SG 50

SINGAPORE'S SCIENTIFIC PIONEERS

BY JULIANA CHAN, GRACE CHUA, SHUZHEN SIM AND REBECCA TAN

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This book is dedicated
to all scientists in Singapore,
past, present and,
most of all,

ASPIRING.

Published by: Asian Scientist Publishing Pte Ltd
5 Toh Tuck Link
Singapore 596224
E-mail: editor@asianscientist.com
Website: http://www.asianscientist.com
ISBN: 978-981-09-5893-0 (hardcover)
ISBN: 978-981-09-5894-7 (paperback)
ISBN: 978-981-09-5895-4 (e-book)

National Library Board,
Singapore Cataloguing-in-Publication Data

Chan, Juliana, author.
Singapore's scientific pioneers / Juliana Chan, Rebecca Tan, Grace Chua and Shuzhen Sim.– Singapore : Asian Scientist Publishing Pte Ltd, [2015]
pages cm
ISBN : 978-981-09-5893-0 (hardcover)
978-981-09-5894-7 (paperback)

1. Scientists – Singapore – Biography. 2. Science – Singapore – History.
I. Title. II. Tan, Rebecca, author. III. Chua, Grace, author. IV. Sim, Shuzhen, author.

Q141
509.225957 -- dc23 OCN910911412

Book design by: Oxygen Studio Designs Pte Ltd
Printed by: KHL Printing Co Pte Ltd

PREFACE

Juliana Chan and Rebecca Tan

Singapore has made much progress in the 50 years since its independence, not least in terms of research output and achievements. Although many people are aware of the importance of research and development for Singapore's growth, little is known about the individuals who laid the foundations for Singapore's scientific achievements. These scientists, although lauded by their peers internationally, are not household names in Singapore; their contributions can seem obscure.

In celebration of our nation's 50th anniversary, and supported by grants from the SG50 Celebration Fund and Nanyang Technological University, the editorial team at Asian Scientist has initiated a combined online and print project to celebrate Singapore's scientific pioneers. In this book, we try to capture the struggles and successes of their extraordinary lives, while articulating their immense contributions to the world of science.

Above all, we thank the 25 people who agreed to be interviewed for this book. They are all above 50—born before Singapore gained independence—and have made exceptional contributions to our country's scientific, engineering, medical and education sectors. Although we approached each interviewee with a similar set of questions, we gave them the freedom to emphasise and elaborate on different aspects of their lives. As such, the reader may notice slight differences in structure and content between profiles. We feel it is important to preserve the voices and inclinations of the scientists, even at the expense of some consistency across profiles.

One major challenge was selecting 25 individuals for this book. There are of course many other deserving Singaporean scientists whom we could not feature. We regret that our own limitations prevent us from being able to commemorate here their significant contributions to Singapore. It is clear to our small editorial team that this book cannot be a comprehensive repository of Singapore's scientific history, and certainly it would be impossible even if we tried. Rather, the stories here are meant to inspire young people to embark on science careers of their own someday.

Finally, we thank Grace Chua and Shuzhen Sim, who wrote many of the chapters; Sudhir Thomas Vadaketh, who edited all the chapters; Cyril Ng and Bryan van der Beek, who took the beautiful photographs that accompany the profiles; Eunice Ong, who edited the photographs; and our design team from Oxygen Studio Designs, who did the design and layout for the book. We appreciate your support and this book is very much your hard work.

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INTRODUCTION

After retiring in 1911 and returning to England, Dr Ridley published in 1930 a seminal and comprehensive work on plant dispersal, based on his scientific expeditions in both Malaya and Sabah, and a review of widely-scattered literature on the subject.

Photo credit: Walter Makepeace, Gilbert Edward Brook and Roland St John Braddell (Eds.) *One Hundred Years of Singapore*, 1921.

Modern Singapore's foray into science is generally believed to have begun with the formation of the Science Council in 1967, two years after the country gained independence.

But in the 1890s, Henry Nicholas Ridley, an English botanist and geologist who was the first scientific director of the Singapore Botanic Gardens, was already carrying out experiments on a plant that would flourish across the Malay Peninsula—rubber.

At the time, the rubber tree (*Hevea brasiliensis*), indigenous to the Amazon basin, had never been commercially grown anywhere else. Malaya's main cash crops then were coffee, nutmeg and cloves. In 1895, Dr Ridley discovered a new method of tapping rubber: by making tiny incisions into the tree's lactiferous vessels (little tubes containing latex), one could spare the cambium (stem cell) layer from serious damage, raising overall yields.

His timing was fortuitous. In the early 1900s, Henry Ford's mass production of the automobile fuelled a worldwide demand for rubber tires. Malayan rubber output, catalysed by Dr Ridley's new method, boomed.

THE SCIENCE COUNCIL—ONE SMALL STEP FOR SCIENCE IN SINGAPORE

In 1965, research and development (R&D) in Singapore was rudimentary—technicians were trained to manufacture products, not innovate.

The Science Council was given a seemingly straightforward task—to raise public awareness of the importance of science and technology (S&T) to industry and academia. But in reality this was a tall order. Most Singaporeans did not have undergraduate degrees, let alone graduate degrees in S&T. Amid the uncertainty of developing a newborn country, R&D seemed like a frivolous pursuit.

Lee Kum Tatt, one of Singapore's earliest homegrown PhDs, was the Science Council's first chairman. Among its many outreach activities were a 1970 survey of R&D activities in the public sector and the 1972 Science Quiz. In 1970 it also mooted the formation of the Singapore Science Centre—a project completed in 1977 at a cost of S$14m (S$32.5m in today's dollars).

SINGAPORE'S FIRST DEDICATED MINISTRY FOR SCIENCE AND TECHNOLOGY

After the 1968 general elections, Toh Chin Chye was appointed Singapore's first minister for science and technology. As manpower development was the top priority, Dr Toh introduced research fellowships and grants for graduate-level research, which were managed by the Science Council.

It was another decade before basic research started to take shape in Singapore. With meagre resources at their disposal, scientists had to be resourceful. Consider Sit (Wong) Kim Ping (see p.74), professor of biochemistry at the National University of Singapore (NUS), whose research into mitochondria required analysis of metabolic processes in rats. In the 1970s, she jury-rigged a pestle onto a rotating drill bit in order to homogenise rat livers at high speed. She also used a cooking pot with holes drilled in it to boil multiple test tubes over a Bunsen burner.

Those were straitened times for researchers. Nevertheless, a 1975 review of the civil service chaired by Lee Kuan Yew, the prime minister, recommended that the Ministry of Science and Technology fund projects that are more applied in nature. "Ours is a nation with no natural resources. Neither can we afford the means to carry out fundamental research…" the review report gravely stated.

In 1981 the Ministry of Science and Technology was folded into other ministries. The Science Council was placed under the purview of the Ministry of Trade and Industry, and its role reduced to promotional activities such as organising conferences and establishing links with international scientists.

Toh Chin Chye (left) viewing a moon rock at the National Museum of Singapore, January 13th 1970. Dr Toh completed a PhD in physiology at the National Institute for Medical Research, London, in 1949. He joined the University of Malaya in 1953 as a physiology lecturer, before entering politics in 1959. Putting him in charge of science and technology was an easy decision—Dr Toh was the only Cabinet member with a PhD.

Photo credit: Courtesy of the National Museum of Singapore, National Heritage Board.

SINGAPORE PIVOTS INTO HIGH-TECH R&D

Despite these setbacks, there was growing corporate interest in Singapore as a gateway to Asia. Large multinational companies in the semiconductor and disk drive industry, such as Seagate Technology, Motorola and Fairchild Semiconductor, set up R&D units here. In 1981, Apple Computer opened a manufacturing plant in Singapore to assemble personal computers.

It was the deep recession of 1985-86—sparked partly by wage inflation among low-cost factory workers—that prompted Singapore's shift into high-tech R&D. The country was no longer able to compete with lower-cost manufacturing destinations, such as China and Malaysia. Singapore thus continued its move up the value chain. It began training a sophisticated workforce and establishing research institutes to attract investors and collaborators around the world.

To lead this charge, Philip Yeo, then permanent secretary of defence and chairman of the National Computer Board (NCB), was appointed chairman of Singapore's Economic Development Board (EDB) in 1986. Under Mr Yeo, the Science Council was replaced by the National Science and Technology Board (NSTB) in 1991. The NSTB was tasked with attracting foreign investment into Singapore. New research institutes in the country focussed on R&D into disk drives, semiconductors, chemicals and pharmaceuticals, among others.

S&T budgets have grown in tandem with the sector's growing importance to the country. The first five-year National Technology Plan for 1991-95 had a budget of S$2bn (S$3.1bn in today's dollars), which was promptly doubled five years later. The most recent five-year budget for 2011-15 is S$16.1bn.

REACH FOR THE STARS

In the 2000s, R&D activity grew exponentially. Mr Yeo became co-chairman and then executive chairman of NSTB in quick succession. He reorganised NSTB-funded research institutes under two councils: the Science and Engineering Research Council, overseeing the physical sciences and engineering, and the Biomedical Research Council, overseeing the biomedical sciences.

NSTB was renamed the Agency for Science, Technology and Research (A*STAR) in 2002. A new scheme called the A*STAR National Science Scholarships was launched to cultivate local PhD scientific talent; it has since funded more than 1,000 Singaporean scholars and fellows locally and abroad. Exploit Technologies Pte Ltd was also established to manage A*STAR's intellectual property and facilitate technology transfer in the form of licensing agreements or new start-ups.

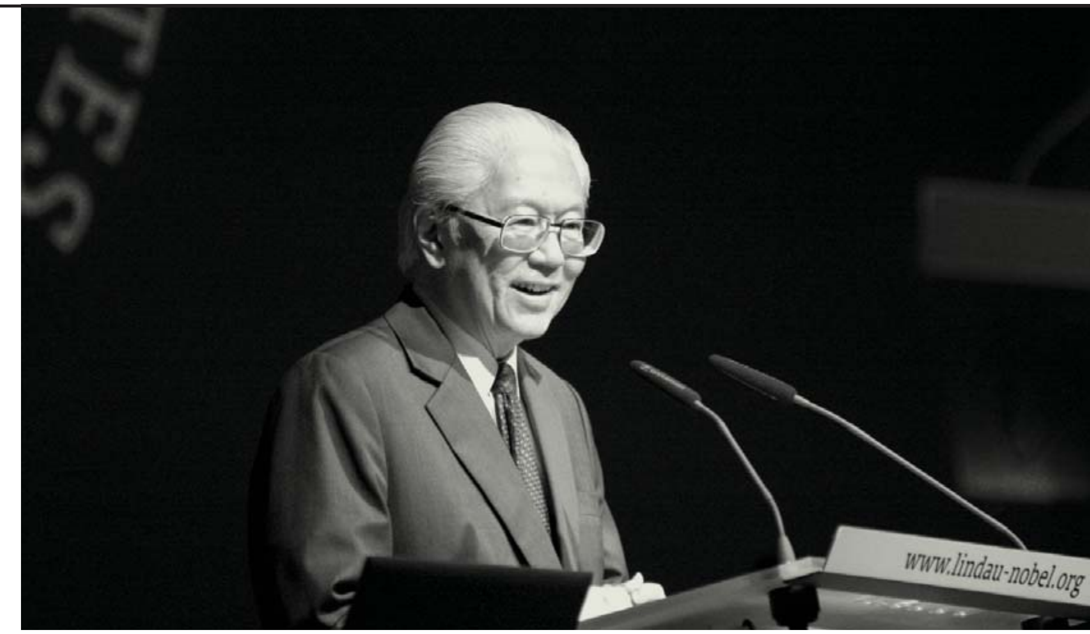
Biomedical scientists had reason to cheer in 2003, when a sprawling research hub, called Biopolis, was officially opened. There, joining four young biomedical research institutes is the much older Institute of Molecular and Cell Biology, established in 1985. Large pharmaceutical and biotechnology companies such as Novartis Pharmaceuticals have also set up facilities there.

All these developments are part of the biomedical sciences initiative, a S$1.48bn plan to establish the sector as the fourth pillar of Singapore's economy, alongside electronics, engineering and chemicals. Many have helped Mr Yeo implement this initiative, including Sydney Brenner (see p.22), an elder statesman of science; Tan Chorh Chuan (see p.86), then dean of medicine at NUS; John Wong (see p.106), then an oncology-haematology professor at the National University Hospital (NUH) and NUS; and Kong Hwai Loong, former executive director of the A*STAR Biomedical Research Council.

The physical sciences and engineering sector has been the mainstay of Singapore's economy since independence. Fusionopolis, which opened next to Biopolis in 2008, was built as a home for all the physical scientists and engineers in Singapore. Exceptions are the Institute of Chemical & Engineering Sciences, which is located on Jurong Island; and the Singapore Institute of Manufacturing Technology and the Data Storage Institute, both of which are located on university campuses. Subsequent phases of development will expand Fusionopolis into a business park for information technology (IT), media, electronics, physical sciences and engineering companies.

Meanwhile, a cluster of start-ups, mainly in the media and IT space, is located in the adjacent Ayer Rajah Crescent area, the so-called "Silicon Valley of Singapore".

In 2006 the National Research Foundation (NRF) was established as a department within the Prime Minister's Office with a mandate to set the national direction for R&D. Among other things, it offers grants to fund research that has strategic importance to Singapore. Its prestigious Singapore NRF Fellowship supports independent researchers based here. In 2013, it launched its flagship Global Young Scientists Summit, an annual conference attracting Nobel Laureates and other award winners, inspired by the Lindau Nobel Laureate Meetings.



Tony Tan Keng Yam addressing the audience at the 2012 Lindau Nobel Laureate meeting. Dr Tan, the seventh president of Singapore, served as the inaugural chairman of NRF from 2006 to 2011. After graduating with a degree in physics from the University of Singapore, he received a PhD in applied mathematics from the University of Adelaide in 1967. He was a mathematics lecturer at the University of Singapore before entering politics.

Photo credit: Markus Pössel/ Creative Commons.

FROM A HUMBLE MAGPIE—THE GROWTH OF SINGAPORE'S MILITARY RESEARCH AND DEFENCE CAPABILITIES

Many are familiar with the narrative of how post-independence Singapore lacked a strong military force, prompting the government to implement mandatory National Service for all Singaporean males, as part of a broader defensive strategy to deter real and present threats to the country.

But few have heard the story of how, in 1971, Singapore also started to prepare for a "future" war. It was the peak of the two-decade-long Vietnam war; the US was fighting Russian surface-to-air missile systems using electronic warfare.

Goh Keng Swee, then minister of defence, realised that mastery of the electromagnetic spectrum would be crucial for military success in the future. He assembled a team of engineers—codename Project Magpie—to develop R&D capabilities for such a scenario.

In 1977, Project Magpie evolved into the Defence Science Organisation (DSO). Unable to acquire defence technologies from other countries, DSO bootstrapped Singapore's modern defence sector partly by investing in PhD-level research. In 1986, Ministry of Defence (MINDEF) appointed Lui Pao Chuen (see p.62) to the new position of chief defence scientist.

In 1997, Su Guaning (see p.78), a founding member of Project Magpie, led the incorporation of DSO as a non-profit company limited by guarantee, henceforth known as DSO National Laboratories. In 2000, he converted MINDEF's Defence Technology Group into a statutory board called the Defence Science and Technology Agency (DSTA), where he served as chief executive until 2002.

These combined organisational changes and scientific advances have helped transform Singapore from a tiny country worried about existential threats to South-east Asia's leader in military spending and arms exports.

Goh Keng Swee (left) at the official opening of the Singapore Mint, 24 April 1968. Often described as Singapore's economic architect, Dr Goh served as minister of finance, minister of defence, deputy prime minister and minister of education, among other roles. During his undergraduate days at the London School of Economics (LSE), he was the founding chairmain of the Malayan Forum, an anti-colonial, nationalist movement, which counted Lee Kuan Yew and Toh Chin Chye as co-founders. Dr Goh later returned to LSE where he earned a PhD in economics in 1956.

Photo credit: Courtesy of the National Museum of Singapore, National Heritage Board.

RECYCLING SEWAGE AND SEA WATER

Independence left Singapore without a sovereign defence force but also without a sovereign water supply—it was almost entirely dependent on imported water from Malaysia. Singapore's long-term water security is guaranteed only till 2061—when its only remaining water agreement with Malaysia will expire.

With this resource constraint in mind, after independence Mr Lee led Singapore on a relentless drive to achieve water self-sufficiency. In 1971, he set up the Water Planning Unit in the Prime Minister's Office.

Tan Gee Paw (see p.90), now chairman of the Public Utilities Board (PUB), oversaw many of its successes, including the decade-long project to clean up the Singapore River. Singapore now has two additional source of water—recycled used water (NEWater) and desalinated seawater, in addition to local catchment and imported water from Johor. By 2061, PUB expects NEWater to fulfill 55% of Singapore's water demand, while desalination will account for another 25%. And the remaining 20%? "Free from the sky," says Mr Tan.

Singapore has today become a global hub for water research, with more than 180 water companies and 26 water research institutes.

SINGAPORE'S ACADEMIC COMMUNITY IN TRANSITION

In the 1960s, there were two universities in Singapore. The Chinese-medium Nanyang University was founded in 1956 to provide higher education to the Chinese community. Meanwhile, the English-medium University of Singapore was founded in 1962 following a split by the University of Malaya (UM) into two autonomous divisions. (The Kuala Lumpur campus retained the UM name.)

Over the next two decades, both universities trained Singaporeans for various professional occupations. But in 1980, in part to consolidate resources and in part to promote the English language, they were merged to form the National University of Singapore (NUS), with Lim Pin (see p.54) as founding vice-chancellor.

The merger met with strong opposition from the Nanyang University alumni and the Chinese-speaking community. Nanyang University's grounds were taken over by a new technical institute, the Nanyang Technological Institute (NTI), with Cham Tao Soon (see p.26) as its founding president in 1981.

In 1991, the government fulfilled a promise it had made to disgruntled alumni ten years before—NTI was upgraded to university status as Singapore's second English-medium university. NTI merged with the National Institute of Education (NIE) to form Nanyang Technological University (NTU), with Professor Cham as founding president, a position he held for 22 years.

In the past two decades Singapore's higher-education landscape has blossomed. In 2000, the Singapore Management University was founded. In 2009, the Singapore University of Technology and Design was founded as a tie-up with the Massachusetts Institute of Technology in the US. In 2011, Singapore's first liberal arts college, Yale-NUS College, was established as a collaboration between Yale University in the US and NUS. The Singapore Institute of Technology enrolled its inaugural cohort in 2014, catering primarily to local polytechnic graduates.

Singapore's hitherto only medical school, the Yong Loo Lin School of Medicine at NUS, was joined in 2007 by Duke-NUS Graduate Medical School, a tie-up with Duke University in the US. The Lee Kong Chian School of Medicine at NTU was launched in 2013 in partnership with Imperial College London. Both medical schools were opened to help meet Singapore's future healthcare needs and to train the next generation of clinician-scientists.

These new developments must seem astonishing for Singapore's older practicing doctors, who trained in diverse, fascinating settings. Consider 94-year old K Shanmugaratnam (see p.70), who in 1938 enrolled at Singapore's King Edward VII College of Medicine (one of UM's predecessors). When World War II interrupted his studies, he found work under the Japanese in their bacteriology and serology laboratories, and then at the *Chuo Byoin* (Central Hospital)—present-day KK Women's and Children's Hospital—which treated both locals and Japanese civilians and soldiers.

Lee Kuan Yew (left), Singapore's founding prime minister, visiting the Institute of Molecular and Cell Biology (IMCB) in 1988. Mr Lee is recognised for his visionary leadership and for developing Singapore into a high income country. He supported the establishment of the IMCB to help Singapore become a key player in the emerging field of biotechnology. To achieve water self-sufficiency for Singapore, he encouraged R&D in water recycling and desalination.

Photo credit: Courtesy of the Institute of Molecular and Cell Biology

SINGAPORE THROUGH THE EYES OF ITS SCIENTIFIC PIONEERS

When one considers the long arc of history through the lives of Singapore's scientists—from Professor Shanmugaratnam, who learned his trade during some of the country's darkest days, to the relatively youthful Tan Tin Wee (see p.98), an Internet pioneer comfortable hobnobbing in Silicon Valley—it becomes apparent just how remarkable the last fifty years have been; not simply for Singapore, but for the wider world with which the "tiny red dot" is inextricably linked.

These scientists' stories embody the struggles and successes of Singapore. Common themes emerge: dealing with the limited resources available in a young country; the need to both persevere and adapt when there is no clear goal in sight; the thankless and unglamorous nature of much research; the value of pursuing one's passions; and the importance of family and colleagues in overcoming adversity.

Much as they acknowledge Singapore's tremendous accomplishments, the scientists profiled here do not shy away from highlighting areas in which there is room for improvement. These include: encouraging a culture of debate and dissent; making data more transparent; mitigating environmental damage; and reducing gender imbalances.

As the scientists here admit, science is not necessarily a path that leads to fame or fortune. Sometimes the thrill and validation is intensely personal. "I think it's the greatest adventure in the world to really know, at a given point, that you're the only person in the world that knows something new," Professor Brenner says.

Like the slow, steady growth of a coral reef, scientific contributions may only be truly apparent decades or even centuries later. In 2015, when the 74-hectare Singapore Botanic Gardens, home to more than 10,000 types of plants, was declared the country's first UNESCO World Heritage Site, it was is no small part due to the efforts of pioneers long gone, including Dr Ridley, who chipped away, patiently, at the bark of the rubber tree.

THE BASEMENT TINKERER

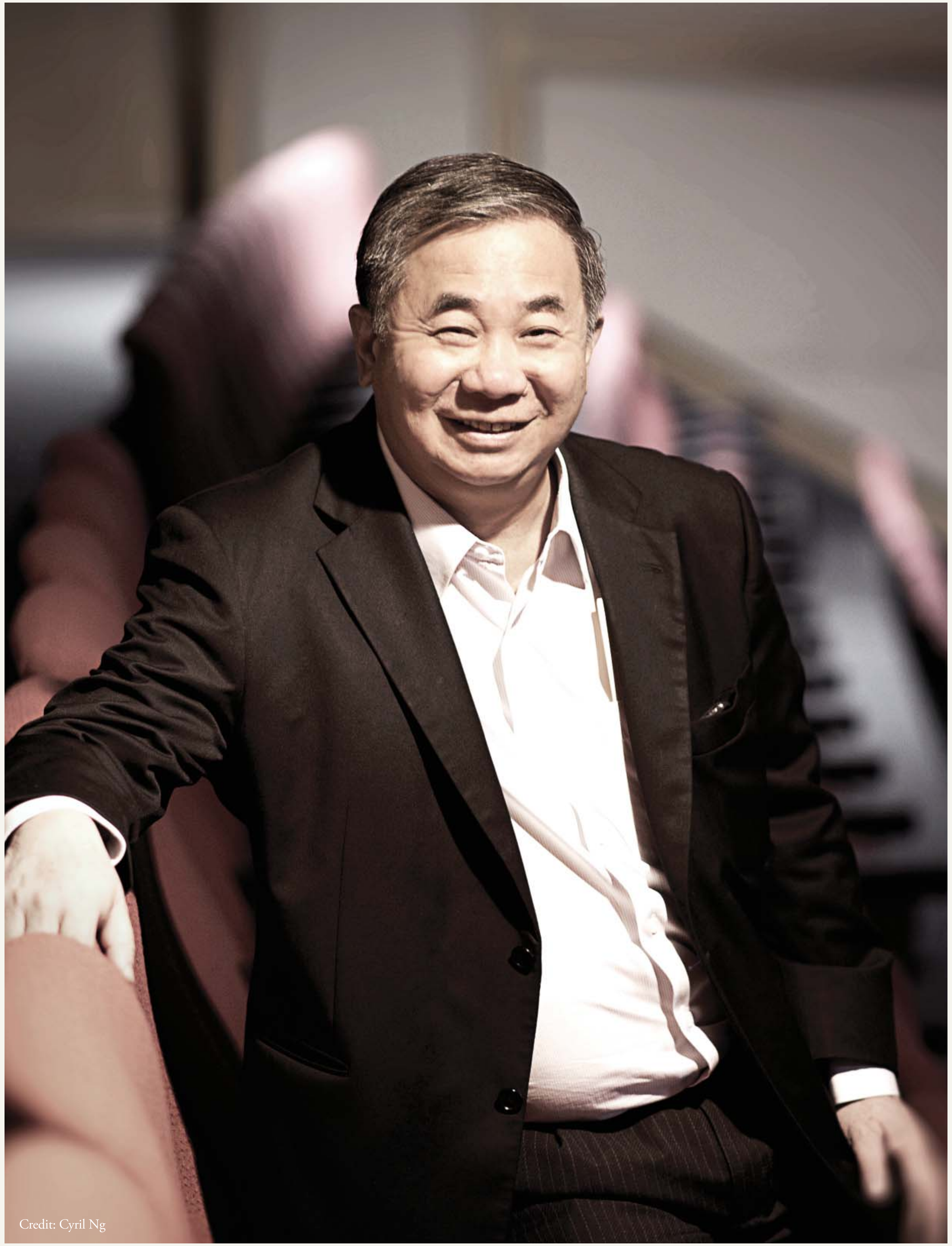
FREDDY BOEY

By Grace Chua

As a child, Freddy Boey took no plaything at face value. A metal helicopter was something to be taken apart and put back together. Wooden blocks and a pile of sand became railroad tracks and tunnels. Two pieces of wood and some nails became a replica of a toy airplane.

He progressed from taking apart and reassembling his toys in the zinc-roofed *kampung* house he shared with his grandmother, parents and ten siblings; to tinkering with inventions in the basement of his home; to becoming a serial inventor and entrepreneur winning more than S$30m of grants and licensing biomedical devices worth millions of dollars over the years.

