



Taiwan's science miracle

Toni Feder

In the past two decades, a flourishing economy and maturing infrastructure have Taiwanese physicists both staying home more and engaging internationally.

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National Taiwan University in Taipei is one of the top research universities on the island.

Fu-Jen Kao returned to Taiwan in 1993 after spending more than seven years in the US and was “startled” by what he found. That year, fresh physics PhD in hand from Cornell University, he joined the faculty of National Sun Yat-sen University, on the southern part of the island. There, he says, “I had to make my own machine shop. We didn’t have an electronics or technical shop either. The research infrastructure was minimal. It was difficult to retrieve journal papers—the collection in the library was limited.” Looking back now, he sees that the situation was not much different than at the country’s other universities. “Physicists need support. Information, interaction, and infrastructure are what allow us to do decent work. All this was latent.”

Moreover, Kao recalls, “personal connections counted somewhat more than merit” in the allocation of resources, young faculty didn’t get enough startup money, and standards were generally low—junior faculty were promoted to tenure with just a few publications. In Taiwan in 1993, he says, “if you published in [*Physical Review Letters*], you instantly became a national star.”

Much has changed in the intervening two decades: Taiwan’s science communities have gone from being backwaters to becoming vibrant, connected, well-funded research centers that in certain areas hold their own on the world stage. All the while, Taiwan remains in political limbo. With its population of 23 million, Taiwan upholds its independence, even as its neighbor across the strait, the 60-fold more populous mainland China, maintains its claim over the roughly 36 000-square-kilometer island. The transformation in research and higher education in Taiwan came about thanks to a strong economy, government support for education and research, and Yuan Tseh Lee.

Homecoming

In 1986 Lee became Taiwan’s first Nobelist, sharing the chemistry prize with Dudley Herschbach and John Polanyi “for contributions concerning the

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Yuan Tseh Lee at the dedication of the Submillimeter Array on Mauna Kea in 2003. Taiwan's first Nobel Prize recipient and later president of the country's Academia Sinica, Lee has been key in building up science in Taiwan. (Courtesy of the Institute of Astronomy and Astrophysics, Academia Sinica.)

dynamics of chemical elementary processes" (see *PHYSICS TODAY*, March 1987, page 17). Eight years later, when Lee was a professor at the University of California, Berkeley, Taiwan's president at the time, Teng-Hui Lee, asked him to return to his country of birth after more than 30 years in the US. Lee accepted the invitation, and for 12 years he served as president of Taiwan's Academia Sinica—the country's national academy and foremost research organization, with 30 institutes spanning humanities, social sciences, and natural sciences. He championed research and education at all levels throughout the country.

"To promote science in Taiwan," Lee says, "I needed to do two things. One was to get science funding increased substantially." He was instrumental in getting the government to raise Academia Sinica's budget by 10% per year for 10 years. In 2013 its internal budget, which covers salaries, infrastructure maintenance, and research activities, was about \$450 million (or roughly 14 billion New Taiwan dollars), with about \$120 million for the physical sciences. "People respected me immensely because of the Nobel Prize," he says. The president of the academy has direct access to the country's president and prime minister. "That made it easier to convince them that science was important. Of course, the economy improved in Taiwan at that time." In 1994 the science budget for Taiwan was about 1.6% of the GDP. Today it exceeds 3%; and from 1994 to 2013, the GDP increased from \$250 billion to \$470 billion. In short, Lee effectively channeled part of the country's remarkable economic growth—sometimes called the Taiwan Miracle—into its sciences.

Lee's second mission was to bring in top scientists from all fields. "Whenever I set up a new institute [within the Academia Sinica] or needed a new director, I went to Harvard, MIT, Illinois, Stanford," he says. "I put enormous effort into attracting excellent scientists to return to Taiwan." Yuh-Lin Wang, who moved to Academia Sinica's Institute of Atomic and Molecular Sciences (IAMS) in 1991 after graduate studies at the University of Chicago and a postdoc at Bell Labs, says Lee "single-handedly transformed the Academia Sinica system during his tenure."

Conditions at Academia Sinica are cushy. Like the Max Planck Institutes in Germany or the Russian Academy of Sciences before its decline at the end of the Cold War, Academia Sinica attracts top researchers, funds them well, and expects them to focus on research; many also take appointments at universities to gain access to students. After its dramatic rise during Lee's tenure as president, funding has settled "at a level that is very comfortable," says Wang. The budget "is sufficient to support the curiosity-driven research conducted by [the Academia Sinica's roughly] 900 principal investigators," he says.

