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FUTURE OF TAIWAN'S ECONOMIC COMPETITIVENESS

Assuring Taiwan's Innovation Future

Evan A. Feigenbaum

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Future of Taiwan's Economic Competitiveness

In 2019, the Asia Program of the Carnegie Endowment for International Peace, in collaboration with the Taiwan WTO & RTA Center of the Chung-Hua Institution for Economic Research (CIER), began to jointly convene a series of roundtables with U.S. and Taiwan stakeholders.

The initiative has two major goals: first, to examine challenges to Taiwan's future competitiveness and comparative advantage amid technological change, global economic disruption, and rapidly evolving political risk; and second, to explore where and how fresh partnerships between U.S. and Taiwan players can help to bolster Taiwan's economic future.

The initiative is focused in three areas:

1. assuring Taiwan's technological advantage amid significant challenges to its innovation ecosystem;
2. disruptive energy futures as Taiwan grapples with the trilemma of security, affordability, and sustainability; and
3. improving Taiwan's investment climate to attract not just more but also highest-quality foreign investment.

This paper on Taiwan's innovation future is the first in a series.

The principal author, Evan A. Feigenbaum (Carnegie Endowment for International Peace), has drawn on collaboration with Roy C. Lee of CIER and especially the extensive insights and contributions of a distinguished group of policy and industry practitioners in both Taiwan and the United States, as well as leading academic and policy analysts.

We particularly acknowledge the detailed comments and critiques on a draft of this paper received from Glenn Gaffney, Alexa Lee, Tim Maurer, AnnaLee Saxenian, and Matt Sheehan.

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Executive Summary

Innovation has been a source of comparative advantage for Taiwan historically. It has also been an important basis for U.S. firms, investors, and government to support Taiwan's development while expanding mutually beneficial linkages. Yet, both Taiwan's innovation advantage and the prospect of jointly developed, technologically disruptive collaborations face challenges.

For one, Taiwan's technology ecosystem has been hollowed out in recent decades as personal computing (PC), component systems, and mobile device manufacturing moved across the Taiwan Strait to mainland China. Meanwhile, Taiwan's innovation ecosystem has struggled to foster subsequent generations of startups to replace these losses in electronics manufacturing. Despite a freewheeling startup culture, internationalization has been a persistent challenge for Taiwan-based firms. Technological change and political challenges from Beijing present additional risks to Taiwan's innovation future.

In this context, it is essential that Taiwan get back to basics if it is to assure its innovation advantage. One piece of this will involve taking a hard look at the domestic policy environment in Taiwan to ensure a steady pipeline of next-generation engineering talent. Yet Taiwan also needs to address several structural and policy factors that, over the last decade, have eroded its enviable innovation advantage.

This paper examines five pressing challenges to Taiwan's innovation future and proposes an array of specific solutions to promote Taiwan-based innovation, better leverage partnerships with U.S. and other international players, and bolster Taiwan's standing in the global marketplace.

A particular focus is the need to foster a next generation talent pool with expertise in computer and data sciences, machine learning, and other fields that could contribute to the integration of software with Taiwan's long-standing comparative advantages in hardware.

Taiwan's innovation ecosystem has faced particular pressures on its ability to reorient from semiconductor and chipset design and fabrication toward new, future-facing industries. Many of the new systems in these industries do require advanced hardware. But they also require parallel adaptations in software, and the firms and national innovation systems that lead these industries tend to derive their competitive advantages from hardware-software integration.

To this end, forward-looking partnerships between Taiwan and U.S. players could naturally complement a revitalized and broadened innovation strategy for Taiwan.

Introduction

Innovation has been a source of comparative advantage for Taiwan historically. It has also been an important basis for U.S. firms, investors, and government to support Taiwan's development while expanding mutually beneficial linkages.

But both of these things—Taiwan's innovation advantage and the prospect of jointly developed, technologically disruptive collaborations—face challenges.

In the 1980s and 1990s, mutually beneficial collaborations between Silicon Valley and the broader Hsinchu-Taipei region supported entrepreneurial dynamics and the growth of the indigenous semiconductor and PC industries in Taiwan. In the 2000s, however, Taiwan's technology ecosystem hollowed out as PC, component systems, and mobile device manufacturing moved across the Taiwan Strait to mainland China. Today, the Ministry of Economic Affairs (MOEA) annual survey has shown that over 80 percent of Taiwan's information and communication technology (ICT)–related products are manufactured in China.[1]

Bluntly put, Taiwan's innovation ecosystem has struggled to foster subsequent generations of startups to replace these losses in electronics manufacturing—for instance, in software, computer security, data, chips, and artificial intelligence.

But that is not all. Despite a freewheeling startup culture, internationalization has been a persistent challenge for Taiwan-based firms. A 2018 report from the Chung-Hua Institution for Economic Research concluded that while Taiwan's total research and development (R&D) investment accounted for 3.05 percent of gross domestic product (GDP) in 2015, just 0.06 percent of private sector R&D activities are funded by foreign sources.[2] Similarly, a 2018 PWC survey of Taiwan's startup ecosystem revealed a significant lack of internationalization, with 71 percent of revenue sources for Taiwan-based startups generated by the comparatively small domestic market.[3] Successful Taiwan startups with ambitions to expand overseas were revealed in this survey to lack the resources to do so.

This is just one of many areas that revitalized and strengthened partnerships between Taiwan and U.S. players could help to address. Taiwan-based startups appear keen to attract external investment, not just to obtain capital but also to plug into global networks.

Meanwhile, technological change and political challenges from Beijing present additional risks to Taiwan's innovation future.

For one, Chinese state policies have thus far precluded Taiwan from forging industrial and commercial links in the context of formal investment, trade, or other framework agreements with regional governments, especially in the Southeast Asian countries that are critical parts of the East Asian manufacturing supply chain.

For another, the bleeding of talent across the Taiwan Strait has been a persistent challenge to Taiwan-based industry. Since 2017, Beijing has sought to ramp up its own domestic semiconductor industry, in part by poaching Taiwan-based talent.[4] One recent report suggests that as many as 3,000 semiconductor engineers have departed Taiwan for positions at Chinese companies, a figure that would amount to nearly one-tenth of Taiwan's roughly 40,000 engineers involved in semiconductor R&D.[5]

In this context, it is essential that Taiwan get back to basics if it is to assure its innovation advantage.

One piece of this will involve taking a hard look at the domestic policy environment in Taiwan to ensure a steady pipeline of next-generation engineering talent. Yet Taiwan also needs to address several structural and policy factors that, over the last decade, have eroded its enviable innovation advantage.

Among the most important of these is the continuing concentration of Taiwan's innovation strengths around hardware, even as the emerging and foundational industries of the future are increasingly being defined by hardware-software *integration.* There is no question that hardware will remain relevant to comparative advantage—for instance, through chips optimized to specifically perform artificial intelligence (AI) and especially AI on the edge-related functions. But the next era of chip design is in play, and partnerships and supporting policies to quickly research, develop, and test this hardware will be critical.

If Taiwan can secure its design data—and the data of its partners—while also securing its intellectual property from poaching and theft, it could reemerge as a key partner in multinational strategies to successfully shape the future market. Meanwhile, in various areas of AI (as well as an array of AI-enabled technologies, such as drones), success at integrating software with this new hardware will be the major point of differentiation in a truly global competition for advantage.

Another critical means to reinvigorate and assure Taiwan's innovation advantage will be to focus on market-based rather than technology-based strategies. Yet because Taiwan itself, with just 23 million people, does not provide a market of sufficient size to support some such innovations, looking beyond the domestic setting by relying on third markets while broadening international partnerships will be essential to achieving scale.

The most successful market strategies are likely to be those that secure the emerging autonomy market. This includes AI-enabled markets in areas from bioinformatics to healthcare, the Internet of Things (IoT) to critical infrastructure protection, and, in time, quantum sensing and communications.

Speed, data crunching, and security at the edge will be major differentiators for those who become leaders in these areas.

There will be a strong technology strategy element to determining success. But tailoring those strategies to the emergent markets in these new industries will be *the* crucial long-term play. The tools that will enable manufacturing—and the manufacturing itself—including silicon- or bio-substrate, will be crucial to ensure strong and sustained growth in the mid to long term.

The good news is that there have been positive steps in Taiwan in recent years to redress at least some of these challenges.

For its part, Taiwan's government initiated an "Asian Silicon Valley" project in 2016, with a base in Taoyuan and an initial budgetary outlay from President Tsai Ing-wen's administration of 11.3 billion New Taiwan dollars ($350 million).[6]

Among other efforts under this initiative, the government subsidizes selected Taiwanese startup teams to spend a few months in Silicon Valley, normally with Valley-based accelerators. With the help of mentors from the accelerators, these teams have the potential to gain firsthand knowledge of the American market. That in turn can shape modifications to their products, services, and business models. They also come into direct contact with consumers and buyers beyond Taiwan itself. In select cases, they have found U.S.-based business partners and investors for their companies.

Similarly, the government adopted an action plan for enhancing Taiwan's startup ecosystem in February 2018.[7] This plan includes government backing for startups to participate in international accelerators and trade shows, as well as incentives for government procurement from startups and legal changes to the regulations governing the recruitment of foreign talent.

Beyond these government-sponsored efforts, however, private accelerators and "ecosystem builders" have also emerged.

One example is the Taipei-based Startup Stadium, which offers boot camps and other mentoring services aimed at helping local startups tap global knowledge and best practices, while also helping them try to scale for international markets.[8] One illustration is in the area of fintech, where the

Startup Stadium has connected the very modest number of Taiwan-based fintech startups to regional and global fintech accelerator programs.[9]

Other private Taiwan-based accelerators, such as AppWorks, have focused on new-generation fields like blockchain. And they have attracted not just local startups to their fold but also Southeast Asian startups that seek investment from Taiwan's thriving venture capital industry and corporate partnerships in Taiwan.[10]

These successes demonstrate that international partnerships, particularly with U.S. players, could naturally complement a revitalized and broadened innovation strategy for Taiwan. The purpose of this paper, then, is threefold:

- to identify the most pressing obstacles that presently stand in the way of Taiwan's innovation future;
- to offer specific ideas to government, industry, and capital markets players to help alleviate and overcome some of these obstacles; and
- to explore how forward-looking partnerships between Taiwan and U.S. players could potentially contribute to those ideas.

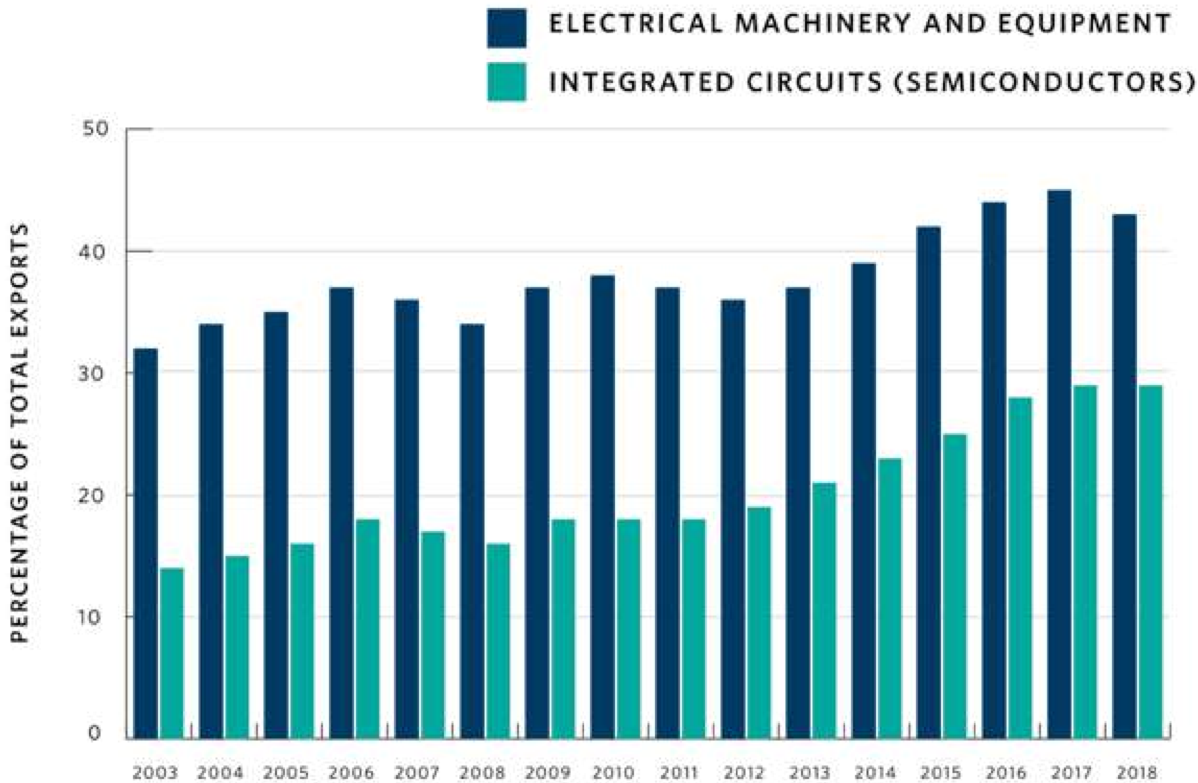
Historical Context of Taiwan's Technological Success

AnnaLee Saxenian of the University of California, Berkeley, has traced the basic contours of how IT-related industries became so central to Taiwan's post-1980s growth story: In 1980, Taiwan's IT output was less than $100 million.[11] By 1989, it had grown to over $5 billion, and then grew by over 20 percent annually in the 1990s—a period when Taiwan's GDP growth was in the 6–7 percent range—to about $21 billion in 1999.

Ministry of Finance (MOF) data shows that advanced technology-related devices comprised a staggering 46 percent of Taiwan's total exports for the first ten months of 2017, with the focus disproportionately on hardware as part of the global electronics supply chain.[12]

Not surprisingly, a single industry—semiconductors—dominates this picture, just as it has for nearly four decades. MOEA figures show that semiconductors accounted for 29.1 percent of Taiwan's total exports in 2017 and, according to MOF data, a whopping 62.6 percent of its exports of technology devices.[13] Three other hardware-related sectors—flat panels, wireless transmission devices, and mobile phones—comprised another 10.5 percent of the 2017 technology product export mix.

FIGURE 1
Hardware as a Percentage of Taiwan's Total Exports, 2003–2018



SOURCE: "Trade Statistics," CPT Single Window, Taiwan Ministry of Finance, accessed January 7, 2020, https://portal.sw.nat.gov.tw/APGA/GA30E.

In fact, Taiwan's dependence on hardware has only become more acute over the last decade. The same MOF data noted, for example, that these items have grown steadily as a proportion of Taiwan's overall exports—from 39.5 percent of the total export mix in 2012 to 40.8 percent in 2013, 41.9 percent in 2014, 43.5 percent in 2015, 45.6 percent in 2016, and 46 percent in 2017 (see figure 1).[14]

The dominance of hardware, especially of semiconductors, reflects the core features of the three-legged model that made Taiwan so successful in the formative developmental period of the 1980s and 1990s.

The first leg of this model was the government's competition policy, which played a crucial role in laying the foundations for Taiwan's more flexible and decentralized model of hardware production at a time when bigger Asian economies chose a more centralized, less diverse pathway.

Taiwan's government did not necessarily refer to its unique approach as "industrial policy." Yet savvy technocrats, such as Li Kwoh-ting, invested aggressively in higher education. They promoted technology transfer, especially from the United States. They targeted R&D funds into electronics through the Industrial Technology Research Institute (ITRI), founded in 1973, and they launched an indigenous venture capital industry in Taiwan.

By contrast, Japan and South Korea established an especially close nexus between government industrial policy and a handful of large firms, such as the leading Korean *chaebol*. Taiwan's model relied more heavily on strong market competition, which in turn supported a decentralized ecosystem and the development of technology startups.

Saxenian captured this dynamic well:

> The dynamism of Taiwan's IT industries, like those of Silicon Valley and its other "imitators," [was] rooted in the incremental deepening and broadening of the capabilities of a localized cluster of specialist producers as well as in its close economic ties to the original Silicon Valley. This differs fundamentally from the privileged relationship between the state and a handful of large, established corporate giants that characterized IT development in Japan and Korea in the 1980s. If the East Asian case is viewed as state-led development, then the experience of Silicon Valley, Taiwan, and its other "imitators" is best understood as entrepreneurship-led growth.[15]

This points to the second leg of the model that undergirded Taiwan's past success—internationalization, especially through links to the world's leading global innovation ecosystem in California's Silicon Valley.

Taiwan, in effect, discovered Silicon Valley decades before the rest of the world. That discovery—and the process of "brain circulation" of Taiwan-born but U.S.-educated and -trained engineers and entrepreneurs—in turn drove a wave of entrepreneurial growth in semiconductors, PCs, and other hardware-related industries.[16]

Taiwanese from the United States advised policymakers in Taipei during the 1960s and 1970s on economic development strategies, successfully advocating a focus on developing capabilities in leading edge technologies, such as semiconductors, rather than following the Korean model of moving into automobile manufacturing. They also worked with their peers at home. Some ultimately returned to Taiwan to take up leadership positions that helped expand the island's system of higher education; its research capabilities, including the formation of the Electronics Research Service Organization (ERSO) and ITRI; and the development of a domestic venture capital industry.[17]

For these Taiwan-origin entrepreneurs and engineers who subsequently returned to Taiwan after education and work stints in Silicon Valley, the connection with California specifically and the United States generally provided a crucial store of knowledge, technology know-how, and strategies for market development.

This era was characterized by intensive exchanges of both hardware systems and underlying expertise between, on the one hand, California firms and individuals and, on the other, those in Taipei-Hsinchu. Soon, a set of transpacific social and professional networks formed.

Starting in the 1980s, this generation of returnees to Taiwan began to set up their own firms. Many of these became the backbone of Taiwan's early wave of semiconductor, PC, and electronic systems producers. The new Taiwan-based firms subsequently forged additional and follow-on connections to Silicon Valley firms, who then set up their own manufacturing bases in Taiwan.

In this way, cross-regional partnerships facilitated mutually beneficial upgrading. Through a range of collaborations, including original equipment manufacturing and design (OEM/ODM) partnerships with leading U.S. firms, the competitive advantage of Taiwan's manufacturers shifted from that of low-cost imitators to global leaders in electronics production based on speed, quality, and competitive costs.

A third leg underpinned Taiwan's successful model: its ability not just to combine quality with cost advantage but to innovate independently. This is a feature that others, including China, have sought to replicate in their technology-based development strategies during recent decades.

Taiwan's cheap labor advantage allowed it to quickly enter the global semiconductor market, which had been established in the United States in the 1950s by firms such as Fairchild (founded in 1957), National Semiconductor (founded in 1959), and Intel (founded in 1968). But Taiwan-based firms then quickly upgraded their quality, specialization, and production capabilities.

Probably the best example of this is Taiwan Semiconductor Manufacturing Company (TSMC), founded in 1987 by a Taiwanese returnee from Texas Instruments, Morris Chang, as a spinoff from the Li Kwoh-ting–inspired ITRI.

TSMC and other Taiwan-based market leaders in semiconductors and chipsets—such as United Microelectronics (UMC), founded in 1980 as another spinoff from ITRI—pioneered the dedicated semiconductor foundry business model, providing advanced chip production capabilities as a service.

All semiconductor firms at the time were vertically integrated, with both chip design and manufacturing conducted in-house. The foundry model proved to be a significant innovation because it allowed for the flourishing of new generations of firms that focused only on chip design and avoided the huge costs and complexities of production facilities.

Taiwan soon became a center of chip design expertise, with fabless chip design firm Mediatek (founded in 1997) as an early success story. Today, TSMC remains the world's leading semiconductor fab, with cutting-edge production technologies and close to half of the global foundry market.

What makes TSMC so unique is both its mastery of chip design and its huge scale advantages. Its size means that it can spread out fixed costs and maintain lower per unit costs while pumping its considerable financial resources into next-generation R&D.

This three-legged model—smart government competition policy, aggressive internationalization, and the incubation of an independent innovation capability—yielded a highly decentralized and competitive manufacturing ecosystem. This promoted Taiwan's leadership in semiconductor design and production, contributing to a flourishing period for its ICT manufacturing during the 1980s and 1990s. From the earliest days, the focus within this emerging ecosystem was on production for export, particularly of intermediate goods. The keys to the success of these globally competitive, Taiwan-based hardware firms became offshoring and comprehensive integration into global value chains.

But Taiwan's sheer dependence on the IT sector in the overall export picture has been a critical and persistent theme in its economic development. Because that dependence has continued to this day, it has created vulnerabilities, even though champion companies like TSMC have capitalized on sales and supply chain opportunities to become globally dominant industry players in such areas as semiconductors and chips.

Challenges to Taiwan's Innovation Advantage

By the 2000s, this terrifically successful model was being increasingly buffeted by significant changes to Taiwan's twin relationships with China and the United States.

With China, while much R&D remained in Taiwan, particularly critical semiconductor-related design knowledge, many hardware manufacturing supply chains shifted across the Taiwan Strait, especially to the Pearl River delta in Guangdong Province and the greater Shanghai region, because of cost advantages. By the middle of this decade, especially with the transition of mobile phones from a premium product to a globally popular one, the hardware ecosystem around the southern Chinese city of Shenzhen, in particular, had developed distinctive and dynamic characteristics.[18] Above all, Shenzhen boasts rapid and efficient logistics to enable hardware innovators to design, prototype, and then repeatedly tweak and retweak a hardware product on very short production cycles. Today, that unique Shenzhen ecosystem mixes manufacturing prowess—much of it acquired from U.S., European, Taiwanese, and other Asian firms that set up fabrication shops there—with a deep stock of engineers.

With the United States, meanwhile, Taiwan saw diminished connections to Silicon Valley in the 2000s for two reasons: first, with more opportunities at home, fewer students from Taiwan came to the United States to study; second, Silicon Valley firms like Apple increasingly partnered with lower cost Chinese, not Taiwan, firms for their manufacturing needs.

This whipsawed the transpacific integrative model that had been so essential to Taiwan's hardware success. It meant fewer connections to U.S.-based innovation and less of the intensive "brain circulation" that had characterized Taiwan's formative period.

Meanwhile, U.S. innovators, including Silicon Valley's principal market makers, increasingly shifted their focus away from hardware toward software—a shift that yielded new pressures on Taiwan's hardware-dominant technology and innovation industries.

Above all, the Taiwan ecosystem has faced special pressures on its ability to reorient from semiconductor and chipset design and fabrication toward new, future-facing industries. Many of the new systems in these industries do require advanced hardware. But they also require parallel adaptations in software, and the firms and national innovation systems that lead these industries tend to derive their competitive advantages from hardware-software integration.

Around the world, there are useful models of successful adaptation whose features Taiwan could assimilate. Other economies, such as Israel's and Estonia's, have capitalized on these trends by forging niche advantages in cybersecurity and other new software-related industries. Singapore likewise aspires to be a fintech data hub.[19] This has important implications for Taiwan because it demonstrates that small economies can be globally competitive if they both prioritize integration and decisively pursue specialization.

Still, the net effect of these changes has been that Taiwan's ecosystem has fallen a few steps behind the United States, Canada, and other global technology leaders. Bluntly put, a new generation of Taiwan-based technology startups has yet to emerge. Indeed, while Taiwan now has a vibrant and flourishing startup scene, few of these firms have agglomerated around new or fast-growing areas of science, technology, engineering, and mathematics (STEM).

An overarching challenge, then, is for Taiwan to compete based on innovation rather than just continually moving up the value chain in legacy industries. In fact, this is a challenge for all economies, including the United States'.

But achieving this will require the concentration of resources, careful choices, and more strategic investments in knowledge-based industries of the future—for instance, those touching cybersecurity, big data, and such areas of artificial intelligence as machine learning and natural language processing.

Five major issues pose the most acute challenges to Taiwan's innovation future:

1. **STEM Talent and Human Capital:** Taiwan faces significant obstacles in its effort to assure a robust and growing STEM talent pool amid international competition, especially from mainland China.
2. **Scale:** It can be difficult to scale industries and business models because of Taiwan's small domestic market.
3. **Beyond Hardware:** Taiwan has yet to transition from a hardware-dominant ecosystem to greater emphasis not just on software but especially on hardware-software integration.
4. **Value Added for Taiwan:** Too little of the value added within technology-related supply chains resides in Taiwan itself.
5. **Policy Enhancements:** Political leaders and bureaucrats have yet to fully adapt government technology and education policies to enhance competitiveness in newer and emerging technology industries.

The next sections examine these five pressing challenges in detail—and propose an array of specific solutions that would promote Taiwan-based innovation, better leverage partnerships with U.S. and other international players, and bolster Taiwan's standing in the global marketplace.

STEM Talent and Human Capital

The first challenge—one that is front and center for Taiwan's industry leaders—is an insufficient replacement pool of talented and qualified next-generation specialists.

Taiwan needs not just improvements to general STEM education but innovators with specialized skills in math, statistics, computer science, and data science. These skills lie at the heart of such emerging fields as machine learning, AI, and cybersecurity.

Taiwan faces gaps and shortfalls across the board in these areas. And this is compounded by dynamics in startup sectors, with company founders in Taiwan today disproportionately untrained in engineering or technical subjects, much less in specialized and emerging STEM fields.