As he is being readied for this profile's photo shoot, the 59-year-old professor of materials engineering—also deputy president and provost at the Nanyang Technological University (NTU)—looks uncomfortable. "Do I need a jacket? You can take all the pictures you want, I'm not going to get any more handsome," he quips.



Credit: Cyril Ng

FROM *KAMPUNG* TO BASEMENT LAB

Professor Boey has always been more ready to get his hands dirty than pose for corporate pictures. The ninth of eleven children born to a mechanic and a housewife, he was largely left to his own devices as a child. "My parents and siblings didn't have a clue what I was doing," he says.

Even without parental pressure, he breezed through secondary school, then topped his cohort at St Andrew's Junior College. But he was denied a government scholarship due to his congenital kidney illness.

Instead, Professor Boey scraped together savings from odd jobs during National Service, and went to Australia's Monash University, which at the time offered free tuition. There, he remembers sneaking out of a dull chemical engineering lecture into the next class. It happened to be on materials science. "The professor was explaining how an airplane wing can bend, and it blew my mind," he says.

With that, Professor Boey switched to materials science—and evangelised to friends about it. (The department's class size promptly doubled, said Ian Polmear, a materials science professor at Monash, in 2011 at an award ceremony recognising Professor Boey as Monash's Distinguished Alumnus of the Year.) In 1980, he graduated top of his class—all while holding down a variety of jobs, from cleaning pubs to delivering eggs, to make ends meet.

Professor Boey then spent a year as a metallurgist at the Singapore Institute of Standards and Industrial Research (SISIR), developing its trademark gold-plated Risis orchids, and a further ten months volunteering with an aboriginal community in a remote part of North Queensland. He then began graduate studies at the National University of Singapore under Teoh Swee Hin (see p.102), a materials engineering pioneer.

There, Professor Boey examined the impact of impregnating polymer into wood—wood's fire- and water-resistance is raised, boosting its value. "My job was to do the modelling," he remembers. "I had a modelling equation with nine or ten variables, and we were using this so-called 'supercomputer'—you put the question in in the morning, and you could go to lunch before the answer came out."

By 1987, he had completed his PhD and found a job. "I joined NTU because I was given the freedom to do what I could do, and I've been here since," he says. And one thing he could do was invent things.

For instance, for Singapore's Mass Rapid Transit (MRT) system, which began running in 1987, he made soft plastic ticket barriers—the distinctive red fare gates. He developed the material, then ordered a first batch from plastic moulders in Australia.

Another project involved developing carbon-fibre parts for the A-4 Skyhawk jet fighter. At the time, he says, use of the laboratory for non-academic pursuits was frowned upon, so he set up a lab in his home basement.

"For two years, late at night when my children and wife were asleep, I'd work for a couple of hours," he says. "I bought my own materials—I remember buying carbon fibres from Russia as they were cheaper." Professor Boey's carbon-fibre parts, though approved, were never used by the Singapore Air Force, which later decided to upgrade its fleet of A-4 Skyhawks.

For Hewlett-Packard's semiconductor factories, Professor Boey designed a series of carbon-foam indexer wheels on which to mount robotic arms. His wheels were less than half as heavy as conventional aluminium ones, and less susceptible to vibrations that slowed the pace of the robots' work. To get the wheels perfectly flat, he cast them on large pieces of float glass—glass made by floating molten glass on a bed of molten lead.

All this work in the basement laboratory caused little marital friction, until his wife Celina, a general practitioner, discovered epoxy cooling in the kitchen fridge. "When I told her what it was, it was not funny," Professor Boey grimaces.

ROBOT ARMS TO NANOMEDICINE

Such tinkering, he says, was not discouraged by NTU, but neither was it actively promoted at first. Only from around 2000 did the university begin to ramp up its research and innovation efforts. That year, NTU's materials engineering division was upgraded to a full-fledged engineering school, and Professor Boey became its vice-dean of research.

When Professor Boey's eldest sister died in London of lung cancer that year, in her early 60s, he was driven to study biomedical devices. "Why can't a device delivering a small dose of radiation be implanted next to a cancer?" he asked himself.

He soon realised that the techniques and ideas used in one domain could be applied to another. For instance, to make very thin biodegradable heart stents of an even thickness, he used a technique called multilayering, commonly used in microelectronics, which involves spinning drops of liquid material till they become flat layers. "It's a lot of lateral thinking," he says.

With colleague Subbu Venkatraman, a polymer chemist, he developed fully biodegradable heart stents that can deliver drugs. They spun off a company, Amaranth Medical, in which Boston Scientific, a medical device giant, bought a stake. They also redesigned the surgical tissue retractor, which surgeons use to expose a surgical site. Their now ubiquitous disposable version is gentler than conventional metal ones.

Profesor Boey's newest company, Peregrine Ophthalmic, expects in three years to gain approval from the US Food and Drug Administration (FDA) for a treatment that would replace glaucoma-drug eyedrops with an injection that delivers drugs slowly for months.

Though he holds countless patents, Professor Boey does not believe in filing new ones uncritically. "I don't file unless I believe they can be licensed; more than two-thirds are," he says.

FOSTERING INNOVATION

"I'm glad the experience I have is helping to shape the whole of NTU," he says. "The culture here today is very different from the time I was doing things in my basement."

In 2011, Professor Boey was appointed NTU provost, and created a new path for researchers to get tenure through world-class, high-impact innovation. Likewise, as dean of the school of materials science and engineering, he challenged the faculty and students to spin-off at least one company a year—a target they promptly exceeded.

For instance, Hydroemission Corporation makes biodegradable controlled-release technology for water treatment, waste treatment, and other applications; and NanoFrontier develops nanoparticles for applications such as detecting biochemicals. Meanwhile Vincent Lau, a materials science alumnus, developed an online-retail solution called Paywhere.

"I think innovation can come in any environment; but you need to have an inquisitive mind, and you need a sense of optimism," Professor Boey says. "Most of the time invention comes when you persist, and it happens by accident more often than not. If you are a pessimist looking for a perfect answer, you'll never get it done."

And as provost, he is trying to encourage that happy optimism and innovation in the undergraduate population. "I believe in having an education, not a degree," he says. "A lot of our education is spent on feeding the students information, where exams are the focus."

> "Most of the time invention comes when you persist, and it happens by accident more often than not."

He would like to teach students the basics better and faster, perhaps using online learning technologies, "and the rest of the time educate them as a person, as a leader. What you learn in class lasts only for a couple of years, but inquisitiveness and learning how to learn lasts you longer."

As Professor Boey shows off photos of his family—three daughters, a son, three dogs, "and one illegal cat who walks in and out and doesn't even pay rent"—he shares his equally relaxed approach to parenting. "I am not someone whose aim in life is to sit down with all my children and make sure they pass their PSLE [Primary School Leaving Examination] with flying colours," he says. "I said to them, whatever result you get is all right; there will always be a place for you whether you are a top student or not."

In the long run, he believes Singaporean researchers are capable of inventing things that will have a world-class impact, and materials science is a field ripe for such invention. "Today, energy depends on new catalysts and storage; clean water depends on new materials to purify the water. Materials science is going through a golden age—and the sun hasn't set."

Conceiving Many World Firsts

Ariff Bongso

By Rebecca Tan

In 1965, Singapore had a total fertility rate (TFR) of 4.66 children per woman and an average household size of about six, according to the Singapore Department of Statistics.

By the time Samuel Lee was born in 1983, however, the situation had changed drastically, with the TFR dropping to 1.61, below the generally-accepted replacement rate of 2.1. But Mr Lee was no ordinary baby: he was Singapore's—and Asia's—first "test-tube baby", brought into the world by a team led by the late S. S. Ratnam.

Since then, thousands of babies have been born in Singapore through assisted fertility techniques, with 1,158 in 2009 alone [the most recent publicly-available datum]. Although these numbers are not high enough to cause a discernible rise in birth rates, perhaps more importantly, *in vitro* fertilisation (IVF) has given many infertile couples a shot at parenthood.

Much of the credit for this should go to Ariff Bongso, professor of the department of obstetrics & gynaecology at the National University of Singapore, who has made several pivotal research breakthroughs that have improved IVF success rates.

"I have watched some of the children born through IVF grow up and enter university. To me, it is overwhelming to know that a technique conceptualised in the lab ultimately results in so much happiness and joy," says Professor Bongso, who is a faculty member at the Yong Loo Lin School of Medicine and the National University Health System.

Over the course of his still active career, Professor Bongso has also been at the forefront of one of the most exciting fields of the last decade: stem cell research.

Credit: Cyril Ng

REACHING PEAK PRODUCTIVITY IN SINGAPORE

Like many other IVF pioneers in his time, Professor Bongso, a native of Sri Lanka, first perfected his skills on animal embryos before making the jump to humans. Although offered a place to pursue medicine overseas, he chose to study veterinary medicine instead, completing a five-year programme at the University of Ceylon in 1970.

"The initial shift from human to veterinary medicine turned out to be a defining moment in my education," Professor Bongso recalls. "My strong background in comparative mammalian reproduction has in fact been an asset in understanding and providing solutions to some of the problems in humans."

He went on to complete a master's and PhD in mammalian reproductive biology at the University of Guelph in Ontario, funded by a Canadian Commonwealth Scholarship. He then returned to Sri Lanka to work but after ten years, and in inauspicious circumstances, felt the pull of Singapore.

In 1987, while attending the funeral of his close friend, S. M. Ratnam, in Kuala Lumpur, Professor Bongso met the deceased's brother, Professor S. S. Ratnam, who persuaded Professor Bongso to join him in Singapore. Professor Bongso and his family liked Singapore so much that he took up citizenship in 1991.

"Without a doubt, the most productive part of my career has been during my stay in Singapore," he muses. "In those early years of my career in Singapore, I spent less time on writing and winning research grants… manpower, material and funding were all provided by the department. These to me were the key ingredients that resulted in several breakthroughs and world firsts."

LIVING PROOF OF A LIFE'S WORK

Although the very first IVF baby was born in 1978, IVF techniques were still relatively crude in the late 1980s and had a very low success rate of 10-15%.

Conception begins when a sperm cell meets an egg cell in the fallopian tubes. Each sex cell has only one copy of the pair of chromosomes found in non-reproductive cells. When sperm and egg fuse, the resulting embryo has a full set of chromosomes. If all goes well, it starts developing into a baby.

However, getting the sperm and egg to meet in the first place is challenging. For roughly one-third of infertile couples, the male's sperm is lacking in either quantity or quality. In another one-third of cases, the female experiences hormonal imbalances resulting in the egg not being released into her fallopian tube; or she has structural defects in her fallopian tubes which prevent the sperm and egg from meeting. In all other cases, both male and female partners have one or more issues resulting in infertility.

IVF can be thought of as speed dating, concentrating sperm and egg cells outside the body to increase their chances of meeting and fusing. The embryos thus formed in "test tubes"—or, more likely, petri dishes—are then transplanted into the womb where they hopefully begin to grow.

"Back then, the culture conditions for the growth of human embryos in the laboratory were suboptimal," Professor Bongso explains. "As a result, IVF specialists were transferring fertilised embryos after culturing them for only two days, whereas in natural conception the embryos reach the uterus from the fallopian tube on day five—at the blastocyst stage."

> "I strongly believe that in the biomedical field research teams should comprise a mix of clinicians, basic research scientists and clinician-scientists working together."

In 1988, Professor Bongso and his team attempted to develop a co-culture system in the lab that would mimic the conditions of the human fallopian tube. They grew the embryos on a bed of human fallopian tubal cells in a plastic dish in the presence of a synthetic formulation of fallopian tube fluid that they developed. "This allowed us to prolong the growth of human embryos to the blastocyst stage and doubled the IVF pregnancy rates," he says.

Professor Bongso's co-culture technique soon spread from Singapore to IVF programmes all around the world, where it remained the gold standard until recently, when a new cell-free liquid culture medium formulated on the knowledge gained by the co-culture system replaced it.

Apart from co-culture, Professor Bongso has also been involved in developing IVF techniques ranging from microinjection—a procedure enabling men with poor sperm counts to father children—to zona-free blastocyst transfer, whereby the outer shell of the embryo is enzymatically removed to increase the chance of implantation in older women.

ENTERING THE STEM CELL FRAY

While his success in the field of IVF made him something of a household name in Singapore and the region beyond, Professor Bongso's next discovery launched him onto the world stage. In 1994, he became the first scientist in the world to report the isolation of human embryonic stem cells (hESCs), which have the potential to develop into any human cell.

Building on his IVF-related knowledge, Professor Bongso used a fallopian feeder culture, in which he was able to maintain the hESCs for two generations. In contrast, a group in Wisconsin using mice cells as a feeder culture succeeded at maintaining their hESCs for over 40 generations, receiving a patent for their work in 1998.

By this time, stem cells had evolved from a purely academic research interest to an intensely commercial one, with many companies realising their vast potential for treating diseases such as Alzheimer's and diabetes.

Arguing that patents on hESCs restricted access to the potentially revolutionary cells, several groups sought to overturn the patent held by the Wisconsin group. In the ensuing legal battle, Professor Bongso's work was cited as evidence that the Wisconsin group was not necessarily the first to have discovered hESCs.

However, culturing hESCs on mouse feeder cells is not without its limitations. "Cell lines grown on mouse or other animal cells could possibly be contaminated with viruses and bacteria from the feeder cells," Professor Bongso says. "This risk seriously curtailed the possible downstream applications of hESCs."

In 2002, Professor Bongso and his team succeeded in establishing a "pure" stem cell line grown in completely animal-free conditions, by using embryonic muscle and skin cells rather than adult fallopian tube cells for the feeder culture. This removed a major obstacle to the progression of stem cells from lab to clinic.

RIDING THE WAVE

But the problem of mouse feeder cells was only one of many. Still, unfazed by the challenges and convinced that the opportunity was promising, Professor Bongso co-founded ES Cell International (ESI), a biotechnology startup supported by the Economic Development Board of Singapore.

Incorporated in 2000, the company had early success, including the patenting of Professor Bongso's human feeder method and its selection by the US National Institutes of Health as one of ten groups to have its stem cell research eligible for federal funding. The company also scored a coup with its recruitment of Alan Colman—famous for cloning Dolly the sheep—first as chief scientist and then as CEO.

But in the wake of that early euphoria, the stem cell industry at large was about to experience its first boom and bust cycle. By 2007, ESI had given up its research on treatments for diabetes and heart failure, switching instead to the less risky option of licensing hESC lines and using them in screening assays for drug development. A US company eventually acquired ESI in 2010 and renamed it ESI BIO.

PRESSING ON

Professor Bongso has continued slowly chipping away at the hurdles in stem cell research. In particular, his research group has focussed on cells isolated from the Wharton's jelly of the human umbilical cord, a much less controversial and more readily available source of stem cells than discarded embryos.

As excited as Professor Bongso is about his current research, he has not neglected to train the next generation of scientists. Fong Chui Yee, for instance, was once his student and is now a respected researcher in her own right. She has worked closely with Professor Bongso over the years and is poised to take over his lab when he retires.

"I strongly believe that in the biomedical field, research teams should comprise a mix of clinicians, basic research scientists and clinician-scientists working together," Professor Bongso says. "Synergy between all these three types of specialists in a complementary manner will draw in diverse ideas and fruitful results."

THE GREATEST ADVENTURE IN THE WORLD

SYDNEY BRENNER

By Shuzhen Sim

In 1953, Francis Crick and James Watson, two scientists working at the University of Cambridge in the UK, deduced the molecular structure of DNA, proposing a double helix formed by paired chains of the nucleotide bases A, C, G and T.

Sydney Brenner, then a 26-year-old PhD student at Oxford University, describes seeing their model of DNA for the first time as a watershed moment in his scientific career. At that point, the question of how a mere four bases could encode the information required for cells to make all the proteins necessary for life—the genetic code—was as yet unsolved. In the early 1960s, Professor Brenner's role in deciphering the genetic code helped lay the foundation of modern molecular biology.

Few scientists make their mark on even one specialised field of research. Several years later, Professor Brenner's pioneering use of the nematode worm *Caenorhabditis elegans (C. elegans)* as a model for understanding human biology revolutionised research in genetics and developmental biology, and in 2002 earned him the Nobel Prize in Physiology or Medicine.

Since 1983, in his capacity as a trusted advisor to the Singapore government on scientific policy, Professor Brenner has been instrumental in establishing Singapore as a biomedical research centre of international repute. In 2003, Singapore conferred on him its inaugural Honorary Citizen Award, the nation's highest form of state recognition for non-citizens.

Today Professor Brenner, 88, is senior fellow at Singapore's Agency for Science, Technology, and Research (A*STAR), and also holds senior faculty positions at the Salk Institute and the Howard Hughes Medical Institute in the US. "I've had a good long run in science," he acknowledges.

Credit: Bryan van der Beek

THE GENETIC CODE AND NEMATODE WORMS

Professor Brenner developed an interest in molecular biology as a medical student in the 1940s in his native South Africa. Keener on research than medical practice, he moved to the UK in 1952 for a PhD at Oxford. Then in 1956 he joined the Laboratory of Molecular Biology (LMB) at Cambridge, where he would share an office with Dr Crick for twenty years.

In 1961, together with Dr Crick and others, Professor Brenner showed that the genetic code is composed of non-overlapping triplets—three bases, or a codon, encoded one amino acid, the basic building block of proteins.

Turning next to the question of how information is transferred between DNA and proteins, Professor Brenner demonstrated the existence of messenger RNA, an unstable intermediate molecule that carries information from DNA in the nucleus to ribosomes—the cell's protein making machinery—in the cytoplasm of the cell.

> “[At MEL] you're independent, but you're also responsible. If you've got ideas, you implement them. You really need to take it all the way through.”

Today, “DNA makes RNA and RNA makes protein” is considered the “central dogma” of molecular biology. But in the 1950s, the scientific establishment ridiculed the idea that DNA could carry all the information required for life. Professor Brenner had “to preach to the heathen”.

In the late 1960s, Professor Brenner became interested in the genetics of how complex organisms grow, particularly in the development of the human brain and nervous system. Scientists often study model organisms—simple organisms that can be easily handled in the laboratory—to gain insights into the biology of more complex animals, such as humans. In genetics, for example, the fruit fly *Drosophila melanogaster* and the yeast *Saccharomyces cerevisiae* are widely-used model organisms.

Professor Brenner recognised the potential of *C. elegans*, a one millimetre-long nematode worm with a transparent body and simple nervous system, for studying developmental biology. In a 1974 paper, he described important aspects of its genetics, along with methods for studying it in the laboratory, thus establishing it as a new model organism.

Research on *C. elegans* blossomed. Scientists tracked the development of every single one of its 959 cells and mapped the wiring of its 302 neurons. By the early 1990s, scientists had started to sequence entire genomes of simple, single-celled organisms—the first was the bacterium *Haemophilus influenzae*.

In 1998, thanks to a consortium of researchers in the UK and US, *C. elegans* became the first multicellular organism to have its complete genome sequenced. Dubbed “nature's gift to science” by Professor Brenner in his 2002 Nobel lecture, this humble organism has helped researchers understand fundamental cellular processes such as cell division, embryogenesis, ageing and cell death.

DEVELOPING BIOMEDICAL RESEARCH IN SINGAPORE

In 1983 the Singapore government, eager to diversify the country's economy away from low-cost manufacturing, sought Professor Brenner's advice on developing a biotechnology sector. He proposed setting up the Institute of Molecular and Cell Biology (IMCB) at the National University of Singapore (NUS) in order to train Singaporeans and provide research infrastructure.

Inaugurated in 1987, the IMCB's mandate was also to prove that Singapore, despite being a tiny population with little experience in basic research, could produce high-calibre scientific research.

Professor Brenner ran a laboratory at the IMCB, and led efforts to study the genome of the *Takifugu rubripes* puffer fish—or *fugu* in Japanese. His team showed that the *fugu* and human genomes share similar blueprints, even though the former is about eight times smaller than the latter.

Like *C. elegans*, the compact *fugu* genome is an ideal model for studying larger and more complex genomes. The IMCB enhanced its international reputation when it became a key member of an international consortium that in 2002 published a draft sequence of the *fugu* genome in *Science*, a journal.

Professor Brenner is, understandably, tired of talking about his older achievements. But ask him about his latest endeavour, the Molecular Engineering Laboratory (MEL), set up in 2009 at the Biopolis, and his eyes light up.

In the early, heady days of molecular biology, Professor Brenner and his fellow rebels at Cambridge did not accept students. “Who wants to be stuck with a student for three years when the field was changing almost every month?” he muses. “In a dynamic field you can't maintain a project because a student has to get his PhD.”

Today, under constant pressure to compete for grants and pass performance reviews, principal investigators (PIs, the heads of laboratories) tend to maintain large groups of graduate students and post-doctoral fellows, on whom they rely to produce the science. In the US, especially, this has resulted in a glut of PhD holders, without a corresponding increase in jobs for them.

The entire system of academia, thinks Professor Brenner, is bad for scientific innovation. The bureaucracy stifles talent. “PIs have ceased to become scientists,” he worries. “They become managers and sit in offices all the time and have group meeting and so on. That's not the way you create new science.” As employees of the PIs, students and “post-docs” also lack the independence to work on problems that really interest them.

In a bid to liberate them, Professor Brenner established MEL. Here, freshly-minted PhDs are their own bosses. “You're independent, but you're also responsible,” he says. “If you've got ideas, you implement them. You really need to take it all the way through.”

MEL is not only unique in its structure, but also in the scope of its research. It was the first place, Professor Brenner says, to institutionalise molecular engineering, an extremely broad, interdisciplinary field involving the design, manipulation, and synthesis of molecules for myriad applications. These proteins can be used to make materials with unique properties, for example, or chemical scaffolds that can be used to design better drugs.

One area of research at MEL is biomimetics—a field in which the imitation or mimicry of nature is used to solve engineering problems. Here, the team is studying and designing potentially useful proteins from marine organisms. For instance, suckerin, the protein present in the sucker ring teeth of squid, could be used to make strong, flexible materials for applications ranging from reconstructive surgery to eco-friendly packaging.

Others in the laboratory are developing molecular probes—molecules that exhibit a measurable change, such as emitting fluorescence, after interacting with other molecules. These are useful in a wide variety of industrial and research applications—monitoring chemical manufacturing processes, for example, or detecting a specific DNA sequence.

MEL, Professor Brenner hopes, will nurture talented young researchers, whom he views as the biggest investment in the future that Singapore can make.

“Ninety percent, maybe even more, of what goes on in research and development is essentially routine,” he says. “And that's fine. But you also need the talent to do something new.”

Constant reinvention, he thinks, is especially important for small countries like Singapore, which must keep creating new possibilities and opportunities for their people. It certainly helps that Singaporeans, in his opinion, are focussed on self-improvement. MEL often loses talented research technicians to graduate programmes at top-notch universities.

Singapore, Professor Brenner believes, like most of Asia, has a problem that cannot easily be solved by throwing money at it. “There is a lesion which is very bad, and that is respect for seniority,” he says. “People don't ask questions in lectures. I think we've got to encourage the questioning.”

A THRILL THAT'S WORTH IT

For Professor Brenner, science has always been all consuming. “Work doesn't start at 8 and finish at 5 and then you forget about it,” he says. “It goes on day and night. And of course it's hard to keep a family life when most of the time you're living in your own head.” Nevertheless, Professor Brenner and his late wife May raised four children, and were married for 58 years, until her death in 2010.

Professor Brenner believes that any sacrifices he has had to make pale in comparison to the excitement of discovery. “I think it's the greatest adventure in the world to really know, at a given point, that you're the only person in the world that knows something new,” he enthuses. “That's a thrill that's worth it.”

THE PRAGMATIC UNIVERSITY-BUILDER

CHAM TAO SOON

By Grace Chua

In his book on the evolution of Nanyang Technological University (NTU), Cham Tao Soon, professor of fluid mechanics and its founding president, explains the relative youth of the administrators and leaders involved: “It was a different age, and many things were started by young men.”

Again and again in the Singapore story this comes up, and it is nearly always young men in their twenties, thirties and forties who are the key players in the tale—men whose wives gave up thriving careers to support their husbands’ endeavours, men who loved and provided for their children but saw them rarely, men who sacrificed lucrative job offers and personal dreams for duty, for country, for the things they built from scratch.

It was indeed a different age: in 1981 Singapore’s population was less than 2.5m (more than 5m today), its gross domestic product per person only US$5,000 (more than US$50,000 today). The then 41-year-old Professor Cham was tasked with training engineers for the nation’s future.

Credit: Cyril Ng

A SWEATY, UNGLAMOROUS JOB

The new president had nearly become a musician. As a child he had taught himself several instruments, including the piano and violin, and as an upper-secondary student at Raffles Institution, he had told his father he wanted to study music.

His father, a court interpreter and film censor for the Ministry of Culture, discouraged him, saying it would be difficult to make a living. Instead, he urged his son to take up engineering—seen as a sweaty, unglamorous profession by most.

"Either you worked in the sun as a builder or you tinkered with your car engine," Professor Cham recalls. But it was a secure living, his father insisted; engineers created wealth and comfort, improving people's quality of life by building material things.

So off Professor Cham went, on a government scholarship, first to the University of Malaya in Kuala Lumpur (as the Singapore campus had no engineering school at the time); then to the University of Cambridge for a doctorate in fluid mechanics. When he returned to serve his bond, it was as a pioneer member of the University of Singapore's engineering faculty. "I remember when the faculty of engineering started," he says. "April 1st, 1969. Everybody thought it was an April Fool's joke."