Lee also recruited expats for university positions; he set up a private foundation that raises funds to add to the salaries set by the government. Public money for university researchers comes mainly from the National Science Council (NSC), a body that is slated to be replaced this month by a new ministry of science and technology. Over the past decade or so, there have been national programs—funded by the NSC and other agencies—in such areas as telecommunications, nanotechnology, digital archives, genomic medicine, and energy, with targeted funding ranging from about \$30 million (telecommunications) to \$200 million (energy) annually. In 2013, separate from such national programs, the NSC annual physics budget was about \$24 million; that budget has been stable since about 2009, when it dipped due to the global economic slump, and represents about a 50% increase over a decade earlier. The largest industrial investor in physics-related R&D is the Taiwan Semiconductor Manufacturing Co, which in 2012 spent about \$1.4 billion.

Universities also got a boost with an investment in infrastructure from the Ministry of Education, totaling nearly \$1.7 billion from 2005 to 2010. At the time, Maw-Kuen Wu, codiscoverer of superconducting yttrium barium copper oxide, was serving as chair of the NSC; he says, "we [the NSC] strongly recommended that the government put in extra investment in universities to be competitive with

China, Singapore, Hong Kong, and [South] Korea.” Seven major universities shared the investment, says Wu, who returned to Taiwan in 1989 from Columbia University and is now president of the 20-year-old National Dong Hwa University, on Taiwan’s east coast.

Whereas money used to be distributed quite evenly among Taiwan’s university researchers, tighter budgets and new policies at the NSC raised the competitiveness bar and, consequently, the level of science. The approval rate for grants is less than 55%, down from 70–80% a decade or so ago. The pie chart below shows the distribution of NSC funds in physics by subfield for 2013.

The new NSC policies include making grant money more flexible. For example, says Hsiu-Hau Lin, a physicist at National Tsing Hua University, budgets for manpower—students and assistants—and for consumables can now be mixed, funding intended for hardware can be transferred to other uses, and funding in multiyear grants is not restricted by year. Moreover, the peer-review process for grant applications has been made more transparent, says Kao, who is now at National Yang-Ming University and in January became president of Taiwan’s physical society. The average grant for theoretical physics is about \$30 000 per year, and the average for experimental physics is double that, says Lin. A few of the best university groups have much higher funding.

Mei-Yin Chou, a Taiwanese physicist who spent three decades in the US, mostly at Georgia Tech, compares research funding in the two countries: “In Taiwan, if you are doing well, you probably don’t need to worry for funding. In the US, there are very good scientists who are struggling for funding.” She notes that personnel costs and overhead are lower in Taiwan, so a higher portion of each grant goes into research.

Many universities offer bonuses for publications, a practice that was introduced because faculty salaries are lower than in neighboring countries, says Minn-Tsong Lin of National Taiwan University and current chair of the NSC’s physics review panel.

The bonuses are intended to stimulate research, with amounts as high as \$20 000, depending on the impact factor of the journal. For example, Shih Ping Lai, a radio astronomer at National Tsing Hua University, says she got a bonus of about \$1700 for her last paper, which appeared in *Astrophysical Journal*. “The university wants to promote publications,” she explains. “But if they don’t give me a bonus, I still want to work.” Such bonuses are falling out of favor.