PWC's 2018 Taiwan startup survey starkly illustrates this gap. Of Taiwan-based startups surveyed, 70 percent had been founded by first-time entrepreneurs but just one-third of these had educational backgrounds in engineering (13 percent), science (7 percent), or information technology (13 percent). Nearly 60 percent of all Taiwan startup founders have backgrounds in the liberal arts or business disciplines. Nearly twice as many startup founders have backgrounds in marketing (14 percent) as in all of the sciences combined.[20]

Ironically, the lack of technically trained entrepreneurs who have established or worked in future-focused startups is a function of Taiwan's remarkable past success. Indeed, so successful was the hardware-based manufacturing model that just two companies, TSMC and MediaTek, employ nearly 66,000 engineers.[21] As a result, well-paid technical specialists have scant incentives to abandon their pivotal roles in a crucial industry by dipping their toes into the riskier world of next-generation startups.

But Taiwan's broader talent base is also at risk. For one thing, Taiwan's workforce is set to shrink. In 2018, Taiwan's birthrate plummeted to an eight-year low of just 181,601 births, according to Ministry of Interior statistics.[22] Taiwan now has the world's lowest birthrate, with the National Development Council projecting meaningful declines as soon as 2021 or 2022, with likely negative effects on productivity as well as on the available pool of younger, educated workers available to the technology industry.[23]

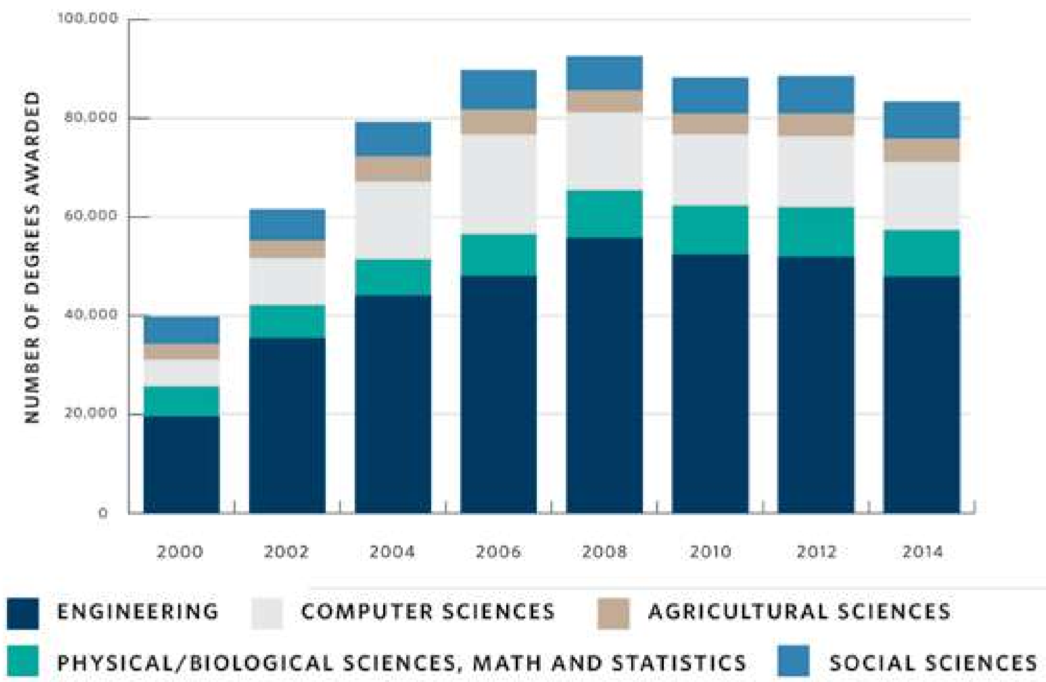
For another, Taiwan is producing fewer science and engineering graduates. From 2007 to 2014, the number of science and engineering first university degrees in Taiwan declined by nearly 10,000, from 92,167 to 83,394, although the total number of engineering graduates has risen sharply compared to, say, the 1990s.[24] What is more, within this talent pool, the number of computer scientists and specialists in math, statistics, and the physical and biological sciences has not expanded in a significant way (see figure 2).

This means that Taiwan's education system is producing insufficient technical talent while concentrating the talent pool that it does produce into legacy fields connected to semiconductor design, such as electrical engineering. Taiwan has underinvested in emerging areas, such as computer and data sciences.

A related challenge is that the number of Taiwan students going to the United States for study has trended downward over the last twenty years at every educational level.[25] Between 2000 and 2017,

FIGURE 2

First University Degrees Awarded to Taiwan Students in Science and Engineering, 2000–2014



SOURCE: "Science and Engineering Indicators 2018," National Science Foundation, Appendix Table 2-35, accessed January 7, 2020, https://www.nsf.gov/statistics/2018/nsb20181/assets/561/tables/at02-35.pdf.

U.S.-bound undergraduates from Taiwan declined from 10,668 to 7,003, while U.S.-bound graduate students declined from 15,022 to 9,236 (see figure 3).

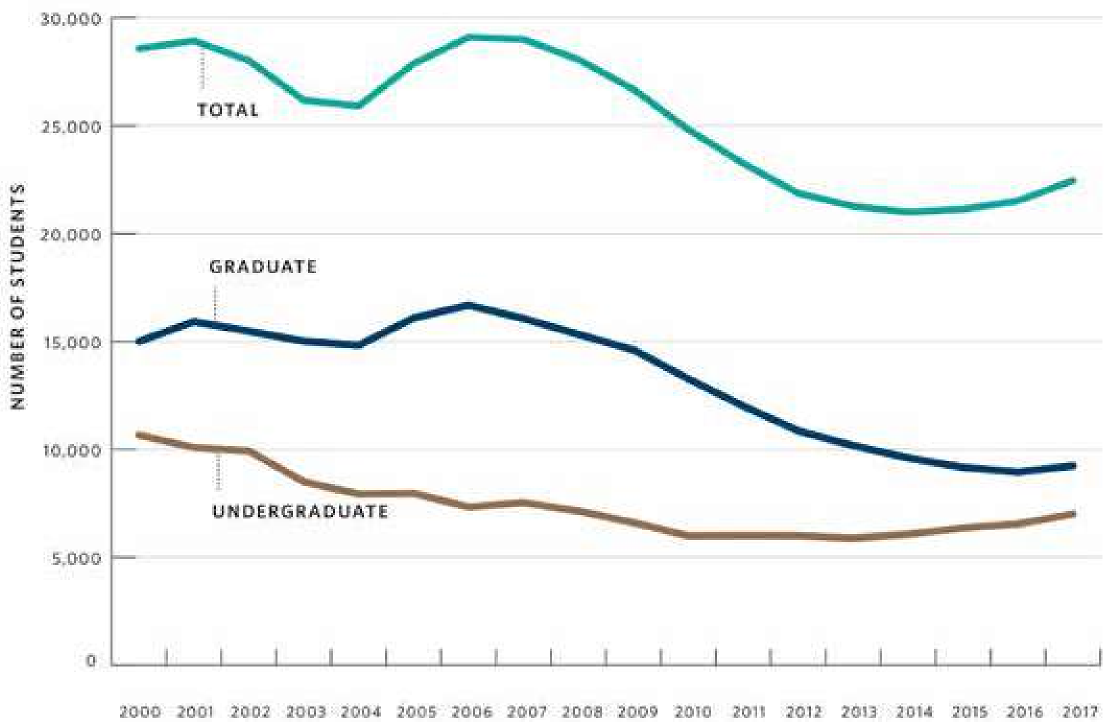
And more of these students, especially those with the most experience, are choosing to stay in the United States, not return to Taiwan. Roughly 65 percent of Taiwan-origin, U.S.-educated PhDs in the sciences and engineering planned to stay in the United States in surveys from 2004 to 2007—already a staggeringly high number. By 2012 to 2015, this number had risen to nearly 75 percent (see figure 4).[26]

This is important because so many of Taiwan's initial successes of the 1980s and 1990s were enabled by "brain circulation" among Taiwanese returning home from the United States. Today, 3 of every 4 Taiwanese with American PhDs choose not to return home.

This will put a premium on forward-thinking educational initiatives, including public-private and international initiatives that aim to urgently ramp up Taiwan's talent and skill base. Reinvigorated

FIGURE 3

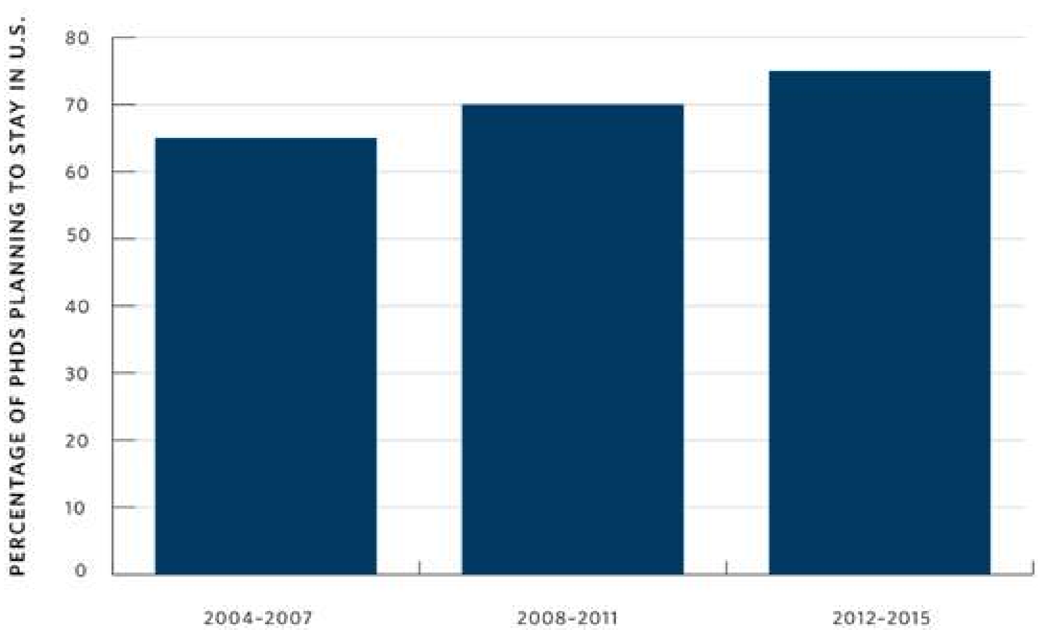
Number of Taiwan Students in the United States



SOURCE: "Open Doors Data Portal," Institute of International Education, accessed November 9, 2019, https://www.iie.org/Research-and-Insights/Open-Doors/Data/International-Students/Places-of-Origin.

FIGURE 4

Percentage of Taiwan Science and Engineering PhDs Planning to Stay in the United States



SOURCE: Science and Engineering Indicators 2018," National Science Foundation, Appendix Table 3-21, accessed January 7, 2020, https://www.nsf.gov/statistics/2018/nsb20181/assets/901/tables/at03-21.pdf.

partnerships with universities and companies in the United States should, of course, be part of a next generation talent-building strategy.

Without more of these initiatives, Taiwan will face significant long-term headwinds. The AI industry today is being driven, in no small measure, by graduate and postgraduate students, much as computer science once was before the dot-com explosion. So, the fallout or mismatch between Taiwan's STEM education and the need for talented experts who can drive the incubation of future-oriented industries in Taiwan will be acutely felt.

Any strategy must take into account the time needed to build and sustain expertise, as well as the flexibility needed to deploy it. A thoughtful STEM strategy for Taiwan focused not just on the engineering of hardware through electrical and mechanical engineering but also chemistry and biology as a substrate could help to produce both the disruptive force for the next market and the long-term foundation needed to sustain it.

Much of this challenge is, quite clearly, going to play out at the university level. But recent revolutions in technology have accelerated the pace of change. One Taiwan industry insider consulted for this paper argued that university curricula and new degree programs usually lag at least three to five years behind cutting-edge technology, and even this may be optimistic.[27] So, Taiwan, like many other advanced economies, including the United States, needs to compete through enhanced STEM-related instruction at both high school and university levels. And where science and engineering education have tended to emphasize the hard sciences, new and emerging technologies—from AI to the Internet of Things (IoT) to blockchain—turn even more on specialized knowledge of software and data science, especially on mathematics and statistics.

Taiwan faces an additional challenge to its talent base: Beijing. Chinese markets have yielded high returns to capital, with a special segment of the mainland's capital market devoted to technology, a good deal of flexibility built into it, and higher returns to investment in the Chinese technology segment than in Taiwan's. That makes it an attractive destination for well-educated Taiwan technical specialists.

Beijing poses another problem too: brain drain from Taiwan to the mainland has been enabled by Chinese companies that have paid Taiwan-origin engineers as much as three to four times what Taiwan firms do. And Beijing has set into place both official and unofficial programs to attract and poach Taiwan's talent.

The bottom line is this: Taiwan succeeded in the past through policies that attracted talented engineers back home from the United States. It would do well, then, to reinvigorate its ability to compete for global talent—from the United States, of course, but potentially from mainland Chinese expatriates too. The latter would be especially attracted by Taiwan's comparatively better quality of life and the political openness of its democratic system.

Scale

Taiwan's small size also presents a barrier to creating scale in certain industries. Its population hovers around just 23 million, and the National Development Council predicts that Taiwan will likely bump up against a negative population growth rate by 2021 or 2022, with damaging effects on workforce composition.[28]

Scale and the resulting limitations of a small domestic market are not new problems for Taiwan. Other small markets have been able to foster large internet and platform companies—Spotify, for instance, was incubated in Sweden—but the underlying problem of scale is compounded by Taiwan's urgent and growing labor skills challenge, which exacerbates handicaps associated with declining cost competitiveness. Scale problems could be better dealt with in the context of investments in a skilled labor pool and a STEM-enabled workforce.

Taiwan today largely cannot offer the unique manufacturing ecosystem of Shenzhen. That southern Chinese city does today what Taiwan did in the 1990s: speedy turnaround of low-cost manufactured electronic products. This is no longer an option for Taiwan because of its cost structure, where leading Taiwanese contract manufacturers, including Foxconn and Pegatron, which depend on low labor costs and huge supplies of unskilled labor, are doing most of their production in China. In Guangdong, labor and land have been abundant and they can leverage these operations to serve global markets. Taiwan, by contrast, can no longer itself house such cheap land and labor.

The good news is that capital is abundant and Taiwan's venture capital (VC) industry remains especially strong. But one local industry player argued to this author that there have not been enough startup cases for Taiwan-based VCs to invest in for at least a decade. These essential VC funds have often been lost to mainland China, where they are being plowed into investments in China-based technology startups instead of into analogous firms in Taiwan itself.

A central challenge, therefore, will be how to attract not just Taiwan but also U.S. and international VCs and investors. This challenge is situated against the backdrop of a bubbly and potentially overvalued market in which Taiwan's market capitalization has been comparatively high as a percentage of GDP, accounting for 159.8 percent of Taiwan's nominal GDP in December 2018, down slightly from an all-time high of 177.0 percent a year earlier.[29]

The central dilemma in this basket of challenges is how to herd investments into next-generation industries and emerging fields. For AI, for example, Taiwan faces acute problems of scale for data. For quantum, it faces acute problems of scale for talent.

China and the United States have the clear edge in terms of sheer numbers of people. And China has worked hard to leverage a talent pipeline within that sizable population.

Just consider AI. One study notes that "Chinese-born researchers conduct a relatively small portion of the most elite AI research (~9 percent), but a substantial portion (~25 percent) of upper-tier AI research." Another finding from the same study indicates that "while Chinese-born researchers have not quite scaled the peak of the AI research pyramid, they make up a sizable chunk of upper-tier AI research."[30]

Notably, the bulk of these "upper tier" Chinese AI researchers (59 percent) work at U.S.-based institutions.[31] This is important in two respects.

First, where the transpacific ecosystem that defined semiconductors and hardware innovation in the 1980s and 1990s linked Taiwan to Silicon Valley, the one that has now come to define AI links China to Silicon Valley. In effect, it is mainland China-based, not Taiwan-based, engineers and entrepreneurs who have forged the links to the United States that will define many aspects of the future of AI. Ironically enough, such a highly internationalized transpacific ecosystem between Beijing and California mirrors the internationalization and brain circulation that defined Taiwan's past success.

Second, as technology-related competition accelerates between Washington and Beijing, many of these China-born AI experts may now leave the United States for home. This will likely further fuel the growth of AI research in major Chinese hubs like Beijing. In short, the "flow and retention" of Chinese AI talent may now reverse—from elite researchers building the U.S.-based industry to a returned cadre building AI firms in China.

This could have far-reaching effects on the competitive landscape for industries like AI.

But it could also buffet Taiwan, which has tried to achieve greater scale in part through closer economic links with the $14 trillion Chinese economy across the Taiwan Strait.

If trade and technology competition fracture the world into two camps, the private sector will try to straddle. Beijing is almost certain to ratchet up the pressure on Taiwan and its firms as they try to pursue economic integration elsewhere. Indeed, Beijing will continue to pressure Taiwan in multidimensional ways. And this is certain to be true of technology leadership, with Chinese firms continuing to try to poach Taiwan talent, among other effects.

Taiwan's challenge will be to position itself as a more attractive alternative to China for multinational firms, globally oriented talent, and the R&D partnerships that define these nascent industries. There has been a spate of R&D labs of key global tech firms locating and/or expanding in Taiwan in recent years, including in emerging industries such as AI. These firms include global market leaders such as Google, Intel, Microsoft, and Qualcomm. This suggests the potential value of this play if Taiwan is able to leverage itself in these next-generation and emerging fields.[32]

Beyond Hardware

Taiwan faces additional headwinds because of the concentration of so much of its comparative advantage into hardware manufacturing, just as next-generation industries are moving toward an emphasis on integration of software and hardware.

Drone technology is one example. Drones begin with high-quality hardware but have advanced rapidly on the basis not of progressive hardware tweaks but rather the application of advanced AI algorithms to the hardware. So, in this market segment, the ability to advance and adapt these AI technologies has defined the scope and outcomes of competition.

The global market leader in drones for aerial photography and videography is Shenzhen-based DJI, a Chinese firm that has captured 70 percent of the global market because of its advantage in flexible hardware manufacturing.[33] Not surprisingly, it now seeks to make a transition to making AI and computer vision a new basis for growth. For DJI, that has yielded both global and U.S. partnerships, including one with Microsoft that uses edge computing to analyze data close to its source—namely, the sensors and computers that fly aboard the drone.[34]

But Taiwan will have a unique opening because of the growing aversion in some economies, not least the United States, to Chinese-origin AI technologies. Taiwan could potentially substitute for products designed or made in Shenzhen in such areas as intelligent robots and drones.

For example, suspicion of Shenzhen-origin technology could ultimately enhance Taiwan's connections to the U.S. market. DJI's partnership with Microsoft, after all, illustrates the strong interest in this area among major U.S. players, as well as the potential for new connections to the United States for the development of these technologies.

Yet a legacy ecosystem focused largely on hardware is unsuited to this opportunity. There will be a premium—and a substantial payoff—for technology-intensive economies best able to prioritize hardware-software integration.

Adaptive steps taken in other economies illustrate this: Taiwan could have, for example, innovated more rapidly to integrate its hardware advantage with software advances. Instead, other economies such as Israel and Estonia have taken a lead.

The good news is that Taiwan's strengths in hardware are a necessary prerequisite to integrating new-generation software advances into future hardware advances. The bad news is that such integration can happen only if parallel efforts are now made to enhance and build complementary comparative advantages in software.

For instance, Taiwan could also have an opportunity to begin crafting the infrastructure of the bioeconomy through a focus on the biochip as infrastructure. Such technology, too, is about much more than just hardware. It integrates hardware, firmware, and software and could enable a huge new swath of the next-generation economy.

Engineering the flexibility into infrastructure to rapidly shift and grow as part of this next economy is a high-technology design problem with potentially huge payoffs. The infrastructure and tools necessary still need to be designed and developed, so the time for Taiwan to educate and build in this space is now.

Value Added for Taiwan

The East Asian manufacturing supply chain, including in electronics, is also evolving rapidly. Movement out of China to Vietnam, Malaysia, and Indonesia, among other locales, began in the last decade because of rising Chinese labor costs. But now unilateral, reciprocal, and retaliatory tariffs flowing from the U.S.-China trade war since 2017 have accelerated this organic process, particularly for low- and mid-end products.[35]

This story is more complicated, however, for higher-end manufactured products—for instance the microelectronic components produced in Guangdong by Taiwan-headquartered Foxconn. South China's well-established and smoothly functioning manufacturing ecosystem cannot be moved or replicated so easily.

Alternative locales, such as Thailand and Vietnam, are limited in their capacity to absorb these types of manufacturing. The establishment of new Foxconn facilities in India has mostly aimed not at the integration of India-based facilities with the broader East Asian manufacturing supply chain but at servicing India's huge domestic smartphone market. Foxconn's India-based facilities make most of their devices for companies like Xiaomi, whose competitively priced smartphones are especially popular in India.[36]

Taiwan's challenge, then, is twofold.

First, it can grab a slice of the rapidly evolving manufacturing chain but focus on higher end manufacturing and especially the emerging AI and quantum value chains. These center primarily on big platform companies, such as Amazon and Google in the United States and Baidu, Alibaba, and Tencent in China, and on second-tier unicorn firms like China's Bytedance and Pinduoduo.

Second, Taiwan can seek to innovate in areas where one does not find these big platform companies, which mainly serve consumer markets. There is considerable opportunity to integrate software, AI, and data science into established industries ranging from healthcare to education to information security.

The success of both platform and niche firms yields two lessons.

One, AI is a data-driven enterprise. Thus, big companies often have the edge because their sheer size means they naturally acquire huge troves of data.

Second, big data is not the whole story of the AI value chain. Some new algorithms require less data to train and thus could be useful market segments for Taiwan to target in upgrading its R&D capabilities.

Moving more of Taiwan's economy into those segments will be a challenge because, for the last twenty years, Taiwan's efforts to move beyond low-value-added manufacturing through upgraded R&D have yielded mixed results. Manufacturing today accounts for just under 30 percent of Taiwan's GDP and job creation. Yet Taiwan ranks five to six points below leading countries in value added—with the exception of the ICT and semiconductor sectors.

Two Taiwan firms, both of them established market leaders in this segment—TSMC and MediaTek—are highly competitive in terms of value added. Yet the majority of large Taiwan manufacturers remain well behind these two firms.

The challenge Taiwan faces today is analogous to the one facing China's Greater Bay Area (GBA), another leading electronics manufacturing center. Like Taiwan, government and industry leaders in the GBA aim to move into advanced technologies, including AI and data-driven fintech. But the most successful Shenzhen startups, like drone maker DJI, are already combining precision hardware manufacturing capabilities with an array of AI applications. These Chinese companies have an advantage over prospective Taiwan competitors because of the huge scale of the mainland's domestic market and links to the global market.

Still, this need not be a zero-sum game. There will be considerable opportunities for innovation with new software and technologies. Taiwan's best course is to complement global trends by developing new, high-end manufacturing and R&D capabilities that leave a larger share of value added in Taiwan itself.

This will compensate for the smaller scale of its domestic market when compared to, say, China or India. For example, new semiconductor and AI investments could aim to complement the U.S. buildout of cloud and quantum computing.

Policy Enhancements

The visionary behind Taiwan's economic miracle Li Kwoh-ting and other pioneers of Taiwan's growth story demonstrated that policy decisions and effective signaling to businesses and markets can incentivize entrepreneurship.

The current government has tried to draw lessons from their example with President Tsai Ing-wen's launch of the so-called 5+2 Innovative Industries Plan.[37] This plan aims to move seven industries and areas beyond their roots in contract manufacturing into high-value-added businesses and services:

1. smart machinery,
2. clean energy,
3. biomedicine,
4. defense industries and aerospace,
5. new agricultural technology,
6. the circular economy, and
7. the aforementioned Asian Silicon Valley project.

The good news is that many of these areas are inherently related to next-generation, knowledge-based industries like AI. Take new agricultural technology: AI algorithms can be applied to large-scale data on weather patterns, crop and soil conditions, and water usage. One estimate predicts that as many as 75 million IoT agricultural devices will be in use by 2020, leveraging 4.1 million daily data points per farm by 2050.[38] So, Taipei's emphasis on new agricultural technology offers an example of how to help enable the transition to a greater emphasis on hardware-software integration.

Still, many aspects of these government plans remain declaratory and aspirational. The government has, for example, identified ways to boost investment in AI research but has not articulated a strategy to target particular niches for specialization.

The United States and Europe, by contrast, have developed such strategies. So has Japan for AI-related healthcare, with the government establishing ten AI-enabled hospitals to serve a Japanese AI healthcare market expected to reach US$100 million by 2025.[39]

Beijing is likewise pursuing AI-enabled facial recognition technologies in a highly strategic fashion, steering contracts and opportunities to global market leaders like Megvii—a Chinese unicorn that has recently been added to the U.S. Commerce Department's Entity List.[40]

The lesson—once again—is that a comparative advantage in hardware is important, but this, by itself, will not set Taiwan up for the industrial and technological challenges of the future.

An entirely new set of policy signals will be needed for a new era. Specifically, Taiwan needs the ability to absorb timing mismatches driven by longer-than-anticipated technology development in some market and infrastructure areas. The government should seek to enable an environment conducive to foreign investment in these segments. That also means that well-intentioned government policies toward both foreign and domestic investors should not be burdened by cumbersome and costly tax schemes.

Solutions and Partnerships

As it seeks to recalibrate and enhance its longstanding innovation advantages, Taiwan should aim to overcome these five obstacles. More focused policies and strategic investments are needed. So too are enhanced international partnerships, particularly with the United States.