The main task of the 13 pioneer faculty members was to train some 120 undergraduate engineers a year for the massive infrastructure projects that marked Singapore's early years—housing; roads; and drainage to help prevent the floods that tormented neighbourhoods in the monsoon season. In 1974, weeks before the start of the term, the Ministry of Trade and Industry rang with a request: please double your enrollment to 240 students. On the list of national priorities, research was rock bottom.

Professor Cham kept busy by consulting for Singapore's rapidly growing industrial sector. For instance, he designed a water-based cooling system for a printing firm that took advantage of air-conditioner discharge. He also literally helped build the university, by designing some of its air-conditioning systems.

In 1975, restless, he wanted to leave the university to start an engineering firm with a friend. "But we already allow you to do consulting," Regina Kwa, the deputy vice-chancellor, retorted. Professor Cham took the hint and stayed.

AN ENGINEER'S UNIVERSITY

By 1981, Professor Cham had been dean of the engineering faculty for three years.

Then came word from higher up. To address Singapore's persistent shortage of engineers, the government had decided to open a new school: the Nanyang Technological Institute (NTI). Together, the National University of Singapore (NUS) and NTI would train 1,200 engineers a year to feed the burgeoning building, electronics, petrochemical, and other industries, which Singapore aimed to modernise with technology-intensive activities such as R&D, engineering design and computer software services.

The new institute was something of a political hot potato. The Chinese-medium Nanyang University was a hallowed institution among overseas Chinese, whose alumni ranged from Singapore to Vancouver. When the University of Singapore merged with the original Nanyang University to form NUS in 1980, it rankled the alumni that the government had simply done away with their alma mater at the stroke of a pen.

In that sense, NTI was partly a political project to appease this large Chinese-educated constituency. NTI later became the full-fledged Nanyang Technological University (NTU) in 1991.

From the start it was Professor Cham who supplied the vision for modernising engineering education. He desired an engineering school with a difference. Unconvinced by what he saw as engineering's excessive emphasis on academia and theory, he recruited lecturers with extensive industry experience, such as Brian Lee, an electrical and electronic engineer, who had spent more than a decade at General Electric, and Bengt Broms, a soil foundation engineer, who had earlier worked for Shell, and on geotechnical projects in Sweden.

Like medical students, the new engineering students would shadow and learn from the professionals. They helped build and design parts of their own school, such as several thin-shell concrete roof structures, during a second-year training stint. And, uniquely for Singapore at the time, they did compulsory six-month internships in their third year.

"The companies welcomed it," Professor Cham says. "There were more places on offer than we had students! Why? In the usual two- to three-month internship, by the time they know the work, it's time for them to leave. In six months, they can learn a meaningful job."

As for building the university itself, the sturdy, bespectacled Professor Cham would roll up his sleeves and sweat through a plate of fish-head curry at a Jurong *kopitiam* (traditional coffee shop) each week with his colleagues. The tableful of men in button-down shirts would eat and talk through decisions informally before going back to the office and signing off on them. In all, the university's initial development budget was a generous S$170m. As a political project which had to succeed, it did not want for funds, he says.

Physically, NTU is a school evidently designed by engineers. Visitors are often bemused by its floor numbering system, in which all the levels marked 1 are at the same altitude across campus, all those marked B1 at the same level, and so on down.

"For a large and undulating campus this was deemed to be the most sensible way to determine the altitude with respect to outside roads," Professor Cham says.

Buildings and hostels, too, were numbered—N1, N1.1, S1, Hall 4, and so on—temporarily, in the hope of raising funds with naming rights. Alas, there have been no takers.

The 107-hectare campus, in the far reaches of Jurong, was in the middle of a jungle. "There were still squatters, feral dogs, and it was heavily overgrown," Professor Cham says. One morning, he arrived in the office to find a snake in his dustbin. Meanwhile, the staff operated out of an old auditorium which some were convinced was haunted.

> "I always try my best and if it doesn't succeed, too bad. I sleep very well at night."

All this took Professor Cham away from his family. When work started on the institute, he and his wife Ee Lin—a geophysicist he had met in secondary school when they attended the same music competitions—decided she would give up her job so someone could be home with their children.

Today Gee Len, his daughter, is a project manager, while Tat Jen, his son, is a computer engineering associate professor at NTU.

"It was a very easy decision as our philosophy is family above career. Even for me if I have a family appointment which clashes with a business appointment, the former prevails," he says.

Professor Cham also says he turned down a lucrative job offer when he was tapped to run NTI. "At the time, my income was about $200,000," he says. "This was in the 80s, so that was quite a lot, but I was offered a million dollars a year to run a company."

Good thing he stayed. Within four years, before its first students had even graduated, NTI was named one of the best engineering institutions in the world by the Commonwealth Engineers Council, the Commonwealth's professional-engineering body.

A MELODIOUS RETIREMENT

Professor Cham remained president of NTU till 2002. Over the years, he has also found the time for many corporate, non-profit and educational board positions.

After starting up NTI, he joined the board of Keppel Shipyard. He has also held directorships at firms such as NatSteel, Singapore Press Holdings and United Overseas Bank. The music-lover at one time also chaired the Singapore Symphony Orchestra's board of directors. "I'm down to just two listed companies now," he laughs.

Last year, he retired as chancellor of SIM University (UniSIM; formerly Singapore Institute of Management, SIM) as well. Today, he remains special advisor to the SIM governing council and senior advisor to the president at NTU.

How does he juggle all these commitments? He plucks out a small diary from a shirt pocket. "By November, I've already got all my meetings planned for the following year," he says. That includes family functions and regular SSO concerts, such as a performance by renowned pianist Krystian Zimerman.

Ask if he would have done anything differently, and he claims he has no regrets, aside from wishing he were less impatient and more compassionate. "I always try my best and if it doesn't succeed, too bad. I sleep very well at night," he says.

A SERIES OF RARE EVENTS

Louis Chen

By Grace Chua

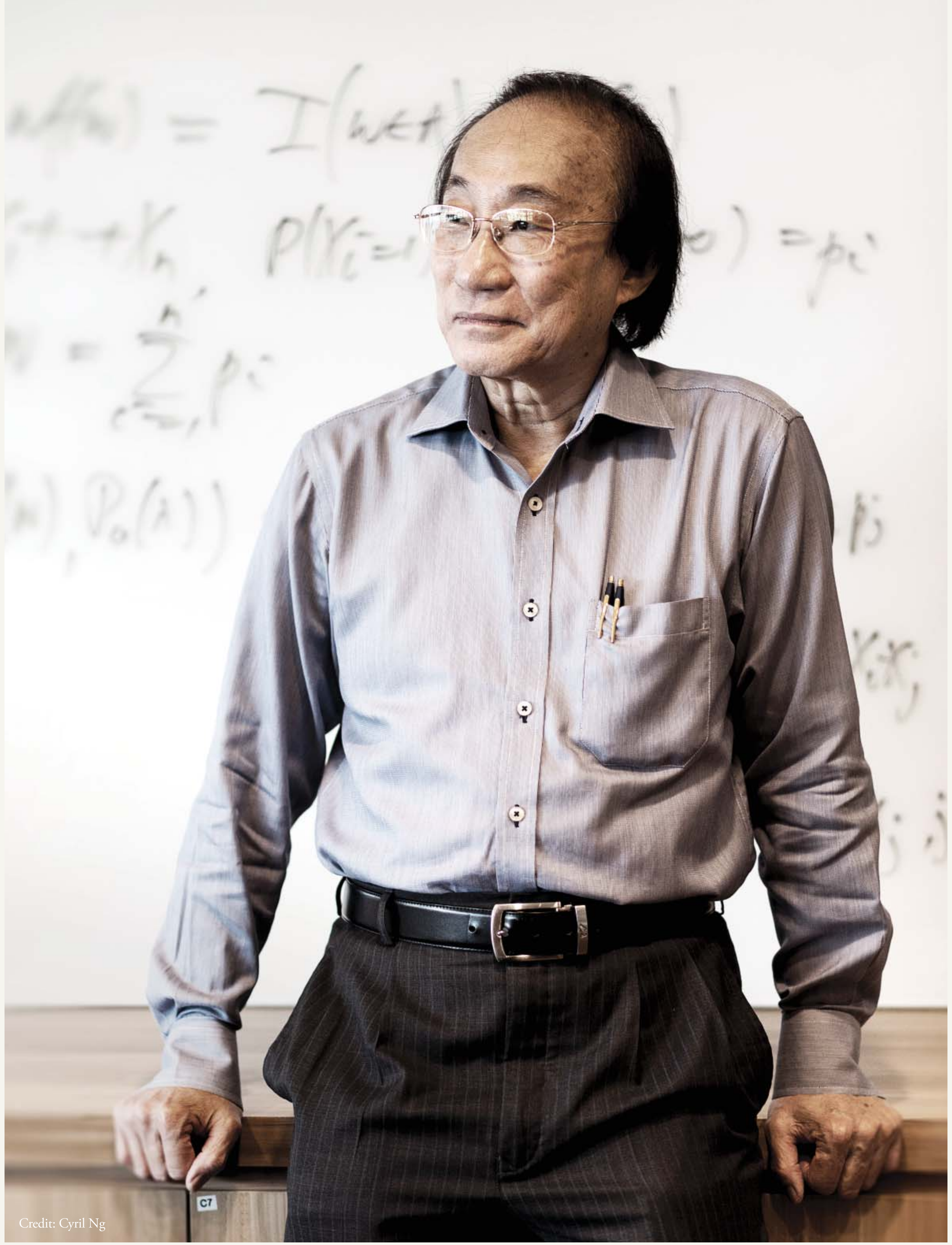
Picture the young mathematician, a recent Stanford University graduate, among a pioneer batch of Singaporean scholarship holders who have returned home to teach.

In the early 1970s, the University of Singapore is a quiet academic backwater, not the bustling campus with the tens of thousands of local and international students it has today. Laboratories are rudimentary. The Internet does not yet exist and postal services are slow—by the time a journal or book arrives in the university library, it is already out of date. Funds for travel to mathematics powerhouses in Europe and the US are meagre.

But pure mathematics is part of the life of the mind, limited not by technology but only by one's imagination and work ethic. Thus the young mathematician, who lectures in the day and works on his doctoral thesis at night, publishes in 1975 a seminal paper in a relatively new field—a new method for understanding the probability that rare events will occur.

The paper will give rise to a new area in discrete probability, with applications in many fields including computational biology, epidemiology, economics and computer science.

This is the life and work of Louis Chen, 74, distinguished professor of mathematics and statistics at the National University of Singapore (NUS). In the 43 years he has been there, NUS's mathematics department has climbed from the doldrums into the world's top-20-ranked programmes.



Credit: Cyril Ng

A SEQUENCE OF RARE EVENTS

Professor Chen almost missed out on Stanford University. He had applied for the US's Fulbright-Hays Program, which gave students travel grants for their PhDs, and was offered a scholarship to either Adelphi University or Ohio State University.

To meet the looming acceptance deadlines, Professor Chen thus accepted the Ohio State offer before the other schools he had applied to—Stanford and the University of California, Berkeley—had responded. Then came a fateful phone call from the office in Kuala Lumpur that administered the Fulbright-Hays Program.

"Congratulations Mr Chen," the administrator said. "You have got an offer of scholarship from Stanford University!" The admission would prove fortuitous not only for Professor Chen, but the whole mathematics world.

At Stanford, keen on pure mathematics, he had hoped to complete his thesis on probability theory with Rupert Miller, the department's chairman. But Professor Miller referred him to Charles Stein, a mathematical statistician, who had just come up with a novel idea in probability—a new way of proving the central limit theorem, a fundamental theorem that says that enough random observations will be distributed according to a normal distribution, the classic "bell curve".

Professor Stein was the quintessential brilliant mathematician. "He's the sort of person who goes to the lecture room to talk about his latest ideas, and gets stuck halfway," Professor Chen says. "He'd tell us to come back next week, but be talking about something else altogether the following week. But we heard his latest ideas. It was a goldmine."

Professor Chen's eventual research—applying the so-called "Stein's method" to Poisson distributions as probability approximations for the occurrences of rare events—would be published in 1975.

But its real impact would come years later. In the 1980s Persi Diaconis, a Stanford probabilist, brought the research to the attention of computational biologists. They soon realised its applicability to sequence comparison in bioinformatics and began calling the new formula the Chen-Stein method.

DNA sequences, which encode the biological instructions for building an organism, can consist of millions of pairs of "letters"—the chemical building blocks adenine, thymine, cytosine and guanine (commonly known as: A, T, C and G). By comparing two sequences and using the Chen-Stein method to work out whether their similarities are due to mere chance or something more fundamental, scientists can make inferences about the sequences' biological functions.

One component of sequence comparison is the calculation of p-values, a probability function for a particular sample. Before biologists discovered the Chen-Stein method, they calculated the p-value through the relatively tedious inclusion-exclusion formula.

The Chen-Stein method offers a simpler formula for calculating p-values; as a corollary of that, it provides a theoretical basis for the Basic Local Alignment Search Tool (BLAST), an algorithm that is used widely in sequence searching and comparison.

In short, by helping to speed up sequence comparison, the Chen-Stein method has been a boon for computational biology and genomics.

> "I wanted to do physics, because there was no Nobel Prize in mathematics, but in the end I found that my first love was still mathematics."

How might one researcher stumble into work that will become highly influential years down the road, and another researcher end up in a cul-de-sac?

It is fate, Professor Chen believes. Although his professional end-point was not obvious initially, he now believes that each step in his life somehow guided him towards it.

EARLY LIFE

Born on the eve of the Japanese Occupation to immigrant parents from Chaozhou, Guangdong, Professor Chen was the second of seven children.

During the war his father, a primary school principal, became a vegetable seller in order to escape the infamous *Sook Ching*: Japanese purges of intellectuals, particularly teachers and journalists, who were thought to harbour anti-Japanese sentiments.

After the war, Professor Chen attended Catholic High School and St Joseph's Institution. From an early age, he was keen on mathematics and physics. "I wanted to do physics, because there was no Nobel Prize in mathematics, but in the end I found that my first love was still mathematics," he says.

He also liked music, and continues today to play the recorder—not the squeaky plastic device played by children, but a sleek professional woodwind.

"One fortunate thing was that all of us could study," he says. "We could get good grades." Unusual for an eldest son at the time, his parents did not pull him out of school to support the family.

Professor Chen's teachers were also encouraging. Sheng Chen Kuo, a Marist Brother, nudged along the nascent talent, entering him into inter-school mathematics competitions, which he won thrice. Meanwhile, popular science books such as *One, Two, Three... Infinity* by George Gamow, a physicist, captured his imagination with simple, entertaining explanations of the concepts of infinity, exponential growth and topology.

But Professor Chen could not afford to go to university. Fortunately, his grades earned him a prestigious state scholarship to the University of Singapore. He graduated in 1964 then left for Stanford.

And in perhaps the most important chance event of all, Professor Chen met his wife-to-be in the library at Stanford while looking for reference material. Today they have two daughters and two granddaughters.

NURTURING SINGAPORE MATHEMATICS

Upon Professor Chen's return to Singapore in the 1970s, he remained focussed on his research, driven by ambition and a good work ethic, imbibed at Stanford.

"I was working in an area which was the beginning of a field," he says. "When you work in the beginning of a field, there are always problems you can solve; there are many open questions to tackle."

As the university's lone probabilist and statistician, and one "not shy to express opinions about things", he was often shepherded into administrative roles, such as head of the mathematics department, head of the statistics and applied probability department, and eventually director of the university-level Institute for Mathematical Sciences, which promotes research interaction between local and foreign mathematicians.

The institute also organises research programmes, conferences, workshops, and academic and public talks in mathematics; the subjects of these range from the highly theoretical to those directly relevant to various fields such as finance, epidemiology and computing.

NUS's mathematics department has grown from fewer than 15 faculty members in the 1970s to more than 70 today. It is also globally renowned—at the last International Congress of Mathematicians, a kind of world summit of mathematics held every four years, four of its members were among the 200 or so invited to give lectures.

Unsurprisingly, Professor Chen agrees with the Singapore school curriculum's emphasis on mathematics. "Mathematics is so fundamental to science that everybody should have some understanding of it," he says.

As for research, "the mathematics community as a whole understands that we have to continuously move up, to continuously get better," he says. Mentoring individual students, passing on a passion for mathematics, and being role models can help make the difference in inspiring students to pursue graduate studies and become mathematicians themselves, Professor Chen adds.

RETIREMENT PLANS

Even though Professor Chen plans to retire in 2015 from administrative and teaching duties, he is nowhere near done with research.

In particular, he plans to study the connections between Stein's method and other branches of mathematics, such as number theory, which includes problems involving prime numbers.

Another branch is a species of non-Newtonian calculus called Malliavin calculus. While conventional calculus is the study of change for functions of the real number, Malliavin calculus studies change for functions of normally-distributed random variables, i.e. those exhibiting a bell-shaped distribution.

And while other researchers may use computer models to simulate their results, Professor Chen says he could work on a couple of blackboards if need be.

"In the past, we did not have the environment that young people enjoy today—the Internet, funds for travel, and so on," says Professor Chen. "And for many years I was always involved in some sort of administration. So now the time has come for me to do the things I am really interested in without distractions. I'm really looking forward to it."

This also includes indulging in hobbies such as travel and music, and spending time with his peers. In 2000, friends and colleagues organised a mathematics conference to mark Professor Chen's 60th birthday. Ten years later, they outdid themselves with an even bigger conference, with more international invited speakers.

In a lifetime of rare events, it appears some traditions still have a comforting predictability.

A CHAMPION FOR CONSERVATION

Chou Loke Ming

By Rebecca Tan

Dotted with old shophouses that are home to a 90-year-old Hainanese *kopitiam*, achingly hip cafes, and much else, Singapore's East Coast area is known for its laid back charm. For Chou Loke Ming, a recently retired professor of biological sciences at the National University of Singapore, it is the place where he first fell in love—with the sea.

"When the fishermen came back from a day's work and started to put their catch on the shore, the whole community would come down and have a look, myself included," Professor Chou muses, recalling his childhood growing up in the Siglap neighbourhood. "That's when I started to become very interested in the sea and anything to do with marine life."

After completing his PhD on house lizards at the University of Singapore—because the university was looking for lecturers to teach vertebrate zoology—Professor Chou turned his fascination with the sea into a thirty-year career in marine ecology and conservation, with a special focus on coral reefs. Commonly mistaken for plants due to their extremely slow growth, corals are actually animals closely related to sea anemones and jellyfish.

The so-called "rainforests of the sea" occupy only 0.1% of the ocean's surface yet are home to 25% of the world's marine species. The secret to this amazing biodiversity is a unique partnership between coral animals and single-celled algae known as zooxanthellae.

These photosynthetic algae reside within each coral polyp, supplying the corals with as much as 90% of their energy requirements. In turn, the corals absorb calcium from the surrounding seawater, building a hard, protective structure that can grow to become a massive coral reef like Australia's Great Barrier Reef, the only living entity visible from space.

Credit: Bryan van der Beek

SHAPING AND RE-SHAPING SINGAPORE

Although coral reefs need a long time to develop—the Great Barrier Reef has been growing for half a million years—their destruction can be swift. In the 1960s, Singapore was looking for a fast way to meet the demands of a growing population. Land reclamation had long been part of Singapore's developmental strategy; it was first used in 1822 to create the area today known as South Boat Quay.

However, land reclamation reached an unprecedented scale in the post-independence years, with an aggressive plan that saw Singapore's land area increase from 580 sq km in 1960 to 630 sq km by 1990. Today, it stands at 720 sq km, almost 25% larger than it was just before independence.

Involving the levelling of hills and dredging of the sea floor, the extensive land reclamation has almost completely smothered the costal coral reefs surrounding mainland Singapore and left whatever remains threatened by extremely high sedimentation levels that block out the sunlight needed for photosynthesis.

Research by Professor Chou shows that Singapore has lost 65% of its coral reefs since 1986, in large part due to land reclamation. [By comparison, over the same period the Great Barrier Reef lost 50% of its coral coverage, largely due to cyclone damage and a population explosion of destructive crown-of-thorns starfishes.]

Most of Singapore's reefs are now found only off surrounding islands such as Pulau Pawai and Pulau Semakau, which are used for live firing exercises and a landfill, respectively. One of the very few mainland areas where corals can still be found is off Labrador beach.

"I remember Labrador beach from my student days, before the land reclamation, when there was still an extensive rocky shore," Professor Chou says. "We used to find all kinds of different seashells, cones and cowries, in huge numbers. You can still find them there these days, but you will have to hunt very hard."

> "I remember a permanent secretary asking me why we should preserve the reefs since Singaporeans could easily go to Malaysia or Indonesia if they wanted to go diving."

CORAL REEFS OR GOLF COURSES?

At an estimated 7,618 people per sq km, Singapore has the third highest population density in the world after Macau (21,190 people per sq km) and Monaco (18,475 people per sq km). With so many competing land-use demands, marine conservation has historically been a low priority. But since the 1970s, Professor Chou has tried convincing Singaporeans that coral reefs are worth saving.

"I remember a permanent secretary asking me why we should preserve the reefs since Singaporeans could easily go to Malaysia or Indonesia if they wanted to go diving," Professor Chou shares. "I thought for a while and then said, 'Yes, but the same is true of golf courses.' The meeting stopped soon after that!"

But by the late 1980s, he says, attitudes had begun to change, in tandem with rising incomes and growing local environmental activism. The government, meanwhile, started participating in international conservation pow-wows such as the 1992 United Nations Earth Summit.

Today, for any construction project, developers need to conduct impact assessment studies, mitigation exercises, and real-time monitoring programmes.

"Projects must be stopped if measurements such as sedimentation exceed certain limits," says Professor Chou. "[In the past] if we had these measures in place, it would really have helped slow down the total impact to the reefs."

REGIONAL RESEARCH

In the late 1980s, Singapore lacked adequate marine science research, which was needed by conservationists both to understand the scale of

the environmental damage and as evidence to convince policy makers to act. However, Singapore was not well known for marine biology and a lack of government support meant that research facilities were few and far between.

"Thankfully, there were a few Association of Southeast Asian Nations (ASEAN) projects on marine science in the late 1980s, supported by Australia, Canada and the United States," Professor Chou recounts. "At that time, there were only four other countries in ASEAN [Thailand, Malaysia, Indonesia and the Philippines], each of them big countries with a lot of marine space."

> "But if there is one wish I could have, I would like to see the waters become clear again."

It wasn't apparent why Singapore deserved a slice of ASEAN's marine budgets. "Scientists in the other ASEAN countries would tell me, 'Singapore is so small, you just need a bicycle to get from one end to the other; you don't need a boat!'" Professor Chou says. "But in the end, the collegial spirit prevailed and the budget was equally shared."

The money helped him establish facilities for marine biology—focussing on underwater and scuba capabilities—which allowed more research to be conducted.

Professor Chou has also worked on other international projects. Among other things, he contributed to the United Nations Environment Programme (UNEP), helping to edit the *State of the Marine Environment Report for the East Asian Seas (2009)*, the first such assessment for the region; and was appointed to the UNEP's regional office in Bangkok to review Cambodia's coastal management plans.

SINGAPORE'S SURPRISINGLY RESILIENT REEFS

Professor Chou's local research revealed a pleasant surprise. In spite of all the damage done to them, Singapore's coral reefs have still managed to sustain a wide range of wildlife, including 130 species of fish, 250 species of molluscs and over 800 crustacean species.

"The rate of species extinction has not been as drastic as expected, given the scale of the environmental changes," Professor Chou shares. Of Singapore's 250 recorded coral species, for instance, while 70 are now "quite rare", only two have gone extinct locally.

Even those that have disappeared may one day return. In 2014, divers spotted a Neptune's cup sponge (*Cliona patera*)—believed to be extinct since 1908—incongruously clinging on to a landfill lagoon. Today the western reefs of both Pulau Tekukor and St John's Island are part of the Sister's Islands Marine Park, the first of its kind in Singapore, which was established in 2014 after some thirty years of lobbying by Professor Chou.

"[The park] will inspire more people to understand that the environment is part of our national heritage, something that we should try to conserve and protect," Professor Chou says.

"But if there is one wish I could have, I would like to see the waters become clear again," he quips brightly. "It will take a lot of effort. It will take a lot of money as well. It will take a lot of commitment on the parts of the different agencies. Anything on land development also flows out to the sea, so it's not work that can be done by a single agency. It will be challenging, but I don't think it's impossible."

Part of his optimism no doubt comes from the knowledge that the many of his former students have taken up the cause and are continuing his work. Karenne Tun and Jeffrey Low, for instance, are deputy director and senior manager respectively at the National Biodiversity Centre Division.

"If we look at the past 50 years, after all the impact, our natural resources are still there, they haven't been completely degraded," says Professor Chou. "Now with all the measures in place—the national marine park, the government agencies, the NGOs—we're beginning to have more discussion and collaboration. I hope that we will somehow make the waters clear again in the next 50 years, so that the next generation will be able to enjoy the environment just as we have."

Wealth and Intelligence, Re-defined

Hang Chang Chieh

By Juliana Chan

Singapore, an island city-state just north of the equator, has a hot and humid climate. To compensate, Singapore's buildings maintain some of the world's coldest indoor temperatures, powered by air-conditioners that whir along day and night, 24/7.

The late Lee Kuan Yew, Singapore's first prime minister, used to joke that when indoors he needed to wear clothes intended for European climates. More seriously, Mr Lee has argued that the greatest invention of the 20th century is the air-conditioner, especially for those living in the tropics.

But in order to run air-conditioners efficiently, intelligent thermostats are needed. This is where Hang Chang Chieh, professor of electrical engineering at the National University of Singapore (NUS), comes in.

"When it rains, the air-conditioner continues to work, wasting a lot of energy. It is not only energy-inefficient, it also makes people very uncomfortable," says Professor Hang.