Hot topics

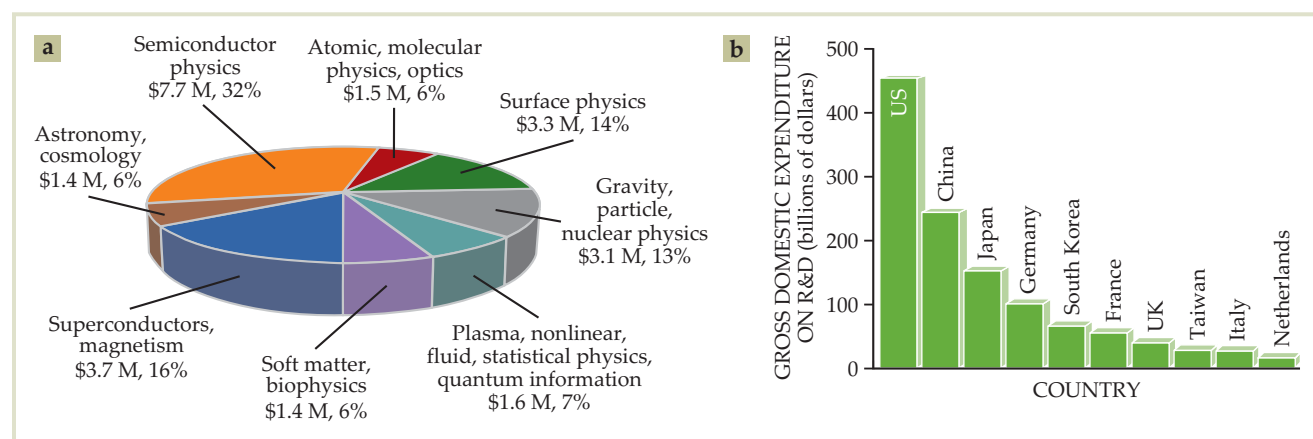
More than half of the country’s physicists work in areas related to condensed matter. And the field benefits from Taiwan’s world-class industry in integrated circuits, semiconductors, and optoelectronics. Nonlinear optics, nanoscience, biophysics and biophotonics, plasmonics, high-energy physics, and astronomy—especially radio astronomy—are also strong. A few examples suggest the breadth of top-notch research in Taiwan:

► Chia-Liang Cheng of National Dong Hwa University focuses on bioapplications of nanodiamonds. Currently, he is working to create artificial blood by embedding nanodiamonds in hemoglobin molecules; the nanodiamonds form a biocompatible core and their fluorescence tracks the artificial cells with confocal microscopy. “We can use old blood, waste blood, because we destroy the original cell and make use of the hemoglobin molecules,” he says. “Using Raman spectroscopy, we have demonstrated that this artificial blood will carry oxygen.”

► Jim Lin at the Academia Sinica’s IAMS in Taipei led an effort to quantify the absorption cross section of chlorine peroxide using molecular-beam measurements of the compound’s dissociation by light. The measurements are important for understanding the dynamics of ozone-hole formation.¹

► Mitch Chou runs a crystal-growth laboratory at National Sun Yat-sen University, where he builds specialized ovens and grows thick-film and bulk crystals for users around the world.²

► Beginning with his accidental discovery more than two decades ago that micron-sized silicon



Taiwan’s science funding. (a) The distribution by subfield of \$24 million for physics in 2013 by Taiwan’s National Science Council. (b) Total R&D expenditure for selected countries in 2012. The dollar amounts are adjusted for differences in purchasing power. (Comparative data from the Organisation for Economic Co-operation and Development.)

dioxide particles were highly charged and could be suspended in plasma, Lin I of National Central University has long been at the forefront of research on dusty plasmas. The suspended particles can be condensed from the gas to liquid and crystal states using RF power to reduce the temperature. (For more on dusty plasmas, see the article by Robert Merlino and John Goree in *PHYSICS TODAY*, July 2004, page 32.) Recently he and colleagues have been investigating the self-organization of such particles.³ Another current area of study is nonlinear acoustic waves in a gas-state dusty plasma.⁴

► Lain-Jong Li of the Academia Sinica's IAMS works in the field of novel two-dimensional materials. He has developed a method to grow thin layers of highly crystalline molybdenum disulfide in large areas on insulating substrates.⁵ With his approach, which he says is simple and scalable and can be used with other materials, the MoS₂ films can be transferred to other substrates.

Going forward, Wu hopes that Taiwan's scientists will form more interdisciplinary collaborations and apply their expertise to problems relevant to the local environment and society. Possible topics, he says, include local rock formations, seismicity, and geothermal energy sources.

Big science

Taiwan's major user facility is a 1.5-GeV light source at the National Synchrotron Radiation Research Center, located in the Hsinchu Science Park, near two universities, National Tsing Hua and National Chiao Tung. First opened in 1993, the Taiwan Light Source serves about 2200 users per year, 10% from abroad. A second light source, described in the box on page 49, is set to open next year with double the electron energy, higher luminosity, and lower emittance—a measure of the spread of circulating electrons in position-momentum space.

Another facility, the Academia Sinica Grid Computing Center, is one of 11 top-level centers—the only one in Asia—that support the Large Hadron Collider at CERN. In addition to high-energy physics, the center collaborates with universities in Taiwan and in the Asia Pacific region in earthquake and tsunami simulation, drug discovery, social sciences, and other fields.