It was the Taiwan–Silicon Valley connection, after all, that contributed so much to Taiwan's first-generation talent pool and the creation and subsequent dominance by Taiwan firms of essential hardware industries. A new generation of Taiwan-U.S. partnerships, built on a forward-looking foundation that works to overcome these five challenges, could play an analogous role today.

STEM Talent and Human Capital

Taiwan would be better positioned to play this role if it could enhance its status as a truly bilingual economy. Alongside bolstered investments in STEM education, English language facility will be an essential ingredient of Taiwan's efforts to overcome the challenges of scale by internationalizing and playing a mediating or conduit role regionally and globally.

What is more, Taiwan could make itself into a regional hub for high-tech education by offering engineering programs in English, in particular for the electrical and mechanical engineering requisites of semiconductors and chipsets. Students from Southeast Asia, South Asia, and other parts of the world may find the cost of engineering programs in the United States, Europe, or Australia to be prohibitive. So, Taiwan should aim to make itself into the next alternative for international students in these specialized areas of engineering.

Yet the central question for Taiwan is whether it can cultivate a STEM talent pool not for right now but for ten to twenty years down the road—a pool that combines technical with operational and business skills, focuses not just on hardware but software and integration, and moves beyond traditional strengths in semiconductors and chips into fields like AI, quantum, and cybersecurity.

Taiwan could enable this through several steps in the area of university-industry partnerships:

For one, the government and industry should partner to establish university-based startup incubators, perhaps mirroring the areas under the 5+2 program with a cluster of incubators at certain universities—or else one incubator for each of the seven industries—spread among distinct locales.

A model of sorts already exists in Taiwan's semiconductor industry. As public funding declines, industry players have agreed to furnish matching funds for university professors and laboratories. This government-industry match funding model could be extended to next-generation fields.

To hedge against the short-term return-on-investment (ROI) focus that dominates the venture capital community, this startup incubator effort should be tied to, and ultimately supportive of, the longer-term ROI of retooling and supporting next-generation infrastructure.

Second, Taiwan should look to marry technical with business training. The government could encourage business schools to integrate technical training into their curricula, endowing programs and financing courses of study in computer science and IT at these institutions.

The reverse is also true: institutional partnerships could be better leveraged to help business schools teach operational skills to those enrolled in Taiwan's technical and engineering schools. Taiwan has strong hardware and improving software talent, after all, but a much weaker supply of international operational talent.

Such an effort to merge technical with internationally oriented operational talent is especially needed to build Taiwan's startup sector.

The 2019 PWC Taiwan startup survey reveals that local startups are disproportionately anchored in Taiwan's domestic market. This is as true of their talent base as it is of their market orientation and operational focus: 60 percent of Taiwan-based startups have not begun hiring or fostering international talent. As many as 54 percent have not approached foreign markets in expos or pitches, and just 30 percent have even begun to evaluate target foreign markets.

In short, even if Taiwan-based startups are able to leverage technical skills and disruptive technological breakthroughs and ideas, they would lack internationally oriented managers who could help to build the businesses by leveraging these technologies for markets outside Taiwan.

The most acute need of all is for aggressive steps to assure a steady pipeline of STEM talent as Taiwan builds knowledge-based industries.

Israel provides reference points for one potential model. The Israeli Talpiot program has trained top military recruits in technical subjects.[41] Talpiot graduates have provided a stream of technology talent to the country's vibrant startup sector, with some graduates founding companies including Check Point, Compugen, Anobit, and XIV (the latter two having been subsequently acquired by Apple and IBM).

Israel fostered an enviable startup-friendly nexus between government, industry, and universities. As one example, Israel made a commitment to move units of its intelligence service to the town of Be'er Sheva, and that unit's members became eager to look for startup opportunities once they finished their three-year (or longer) commitment to military service. Then, they were able to apply the technical knowledge they gained in the military to private ventures, including an array of successful technology startups.

For its part, Israeli industry agreed to colocate R&D units in Be'er Sheva with VC firms, which also established a presence there. Taken together, this provided access to larger companies and financial fuel to support the growth of a startup ecosystem. Finally, Ben Gurion University was the academic partner for this effort, injecting research into business ideas and providing the space to test and "red team" innovations.

The Be'er Sheva model is just one example of how a strategic approach that marries government, industry, and universities can foster a tech- and startup-friendly ecosystem.[42] Like Taiwan, Israel confronts a scale problem: with just 8 million people, its population is nearly two-thirds smaller than even Taiwan's. And much like Taiwan, it also faces strategic pressures from larger neighbors and is vulnerable to those strategic pressures and disruptive global economic trends.

Some elements of Israel's model may be adaptable, specifically:

- making a long-term commitment to emerging technology, whose benefits will only materialize several years (and election cycles) later;
- focusing on niche and specialized efforts—for example, Israel identified science and computer science as strategic priorities decades ago, granting first pick from among all new recruits to tech-focused units of the military and intelligence services; and
- establishing programs along the lines of Talpiot and assigning the top 1 percent of military recruits to technology and cybersecurity jobs, thus positioning them for technology-related jobs at the end of their periods of service.

Many Israelis also happen to speak English—something Taiwan can emulate by becoming a bilingual economy. Ultimately, Israeli entrepreneurs tend to think globally from the inception of a venture, eyeing larger markets abroad in Europe and the United States.

But Taiwan's government should take other forward-looking steps to build the pipeline too:

- **Easing work visa and market entry policies.** This would encourage global startups, not just the big players like Google and Microsoft, to set up shop in Taiwan.
- **Supporting industry-led mentorship programs**. For example, Wistron, an ICT original design manufacturer (ODM) with some 80,000 global employees, has promoted a program to bring foreign AI experts to serve as mentors-in-residence in Taiwan. AI mentoring programs could be scaled through public-private partnerships, but then replicated in other areas like quantum computing, cybersecurity, and biotechnology.
- **Expanding the "gAsia Pass" scheme**. The "gAsia Pass" is a digital entrepreneur card that gives equal national treatment to like-minded economies, thus promoting freer talent flow.[43] This scheme originated with Taiwan and five other Asian economies, all of which are priority countries for Taiwan's New Southbound Policy—India, Indonesia, New Zealand, South Korea, and Thailand.
- **Establishing a transpacific advisory panel.** To expand partnerships with American interests and institutions, a transpacific advisory panel could be established encompassing domestic technology leaders in Taiwan, representatives of U.S. firms doing R&D in Taiwan, the VC industries on

both sides of the Pacific, and university leaders. The goal of this panel should be to better address gaps in Taiwan's domestic skills base and then connect efforts to *redress* those gaps to anticipated focus areas for investment.

- **Ramping up educational exchanges.** A Taiwan-U.S. educational panel parallel to the above advisory panel could also aim to foster transpacific cooperation in areas of data science, AI, and cybersecurity, in particular.

Scale

To overcome some of the challenges of its small-scale domestic market, Taiwan needs a three-pronged strategy: Taiwan must be a hub, a trusted vendor, and a conduit. Such a strategy could be leveraged to operate on a global scale even though its economy is comparatively smaller than its giant neighbors.

Taiwan as Hub

Above all, Taiwan should aim to become a hub for a new generation of knowledge-based industries, products, and services. But that will be no easy thing in a competitive marketplace where the technologies in question, particularly those that integrate AI applications, rely heavily on big data.

The bigger the market, the larger the available data sets. So, logically, more access to more data will give a firm anchored in a larger marketplace a comparative advantage. Yet as Matt Sheehan has argued, "data is not a single-dimensional input into AI." While it is true that China, the United States, and India, for example, have large populations and more access to domestic data than Taiwan, "the relationship between data and AI prowess," Sheehan argues, "is analogous to the relationship between labor and the economy." For example, "China may have an abundance of workers, but the quality, structure, and mobility of that labor force is just as important to economic development."[44]

Put bluntly, data quantity matters but so too does data processing, synthesis, and deployment. That is precisely why small economies, including Israel and Estonia, have been able to overcome their small scale by prioritizing sectors, capabilities, and specific parts of the knowledge industry value chain.

One solution, then, would be for Taiwan to emulate and adapt another Israeli example—becoming an industry- and service-specific hub in cybersecurity.

Specifically, Taiwan's government could define a comparative advantage against larger economies by enabling access for its own startups to high-quality government data. In China, firms have been given increasing access by the government in Beijing but the data itself is of low quality. In the

United States, firms tend to have low access although the data itself is actually of high quality. Taiwan could distinguish itself from both China and the United States if it can marry these two pillars by assuring both high quality and easy access for some nonsensitive public sector data sets.

In addition, Taiwan could further leverage an effort to make data a comparative advantage by building on its role as a leader in data protection and privacy standards. Taiwan has strong laws in place, especially when compared to those in mainland China and Southeast Asia. And these are an attractive selling point for Taiwan-based partnerships with U.S. and global firms.

Several specific steps could help in this regard:

- **Take a leadership role in the Asia-Pacific Economic Cooperation (APEC) context.** Despite Beijing's concerted effort to restrict Taiwan's international space, it is a member of the APEC forum, where working groups are now attempting to set cybersecurity standards in IoT and the digital economy. Taiwan should aim to lead within the APEC framework, leveraging and promoting its domestic data practices as regional standards.
- **Leverage European best practices.** With Europe's General Data Protection Regulation (GDPR) having become the global gold standard, enhanced partnerships with—and within—the EU would give Taiwan an opportunity to gain access to global data.
- **Coordinate regulatory frameworks with Washington.** The U.S. Government's Indo-Pacific Strategy includes a cybersecurity component that could coincide with Taiwan's South and Southeast Asia–focused New Southbound Policy. Taipei and Washington should push for coordinated cybersecurity and data governance regulations, and then jointly press their approach in the APEC and global context.

This is an area especially ripe for potential Taiwan-U.S. collaboration on standard setting. Even beyond the cybersecurity-specific issues, the combination of U.S. design and Taiwanese production of chips can, and should, open the door to cooperative standard setting.

What will drive the emergence of a next-generation economy is the development of tools to enable its creation. Becoming a center for the tooling of economies of the future could become an advantage for Taiwan and the United States in a new Taiwan–Silicon Valley partnership.

Taiwan as Trusted Vendor

Earning a reputation as a trusted vendor or supplier can be the second dimension of dealing with Taiwan's scale challenge.

The government should look to enhance the 5+2 Innovative Industries program with a complementary trusted vendor certification program (TVCP), deploying the weight and credibility of the state to incentivize specific standards in specific emerging industries and then leveraging this advantage with foreign partners.

Amid growing U.S.-China tensions and increased suspicion of China-origin advanced technology products, demonstrating that Taiwan is a secure and trusted partner could help to compensate for the mainland's obvious scale advantages. This environment could be conducive to fresh partnerships between Taiwan and U.S. universities as collaboration with mainland institutions falls out of favor.

It could also help to reinvigorate Taiwan's once-intensive connection to Silicon Valley. Alongside a trusted vendor program, Taiwan should pursue a trusted tester effort—taking steps to make Taiwan a preferred location for knowledge-intensive U.S. technology products to be tested for cyber, 5G, and AI-related applications. One way to do this would be to develop sister cluster partnerships with U.S. innovations hubs, not just in Silicon Valley but in Japan and Europe too.

Taiwan as Conduit

Taiwan should also continue to advertise itself as a more trusted gateway than mainland China to Southeast Asia's fast-growing markets for knowledge-intensive products and services. U.S. firms hope to market such knowledge-intensive products to Asia writ large but often lack some of Taiwan's advantages. Especially for smaller and midcap U.S. firms, Taiwanese partners could serve as a conduit.

Taiwan can also be both conduit and trusted partner in the context of linkups between its New Southbound Policy and the U.S. Indo-Pacific strategy. One pillar under the U.S. effort is a "digital connectivity and cybersecurity partnership" program.[45] South Korean companies, for example, are now actively working with the United States on cybersecurity capacity training for the Southeast Asian market.[46]

Taiwan's rich network of corporate and industrial relationships, combined with its emphasis on the region in the New Southbound Policy, argue for a similar effort through which the United States and Taiwan seek complementary or joint opportunities to enhance Southeast Asian capacity in this and related areas.

Beyond Hardware

With competition intensifying in software-enabled industries, Taiwan should prioritize carving out a specialized niche in the newly emerging, rapidly evolving global value chains for knowledge industries like AI and IoT.

The focus should be in two areas. First, Taiwan needs to catch up in global user-centric ecosystems and business models, and second, Taiwan needs to choose areas closely related to its current industrial base because two decades of brain drain have taken a toll on the size and diversity of the overall STEM workforce.

Taiwan's success in the 1980s and 1990s was rooted in policies that encouraged a flexible and decentralized ecosystem. More recently, the global success that smaller economies have had with niche industries and applications demonstrates that concentration can also play a role.

With ecosystems for new industries still emerging, increased specialization and focus could be to Taiwan's advantage in areas, such as data integration, that will be important in the rollout of 5G and IoT. Indeed, Taiwan has innate strengths here on the hardware side. For instance, MediaTek is soon to launch its 5G chip, which will be one of just four 5G chips globally alongside those from Huawei, Qualcomm, and Samsung.

Taiwan may also develop opportunities in quantum computing as a result of the 2019 opening of "IBM Q," a co-innovation hub of IBM and National Taiwan University. To date, Taiwan has had fewer uses for quantum at scale. Such hubs give Taiwan an early opportunity to become "quantum ready" just as R&D on this next generation computing technology advances to its pivotal stage.[47]

Value Added for Taiwan

With the East Asian manufacturing supply chain evolving rapidly, not least in electronics, U.S. firms are among those reconsidering whether high-end manufacturing is overconcentrated in some Asian locales. The U.S. government, in particular, is eager to discourage high technology dependence on China-based suppliers.

This should yield at least some new opportunities for Taiwan-based manufacturing because supply chains are almost certain to remain concentrated in Asia, with few firms able to establish such facilities in the United States itself. For instance, some manufacturing supply chains have begun to relocate from China to Taiwan, notably in the ICT industry, including those making servers and telecommunications products. These firms relocated not just to avoid the punitive tariffs imposed by

Washington as part of the U.S.-China trade conflict but also to ensure cybersecurity. Because the integration of hardware with software is essential to these products, parallel investments by related U.S. software companies would further bolster industrial change in Taiwan.

Beyond ICT, Taiwan needs to secure new industries that would bring greater diversity to its industrial structure. One example could be electric vehicles (EVs) because this would provide new opportunities for Taiwan-based electronics firms to join the global supply chains of an emerging industry.

There are other potentially promising sectors too. The fact is, the United States cannot go this alone: it will need partners to drive next-generation infrastructure and tooling in hardware, AI/IoT trusted infrastructure, and even biotechnology.

That is why new U.S.-Taiwan university partnerships designed to support such a future could be incentivized in Taiwan as a hedge against Beijing's long-term STEM efforts. The incubator model is important but not sufficient. For enduring STEM partnerships linking Taiwan and the United States, security should be baked in from the start of design in such areas as AI and IoT.

If Taiwan can succeed at setting high or even best-in-class security standards—for instance, through the efforts described above to become a trusted vendor, trusted tester, trusted conduit, and trusted research hub—it could enable enhanced knowledge partnerships with the United States.

Policy Enhancements

Finally, Taiwan's government can take some additional policy steps.

The role of government in any national innovation system is often described as that of a facilitator, enabling the private sector to exploit the economy's current comparative advantage while strategically guiding a shift toward new areas.[48] That well describes Taiwan's legacy of success. As noted in a recent IMF report, after all, nothing about Taiwan's factor endowments predisposed it to a comparative advantage in semiconductors in the first place.[49]

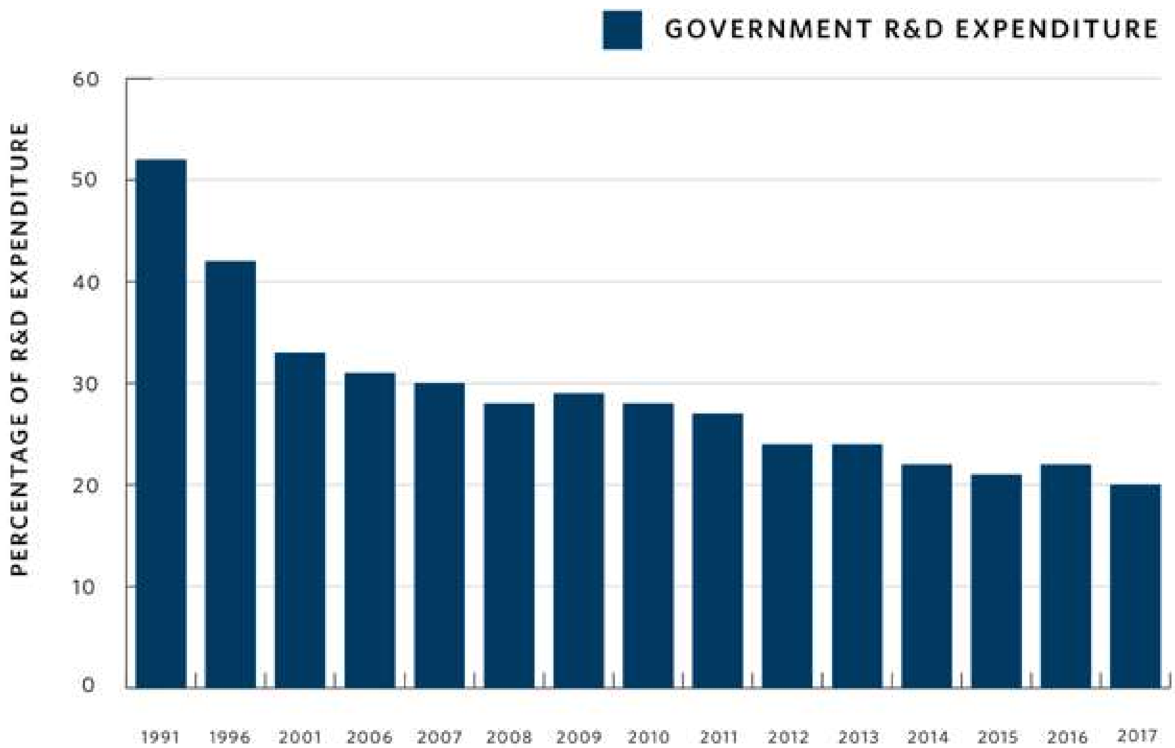
Yet one important lesson of Taiwan's experience with semiconductors is that, much as was the case with hardware, Taiwan's next advantage will likely emerge only through targeted and sustained investment. Boosting research spending should be a particular priority: for long-term investment in emerging technologies, Taiwan's government will need to administer a steady supply of "patient capital" to enable new industrial clusters and advantages to emerge.

For instance, due to the lack of a pipeline, Taiwan's leading semiconductor firms have proposed more spending in at least three key areas: advanced manufacturing cycles, radio frequency, and quantum. Such increased research spending is particularly urgent in the context of the global productivity slowdown. A recent Organization for Economic Cooperation and Development (OECD) report estimates that between 2001 and 2013, frontier firms experienced productivity growth of 2.8 percent per year compared to just 0.6 percent for others.[50] Declining productivity means, in turn, that a proportionate increase of effort will be required just to maintain the status quo level of growth.

Another study showed that although the United States has managed to sustain its technological progress over many decades, research productivity falls in half every thirteen years, which means that "the economy has to double its research efforts every thirteen years just to maintain the same overall rate of economic growth."[51] In Taiwan, the public sector contribution to total R&D has plummeted from 52.1 percent in 1991 to just 20 percent in 2017 (see figure 5).[52]

FIGURE 5

Government R&D Expenditure as a Percentage of Total R&D Expenditure, 1991-2017



SOURCE: "Table 18. Summary of R&D expenditure," Statistical Yearbook of the Republic of China 2019, Taiwan Ministry of Economic Affairs Department of Statistics, accessed January 7, 2020, https://eng.stat.gov.tw/public/data/dgbas03/bs2/yearbook_eng/y018.pdf.

Taiwan's government can do more through public-private partnerships to encourage commercialization. Many university professors, especially in technical subjects, owe their research sponsorship to the government—for example, through subsidy programs of the Ministry of Science and Technology. But few have been able to respond to government entreaties to commercialize the fruits of this research.[53] Fostering links between basic research funding and commercial accelerators and incubators will be essential.

Meanwhile, with political risk rising between Washington and Beijing, Taiwan could be an attractive locale for some of the AI and other laboratories and research partnerships that American and global companies have established in mainland China. Some of these U.S.-Chinese partnerships may erode, or even dissolve, putting Taiwan in a position to potentially pick up the ball if it enhances its own network of partnerships with U.S. corporate and university players over the next three to five years.

Taiwan could also get a boost by continuing to follow international standards and regulatory policy best practices. With competition for foreign investment intensifying, companies will compare policy environments as they weigh where and how to do business around the world. Taiwan's legal and regulatory requirements can bolster its opportunities if it follows international best practices and advertises itself as a global center of excellence.

For instance, Taiwan has already joined the APEC Cross-Border Privacy Rules system for privacy and data transfer.[54] It could continue to uphold its privacy standards and potentially aim to seek an adequacy decision, which is a determination on the basis of Article 45 of EU Regulation 2016/679[55] that a party outside the EU offers an adequate level of data protection to meet tests under Europe's GDPR system.[56]

The United States, Canada, and Japan are among the very small number of economies to have won such decisions from Brussels. EU talks with South Korea are ongoing. Taiwan should aim to become one of the first few economies in the world to have free data flows with Europe, or else consider some type of privacy and data flows agreement with the United States.

Beyond privacy, Taiwan should also become more active in joining international discussion on technology standards—for instance, by participating in the International Organization for Standardization and International Electrotechnical Commission standards working group on issues like IoT, cyber, and other emerging technologies, where it could help to actively drive the dialogue.[57]

Conclusion

Taiwan has faced strategic and economic obstacles for decades. Yet smart policies, economic heft, and a culture of innovation have helped to make it more secure.

To remain secure for the long term, Taiwan needs to make its economy more robust and to integrate with the broader international environment. Above all, it needs a concerted effort to adapt its economy to rapid industrial and technological change.

One solution is to leverage the harmonization of standards through a U.S.-Taiwan trade agreement, which could include chapters covering trade in both goods and services, as well as e-commerce and investment rules. A stronger trade relationship between the United States and Taiwan would offer a platform to lock in mutually beneficial gains between two APEC partners by negotiating a formal system of shared standards.

To be sure, reaching a free trade agreement (FTA) is rarely a simple endeavor. But for both sides, it offers commercial promise, and for Taiwan it offers a pathway to greater economic security and enhanced international integration.

Still, enhancing trade and investment alone is not enough. An FTA would not, for example, resolve some of the inherent but pressing innovation-related challenges to Taiwan's economy. And it would hinge heavily on legacy industries, not the emerging fields that are rapidly reshaping the future of work, service delivery, and defense.

Without a reinvigorated innovation ecosystem, Taiwan's economic prospects will dim. Yet by deploying resources and focusing its educational and innovation strategies in creative ways, Taiwan can adapt to the fresh challenges of this new era. By freeing up access to its talented, well-organized, creative, and educated population, Taiwan will, in time, become a more attractive investment, innovation, and testing hub for a greater variety of international partners.

That is manifestly in Taiwan's interest. It is precisely why it is so essential to Taiwan's economic future that it overcome the innovation-related challenges at the heart of this paper.

About the Author

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From 2001 to 2009, he served at the U.S. State Department as deputy assistant secretary of state for South Asia (2007–2009), deputy assistant secretary of state for Central Asia (2006–2007), member of the policy planning staff with principal responsibility for East Asia and the Pacific (2001–2006), and an adviser on China to Deputy Secretary of State Robert B. Zoellick, with whom he worked closely in the development of the U.S.-China senior dialogue.

Following government service, Feigenbaum worked in the private and nonprofit sectors. He was vice chairman of the Paulson Institute at the University of Chicago and the co-founder of MacroPolo, its digital venture on the Chinese economy; head of the Asia practice at the markets consultancy Eurasia Group, a global political risk consulting firm; and senior fellow for East, Central, and South Asia at the Council on Foreign Relations. Before government service, he worked at Harvard University (1997–2001) as lecturer on government in the faculty of arts and sciences and as executive director of the Asia-Pacific Security Initiative and program chair of the Chinese Security Studies Program in the John F. Kennedy School of Government. He taught at the U.S. Naval Postgraduate School (1994–1995) as lecturer of national security affairs and was a consultant on China to the RAND Corporation (1993–1994).

He is the author of three books and monographs, including *The United States in the New Asia* (CFR, 2009, co-author) and *China's Techno-Warriors: National Security and Strategic Competition from the Nuclear to the Information Age* (Stanford University Press, 2003), which was selected by *Foreign Affairs* as a best book of 2003 on the Asia-Pacific. He has also authored numerous articles and essays.

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附錄 1-2

Facebook’s advice to students interested in artificial intelligence

John Mannes@johnmannes / 12:29 AM GMT+8•December 2, 2016

擷取檔來源**:** Facebook’s advice to students interested in artificial intelligence | TechCrunch

Math. Math. Oh and perhaps some more math.

That’s the gist of the advice to students interested in AI from Facebook’s Yann LeCun and Joaquin Quiñonero Candela who run the company’s Artificial Intelligence Lab and Applied Machine Learning group respectively.

Tech companies often advocate STEM (science, technology, engineering and math), but today’s tips are particularly pointed. The pair specifically note that students should ~~eat their vegetables~~ take Calc I, Calc II, Calc III, Linear Algebra, Probability and Statistics as early as possible.

