real users, as Theranos did. Instead, deep-tech entrepreneurs must *decouple* the launch and development processes, advancing first their technologies to a significantly mature stage before deploying them in the real world. And this decoupling fundamentally shapes the creation process of a deep-tech startup.

Indeed, postponing the product launch after the development process is fully complete significantly extends the time required for market entry. Bringing a new drug to market, for example, takes an average of ten years, while quantum computing continues to strive for commercial viability despite years of development. As a result, deep-tech ventures face an extended period of generating no revenues.

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In fact, deep-tech investors frequently discourage entrepreneurs from seeking alternative revenue sources, emphasizing the sole focus on technology development.

This prolonged delay requires deep-tech startups to secure most of their funds before the launch of their product, in contrast to their low-tech counterparts. This delay also implies that deep-tech start-ups cannot rely on early revenue streams as proof of concept to secure funding for their ideas, unlike low-tech ventures. Instead, they must conduct controlled experiments and generate scientific data to convince investors. This requires investors to possess a solid comprehension of the science underlying the technology to properly assess its potential.

The inherent risk associated with deploying a novel technology also affects the business environment in which deep-tech ventures operate. In particular, novel technologies are often subject to stringent regulations and necessitate costly trials to persuade regulators of their safety and efficacy. This is notoriously true in the healthcare industry, where the cost of trials for securing a new drug's approval is approximately $50 million and sometimes exceeds $100 million.

Due to the novelty of these technologies, regulatory agencies themselves must occasionally innovate in their approval requirements. This is especially evident with AI systems, whose performance can vary depending on the specific conditions of their applications.

Taken together, the inherent risks associated with deep-tech innovation significantly increase the development time, financial uncertainties, and the need for governmental oversight. Yet, over the last two decades, a quiet revolution has been reshaping the advancement of science-based technologies, holding the promise of substantially diminishing these very risks.

The deep-tech revolution

Traditional drug development primarily revolves around identifying compounds with molecular structures similar to effective ones. However, this approach has limitations when it comes to antibiotics. Most substances with similar compositions have already been explored, and new antibiotics often have structures so close to existing ones that bacteria rapidly develop resistance. This alarming situation could lead to ten million deaths annually from infections that current antibiotics are unable to cure, as reported by the World Health Organization.

In early 2020, a team at the Massachusetts Institute of Technology (MIT) took a different approach to address this pressing issue. They viewed the challenge of discovering new antibiotics not as a biological problem, but as an informational one. Their solution involved training an algorithm on over 2,300 compounds with antimicrobial properties to identify potential inhibitors of E. coli, a harmful bacterium. Subsequently, they deployed the model to evaluate over one hundred million molecules from various databases, eventually pinpointing a standout candidate known as “halicin,” named after HAL, the renegade computer in the film “2001: A Space Odyssey.”

This discovery highlights the profound revolution that is reshaping deep-tech innovation. At its core, deep-tech innovation revolves around scientific representations of how the world works. These models and theories constrain the imagination of innovators to focus on thoseb solutions that are most likely to succeed. In essence, science empowers innovators to conduct insightful thought experiments, exploring in their head hypothetical scenarios where various element of reality are altered.

The MIT team relied on science to frame the problem, choose the molecules to train the algorithm, and select the databases of potential antimicrobial candidates. However, in contrast to the approach of the Wright brothers and Marie Curie, who depended on their minds and experiments, the team placed their trust in the computer to conduct the search.

This computer-assisted approach significantly accelerates the discovery process and expands the range of potential solutions under consideration. It further reduces the costs of experimentation, as simulations and tests are conducted digitally rather than directly in the real world. As such, the approach considerably mitigates the huge technological and financial risks associated with deep-tech innovation.

For instance, Terrapower, a startup founded in 2006, aimed to develop a revolutionary technology that utilizes spent fuel from existing nuclear reactors as input. This technology could power the world’s electricity needs for centuries without emitting CO2. However, concerns about catastrophe risk posed significant challenges.

Testing this innovative technology required constructing an entire nuclear power plant costing billions of dollars and taking years to complete, which was impossible to finance. With the advent of supercomputers, however, Terrapower’s engineers could simulate the inside of a nuclear reactor, assess the viability of their technology, and make cost-effective iterations to gain confidence before constructing a physical nuclear power plant. This breakthrough enabled early-stage investors, including Bill Gates, to recognize the startup’s potential and support it financially.

The rise of computers and artificial intelligence is prompting innovators to rethink their approach to deep-tech innovation. Involving machines in this process often requires conceptualized problems as a combinatorial search guided by specific data.

And, thus, innovators no longer simply ask what might work to solve a problem, but how to represent the problem in a way that enables computers to find a solution.

This revolution is not only affecting the process of deep-tech innovation but, more fundamentally, accelerating a pivotal transformation in scientific research. This shift has been unfolding over the last 150 years and has deeply influenced the economic environment of deep techs.