Taiwan participates in the Atacama Large Millimeter/submillimeter Array in Chile through agreements with the facility's East Asian and North American partners. And, explains Lai, the Academia Sinica's Institute of Astronomy and Astrophysics, where most of the country's astronomers work, arranged that Taiwan's astronomers "would not get guaranteed time. Instead, we compete based on merit." That's worked out well for Taiwan's radio astronomers, she says. "Just by money, we would probably get 2% of the time. But we get about 6% of the total time."

Other major facilities and experiments in which Taiwan's universities or the Taiwanese government participate include Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) in Hawaii; Australia's neutron source; the Alpha Magnetic Spectrometer, which studies cosmic rays and dark

matter from aboard the International Space Station (see *PHYSICS TODAY*, June 2013, page 12); Japan's B-factory experiments, Belle and Belle II; the China-US Daya Bay reactor neutrino experiment north-east of Hong Kong; PandaX, a dark-matter experiment in China's underground laboratory; and the ATLAS and Compact Muon Solenoid experiments at CERN.

An ongoing debate

The vast majority of Taiwan's senior scientists and engineers—those perhaps age 40 and older—spent significant periods abroad, overwhelmingly in the US. But over the past 20 years, the country's research and education have matured to the point that scientists now often prefer to stay home for their education. The number of Taiwanese students in the US peaked in the 1993–94 academic year at 37 581; in 2012–13, that number was 21 867.⁶ The healthy research environment and the availability of jobs in industry are both reasons that students choose to stay in Taiwan. Even so, among international students in the US, Taiwanese make up the sixth-largest group.

In recent years, students from Taiwan have also enrolled increasingly in schools in Australia, Canada, Europe, and Japan. Contributing to that trend, Kao notes, were the tightened visa controls implemented in the US after the 2001 terrorist attacks and greater competition from China for limited university spots in the US.

According to the NSC, some 32 731 students were working toward their PhDs in Taiwan in 2012; about 2440 PhDs were granted in the natural sciences that year, 722 of them in physics and related fields.

But in just the past two years, the number of applicants to PhD programs in Taiwan has plummeted. At National Taiwan University, the crown jewel among the country's universities, the number of applicants last year was half that of the previous year. It's become easier for them to get a job with a master's than with a PhD, explains Yang Chan Chang, the Los Angeles and Houston attaché in the science and technology division of the Taipei Economic and Cultural Representative Office.

A natural tension arises from the fact that students can now get a competitive graduate degree in Taiwan. On the one hand, it's a welcome metric of the quality of education: Several Taiwanese researchers say an education in Taiwan compares favorably with good state schools in the US but "not yet" with Harvard University or MIT. And in light of the diminishing numbers of students, group leaders in Taiwan want to attract and retain good students in their labs. On the other hand, there remains a general recognition that international experience is valuable. "That's how people gain the skills of communication, presentation, generating ideas," says Kao. "If they want to stay in academia, they better spend a year or two abroad." At the PhD level, says Hsiu-Hau Lin, the most talented students still go abroad.

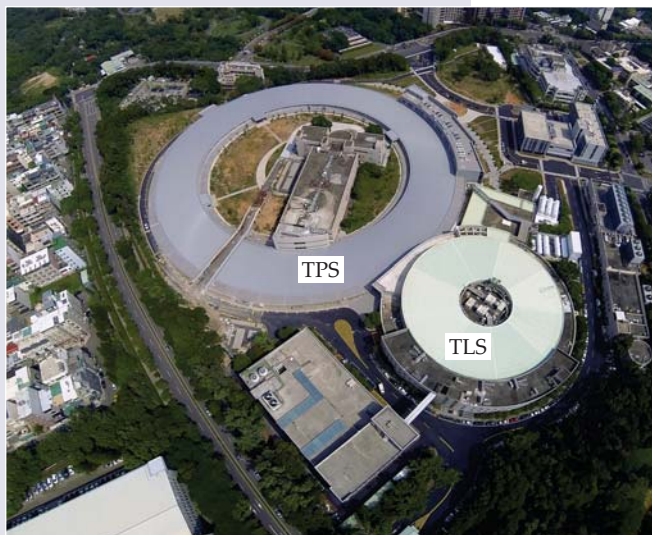
Chih Wei Luo, who earned his PhD in 2003, initially intended to study abroad but ended up stay-

A state-of-the-art synchrotron light source

The Taiwan Photon Source (TPS), designed to provide high-intensity, low-emittance beams at both hard- and soft-x-ray wavelengths, is set to open in mid 2015. It is intended to support users from Taiwan and abroad in industrial and basic research, especially in the areas of biology and nanotechnology—among the initial beamlines are ones optimized for protein micro-crystallography, low-energy excitation of materials with atomic specificity, and scanning nanoprobe studies that resolve structures with 40- to 50-nm resolution. The Taiwanese government footed the \$235 million tab for construction, plus \$62 million for the first 7 beamlines; the machine can accommodate a total of 44 beamlines.