From this list, probability and statistics are perhaps the most interesting. From what I remember about high-school, those two subjects are regularly dismissed as too-obvious strategies for skirting the informal AP Calculus preference of top colleges and universities (AP Statistics is often thought of as a cop-out by students).

If differential equations represents the electricity that powers machine learning, statistics represents the gears of the machine itself — as the company touches on in a series of AI explainer videos we linked to at the bottom of this post.

To be fair, LeCun and Candela are most likely addressing the college crowd, though its important to consider incentives across all levels of education. Simply, we all could probably use some more statistics in our lives. Beyond math, the two say ~~more math~~ engineering, computer science, economics and neuroscience are also important subjects in today’s economy. How else would a fledgling machine learning student learn to leverage neuroeconomics and cognitive bias to target ads?

The pair also point to philosophy as a necessary prerequisite to understanding knowledge and learning. Amidst all the talk of News Feed bias, it’s important to remember that there is a human behind every application of machine learning. We don’t yet know how to escape the black box problem, but we do know that it will be humans working to figure it out and it would sure help if those humans understood how learning works before they start manipulating data.

Lastly, Facebook turns its attention to the actual mechanics of getting a job in the field of machine learning. Most of these tips are self-explanatory: find a professor to work with, consider working with PhD students who have more time on their hands and try to secure an industry-focused internship regardless of your future aspirations to understand how AI works in the real world.

When applying to PhD programs the two note that being able to identify a professor you want to work with is far more important than program ranking. Once there, students should work to address a specific problem and try to release a piece of open source code before all is said and done.

附錄 1-3

華為的 700 多數學家這次能否助華為走出困境？

天天要聞　2020 年 09 月 01 日 *21:12:05*

關鍵字：華為、數學、任正非、埃達爾·阿勒坎、基站、5g 通信

擷取檔來源: https://daydaynews.cc/zh-hant/technology/777944.html

摘要
2008 年，華為俄羅斯研究所一名數學天才，用非線性數學多維空間逆函數，解決了基站多載波干擾問題，並通過軟件打通了 2G、3G 的算法

任正非在去年的媒體採訪中說，華為有大量的科學家，其中至少有 700 多位數學家，800 多位物理學家，120 多位化學家。很神奇！一家通信企業需要這麼多科學家嗎？特別是數學家，這些數學家在華為幹什麼？此次，境外大國揮舞大棒，讓華為陷入困境之時，這些數學家們能否助力華為走出困境？

先看兩個華為無線通信領域著名的案例。

案例一

無線通信的不同網絡制式，如 2G 和 3G，基站內部算法不同，不同制式的基站相互干擾嚴重。2008 年，華為俄羅斯研究所一名數學天才，用非線性數學多維空間逆函數，解決了基站多載波干擾問題，並通過軟件打通了 2G、3G 的算法。

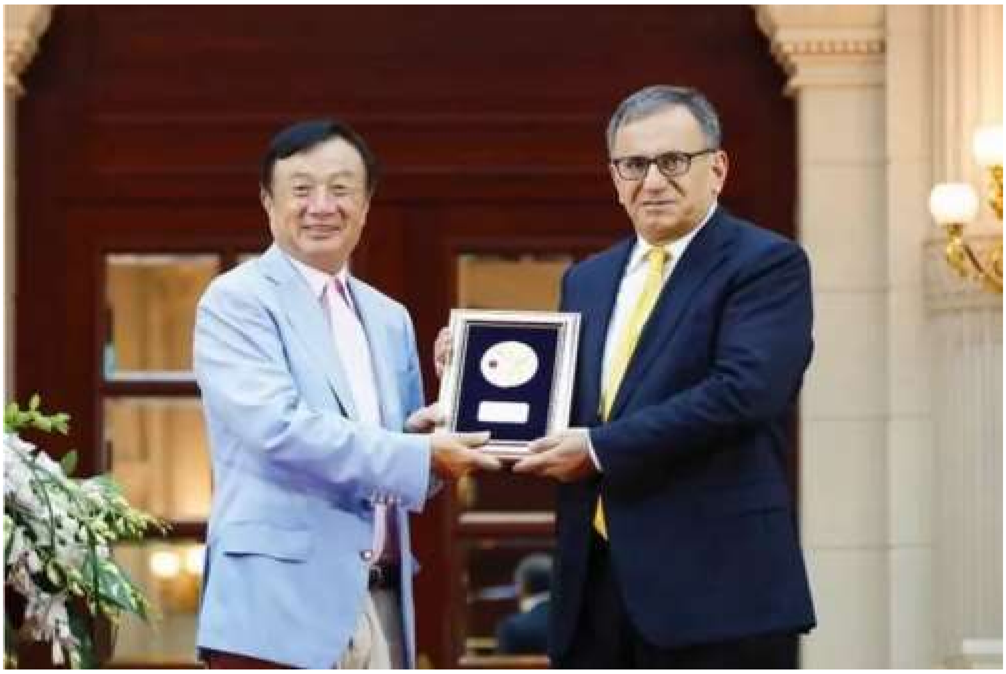
在此基礎上，華為開創性的將 2G、3G、4G 融合，開發出 SingleRAN 一體化無線網絡解決方案，基站三合一，體積小了一大半，成本少了三分之二，賣價少了一半。用戶節省資金 50%，華為毛利率卻大幅上升。華為憑藉 SingleRAN 迅速佔領歐美移動通信市場，保持多年全球移動網絡設備市場份額第一。

進入 5G 時代，華為同樣將 2G、3G、4G、5G 基站融合，多模共建，基站功耗降低 50%，集成度大幅提升，由此夯實了華為 5G 通信全球領先的地位。

上圖是華為多模共建的 4G/5G 站點，華為的極簡 5G 站點，兼容了目前的 GSM/CDMA/WCDMA/EVDO/TD-LTE/FDD-LTE/NB-IOT/NR 所有制式基站。

案例二

土耳其畢爾肯大學教授埃達爾·阿勒坎（Erdal Arikan），2008 年在 IEEE 期刊上，發表了通信編碼的極化碼技術方案，引起華為專家的關注。華為在阿勒坎極化碼的基礎上開發出 5G 通信技術，極化碼作為 5G 控制信道的編碼方案，成為 5G 通信的標準，這個已為大家熟知。下圖是任正非向阿勒坎頒獎，給這位為人類通信事業作出傑出貢獻的專家致以崇高的敬意！



極化碼方案看似和通信與編碼相關，實質是數學上的線性代數運算。看上去很複雜的極化碼，實際上是一些矩陣的乘法，比如，如果要對 4 個比特的[u1 u2 u3 u4]用極化碼編碼，得到另外一個 4 比特的信號（碼字）[x1 x2 x3 x4]，等價於以下的矩陣乘法：

$$[x_1\, x_2\, x_3\, x_4] = [u_1\, u_2\, u_3\, u_4] \times \begin{bmatrix} 1\,0\,0\,0 \\ 1\,0\,1\,0 \\ 1\,1\,0\,0 \\ 1\,1\,1\,1 \end{bmatrix}$$

線性代數成就了極化碼，極化碼成就了華為在 5G 通信方面的領先優勢。

從以上兩個案例可以看出，頂尖的數學家，助力華為在無線通信領域獲得競爭優勢，不僅取得全球領先的市場份額，在標準、專利方面也持續保持領先。

在華為，不僅無線通信領域需要數學家，芯片的設計與製造中，建模、仿真、算法、AI、材料、工藝等，也需要數學家。正是因為數學家們的參與，華為海思的麒麟、鯤鵬、昇騰等各系列芯片突飛猛進。有理由相信，在外界強大壓力下，在華為數學家們和研發工程師們的不懈努力下，華為在芯片 EDA（建模/仿真）、新材料、新工藝等方面，不久將能取得突破，走出“卡脖子”的困局，估計不會太久！

華為在人工智能、大數據、雲計算、操作系統、數據庫等方面，架構、建模、算法、仿真、數據分析等等，同樣需要數學家們參與。

華為對數學的重視，不僅體現在持續不斷的引進數學人才，早在 1998 年，華為在俄羅斯成立了第一個數學研究所，2016 年又在巴黎成立了第二個數學研究所，俄羅斯和法國都是全球頂尖的數學人才薈聚的地方。

在國內，華為與眾多的數學領軍專家開展了深度的合作，例如，華為與張平文院士、徐宗本院士、李安民院士都建立了數學聯合實驗室；同時，還有與高校和研究機構有大量合作課題，如與中國科學院馬志明院士、天津大學陳永川院士合作等。

7 月底，任正非走訪滬寧四所知名高校，講得最多的是基礎理論研究，他說，基礎理論的成果象燈塔，不僅照亮我們，也照亮別人。

前兩天，華為戰略研究院院長徐文偉，在長沙的一場數學論壇上說，數學作為基礎的基礎，將決定未來發展的邊界。過去 20 多年，數學在提升華為產品競爭力方面起了極大作用。

綜上，華為的 700 多數學家，不僅體現了華為獨到的戰略眼光，也很值得，在華為的關鍵技術、關鍵工藝、關鍵材料的突破中，起中流砥柱的作用，有了他們，走出“卡脖子”困境指日可待！

附錄 1-4

華為在法國設立第 6 家研發中心 主攻數學與計算領域

2020-10-10 *由 看看新聞 發表于科技*

新華社記者 陳晨　2020-10-10 08:15

中國華為公司 9 日在法國巴黎舉行拉格朗日研發中心落成典禮，這是該公司在法國設立的第 6 家研發中心，主攻數學與計算領域。

華為公司董事、戰略研究院院長徐文偉通過視頻致辭表示，過去 30 年裏，數學在通信行業發展中發揮了關鍵作用。華為與許多數學家密切合作，共同實現了重大創新。拉格朗日研發中心是一個向全世界所有數學家開放的平台，未來這裏的研究成果將服務於整個通信行業。

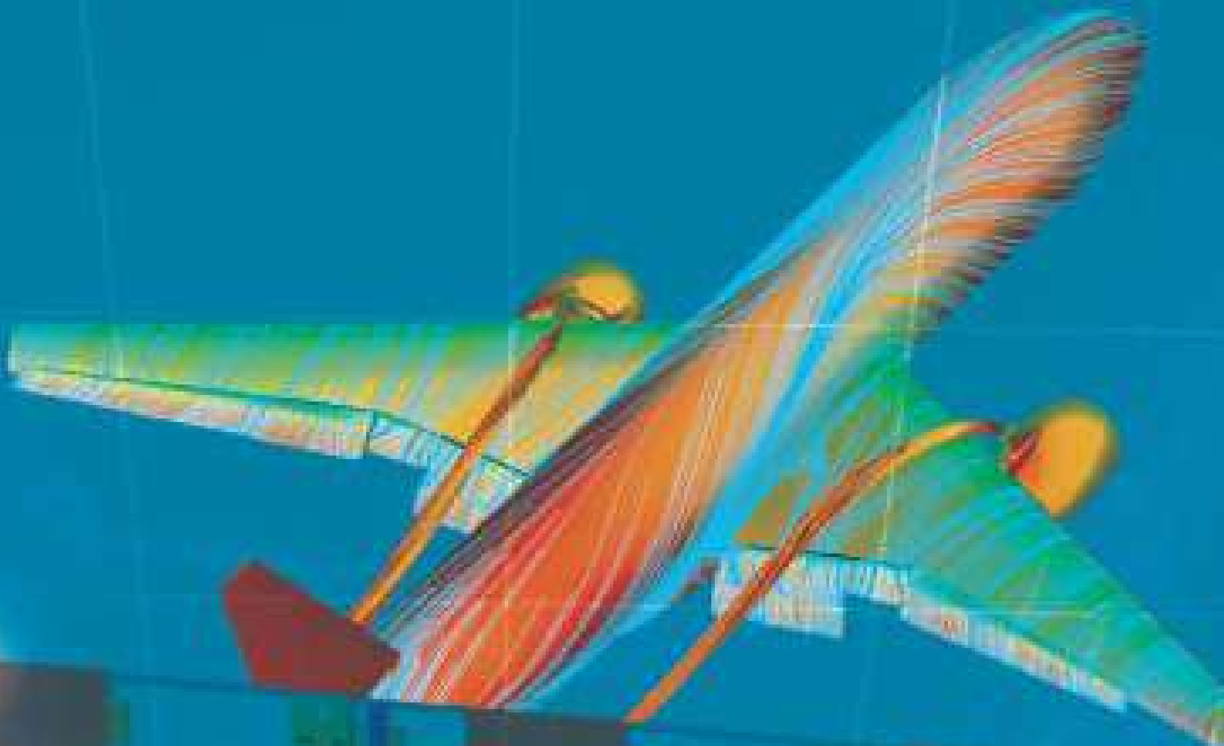
法蘭西島大區主席瓦萊麗·佩克雷斯通過視頻祝賀華為成立新的研發中心，並表示該中心有助於吸引世界上最優秀的數學天才來到法蘭西島大區。

拉格朗日研發中心負責人邁爾萬·德巴接受媒體採訪時介紹說，該中心將聚集 30 餘名科研人員，從事數學與計算領域科研工作，其目標是未來發展成一個獨立基金會，通過支持科技創新在人工智能等領域取得重大進展。

2013 年，華為在法國宣佈了一項 15 億歐元的投資計劃。此前，華為已在法國設立了晶片、數學、家庭終端、美學以及傳感器和軟件研發等領域的 5 個研發中心，其研究成果在全球範圍內得到應用。

原文位址：https://kknews.cc/zh-hk/tech/1vjo5ob.html

附錄 1-5



Mathematics in Industry

產業中的數學

Society for Industrial and Applied Mathematics
3600 Market Street, 6th Floor • Philadelphia, PA 19104-2688 USA
www.siam.org • siam@siam.org

封面圖呈現的是流過一飛機上方的氣流流體計算結果。據此設計，除了機翼末端以及機身側邊附近之外，機翼上幾乎沒有氣流分離的現象。此外，從引擎艙一路向上越過機翼的流場流線，呈現了來自「脊線」的旋流。脊線是引擎艙上的結構，特別設計用來製造與最佳化此旋流。若無脊線的設計，則如圖將引擎艙安裝在機翼前方時，不僅會降低機翼的效率，也會降低飛機的最大升力。

ISBN 978-1-611972-37-5

http://www.siam.org/reports/mii/2012/report.pdf

中文版經美國SIAM授權，由中華民國數學會與臺灣工業與應用數學學會製作發行

翻譯：立言翻譯社

翻譯與校稿：游森棚教授（國立臺灣師範大學數學系）

http://www.taiwanmathsoc.org.tw/mii%20report.pdf

目錄

執行摘要

……美國經濟重心正從製造業轉向服務業，因此數學專業人員也獲得許多企業界的就業機會，在企業營運、科學與工程等領域提供諮詢服務。

美國工業與應用數學會（Society for Industrial and Aplied Matheamtics，簡稱SIAM）於1996年發表了由美國國家科學基金會（National Science Fundation，簡稱NSF）與美國國家安全局（National Security Administration）所資助的報告《SIAM 報告：產業中的數學》）SIAM Report on Mathematics in Industry）。該報告連同隨由 NSF 所資助的一系列區域性研討會，都幫助提高了學界中的數學家對於數學在產業界中所扮演角色的意識。該報告被廣泛引用，且用以驅動針對解決產業界與政府部門問題的諸多課程與計畫。

自 1996 年迄今，產業界與政府所面臨的挑戰，不論是類型或規模，都經歷了許多了變化。舉例來說，人類基因的解碼，以及分子動力學模擬的發展，開始改變了製藥業的生態。這些改變使得擁有統計、資料探勘與模擬背景的畢業生獲得許多新的就業機會。金融業自 1996 年以來聘僱的數學家人數亦出現驚人的成長。即使 2007 到 2008 年的信用危機讓人們對「定量分析家」的觀感不佳，金融公司仍急於聘僱能同時洞識數學與金融的畢業生。再者，美國經濟重心正從製造業轉向服務業，因此數學專業人員也獲得許多企業界的就業機會，在企業營運、科學與工程等領域提供諮詢服務。

這些變化讓我們覺得現在是更新 1996 年報告的好時機，並且檢視數學是如何應用於現今的產業界。部分新科博士選擇投身產業界，我們亦想瞭解他們的經驗。因此，我們和產業界科學家進行小組聚會，對剛取得博士學位的學者進行線上調查，並與來自 23 間企業的 56 位資深科學家與經理人進行實地訪談。總計我們一共訪談或調查了來自 14 家主要產業公司的 145 位數學與計算相關的科學家。

我們最重要的結論是：不論是在傳統或嶄新產業，數學與科學計算皆有愈來愈多的應用。若干應用會對公司的盈虧造成極大幅的影響，常常數以千萬美元計。其他應用對盈虧帶來的衝擊或許無法簡單衡量，但至少能使公司在 21 世紀資訊爆炸的市場上繼續經營；還有一些應用對科學帶來了極大的貢獻與價值。我們要強調的是，技術轉移（technology transfer）── 包括數學想法的轉移 ── 並非是單向的：由公司所發展出的技術亦常可以使科學的整體更佳豐富。

本報告的核心是一組涵蓋不同應用的個案研究，領域包括商業分析與最佳化、生產設計與虛擬原型設計、定量藥物設計、金融風險分析、產品規劃與供應鏈管理、以及資訊檢索與資料探勘。我們希望這些個案研究能傳達有用的資訊並啟發廣大的讀者群：這些讀者群從包括想知道「數學到底有什麼用」的學生、想知道如何協助學生找非學術工作的學術機構，到想要將數學方法的價值傳達給經理人的產業中的數學家。我們發現產業中的數學家常覺得不夠受到學術圈同儕的尊重。我們希望報告中諸多令人印象深刻的應用能說服學界的數學家，向他們證明產業問題是多麼困難、重要又有趣。

在產業界工作的數學家以高度跨領域的形式進行團隊合作。他們對團隊的貢獻經常展現在重要的領域中。我們在 1996 年寫道：「數學是活躍、健康的有機體，只是在不同的領域裡有不同的名字。 」這句話迄今依然正確。不幸的是，這也表示一個能處理產業問題的新數學方法，卻可能難以被管理高層採納 —— 他們缺乏欣賞的能力。我們所訪談的一位數學家兼經理回憶起另一位資深經理人對某個增進生產線效率的回應。該位資深經理說：「上頭會用這五項給我評鑑，但是你的建議一點都幫不上忙。」正因為這種態度，產業界中的數學家才需要發展溝通技巧與創業能力，而這些能力對學術圈中的數學家並不那麼重要。光有好點子是不夠的，好點子必須要以管理階層能理解的語言呈現才有機會落實。

此報告也指出了業界與政府雇主，在此跨學科的環境中認為雇員所必備的技能與特性。我們的受訪者所重視的特性包括了溝通技巧、在團隊中有效合作的能力、熱忱、自主能力、完成專案的能力、以及對該行業的判斷力。

在本研究中我們亦進一步檢視了畢業生必備的技能。這些技能通常落在三項彼此重疊的領域上：數學、計算，及特定的應用領域。實用的數學能力包括數學、統計、數學建模、數值模擬等基礎課程的廣泛訓練、以及適當專長的深度訓練。電腦能力則至少要有一個或多個語言的程式設計經驗。其他特殊需求，諸如C++，MATLAB 或像 Python 這種手稿語言（scripting language ）則依公司或產業的性質有所出入。善用高效能計算（如平行計算、大規模資料探勘、可視化技術）的能力漸漸成為重要的優勢，對某些職位更是必要條件。畢業生的職涯目標與潛在雇主的要求會強烈影響業生想鑽研的應用領域。一般而言，學生需擁有足夠的知識，才能瞭解該領域的語言，並補足理論與應用之間的缺口。

報告的結論包括一系列改進研究所課程，以及連結產、官、學領域科學家機制的建議策略。有些建議針對學生，雖然多數是老調重彈，但是還是常被學生忽略。譬如，我們認為到業界實習，或在研究所期間直接與業師學習，兩者皆相當重要。其他的建議則針對系所及其業界或政府部門的合作夥伴。一些直接的建議容易實行，可在當地落實；其他建議則涉及全校、全國、或全球間的合作。

…… 產業界中的數學家才需要發展溝通技巧與創業能力，而這些能力對學術圈中的數學家並不那麼重要。光有好點子是不夠的，好點子必須要以管理階層能理解的語言呈現才有機會落實。

1 導論

在 1996 年，製造業佔美國 GDP 的15.4%，而金融、保險、科學、與科技服務加起來只佔了 12.5%。到了2010年順序已倒過來，該年製造業佔了11.7%，而金融、保險與專業科技服務則佔了 15.9%。

產業界中的數學（Mathematics in industry）是一個特別有趣的領域，它具有「雙重隱形」的特性。在學術圈中的隱形是因為只有極少數的數學家會主動解決產業中的數學問題，而產業界相關的數學文章或研究又常無法在研究期刊上發表，這常常是因為主導研究的公司不欲其研究成果曝光（有些公司鼓勵發表研究成果，但有些則否，政策相當分歧）。而從畢業生進入業界之後，原指導教授也因缺乏資訊而可能無法瞭解學生的動態，這一點和進入學界的學生有相當的不同。

在商業中的隱形則因為它經常不叫作「數學」，而是「分析（analytics）」、「建模（modeling）」、或泛稱為「研究（research）」。數學的功勞似乎被「資訊科技 （information technology）」瓜分了。事實上，功勞應歸於那些知道如何能使資訊科技大展身手的人。

當然，對於 SIAM 的會員來說，數學能為私人企業甚至為整個社會帶來巨大的改變，這並不是什麼新聞。但我們希望這份報告也能傳到非 SIAM 會員的手上，這些讀者可能從未接觸過產業界裡有關數學的研究。更重要的是，我們希望這份文件能幫助各種不同背景的讀者：不論是想要了解產業界職涯的學生、提供學生建議指導的學界數學家、鼓勵產學合作的大學行政階層、以及想要利用數學幫助公司成長的公司經理，都能從此份報告獲益。

如果讀者想要了解什麼是產業數學，我們建議您略過後續的簡介，直接閱讀第二章。該章節將介紹如何應用數學（計算與統計也算入）到八個一般的產業。您將會看到 18 個個案研究，每一個都展示了數學在產業的應用是多麼令人興奮、充滿活力、而且重要。

1.1 2011 SIAM 產業界中的數學研究：緣起

SIAM 在 1996 年發表了《SIAM報告：產業界中的數學》（SIAM Report on Mathematics in Industry）[MII 1996]。該報告與隨後一系列的區域研討會，都有助於學界認識數學家與數學在產業中的角色。該報告提供了畢業生就業機會綜覽，迄今許多數學系仍提供給學生做為就業資訊。該報告隨後被史密斯研究所（Smith Institute）、經濟合作與發展組織（Organisation for Economic Co-operation and Development）與歐洲科學基金會（European Science Foundation）引用，用於報告產業界中的數學應用（詳見[Smith 2004]、[OECD 2008] 與 [ESF 2010]。）有意思的是，此報告亦促進了業界關於數學與計算科學的需求與期待，促進了業界方案與課程的設計。

1996 年報告裡的諸多建議與洞見迄今皆仍適用。不過數學與計算機科學在產業界中的樣貌卻經歷了大幅變化。機構與公司如今蒐集的資料比以往多出好幾個數量級，面臨的挑戰是如何從這些資料中萃取出有用的資訊。計算科技持續快速發展，公司也愈來愈積極使用高效能平行計算。

另一個重要趨勢是美國經濟體從製造業轉向愈趨重要的服務業。在 1996 年，製造業佔美國 GDP 的 15.4%，而金融、保險、科學、與科技服務加起來只佔了

12.5%。到了 2010 年順序已倒過來，該年製造業佔了 11.7%，而金融、保險與專業科技服務則佔了 15.9% [BEA 2011]。

自 1996 年起，美國政府與私人基金會贊助了許多計劃，得以在產、官、學領域的科學家之間分享知識。舉例來說， NSF 成立了 GOALI （Grant Opportunities for Academic Liaison with Industry）計畫；美國能源部擴充了計算科學畢業生獎學金（Computational Science Graduate Fellowship，簡稱 CSGF）計畫與使用先進計算的科學發現（Scientific Discovery through Advanced Computing，簡稱 SciDAC）計畫；能源部也啟動了創新與新型計算對理論及實驗影響（Innovative and Novel Computational Impact on Theory and Experiment，簡稱 INCITE）計劃，此計畫提供企業超級電腦的使用機會與相關的專業知識。史隆基金會（Sloan Foundation）對發展專業碩士學位（Professional Science Master，簡稱 PSM）提供贊助，涵蓋了數學與計算科學領域。有些大學與學院已經開始打造數學與計算中心與相關課程，聚焦於實際情況的應用。

商業評論報導也展現了數學、統計與計算機科學對創新的重要性。請參閱 [Baker 2006]、[Baker 2008]、[Lohr 2009]、[Baldwin 2010]、[Cohen, N. 2010]、[Cohen, P. 2010] 與 [Hardy 2010]。在近期的信貸危機中，信用互換模型與量化模型飽受來自商業評論內外的批判（[Patterson 2010]、[Taleb 2007]、[Triana 2007]）。然而，這並沒有澆熄商業評論報導的熱情。由於企業管理階層與股東會閱讀這些文章與書籍，我們希望這些資料能讓他們接受數學與計算機科學的潛在價值。

審視自 1996 年以來的變化後， SIAM 決定更新舊版的報告，以期新版報告能反映新企業、新經濟環境與新的機會。我們也趁機納入了原報告缺乏的部分，例如一系列詳盡的個案研究，以展示數學在當今產業界的種種應用。