To improve the technologies behind air-conditioners—and many other consumer goods—Professor Hang has, among other things, taken sophisticated control systems found in the military and aerospace industries and made them cheaper and simpler.

Credit: Bryan van der Beek

"INTELLIGENT" CONTROL SYSTEMS

As a student Professor Hang built his own radio and hi-fi audio speakers, and had a knack for repairing things. His PhD research topic covered adaptive control, a field where control systems are programmed to detect changes in the environment and adjust their parameters automatically.

This field is at the heart of the aerospace industry, where adaptive control systems are critical in stabilising airborne aircraft. For example, as a plane progressively depletes its fuel supply along its flight path, lightening its load, it needs to detect the change of its mass to maintain a comfortable experience for those on board, while burning less and less fuel to maintain its speed. Conversely, as and when air resistance increases, the plane needs to burn more fuel.

But the technology used in commercial airplanes—and also in space programmes and the military—remains too expensive for everyday applications such as air-conditioner thermostats. To sharply reduce costs, Professor Hang had to imbue these control systems with some kind of artificial intelligence.

These systems are "intelligent" in that they are able to measure a variable (e.g. the outdoor temperature after a rainy spell) and adjust the control parameters accordingly (e.g. raise the temperature setting on an air-conditioner thermostat) without the need for human intervention.

Beyond air-conditioners, intelligent control systems have much wider application in robotics, disk drive manufacturing and even in healthcare. "We are now coming up with the next generation of rehabilitation equipment, which are light weight, low cost, and can be rented or borrowed and put at home, cutting out travelling time," says Professor Hang.

> "Don't chase money, let money chase you. When you are successful in your work, at the minimum, you will be wealthy in knowledge."

A CLARION CALL TO SERVE

Like many young people growing up in Singapore today, CC—as he is often referred to—was determined to get into medical school.

In the 1960s, medicine was offered only by the University of Singapore—not by the country's only other university, the Chinese-language Nanyang University.

Professor Hang, who was then enrolled at the Chinese-language Chung Cheng High School, realised that he would not be able to pass the medical school qualifying exams if he was not proficient in English. In 1964, he transferred to Anglican High School, also a Chinese-language school but allowed him to take his papers in English and was strong in biological subjects.

One incident, however, would change the course of his life. During his school holidays after his first year studying for a higher-level certificate (HSC, the precursor to the GCE 'A' levels), he read in a magazine that Japanese youth were applying in droves to study engineering as they wanted to help rebuild the country's shattered economy after the Second World War.

Intrigued, Professor Hang started reading lots of engineering articles and introductory textbooks. It was a revelation to the wannabe-doctor, who changed his mind and decided to become an engineer instead.

"Singapore was in bad shape in the 60's; we were still a colony. There was poverty and many people could not afford medical healthcare," he says. "I thought, at that time, instead of being a doctor, if I became an engineer, I could help the country create wealth, and more people could afford healthcare."

It was all rather anti-climactic when Professor Hang found out that the University of Singapore did not have an engineering programme in 1966.

Undeterred, he studied in the electrical engineering degree course at the Singapore Polytechnic (the only polytechnic in Singapore at that time) for two years before the University of Singapore department of engineering absorbed the programme. His entire graduating class had only 40 engineering students, of whom 18, including him, majored in electrical engineering.

Professor Hang later received a bond-free scholarship from the UK government to pursue a PhD at the University of Warwick.

His post-PhD career as a control system designer at the Shell Eastern Petroleum Company ended after three years when he received a phone call from Jimmy Chen, head of NUS's department of electrical engineering, who wanted to recruit him. Acquiescing, Professor Hang took an immediate pay cut of 20%, a choice he has never regretted.

THE FIRST OF MANY FIVE-YEAR PLANS

Though the veteran engineer has long been focussed on his research into control systems, he has also had to wear many other hats along the way.

NUS appointed Professor Hang consecutively to three senior roles—vice-dean of the faculty of engineering in 1985, head of the department of electrical engineering in 1990, and deputy vice-chancellor (research and enterprise) in 1994—during which time he has had to oversee the university's transformation from a primarily teaching institution to one that is research intensive.

Part of his mandate was to raise research funds. "I was one of the most expensive beggars around. I asked for hundreds of thousands, millions," he says with a laugh.

In parallel, he became the founding deputy chairman of the National Science and Technology Board (NSTB) in 1991, a part-time position he held until 1999. The government gave NSTB just five years to produce concrete results, such as helping to attract foreign investment and growing local industries. "We had to make sure the first five years succeeded so that we would have a next five-year plan," he says.

By seeding a group of talented researchers, his efforts would eventually bear fruit and lead to multinational companies making significant investments here. The first five-year National Technology Plan in 1991—with a budget of S$2bn (S$3.1bn in today's dollars)—was renewed; two decades later, the 2011 plan had a five-year budget of S$16.1bn.

For his contributions to championing research in NUS and NSTB, Singapore awarded Professor Hang the Public Administration Medal (Gold) in 1998, and the National Science and Technology Medal in 2000. In 2001, NSTB was renamed the Agency of Science, Technology and Research (A*STAR), where he was seconded full-time from 2001 to 2003 as its executive deputy chairman.

WEALTHY IN KNOWLEDGE

Professor Hang remains active in engineering education—as head of NUS's division of engineering and technology management since 2007 and as executive director of NUS's Institute for Engineering Leadership since 2011.

He encourages bright, young people to study engineering because of the many academic, industry and entrepreneurial careers available to them. To prepare them for a life of entrepreneurship, the NUS faculty of engineering is making curricular changes to allow students to enter a design and innovation pathway.

The engineer in him also wants to let the facts speak for themselves. He cites a 2013 *Wall Street Journal* article, which described how participants of an investor conference voted engineering as the number one subject to study for a life of innovation, and their top choice for their children's college major. A 2015 article in *The Telegraph* also noted that more than a fifth of the world's wealthiest people studied engineering in university.

"Parents of course always say those in the finance sector, property, can make money," he says. But regardless of one's career ambitions, he believes engineering will provide a strong foundation. Consider his daughter, 33, who studied electrical engineering and later worked in public service, consulting and then banking.

Nevertheless, despite the allure of these high-paying professions, Professor Hang has some financial advice for Singaporean youth, including his daughter and son, 26. "Don't chase money, let money chase you. When you are successful in your work, at the minimum, you will be wealthy in knowledge."

Singapore should certainly be thankful that Professor Hang himself chose not to "chase money". Among his many engineering and research contributions to the country, one bears reiteration: the "intelligent" air-conditioner, which will help reduce energy use—and sweater sales—in this tropical island.

Shaping Molecules and Universities

Huang Hsing Hua

By Shuzhen Sim

In biology, form and function are inseparable. Molecules of identical chemical makeup can bend, twist and rotate into a variety of different conformations. This affects their physical interactions with other molecules, and determines how accessible their reactive groups are to enzymes, the proteins that catalyse chemical reactions essential to life.

For instance, our basic senses—sight, smell, sound, taste and touch—depend on cascading signals initiated by the docking of appropriately-shaped molecules onto receptor proteins.

As molecules are tiny—a raindrop contains about one billion billion (10^{18}) water molecules—chemists have developed ingenious techniques to determine their shape. They bombard molecules with electron beams, magnetic fields, and just about every wavelength along the electromagnetic radiation spectrum from everyday radio waves to biologically-hazardous gamma rays. The molecule's response to these perturbations offers insights into its structure.

Huang Hsing Hua, professor emeritus of chemistry at the National University of Singapore (NUS), is one such molecular detective. A physical organic chemist, he has spent his career developing methods to reveal the shape of organic molecules, and thus better understand the mechanisms behind the reactions they participate in.

Credit: Cyril Ng

SCIENCE ON A SHOESTRING

Professor Huang came to Singapore from Malaysia in 1952 to study chemistry at the University of Malaya (UM). After doctoral studies at Oxford University, he returned to Singapore in 1959 to work as a lecturer.

At the time, many university faculty and staff had left for Kuala Lumpur, where another UM campus was being established. "We were left with only a skeleton staff in Singapore," he recalls.

Given these meagre resources, Professor Huang decided to revisit a research area from his master's programme at UM. This involved using dipole moments to deduce the shape of organic molecules.

Chemical bonds—in essence, electrostatic attractions between atoms—hold molecules together. In some molecules, these bonds are polar, meaning that there is a separation of positive and negative electric charges within the bond, known as a dipole.

A water molecule (H_2O), for example, is polar because its electronegative oxygen atom attracts negative charge away from its two hydrogen atoms. The dipole moment is a measure of polarity or the degree of charge separation, and can provide information about the position of atoms around the bond.

As research funds were low in pre-independence Singapore, UM was focussed mainly on teaching. So Professor Huang, in keeping with the resourcefulness of the times, used a dipolemeter built from scratch by his supervisor. It was made out of inexpensive radio components: oscillators that emitted radio waves at fixed and variable frequencies, a high-precision condenser (a glass tubing that cools hot gas into its liquid state), as well as a cell made by a local glass-blower.

In addition to this improvised equipment, Professor Huang also used a simple but novel method of synthesis to create new organic molecules—derivatives of ethane (C_2H_6)—that would serve as his subjects for study. He designed the molecules to have two polar symmetrical halves connected by a bond between the two carbon atoms. Because the two halves rotate around the carbon-carbon bond, the molecules cycle through several different conformations and energy states.

By measuring the various dipole moments Professor Huang could work out the angle of rotation, and thus deduce the molecule's conformation, along with its potential reaction mechanisms.

Although Professor Huang worked with synthetic organic molecules that do not exist in nature, this technique could also be broadly applied to other naturally-occurring molecules that are soluble in non-polar solvents such as benzene.

> "No one can predict the issues that science and society will consider most pressing in the decades to come."

Professor Huang's molecular-detective work—first on dipole moments, then later on other analytical techniques such as infrared spectroscopy, ultraviolet photoelectron spectroscopy, and X-ray crystallography—has contributed to the theoretical understanding that chemists now have of molecular conformation and reactivity.

This knowledge underpins modern advances in applied fields such as molecular pharmacology. This includes the design of effective drugs, which requires detailed knowledge of how molecules interact in three-dimensional space.

For his scientific contributions to the field of physical organic chemistry, Professor Huang received the National Science Award in 1994 from the National Science and Technology Board.

SHAPING A UNIVERSITY

Funding for research remained extremely limited in the 1960s-70s, and many would-be academics turned instead to careers in the foreign service or in politics. During those years the research budget for the entire university was a few hundred thousand dollars. "You can imagine how much each department got," Professor Huang says.

The situation improved in the 1980s, when the government began to place more importance on research and innovation as an economic driver. The Science Council started to accept applications for research funding. Meanwhile, money began to flow in from unconventional sources such as Singapore Pools, the state-owned lottery firm.

In 1981, the newly-formed NUS appointed Professor Huang as deputy vice-chancellor. He was charged with promoting interdisciplinary research, which integrates concepts, techniques and data from multiple fields of study to solve complex problems. Dealing with outbreaks of infectious diseases such as influenza and Ebola, for example, requires cooperation between medical professionals, biologists, epidemiologists and public health authorities.

"No one can predict the issues that science and society will consider most pressing in the decades to come," says Professor Huang. "The integration of research and education through interdisciplinary training prepares a workforce to undertake scientific challenges in innovative ways."

The value of interdisciplinary collaboration is well accepted today. But researchers at the time felt that they could more easily make advances and achieve recognition within their own fields, and were thus reluctant to engage with those outside. "Nevertheless, it was important because real life problems or issues require for their solution a combined attack using knowledge from different disciplines," says Professor Huang.

To encourage them to venture outside the confines of their own fields of expertise, Professor Huang held formal seminars and informal conversations with NUS staff. From his tenure onwards, NUS started to look favourably on funding requests for collaborative projects, and hosted interdisciplinary conferences in a variety of areas, including environmental science, computer science, mathematics and biomedical engineering.

Professor Huang's own field of research had already matured by the time he became deputy vice-chancellor. Another of his roles, then, was to identify new research niches in which Singapore could develop an expertise. He recruited talented faculty members in burgeoning fields such as nanotechnology and surface science.

Surface science, in particular, was where Professor Huang saw opportunities for interdisciplinary collaboration. The field deals with the unique chemical and physical properties occurring at the interface of two phases, such as solid-liquid or solid-air, and has applications in areas such as semiconductor manufacturing, industrial catalysis and fuel cell production. Under his leadership, NUS established a surface science laboratory in its department of physics, which allowed for collaborative work with its department of chemical engineering.

This laboratory was an early iteration of the many NUS-founded research institutes that are multidisciplinary in nature today, including the Institute of Molecular and Cell Biology (IMCB), the Institute of Materials Research and Engineering (IMRE), and the Institute of Systems Science (ISS).

As the research environment at NUS improved, the university started to attract talented students and post-doctoral researchers from around the world. "By the time I retired [in 1997] NUS had started to make a name for itself," says Professor Huang.

In recognition of his contributions to science and to the university, Professor Huang received the NUS Distinguished Science Alumni Award in 1999.

GOING BEYOND HEAD KNOWLEDGE

Professor Huang is optimistic about the future of NUS under its current administration, although he is unsure when it will achieve its ultimate goal of producing a Nobel laureate. "Singapore has been very successful in producing people with book knowledge," he says. "But beyond that you need people who can think originally to really make a huge impact."

Since his retirement in 1997, Professor Huang has dedicated a large portion of his time to studying the Bible. But that's not enough. With religion, as with science, he believes in the importance of linking theory with practice, of translating book knowledge into action. For him, part of the answer lies in volunteering at St Andrew's Community Hospital, where he spends time talking with patients and keeping them company.

THE RAINMAKER

LAM KHIN YONG

By Grace Chua

How does an underwater mine shockwave travel through the sea towards its target? What happens to a pager when it is dropped from a certain height? And if a fire breaks out in an enclosed space, how does the smoke fill the room?

Lam Khin Yong, 58, chief of staff and vice-president for research at Nanyang Technological University (NTU), has explored or managed all these research questions and more in a three-decade career.

A professor of mechanical engineering, his expertise and consultancy work for companies has also helped secure more than S$200m of research grants and collaborations for the Singapore research community, including a S$75m lab with aerospace giant Rolls-Royce.

In other words, Professor Lam has managed to combine two successful careers: one as a hands-on scientist and another as one of Singapore's preeminent research rainmakers.

HUNGRY FROM DAY ONE

As a young graduate student at the Massachusetts Institute of Technology, Professor Lam developed hydraulic fracturing methods—the same technology widely used in the oil and gas industry, especially for shale gas extraction today.

His research focussed on modelling a fluid as it travels through a narrow channel and interacts with its surroundings. He worked on a complete simulation of hydraulic fracturing in three dimensions, first understanding the basic physics behind fluid movement, then building mathematical models to explain how fracking would work under various field conditions.

With his advisor, Professor Lam developed software based on this work. It was later used by industry to simulate underground oil extraction.

Credit: Cyril Ng

Most importantly, he learned to be entrepreneurial. "I think my MIT training gave me an added advantage," he says. "My professor was always on the lookout for funding and I learned to be hungry from day one."

When he graduated, oil and gas companies tried to recruit the newly-minted PhD, but he decided to return home in 1985 to be nearer to his family.

He joined the National University of Singapore (NUS), which at the time was just beginning to grow into a major research university.

But research funding was hard to come by at the time. "There was no NSTB [National Science and Technology Board], no A*STAR [Agency for Science, Technology and Research], only the Science Council of Singapore," he says. "It was one or two years before I got my first PhD student."

A LUCKY BREAK

In 1991, while working as the principal investigator on a project to model the effectiveness of civil-defence shelter doors, Professor Lam dreamt up his first big research project for Singapore.

Having served his reservist duty in the Singapore Navy, he was already familiar with its design and testing procedures for new vessels and equipment. Recognising the need for vessels to better withstand shock, Professor Lam and his team carried out computational modelling to simulate field conditions.

> "I think my MIT training gave me an added advantage… I learned to be hungry from day one."

In 1993, his project proposal received a S$3.13m (S$4.6m in today's dollars) grant—one of the biggest at the time—from the Naval Logistics Department and DSO National Laboratories. Thus was born the underwater shock laboratory at NUS.

Professor Lam, with support from his colleagues and students, used a mini supercomputer bought with the grant money to model shock waves and the resulting bubbles travelling through water, such as from underwater mine explosions, analysing their interaction with the surroundings. The research helped the Navy design naval vessels that could better withstand underwater shock.

Five years later, his team became the first led by a university academic to win the Ministry of Defence's Defence Technology Prize for its work.

BEYOND EXPLOSION SIMULATIONS

One advantage of Professor Lam's specialty, computational modelling, is that it is endlessly versatile.

"If you have the skills and the basic understanding of physics, you can apply these to any other domain," he says. "Before computational modelling, you had to do experiments; these could tell you whether a design would pass or fail in the engineering sense, but computational modelling helps you understand its behaviour in various conditions."

With the Navy as its first major client, word soon spread of Professor Lam's underwater shock laboratory. This spawned several more industrial collaborations with firms such as Motorola and ST Kinetics.

For instance, in a project for Motorola, Professor Lam's modelling was used to answer the question: how will a pager casing behave when it is dropped from a certain height? (In the process he surely saved the lives of many "crash-test" pagers.)

One memorable project, Professor Lam recalls, was modelling the ventilation system for the Esplanade's theatres. His research questions included: how will cool air flow through the space to make the temperature even for all audience members? If there is a fire, where will the smoke go?

In all, between 1995 and 2007, Professor Lam helped secure more than S$30m of external, competitive research grants for computational mechanics work, from companies and organisations.

Over the years, advances in computing power have sped up modelling and simulation tasks. Supercomputers that once performed one million operations a second can now perform a billion times that, Professor Lam explains.

"Problems that seemed insurmountable years ago have become routine tasks," he says. "And we now have the capacity to solve challenges in a virtual environment on a scale never dreamt of before."

By 1998, the NUS centre for computational

mechanics had merged with the national centre for supercomputing research and services to form the Institute of High Performance Computing (IHPC), under the auspices of the NSTB and later A*STAR. As the NUS centre's founding director, Professor Lam also became founding director of IHPC, which studies the properties of materials and fluid movement. Its visualisation group is the first in Asia to have a three-dimensional immersive visualisation "cave".

"The most interesting and fun years I had were when I was running IHPC," he says. "You are like a 'super-PI' [principal investigator, the lead researcher in a group], running research in your fields of interest and managing a large team. You, your colleagues and PhD students do basic research, but the results get adopted by companies and agencies."

Despite his intimate knowledge of academia-industry collaborations, Professor Lam never really considered joining the private sector.

"It was always clear that my primary interests lay in academia," he says. "I also enjoy forming research partnerships and naturally gravitated towards bringing like-minded researchers and industry counterparts in collaboration. Therefore, IHPC was a natural progression while I was in NUS."

Following IHPC was a string of more administrative appointments, such as head of A*STAR's graduate academy, to nurture students for science and engineering fields; chair of NTU's school of mechanical and aerospace engineering; associate provost for graduate education and special projects; and chief executive officer of NTU Innovation. In these capacities, Professor Lam helped manage ever-bigger budgets and tasks.

LINKING INDUSTRY AND ACADEMIA

As NTU's chief of staff and vice-president for research today, he helps to manage research in an array of fields. In 2013, for example, he helped the university secure a major collaboration with Rolls-Royce, a renowned British engine and power-systems firm.

But the S$75m lab, which studies electrical power and control systems, manufacturing and repair technologies, and computational engineering, is actually the product of a long courtship.

In 1999, the IHPC signed a research agreement with Rolls-Royce and Imperial College London. "We had a supercomputer in Singapore, but the data had to be couriered to Imperial in those days because the network link was not strong," Professor Lam recalls.

Meanwhile, NTU and Rolls-Royce had been collaborating on an ad-hoc basis since 2005, but a long-term working relationship had yet to crystallise.

"Essentially, we needed to find a common platform and agree on thematic research areas that integrated the university's mandate of basic research and innovation with Rolls-Royce's emphasis on fast-tracking applications for commercialisation," Professor Lam says.

So when the National Research Foundation announced its Corporate Laboratory scheme in 2013, in which major firms would co-fund dedicated research labs at local universities, NTU and Rolls-Royce were perfectly placed to work together. The Rolls-Royce@NTU Corporate Lab, jointly funded by the National Research Foundation, Rolls-Royce and NTU, was born.

"I believe it is our long partnership of trust and mutual understanding which allowed us to resolve any differences, and come to mutual agreement with relative ease," he adds.

In April 2015, NTU and ST Engineering, a local engineering giant, announced a S$53m corporate laboratory in robotics and autonomous systems. "It took me and my colleagues more than a year to get the lab proposal approved," Professor Lam says.

Today, Professor Lam continues to help guide NTU's research directions and hopes to be active for many years yet.

At a larger level, Professor Lam believes Singapore should strengthen its collaborations between universities, research institutes, national agencies and industry in a triple helix partnership, to create real research impact and innovation.

It should also continue efforts to get students excited about a science or engineering career.

"I hope these efforts will translate not only into creating a future generation of exemplary STEM [science, technology, engineering, mathematics] leaders and researchers at home but also create a generation of Singaporeans who are curious and appreciate the spirit of scientific inquiry and innovation," he says.

Bloom where you are planted

Gloria Lim

By Rebecca Tan

Female researchers make up 27% of all researchers in Singapore today, a figure close to the global average of 30%. While this puts Singapore ahead of Japan and South Korea (13% and 15% respectively), it is still far from parity and lags behind Malaysia (37%) and the Philippines (52%).

One of the factors contributing to the imbalance is that girls have historically been given fewer educational opportunities. Even when they were allowed to go to school, science was not deemed a suitable subject. Such was the case for Gloria Lim, a retired professor in botany at the National University of Singapore (NUS). Although she had no background in science, having come from a girls' school which did not teach science at all, she nonetheless found her way into the science faculty, joining the University of Malaya (UM) the year it was founded, 1949.

"When I applied to the university, they first gave me a course in the arts faculty," Professor Lim recounts. "My mother said, 'No, if you're going to do arts you might as well go to teacher training straight away.' So I appealed to the university and they put me in science. And lo and behold, in my first year I was like a sponge, absorbing all the scientific things around me."

Professor Lim went on to become one of two inaugural honours graduates from the department of botany. Subsequently, she served as the first—and only—female dean of science, as well as the first female member of the Public Service Commission (PSC), roles for which she was awarded the Public Service Star in 1993 and the title of distinguished science alumni in 2005 by the NUS faculty of science.

Credit: Bryan van der Beek

MAD ABOUT MYCOLOGY

As much as she enjoyed and excelled at science, a life in academia was then seen as an unconventional career path for women. Therefore, in addition to completing a master's in plant pathology, she hedged her bets by doing a diploma in education, at the suggestion of her mother.

She was then posted to Raffles Girls' School. But the university's botany department also wanted her. "So I would teach in the morning and rush back to the university in the afternoons—I had more energy in my younger days!" she shares, laughing.

Eventually, H. B. Gilliland, the head of botany, submitted Professor Lim's name for the Inter-University Council Fellowship, which allowed her to complete her PhD at the University of London. Upon her return to Singapore, she continued her work on fungi, establishing a name for herself as a mycologist.

For Professor Lim, living in the tropical climate of Singapore is a mycologist's dream—the humid environment supports a diverse array of fungi, as anyone who has ever left out a slice of bread would know firsthand.

Over the course of her career, she painstakingly built up a fungal collection, maintaining a unique repository of the region's under-studied fungal species. Unfortunately, when the zoology and botany departments were later merged after Professor Lim's retirement, there was a shift in emphasis towards zoology, perhaps because fungi was generally then seen more as a problem than a resource.

"Yes, they can cause disease, but they can also heal you," Professor Lim stresses. "For example, important drugs like penicillin were first found in fungi."

The new department discarded her fungal collection, which is ironic, considering that as eukaryotes or cells with nuclei, fungi are actually more closely related to animals than plants, despite their plant-like appearance. "The botanists left the department one by one," she says.

Despite funding constraints, Professor Lim over the years managed to publish hundreds of research papers, with the help of her students and through experience gained from sabbatical stints overseas.

Apart from authoring several books on mycology, she has also consulted for both the private and public sectors—serving on the scientific advisory board of MycoBiotech, a company focussed on medicinal mushrooms, and advising the Ministry of Defence when they had mould problems in their underground storage bunkers.

> “[Fungi] can cause disease, but they can also heal you… important drugs like penicillin were first found in fungi.”

NAVIGATING POLITICAL TURMOIL

Professor Lim's ability to "cut according to the cloth given" also served her well during two stints as dean of the University of Singapore's science faculty—first in 1973-77, then for a period in 1980. Right from the start, certain colleagues questioned her suitability for the role.

There were other problems at the student level, too. "I remember being stuck at the top floor of the Bukit Timah campus during a student riot protesting the arrest of Tan Wah Piow," Professor Lim says. "It was an exciting time for me—I learnt a lot of lessons on how to cope with situations of that kind."

[In 1974, Mr Tan, president of the University of Singapore's Students' Union, was charged, convicted and sentenced to one year in prison for unlawful assembly and rioting, after being accused of instigating shipyard workers to agitate against their employers. He moved to London in 1976 and has been living there in exile ever since.]

Professor Lim's second term was much shorter. Shortly after she was re-elected as dean of the science faculty, the University of Singapore and Nanyang University merged. She then stepped down in favour of Koh Lip Lin, the Nanyang dean and a former member of parliament.

IT'S (STILL) A MAN'S WORLD

In 1982, Professor Lim was invited to join PSC, a body tasked with recruiting and managing civil service talent. Approached for her extensive experience in the university, particularly in managing tenure committees, Professor Lim served PSC for 14 years, bringing a different perspective to their selection policies.