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Collaborating

Since the 19th century, science has tremendously advanced in various ways, leading to a highly diverse scientific landscape. This fragmentation of scientific disciplines has resulted in longer training times for scientists and an increasing knowledge burden on them. As a result, the traditional model of a single scientist serving as the principal investigator within a specific discipline has been evolving. Recent research analyzing over 21 million papers published worldwide since 1945 has shown the growing importance of teams in producing high-impact research.

These teams are not only increasing in size but also crossing disciplinary boundaries and institutional affiliations.

Deep-tech ventures have adapted to this trend. Gone are the days when inventors lacking formal scientific training, such as the Wright brothers, could create groundbreaking technologies. To achieve success, deep-tech startups must now harness highly specialized scientific expertise from a variety of fields. Take, for instance, the French quantum computing startup Quandela, which integrates advanced optics, semiconductor nanotechnologies, and algorithmics. Its founders hold doctorates in quantum optics and nanotechnologies – a significant contrast to college dropout Elizabeth Holmes. However, solid scientific training alone is insufficient. Today, no startup can possess all the requisite knowledge and resources to develop novel technologies independently. For this, deep-tech ventures need an ecosystem.

Ecosystems are economic organizations that enable firms to expand beyond their traditional boundaries. Through collaboration, firms and institutions engage in mutually beneficial exchanges of diverse resources, such as knowledge, data, talent, infrastructure, networks, funding, and market access. These ecosystems bring together diverse participants in a shared geographical location, fostering synergies and cooperation.

A notable example is the biotech ecosystem of the Boston area, which encompasses renowned academic institutions like Harvard University and MIT, successful biotech companies like Genzyme, prominent hospitals, and venture capital firms such as Flagship Pioneering and Third Rock Ventures. This concentration of resources and expertise has contributed to Boston's position as the leading biotech hub in the world.

In the end, deep-tech ecosystems are where science meets business. Studies indicate that corporate patents rely significantly on academic publications from these ecosystems, approximately five times more than from other academic sources. And academic publications stemming from ecosystems tend to be 30 percent more applied than their non-ecosystem counterparts. Further, ecosystems allow for the adaptive allocation of scientific and financial resources to tackle the inherent uncertainties in deep-tech innovation.

In this sense, the development of new technologies is better understood as an emergent outcome of the ecosystem, rather than the sole achievement of an individual deep-tech venture. As such, regions across the globe that effectively nurture deep-tech ecosystems will be the ones generating the most groundbreaking, science-based technologies and reaping the greatest rewards from the ensuing economic growth.

A new world order

China's development in the 18th century matched Britain in terms of life expectancy, literacy, and GDP. It even excelled as an early leader in technology, often surpassing Western advancements. Inventions such as the wheel, gunpowder, and the compass all originated in China and took centuries to reach Europe.

Why then did China miss out on the transformative industrial revolution that Europe experienced in the 19th century? The fundamental reason lies in China's failure to develop anything close to modern science. Chinese thinking at the time lacked the concept of natural law separate from human law, which was crucial for scientific progress. China continued to rely on a trial-and-error approach to innovation while Europe embarked on science-based, deep-tech innovations, leading to a significant development gap that took over a century to bridge.

Intriguingly, Europe is today the one facing an imminent risk of missing out on the current deep-tech revolution. Over half of the recently established deep-tech companies are in the US, and. in 2022, European investment in deep tech culminated at approximately $20 billion—a starking contrast to the substantial $51 billion poured into the US. The difference is even more striking for AI technologies. In this sector, venture firms injected a staggering €38 billion into US-based startups, against a more modest funding of €10 billion in Europe. China is also rapidly catching up, investing significantly more in specific technologies – like autonomous mobility, generative AI, and nuclear fusion – than European countries.

Europe's current predicament took root two decades ago, when it became remarkably complacent due to a misguided belief that scientific achievements would inevitably translate into innovation and foster economic growth. But science alone is insufficient for deep-tech innovation.

This was already evident in the birth of the Industrial Revolution, which emerged in Britain rather than France. Both countries showed similar overall development, but the key distinction was the influence of of Newtonian science in British society. It shaped the thinking of British industrialists, engineers, entrepreneurs, and even the public, providing practical problem-solving techniques, particularly in mechanics. In contrast, French scientific thinking remained confined to abstractions, as exemplified by Descartes' physics, with many insights but limited practical applications. France possessed the scientific mindset but lacked a deep-tech mindset – the ability to translate scientific discoveries into disruptive innovations.

Similarly, Europe's current lag in the recent deep-tech revolution is not due to a deficiency in scientific research.

Europe is actually on par with the US and still ahead of China in terms of the number of scientific publications per capita. But Europe's deep-tech innovation is currently hindered by several economics and political factors.

First, Europe lacks powerful ecosystems that foster modern, deep-tech ventures, hindering effective collaboration between business and science. Second, European investors and institutions overseeing significant funds are often risk-averse. For instance, the pension fund for Washington civil servants in the US allocates approximately 30 percent to venture capital, the primary source of deep-tech funding, whereas the pension fund for German civil servants does not make such investments. Finally, Europe is plagued by fragmented regulations and national rifts. Big and homogeneous home markets give the US and China the huge advantage of scale. For example, the US and China will hold each 30 percent of the world's data by 2030, which is essential to developing AI technologies. Europe possesses valuable data, too, but struggles to effectively pool them.