1.2 研究範圍與研究方法

最初，我們建立了五個小型焦點團體，受訪者為產業界中的科學家。一共有來自 9 間產業界公司的 21 位數學與計算相關的科學家參與了我們的研究。我們的目標是整理出一份廣泛的概要，呈現當今產業界中的數學應用，並為接下來的研究提出更多問題。接著，我們針對在產業界中任職的新科數學與統計博士進行線上調查。問卷調查了他們的背景、在團隊中的工作，以及學位對職業的助益。我們也請他們對在學的學生提出建議。從 2004 年 6 月至 2007 年 7 月間，一共有 550 位博士畢業生在產業界任職，此數字只計算了受僱的畢業生。我們從這 550 位博士畢業生之中取得 200 組有效的電子郵件地址。調查的回收率是 30%，與一般的線上調查相近。

最後，除了線上調查，我們還與來自 23 間不同的業界公司的 56 位資深數學或計算科學家進行了深度訪談（其中 21 位是資深經理人）。透過焦點團體、線上調查與深度訪談，我們一共募集了來自 14 間不同產業的 145 位數學家的許多寶貴意見。

與 1996 年的報告相比，這份報告在範圍上有四個很大的不同點。首先，關於統計專業，我們納入了從統計系畢業的博士，而前一份研究只納入在數學暨統計系取得學位者。第二，我們沒有調查這些畢業生的直屬上司，這也與 1996 年的不同。不過，在深度訪談與實地訪查時，我們對資深經理人提出的問題與 1996 年相同。第三，我們的訪談與實地訪查並不只針對數學家與統計學家，也包括了在任何系所獲得博士學位的數學與計算科學家。最後，此報告中沒有訪談或調查碩士畢業生。SIAM 受史隆基金會的贊助已於 2002 年對應用數學碩士課程進行調查 [Crowley 與 Seitelman 2003]，因此我們認為沒有必要再重複。

但在這份報告中，我們討論了專業碩士（Professional Science Master，PSM）學位的興起與發展。SIAM曾參與孕育 PSM 的早期階段：SIAM 教育委員會曾為主修應用與產業數學的專業碩士學位制訂方針，[《SIAM Guidelines》1998]，並以 1996 年的產業界中的數學報告 [MII 1996] 為參考資料。

最後值得一提的是，本報告第二章中大部份的個案研究皆由實地訪談衍生。每個個案的訪談資訊皆輔以可公開取得的已發表文章與公司新聞稿佐證。 18 份個案研究中，有 6 份的公司我們並沒有直接接觸，這幾個個案的資料完全取自已發表文章以及公司新聞稿。

2 數學的角色

趨勢與個案研究

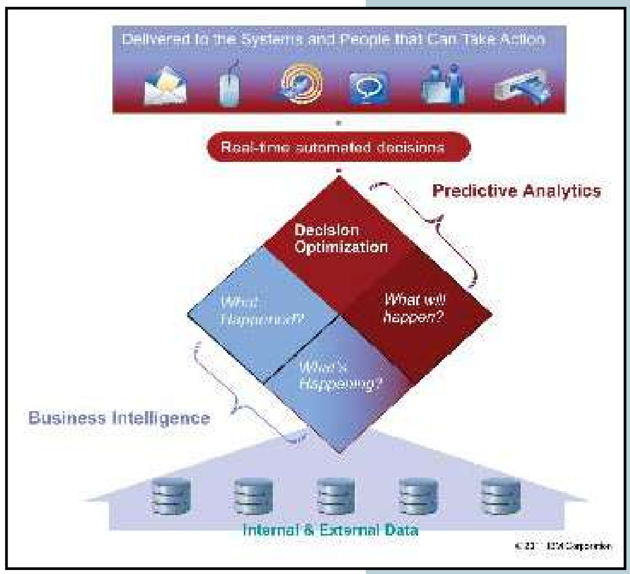
在本章中，我們給出一個廣泛但不盡全面的，關於數學商業應用的綜覽。對於想要認識數學怎麼在「真實世界」應用的學生，我們希望以下 18 份個案研究可以提供一些答案。多數的個案都是實地訪查後才得知的，輔以已出版的文件作參考。

2.1 商業分析

軟體產業正在進行一個龐大的賭注...他們認為資料導向決策是未來的趨勢。協助企業在資料中找尋有意義的資訊，則成為在軟體與服務業中所謂「商業智慧」或「商業分析」的一個快速成長的產業。科技大廠–IBM、Oracle、SAP與Microsoft–共花費了超過250億美金併購此領域的專業公司。[Lohr 2011-a]

「商業分析」已成為無所不包的新詞，包含許多應用數學中生根已久的領域，像是作業研究與管理科學等等。但這個詞彙同時也有新的含義：對企業主管而言，巨大資料庫的應用愈來愈加可行。

至少從 1950 年代開始，數學就一直應用在物流、倉儲與設施位置選擇上。美國空軍與美國海軍研究辦公室的物流規劃採用了 George Dantzig、William Karush、Harold Kuhn 與 Albert Tucker 早年針對最佳化的所進行的研究結果。諸如線性規劃及其變形等最佳化技術，直到今日仍對業界至關重要。



業務過程中的自動化決策，IBM提供

對於想要進入產業的企業及學生而言，機會就在於發展低成本的演算法與相關技術，使其能處理大量結構化或非結構化的資料。因為企業正在各個層面採納其商業情報（即資料）與分析結果（即量化方法），包括行銷、人力資源、金融、供應鏈管理、設施位置選擇、風險管理和產品與流程設計等等。

個案研究 1：預測分析學

IBM 在 2009 與 2010 年協助紐約州稅務廳（New York State Division of Taxation and Finance，簡稱 DTF）安裝一組全新的預測分析系統，該系統源於 IBM 極成功的西洋棋軟體「深藍」，以及電視節目 《危險邊緣！》（譯註： Jeopardy! 機智問答節目）裡使用的遊戲引擎「Watson」。這套系統稱為「稅捐稽徵最佳化解決方案」（Tax Collection Optimization Solution，簡稱 TACOS），可用來蒐集各種資料，包含國稅局的各種動作（如撥打電話、探訪、追繳欠稅令、徵稅、資產扣押）及納稅人的回應（如付清稅款、申訴、宣告破產）。在實務上這

些動作有時受制於有限的人力，或預算不足以架設電話客服中心等。TACOS 中的模型涵蓋這些活動間的相依性，能預測各種收稅策略可能造成的結果，像是通話與探訪的時間點等。模型採用的數學方法稱作馬可夫決策過程，該流程會將每個納稅人賦予一個狀態，並預測在此狀態之下進行某個動作能獲得什麼報酬。依據這個過程得出的計畫或策略可最大化來自整個納稅族群預期收益，而非僅最大化來自單一納稅人的收益。

DTF 系統使 TACOS 在 2009 與 2010 年的收益增加了 8300 萬美金（增加了 8%），但支出卻沒有增加。其中，每封追繳欠稅令（或稅務扣押權）所追回的美金增加了 22%，每一份扣押信函追回的美金增加了 11%，案件分派到各地辦公室所需的時間也減少了 9.3% [Apte 2011]。縱使細節或許不同， 但其他企業顯然也可以使用類似的方法處理收款與帳款。

個案研究 2：影像分析與資料探勘

SAIC這間公司主要發展軍事目的的情報、監視與偵查（intelligence,surveillance，and reconnaissance，簡稱 ISR）系統。軍方在阿富汗戰爭裡大量佈署這些自動系統：在 2009 年，無人航空載具（unmanned aerial vehicle，UAV）拍攝了整整 24 年份量的全動態影像。軍方預計這些載具在 2011 年會拍攝 30 倍份量的影像。

這時便產生了一個大問題：影像要如何整理才能變成有用的資料？軍方當然不可能讓數千名士兵守在電腦螢幕前看數十年份的影像。即使真這麼做，人工不僅容易犯錯也容易疲勞。連續監看數小時的影像很可能遺漏掉問題真正發生的關鍵片段 —— 比如，涉及之前炸彈事件的轎車停在某間屋子前。

SAIC 研發的「後設資料」系統稱為 AIMES 。這系統會向人們指出資料堆中的疑點。首先， AIMES 處理影像，補償並修正 UAV 因移動而造成的影像偏差，光是這點就是有趣的數學挑戰。接著， AIMES 會搜尋影像視野中的物體，並存入可搜尋的資料庫。 AIMES 也會「融合」影像資料與其他類型資料。例如，若 UAV 的操作者說：「把畫面拉近那輛卡車！」。程式就會知道視野中的物體是一輛卡車，且該物體可能十分重要。再者， AIMES 方便攜帶佈署在戰場上：只需要一個伺服器與二到三台螢幕即可使用。可參閱 [《SAIC AIMES》2010]。

即便位居美國本土的產業不需如此顧慮恐怖分子或路邊炸彈，但影音監視仍是保護廠房或其他建築安全不可或缺的設備。相機加麥克風的組合還能用於其他用途: 比如，麥克風能比操作者先知道機器的異常，監視設備能讓首批抵達人員找到火警或意外中的受害者。請參閱 [《SAIC Superhero Hearing》2010]。

個案研究 3：作業研究

美國第七大的水泥公司維吉尼亞水泥（Virginia Concrete），自 2002 年起運用

最佳化軟體，為駕駛安排運送順序。該公司擁有 120 輛卡車，供 10 座水泥廠使用。一個很大的限制是水泥在卡車裡大約兩小時就會乾掉，因此得在兩小時之內運送。而且，營造業非常不可預測，常常在一天之內有 95% 的訂單臨時改變。

維吉尼亞水泥從喬治梅森大學（Goerge Mason University）與決定性分析公司（Decisive Analytics Corporation）引進一群數學家研發可自動派車的工具。數學家發現，在舊的模型裡，每一台卡車會被指派至一個「主要」水泥廠。若捨棄此模型，便能大幅減少水泥運送時間。數學家因此建議卡車應該前往最近的水泥廠。至於跨夜排程，虛擬卡車的概念很有幫助：虛擬卡車代表可能被取消的訂單，而沒被取消的訂單則可重新指派至實體卡車。

為了測試，維吉尼亞水泥用此軟體做所有的排程決策，然而派車人員仍擁有變更電腦決策的權限。結果是該系統讓維吉尼亞水泥每一位駕駛所運送的水泥量增加了 26%。[Cipra 2004]

2.2 金融數學

……市場可能越來越不重視特殊的金融衍生品（exotic derivative），更多的交易將發生在匯兌上。

未來的模型都應呈現符合觀察結果的真實動態，執行成本控管也至關重要。要順利控管，深入了解市場的微結構與交易資料是不可或缺的。[摘自訪談]

2007 與 2008 年的信用危機重挫了人們對金融量化方法的信心，多數專家將此解釋為量化模型無法正確權勢市場資料的依存關係。風險模型假設兩地（比如邁阿密和洛杉磯）的房地產違約互不相關，或相關性很低；但實際上當恐慌發生時，所有事情之間的相關係數都變成 1 了（意即完全正相關）。

然而，經此危機震撼以及隨後的經濟衰退，金融經理人也學到了很有價值的一課。他們學到了數學模型不是可以隨便套用，而必須嚴肅地檢視模型背後的假設。若干簡化模型的失敗並不代表數學模型都是糟糕的，而是模型必須要更加貼近現實。最重要的是，學生要了解金融產業不需捨棄量化研究。數學家與應用數學家的需求仍高居不下。隨著量化模型越來越複雜、以及經理人想知道這些模型的極限，數學家的專業只會越來越受到重視。只是，相較於以往，學生的數學技能應該要建立在更廣博的金融產業知識之上。

個案研究 4：算法交易（自動化交易）

在 2009 年， 克利斯丁· 霍夫 （ Christian Hauff ） 與羅伯 · 艾姆葛連 （ Robert Almgren ） 離開了美國銀行（Bank of America）這家世界頂尖的股票與衍生物算法交易公司，創立了一家叫做量化經紀人（Quantitative

未來的模型都應呈現符合觀察結果的真實動態，執行成本控管也至關重要。要順利控管，深入了解市場的微結構與交易資料是不可或缺的。

量化經紀人的 STROBE 演算法能找出一路線以最佳化客戶的效用函數。該演算法並能生成最佳值附近的一個包絡以概括出可接受的偏差範圍。

Brokers）的公司。他們發現了一個難得的良機，打算將高頻交易的相同原則應用在尚未高度自動化的一類資產：利率期貨。

自動化交易在選擇權市場早已司空見慣。部份原因是金融數學迫切需要自動化交易這項工具。大銀行想要以風險中立的方式擁有資產：無論市場怎麼變化，都能讓銀行賺錢（或至少避免虧損）。1970 年代早期，麥倫·休斯（Myron Scholes）與費雪·布萊克（Fischer Black）發現了動態避險（dynamic hedging）策略而能達成風險中立。此策略需要持續進行小規模交易。

布萊克與休斯考量的重點是選擇權定價。又過了二十年，金融工程師才開始將執行交易的過程納入考量。不貿然進行全盤交易有許多原因：你也許想等等看是否有人願意出比較好的價錢，或者等到市場價格接近你的目標價之後再出手。如果你交易的資產在市場的當日交易佔了重要比例，你或許會審慎進行，以免過度影響市場價格。

量化經紀人這間公司的主要業務是執行交易。該公司運用電腦演算法，為客戶規劃策略路徑，從交易一開始的狀況導向客戶所期望的形勢（例如以低於 Y 價格購入 X 股的歐元期貨）。每一位客戶都有一定程度的風險規避，因此，客戶的效用函數是期望獲利與期望風險的線性組合。而量化經紀人的 STROBE 演算法能找出一路線以最佳化客戶的效用函數。該演算法並能生成最佳值附近的一個包絡以概括出可接受的偏差範圍。用到的數學工具包括微分方程以及變分學。請參閱 [《Anatomy of an Algo》2011]。

2.3 系統生物學

製藥研究者嘗試了許多先機與科技以應對研發藥品逐漸攀升的費用。生物標記、適應性試驗設計、建模、試驗模擬、預測性新陳代謝、資料探勘與疾病模型等等都重塑了研發的方式。量化製藥學在以模型為基的製藥學中發揮重要作用，並且無論在文化與技術層面，都結合了資料與科學原理...... [Allerheiligen 2010]

在 2000 年完成的人類基因組計劃應該引領我們進入一個發展個人化醫療與標靶藥物的新紀元。但是我們最終發現，只有少數不尋常的疾病或其變種直接源於獨立的幾個基因突變。多數常見的疾病，像是糖尿病以及癌症（藥品研究的頭號目標），都肇因於複雜基因網路的機能失常。修復單一基因就能治好這類疾病的想法變得有點天真，就像以為更換一顆螺絲能修好引擎一樣。醫生實際上需要以特定的劑量、在特定的時間、於基因網路裡特定的地點實施一連串的介入治療，才有可能治療這些疾病。隨著其複雜度愈加明顯，分析基因網路的數學方法就變得更重要。

若干生物科技的研究重點已經從基因體學（genomics）轉到「體學（omics）」，像是蛋白質體學，主要研究藥物所標靶的蛋白質其形狀與摺疊方式。分子動力學模擬則從最根本的層級著手，利用量子力學的原理進行研究。近幾年，演算法、

軟硬體的發展讓一毫秒內就能模擬數以千萬計的個原子組成分子，而一毫秒正是許多重要生物現象發生的時間尺度。

其他數學模型則反其道而行，分析整個有機體。譬如說，這樣的模型可用來預測病人族群（其中的病人生理機能各自不同）會在不同的公衛介入下有何反應。

最終，病人組模型可能與基因組資料結合，為病人提供真正的個人化醫療服務。這些模型背後的功臣是數學與計算科技，包括網路科學、確定性與隨機微分方程、貝氏網路與隱式馬爾可夫模型、最佳化、統計、控制、模擬以及不確定性量化分析等。

近幾年，演算法、軟硬體的發展讓一毫秒內就能模擬數以千萬計的個原子組成分子，而一毫秒正是許多重要生物現象發生的時間尺度。

個案研究 5：分子動力學

大衛·蕭（ David Shaw ） 是位電腦科學家。先前他是某避險基金的執行長，一向以電腦執行交易策略。在 2001 年，他建立了一間全新的私人研究實驗室，專注於解決蛋白質摺疊相關問題。蕭的實驗室量身訂作了一台名為 Anton 的超級電腦，配備了512顆晶片，用來加速計算原子間的交互作用。然而，即使有如此強大的硬體，卻仍然無法在合理時間內對蛋白質分子完成暴力的模擬計算。另一個關鍵是蕭實驗室裡的分子動力學軟體，此軟體稱為 Desmond，使用明斷近似法（judicious approximation）簡化力場的計算過程，同時也運用新平行演算法來減少 Anton 處理器之間的通訊量。

一開始沒人知道 Anton 會比其他方法來的有效。比如說，將計算問題分割，並分配至不同電腦的演算法（這是美國史丹佛大學 Folding@Home 計畫採取的方法）。然而在 2010 年，D. E. Shaw Research（簡稱DESRES）宣布，他們已經完成了週期為 100 微秒的 FiP35 蛋白質摺疊與展開模擬。FiP35 有 13,564 個原子。與以前的程式相比，此模擬涵蓋的時間長了十倍，模擬程式約花了三個星期進行運算。

選擇了 FiP35 是因為以往的實驗已經對該蛋白質摺疊和展開時的結構有相當的理解。即使如此，此模擬仍然為我們帶來嶄新的科學洞見：每一次從摺疊到展開的途徑基本上是相同的。科學（Science）雜誌將蕭的模擬成果列為所有領域裡的年度十大科學突破。相關模擬可能在未來開啟新一波的藥物與蛋白質交互作用研究。這種交互作用發生得太快，讓科學家無法在傳統實驗室裡進行研究。請參閱 [D’Azevedo 2008]。

個案研究 6：全病人模型（Whole-patient model）

在 2020 年之前，虛擬細胞、器官與動物都會廣泛應用在製藥研究中。

- PricewaterhouseCoopers，Pharma 2020：虛擬 R&D

Entelos 與 Archimedes 這兩家位於舊金山灣的公司是全身電腦建模領域的先

驅。雖然兩家公司離完成人體生理的完整模擬還很遠，但至少已經成功模擬了主要的子系統，像是心血管系統以及與糖尿病相關的新陳代謝網路。

Entelos 的 PhysioLab 模型以及 Archimedes 的模型能預測臨床藥物的不良反應與結果。顯而易見的，藥廠就可以在投入臨床試驗之前先篩掉無效或有害的化合物，從而省下大量的時間和金錢。除此之外，模擬能探索多重藥物療法的效果，而這些效果極難透過臨床實驗測得。20 種不同的藥物組合可能需要 20 個不同的臨床試驗，但模擬實驗可以快速鎖定出最可能有效的特定組合。

Entelos 與 Archimedes 使用的數學與計算機科學包括了非線性動力學、控制理論、微分方程與物件導向程式設計等等。

舉例來說，Archimedes 曾受某健康維護組織（health maintenance organization，簡稱 HMO）委託，評估一種針對糖尿病與心臟病患者，稱為 A-L-L（aspirin，lovastatin，lisonopril）的新預防性療法之效果。根據 Archimedes 模型的預測，該組合療法應能降低目標族群 71% 的心臟病發作與中風機率。此模型隨後在臨床研究獲得證實：心臟病發作與中風機率降低了 60%。從而 HMO 建議組織中的醫師，只要病人符合標準，都可採取這種新療法。

Entelos 與 Archimedes 使用的數學與計算機科學包括了非線性動力學、控制理論、微分方程與物件導向程式設計等等。

請參閱 [《Virtual Patients》2010] 和 [《The Archimedes Model》2010]。

2.4 石油探勘與開採

對石油開採業來說，這是一個充滿風險與機會的時代。即使全世界都關注氣候變遷與致力減少碳足跡，至少在可預見的將來我們仍得依賴石油與天然氣。對「石油產量頂峰」的憂慮至今未減，但主因可能是我們低估了石油工業創新和研發非傳統石油來源的能力。

諸如把二氧化碳注入地面之類的進階生產技術，能從現有油井取得更多石油，也能隔離原先會洩漏到空氣中的碳。以往我們認為重油堆積物的萃取研發太過昂貴（如艾伯塔的瀝青沙和科羅拉多州與懷俄明州的油頁岩），但隨著石油價格飆升，相關的研發也變得越來越有吸引力。深海鑽井亦已受到重視，但也存在許多新的風險，像是英國石油（BP） 2010 年在墨西哥灣的漏油事件。

隨著石油探勘的難度與開採成本越來越高，數學演算法模擬對企業就變得更加重要。震測逆算（用地震軌跡定位地下岩層）一直以來都是石油探勘的重要工具。演算法與電腦軟

硬體的演進讓三維、甚至四維的模擬不再遙不可及。大規模的流域模型（basin model）可幫助公司決定某塊岩層適不適合鑽井。小規模的油藏模型能用於已開採區塊，預測該區塊的石油流動、研擬最佳開採率的策略，以及預測像是地質斷層因為油藏岩塊的壓力改變而重新活動等問題。

在設施正式開採之前，動態模擬能讓石油公司分析並將意外風險降至最低。但 BP 的漏油事件讓大家了解更有效的風險分析與建模是必要的。顯然，我們需要更快的、可針對即時資訊分析的模型，以便當突發狀況發生時能快速監控油井與評估意外損失。

個案研究 7：流域建模（basin modeling）

必須要在非常特別的地質條件的許可下才能孕育出石油。首先要有油源岩（含有有機質的沈積岩）、讓石油流往的儲油岩（通常不會是油源岩）、能困住石油不讓其漏出地表的圈閉岩（不透水岩層），以及迫使油源岩深入地底的覆蓋岩層, 使高溫高壓得以「煮熟」有機質並生成石油。即使這四種岩層都齊備了，還是有可能沒有石油，因為時機也很重要。如果圈閉岩層太晚形成，石油可能早就漏光了。

流域模型能用基本物理原理模擬石油形成的所有步驟。例如 Schlumberger 的 PetroMod 軟體會從每一層岩層的年齡與性質的資料開始，然後基於地層年代來計算每一層的壓力與溫度，建立起探討影響岩石多孔性、密度與其他特性的模型。這些資訊可送回另一個化學模型，該模型能模擬原油生成，以及原油如何裂解為不同分子量的氣體與石油。流體流動模型除了能追蹤烴類的移動，也會考慮烴是液態或氣態、岩石的透水性、與是否有斷層等資訊。模型的計算結果會與試驗鑽孔的測量結果比較，以驗證結果的正確性。多數情況下，模擬會以不同的參數進行多次試驗，才能確認資料中不確定的部分可能造成的結果。

總而言之，流域模型橫跨了許多領域，包括流體流動、熱傳導、化學動力學、地質學、微分方程、隨機分析，以及地球上最強大超級電腦的計算結果等等。流域模型可以攸關數十億美金的收益或虧損。

在此我們提供兩個例子，說明流域模型的優點以及不用流域模型時對石油開採的影響。首先，阿拉斯加普拉德霍灣（Prudhoe Bay）的油田附近有個稱為 Mukluk 的可能油田。石油公司在 1980 年代早期砸下 15 億美金買下 Mukluk 的租賃權，被稱作「歷史上最昂貴的枯井」。雖然 Mukluk 的地質結構與普拉德霍灣非常相似，但可能是時間次序不對，也可能是圈閉岩沒產生效用，該處根本找不到石油。第二個例子比較正面。Mobil 與 Unocal 向印尼買下了一塊深海區域的開發權，這塊區域叫做望加錫海峽（Makassar Straits）。依照以往的經驗，人們咸信這是一塊不適合開採的區域，因為該處的油源岩已經「過熟」了。但是 Mobil 的

…… 流域模型橫跨了許多領域，包括流體流動、熱傳導、化學動力學、地質學、微分方程、隨機分析，以及地球上最強大超級電腦的計算結果等等。

電腦模型卻指出該處的油源岩仍持續生成石油。1998 年的試掘井證明電腦模型是正確的，Unocal 也於 2003 年開始在該處生產石油。這是印尼第一座深海油田，尖峰產量約為一天 20,000 桶。請參閱 [Al-Hajeri 2009]。

2.5 製造業

應用數學一直是製造業中不可或缺的一環，並以不同面貌出現：原型設計、設計最佳化、生產與庫存規劃，以及供應鏈管理等。

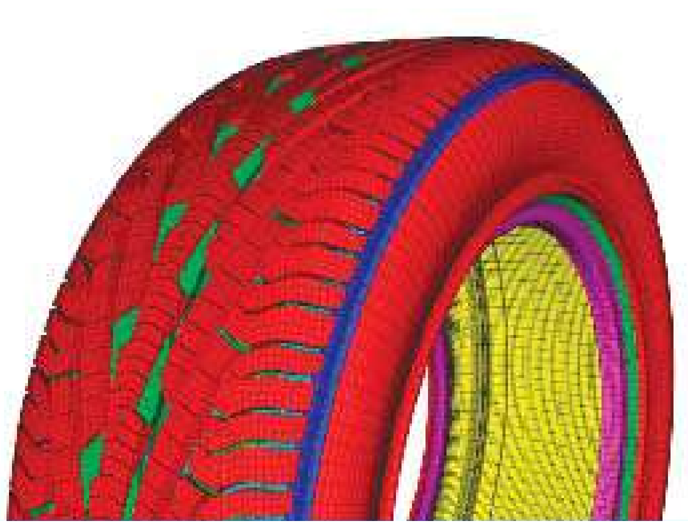
跨領域設計最佳化 (multidisciplinary design optimization，簡稱 MDO) 提供程序與分析計算工具，能讓來自不同領域的設計團隊協調合作。舉例來說，以模擬設計為基礎的航太與汽車複雜系統設計非常仰賴電腦分析 (包括計算流體力學與有限元素分析) 。電腦輔助設計 (computer-aided design，簡稱 CAD) 產業如今依舊面臨的主要挑戰之一是需將設計、分析、驗證統整為一套無縫流程。但往往設計工程師與驗證工程師使用的演算法、軟體、檔案類型都不同，使得轉換 CAD 檔案格式時會產生瓶頸。等幾何分析 (isogeometric analysis) 是一個有希望的新技術，用來創造可直接套入物理微分方程的 3D 虛擬模型。