"One of the things I asked for was more female physical education (PE) teachers; they had never sent a woman to do a scholarship for PE before," Professor Lim says.

When Professor Lim stepped down in 1996, PSC again became a male dominion. That changed in 2009, when Chua Sock Koong, CEO of Singtel Group, and Lily Kong, vice-president of NUS, joined it.

Despite these and other accomplishments by women in Singapore, Professor Lim is sceptical about the progression of gender diversity in the country. Even today, she notes, the fellows of the Singapore National Academy of Science are all male.

"I've come to the stage where I feel that there will always be a gender imbalance in Singapore," Professor Lim contends. "I've seen it in my own life—50 years and still no change. I noticed that all the other retired deans were given appointments. When I retired, I was never offered any opening. It might never have crossed their minds, or they thought I was incapable. Either way, the difference was stark, at least to me."

> “We mustn't keep thinking of only doing applied research because we need basic research as our foundation. Buildings without strong foundations topple over, no matter how pretty they may look above ground.”

CALLED OUT OF RETIREMENT

Although some glass ceilings have been harder to crack, the field of education has been much more welcoming of Professor Lim and many other women before her. In 1991, she was appointed founding director of the National Institute of Education (NIE)—thereby helping to transform the Institute of Education (IE) into a fully-fledged degree-awarding institution.

"My role was very clear: to raise the IE to a university standard," she says. "Going in as a sort of outsider, I could sense a kind of resentment. I knew I had to tread carefully and yet at the same time be firm in implementing the changes required."

By the time she stepped down in 1994, NIE was offering not only four-year bachelor's degrees, but also master's and PhD qualifications.

Professor Lim regards the students she has taught, many of whom have already retired, as her most important legacy. Nevertheless, she remains concerned that too few Singaporeans—male or female—are pursuing science careers.

Although Singapore has achieved economic success, she says, there is still much to do. Complacency is dangerous, partly because resource allocation remains a challenge.

"We have to be careful about the areas of research we go into, because money used improperly can be bad for us," she cautions. "We mustn't keep thinking of only doing applied research because we need basic research as our foundation. Buildings without strong foundations topple over, no matter how pretty they may look above ground. It's also crucial that we develop our own people and put them in leadership positions, people who understand our history and context."

Perhaps some of these roles might even be filled by women, she says, with a twinkle in her eye.

Growing a Research Culture

Lim Pin

By Grace Chua

When he was a young doctor and one of Singapore's early clinician-scientists, Lim Pin, professor of medicine at the National University of Singapore (NUS), saw patients, lectured at the university's medical school, went about "begging" from foundations and firms for research funding, and wrote his papers at night and on weekends.

He proved naysayers wrong, showing that medical papers from tiny Singapore were in fact good enough to be published in brand-name journals such as the *British Medical Journal*.

Today the trim, articulate grandfather of ten is best known for his contributions to NUS. In the course of becoming its longest-serving vice-chancellor, he built the university into a modern research powerhouse.

Credit: Cyril Ng

PUTTING SINGAPORE ON THE MEDICAL RESEARCH MAP

Professor Lim, the son of a Chinese-school principal and teacher, was a top student at Raffles Institution, and subsequently chose to study medicine. "You're always challenged by problems that are not trivial—they involve people's lives and suffering," he says. "The attraction was being able to do something of value."

In 1963, when Professor Lim returned from the University of Cambridge, he spent his days tending to patients at the Singapore General Hospital. A holder of a Queen's Scholarship—the precursor to Singapore's President's Scholarship—he also lectured at the University of Singapore.

Before long, he noticed a clinical problem: kidney- and heart-failure patients, who had ostensibly normal levels of magnesium in their blood, were still suffering the symptoms of magnesium deficiency, such as cramps and muscle weakness.

Magnesium's role in metabolism takes place within cells, where it binds to and guides a molecule called ATP that serves as a key cellular energy source. Professor Lim guessed that any magnesium in the blood must be an imperfect indicator of a person's true magnesium levels.

Professor Lim and his colleagues tested these patients' tiny muscle samples, which proved a more accurate method of assessing true magnesium levels. They found that many patients were suffering from magnesium deficiency. The prestigious *New England Journal of Medicine* and the *British Medical Journal* published their findings.

"That's the secret to any good research project," says Professor Lim. "You start with a question, do a search of the literature, and you find out people have not done something which you think ought to be done. That's what science is about. You look at something strange or unusual, and ask 'Why?'"

Their work shifted clinical thinking on how to treat such patients, prompting doctors to look beyond blood for magnesium deficiencies.

Finding time for research was tough, Professor Lim admits, because doctors then had to do more calls than they do today. "The only time you had for research was weekends and your own time... I had a very indulgent family."

Funding was another challenge. In the university's early days, just after Singapore separated from Malaysia in 1965, scientists often had to seek research support from family foundations and pharmaceutical firms. "We were bankrupt," Professor Lim says, in reference to the entire university's paltry annual research budget of S$20,000 (S$78,000 in today's dollars).

"Whatever money we needed, we sourced on our own," he says. "But even as a lecturer, I thought: unless we do some research, it's not a university; it's a glorified high school."

> "Unless we do some research, it's not a university; it's a glorified high school."

Even the lack of a laboratory did not deter him. In order to analyse samples, he collaborated with colleagues at the hospital's biochemistry department, offering them joint authorship of publications. "Many of my senior colleagues had never dreamed of being able to publish in an international journal [the *New England Journal of Medicine*]," Professor Lim enthuses.

His time in the UK had given him the confidence to successfully break through this psychological barrier. "Our people are equally driven, equally bright, so why are we not there?" he muses. "Had I not gone abroad, I wouldn't have been able to compare."

FROM CLINICIAN-RESEARCHER TO KEY ADMINISTRATOR

By 1978, Professor Lim was head of the university's department of medicine. The following year, the university appointed him deputy vice-chancellor, and then in 1981, vice-chancellor, the university's top administrative post. At 45, he had a chance to really build up NUS's research prowess.

"By the 1980s, [Singapore's] economy had improved, and there was a general realisation that unless we moved up the ladder in terms of manpower training and technology and skills, we wouldn't be able to go much further, other than assembling toys," he says. "We needed scientific expertise, and the mindset of the workers too needed to change, to develop inquiring minds and a research-oriented kind of culture."

With policymakers starting to view research less as wasteful expenditure and more as an investment in Singapore's future, Professor Lim and others successfully lobbied for the Institute of Molecular and Cell Biology (IMCB), opened in 1985 at a cost of S$25m (S$42m in today's dollars) to perform research on subjects from immunology to plant cell biology. It was one of the first research institutes at NUS.

The university had spent years scouting for and recruiting talented Singaporean researchers, such as plant biologist Chua Nam Hai, who had already established careers abroad. "We managed to get a core of maybe half a dozen good people," Professor Lim says. "It was like a crystal—once we were able to get a nucleus sorted out, it grew very nicely."

Even Glaxo, a pharmaceutical firm, donated S$6m (S$10.1m in today's dollars) to the institute, spearheading public-private sector symbiosis in Singapore.

"Glaxo... had a large manufacturing operation in Singapore that made an antacid called ranitidine, and they decided to do something as gratitude to Singapore and encourage it to move up the science and technology ladder," says Professor Lim. "Plus, as the industry became more and more high-tech, you need support, labs, training and so on... So it was also in their interest!"

With encouragement, incentives and funding, the university's research output grew. Professor Lim made research a key determinant of promotion for professors, and prioritised funding for projects that relied on interdisciplinary collaboration.

In the 1980s, the university's research budget was "a couple of hundred thousand dollars a year"; by the time Professor Lim stepped down as vice-chancellor in 2000, NUS had a multi-million dollar annual research kitty and half a dozen research institutes, including those in the social sciences such as the East Asian Institute.

"I think my biggest contribution was to create and strengthen the research culture on campus, and I hope that has rubbed off onto the whole country," he says.

Today, the private sector contributes about two dollars of R&D funding for every public dollar—the right mix, contends Professor Lim, and in line with other developed countries.

But he believes the prerogative is still with the public sector to initiate and direct research. "And if the private sector sees that the research is relevant to their needs, they'll join in," he says.

A MATURE RESEARCH CLIMATE

In 2004, the IMCB was incorporated into the Agency for Science, Research and Technology, which was setting up its Biopolis research campus. "It was a bit painful, but it's all for a good cause," Professor Lim admits. "There is better synergy between institutes if they are managed under one umbrella."

Since those early, lean days, Singapore's commitment to science and technology has been on the right track, he thinks. "In the early days, [science] as a career was not quite as attractive. Now, respect is there and the remuneration is quite respectable."

Importantly, he says, the government believes that science and technology are fundamental for Singapore's future development. "The ultimate objective is to produce something useful to the socioeconomic development of Singapore," he says.

On the question of managing Singapore's human resources, Professor Lim believes it is important to both recruit the best foreign talent available while grooming local scientists for the long term. As vice-chancellor, he scaled up NUS's senior tutor scheme, which hired promising young graduates, sent them abroad for their PhDs, and gave them jobs on graduation. (It was later replaced by the NUS Overseas Graduate Scholarship scheme.)

Today, those onetime senior tutors include Brenda Yeoh, dean of NUS's arts and social sciences faculty, and Karina Gin, professor of environmental engineering.

At 79, Professor Lim continues to see patients and tutor endocrinology trainees and undergraduates. He has also chaired the national Bioethics Advisory Committee and the National Wages Council.

"Endocrinology is my specialty; I still read journals and keep up in this area of medicine—there's always something new. Medicine's always growing," Professor Lim says. "But younger people are more agile; I'm an armchair researcher now."

THE BUILDER

LOW TECK SENG

By Juliana Chan

Some people think of him as an electrical engineer and educator, but "builder" makes perfect sense as well.

From colleges to research institutes and government agencies, Low Teck Seng, professor of electrical & electronic engineering at the National University of Singapore (NUS) and Nanyang Technological University (NTU), has built and run some of the largest organisations in Singapore.

It has been a long journey for the boy from Kuala Pilah, a small town in Negeri Sembilan. When Professor Low moved across the Causeway, it was with only one intention in mind: to complete his pre-university education and apply to a local university.

In those days one could study for the GCE 'A' levels at Singaporean secondary schools, as National Junior College was the country's only junior college. So Professor Low worked towards his 'A' levels at Swiss Cottage Secondary School, under principal Rudy Mosbergen (later Raffles Junior College's founding principal).

But shortly after the exams were over, Professor Low was rejected by both NUS and the University of Malaya. "They didn't want me," he says wryly.

On the advice of a family friend, he applied to and was accepted by Southampton University in the UK. There, his passion for engineering led him to a first class honours degree in electrical engineering in 1978, and a PhD in 1982. In 2009, his alma mater conferred on him an honorary science doctorate.

Credit: Bryan van der Beek

SOME PEOPLE SAID I WAS WORKING ON LODESTONES

For Professor Low, one memorable episode from the UK revolves around his undergraduate final year project—when he developed a two-dimensional model for permanent magnets under the mentorship of KJ Binns, an infamous, cigar-chomping professor.

A magnet, like those on refrigerator doors, is any material that has its own magnetic field, i.e. the property of being ferromagnetic. Permanent magnets are made from "hard" ferromagnetic materials such as ferrite (ceramic) and alnico (iron alloys of aluminium, nickel and cobalt), and do not lose their magnetism easily—as opposed to "soft" materials, such as iron alloys of nickel and zinc, which do. Professor Low modelled the properties of permanent magnets and validated his findings with experimental data.

Despite Professor Low's initial apprehension about Professor Binn's esoteric teaching style, the research led to his first publication, in the *IEE Proceedings Part B* journal, which he says is the most satisfying paper he has ever published.

Returning on a high from the UK in 1983, Professor Low was shocked by the "abysmal" labs and research facilities at NUS's department of electrical engineering.

To make matters worse, NUS did not have graduate students to help Professor Low with his research. But he persevered, writing code with undergraduate students and collaborating with NUS colleagues Chua Soo Jin, Daniel Chan and the late Jacob Phang.

To add to his list of growing concerns, the field of magnetics was "not popular" with funding agencies. "Some people attributed the work I wanted to do on permanent magnets as working on lodestones!" he says.

Lodestones, naturally ferromagnetic materials made out of mineral magnetite, have developed a poor reputation within the scientific fraternity after years of misuse by charlatans, for instance as amulets and good luck charms.

Fortunately for Singapore, Professor Low had by then met his wife-to-be, and they intended to settle down locally. This helped to repel job offers from the UK and the US. And the local naysayers who did not value his research would change their minds in the late 1980s, as the data storage industry grew in significance and importance in Singapore.

With the support of Philip Yeo, then chairman of the Economic Development Board of Singapore (EDB), and funding from the National Science and Technology Board (NSTB), Professor Low founded the Magnetics Technology Centre (MTC) in 1992.

As founding director of MTC, later re-named Data Storage Institute (DSI), he diversified its initial portfolio of mechatronics, tribology and coding to encompass magnetic sensors, media and optics. MTC helped to attract and root key data storage manufacturers in Singapore, including multinational companies such as Seagate, Maxtor, Conner Peripherals and key magnetic media companies. Today Singapore manufactures about 40% of the world's hard disk media, a key component of hard disk drives.

Professor Low attributes his success at DSI to good luck and friends, including senior colleagues from around the world who helped him chart a road map for the fledgling institute.

DSI would go on to spawn many successful alumni, such as Lee Yuanxing of Avago Technologies, a Singapore-based global microelectronics and technology firm; Gu Guoxiao, who runs a design centre in Singapore for Western Digital, a US technology firm; and Wang Jian-Ping, professor of electrical and computer engineering at the University of Minnesota.

For his role in establishing DSI and the support it provided for the growth of the data storage industry here, Professor Low received the National Science and Technology Medal in 2004.

A BIRD'S EYE VIEW OF R&D IN SINGAPORE

In 2012, after serving as dean of engineering at NUS, founding principal of Republic Polytechnic, and managing director of the Agency for Science, Technology and Research (A*STAR), Professor Low took on a new, complex portfolio, as chief executive officer of Singapore's National Research Foundation (NRF).

The NRF is a department in the Prime Minister's Office that coordinates the R&D efforts across Singapore. It also funds projects in areas where Singapore has a strategic interest, such as water technology, clean energy, satellite technology and urban sustainability.

Of the many areas NRF has supported, one of them is particularly close to Professor Low's heart: spintronics, an emerging technology that uses the intrinsic spin of electrons and their associated magnetic moment to develop new magnetic materials and structures for circuits and devices.

> "It's a good and bad thing, right? Today our young people have options because of Singapore's success."

Bringing together researchers at NTU and NUS, the Singapore Spintronics Consortium (SG-SPIN) was established in 2015 to develop next generation technologies for data storage and microchips. Founding industry members are Applied Materials Inc, Delta Electronics and GlobalFoundries.

Advances in spintronics could lead to, among other things, personal devices that are faster, more energy-efficient, and have a larger capacity. Imagine not having to charge mobile phone batteries on a daily basis; and being able to store almost infinite amounts of data on laptops, accessing them in a fraction of a second.

When Professor Low took charge at NRF, Teo Chee Hean, Singapore's deputy prime minister and chairman of NRF, gave him two key objectives. The first is to foster collegial competition between the various research groups across Singapore.

Collegiate competitiveness, Professor Low says, is achieved when scientists have the ability to work together on collaborative projects, such as SG-SPIN, while maintaining a healthy competition between themselves, to "egg each other ahead". It is a delicate balancing act, he says.

Professor Low's second target is to realise benefits from Singapore's R&D investments for Singapore and Singaporeans. But assessing R&D outcomes is an inexact science.

In Singapore, there has traditionally been an emphasis on individual KPIs (key performance indicators), which distill a researcher's output into a set of numbers.

"Forget about KPIs," Professor Low says, believing they are reductive and force unnecessary focus on individual achievement. He calls for a more nuanced approach to assessing R&D outcomes, one which shifts the pressure of achieving results from the individual to the system as a whole.

No doubt, individual assessment is necessary. But Professor Low believes that the system can become more effective at assessing individual performance without compromising the intellectual freedom on which discovery science depends.

To gauge Singapore's R&D performance, Professor Low believes the overall rankings of institutions are important, to a degree. Being ranked highly on international lists helps EDB and NRF attract global technology companies to Singapore, where they will co-create intellectual property and contribute to the economy, he says. These rankings also help academic institutions in Singapore recruit talented faculty and graduate students.

"I think our government has been very, very patient," he says, about the time that has been taken to get Singapore's R&D off the ground.

BUILDING A PIPELINE OF YOUNG SINGAPOREAN LEADERS

His portfolio may have since changed, but you cannot take the educator out of Professor Low. Of the various institutions Professor Low has contributed to, he is most sentimental about his stint as founding principal of Republic Polytechnic in 2002, which led to him receiving the Public Administration Medal (Gold) in 2007.

At Republic Polytechnic, he established a problem-based learning approach, modelled after the one employed by Olin College in the US. "It contextualises concepts that you want students to learn and it is very integrative. You don't silo things," he says. He is hopeful that this type of integrative curriculum will help to build a strong pipeline of young, enthusiastic and entrepreneurial technologists for Singapore.

On the broader national R&D landscape, it is essential for Singapore to have a vibrant talent pool of scientists and engineers. Professor Low says that Singapore must have deeply-rooted locals in leadership positions to complement the many foreign scientists who have come to develop their careers in Singapore.

Nevertheless, he is well aware that young people today, like his son, a National Serviceman who intends to study chemical engineering at NUS, may have other career plans. "It's a good and bad thing, right? Today our young people have options because of Singapore's success," he muses.

Brick by brick, his generation has laid the foundations; Professor Low often wonders who will take over.

THE DEFENCE SCIENCE MAVERICK

LUI PAO CHUEN

By Grace Chua

When armies store explosives, it is in heavily-secured ammunition dumps equipped with blast barriers, vast buffer zones and other safety measures. In 2000, the North Atlantic Treaty Organization (NATO) was so impressed by Singapore's R&D in ammunition storage that NATO incorporated the findings, sparking a revision of international safety standards.

Singapore's efforts effectively made ammunition dumps around the world more compact and space-saving than ever before. But how is it that a tiny country in South-east Asia, which has never expended a single round on a battlefield, could become a guide for a war-seasoned region 10,000 km away?

All this is the result of a calculated risk by one man: Lui Pao Chuen, adjunct professor of industrial and systems engineering at the National University of Singapore, and Singapore's chief defence scientist from 1986 to 2008.

GOING UNDER

In an effort to free up land for residential and industrial use, in 1994 Singapore's urban planners asked the Ministry of Defence (MINDEF) to move its ammunition storage site, a British colonial vestige, out of Seletar East. The 100-hectare site crippled land usage far beyond its own boundary—nothing could be built for 300 hectares around it, while buildings for 800 hectares around could not have large glazed windows in case of an explosion.

MINDEF tasked Professor Lui with finding an alternative site. He thought of moving the dump underground at a disused granite quarry. One at Mandai appeared the most feasible. The quarry had already been dug out, providing easy access; it was not being used for anything else, and any potential blasts would be shielded by solid rock.

Credit: Cyril Ng

There was just one problem: the existing safety codes, which had been developed for rural mining in an earlier era, did not adequately address ground shock—specifically, the impact of an accidental blast on surrounding high-rise concrete buildings. Singapore thus had to begin developing its own safety models.

"That motivated me to go back to the fundamentals," says Professor Lui, who studied physics as an undergraduate at the University of Singapore. He soon discovered a simplification in the formula used to determine safety distance in the current ammunition storage standards. When 20 ammunition pallets are placed together, for instance, conventional explosion models regarded them as a single large mass. "But in a realistic storage configuration, they behave more like 20 smaller masses," explains Professor Lui. "The peak pressure from an explosion would be much lower than if they were a single mass."

To develop and test the models, the Singapore Armed Forces (SAF) gathered local and international experts from as far as Norway and the US. The team tested explosions of up to ten metric tonnes of ammunition in varying terrains, including the harsh deserts of New Mexico and the snowy landscapes of Sweden.

Work at the Mandai quarry began in 1999, and the underground ammunition facility was officially commissioned in 2008. It is recognised as the world's most urban and compact ammunition dump for its large capacity.

Building the underground facility, a world first for such an urbanised area, "created a different mindset—that we dare, that we believe in our physics," Professor Lui says. Moving the ammunition facility from Seletar to Mandai has freed up about 300 hectares of land, or an area half the size of Pasir Ris New Town.

Moreover, as with water purification, a resource shortage—land, in this case—had spurred Singapore to innovate, in the process setting new global standards. "The top expert from Norway sponsored Singapore to become a member of the NATO underground storage working group," says Professor Lui. "The international experts participated in our tests and were satisfied with the scientific evidence that we had used to determine our safety codes and gladly accepted them. That's how Singapore's safety codes became international codes."

> "While some things must be kept secret, you must also allow information to flow so that knowledge can be accumulated. Knowledge, if not shared, is lost."

HAIRY ESCAPES

Professor Lui's journey from young physics graduate to chief defence scientist was, in his opinion, fortuitous. In 1966, the 22-year-old was working for a British science research body—part of the country's lingering presence in Singapore in the immediate post-independence period—capturing radio signals from a satellite that orbited Earth.

A former classmate who was helping develop Singapore's nascent defence industry informed Professor Lui that the military needed technical personnel.

"I went to see the director of logistics at the MINDEF headquarters on Pearl's Hill. In the organisation chart of the logistics division there was a section called Test, Evaluation and Acceptance and I would be the officer-in-charge. I asked: 'What do I do?' 'Everything we buy, you test,' he said."

Professor Lui soon had a personal hand in almost all new military supply. Consider uniforms. "We couldn't use the Western sizes, so the tailor measured me and we decided I was a medium. So whenever I went to the store and drew a uniform, it was a perfect fit," he says. (Sizing charts have since been reassessed for today's better-nourished soldiers.)

He grew similarly acquainted with bullets for the AR15 assault rifle. "When the first batch was ready, I tested it and bang! A bullet exploded. They had put too much charge in the casing... bits of brass embedded in my arm were quickly removed."

Later that year, the British shocked many when they announced that they would withdraw their military presence from Singapore by the middle of 1968. As the SAF rushed to mechanise with tanks, artillery, new aircraft and ships, Professor Lui was caught up in the resulting scramble. "The jump from infantry force to armoured force was actually a consequence of... the withdrawal of the British," he says.

As project director for the SAF's first armoured vehicle, Professor Lui was placed in some precarious positions.

One narrow escape was while he was testing an armoured vehicle for amphibious use in the Jurong River. The driver had his hatch open, as per testing procedure, but Professor Lui, up in the turret, saw the vehicle tilting nose-down when it entered the river.

"I went down to tap the driver on the shoulder to close the hatch and bring the vehicle up, and at that moment, I saw a wall of water," says Professor Lui. "It struck me, and I didn't have a helmet on so my head hit the turret basket, which knocked me out. I was unconscious for two minutes."

Although the driver floated up, Professor Lui was trapped inside the vehicle, which had gone down sideways in the water. "When I came to, my first thought was: 'If I don't find my way out, my son will have no father'," he says.

Fortunately he managed to escape through one of the vehicle's side doors. From that point on, he conducted all water training with a scuba diver in attendance.

In 1973, he returned from a two-year stint at the US Naval Postgraduate School with a master's degree in operations research and systems analysis. At the time, the amount of engineering work at MINDEF had dipped, and the engineers there were farmed out to the rapidly expanding commercial defence industry, and to places like the Public Works Department. That era marked the growth of the Chartered Industries of Singapore, which was producing weapons, ammunition and other equipment, and of defence firms like Unicorn International.

But by 1980, Professor Lui says, "it was very clear that we were spending a lot on defence, but the engineering capacity was inadequate to support that level of capital expenditure." Compared to Israel or Sweden, Singapore had a sixth of the engineers per dollar of military spending. "Either we were six times as smart, or we were doing only a sixth of what they were doing."

He presented the finding to Goh Chok Tong, then the defence minister, to lobby for more engineers, to maintain equipment, test it, and write the software for it.

Three decades on, the military employs some 5,000 engineers, up from 250 at the time. "Without that jump, we could not have gotten the maximum benefit from all the investments we had made," Professor Lui says.

Singapore's modern-day military and defence industry is a well-oiled machine, a far cry from those gung-ho days when young graduates like Professor Lui were entrusted with large responsibilities. "We must make full use of the knowledge that has been created over some 50 years, and not have to make the same mistakes again," he says.

But for all the military's technological might, to Professor Lui, it is still people who are the source of its strength. "When I look back, armoured vehicles, aircraft missiles—all these are objects," he says. "It's people and organisations that live and grow and appreciate over time, while equipment depreciates. It's the people that make the difference, not the hardware."

A CULTURE OF SECRECY

Professor Lui's own career path, from young graduate experimenting with standards to chief defence scientist, has mirrored the evolution of Singapore's military, from a young nation just finding its way to a technologically advanced force to be reckoned with.

Perhaps it is unsurprising, then, that he believes that the next stage of the military's maturity will depend on greater openness.

"While some things must be kept secret, you must also allow information to flow so that knowledge can be accumulated," he says. "Knowledge, if not shared, is lost."

For instance, researchers often buy satellite images of Singapore from commercial firms. But there are local agencies and institutes taking images of Singapore that are newer and of higher-resolution. If scientists are barred from using these for security reasons, Professor Lui argues, science loses out.

"If you don't know what you don't know, then you are making decisions based on only a subset of available knowledge," he says. "That's a very serious loss. So I'm an advocate of openness and shared data."

For that spirit of generosity and universality it is not just all Singaporeans, but ammunition-storing countries across the world as well, who owe Professor Lui a debt of gratitude.