The storage ring is about 518 meters in circumference, with an electron beam energy of 3 GeV. It will have three superconducting RF cavities to power high-current (500 mA) operation. The TPS will provide coherent x rays in a narrow spectral bandwidth, which is key for high-resolution spectroscopic measurements. Similar machines are in operation in Australia, France, Spain, South Korea, Switzerland, and the UK and are being built in Brazil, Sweden, and the US. Thanks to advances in electron storage rings and undulators, such intermediate-energy rings perform on a par with older, more expensive, higher-energy ones.

Located next to the Taiwan Light Source (TLS), which opened more than 20 years ago at the National Synchrotron Radiation Research Center in Hsinchu Science Park on the island's northwestern coast, the TPS storage ring circulates a beam that is double the energy and two to five orders of magnitude brighter than the TLS beam. For the first few years, at least, both light sources will operate—the TLS at visible UV and IR wavelengths, and the new TPS in the hard- and soft-x-ray regimes.



ing in Taiwan for family reasons. Now a professor at National Chiao Tung University, Luo (shown on page 50) does research that involves developing and using ultrafast optical techniques. The advantages of staying, he says, are not having to put in the time, effort, and money to apply to study abroad; the lower prices in Taiwan; and tighter ties to the local physics community. On the downside, he notes the obvious: It's harder to interact with foreign students and to form international collaborations. But, he says, research infrastructure has improved greatly in Taiwan, and with the internet, "the world becomes small. . . . Students can obtain news or reports from other places immediately."

Culture shock, cultural fusion

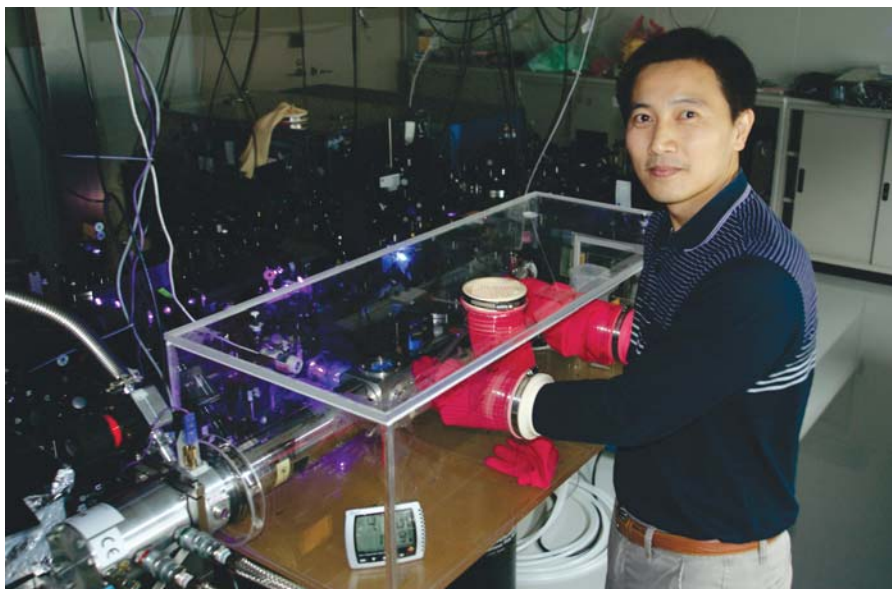
For students who do stay in Taiwan, scientific advisers and the government create international cultural and networking opportunities. Juhn-Jong Lin, a low-temperature experimental physicist who earned his PhD in the US in 1986 and is now a professor at National Chiao Tung University, says it takes a couple of years abroad "to learn to appreciate the deep-rooted Western science culture and tradition." But National Dong Hwa's Cheng observes that "students today want to go for three months, not for nine years [like I did]." Short trips are worthwhile, he says. "They still get the culture shock, or cultural fusion. It makes an impact." Some students go abroad for a year during their PhD studies, or for a postdoc. "Another way to bridge," says Cheng, "is to bring foreign students in. The numbers are increasing."