生產規劃的目的是建立能善用資本來源，也盡可能滿足需求的排程。生產排程需考慮資源的彈性、供應鏈中供需的隨機性、新產品發表時機以及生產設施的改善等等。對於擁有複雜產品與生產流程的產業而言，規劃流程不適合仰仗直覺或人工決斷。真正需要的，是更好的決策演算法、更好的資料管理，以及自動化與整合的流程規劃。

應用數學一直是製造業中不可或缺的一環，並以不同面貌出現：原型設計、設計最佳化、生產與庫存規劃，以及供應鏈管理等。

個案研究 8：虛擬原型設計

固特異 (Goodyear Tire & Rubber) 在 1992 年耗時好幾個月用電腦進行有限元素分析以預測產品設計與效能。雖然輪胎從外觀看來是簡單的東西，但事實上輪胎的幾何構成非常複雜。每一條輪胎都混入超過 18 種不同的原料，每一種都由不同的材料製成，諸如橡膠、聚酯纖維、鋼鐵與尼龍等。橡



固特異採用了桑迪亞所研發的幾何形狀和嚙合技術以改善其輪胎性能。

膠在工程學裡可是非常複雜的材料。固特異的四季通用胎設計一直是他們的競爭優勢，因此，必須考慮各種駕駛情況以評估輪胎效能。

即使固特異自己擁有超級電腦，他們卻也認清他們建立的模型連超級電腦都完全無法處理。因此，固特異於 1994 年與桑迪亞國家實驗室（Sandia National Laboratories）簽署了一紙協同研究與發展協議（Cooperative Research and Development Agreement，簡稱 CRADA），讓固特異能享用桑迪亞的物理建模與模擬等專業資源。固特異與桑迪亞利用了接下來的十年發展出一套新軟體，能精簡複雜模型的求解時間。因而固特異首度能在道路實測之前先進行電腦模擬。此協同研發案孕育出的「創新引擎」可將研發時間從三年縮減至一年，製作原型的成本也減少了 62%。

對固特異來說，這次合作最大的收益是多項獲獎無數的新產品，像是結合 TripleTred 科技的 Assurance 輪胎。此種輪胎包含不同的區塊，讓車輛無論在潮濕、結冰或乾地上都能抓地。TripleTred 科技更贏得了 R&D 雜誌的 R&D 100 大獎。請參閱 [《A New Approach》2005] 與 [Sandia 2009]。

……在實驗室裡無法完成這樣的研究：製造泡沫的自我組合結構尺寸過小，無法使用顯微鏡觀察。為了看到發泡過程，P&G 轉而使用電腦分子動力學模擬。

個案研究 9：分子動力學

分子動力學不只是用在生物科技或製藥研究。寶僑（Procter and Gamble，簡稱 P&G）與許多公司一樣，受到市場壓力的影響，必須將產品中的石油原料更換為所謂的「綠色」原料。但同時，公司也不想犧牲顧客期待的產品成效。舉例來說，顧客在乎的洗碗精特性，像是濃稠度、手感、起泡與除汙能力、以及保存期間內成分的分離程度。為了研發出所需特性的新化合物，就得對表面活化劑與聚合物進行分子層級的基本研究。不幸的在實驗室裡無法完成這樣的研究：製造泡沫的自我組合結構尺寸過小，無法使用顯微鏡觀察。為了看到發泡過程， P&G 轉而使用電腦分子動力學模擬。

然而， P&G 的超級電腦早就被其他研究計畫與例行工作預約了。研究團隊最多只能模擬數千個原子，而不是實際上所需的數十億個原子。於是 P&G 透過美國能源部的 INCITE 計畫，向亞崗國家實驗室（Argonne National Laboratory）申請使用高效能電腦。 P&G 科學家與賓州大學（University of Pennsylvania）的研究人員合作，將模擬時間從數月減少到數小時，也成功改善了公司產品的配方。往後， P&G 還期望運用分子動力學模擬建立全新的「設計師」分子。請參閱 [《Procter and Gamble’s Story》2009]。

波音787首航結束時的降落畫面。機翼彈性程度由此圖可見一斑。

個案研究 10：跨領域設計最佳化與 CAD

波音 787「Dreamliner」在 2011 年 10 月展開了由東京飛至香港的商業首航。為了因應日漸高漲的航空燃油價格，787是第一台主要以複合材料（碳纖強化塑膠）、而非鋁金屬打造的商用客機。這種材料的單位重量能承受的強度較鋁為高，故能打造更輕的飛機，耗油量也比尺寸類似的飛機少 20% 。另外， 787 的窗戶較大，並可承受更高的艙壓，因此能提供較舒適的環境以減輕旅客時差的不適。

設計一台塑膠飛機涉及許多工程上的挑戰。比如， 787 的機翼會在飛行中向上彎曲三公尺。傳統的剛體模型雖然能正確呈現工廠裡或地面上的機翼形狀，卻無法正確呈現飛行中的機翼形狀。對航太工程師或結構工程師而言，這根本是兩種完全不同的機翼 —— 但是兩工程師都要用相同的電腦模型來工作。因此電腦必須要「知道」飛行中的機翼會如何彎曲。

整架飛機的設計都是在電腦上完成的；完全沒有畫板，也沒有實體原型機。要由 40 多個承包商製造的超過 10,000 個零件，都是在相同的虛擬環境中設計而成。承包商不只負責製造，他們其實都是設計團隊的一份子。該虛擬環境還能實現「直接設計」。如果顧客（航空公司）需要某個特別的式樣，比如說不同的門把或不同的地板，工程師直接在電腦上作圖後就可以製造了。每一個東西都視為等值的裝配線年代已經一去不復返了。

如今，設計流程所使用的數學工具包括了計算線性代數、微分方程、作業研究、計算幾何學、最佳化、最佳控制、資料管理與各種統計方法。請參閱 [Grandine 2009] 與 [Stackpole 2007]。

個案研究 11：機器人科學

業界在乎的不只是產品最後是否符合標準，製造的過程也至關重要。美國馬里蘭州洛克維爾的自動精密工程公司（Automated Precision Inc.，簡稱 API）最近引進了最新科技，結合了雷射追跡與多項式運動方程式以改進工具機的準確性。一般而言，機器人工具機有能進行三軸旋轉的手臂。手臂的每個關節都是分開控制的，因此三個不同的座標系統的誤差一累積起來，誤差參數可達到 21 個之多。在 API 的空間誤差補償（Volumetric Error Compensation，簡稱VEC）系統裡只有一個座標系統，誤差參數也只有 6 個。

VEC 軟體運用了基於切比雪夫多項式（Chebyshev polynomials）的演算法，可以計算出任何座標系統內的正確工具軌跡。

根據 API 的一位航太產業客戶所述， VEC 幫他們將工具機的校正時間從「一周每天輪班 12 到 14 小時縮減為一班 8 小時」。另一位客戶估計，此流程一年能省下一億元美金的裝配成本。因此， R&D 雜誌將 VEC 選為 2010 年度的前一百大科技突破。請參閱 [《Precision Machining》 2010]。

個案研究 12：供應鏈管理（生物科技產業）

設計製造之後還需要上市。這看來基本的一步卻可能異常複雜。Dow AgroSciences 的自動化供應鏈管理案例便相當有啟發性。這家國際公司製作殺蟲劑與其他生物科技產品，而殺蟲劑市場限制重重，且稅金奇高無比，商品運送到不同國家也會嚴重影響應付的關稅，有些國家甚至不允許從某些國家進口特定化學藥品。因此，產品的每一項原料來源都必須追蹤紀錄。

起初，Dow 嘗試找了一家外部供應商將供應鏈自動化，但因企業特性過於獨特，最終只能從內部對供應鏈建模。此模型將生產鏈表示為有向圖或網路，圖上的箭頭代表從供應商到工廠到其他工廠，再到顧客的可能路徑。決策變數包括庫存、售出、製造量；參數包括稅率、運輸與材料成本。此網路總共涵蓋了 6 個供應商、36 座工廠與超過 100 位顧客（一個國家算作一位顧客）。解出混和整數線性規劃問題後，就能得出對每個產品最具成本效益的路線。

實際上，求解遠比上述幾個數字的寥寥說明困難，因為每一條通過網路的路徑都需要不同的決策變數集合。 2,100 條路徑與 350 個最終產品讓這道線性規劃問題有 750,000 個變數，以及 50 萬個方程式。即便如此，一個四核心的電腦工作站在兩小時內就可以為單一情境求出利益最大化的解了。請參閱 [Bassett 與 Gardner 2010]。

個案研究 13：供應鏈管理（汽車產業）

福特汽車（Ford Motor Company）在 2006 年幾近面臨「恐怖的供應鏈失效」問題。福特主要的零件供應商 Automotive Component Holdings（ACH）雖為福特所擁有，獨立營運但卻不斷虧損。 ACH 並沒有充分利用位於密西根州 Saline 與 Utica 的廠房來生產零件。公司立即面對重要的決策問題，是否要關閉兩座廠房然後將所有產品都外包（包括更換大部分生產機械的地點）；或是將兩座廠房合併，或是採取外包合併混用的綜合策略。

福特的管理階層很快就意識到，眼前需要評估的可能性涉及要怎麼在超過 50 座潛在廠址、 26 套生產流程之中處置超過 40 條生產線，這遠遠超過「傳統商業分析」的能力。福特的研究部門花費兩個多月，建立了一套適用於各種生產階段的

美國馬里蘭州洛克維爾的自動精密工程公司（Automated Precision Inc. 簡稱API）最近引進了最新科技，結合了雷射追跡與多項式運動方程式以改進工具機的準確性。

研究人員想出了聰明的替代方案。他們將大模組切割為設施產能模型與設施利用率模型，這兩個都是線性的。研究人員以疊代法將解答在兩個模型間來回傳遞，最後成功收斂到兩模型的最佳解。

限制與成本模型。不過，該模型有 359,385 個變數與 1,662,554 個限制條件。更糟糕的是他們要處理的問題是非線性的（主要是因為產能利用率的緣故）。這麼大的問題，如果是整數線性規劃問題還有可能解（請與個案研究 12 比較），但非線性規劃通常是無法解的。

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這些解是權衡了無數情況所得的結果，成為經營上極關鍵的工具。與福特原先偏好的完全外包策略相比，該模型找出的混合策略為福特省下了 4,000 萬美金。最後，該模型產出的 42 個採購決策中，福特資深經營階層採納了 39 個。 Saline 廠房將繼續營運並不斷改組以提升效能，直到福特找到適合的買家。請參考 [Klampfl 2009]。

2.6 通訊與運輸

長久以來，數學一直大量用在通訊與運輸產業。作業研究最早的應用就是供應網排程，直至今日還是如此。網路流量和程式碼的演算法使手機能共享頻寬，對網路商業與無線通訊的成功有關鍵的貢獻。

專案研究 14：物流業

如果要說哪個公司就是「物流」的代名詞，那就是 United Parcel Service（簡稱 UPS）了，這要歸功於大量的廣告。UPS 現在是世界上第九大航空公司，不載客，只運貨。為了善用機上空間以便聖誕節包裹能在時限內送達，UPS 求助電腦演算法與作業研究協助就不意外了。

事實上，UPS 使用三類不同的軟體：姑且稱為短期、中期、長期規劃。長期規劃軟體能預測未來十年的送貨量，也能為併購新公司做出決策；中期最佳化用來計畫路線；而稱為負載規畫助手（Load Planning Assistant, LPA）的短期最佳化工具，能協助集貨站在兩周前提早規劃作業流程。另外，名為 VOLCANO 的全系統工具策畫隔天的航線網流程，將目前包裹量與可用飛機的數量配對，並能將飛機容量與機場限制等因素納入考慮。 LPA 與 VOLCANO 分別是美國普林斯頓大學

（Princeton University）與麻省理工學院（MIT）學者群共同研發的成果。

UPS 利用作業研究已經 50 多年了，因此我們很難判斷這幫他們省下了多少錢。不過可以確信的是， UPS 的聲望與作業研究密不可分。請參閱 [《Analytics at UPS》 2011]。

個案研究 15：雲端運算

卡崔娜颶風於 2005 年襲擊紐奧良時，美國紅十字會的網站流量瞬間增加了 14 倍。網站整個當機，想提供緊急捐助的善心人士不得其門而入。於是紅十字會聯繫 Akamai 科技處理這場危機。不到八小時後，紅十字會的網站重新恢復運行，捐款也繼續湧入。紅十字會從此之後持續與 Akamai 維持合作關係。 2009 年的加州森林大火時，紅十字會的網站承受了 15 倍的流量， 2010 年的海地地震時也遽增 10 倍的流量，但是網站都沒有因此當掉。

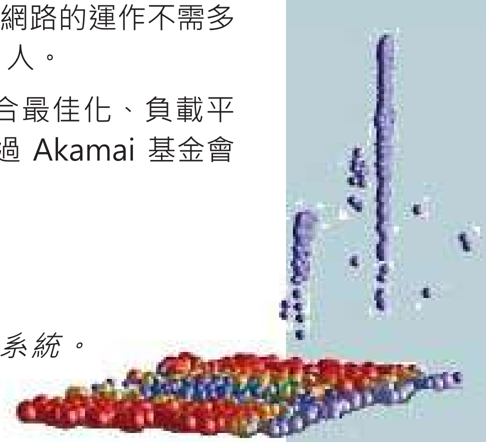
Akamai 的營運項目專攻高流量網站，秘方是軟體和硬體的配合。多數的網路變慢情形都發生在網際網路上雜亂無章、難以預測的中段（middle mile）上。 Akamai 能將大量的即時運算需求指派給離個人用戶最近的網際網路伺服器，藉此大幅繞過中段。此方法可讓用戶明顯感覺到網站回應與互動變好了。 Akamai 安置超過 35,000 台伺服器，幾乎就是讓每個用戶的附近都有伺服器。

但伺服器還是得透過「中段」進行溝通， Akamai不欲建造專屬網路（此種網路價格驚人），僅想使用公共網路。 Akamai 運用各種方法以繞過中段的限制。所有伺服器都安裝了改善笨重標準網路協定的軟體。同時，負載均衡與負載管理軟體能預測並因應網路的故障並自動找出替代路線。因此，整個網路的運作不需多少人力介入：平均下來，讓 35,000 台伺服器運作只要 8 到 12 人。

Akamai一直高度仰賴數學與運算技術，如機率演算法、組合最佳化、負載平衡、圖論、離散數學與作業研究等技術。另外，Akamai 也透過 Akamai 基金會推廣數學教育。

2.7 複雜系統建模

以往，我們販賣元件給他人的產品使用，現在我們也販賣系統。我們企業的特色改變了。數學、分析、模擬、運算已變得不可或缺。[摘自訪談]



雷射與電漿互動並加速電子的視覺化圖像。本圖由 VorpalTM， TechX 股份有限公司的電腦運算得來。

數學建模是複雜系統工程的關鍵科技，從科學上的多尺度系統分析，到評估架構權衡，再到驗證系統設計，都要用到數

隨著人口愈加都市化，城市人口賴以為生的交通、公共安全、水、電與醫療系統的管理是越來越大的挑戰。IBM 帶頭倡導「智慧城市」……

學建模。建模、分析、模擬、最佳化與控制能縮短商品的設計週期；可記錄、視覺化、確保最終系統的品質；也可發現並預估大型故障的風險。複雜分散式系統包括新一代電力網格（又稱「智慧電網」）[Beyea 2010]、交通網路、水供應系統、節能建築與醫療資訊網路。若想知道更多複雜系統中的數學挑戰，可參閱 [Hendrickson、B.A.與Wright M.A. 2006]。

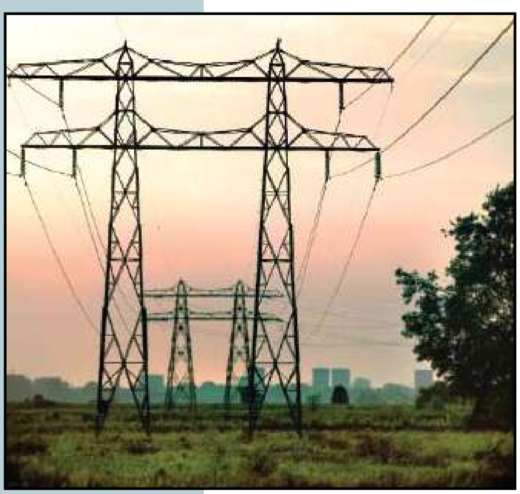
另一種複雜是在許多科學、工程系統出現的非線性行為，且此非線性行為出現在多重尺度中。這表示輸入端一點點的微小變化有時會導致輸出端不可預測的巨大變化。非線性動力系統一直是個活躍的研究領域，它結合了理論數學與計算技術的應用。

個案研究 16：黏滯流體流

一般人只對螢幕上的東西感興趣，不會去思考電腦或電視螢幕是什麼做的。然而，近年來大型平面電視、電腦螢幕與智慧型手機在市場上的巨大成功，必須歸因於全新的玻璃科技。

隨著液晶顯示器（liquid crystal display，簡稱 LCD）科技不斷進步，我們對於規格（例如厚度均勻性與平整度）與品質標準的要求變得越來越高，消費者期待的進步速度更數倍於前。 LCD 玻璃基板的領導製造商康寧（Corning）用數學模型研究如何提高製程技術，以改進其玻璃產品的特性。一如製作玻璃的配方，這些數學模型也經過了長時間的調整修正。舉例來說，熔合拉製法（fusion-draw process）需要兩道熔融玻璃流下 V 型溝槽兩側，最後合併為一張平板。若要為這張平板的流動建模以了解振動與彎曲等不穩定性，就需要解一個複雜的非線性微分方程組。

運用數學模型使康寧能以快速、低風險的方式推出新產品。康寧的Gorilla 玻璃是最好的例子，Gorilla 玻璃的組成與 LCD 玻璃不同，因此在製程中顯出的特性也不同。數學模型讓康寧能快速找出新組成的製程容許度（process window），所以只需在初期進行一點試作實驗，產品的上市時程就能從數年減少至數個月。請參閱 [《Glass once used》 2012]。



個案研究 17：智慧城市

全球城市人口比率在 2008 年首度達到 50%，在美國此數字已經超過 80%。隨著人口愈加都市化，城市人口賴以為生的交通、公共安全、水、電與醫療系統的管理是越來越大的挑戰。 IBM 帶頭倡導「智慧城市」這個必將蔚為風潮的運動。 IBM 投入的計畫可在以下兩個範例中可以一窺端倪。

哥倫比亞特區用水與汙水管理局（DC Water）在 2008 年

與 IBM 全球服務（IBM Global Service）簽約，希望能改善其基礎設施的管理。IBM 為 DC Water 安裝了一套能追蹤系統中所有財產的資料庫，甚至包括管線與人孔蓋。從而 DC Water 可以防患未然，而非僅能亡羊補牢了。當局就能用更充裕的資料擬訂維修方針，客訴減少了，故障儀表也更換了。該計畫只不過花費不到 100 萬美金，就讓 DC Water 在三年內省下了足足 2,000 萬美金。請參閱 [《DC Water》 2011]。

資訊科技正在改變警察局的作業方式。 IBM 協助紐約市建立了一個全新資料庫，稱為犯罪訊息倉儲系統（Crime Information Warehouse），供分析師即時找出犯罪模式。田納西州曼斐斯市（Memphis）更進一步，使用 IBM 的統計軟體預測哪些區域可能有較高的犯罪率。雖然無法斷言為這些措施的成效，但紐約重罪犯罪率自 2001 年起下降了 35%，曼非斯的犯罪率自 2004 年起也下降了 30%。請參閱 [《Memphis PD》2011]。

芝加哥警局在虛擬防範行動（Operation Virtual Shield）專案中於全市佈建 15,000 支監視攝影機的監視網。一旦有人報案時，系統會立即調出離現場最近的實況影片（以及案發當時的監視錄像）。依芝加哥警方所述，該系統已協助了數千次逮捕行動。請參閱 [Bulkeley 2009]。

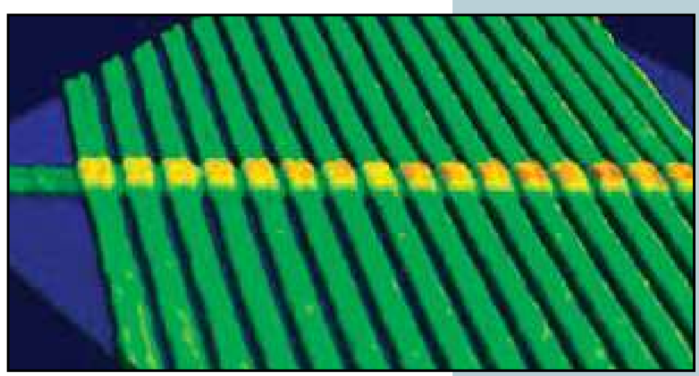
這些計畫牽涉的數學與計算領域包括資料探勘、資料儲存、生物識別、模式識別、風險評估、統計、統計建模等等。

……光是擁有超級電腦是不夠的。企業需要的是程式設計、建模專業技術、數字庫，以及各式各樣能在平行與分散平台執行的軟體。

2.8 電腦系統、軟體與資訊科技

超級電腦「華生」在深度分析的進步以及處理未結構化資料、詮釋自然語言的能力，可以為科學、保健、金融服務與其他產業推出量身訂做的服務並滿足其需求。 [Groenfeldt 2011]

許多企業為了應對產業問題而關注「高效能計算」（或「超級計算」）。但如前面個案研究所示，光是擁有超級電腦是不夠的。企業需要的是程式設計、建模專業技術、數字庫，以及各式各樣能在平行與分散平台執行的軟體。通常中小型企業沒有能建構支援高效能運算的專屬資訊科技的財力。但若能在大型分佈網路上（如雲端運算）使用軟體，這些企業的建模能力便能大幅提升。



17組氧化鈦憶阻器，HP實驗室提供

資訊科技產業裡有些領域正快速擴張，包括電腦視覺與成像、自然語言處理、資訊檢索與機器學習等等。關於自然語言處理（還有資訊檢索與機器學習）最驚豔的例子之一是 IBM 的「華生」電腦系統，它曾在《危險邊緣！》機智問答節目中擊敗兩位最厲害的人類參賽者。 IBM 已經開始在各個領域運用這項科技。

個案研究 18：意外發現

不知道有哪一個好奇卻還不知道要選哪門電機課程的學生，將來哪一天會發明憶阻器最厲害的應用。[Williams 2008]

對任何一家商業公司都一樣，最難證明有用的研發莫過於看不到結果的基礎研究了。正因如此，純由好奇心驅使的研究卻帶來革命性成果的少數幾個例子特別值得讚揚。最近的一個漂亮實例是HP實驗室2008年發明的憶阻器 (memristor)。

1995 年 HP 聘請史丹利 · 威廉斯（ Stanley Williams ）創立一個基礎研究小組，以回應 HP 創始人 大衛·普克德 David Packard 的理念：「HP 應該飲水思源，貢獻知識至其長期汲得知識的科學之井。」[Williams 2008]。十年後（2005），他在研究分子層級記憶體時，將二氧化鈦夾入兩層白金電極之間，意外發明了一種全新的裝置，其電阻會依穿過夾層的電子數量而變化。簡單來說，該裝置會記憶前一個狀態的電阻值。這也是憶阻器一詞的由來。

最讓人吃驚的或許是在 1971 年加州大學柏克萊分校 (UC Berkeley) 的 蔡少棠教授 (Leon Chua) 就在一篇少為人知的論文中，以純數學的方法建構並預示了預阻器的發明。憶阻器是除了電阻、電容、電導之外的第四種基礎被動電路元件（不汲取能源的元件）。前三種元件早在 19 世紀就發明，是當今所有電子產品的基本要素。 Williams 表示，要不是他先前曾讀過並仔細思考蔡教授的論文，也不會意識到實驗室究竟製造出了什麼東西。事實上，其他研究人員也曾注意到相同的特性，卻沒有人了解原因。

目前，人們預測憶阻器的未來主要應用將是電腦記憶體，HP也挹注資源賭一把。配備憶阻器儲存裝置的電腦將不用「開機」— 只要開啟電源，電腦會記憶並回到關機時的狀態。長期來說，就像引言中威廉斯的預測，憶阻器會被用在現在根本還沒人想得到的地方。比如說，憶阻器的行為有點相似神經元，也許在未來會成為真正的人工腦之關鍵元件。請參閱 [《Properties of memristors》2011]。

3 博士後的生涯

憶阻器的故事至少讓 R&D 經理學了兩課。第一，基礎研究最終會展現價值。第二，要重視數學。

MII 調查結果

與 1996 年的 MII 調查的結果相比，現今數學博士的就業機會幸運地變得寬廣許多。當時的調查中，大量博士生找不到學術研究工作，甚至連一般工作都找不著。相較之下，本次調查中很少人因為找不到學術研究工作而被迫進入業界。