The Physicist Turned Publisher

Phua Kok Khoo

By Rebecca Tan

Laborious experiments are conducted with expensive equipment. The results are painstakingly recorded, then depicted on graphs and narrated in prose. But those findings do not become part of our collective scientific knowledge until journals publish them. In that sense, academic publishing is the handmaiden of science, helping to disseminate knowledge and spark new ideas.

The industry has evolved dramatically from its humble origins, 350 years ago, when the Royal Society of London published the world's first scientific journal. Today it is a multi-billion dollar industry dominated by an oligopoly of for-profit publishers, "The Big Four": Reed-Elsevier, Wiley-Blackwell, Springer and Taylor & Francis. (Elsevier is the science and medical publishing arm of Reed-Elsevier.) In the natural and medical sciences, the Big Four and the American Chemical Society together accounted for more than half of all journal articles published in 2013.

The Big Four were all founded sometime between 1807 and 1880. Each has hundreds of years of institutional history and significant economic clout. But in 1991 they were in for a rude shock. World Scientific Publishing Company (World Scientific henceforth), a young, Singapore-headquartered firm, won the publishing rights for the Nobel Lectures, which had been held by Elsevier since 1901.

"When we started World Scientific in 1981, there weren't any world-class international publishing houses in Asia," recalls Phua Kok Khoo, the firm's founder and director of the Institute of Advanced Studies at Nanyang Technological University. "There were established publishers in Japan and China, but they focussed on Japanese or Chinese language titles. Encouraged by Nobel Prize winners that I knew personally—Abdus Salam and C. N. Yang—we decided to start something in the English-speaking environment of Singapore."

(Full disclosure: World Scientific is a shareholder of Asian Scientist Publishing, the publisher of this non-commercial book.)

Credit: Bryan van der Beek

THE 'GOLDEN AGE' OF THEORETICAL PHYSICS

Professor Phua, who obtained his PhD from the University of Birmingham in 1970, began his scientific career as a theoretical high-energy physicist, seeking to understand the mathematical behaviour of elementary particles within an atom's nucleus.

"In the early 1970s, there were many theoretical physicists returning to Singapore from their training overseas," he says. "Many of them were alumni of Nanyang University and returned there to teach, making its theoretical physics department very strong."

As opposed to experimental physics research, which sometimes requires multi-billion dollar facilities such as the Large Hadron Collider, the field of theoretical physics can progress with little more than a pen and a piece of paper. More important than computers, contends Professor Phua, are "ideas, creativity and innovation".

> "Publishing is not like banking or opening up a restaurant—it's a cultural activity, not totally commercial."

The discipline's low budgetary requirements, combined with the wave of returnees, meant that theoretical physics enjoyed what Professor Phua considers a "golden age" in Singapore's post-independence years.

"Right up to the merger with the University of Singapore in the 1980s, we [Nanyang University] were publishing papers in the best journals in the field, places like the *American Physical Review* and others," says Professor Phua. "But when the funding shifted to more applied research we had to change our focus to survive."

For Professor Phua, that was the spur not for a simple research shift, but a foray into an entirely new industry—science, technology, engineering and mathematics (STEM) publishing.

KEEPING IT IN THE FAMILY

Thankfully he had a hereditary head start. Professor Phua's father, Phua Chye Long, owned a Chinese publishing company, South Island Press. Furthermore, Professor Phua was certain that the world's scientific centre of gravity was shifting to Asia. He was eager to free researchers in Asia of their dependence on Western publishing houses.

Starting a publishing company from scratch, however, was risky. Professor Phua and Doreen Liu, his wife, had two young children at the time. In order to raise the necessary capital, they had to mortgage the family home. Thankfully, their gamble paid off.

Now in its third decade, World Scientific has a stable of 10,000 books and 130 journals and more than 500 employees across its offices in China, India, Israel, Japan, Germany, the UK, the US and, of course, Singapore. (By comparison, Elsevier, the world's biggest journal publisher, has a stable of 33,000 books and 2,500 journals.)

"If you look at the statistics, more and more good research papers are being published by Asian researchers. We were fortunate to have entered the market at the right time," Professor Phua quips.

Despite its international growth and interest from potential buyers, Professor Phua is adamant that World Scientific must remain a family business. Ms Liu is the firm's group managing director while their son, Max Phua, is its managing director.

"Publishing is not like banking or opening up a restaurant—it's a cultural activity, not totally commercial," he stresses. "Running World Scientific as a family business allows us to publish books that might not make a lot of money but are the best in the field. For example, we just published a book of selected writings of the leading physicist Freeman Dyson. It probably won't be a bestseller but it is an important record of the life and work of a world-class scientist."

According to Professor Phua, what distinguishes World Scientific from the competition is the fact that it is run by a scientist with a natural love for science. Other firms tend to be managed by "accountants, lawyers and businessmen", who may not have had research experience. They can end up prioritising commercial imperatives to the detriment of the science.

THE DIGITAL AGE

Just like the rest of the publishing world, academic publishing is facing severe digital disruption. The unusual structure of the industry has long made for a very profitable business. Driven by the need to "be published", the scientists who produce the content relinquish copyright control to the journals for free; the content is then peer reviewed for free; and the demand for subscriptions is inelastic. In 2012 Elsevier enjoyed a profit margin of 38% on revenues of £2.1bn (about S$4.2bn).

Journals used to turn a blind eye on informal sharing of published works within the scientific fraternity. But in recent times, as the world wide web has catalysed the (free) distribution of published papers, copyright holders have sought to exercise their legal rights, ordering the removal of content from websites, including professors' home pages.

> "There's no point in talking about how many years it will take for Singapore to produce a Nobel laureate; we need to talk about creating the right environment first."

All this has attracted a growing chorus of dissent. Arguing that publishers make huge profits out of what is typically publicly-funded research, scientists such as Fields medallist Timothy Gowers have called for a boycott of major publishers that hide their research behind expensive paywalls.

New business models, including the successful open-access Public Library of Science series, have also sprung up in the last decade. Many countries, including the UK and the US, are in the midst of a legislative shift towards greater open access.

Through it all, Professor Phua remains confident that World Scientific will continue to succeed if it sticks to its guiding principles. "I think the game is still the same. The most important thing is still content—whether people access it electronically or on hard copy," he says.

In any case, World Scientific's digital transition appears well underway. All of its journals are currently available digitally as "hybrid journals"—with the option for authors to pay to make their articles open access. Digital's share of revenues is already some 65%; the company expects it to rise to a long-run equilibrium of about 70%.

A HUNGER FOR HOME-GROWN HEROES

What does concern Professor Phua, however, is the relative lack of a culture of reading and creativity in Singapore. "What students here lack is the urge to learn," he notes. "Unlike Cambridge or Harvard, you don't see students on the campuses here reading. Without that habit, we become machines, able to read and write but not think out of the box."

This segues onto another of Professor Phua's longstanding concerns: the need for Singapore to better groom home-grown scientific talent. Citing the example of Nagoya University in Japan, which has produced six Nobel laureates since 2001, he feels that it is possible for other Asian countries to create a culture of research excellence.

"If you study how Nobel laureates produced their best work, you will see that flexibility and the courage to try new ideas was instrumental," he says. "So there's no point in talking about how many years it will take for Singapore to produce a Nobel laureate; we need to talk about creating the right environment first."

As a recently appointed fellow of Singapore's National Academy of Science, Professor Phua hopes to influence more young people to choose science as a career. He also serves on the board of schools including Hwa Chong Institution, the National University of Singapore High School and Pioneer Junior College. Meanwhile, World Scientific sponsors one student every year to attend the Lindau meeting where they get to meet Nobel Laureates.

"While some of our top students may still end up in law school or medical school because their parents feel those are 'safer' careers, we cannot be too practical," he says. "Science, after all, is more than a means to an end but a culture and tradition, something I hope I can impress upon younger Singaporeans."

Building a Treasure Chest of Medical Data

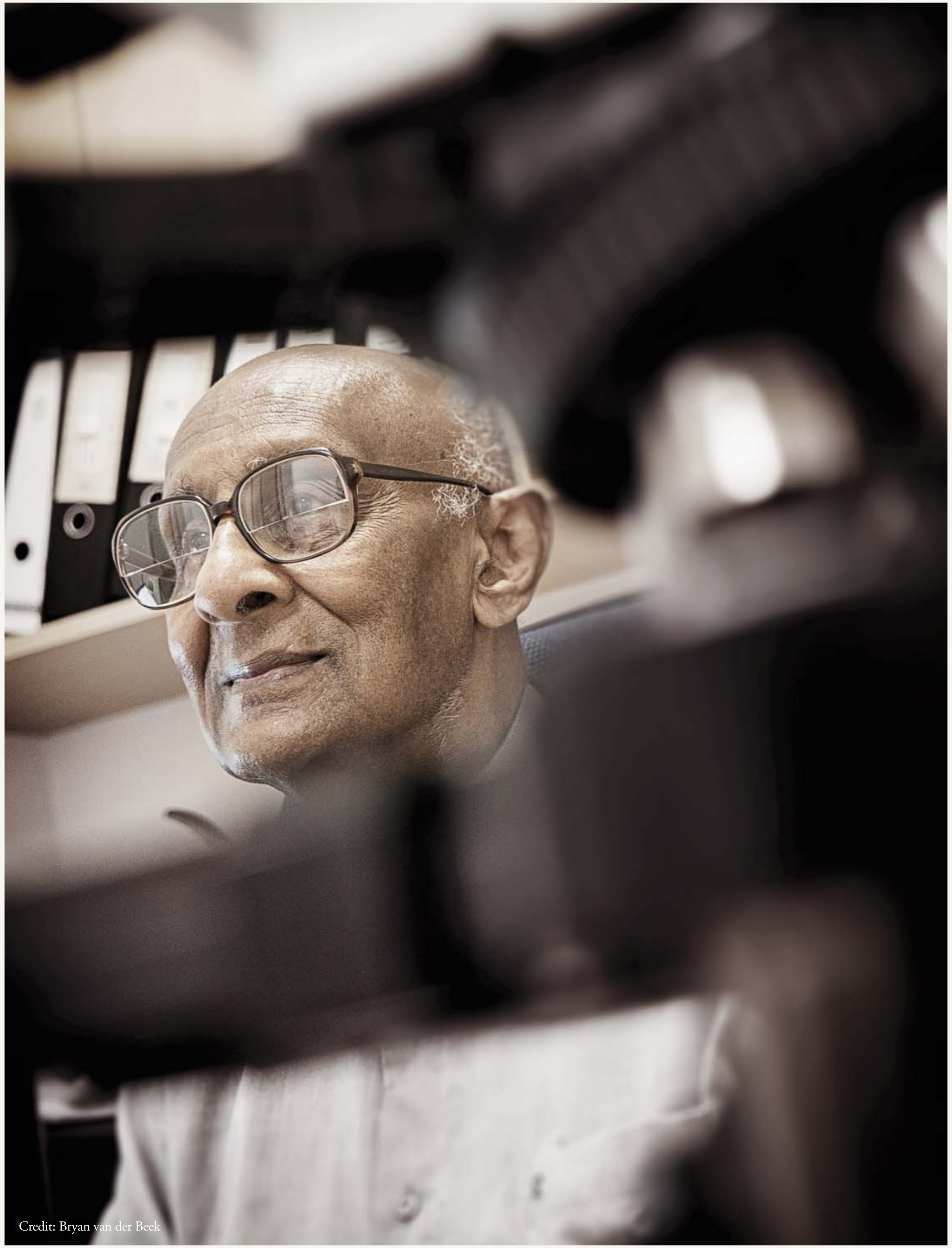
Kanagaratnam Shanmugaratnam

By Shuzhen Sim

Kanagaratnam Shanmugaratnam, emeritus consultant at the National University Hospital (NUH) and emeritus professor of pathology at the National University of Singapore (NUS), holds court in his NUH office, surrounded by the tools of his trade—microscope, slides and years of carefully-collated reports.

Sprightly, razor-sharp and Internet-savvy at 94, Singapore's "Father of Pathology" exudes an air of calm, methodical professionalism. "I've been looked after very well by all the consultants here," he says matter-of-factly, referring to the three stents in his heart.

Professor Shanmugaratnam has been working continuously in the field of histopathology—a medical specialty in which diseases are diagnosed by the microscopic examination of tissue samples—since 1948. He is best known for establishing the Singapore Cancer Registry (SCR), a treasure trove of data that has proved invaluable to clinicians, researchers and public health administrators seeking to monitor and control cancers afflicting the Singaporean population. He is also an internationally-renowned expert on nasopharyngeal carcinoma, a cancer of the upper respiratory tract, which disproportionately affects ethnic Chinese.



Credit: Bryan van der Beek

THE WAR YEARS

Professor Shanmugaratnam enrolled at Singapore's King Edward VII College of Medicine in 1938. But the Second World War and the attendant Japanese occupation of Singapore, which lasted from 1942 to 1945, interrupted his studies. Left adrift, he and his fellow medical students had to find work of some sort to avoid being taken away for manual labour.

The Japanese Army Medical Corps had taken over and converted the College of Medicine building into bacteriology and serology laboratories. Professor Shanmugaratnam found work there as a laboratory technician, and later also at the *Chuo Byoin* (Central Hospital)—the pre-war KK Women's and Children's Hospital, which during the war was turned into a general hospital for local and Japanese civilians.

"It was a very tough time, of course—no medications, and difficulties with food and personal safety," he says. "But as far as laboratory work was concerned, under limited circumstances, we did fairly well. It was during those years that I developed an interest in pathology. I was always interested in laboratory work on the science side, rather than the actual care of patients."

Professor Shanmugaratnam's classes at the College of Medicine resumed in June 1946. He graduated in 1947, and joined the Government Medical Service as an assistant pathologist the following year. He went on to complete a PhD in pathology at the University of London in 1957.

CATALOGUING DECADES OF DATA

In 1950, keen on observing local disease patterns, Professor Shanmugaratnam started a simple card index of all histologically-diagnosed cancers in Singapore. At the time, the government's department of pathology, where he was based, provided histology services for the whole island, making record-keeping a simple undertaking.

But not all cancers are histologically diagnosed. Other methods, such as radiology (the use of imaging techniques, including X-rays and ultrasound) are also used, especially when tumours are located in inaccessible locations such as the lung. In 1967, Professor Shanmugaratnam founded the Singapore Cancer Registry (SCR)—a nation-wide registry that would capture all cancers regardless of how they are diagnosed.

Established in NUS's department of pathology, the SCR was initially funded by the International Agency for Research on Cancer (IARC), a World Health Organization (WHO) agency based in Lyon, France, and later by annual donations from the Singapore Cancer Society and research grants from NUS.

The SCR was the first comprehensive, population-based cancer registry in South-east Asia. Singapore, says Professor Shanmugaratnam, was an ideal country in which to establish such a registry. Even back then, there were regular censuses of the population, identity card numbers for all citizens and permanent residents, and good hospital diagnostic facilities that were easily accessible across the island.

Still, the sheer amount of data posed challenges. To ensure completeness, registration was based on information from several sources: cancer notification forms submitted by doctors, hospital discharge forms from all government hospitals, reports from all pathology departments, and death statistics from the Registrar of Deaths.

"The difficulty was that we had no computing facilities when we first started, and that made cancer registration a very difficult, time-consuming operation," recalls Professor Shanmugaratnam. "Everything had to be done by hand."

The SCR employed just two secretaries and one record searcher to handle its day-to-day operations. They would manually collate the data and transfer it to 80-column punch cards—a now-obsolete data entry system that involved punching holes in stiff IBM-made paper cards to encode the information. These were shipped to Lyon where they could be read and tabulated by IARC computers.

After a decade of operations, the SCR eventually acquired its own computing equipment, largely through the efforts of Chia Kee Seng and Lee Hin Peng, now professors at the NUS school of public health, who were actively involved in developing the registry.

Since 1983, the SCR has published regular, detailed reports on the incidence and patterns of various cancers in Singapore. This data allows public health personnel to identify interesting or unusual trends among different ethnicities, age groups, occupations, or other demographic groups.

For example, Singapore's three major ethnicities—Chinese, Malays and Indians—have differing cancer incidence rates: Chinese have the highest risk of developing nasopharynx, lung and colon cancers, Malays ovarian cancer, and Indians mouth cancer. Among the major Chinese dialect groups in Singapore, nasopharyngeal cancer (NPC) is more common among the Cantonese, whereas oesophageal and stomach cancers are more common among the Hokkiens and Teochews.

Patterns of cancer occurrence in Singapore have also changed over time—incidence rates for prostate cancer, colon cancer and lymphomas have risen, while incidence rates for oesophageal and stomach cancers have dropped. Understanding these trends allows high-risk groups to be targeted with screening and prevention programmes. Follow-up studies, which monitor patients over time, can also be done to assess the effectiveness of treatment regimes.

Professor Shanmugaratnam served as the SCR's director from 1968 to 2002. "As a pathologist my main concern was diagnostic work," he says. "But I felt that this was important data to collect. Such information is essential for the development and evaluation of cancer control programmes."

> “Patterns of cancer are changing so rapidly that what happens in the next 10 to 15 years may not be representative of what happened before.”

In 2001, the SCR, bulging with more than thirty years of data, was transferred to the Ministry of Health. It is now part of the National Registry of Diseases Office, which also comprises registries for acute myocardial infarction (heart attack), chronic kidney failure, stroke and trauma injuries.

While electronic medical record systems have simplified the maintenance of disease registries, their importance has not diminished. "Patterns of cancer are changing so rapidly that what happens in the next 10 to 15 years may not be representative of what happened before," says Professor Shanmugaratnam.

CLASSIFYING CANCERS

In addition to founding the SCR, Professor Shanmugaratnam is an expert in the histopathology and epidemiology of NPC, one of the cancers affecting the upper respiratory tract. NPC caught Professor Shanmugaratnam's attention because of its unusual disease pattern. Rare in most countries, it is one of the leading cancers in southern China and South-east Asia.

Once cancers have been diagnosed, histopathologists further classify them according to a detailed range of criteria. These include the type of tissue in which the cancer arises, how abnormal the cells of a tumour look, and the severity of the disease—whether or not it has spread to other organs, for example. Classification is not just an academic exercise; it helps doctors make a prognosis and decide on a course of treatment.

Drawing on his expertise in histopathology, Professor Shanmugaratnam was largely responsible for developing the WHO's classification of NPC. He is the leading author of the first (1978) and second (1991) editions of the book, *Histological Typing of Tumours of the Upper Respiratory Tract*, and also an editor on the third edition of the book, *The International Classification of Diseases for Oncology (2000)*.

AN EVOLVING DISCIPLINE, AND A LIFETIME OF LEARNING

Over the course of a career that has spanned almost seven decades, Professor Shanmugaratnam has seen the discipline of pathology change dramatically. While simple tissue sections and stains were the standard in the 1950s, pathologists today have access to a range of techniques, including electron microscopy, cytopathology (examining cells instead of tissues), immunohistochemistry (the use of antibodies to label cell constituents) and molecular diagnostics (detecting genetic changes in cancerous cells, for example).

Professor Shanmugaratnam still conducts fortnightly seminars for trainee doctors in the department of pathology, and consults on difficult cases referred to him by colleagues from both public and private hospitals. Keeping up with new developments in the field has thus become a deeply-ingrained habit, now facilitated by modern technology.

In his free time, Professor Shanmugaratnam enjoys reading about local history, and also listens to Indian classical music, in which he was trained. He used to play the *pullankuzhal* (or *venu*), an Indian bamboo flute.

But simply being able to do his job, he says, is what gives him the most satisfaction. "I'm glad I have been able to continue working after retirement as a part-time consultant in the NUS department of pathology."

And so every weekday morning, without fanfare or ceremony, Professor Shanmugaratnam arrives at his office to peer quietly down the eye-piece of his microscope, looking for the answers within.

Tea and Mitochondria

Sit (Wong) Kim Ping

By Grace Chua

In most animal cells, there are tiny structures called mitochondria, often called the powerhouse of the cell. They convert the food we eat into the energy needed for a cell to run, and are thus part of the very fabric of life.

But what about the fabric of a quilt? Sit Kim Ping, professor of biochemistry at the National University of Singapore (NUS), weaves mitochondria into the quilts she makes in her spare time.

The petite, dapper 75-year-old spreads out one of these elaborate quilts, as long as she is tall, on a couch at the home she shares with her clinician husband.

"It took me three years to make this. Here, you can see the date, 2008," she says. The intricate fabric—patterned with squares, hexagons and triangles—bears words such as "mitochondria" and "ATP", a molecule that ferries energy around cells.

Professor Sit has applied the same dedication to her 50-year career, which has been spent studying metabolism—the cellular interactions that make life possible. With more than a hundred international publications, she has, among other things, shed light on human brain and liver functions, as well as the workings of cancer cells.


Credit: Cyril Ng

EARLY LIFE

The fifth of nine children born to a successful restaurateur and his wife, Professor Sit grew up in Katong in the postwar years. At Tanjong Katong Girls' School, she developed a love for mathematics and science. Later, at the University of Singapore, she chose to study science and topped her cohort with first-class honours.

"Medicine was a long course, five years, and very structured. I decided to do science, as it was only three years long, but at the end of the day, with postgraduate studies, I graduated later than my schoolmates," she laughs.

In 1965, she went to Canada's McGill University on a Commonwealth scholarship for graduate studies in biochemistry. "In those days, if you wanted to study the body at that level, it was all biochemistry," she says. "There was hardly anything about cell or molecular biology; those came much later."

Amidst the chill and dark of the Canadian winters, where graduate students often laboured till the wee hours of the morning and slept in the department's sick-bay, something clicked for Professor Sit.

The specifics of the experiment are lost to time, but she says, "I was doing thin-layer chromatography [a type of separation technique] and suddenly I saw something and said, hey, that's interesting... You see something that you didn't expect, and you have to figure it out." But such little "perks" of research are few and far between, she admits, "because most experiments don't work."

Soon, she became interested in metabolic processes. She carried out experiments in which she fed or injected different substances into rats, and then analysed their metabolic products. "There was lots of testing of rat urine," she says. "You put the rat in a cage with wire netting at the bottom, and collect the urine."

In particular, Professor Sit was fascinated by a biological process called detoxification (much different from today's faddish "detox" diets, which have no scientific grounding). Things that enter the body, such as foods we eat or drugs we take, get metabolised for use by the body, and they or their metabolic by-products must be excreted somehow.

To be excreted, those by-products must be made water-soluble by having a small molecule produced by our cells such as a sulphate attached to them, in a process called conjugation. Only then can they be passed out in urine or bile. The liver is the main organ that performs this function, but the kidneys and brain do too.

> "When you're desperate enough, you innovate."

THE INCREDIBLE MITOCHONDRION

Early on, Professor Sit's research centred around understanding the mechanisms by which this conjugation process occurs. For instance, she examined how various substances are conjugated and excreted in rats—not only within the liver, but in other tissues and organs in the body. Where do conjugation reactions occur? How do different drugs or their by-products, for example, get removed from the body and how long does this take?

Even the brain, she found, is able to carry out these conjugation reactions. "Nobody expected that," she says. "Up to now, I'm still thinking about these possibilities, particularly in relation to children with autism."

One research hypothesis she had hoped to test is whether autism is related to a disorder where either some brain neurotransmitters are not conjugated properly and thus cannot be excreted; or some other molecule in the brain gets conjugated instead of the target neurotransmitters. Unfortunately, she retired before she could explore this idea further.

Meanwhile, she was also fascinated by another research question that involved cancer cells and the mitochondria within them.

About 80 years ago, Otto Warburg, the German biologist and Nobel laureate, observed that cancer cells produce energy by a process called glycolysis, which does not involve oxygen, rather than by ordinary mitochondrial (aerobic) respiration, which does. He hypothesised that mitochondrial respiration was impaired in cancer cells.

"With oxygen, you get 32 molecules of ATP with every molecule of glucose [that is broken down]. But anaerobically, you only get two molecules of ATP," Professor Sit explains. What baffled scientists: why would cancer cells use a respiratory process that produces fewer ATP molecules with which to ferry energy around the cell? And, with fewer ATP molecules than cells that respire aerobically, where do cancer cells get the energy to grow?

However, on further investigation, Professor Sit and her colleagues found mitochondria still working and respiring aerobically in cancer-tissue samples, which ran counter to "the Warburg hypothesis". They published their data on ovarian cancer in 2011 and renal cancer in 2015.

Professor Sit says that for years, the mitochondrion has been her favourite organelle (a specialised subunit within a cell, with its own specific function). "In metabolic pathways, without the mitochondria, nothing would work," she says. So for instance, while processes inside the cell—in the liver or, say, the brain—make metabolic by-products water-soluble, it is mitochondria that generate the energy to pump them out of the cell.

BIOCHEMISTRY IN SINGAPORE

Over tea, fruit, and a ginger and pear cake, Professor Sit reminisces about improvised lab equipment in the 1970s, such as one made by a colleague: it was a cooking pot with a stand drilled with holes to accommodate multiple test tubes for boiling over a Bunsen burner.

"When you're desperate enough, you innovate," she says. "When I moved out of my lab the research assistant said, 'Prof Sit, what is this? It looks like a power drill.' These days we have lots of ready-made equipment, so we didn't need the drill anymore and they didn't know what it was." It turned out that a pestle, which replaces a rotating drill bit, was used to homogenise rat livers at high speed.

Early in Professor Sit's career, biochemistry was regarded as an illustrious discipline. But as molecular and cell biology techniques improved in the last two decades, biochemistry became "like an antique". But it is making a comeback, she says: "Once you've done the cell biology manipulation, you still need the biochemistry techniques to prove what has happened to its metabolism."