Compounding these factors is the global mobility of capital and scientific expertise, as successful European ventures tend to relocate to US-based ecosystems. This makes sense – studies have shown higher success rates and increased funding for entrepreneurs who migrate to these ecosystems compared to their counterparts who remain in non-US hubs.

Even notable success stories like BionTech, often hailed as a German deep-tech startup, conducted their initial public offerings on the New York Stock Exchange. And, in 2023, the company relocated its cancer research to the London ecosystem, citing the exemplary collaboration between the National Health Service, academia, the regulator, and the private sector – all hallmarks of a superior ecosystem, compared to what Germany could offer.

Deep-tech innovation possesses immense potential to drive significant long-term economic growth. But regions that fail to harness this transformative power run the risk of falling behind, especially in today's global economy. Europe, like China before it, now stands on the brink of confronting this harsh reality.

The paradox of deep-tech Innovation

Throughout history, technology has served as humanity's medium for interacting with the environment, enabling us to overcome physical limitations and shape the world around us. From domesticating fire for warmth to inventing the wheel for efficient transportation, we have consistently developed novel tools to improve our lives.

However, the advent of science-based technologies has ushered in a new era, fundamentally transforming our relationship with nature. No longer mere interaction, we now find ourselves altering the very fabric of the natural world. We manipulate genes for curing diseases and split atoms to produce energy. This ability to actively alter nature has yielded remarkable benefits but has also introduced formidable challenges.

In 2015, the United Nations identified 17 Sustainable Development Goals (SDGs) – critical issues that humanity must address "to ensure that our planet is peaceful, prosperous, and safe for all." Strikingly, these problems are all human-made; half of them are directly linked to the technological achievements spurred by the Industrial Revolution. Among these challenges are global warming, the urgent need for clean water, and the depletion of marine resources. Technology's impact on nature is fundamentally reshaping the earth and poses a threat to our very existence.

At the same time, a survey of 8,600 deep-tech companies revealed that over half of them aimed to address at least one of the UN's 17 SDGs. Many of these challenges require the development of deep-tech solutions that do not currently exist. For example, achieving CO2 emissions neutrality by 2050 demands advanced batteries, hydrogen electrolyzers, and direct air capture and storage technologies that are yet to be developed.

This is the paradox of deep-tech innovation. Deep-tech advancements have the potential to disrupt our world, prompting a need for further deep-tech innovations to rectify these issues. Indeed, as science pushes the boundaries of human knowledge, unanticipated and unintended consequences inevitably arise. The Wright brothers could not have predicted that aviation would one day contribute to global warming, nor could Marie Curie foresee that her work on radioactivity would lead to radiation-induced diseases. But because science-based technologies manipulate the material world at a more fundamental level, addressing these unintended consequences necessitates the development of novel, science-based technologies.

The future of humanity, its survival, and its potential for evolution rest on its capacity to resolve this very paradox. This demands a fundamental shift in the way we perceive the natural world and allocate our efforts. The advent of science, which suggests the existence of natural laws independent of humanity, has inevitably shifted human consciousness away from nature. Rather than viewing nature as an object to be controlled or mended, we must foster a deep-tech mindset that cultivates a sustainable world in which humanity belongs.

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According to Greek mythology, Prometheus bestowed fire upon humanity as a gift, aiming to empower them with knowledge for the betterment of their lives. His cult in ancient Greece was closely associated with Athena and Hephaestus, the deities personifying creative skills and technology. As such, Prometheus embodied a bridge between ideas and practice.

At its core, deep-tech entrepreneurship represents a Promethean feat. Just as Prometheus descended from Olympus with fire to improve the lives of humankind, so too do these startups endeavor to bring scientific breakthroughs out of the confines of research labs and into the realm of practical application. And, like fire, these innovations have the potential to be transformative.

Yet Prometheus' gift was also an act of defiance against the gods, who had withheld fire from humans to keep them in a state of ignorance and submission. In our time, it is not divine forces that impede our ability to turn science into transformative technologies, but our own choices and actions, or lack thereof.

Translating science for the betterment of our lives hinges on our ability to properly understand science-based innovation, foster collaborations that transcend organizational boundaries and scientific domains, and manage the financial risks inherent in deep-tech entrepreneurship. Failing to meet these challenges will unquestionably imperil humanity's ability to evolve and survive.

About the author

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Francis was the first Associate Dean of Research at ESMT Berlin and held faculty positions at Duke University and INSEAD, and was a post-doctoral researcher at Massachusetts Institute of Technology (MIT). He is the author of numerous academic articles in prominent management, analytics and economics journals such as Management Science, Operations Research, American Economics Review and received several outstanding research awards for his work. He has extensive experience in executive education and corporate learning solutions, and is a regular speaker in academic and industry forums.

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