調查結果的詳細討論請容後述，以下列舉一些重點：

- 被業界聘用的數學科學家大約有一半是統計學家，第二多的是有學術專長的應用數學家。
- 目前為止，金融保險業與製藥/醫療器材產業聘用最多數學家。製藥業幾乎只聘用統計學家，而金融產業大部分則聘用一般數學家。
- 如 1996 年的報告所示，幾乎沒有任何數學家的職稱包含「數學」二字。相比之下，統計學家的職稱通常與專業相關。
- 應答者的工作滿意度相當高，將近 90% 對薪酬與福利感到滿意。男性與女性應答者的薪水中位數都約為 100,000 美金。
- 與 1996 年的調查相比，較少畢業生認為「建模與模擬」是工作中重要的學術專長，更多畢業生說的是「統計」。
- 不過，矛盾的是數學模型卻是績效考評中最重要的評估項目。
- 程式設計與電腦技能仍然是新員工在工作崗位上最重要的技術類技能。

3.1 背景資料與人口統計

如引言中所述，與 1996 年調查最大的不同是本調查主要涵蓋了統計與生物統計系所的研究生。我們相信這可讓數學科學學生獲得就業市場更真實的觀點。然而，當我們比較兩份調查時，為了一致性我們只採納了數學系與應用數學系學生的資料。

此調查涵蓋了四組僱主與僱員：2004-05年、2005-06、2006-07與2007-08。一些基本的統計資料來自年度 AMS-IMSSIAM 針對博士候選人的調查。在 2004~2008 年間所有數學科學的博士畢業生之中，共有 787 位（15%）進入業界。其中有 426 位（54%）的論文與統計相關， 361 位（46%）的論文與數學相關。最常出現的數學領域是應用數學（10%）與機率（9%），請參閱表1。需注意的是，這些數字的參考來源為 AMS-IMS-SIAM 資料中被業界聘僱的博士。

	All	Survey
Area of Degree	%	%
statistics	54	39
applied mathematics	10	18
probability	9	5
discrete mathematics	6	4
algebra	5	4
numerical analysis	5	5
differential equations	4	2
optimization	3	5
geometry	3	4
analysis	2	5
other	0	4

Table 1: Degrees of all hires 2004-2008 and those in the survey

我們原本想對以上資料中所有的博士進行電子郵件調查。但資料

中或是網路搜尋來的電子郵件地址，只有 40% 有效。網路調查的回收率為30%，與類似調查相符。因此我們不宣稱實驗結果有統計上的顯著意義。不過，由於調查中應答者的專長分布與整體相近（請參閱表1），我們相信樣本具有代表性。統計學家略為不足，而應用數學家則略高。

應答者包括 19 位女性，37 位男性。由於樣本數小，無法對兩組進行嚴格的比較分析。我們只能說，調查中統計學家女性佔多數（12 位女性，10 位男性）；應用數學家則幾乎都是男性（1 位女性，9 位男性）。我們沒有對此不均現象不做任何詮釋，但值得在未來進一步觀察。

此次調查中的博士大部分（81%）在員工數超過 250 人的公司工作。13% 的博士服務於員工少於 50 人的小公司。薪水中位數（100,000 美金）在男女組別間完全相同，中位數的變動在兩組間也非常相近：第一四分位數皆為 90,000 美金，男性的第三四分位數為 115,000 美金，女性的第三四分位數則是 123,000 美金。

Employers	Total % hires	Stat % hires	Math % hires	Survey % hires
aerospace and defense	3.4	0.2	7.2	9.4
business services	14.2	15.0	13.3	5.7
engineering and scientific services	4.2	1.9	6.9	5.7
finance and insurance	30.4	21.1	41.3	28.3
pharmaceutical and medical devices	28.2	50.7	1.7	18.8
software	5.0	1.6	5.8	20.8
research and development	4.3	3.1	8.9	0.0

Table 2: Top employers 2004-2008 by broad industry classification. Statistics and mathematics are broken out separately. The last column is the employers from the survey.

根據 AMS-IMS-SIAM 年度報告的數據，我們將僱主大略歸類到不同的產業。金融與保險業（30%）與醫療和醫療裝置產業最多（28%）。這些產業聘用的新畢業生人數有次多的商業服務的兩倍（14%），請參閱表 2。製藥產業裡幾乎所有主要公司每年都會聘僱幾位博士，且幾乎都從事統計工作。多數主要的金融公司一年會聘用約兩位博士生。另外，諸如 SAS Institute、Google、IBM 與 Microsoft Research 等不屬於這兩類的公司，每年也平均聘用兩位博士。表 2 的最後一行比較了應試者完整的人數資料。因調查的統計學家數量過少，也因調查要求應答者將他們任職的公司部門分類（部門可能與公司本身的類型相異），因此資料中有一些不一致。

我們分析了 2008-2009 年與 2009-2010 年的群體，詢問他們在 2009 與 2010 年的蕭條時期主要的僱主或聘僱人數有何改變。基本上答案是沒有改變。主要僱主在比例上一樣聘任了 87% 到 94% 的博士。

雖然我們沒有調查在政府機關任職的博士，透過這些畢業生的 AMS-IMS-SIAM 相關資料我們還是能對他們的研究背景以及僱主做出分析。研究結果指出，在政府機關任職的畢業生的研究領域與進入業界的博士相似，多數集中在統計、應用數學、數值分析、微分方程與離散數學（人數依此順序）。主要僱主包括了 FDA、NSA、NIH、洛斯阿拉莫斯國家實驗室（Los Alamos National

Laboratory）、桑迪亞國家實驗室（Sandia National Laboratories）、其他國家實驗室，以及美國退伍軍人事務部（U.S. Department of Veterans Affairs）。以上機關的僱員佔了政府機關的所有博士聘僱人的 81%。而 2004 至 2008 年間任職於政府機關的博士佔全體博士的3%。有趣的是，即使金融業不斷增加數學博士的任用人數，相應地美國政府卻只在聯邦存款保險公司聘了一位博士而已。

我們同時也分析了 2004-2008 年間有最多博士畢業生進入業界的25個系所。最頂尖的 25 個統計系所送進業界的畢業生相較於數學系所平均多了一倍（以比例而言）。這些統計系所進入業界的畢業生比例從15%到70%，數學系所從 10% 到 40%。我們也獲得指導教授及經這些教授指導並進入業界的博士生人數資料。進入業界的博士之中， 82% 的指導教授在四年間只有一位博士生畢業後進入業界，11% 有兩位，6% 有三位，而 1% 超過三位。

這些資料顯示大多數學生是基於個人選擇進入業界，而非源於指導教授的壓力或期待。我們調查的多數學生都曾在業界實習，或曾與企業有過正式交流（比如產業工作坊或受產業界科學家指導）。在這些情況下，沒有與業界合作的指導教授也可能鼓勵學生與業界交流。

3.2 新近畢業生在公司裡扮演的角色

此工作是非常刺激的智力活動，卻不會像學術研究那樣天生易有挫敗。學術圈為了終身職（tenure）在早期職業生涯就養成了「不出版，便成仁」的心態，沒有人鼓勵或重視工作與生活的平衡。

Rationale for Taking a Job in Industry	%
higher compensation	66
opportunities for career advancement	52
experience with industrial internships or programs	48
intellectual challenge	32
had a job in industry	32

Table 3: Rationale for joining industry

調查中的博士受訪者進入業界的理由中，最常見的希望薪酬增加及更好的升遷機會（請參閱表 3）。將近半數受訪者提到在業界實習的經驗，約三分之一的受訪者甚至已經在業界有工作了。這些數字表示在多數情況下進入業界並不是狗急跳牆的決定，這些學生早就做足了準備。因此，意見中隱然可見對學術圈的不滿，並不令人驚訝（參閱上方引用）。只有兩位學生告訴我們，他們到產業任職是因為無法進入學術圈或政府機關工作。

Very Satisfied/Satisfied with	%
compensation and benefits	88
lifestyle	80
intellectual challenge	74
opportunities for career advancement	72
opportunities for scientific growth	56

Table 4: Satisfaction with aspects of the job

調查中很高比例的博士都對薪酬與福利（88%）、生活型態（80%）感到非常滿意或滿意（請參閱表4），即使對於這些因素並非進入業界主要原因的受訪者都一樣。他們的工作無需犧牲受到高度評價的智力挑戰。不過，對科學成長的機會感到滿意的博士就沒這麼多了。出現這種反差現象的原因可能是業界的工作較注重專案，尤其是在研究所剛畢業的前幾年。

我們也調查了聘用博士數學科學家的企業的主要目的為何，請參閱表5。調查結

> 調查中的博士受訪者進入業界的理由中，最常見的希望薪酬增加及更好的升遷機會。

果沒有出現特別明顯的結果。但值得注意的是，與 1996 年的調查相比，主要目的為軟體的企業比例有下降的趨勢（1996 年的 35%, 相較於本調查的 13%。）。除了小於五人的小型企業，其他企業的員工組合囊括各個領域，包括工程師、電腦科學家、物理科學家或金融經濟畢業生等等。

我們曾在 1996 年指出，數學家的職稱很少與學位相關，請參閱表 6a，唯一的例外是統計學。尤其在製藥公司，他們最常見的職稱是「資深統計學家」或「生物統計學家」。

數學家常被視為「分析師」、「建模師」或僅僅是個「研究員」。在實務上，非統計學家的數學研究者可能得來自面對其他領域、擁有純熟量化技巧的畢業生的挑戰。他們必須證明數學背景與自身工作有何關聯，以便向僱主證明他們的價值。在表 6b 裡，我們列出了一些應答者提出的工作技能，從這些職能中我們看見對統計、軟體、程式設計及計算機科學的重視。

在應答者中竟有 15% 人員已有「經理」的頭銜，而 21% 的應答者將管理列為其中一項技能。學生原本投入業界的期待是能在學術圈晉升速度更快，從這些數據看來，期望多半會成真。

Group Mission	%
engineering	9
investment/trading	11
modeling	15
analysis/finance	9
research in engineering/science	16
software development	13
statistics	16
business strategy	11

Table 5: Mission of groups from survey

Job Title	%
statistician	17
analyst/ modeler	20
researcher	21
management	15
consultant	9
engineer	7
software developer/programming	11

Table 6a: Job titles from survey

Primary Job Function	%
computer Science	7
consulting	6
engineering	10
modeling	17
operations research	1
scientificprogramming	6
software development	8
statistics	33
strategy	7
other	6

Table 6b: Primary job function for respondents ("other" includes financial trading, business analysis, technical support)

3.3 資格與能力

光是會計算已經不夠了。新成員必須懂得演算法、數學建模與其應用。 20% 的工作可以由電腦執行，但 80% 的工作需要懂得物理與工程。

畢業生需具備的能力包括以下：相關領域的專業深度、數學與計算科學的知識廣度、對僱主的科學與業務相關的興趣與經驗、面對各種挑戰的熱情、與跨領域團隊合作所需的彈性與溝通技巧、時限內完成工作的自律性、以及合理解決問題的直覺等等。

自 1996 年起這些要求就沒有什麼改變，不同之處大部分取決於任職的部門與團隊，請見表 7。

與先前的調查相比，此調查較少有應答者把「建模與模擬」視作必要或重要。然而這似與「哪些項目在年度考評中較為重要」的調查結果相矛盾。對此問題，67%應答者的答案是「數學模型」， 64%應答者的答案是「向管理階層報告」（請見表 8）。也許此明顯矛盾的原因是，雖然數學模型仍是影響工作表現的重要因素，但數學建模的養成並沒有與時更新。

進階的計算能力在 1996 年的調查中被 83% 的畢業生評為必要或重要。在這份調查中我們進一步探討細節。程式設計（86%）、計算科學（57%）、資料探勘（40%）與軟體工程（34%）被評為必要或重要的計算訓練。整體而言， 65% 的應答者認為數學或計算科學對他們的成功至關重要。

我們在 1996 年的報告中明白強調溝通技巧的重要性。表 8 顯示，與溝通技巧有關的工作成果（「對管理階層報告」、「準備內部報告」）至少與技術成就（「數學模型」、「軟體開發」）一樣重要。

類似地，在實地訪談中被訪談者也不斷提及軟實力，像是溝通、團隊合作、靈活性、願意聆聽等等。以下列出一些我們收到的建議：

「軟實力有重要影響。」

「很難說有什麼人不能從學術界轉到企業界。但成功轉型的人都是好的傾聽者，對其他人的點子有耐性，也樂意改進。」

「你必須能向外行人解釋專案。博士的適應力通常比碩士更好，因為他們一直都被要求跳脫框架思考。 」

「要願意『撩下去』來幫助企業達到目標。」

「必須有能力處理並解決非結構化的問題。」

Rated essential/important	Survey	MII96
	%	%
statistics	61	51
probability	60	50
applied mathematics	56	-
modeling and simulation	49	73
numerical analysis	42	65
optimization	38	38
discrete mathematics	30	26
differential equations	29	50

Table 7: Percent of mathematical specialty rated as an essential or important requirement for their job. Multiple answers allowed. Comparison to MII96 included.

Essential/important to annual review	
	%
mathematical models	67
software development	43
presentations to management	64
preparation of internal reports	59
presentations to customers	53
presentations at conferences	39
publication in the open literature	29

Table 8: Percent of respondents rating task outcomes as essential or important for their review

我們的調查也詢問近年的畢業生，請他們為考慮進入業界的研究生提供建議。我們收到21則回應，諸如：

「目前銀行業的挑戰是要在大量顧客資料中篩選有用資料。受過任何『大數據』的訓練都是加分。」

「隨時準備接受新知、參加從業者舉辦的研討會、學習程式設計，就足夠了。」

「尋求實習機會，跟隨你的興趣，學習資料庫技能。」

「博士生通常會低估業界裡的科學水準。其實在業界要解決許多有挑戰性的問題。」

「到企業實習，學習程式設計。在我看來，程式設計對幾乎所有產業數學家都是必備的。」

4 對研究所教育的看法

提倡雙導師制的碩士學位。雙導師其中一位來自數學或計算機科學系，另一位來自其他科系、政府實驗室、或企業中。

「到你有興趣的產業找實習機會，不要在意學位，跳脫學術框架思考，學習溝通技巧。若沒辦法與團隊溝通或工作，聰明才智一點用處也沒有。」

4.1 博士教育

1996 年的報告針對有興趣踏入業界的學生的研究所教育提出了幾項建議：增加應用課程、形成並解決真實世界問題的經驗、電腦與計算科學的課程。

這次調查中我們提出三個相關問題，試圖釐清這些建議對研究所教育影響的程度。首先，我們詢問畢業生是否曾參與產業界相關計畫。28% 的應答者曾參與業界實習，7% 在業界有專人指導，7%曾參與問題討論，5% 曾參與產業工作坊。問卷題目為複選題，但 59% 的應答者並未回答或指出問題不適用他們的情況。

從另一個角度來看，我們實地訪談的許多公司都強調實習的好處，也提供學生實習機會：如波音、D.E. Shaw、Cray、IBM、通用汽車、AT&T、Intel、Akamai、HP Labs、Google、Solidworks 等公司。同樣的，工作坊已被證明能成功將學術知識轉移至業界，也能讓學生獲得解決產業問題的經驗。居於領先的包括將數學問題納入討論的許多美國產業工作坊，解決產業問題的加拿大亞太數學科學學院（Pacific Institute for the Mathematical Sciences，簡稱PIMS）與歐洲產業讀書會 （European Study Groups with Industry）。

顯然許多公司對實習、工作坊與各式機會非常有興趣，但可惜的是參與類似計畫的人數卻不踴躍，尤其是考慮進入業界的學生

「我覺得銜接理論與實際應用是重要的 ── 但大多數人並不知道。」

「程式設計經驗（尤其是團隊軟體專案）相當重要，但在數學導向的課程中卻常常被忽略。」

Training in another discipline	%
programming	65
scientific computing	35
other computer science	28
scientific discipline	58
business discipline	29
engineering discipline	9
other discipline	4

Table 9: Percent of respondents with training in another discipline

我們曾調查畢業生是否有受過主修以外的研究所等級的訓練。其中 79% 的畢業生至少有一項，請見表 9。這通常是形如程式設計、科學計算與其他計算機科學相關訓練。我們也詢問這些訓練對於到業界找工作有何幫助。 65% 的畢業生表示非常有幫助或有幫助。另外，我們也問團隊合作有何幫助， 70% 的應答者表示非常有幫助或有幫助。

我們聯繫一間畢業生有高比例進入業界的研究所，想了解是否有什麼秘訣為想進入業界的學生做準備，以及哪些想法能複製到其他科系。美國萊斯大學（Rice University）的計算與應用數學系（Computational and Applied Mathematics，簡稱CAAM）自 2004 至 2008 年一共將 20 位中的 8 位畢業生（40%）送進業界，自 2009 至 2010年 9 位畢業生更有 7 位進入業界。以下是該系系主任 麥錫爾斯．漢肯斯克洛斯 （ Matthias Heinkenschoss）的一些想法：

- CAAM與本地公司有很密切的聯繫，包括英國石油、殼牌、ExxonMobil與雪佛龍（Chevron）。即使公司的類型很可能不同，但我們的概念是可以適用到其他系所的。
- 我們的學生不只在本地企業實習，有半數的學生在休士頓之外參加實習。
- 與校友保持聯絡很重要，這樣才能在特定公司與產業「鋪路」。
- 想進入業界的學生修習的課程與其他學生一樣。但我們的必修課涵蓋許多在傳統純數學系所裡非必修的主題，像是數值方法與高效能計算等等。
- 所有學生都得在第二年末撰寫碩士論文，並且修一門論文寫作課。課程中還會學習溝通技巧，譬如說「簡報的藝術」。
- 最後我想說的是，CAAM 就是應用數學系，而不是一個學程或一個研究群。

別的系所難以複製 CAAM 理念的最後一條，我們也不建議系所模仿他們。不過，擁有應用數學學程或研究群的傳統數學系應該要多加考慮如何讓課程因應，並照顧那些想要進入業界的畢業生。

在學校無法學到所有東西，一堆學校知識都是理論上的。

4.2 專業碩士學位

我們曾在 1996 年報告中調查了數學系碩士畢業生及他們的指導教授。目前的這份報告並沒有調查碩士畢業生，而是聚焦於碩士教育的新興趨勢。

1996年的報告剛發表不久，艾爾弗·斯隆基金會（Alfred P. Sloan Foundation）就開設了專業科學碩士（Professional Science Masters，簡稱 PSM）課程，這是一個數學與科學上的創新學位學程，目標是使其畢業生能具備在業界工作的知能。PSM 是嚴格而跨領域的學程，不僅給予學生科學與數學的進階訓練，同時也強調不同領域的僱主皆高度重視的專業技能。

研究院委員會（Council of Graduate Schools，簡稱CGS）在2005年將PSM學位視為正式的學術學位。美國國家專業碩士協會（National Professional Masters Association，簡稱NPSMA）也在2007年成立，為課程負責人、教職員、行政人員、校友與學生等喉舌。NPSMA成立的目的是支援PSM計畫，方法包含研討會、工作坊、資料蒐集，以及實踐發展。斯隆基金會亦贊助了這兩個組織最初的創立資金。

目前已經有將近 110 間大學與學院提供超過 230 個 PSM 課程，遍及美國 30 個州以及哥倫比亞特區、加拿大、英國與澳洲等國家。其中有 23 個課程包含了數學科學以及數個計算科學、生物資訊學相關課程。請見 [《PSM Programs》2012]。

近期針對 PSM 課程畢業生的調查 [NPSMA 2009] 讓我們窺見畢業生在業界的資訊。線上調查的 281 位應答者之中， 80% 的工作非學術相關：其中 62% 在業界， 9% 任職於非營利組織， 9% 在政府相關部門。多數的工作都是大型組織的職缺。薪水的中位數大約是 63,000 美金，第一與第三四分位數約分別為 43,000

與 74,000 美金。但眾數（19%）超過 90,000 美金。 NPSMA 調查的應答者中，19% 畢業於數學或計算科學課程。

PSM課綱中的科學方面包括了數學領域的深度，以及科學、工程、或商業的廣度；技能方面則包含管理、商業與專業技能。 PSM 課程強調寫作與溝通技巧，必須完成期末專案或有團隊合作經驗。課程也提供了結構化的實習機會。一個好的 PSM 課程除了提供創新、目的導向性的課綱，亦應邀請業界、商界、政界領袖組成顧問委員會。課程也應該蒐集公布註冊、學位取得與求職結果等資訊。

美國國家科學研究委員會近期的 Science Professionals：Master's Education for a Competitive World 報告強調了 PSM 學位的重要性：

政策制定者，大學與僱主應通力合作，加速發展在自然科學上的專業導向碩士學位學程。這種課程的畢業生同時具有科學知識與工作應用技巧，可以增加國家的競爭力。[NRC 2008]

至於與 PSM 無關的數學與計算科學碩士課程中，有些非常傳統，但有些則非常聚讓學生投入特定職場。最顯著或許就是財務了，有各式各樣的名稱，比如「財務數學」、「計算財務」、「財務工程」或「計量財務」。某些財務數學課程與 PSM 結合，但多數並沒有。例如，共七個 PSM 的財務數學課程都參加了每年秋天在庫朗研究所（Courant Institute）舉辦的國家金融數學就業博覽會（National Financial Mathematics Career Fair），但與 PSM 無關的 42 個財務碩士班也都參加了。

這樣說來，既然一樣都達到課程專業要求，那為什麼要聘用一般碩士呢？哥倫比亞大學（Columbia University）財務工程碩士班的主任伊曼紐爾·德曼（Emanuel Derman ）在 Advanced Trading 一文中 [Gibbs 2008] 提到，他想要「聘用學過諸如建模等基本知識的量化分析師，但也期望他們懂得模型為何如此運作，並知道哪些是影響市場的因素......在學校無法學到所有東西，一堆學校知識都是理論上的。所以學生修完課後，要從真實的金融世界裡獲得經驗。」這個想法不僅適用「量化分析師」，也適用於大部分想要在學術圈外就業的數學與計算科學碩士畢業生。碩士課程必須要在了解理論、了解企業（或特定企業）與發展實務經驗之間找到平衡。

5 建議與策略

以下的建議是蒐羅不同來源彙整而成，包括焦點小組對談中的對話內容、與數學與計算科學家及管理者的實地調查訪談、會議中的個別訪談、以及委員會成員自身的經驗等等。這些建議也納入了 1996 年報告的建議。事實上後者的建議至今依然有效。此處可算是另一個版本，和先前報告不同之處是強調的重點，而非有什麼新的提議。

教育方面建議的指導原則為以下各項：相關應用的知識、真實世界的問題解決經驗、計算的良好技能、溝通技巧、在跨領域小組中工作與領導能力，以及對企業及其目標有概念。

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5.1 全面性的策略

經濟合作與發展組織（Organization for Economic Co-operation and Development，簡稱 OECD）在 2009 年 7 月發表了一篇報告，是關於如何在產業界中提升數學地位的機制［OECD 2009］，舉出了令人印象深刻（但不一定全面）的清單：

由學術界發起

- 學術圈中的跨領域研究
- 聚焦在產業界的學術職缺
- 學位（博士與碩士）課程
- 建模週活動

產學合作

- 工作坊
- 讀書會
- 實習
- 小組練習
- 學術與非學術機構的網路
- 業界導師（例如 Mitacs 的企業發展主管）

美國、加拿大與歐洲多數的國家所發展的計劃，都圍繞著以上各項。報告指出其中許多計畫都由學術圈組織，政府則透過學術管道提供主要資源。

學例而言，加拿大的中心Mitacs，擁有一個成員有著十八般武藝的團隊，包括深厚的科學背景、商業發展能力、能與非學術界夥伴溝通發展並進行多領域研究的能力。團隊成員向業務發展執行副總報告，也與 Mitacs 的科技人員緊密配合。團隊成員分散到加拿大各區，由當地政府與產業界合作夥伴提供贊助。團隊成員的主要工作為：向公司介紹與學術圈進行進一步研究的合作機會、利用

研究專案連結大學研究人員與產業，以便為學生尋求實習機會（請見 [《Mitacs Accelerate》 2012]）、創造並維護公私機關的合作夥伴網路、為 Mitacs 尋求新的合作關係，以及管理與主要利害關係人（stakeholder）的合作關係。

第二個例子是德國柏林科學基金會的 Matheon 研究中心（DFG Research Center Matheon），這是著重工業導向的研究中心。此中心發展關鍵技術的數學，並對產業界、商業界、科學界的合作夥伴提供協助。中心也與學校與一般民眾互動，以增加應用數學的能見度。

中心用多種方式促使產業界關注數學。中心在其網頁上介紹Matheon成員的專業，並提供往業界專題、文獻、與成功經驗的連結，請見[《Matheon Services》 2012]。中心並擁有一個功能如同知識仲介的辦公室，對產業公司的需求與適合的團體進行媒和。中心並提供產業界實習機會給研究生。學生會在 Matheon 科學家的指導下在產業界伙伴進行研發實習四個月。學生與科學家的資金由 Matheon 與產業界的合作夥伴共同支付。這種產學合作創造了產業界、學生、與學術圈的三贏狀況。這也實現了由產業資助的許多不同領域的專案，包括離散數學、最佳化、數值分析、科學計算與隨機分析等等。