In 2001, Singapore began its push to develop and commercialise the biomedical sciences. At the time, six departments including biochemistry, microbiology, physiology and others taught 90 or so life sciences modules "with considerable duplication". Professor Sit chaired the working committee that integrated and streamlined the modules and implemented its new life sciences curriculum the following year.

From 2007 to 2014, Professor Sit also served as a research integrity officer at NUS, one of five faculty members appointed to look into reports of potential falsification or plagiarism. "The pressure is to publish big—and quick," she admits. "So these cases are everywhere, not just here [Singapore]." The most common issue, Professor Sit says, is possible self-plagiarism, in which a researcher duplicates his or her own previously-published work in another journal without proper citation of the earlier paper.

Asked if there was anything she would have done differently in her career, Professor Sit says, "My only regret is that I did not collaborate with others that much, although I did collaborate and publish with a few clinicians in recent years on tumour biology." Today, producing a high-impact publication often takes a larger group of people to address a research question from different angles. "Nowadays, you don't see any publications with a solo author, and sometimes there are 25 authors or more in one paper," she says.

Since her retirement in 2015, Professor Sit has had more time to spend on her hobbies: crafting and quilting. She sews her own cheongsams, collects fabric swatches from her travels, and knits. "I've quilted for 30 years," she says. "And every Saturday when I was a little girl, I used to go to the Singer [sewing-machine supply] shop to do machine embroidery, and I still have some beautiful pieces."

Although Professor Sit lives far from her daughter and son—a pediatrician in London and a research engineer in Los Angeles, respectively—she makes it a point to have tea every Sunday with her 102-year-old mother and siblings, most of whom are based in Singapore. She shows off a family quilt: a patchwork of fabric tea cups, saucers, plates and cakes, each block picked out and sewn by a family member.

Quite fittingly, the woman who studied the powerhouse of the cell has no shortage of energy herself.

A LASER-FOCUSSED LIFE

Su Guaning

By Juliana Chan

LASER is actually an acronym for Light Amplification by Stimulated Emission of Radiation. Laser light is formed when the electrons in a lasing medium are excited to a higher energy state with light or electricity. When the "pumped" electrons return to a lower energy state, they emit a photon of light, a phenomenon known as spontaneous emission. Occasionally, these photons hit other excited atoms in the lasing medium, amplifying the amount of light by making the atom give off two photons instead of the usual one. Called stimulated emission, this phenomenon is at the heart of how lasers work. In common parlance, the word "laser" can also describe a person's intense focus on achieving a goal.

Interestingly, both the literal and metaphorical use of the word laser can be used to describe Su Guaning, president emeritus and professor of electrical and electronic engineering at Nanyang Technological University (NTU).

Born into a technically-oriented family—his father was an electrical engineer, and his mother taught mathematics and physics—Professor Su was similarly adept at these topics: "I was also comfortable with abstract things, which you tend to need for electrical things, because it is not a physical thing you can see."

His grandparents had migrated from China to Malaysia in the 1920s to start a school at Tangkak, Johor, near the border of Malacca. His parents, who met while studying at Xiamen University, married and relocated to Taiwan, where Professor Su was born.

His family moved back to Malaysia, and then Singapore in 1957, where he joined the primary three cohort two years ahead of his peers at the co-ed Nanyang Girls High School (primary section).

Top of his class at Raffles Institution, Professor Su went on to win a Colombo Plan Scholarship and President's Scholarship to study electrical engineering at the University of Alberta in Canada, and a fellowship from the California Institute of Technology (Caltech) in the United States for a master's degree.

Credit: Bryan van der Beek

PROJECT MAGPIE

It was during Professor Su's master's degree that the Vietnam War and Singapore's newly-implemented mandatory National Service conscription began to define his life and career.

Professor Su had wanted to continue with his PhD under Amnon Yariv, his Caltech professor and supervisor, who is world-famous for his work on lasers and optics. But the Public Service Commission (PSC), which had awarded Professor Su his original President's Scholarship, asked him to return. "They said we need engineers, so please come back," he says. His heart sank, as he had planned on building his own laser that summer.

Back home, he also realised that being two years younger than his classmates made him liable for National Service. "If I was born two years early like the rest of my cohort, things would have been different," he laughs.

While Professor Su was waiting for conscription, Benny Chan, a senior scholar who had studied at the University of British Columbia, recruited him to join a top-secret R&D set-up at the Ministry of Defence (MINDEF). "It was a no brainer," Professor Su says, as the programme allowed him to conduct military research for eight years in lieu of two-and-a-half years of National Service.

Around 1971-72, at the peak of the Vietnam war, there was a fierce air battle over North Vietnam, where the US was fighting Russian surface-to-air missile systems using electronic warfare. Jamming, as it is called, involves sending interfering signals against radars to fool detection systems, making it difficult for anti-aircraft systems to accurately pinpoint the locations of planes, ahead of a missile attack.

Witnessing all these military advancements from nearby, Singapore's then defence minister, Goh Keng Swee, knew that victory in future wars would require mastery of the electromagnetic spectrum—to fight stealthily and remain invisible to the enemy. "Dr Goh Keng Swee felt there was a need to develop something special in R&D, in some sense a secret edge; that others don't expect," Professor Su explains.

Dr Goh assembled a rag-tag team of newly-minted engineers under the codename Project Magpie. Needing a further cover, the team coined the name Electronic Test Centre (ETC), using the initials of its three pioneers: Er Kwong Wah, Toh Kim Huat and Benny Chan. It was completely cut off from other military units. "I still remember our address was PO Box 822 Tanglin Post Office," Professor Su chuckles.

MINDEF recruited the late Tay Eng Soon, then a lecturer at the University of Singapore, to head ETC and lead its research. Meanwhile S. R. Nathan, the director of MINDEF's security and intelligence division from 1971 to 1979, interviewed Professor Su for his role. (Dr Tay would later go on to serve as senior minister of state (education); and Mr Nathan would serve two consecutive terms as Singapore's president, from 1999-2011.)

The government hastily refurbished the top-secret military research facility, and the team soon began its work. ETC conducted all its transactions—some worth up to thousands of dollars—in cash.

BUILDING UP CONFIDENCE IN MINDEF

In 1977, Project Magpie evolved into the Defence Science Organisation (DSO), and Professor Su and colleagues no longer had to hide behind a PO Box address.

Three years later, Professor Su's eight-year commitment to MINDEF came to an end. He applied for a senior tutor position at the newly-established National University of Singapore (NUS), which came with a PhD scholarship to study at the University of Waterloo in Canada.

But MINDEF had other ideas. "In those days, when you applied [for a posting or a scholarship], you had to go through the department head, who at the time was the second permanent secretary, Mr Philip Yeo," says Professor Su.

Mr Yeo shrewdly provided a counter-proposal: a fully-paid PhD scholarship to study at any university of his choice. Professor Su took up MINDEF's offer, and went off to Stanford University to study signal processing.

Looking back, Professor Su believes that it was MINDEF's enlightened decision to support PhD-level researchers like him that helped Singapore's electronic warfare capabilities blossom.

In electronic warfare, other countries would never sell their most advanced equipment; even if they did, they sold the systems without the techniques required to make it work. MINDEF researchers had to develop the techniques to make sure the equipment worked against a real threat.

"All that required confidence," Professor Su says, which the new PhDs provided—they helped transform DSO's old adage of "What have people done, can I do it also?" to "Here's a problem, let's solve it. Doesn't matter if nobody has ever done it before, we can be the first."

In 1983, on his return from Stanford, DSO appointed Professor Su as its deputy director. In 1986, when he became director, he was firm in creating a "black box" environment—from the outside there was a wall of secrecy and from the inside, engineers had the creative freedom to pursue the best science possible, free from financial and operational concerns.

In 1997, in his quest for even more autonomy, Professor Su led the incorporation of DSO as a non-profit company limited by guarantee, henceforth known as DSO National Laboratories. He became deputy secretary (technology) at MINDEF a year later, where he created a new R&D directorate under the Defence Technology Group (DTG) as DSO National Laboratories's contracting counterpart. In the new scheme, DSO National Laboratories was the service provider and MINDEF the customer.

> "Here's a problem, let's solve it. Doesn't matter if nobody has ever done it before, we can be the first."

The navy became DSO National Laboratories's best customer. "They faced the biggest threat, in the open seas, without support from anywhere. It is very critical that they protect their ships," says Professor Su.

Later in 2000, Professor Su spearheaded the conversion of DTG into a statutory board called the Defence Science and Technology Agency (DSTA), where he served as chief executive until 2002.

These are all major milestones in Singapore's long, perhaps never-ending, journey of enhancing defence agencies and structures. With DSO corporatised and DSTA a statutory board, spending could be clearly accounted for and objectives made clear. This move also helped both organisations attract Singaporean engineers despite a dwindling supply of graduates. Feeling sentimental, Professor Su says, "These are my babies, in some sense".

For his contributions to MINDEF as one of its pioneer defence research engineers, Professor Su received the Public Administration Medal (Silver) in 1989; the Public Service Medal in 1997; the Public Administration Medal (Gold) and the Long Service Medal in 1998; he also received the National Science and Technology Medal in 2003. In 2015, Professor Su received the Defence Technology Medal (Outstanding Service) in recognition of his pioneering contributions to defence technology.

MANAGING A YOUNG UNIVERSITY

Taking over at the helm of NTU in 2003 from Cham Tao Soon (see p.26), Professor Su maintained the university's focus on education, with the building of three new schools, and the move towards a US-style system, with students undertaking both majors and minors as part of their degree.

Noting China's growing importance to the world, Professor Su also developed strong ties to the country, not least through NTU's 18,000 alumni there. "In several provinces in China, the very top officials of every city have been to NTU for a short-term programme," he says. China has commemorated his contributions with the State Council's 2011 Friendship Award and Guangdong's 2012 Friendship Award.

Professor Su stepped down as president of NTU in 2011, in the same year Singapore awarded him the Meritorious Service Medal.

Recognising the value of his numerous experiences to young people, Professor Su started teaching a graduate course in 2014, called Systems, Complexity and Innovation, where he encourages electrical engineering PhD students to broaden their research areas by applying the tools of complexity science. He also started a new undergraduate course in 2015 for business minors, called Management of Research and Innovation, where students role-play as CEO and functional heads of companies.

"I wanted people to see complex systems from a big picture point of view," he says. "The best alignment is when you can seize opportunities and do something that you feel is worthwhile."

There may be many CEO role models out there, but if students are looking for a case study combining derring-do and laser beams, Professor Su's own story is a fine one to tell.

Laying a Sound Foundation

Bernard Tan

By Rebecca Tan

Both science and music found a champion in Goh Keng Swee. Few are aware that Dr Goh, better known as the architect of Singapore's economy and a pioneer of national defence, also sparked the formation of the Singapore Symphony Orchestra (SSO). A lover of classical music, the then deputy prime minister remarked in 1973 that it was "a scandal" for Singapore not to have its own professional orchestra.

Five years later, Dr Goh asked Bernard Tan, a young physics professor at the University of Singapore, to draft the SSO's first budget. Professor Tan, today one of Singapore's most frequently performed composers, has juggled science and music throughout his career. He even served as acting head of the university's department of music from 1977 to 1987 while concurrently with the department of physics.

In the realm of science, Professor Tan was instrumental in setting up key facilities such as the Singapore Synchrotron Light Source (SSLS)—the largest single research machine in Singapore—and the Centre for Remote Imaging, Sensing and Processing (CRISP), the country's first major foray into space technology.

"Your generation cannot imagine how primitive research was in the 1970s before we had all these facilities!" Professor Tan exclaims. "In a sense, people like me and all the others who went into administration helped to build up the research infrastructure. But our own research suffered as a result—we are the lost generation."

Credit: Bryan van der Beek

FROM ACCIDENTAL LASERS TO SYNCHROTRONS

Professor Tan completed his undergraduate degree at the University of Singapore and then did his PhD at Oxford University on a Commonwealth scholarship. He went on to serve as vice-dean of the science faculty at the National University of Singapore (NUS) in 1980-85 and subsequently dean in 1985-97.

"The trouble is that I entered university administration at a relatively young age," Professor Tan says. "I became a vice-dean when I was only 37 and stepped down when I was 54—so we're talking about 20 years of my research career wiped out from that point on. I wouldn't recommend it to anybody!"

Part of the problem, he says, was the immature research landscape—rudimentary lab facilities and a shortage of expertise. "If you want to be in university administration, you need to have a lab with reliable post-doctoral fellows or even a colleague who works with you," he says. "I tried to carry on individually with no collaborators. Even with that handicap, I still managed to produce ten PhD students—some supervised jointly with colleagues—which is not too bad!"

> I'd really like to see Singapore become a catalyst for creativity because as we've said so often, all we have are our human resources.

One of Professor Tan's early accomplishments was building Singapore's—and possibly South-east Asia's—first laser in the late 1970s. Armed with barely S$2,000 (S$4,500 in today's dollars) and home-made glassware, he built a carbon dioxide laser together with Tan Kuang Lee, Ong Phee Poh and Tang Sing Hai at the University of Singapore's physics department

The light produced by a bulb is non-coherent, with its photons being emitted randomly in all directions; its intensity dims as it travels from its source. In contrast, laser light is characterised by its coherence, meaning that each photon of light is exactly in sync with all the other photons being emitted, producing a focussed beam of light that is able to maintain its intensity over long distances or cut through metal.

(For more on laser—actually an acronym for Light Amplification by Stimulated Emission of Radiation—see Su Guaning, p.78)

The first few times he and his team turned the laser on, nothing happened. Then one day they noticed that some plastic in the laser's path had melted. Lasers using carbon dioxide as the lasing medium produce invisible infrared rays. They had been lasing all along; they just didn't know it.

"Looking back now it was very dangerous because it could have easily blinded us," he admits. "But such was the state of how we did things back then."

Two decades later, Professor Tan was on to bigger—and much more expensive—things. During the last few years of his deanship, he focussed on raising funds for the largest single research machine in Singapore, a Helios synchrotron for the SSLS. "After a lot of effort and strong support from NUS Vice-Chancellor Professor Lim Pin (see Lim Pin, p.54) and the NSTB (National Science and Technology Board, predecessor of today's A*STAR), we finally managed to get nearly 40 million dollars [S$54m in today's dollars] to set up the synchrotron, which was commissioned in 1999," he says.

The SSLS, like other electron synchrotrons around the world, produces exceptionally intense beams of infrared, ultraviolet and X-ray light by accelerating electrons around a curved magnetic ring up to an energy of 700 MeV. The most powerful electron synchrotron dedicated to the production of X-rays and other electromagnetic radiation is SPRING-8 in Japan which has an electron beam energy of up to 8 GeV. The Large Hadron Collider in Switzerland, the largest and most powerful proton synchrotron in the world at 7,000 GeV, is 10,000 times as powerful as the 700 MeV SSLS.

Nonetheless, SSLS synchrotron radiation allows researchers to "see" structures at the atomic level with unprecedented detail, and has become an invaluable tool in a wide range of disciplines. Materials scientists, for example, have used the SSLS for nanofabrication, while biologists use it to image cells or even viruses.

PUTTING SINGAPORE ON THE MAP AND IN SPACE

Professor Tan is also particularly proud of CRISP, a satellite ground station that collects data and images from remote sensing satellites 2,300-3,000 km around Singapore. Quick to credit Lui Pao Chuen (see p.62) and Lim Hock as the driving force and first director of CRISP respectively, Professor Tan serves as chairman of CRISP to this day.

CRISP was set up in 1992-93, just in time, as it turned out, to monitor Singapore's first haze in 1996. The haze, which has occurred almost annually since, is the result of forest fires in neighbouring Malaysia and Indonesia.

"We were in a position to capture images of the haze, revealing its true extent," he says. "Our images of the 2004 Asian tsunami, which could not have been obtained any other way, similarly helped with disaster relief."

While technologies like SSLS and CRISP were necessary to grow Singapore's nascent scientific culture, being connected to the wider scientific community was equally, if not more, important. Here too, Professor Tan has played a role, helping Singapore become the second node in Asia (after Japan) to join BITNET, a US university computer network, in 1987.

"Before that, access to the Internet and email was intermittent. BITNET was significant because it gave us a 24-hour gateway to the Internet," Professor Tan recalls.

His main motivation for joining BITNET was to make Singapore more attractive to potential hires. "We always found it difficult to recruit good scientists from overseas because they were reluctant to come to the other side of the world and be isolated from the rest of the scientific community," he says. "To me, BITNET was a great way to mitigate that sense of separation."

Thankfully, the NUS administration under Professor Lim and Thio Hoe Ting, director of the NUS Computer Centre, supported his vision. The university established sporadic contact with the City University of New York BITNET node by late 1986. The first official email was transmitted via a 4,800 bps dial-up link on January 13, 1987, marking the official date that NUS joined BITNET. (By comparison, a modern 1 Gbps broadband connection is more than 200,000 times as fast.)

NOW TO BUILD A HERITAGE

Despite the modern facilities and ample funding Singapore's scientific establishment now enjoys, Professor Tan nonetheless feels that there is much to be done for science, particularly in terms of our scientific culture.

"You may say that our publication record is very good, but in terms of people being able to think and argue and talk to their peers—not only in their own departments but other departments as well—I think we still have some way to go in fully developing that kind of intellectual climate," he says. "It's not about being clever; what I mean is being able to accept criticism and discuss differing views with our peers."

While acknowledging there are no easy answers in this quest, Professor Tan feels that giving local scientists a larger say in science policy is one important way forward.

"Do Singaporean scientists, even the senior ones like myself, have great input in the science policy of the country?" he ponders. "To be honest, I'd have to say not enough. In any field which you are trying to build a heritage in—whether it is scientific research or art and music—if you don't put your bets on Singaporeans, you can never build an indigenous capability. It's as simple as that."

Professor Tan also hopes that Singapore will become a nation that leads the world in its understanding and application of science and technology not only as applied to the needs of mankind, but also for the sake of satisfying man's curiosity about the world.

"I'd really like to see Singapore become a catalyst for creativity because as we've said so often, all we have are our human resources," he says. "I believe those human resources reach their fullest potential in creativity, and that's best expressed through science, technology and the arts."

A STEADY HAND AT THE HELM

Tan Chorh Chuan

By Rebecca Tan

With some 600,000 children affected by pre-emptive school closures and thousands placed under home quarantine orders, the 2003 severe acute respiratory syndrome (SARS) outbreak is one of the worst epidemics that Singapore has faced in living memory. And yet for two whole weeks after the first case was detected, it was a fear that had no name, as doctors struggled to tame the highly contagious but completely unknown infectious agent.

"Facing an epidemic is bad enough," says Tan Chorh Chuan, president and professor of medicine at the National University of Singapore (NUS), and Singapore's director of medical services at the time. "But having an epidemic of a completely novel virus adds tremendous complexity and difficulty to the situation as nobody knows the mode of transmission or infectiousness of the new agent. If you don't know these things, it's very hard to think about effective ways of containing it and managing patients."

All this meant, he says, that the degree of uncertainty and fear in Singapore was very high—and not just among the public, but among health workers as well, especially when it became clear that many of the infections were spread in a hospital setting.

Credit: Cyril Ng

STEERING SINGAPORE THROUGH SARS

As frontline health workers began succumbing to the disease, the fear continued to grow. Nonetheless, not a single doctor or nurse abandoned his or her post, recalls Professor Tan, and several even went far beyond the call of duty.

One such doctor was vascular surgeon Alexandre Chao, the son of respected forensic pathologist Chao Tzee Cheng. Upon hearing about the SARS outbreak, the younger Chao rushed back to Singapore from a family holiday abroad to replace colleagues who had been infected and could no longer perform surgeries. Tragically, he too became infected and passed away, leaving behind his wife and two young daughters.

"Seeing people I know pass away, Alex among them, was the hardest part of the SARS crisis for me," Professor Tan reveals, striking a sombre note. But, he admits to being "deeply impressed and appreciative of the fact that our health professionals lived up to their calling; delivering care under very difficult circumstances, living with the fear and uncertainty but remaining driven by the interests of patients and the public."

Professor Tan himself had to make extremely difficult decisions almost on a daily basis. Perhaps the toughest was the temporary re-designation of Tan Tock Seng Hospital (TTSH) from general to SARS-specific care. The call was made very early on.

"Tan Tock Seng is one of the largest hospitals and at the time had the busiest emergency department," explains Professor Tan. "To recommend to close the hospital down to normal operations on the basis of just thirty suspected SARS cases was a very big decision, as it meant taking out quite a bit of capacity of the health delivery system."

In retrospect, it was the right decision, he believes, because it allowed TTSH's staff to focus fully on learning how to manage SARS; their confidence and expertise spread through the rest of the healthcare system. "For example, after Tan Tock Seng Hospital ensured that the personal protective equipment protocol was rigorously adhered to, there were no further cases of healthcare workers who became infected from SARS from looking after patients," he says.

Professor Tan received the Public Service Star in 2003 in recognition of his contributions to the management of SARS, and the Public Administration Medal (Gold) Medal in 2004 for his work in the Ministry of Health.

BEGINNING HUMBLY

Professor Tan first heard his calling to the medical profession as a schoolboy at St. Joseph's Institution, when, as a member of the St. John Ambulance Brigade, he helped resuscitate a footballer who had collapsed during a match.

However, as the seventh of nine children, Professor Tan needed a scholarship to pay for medical school. "It was pretty competitive," he relates, in his trademark, understated style. "I was thrilled to be accepted [by the University of Singapore], and even more so to receive a scholarship that allowed me to stay in King Edward VII hall for the five years of my studies."

Staying at a hall of residence proved to be a formative experience, both in terms of his introduction to medicine as well as his holistic development. In particular, Professor Tan remembers the words of Khoo Oon Teik, professor of medicine and master of the hall, to the medical students just days after they registered. Professor Khoo impressed on them the need to be humble as they were entering a profession with many truly distinguished members, and an institution whose history stretches back to 1905.

> Seeing people I know pass away, [Dr Alexandre Chao] among them, was the hardest part of the SARS crisis for me.

Inspired by dedicated and passionate mentors such as Evan Lee and Woo Keng Thye, as well as Professor Khoo, who set up the National Kidney Foundation, Professor Tan trained as a nephrologist after his graduation from medical school.

Intrigued by the workings of the kidney, he decided to pursue research alongside his clinical practice, completing his research training at the Institute of Molecular Medicine (IMM), Oxford University for a PhD conferred by NUS in 1993, to become one of the first home-grown clinician-scientists in Singapore.

CHARTING A COURSE FOR CAREER AND COUNTRY

At the time of his graduation, however, Singapore was placing greater emphasis on chemicals, electronics and engineering research—fields seen as the three main drivers of economic growth.

Undeterred, Professor Tan continued doing biomedical research while seeing patients, eventually winning the Singapore Youth Award in 1996 for his work on the regulation of erythropoietin, a hormone that controls red blood cell production.

But his hopes for the scientific enterprise in Singapore extended far beyond his own career. Led by fellow SJI alumnus Philip Yeo, and working with John Wong (see p.106) and Kong Hwai Loong, Professor Tan was instrumental in conceptualising and setting up Singapore's biomedical sciences (BMS) initiative. Launched in June 2000, the BMS initiative saw a substantial increase in government investment with the aim of making the biomedical sector the fourth pillar of Singapore's economy.

The BMS's challenges included growing basic science strengths from a low base and developing excellent clinical research capabilities, while fending off naysayers who thought its ambitions unrealistic.

"Today, as we look at the considerable science talent and capability base that we have, it's hard to recall those early days," Professor Tan muses. "I don't feel that there were any substantial shortcomings in the approaches taken, although it might have been good to put a stronger focus on building our translational and clinical research expertise and capabilities earlier on in the process."

AN INTERDISCIPLINARY APPROACH TO THE CHALLENGES AHEAD

Indeed, the main thrust over the course of his tenure as president of NUS has been the need for multidisciplinary research, especially collaboration between clinical research and basic science. Convinced of the importance of such research, Professor Tan played a key role in setting up the Duke-NUS Graduate Medical School to train the next generation of clinician-scientists.

"When I first came back from my research training [1992], there was just a handful of MD-PhD's and a few clinicians involved in research. Today, we have a much larger number of well-trained, active and productive clinician-scientists, at least ten times more than before," Professor Tan enthuses.

In this there are shades of Oxford's IMM, where during Professor Tan's time one-third of the researchers were also practicing clinicians. Quite naturally, he says, IMM's basic science work became related to clinical problems and patient populations. "That rich interaction was very positive in helping to shape the research questions," he says.

Beyond clinical research, Professor Tan believes greater collaboration between basic medical research and the social sciences is necessary.

"It's clear that most of the health challenges that we face will not be solved by science and technology alone," he stresses. "They also require social science research to understand the behavioural and social aspects that influence them."

Professor Tan gives the example of chronic non-communicable diseases such as diabetes, which require the active participation of patients and the community if they are to be adequately managed. This is where social science and behavioural science research can help.

Indeed, Professor Tan's ability to synthesise the medical sciences with the social and behavioural, in a time of blinding crisis, is a big reason why he has already established a rich legacy in Singapore.

"Today, Singapore is immensely better prepared for an infectious disease epidemic," Professor Tan says. "The policies, approaches and protocols are in place, and there are many individuals who have deep experience in the implementation of control measures."

In other words, even if the next enemy has no history or name, Singapore should feel confident in its ability to fight it off.