For example, the Taiwan International Graduate Program attracts students from around the world. They work with researchers at the Academia Sinica but earn their degree from a university in Taiwan. Domestic students may participate, but their number is capped at 50% because of the competition with universities for good students. Each year the program, which covers the physical and life sciences, hosts about 100 students from 40 countries.

So far, foreign students—mostly from India, Malaysia, and other East Asian countries—make up only about 2% of the total student body in Taiwan. Administrators are working to attract more from abroad to keep classrooms full. Not only do fewer students want to pursue graduate degrees, but with Taiwan's low birthrate, the total university enrollment is expected to decrease precipitously in the coming years. In fact, after a dramatic expansion in the number of universities in the past two decades, with vocational schools and the like having been upgraded to universities, a massive cutback is under discussion. Of more than 160 universities, about a dozen do research on an internationally competitive level.

"An international enterprise"

Meanwhile, post-9/11 changes in US visa policies made it much more tedious for Taiwanese students and researchers to visit the US. Whereas Taiwanese scientists were used to being granted five-year visas, new rules shortened that to, typically, one year. The new application process also required people to show up in person in Taipei—and even then, visas



Chih Wei Luo, a homegrown physicist at National Chiao Tung University, specializes in ultrafast optical techniques. He and his group have built a dual-color pump–probe system to study the ultrafast dynamics of electrons, phonons, and spins in strongly correlated quantum matter; an IR pump–probe system tuned to study topological insulators and narrow-bandgap materials; a terahertz generation and detection system; and an ultrafast laser micromachining system to vary material properties such as surface morphology, carrier concentration, and carrier mobility. (Photo courtesy of Sheng-Yang Tseng.)

were delayed often enough that applicants became discouraged. Graduate students began to look more to Europe and Japan, and established researchers increasingly began seeking collaborations in other countries. Although the visa restrictions were relaxed in October 2012, they caused lasting damage, says Mitch Chou, the crystal grower at National Sun Yat-sen University.

For example, Chou, who spends most summers in labs outside the country, turned his attention from US institutes to labs in Germany. And Juhn-Jong Lin now pursues collaborations with colleagues in Japan—which, coincidentally, has been trying to internationalize its science community (see *PHYSICS TODAY*, December 2008, page 28). Having established a joint low-temperature physics lab with RIKEN, he says, “There is now not much incentive to travel to the US.”

“Science is an international enterprise,” says Mei-Yin Chou. “When I was in the US, there were a lot of activities around the world that I did not know about. The US is big enough, you can always find collaborators. But when I came here, I started having interactions with scientists in Asia and Europe, and I realized there are a lot of things going on. . . . The dominance of US science is not as strong as it was 30 years ago.”

One place where science and spending on scientific infrastructure has been growing steadily is mainland China (see the article by Charles Day, *PHYSICS TODAY*, March 2010, page 33). And despite strained relations between China and Taiwan, interactions are becoming more common. Researchers visit each other, cosupervise students, and hold joint workshops. Juhn-Jong Lin travels two or three times each year to mainland China, where he visits labs and serves on the editorial board of the physics magazine *Wuli* (which publishes excerpts from *PHYSICS TODAY*). He describes scientific collaborations with scientists in China as “subtle” and points to difficulties with trust and credit for achievements.

On joint publications, the listing of institutions can become contentious; increasingly, the solution is to list affiliate institutions and cities, with no mention of Taiwan or China. People holding a passport from the People’s Republic of China can come to Taiwan as postdocs or work on temporary contracts, but they cannot be employed by the Taiwanese government; the handful of Chinese faculty members in Taiwan went there after obtaining citizenship in other countries. The NSC sponsors “cross-strait” conferences in various fields—although the council would not reveal how much funding is available for such activities.

What is ahead for science in Taiwan? Many scientists note that Taiwanese culture has relaxed thanks to the wider democratization of the country and widespread internet access. For science, that has translated into more creativity and a departure from what Mei-Yin Chou calls the “me-too” culture. “In the old educational system, we were supposed to follow the book,” she says. “Now the whole society is more open, and that encourages creativity. That’s reflected in the academic world.” Kao agrees: “We are quite a dynamic society. We can provide a model that shows that even a small or medium-sized country can do decent work. If you are willing to work on it, you can improve your relative standing in the world.”

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