該報告的結論是「建立國內與國際網路，不但能對產業界的問題激起數學意識與數學創意，亦可避免重複的研究。」我們支持 OECD 的倡議，也呼籲美國政府大力支持。結果應包括能整理出一份最佳的「執行法則」文件，並討論在 [Holli 2008] 裡提到的技術轉移評估。

也許因為以上報告焦點放在數學而不在計算科學與工程學上，因此報告中沒有提及業界與政府關於高效能計算的合作。我們在稍早討論過此問題，並會在後文提出建議。

5.2 研究所教育

數學及計算機科學的研究所課程培養研究生的專科專長，以及分析思考、形成問題及發展數學模型的能力。這些都是在業界中必備的關鍵能力。然而，這些技能並不足以讓研究生在產業界能有所成。問卷訪問的研究生與實地訪談中的產業界科學家與經理，都強調在業界還需要具備一些額外的技術及經驗。我們在 §3.3 曾提及，此處詳細地討論如下。

接觸相關的應用與解決真實的問題

我們訪談的產業界科學家之中，其大多數所在的公司都提供實習機會，並藉此尋找潛在員工。訪談的應答者與產業界科學家都強烈表示，業界或政府實習是經歷真實問題的最佳管道。要獲得特定實習機會，前提是要修過某些相關的應用課程。數學系所應該要蒐集大量資料，提供業界或政府實驗室暑期打工或實習的機

會。教職員與行政人員應該鼓勵學生申請。但更有效連結研究生與實習的方式是常態地聯繫已在業界或政府就職的碩博士畢業系友，回來給的講座演講或開個工作坊，讓校友談談工作內容或公司能提供什麼機會。

程式設計專業

我們聘請過一位聰明的拓撲學博士。他對自己的程式設計能力太過謙虛，差點就丟了工作機會。

像這樣子的事應該不能再發生。學生要知道，在產業界程式設計是必備工具。如果你能寫程式，就不要隱瞞或不敢提。

對程式設計的要求程度依產業、公司、部門或工作小組而異。在中小企業中，每個人也許都要為公司的 IT 作點什麼。需要哪種程式設計語言也依狀況有所不同。某些情況下，第四代程式語言，例如 MATLAB、R、SAS、或 SPSS 就夠了。其他情況則需要 C++、Java 或是像 Python 的高階手稿語言。（有些受訪者在言談中甚至對「只會」MATLAB 的應徵者略顯輕蔑。）因此，未來的求職者與其導師必須儘早找出業界目前所關心的程式設計專業。

「…… 建立國內與國際網路，不但能對產業界的問題激起數學意識與數學創意，亦可避免重複的研究。」

—— 德國柏林科學基金會的Matheon研究中心

高效能計算

如果系所沒有開設平行計算的課程，是在扯學生的後腿。

DARPA、DOE 以及競爭力委員會 [Council on Competitiveness 2008] 在 2008 公佈的白皮書的結論說：「美國工業界正經歷電腦科技在工業商業問題的應用所驅動的21世紀新工業革命。高效能計算在設計與改進工業產品與工商流程上扮演了關鍵角色。」我們研究提供了高效能計算在解決企業問題中極具幫助甚或不可或缺的許多例子。不少受訪者多少都提到他們公司正缺少合格的高效能計算人員。

對學生而言，能具有特定應用的建模與計算能力有明顯的好處。能有高效能計算的能力亦同。能整合運用兩種能力，絕對是炙手可熱。

溝通與團隊合作

在學校教育中，參與三人以上專案的經驗非常重要。

溝通能力在今日的重要性仍和 1996 年相同。但溝通不只是能寫會簡報那麼簡單。在商業界，個人的成功通常取決於所屬團隊的成功。要在團隊裡與其他人有效溝通，必須具備足夠廣泛的技術知識，才能了解其他人在說什麼。聆聽的能力，以及從其他隊員身上學習的能力，與你自己提供想法的能力一樣重要。你需要領導力與表達能力去傳遞你的想法、你需要對團隊目標的策略有概念、你需要

參與或開設計算科學的學位課程，並強調數學、計算機科學、應用的結合。

在截止日前完成專案所需的驅策力、紀律、與精力。一位業界的科學家將這些統稱為「完成事情因子（get-things-done factor）」

給學生的建議總結

政策及訓練學生進入業界的經驗依系所不同，因此學生可能需要更積極， 遠遠超過畢業的最低門檻。找機會與在學術圈外的成功系友談談。發展多領域技能，包括一個應用領域、計算能力、數學建模等等。在向著你選擇的道路奮進的同時，也別忘了對數學科學有更廣博的認識。僱主希望求職者有「T形」的輪廓 ── 在一個領域有深度，在其他領域有廣度。

努力尋找暑期打工或合作聘僱的機會，特別是看能不能在企業或政府實驗室實習。這些活動不僅對找全職工作頗有幫助，也可讓你看看業界是否適合你。

選擇指導教授或共同指導教授時，選與業界或政府部門科學家有合作經驗的人，也可以在非本系找共同指導教授。

最後，留意外系或學術社群所舉辦的業界與政府單位科學家的演講。

5.3 給教學與行政同仁的建議

以下的建議設計意圖為增進教學同仁間的聯繫。包括數學與計算科學、物理、社會科學、經濟科學的同仁，以及相關領域的非學術同仁等等。但要強調的是以下建議並非意圖取代數學或計算機科學的核心課程教學。

- 提倡雙導師制的碩士學位。雙導師其中一位來自數學或計算機科學系，另一位來自其他科系、政府實驗室、或企業。
- 鼓勵大學生或研究生善用 NSF 所屬數學機構的暑期計畫或其他 NSF 課程，像是大學生研究營（Research Experiences for Undergraduates，簡稱REU），尤其是聚焦工業或商業問題的那些課。
- 開設新數學課程，聚焦在特定領域應用所需的技術，並且囊括會用到的學術教材。這些課程可以與其他系所教師，或學術圈外的科學家一同授課。
- 參與或開設計算科學的學位課程，並強調數學、計算機科學、應用的結合。同上，試著邀請其他系所、業界、政府的科學家共同參與。
- 在專題討論或研討會邀請其他領域或業界科學家主講。這類跨領域聚會可以和其他系所一起合辦。
- 邀請業界或政府科學家以客座教師的身份進行為期一至二週的訪問。鼓勵他們開辦以實務為主的討論班，提出改良目前課程的建議，參與學生發起的討論會。若有需要可補助交通費。

- 設立並管理系所的指導教授委員會，成員來自計算機、科學、商業領域的教員以及業界與政府，以便擔任學生的共同指導教授與導師。安排以「業界與政府工作的事前準備」為題的講座給大學生及畢業生參與。

我們與業界科學家與經理訪談中，一個常被觸及的議題是他們常無法與大學達成智慧財產權（IP）協議。一位受訪者說：「有些大學善於處理IP相關業務，其他則讓你恨得牙癢癢。」面臨重要的合作研究計劃時，教員與行政人員應該願意協商出跨過IP障礙的方法。尤其是行政人員應該要了解，過分熱衷於取得智財權其實會嚇跑業界夥伴，亦是削弱了大學所負的教育任務。

5.4 給產業界與政府機關科學家以及決策者的建議

業界團體、政府實驗室、數學與計算科學學術單位的合作研究能相輔相成且更有效地完成目標。畢竟這就是所謂技術轉移的真義。作法並非單行道， 因此這裡列出一些意見，應能幫助產官學三方使用數學與計算資源，以期為全體博得最大利益。

- 認識學界中的計算科學家，建立人員互訪的產學合作計畫。正式或非正式皆可，短期或中期（一至二週）亦可。這可催生共同研究計劃，也是尋找實習學生的好方法。
- 善用政府主辦的鼓勵產官學互動的計劃。包括 NSF 的 GOALI 課程、REU、NSF 所屬數學研究機構的業界課程，以及美國能源部的 INCITE 與 SciDAC 計劃等等。
- 鼓勵業界、政府員工向學界夥伴分享應用與成功故事。數學家如果看見自己熟悉鍾愛的理論能有效有趣地解決真實世界問題，多半會感到無比愉悅。分享這些成功經驗能大大地在不同的社群間建立聯繫。
- 樂意參與政府關於研究和教育計劃的指導委員會。
- 積極參與學會，志願成為委員會或次團體的委員，籌劃委員會會議，並在全國會議中提出短期課程主題的建議。

對決策者而言，我們訪談的結果顯示了不利於業界研究環境的兩類政策。兩者牽涉的範圍超乎數學科學，為了報告完整而在此提及。

第一，對外國學生與其國家的簽證仍有重重限制。例如，在電腦輔助幾何建模領域中，美國學生比歐洲學生少；因此，仰仗幾何建模的美國航太與汽車公司一直難以找到合格的員工。當然，簽證通過與否與許多其他因素有關，但科學家需要發聲，讓大家了解科學家的流動只會更增加美國的競爭力。

第二，許多受訪的公司都指出，自從 1980 年美國拜杜法案（Bayh-Dole Act）實行以來，各校關於與政府合作案的智慧財產權政策往往阻礙了產學合作。雖然

還是有些成功的政策，卻有更多阻礙了業界合作。大學的決策者應重新審視其政策，以鼓勵產學合作。

鼓勵業界、政府員工向學界夥伴分享應用與成功故事。數學家如果看見自己熟悉鍾愛的理論能有效有趣地解決真實世界問題，多半會感到無比愉悅。

6 結論

本報告依照近年來數學與計算科學的發展、經濟的變遷，與業界和政府應用的進化，更新了 1996 年所發表的《SIAM報告：產業界中的數學》。

美國及其他已開發國家的經濟體正經歷從產品導向轉變為知識導向的變遷，其更新與進步的驅動力來自於個人或團體的專業。我們確信數學與計算科學已對美國經濟做出極大貢獻，未來並將藉由提供新知與新的做生意的方法持續做出貢獻。大學仍是培養優秀年輕人的核心場域，這些年輕人有野心，也有能力運用數學知識解決真實世界的問題。但這些都不會無中生有；大學教師必須積極鼓勵學生踏入業界，並讓學生準備好面臨畢業後完全不同的世界。

在現今的脈絡下，我們再一次對 1996 年報告中的結論做出肯定。在數學科學、計算科學與實際應用裡，種種的新想法與靈感在四面八方澎湃流動。非學術的應用不僅使數學與計算科學增加了深度與廣度，也同時涉及其他領域，包括科學、工程、醫藥與商業。

我們確信數學與計算科學已對美國經濟做出極大貢獻，未來並將藉由提供新知與新的做生意的方法持續做出貢獻。

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產業界中的數學顧問委員會（Mathematics in Industry Advisory Committee）

明尼蘇達大學的道格拉斯．阿諾（Douglas Arnold）；

明尼蘇達大學的瑪麗亞-卡門．凱德爾（Maria-Carme Calderer）；

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讓我們參訪的公司與企業；

透過調查或訪談回答問題的人們；

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REPORT IN BRIEF

The Mathematical Sciences in 2025

Board on Mathematical Sciences and Their Applications ·
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The mathematical sciences are part of nearly all aspects of everyday life—the discipline has underpinned such beneficial modern capabilities as Internet search, medical imaging, computer animation, numerical weather predictions, and all types of digital communications. This report examines the current state of the mathematical sciences and explores the changes needed for the discipline to be in a strong position and able to maximize its contribution to the nation in 2025. It finds the vitality of the discipline excellent and that it contributes in expanding ways to most areas of science and engineering, as well as to the nation as a whole, and recommends that training for future generations of mathematical scientists should be re-assessed in light of the increasingly cross-disciplinary nature of the mathematical sciences. In addition, because of the valuable interplay between ideas and people from all parts of the mathematical sciences, the report emphasizes that universities and the government need to continue to invest in the full spectrum of the mathematical sciences in order for the whole enterprise to continue to flourish long-term.

Broadening of the Mathematical Sciences

Work in the mathematical sciences is increasingly integral to a growing array of research areas, including biology, medicine, social sciences, business, advanced design, climate, finance, and advanced materials. This work draws on the interplay of a wide range of techniques from mathematics, statistics, and computation and makes a critical contribution to economic growth, national competitiveness, and national security. As reliance on complex computer simulations and the analysis of large volumes of data increase, the discipline also naturally expands through its essential role in contributing the framework and tools required to perform such simulations and analyses. The ubiquity of computational simulations and exponential increases in the amount of data available for study are two major drivers of the increased "reach" of the mathematical sciences.

This broadening of the discipline should inform the nature and scale of funding of the enterprise, and education in the mathematical sciences should also reflect this evolution. The mathematical sciences have an exciting opportunity both to solidify their role in underpinning 21st century research and technology while maintaining the strength of the core, which is vital to the future of the mathematical sciences ecosystem. As explored in the full NRC report, the mathematical sciences community is achieving great success within this changing model. However, many mathematical scientists remain unaware of the expanding role for their field, which places a limitation in the community's ability to produce broadly trained students, and a community effort is needed to improve this situation.

Boundaries within the mathematical sciences, as well as boundaries between the mathematical sciences and the disciplines that use them, are blurring. Internal to the discipline, there is more collaboration and more research that melds insights from different subfields. This has enabled some of the most exciting recent advances in fields of study that were rarely brought together in the past. And in terms of external interactions, a sizeable amount of mathematical sciences research is actually conducted by, or with, people from outside of mathematical sciences departments. An inclusive view of the mathematical sciences and of the mathematical sciences community is called for.

In the face of the expanding role of the mathematical sciences and their consequent increase in impact, the adequacy of current federal funding for the discipline is a notable concern. The dramatic broadening of the role of the mathematical sciences over the past 15 years has not been matched by a comparable expansion in federal funding, either in the total amount or in the diversity of sources. The discipline, especially its core areas, is still heavily dependent on the National Science Foundation (NSF).

Other Trends Affecting the Mathematical Sciences

One significant change over the past 10-15 years has been an increase in the number of mathematical science institutes and their greater influence on the discipline and its community. These institutes now play an important role in helping mathematical scientists at various career stages to explore new areas of investigation, and they have facilitated new collaborations and helped to link the mathematical sciences with other fields. Collectively, these institutes have had an enormous impact in changing and broadening the culture of the mathematical sciences.

Another important trend is the rise of new modes of scholarly communication based on the Internet, making it easier for mathematical scientists to collaborate with researchers around the world. However, these new modes of collaboration, as well as any related impacts on publishing, will call for adjustments to the measures of quality control and professional accomplishments.

A final trend, which began decades ago and escalated in the 1990s, is the ubiquity of computing throughout science and engineering. Computation is often the means by which the mathematical sciences are applied in other fields, and it is the driver of many new applications in the discipline. More mathematical scientists need to have a richer understanding of computing as an intellectual discipline and a source of mathematical science challenges, and academic departments should assist in enabling this. A mechanism is also needed to ensure mathematical science researchers have access to computing power at an appropriate scale.

Adjusting the Educational Path in the Mathematical Sciences

The expansion of research opportunities in the mathematical sciences—and in careers that build on mathematical sciences education, regardless of their academic specialty—necessitates changes in the way that students are educated. It also calls for an effective plan to attract a greater number of talented young people into the mathematical sciences. The existing demand for people with strong mathematical science skills is likely to grow as positions requiring these skills continue to expand.

This growing demand has educational implications for the mathematical sciences community as it prepares students for a broad range of science, technology, engineering, and mathematics (STEM) careers. Specifically, it is essential that mathematical science educators at the K-12 and undergraduate levels convey to students how mathematical science coursework is used and the careers it can lead to. Graduate students also should learn this information so they can pass it along as faculty members to their students.

Mathematical sciences curricula need attention. The educational offerings of typical departments in the mathematical sciences have not kept pace with the large and rapid changes in how the mathematical sciences are used in science, engineering, medicine, finance, social science, and society at large. This diversification entails a need for new courses, new majors, new programs, and new educational partnerships with those in other disciplines, both inside and outside universities. New educational pathways for training in the mathematical sciences need to be created—for students in mathematical sciences departments, for those pursuing degrees in science, medicine, engineering, business, and social science, and for those already in the workforce needing additional quantitative skills. There are exciting opportunities for reaching out to new cadres of students.

While the mathematical sciences enterprise has tremendous responsibilities for educating students across the range of STEM fields, it is of course also essential to replenish itself. The federal government should establish a national program to provide extended enrichment opportunities for pre-collegiate students with an unusual talent in the mathematical sciences.

Mathematics and statistics departments, in concert with their university administrations, also should carefully consider the different types of students they are attracting, and wish to attract, and identify the top priorities for educating these students. This should be implemented for bachelor's, master's, and Ph.D.-level curricula. Every academic department in the mathematical sciences should explicitly incorporate recruitment and retention of women and underrepresented groups into the responsibilities of the faculty members in charge of the undergraduate and graduate programs, and in faculty hiring and promotion. With access to the proper resources, departments could adapt successful recruiting and mentoring programs that have been pioneered at a number of schools. These resources could also help locate and correct any disincentives that may exist in the department.

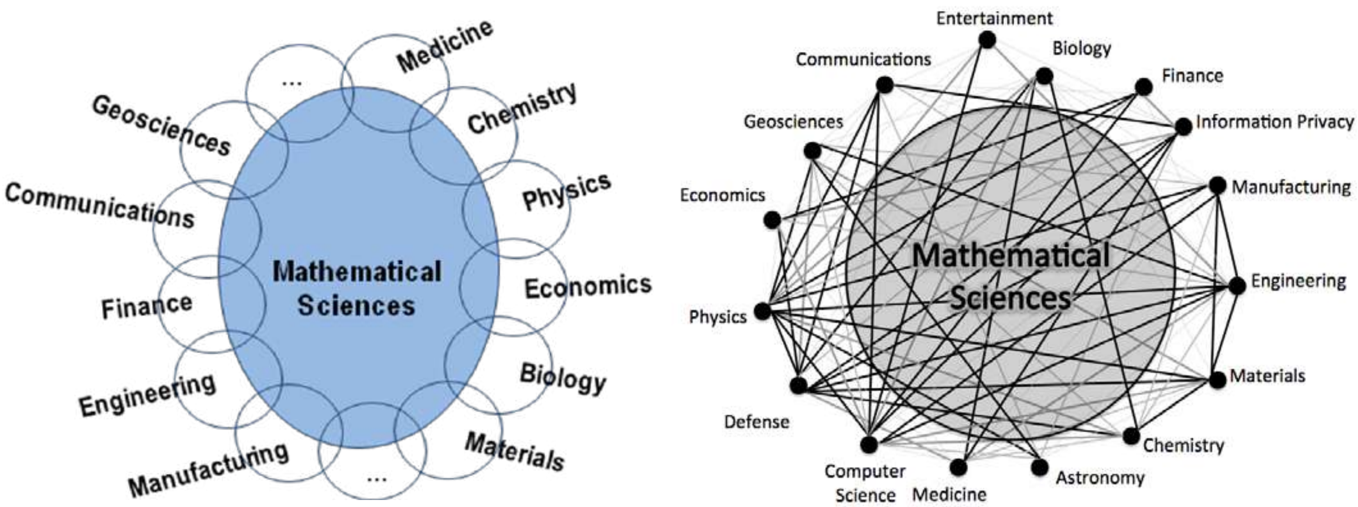
There is another consideration for strengthening the mathematical sciences enterprise: The market for mathematical sciences talent is now global, and the United States is in danger of losing its global preeminence in the discipline. The policy of encouraging the growth of the U.S.-born mathematical sciences talent pool should continue, but it needs to be supplemented by programs to attract and retain mathematical scientists from around the world, who increasingly have options in their own countries.

More professional mathematical scientists should become involved in explaining the nature of the mathematical sciences enterprise and its extraordinary impact on society, and academic departments should find ways to reward such work. Professional societies should expand existing efforts and work with funding entities to create an organizational structure with the goal of publicizing advances in the mathematical sciences.

Stresses on the Horizon

Financial stresses on students and their families, reductions in government funding for universities, and new educational technologies are creating pressure to lower costs. Mathematical science departments, particularly those in large state universities, have a tradition of teaching service courses for nonmajors—this approach helps to fund positions for mathematical scientists at all levels, particularly junior faculty and graduate teaching assistants. The desire to reduce expenses is pushing students to take some of their lower-division studies at state and community colleges or online. It is also leading university administrations to hire a category of faculty members who have greater teaching loads, reduced expectations of research productivity, and lower salaries. Another approach has been to implement online courses that can be taught with less ongoing faculty involvement. The recent emergence of massive online courses, some with mathematical science content, is another potential disruption to the status quo.

Because of their important role in teaching service courses, the mathematical sciences will be disproportionately affected by these changes. However, there may also be expanded opportunities to train students from other disciplines or those who are already in the workforce. Academic departments in mathematics and statistics should begin the process of rethinking and adapting their programs to keep pace with the evolving academic environment and to be sure to engage actively so that they have a seat at the table when curricula are modified and online courses with mathematical sciences content are created. The professional societies have important roles to play in mobilizing the community in these matters as well—that is, through mechanisms such as opinion articles, online discussion groups, policy monitoring, and conferences. Mathematical scientists should work proactively—through funding agencies, university administrations, professional societies, and within their departments—to be ready for upcoming changes to the college and university environment.



Caption: The mathematical sciences and their interfaces in 1998 (left) and 2013 (right). In the figure on the left, the empty "bubbles" are meant to reflect the many other intersections that are not explicitly labeled. As the number of interfaces increase, the mathematical sciences themselves broaden in response and play an important role in a highly-integrated system. These schematics are notional, based on the committee's varied and subjective experience rather than on specific data.

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數學對科學，科技發展，尤其是資訊科學，電子工程，硬體設計的重要性

賴瑾

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我深深相信語言和數學是一切學科的基礎。而數學能力在科學，工程上的 重要性更不可言喻。

我過去 30 年來從事過電腦系統晶片，x86 處理器，固態硬碟控制器，以及存儲系統的設計。目前也在台大電機、資訊系教授【階合成設計於應用加速】- Application Acceleration with High-Level-Synthesis 這門課。

許多科學的研究由於實體實驗的局限性，近幾年朝向發展運用科學計算來 模擬甚至取代實體實驗，因此 Computational Sciences 的重要性越來越高。 社會，商務，工程程也是朝向智能，提升效率的方向，都需要大量的運算、 計算能量，此外，人工智慧、資料科學都是優化（optimization）的技術，也都需要大量的運算。所以，運算、計算能量是一個國力的體現。

【高階合成設計於應用加速】這門課的目的就是設計效率運算的硬體 Efficient Computing。底下以此為例進一步說明。

設計應用加速的第一步即是先在算法上做優化，這需要對數學算式有深入的理解，才能知道那些地方可以簡化，同時需要評估其可接受的誤差。這部分的工作是整個設計的核心部分，對最後的運算效率及資源的使用有決定性的影響。而這工作目前需要對數學有深厚底子的科學家或工程師來設計，沒有機器或工具可以取代。接下來才是工程層次的優化，這部分有很多是可以用工具輔助工程師做優化。若是沒有第一階段在算法上的優化，而只是在工程上做優化，這是捨本逐末的做法。

台灣若是要發展高階的技術，產品要有競爭力，勢必要培養運算效能的人才，而這人才要從培養數學能力著手！

附錄 1-8

科技・人文聯合講座／從電機系減少電子學授課時數談起

李家同

原文網址：https://udn.com/news/story/7339/5367619

近年來，我發現很多大學的電機系在減少電子學的授課時數，在過去，多數大學的電機系必修的電子學要上三學期，每一學期三小時。可是有些大學的電機系必修電子學只有一學期，據說這是因為教育部一再強調必修課要減少。不論電機系學生將來從事何種工作，電子學總是非常重要的，減少必修電子學的授課時數是值得大家注意的。

我們政府非常重視半導體工業，如果電機工程師對電子學了解的不夠，可能對新的電晶體都很難接受，更不要說能夠在半導體工業上有創新的想法。電子學是和物理有關的，如果我們要有非常拔尖的電機工業，工程師應該對物理有相當好的了解。

政府也常常提到５Ｇ，５Ｇ是通訊的一種技術，很多通訊教授在埋怨學生的數學不夠好。通訊技術之所以能夠有飛躍的進步，數學扮了重要的角色。就以載波來說，當然載波與電機是有關的，可是為什麼要有載波，卻又和數學有很大的關係。我們現在用到的數位通訊，裡面用到了相當多的數學，數學根底不好的人是不可能對通訊有重大貢獻的。

ＡＩ更是紅透半邊天的學問，我們可以問一句話，所謂深度學習是由哪一種人發展出來的？內行人都會告訴你，深度學習是與數學有密切關係的。

在大學裡減少很多必修課已經是錯誤的做法，最嚴重的是，在高中也要減少必修課。我實在不知道教育部有什麼權利可以做這種決定。我相信教育部的官員們認為科技千變萬化，不停地有新的科技出現，因此學生們最好早日對新科技有所了解，所以新課綱重視選修課。以中學為例，中學生是不可能真正了解半導體工業或５Ｇ技術的，理由是要了解這些新科技，先要在物理和數學等打下基礎。

我認識好幾位半導體專家，他們都不知道如何能教高中生半導體科學，他們都認為這種學問不妨留到大學來學。我也認識一些通訊系的教授，很多附近高中會請他們授課，講解通訊的原理。多數教授都會婉拒這種邀請，理由是高中生應該先好好將數學學好。

我們也常聽到政府強調創新，在科技方面，如果一個人在基本學問上相當膚淺，是不可能創新的。牛頓說，他是站在巨人的肩膀上，所以可以看得遠。我們還可以用白話來說，那就是他很有學問，所以他能夠創新。政府如果真的希望我們的科技有很好的進步，鼓勵學生爬上巨人的肩膀。