A LOVE OF WATERWAYS

Tan Gee Paw

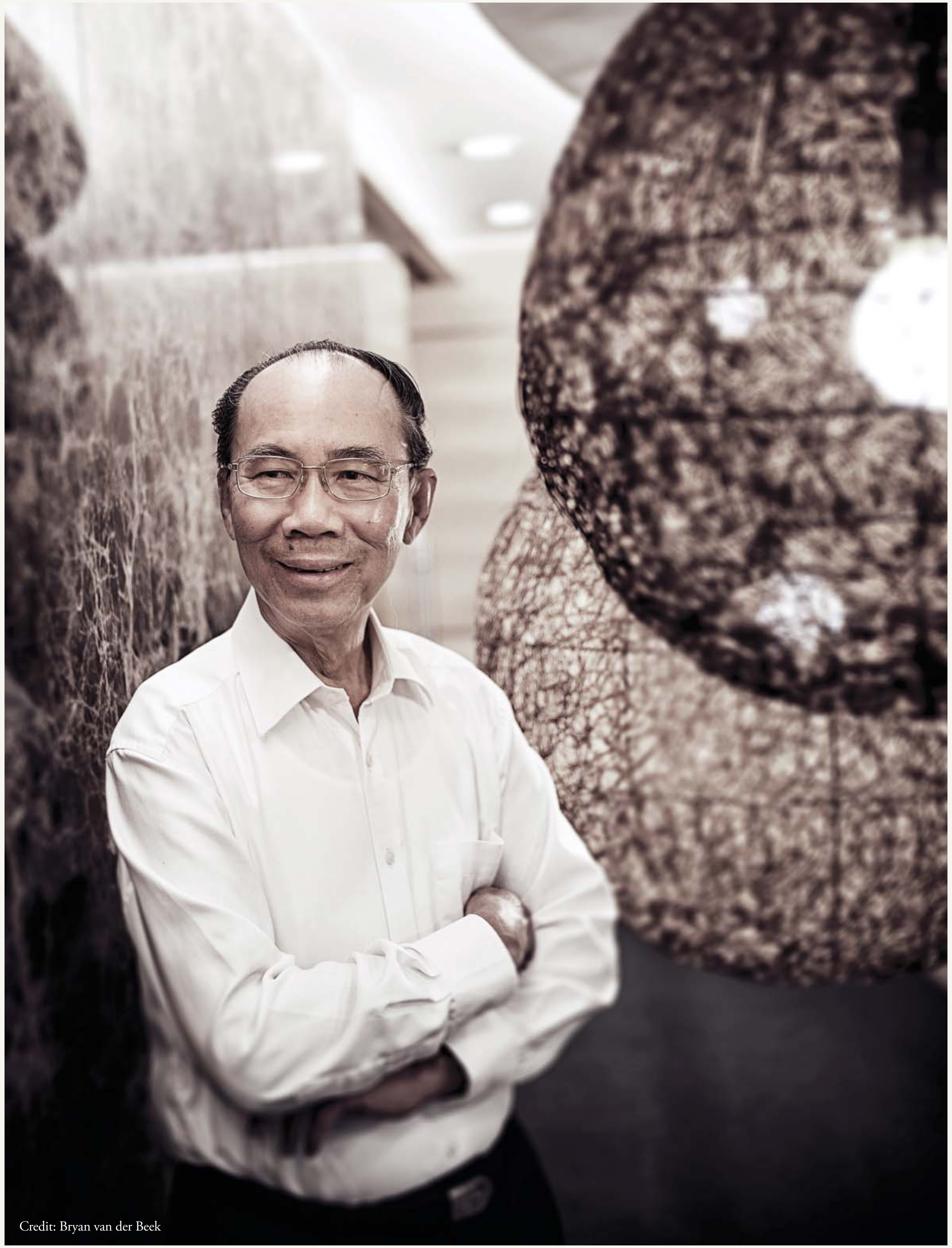
By Juliana Chan

Singapore ostensibly has lots of water. It falls freely from the sky, and surrounds the tropical island in voluminous quantities. But for decades, these two sources remained out of reach to its people, who had no means to capture or purify it in an efficient manner.

In the 1960s, Singapore was almost entirely dependent on imported water from Johor, Malaysia's bordering state. Droughts and floods made water a collective concern of this young nation, an existential threat. For instance, a particularly severe drought in 1963 led to a ten-month rationing period, during which it was common to see long queues at public water taps.

Over the subsequent five decades, Singapore embarked on a relentless drive to achieve water self-sufficiency, led by Lee Kwan Yew, its first prime minister. It built up water catchment areas, modernised sewerage systems, cleaned up waterways, and introduced innovations in water recycling and desalination.

Few people are as intertwined with Singapore's water narrative as Tan Gee Paw, chairman of the Public Utilities Board (PUB).



Credit: Bryan van der Beek

HE KNEW EVERY DRAIN AND CANAL IN SINGAPORE

Mr Tan's career began as a junior engineer at the Public Works Department (PWD) in the late 1960s, but only after a last minute change of heart.

Having won a Colombo Plan scholarship to study marine engineering, Mr Tan was en route to the Public Service Commission (PSC) to complete the necessary paperwork.

Feeling pensive, he stopped by Clifford Pier to look at bumboats, which used to carry cargo back and forth between the warehouses and ships before the arrival of modern containerisation technology.

Although grateful for the scholarship, Mr Tan was not sure if marine engineering was the right course. "I remember sitting on the parapet wall overlooking the sea, with my legs dangling out there," he says. "I just pictured myself as a marine engineer on board a ship, and I said, 'How could I spend my life that way?'"

Mr Tan eventually made it to PSC's office at the Fullerton Building, where he declined the scholarship. He later successfully applied for a PSC bursary to study civil engineering at the University of Malaya.

Returning in 1967 to serve a four-year bond, Mr Tan met the PWD's director, Hiew Siew Nam, who informed Mr Tan that he would be posted to the drainage department.

"My heart sank," he says, "Because if you've done well in your studies you expect to be building bridges, something to show off… Buildings, skyscrapers, funny structures, long structures, and things like that."

Adding salt to the wound, PWD gave him a maintenance role within its drainage department, instead of one of the more coveted positions in design and construction.

However, serendipity came knocking in 1971. Mr Lee had just set up the Water Planning Unit in the Prime Minister's Office. He asked Mr Tan, who by then had an intimate knowledge of every drain and canal in Singapore, to plan the country's long-term water supply.

In those days, to get a single, statistically-relevant figure, a hydrologist had to record a daily inventory of water rainfall and draw-out—input and output, respectively—from every reservoir over a period of fifty or more years.

Mr Tan knew that a computer simulation could generate the same data within minutes. In the 1970s, PWD had a room-sized ICL 1900 series mainframe computer that they used to print their bills. With the help of the unit's manager, Lau Peng Sum, Mr Tan built mathematical models using a computer programming language called Fortran, short for Formula Translating System.

"I would go in at night with stacks of punch cards… I think it is very archaic to you all now," he says, recalling the work he did to complete Singapore's First Water Masterplan.

In 1974, Mr Tan joined the Ministry of the Environment as an engineer in its environmental engineering division. His job entailed, among other things, working with the same bumboats, which by then had become the Singapore River's main pollution source.

The river then was like an open sewer, its stench pervading for miles away. Bumboat residents defecated into the river, whose banks were crowded with illegal squatters and hawkers jostling for a sale.

At the opening of Peirce Reservoir in 1977, Mr Lee challenged the Ministry of the Environment to clean up the Singapore River: "In ten years, let us have fishing in the Singapore River and Kallang River."

Working with Lee Ek Tieng, then permanent secretary of the Ministry of the Environment, and a team of dedicated officers, Mr Tan chaired an inter-agency committee of 11 government departments, which successfully cleaned up the Singapore River. The decade-long project won the team the Clean Rivers Commemorative Gold Medal in 1987.

TWO NEW WATER TAPS FOR SINGAPORE

By 1995, Mr Tan had become permanent secretary of the Ministry of the Environment. He led the re-organisation of PUB from a utilities provider into a national water agency that manages the whole water cycle—from water supply, to drainage, to used water and water reclamation.

He joined PUB as chairman in 2001, where he helped to turn on two additional "water taps" for Singapore—recycled used water and desalinated seawater—which supplemented the country's two older sources (local catchment and imported water from Johor).

To recycle either used water or seawater, a technology called reverse osmosis is used. In osmosis, water moves from a state of higher to lower osmotic pressure across a semipermeable membrane. In reverse osmosis, conversely, applied pressure pushes water against this osmotic gradient, producing clean water and leaving both salts and pollutants behind.

In the 1970s, though the concept of recycled water was around, membrane technology was not advanced or cheap enough to scale up. PUB's first reverse osmosis plant in Ulu Pandan was too expensive and its equipment kept breaking down. It lasted just two years.

> "How does the mangrove swamp desalt seawater? How do some freshwater fish survive in brackish water? The kidneys do it very easily too."

By the 1990s, membrane technology had improved significantly. PUB opened its first used water recycling plants in Bedok and Kranji in 2003.

Public opinion was on its side, Mr Tan says, citing a survey that showed 95% of Singaporeans were in favour of the technology. All the test results underscored the public's belief. NEWater—Singapore's brand of ultra-clean, high-grade reclaimed water—exceeded the drinking water standards set by the US Environmental Protection Agency and the World Health Organization.

"The first time I saw NEWater, it was kept in a well about two stories deep at Bedok, lined with concrete all the way round," Mr Tan says. "The water was sparkling, crystal clear."

Since its introduction in 2003, NEWater has been used mainly for industrial purposes such as wafer fabrication, freeing other sources for residential use. The same membrane technology also made it possible for the Marina Barrage to be built in 2008, creating an expansive freshwater reservoir in the city that meets 10% of Singapore's water needs.

The fourth water tap, desalinated seawater, was also a priority for Mr Tan. In 2005, PUB introduced Singapore's first desalination plant at Tuas, in a public-private partnership project with SingSpring Pte Ltd.

In 2013, PUB and Hyflux Ltd, a pioneering Singaporean water technology firm, opened Tuaspring Desalination Plant, Singapore's second desalination plant and also its largest. Hyflux is now building the world's largest seawater desalination plant in Algeria.

FROM VULNERABILITY TO STRENGTH

Mr Tan's thoughts turn to the 1961 and 1962 Water Agreements with Malaysia, which have guaranteed Singapore access to subsidised fresh water—while also making the tiny country reliant on its much larger neighbour. He says that by the time the second water agreement expires in 2061, PUB plans to have tripled NEWater capacity to meet up to 55% of Singapore's water demand, while desalination will account for another 25%. And the remaining 20%? "Free from the sky," he says with a laugh.

In addition, Singapore is positioning itself as a global "hydrohub" where innovative water research takes place. To date, Singapore's National Research Foundation has invested close to half a billion dollars in water-related research projects via the environment and water industry programme office.

More than 180 water companies and 26 research institutes have set up base in Singapore. In addition, Singapore-based companies have secured well over S$10bn worth of overseas projects in the last ten years.

A recipient of the prestigious Stockholm Water Industry Award in 2007, PUB is collaborating with academic researchers to investigate futuristic biomimetic technologies—designs that are adapted from nature to solve modern problems.

"How does the mangrove swamp desalt seawater? How do some freshwater fish survive in brackish water? The kidneys do it very easily too," Mr Tan says, referring to proteins called aquaporins, which control the water content of biological cells in both plants and animals.

Where water management is concerned, rising sea levels from climate change may lead to yet another existential crisis for Singapore. Mr Tan sits on Singapore's Climate Change Network committee, which explores ways to mitigate the risks involved.

As a young engineer in the maintenance section of the drainage department, Mr Tan may not have predicted that he would receive the 2007 President's Award for the Environment and honorary doctorates from British and Singaporean universities.

But for someone whose lifelong passion even seeps into his hobby of oil and acrylic painting, it is well deserved. "Most of the landscapes that I paint will always have some water in it," he says. "They are very quiet, placid, waters. I love waterways."

A (DINO) BONE TO PICK

Leo Tan

By Grace Chua

Leo Tan, professor of biology at the National University of Singapore (NUS), runs his hands over the grey stone slabs of the Lee Kong Chian Natural History Museum's exterior, designed to resemble aeons-old geological strata. Inside, a cavernous central well shows off three towering diplodocid dinosaur fossils, skeletons of the long, slender, short-legged "daschunds" of the giant dinosaur world, and some of the longest creatures to ever walk the earth. Meanwhile, lining the halls are glass cases of iridescent birds, glossy shells, and even stuffed squirrels and sun bears.

For 70-year-old Professor Tan, the museum, which opened this year, has been a dream four decades in the making. As a schoolboy at St Joseph's Institution, which was then on Bras Basah Road, he remembers wandering across the street after school to visit the Raffles Museum, with its spectacular whale skeleton dangling from the ceiling.

But in 1960 the museum's identity changed. It was renamed the National Museum and its focus correspondingly shifted towards the arts and history. Its bird and animal specimens, no longer wanted, were shunted off to NUS and "moved around like nomads" for nearly two decades. The whale skeleton was sent to Malaysia's Muzium Negara.

A VERY LONG GAME

Professor Tan developed a love for animals while he was growing up near Mount Faber, surrounded by greenery. "Nature came into the house, whether it was a snake, a rat, or a centipede," he says. But in university, his professors dissuaded him from pursuing a doctorate.

"First of all, the University of Singapore was then not highly regarded even though it was the only [English-medium] university here," he says. Moreover, lingering colonial mindsets meant it was relatively harder for Asians to gain employment in academia.

Nevertheless, he persisted, obtaining a PhD in marine biology by studying the biology and ecology of mussels. Inspired, he then hoped to become a mussel farmer, but the entrepreneur he worked with could not obtain a loan.

Credit: Cyril Ng

"The EDB [Economic Development Board of Singapore] wrote a letter of support, but the banks were having none of it," he grumbles. "They said, your collateral is useless; your mussel farm can fall into the sea at any time." So in 1973, he became a senior tutor at the university instead—the very job his professors had told him to shun.

In 1986, as a senior biology lecturer and director of the Singapore Science Centre, he learned that Lim Pin (see p.54), the university's vice-chancellor, had given the collection some room in the new NUS science library building. His former student Peter Ng resurrected the *Raffles Bulletin of Zoology*, arguing that zoology research would be a fillip to the university's reputation.

Hence the collection moved to the new Raffles Museum of Natural History with Professor Ng as its director. It consisted mostly of cramped back-room shelves smelling of formaldehyde and alcohol, accessible only to researchers, and a tiny display space, smaller than two HDB flats, for visitors. In 2009, a surprising thing happened. On International Museum Day, when the museum held an open house, 3,000 people visited, more than in the whole of the past year.

Professor Tan and Professor Ng felt the time was right to lobby for a larger natural history museum. But there were significant bureaucratic and financial hurdles to overcome.

> "Why would I want to stay or invest in Singapore if there is nothing for me after I finish my work?"

AGAINST THE TIDE

Thankfully, by then, Professor Tan had accumulated decades of experience in wearing down bureaucracy by slow-drip persuasion.

While conducting research for his PhD, Professor Tan did whatever was asked of him by Tham Ah Kow, the retired fisheries officer who supervised him, even though Professor Tan knew some of the "tough cookie's" suggestions would not work. On the side, he did what he believed in.

"It was double the work, but it's your PhD," he says. "You want to get it at almost any cost. I found very early that it didn't pay to fight the bureaucracy. You skirt the issue, you go round the problem. It takes a longer time but it pays off."

As a young lecturer, Professor Tan observed reclamation projects claiming his field sites such as Tanah Merah and Tanjong Gul. He argued that Singapore's natural shores, such as Labrador, ought to be preserved. For that transgression he was called up by a very senior civil servant who called him "a stooge of the colonialists".

Professor Tan recalls the conversation:

"They [the colonialists] have destroyed all their forests, all their trees, now they come into the developing world and tell you not to cut down your trees, in order to suppress you and keep you subservient all the time. You are playing into their hands."

"Sir, you are probably right, but I believe in the cause not because Westerners told me to, but because this is my home."

Professor Tan refused to be cowed. "I was very polite, and I think he accepted it," he says. "Are you prepared to get hammered for your beliefs or not? If you aren't, don't start any campaign—because you are a fraud or an opportunist."

And when he became chairman of the National Parks Board in 1998, Professor Tan carried on the fight for natural shores. In 2002, thanks to calls from the public to preserve it, Singapore gazetted a ten-hectare stretch of the Labrador coast as a nature reserve. Today it is part of a 22-hectare park.

Another challenge came during Professor Tan's tenure as director of the National Institute of Education (NIE), a post he assumed in 1994 after ten years as director of the Science Centre.

At the Science Centre, he had observed some teachers' casual indifference towards their students—dumping them inside then heading to the canteen to wait.

Eager to motivate them, at NIE Professor Tan introduced a Caring Teacher Award. He also convinced the NIE staff—the trainers of teachers—to develop better people skills such as

collaborating with others in different fields; being good at research was not enough.

When Professor Tan first joined NIE, few people wanted to join the teaching profession. "I interviewed five potential students and took in six," he jokes. A decade later, NIE was accepting just one out of every five applicants, and training 4,000 teachers a year, double what it had before he arrived. Professor Tan stepped down as director in 2006.

Meanwhile, in 2003 he championed the Gardens by the Bay project, fighting for an expensive piece of downtown real estate. "We have to think about investment for the future, about a liveable Singapore, about recreation, about improving the quality of the air, the quality of life," he says. "Why would I want to stay or invest in Singapore if there is nothing for me after I finish my work?" The project, conceived to rival iconic city parks like New York's Central Park, was approved in 2006.

These are all reasons why Professor Tan describes himself as a "political" scientist—though he trained as a scientist, he has spent the better part of his career as an administrator. "Singapore is such a small country," he says. "To keep the country running, some of us have to double up and do a few more things."

What if he had remained in research? "I'd still be a marine biologist," he proposes. "I'd be enjoying my life, touring all the beautiful reefs and marine stations of the world."


Credit: Cyril Ng

Today, he enjoys playing with his two-and-a-half-year-old grandson ("a Dragon baby, and behaving like one too"). He is married to an ophthalmologist, and they have two sons.

BUILDING A HERITAGE

Walking through the seven-storey, S$56m Lee Kong Chian Natural History Museum today, with ten times the display capacity of the old Raffles Museum, Professor Tan talks about the five-year fundraising process, which he led as director of special projects at the NUS faculty of science.

After the unexpected response to the museum's open house, Professor Ng and he sent out letters to alumni and others. "For 700 letters we sent out, we got 400 responses and almost one million dollars," he says. "The donations came from a cross-section of society—we had support from secretaries, from technicians."

Altogether, they raised S$46m in six months from individuals, foundations, and anonymous donors who contributed multi-million dollar sums. A generous alumnus bought and donated an old but spectacular shell collection worth S$20,000, for instance.

"More important than saying 'We are going to do it at any cost', is persuading people to come along on the journey," Professor Tan says. Ultimately, the museum is for the people of Singapore, he adds.

Singapore needs a natural history museum, he believes, to remind people of its natural heritage and of humans' place in the natural world. It also needs more science-trained leaders, and must continue to nurture its latent research sector.

With regards to Singapore's overall scientific research establishment, Professor Tan believes that long-term investments are now starting to pay off with the emergence of breakthrough findings. "It's not a five-year problem; it's a fifteen-year," he says. "Halfway through, you cannot say, I don't see any results, let's cancel it and start on another Cinderella project. You have to see it through."

Take it from a man who knows how to dream long term.

The Accidental Internet Pioneer

Tan Tin Wee

By Shuzhen Sim

Overwhelmingly white, male, and chock-full of advanced degrees in computer science and electrical engineering, the Internet Society's Hall of Fame could not be more different from its Rock and Roll counterpart.

Alongside luminaries such as Tim Berners-Lee, founder of the World Wide Web, and Vint Cerf, who co-designed the Internet's fundamental architecture, is an unassuming Singaporean: Tan Tin Wee, associate professor of biochemistry at the National University of Singapore (NUS).

From first using the Internet to facilitate his own molecular biology research in the early 1990s, Professor Tan ended up pioneering a slew of technologies that has made the Internet accessible to non-English speakers around the world.

WIRING UP A NATION

Professor Tan's interest in the natural sciences began in childhood, when he would peer through a telescope—a gift from his father—at the night sky. In 1990, after doctoral work at the University of Edinburgh, where he developed vaccines to protect sheep against bacterial infections, Professor Tan returned to Singapore.

In the wake of the gene cloning boom and the initiation of the Human Genome Project that same year, Singapore's government was keen to develop local molecular biology expertise.

While in the UK, Professor Tan had accessed gene sequence databases—valuable resources for molecular biologists—via the Internet. He soon realised that Singapore sorely lacked the essential bioinformatics infrastructure to support the fledgling molecular biology research sector here.

Credit: Cyril Ng

NUS was then linked to BITNET, an Internet predecessor with origins in the United States. Professor Tan quickly became one of its biggest users. "In the daytime I was doing experiments, and in between incubations I was on the computer, connected to the network," he says.

He soon caught the attention of senior administrators at the NUS Computer Centre. They asked him to take over the running and development of TechNet, Singapore's first dedicated network for the nation-wide research community. Professor Tan recalls having to teach immunochemistry in the morning, and then having to sign purchase orders and tenders in the afternoon.

In reality, his new afternoon job was to build the Internet for Singapore. Singnet, Singapore's first Internet service provider, was established in 1994, offering dialup connections to the public. By 1998, almost a quarter of households had Internet access; by 2013, some 87% did, almost all via broadband. Today, Singapore has the fourth highest Internet penetration rate in Asia, behind South Korea, Japan and Hong Kong.

In the early 1990s the Internet was primarily used in scientific circles—unicasting and multicasting, early versions of webcasting, for example, were only used in deep sea and space explorations. However, Professor Tan sensed its potential to transform many aspects of society. In 1994, his team successfully initiated a videocast of the National Day Parade, beaming it to Singaporeans far away.

Keen to see how the Internet could benefit disabled children, Professor Tan also personally wired up the Singapore School for the Deaf, making it the first primary school in Singapore with Internet access. Its students, hitherto reliant on sign language for communication, suddenly had a new way to chat.

MAKING THE INTERNET GLOBALLY ACCESSIBLE

In the 1990s, the Internet was hailed as an "information superhighway". But Professor Tan—who lived in multicultural, multilingual Singapore—noticed a huge digital divide. The Internet's graphical interface could only display ASCII characters (A-Z and 0-9). Entire communities using non-Latin-script languages—Asia's millions of Chinese and Tamil speakers, for example—were unable to access to a wealth of online information without first learning English.

In 1994, taking advantage of the fact that fonts for the Chinese language already existed, Professor Tan and his team wrote a programme that would match the code for each character to its corresponding image, and then piece the images into a bigger picture that could be displayed in Internet browsers. They extended this concept to the Tamil language, and in 1995 demonstrated their work by displaying Singapore's National Pledge online in Chinese, English, Malay and Tamil.

> "In the daytime I was doing experiments, and in between incubations I was on the computer, connected to the network."

By 1996, web browsers were able to display multilingual content. But there was another major accessibility problem. The domain name system (DNS), which translates human-readable Uniform Resource Locators (URLs)—www.google.com, for example—into numeric Internet Protocol (IP) addresses, was still ASCII-only. The digital divide remained—Internet users had to know English in order to type in an address and navigate the web.

In 1998, Professor Tan's team had an answer. If a user entered a URL in a non-Latin script, the team's proxy software would convert the multilingual characters into Unicode, a computing standard for text, and then into ASCII. This got passed into the DNS, which would recognise the ASCII format and return the IP address.

"Everyone got very excited for obvious reasons—the Internet was not big in China back then," says Professor Tan. "It was the same thing for all the different Indian languages, Cyrillic and Arabic."

Properly implementing a multilingual DNS would require some reconfiguration of the Internet's underlying infrastructure. Although no one person or entity runs the Internet, some of its technical aspects are overseen and standardised by the Internet Corporation for Assigned Names and Numbers (ICANN), a governing body headquartered in Los Angeles.

More than a decade after Professor Tan's team proposed their solution, ICANN voted in 2009 to allow domain names in non-Latin scripts, calling it the biggest change to the coding of the Internet since its invention. But because the technology had stagnated for so long, progress to fully integrate it into the Internet's infrastructure has been slow.

PIONEERING A NEW INTERNET PROTOCOL

In addition to his NUS position, Professor Tan now also chairs the Agency for Science, Technology and Research's Computational Resource Centre (A*CRC), which is tasked with equipping Singapore with supercomputing capabilities for the twenty-first century.

In that vein, he is now pioneering the use of new technologies for computers to communicate online. TCP/IP (Transmission Control Protocol/Internet Protocol), the decades-old communications language used by the Internet today, is a low-efficiency, computationally-intensive technology that can barely cope with the billions of devices now online, he says.

A newer communications technology called InfiniBand transmits data with much shorter lag times, less information loss, and higher efficiency than TCP/IP, but is currently used only in supercomputers for short-range communication.

In November 2014, together with Australian, Japanese and US universities, as well as industry partners Obsidian Strategics and Tata Communications, Professor Tan's team at the A*CRC demonstrated the first long-range, high-speed InfiniBand link between supercomputers on three continents, on a platform called InfiniCortex.

In conventional grid computing, distributed processors perform tasks in parallel but more or less independently of one another. InfiniCortex instead allows for concurrent supercomputing, where intermediate results can be swiftly communicated between processors located across global distances. This allows participating centres to run more complex tasks—such as computational fluid dynamics or genomic data analysis—at greater scales without having to invest heavily in their own supercomputing resources.

Professor Tan is also addressing the limiting factor for computing speed: the energy needed for exascale computing—a billion billion (10^{18}) calculations per second—could power entire towns. Data centres worldwide use an estimated 30bn watts of electricity, equivalent to the output of 30 nuclear plants.

Even with the most efficient chips, servers generate a lot of heat. Lots of energy is required to cool them. One proposal to mitigate this involves locating servers in a distributed manner in homes and offices, and using the waste heat they generate to warm buildings.

In Singapore, Professor Tan leads the DataCentreX initiative to explore ways to couple supercomputing operations with heat-requiring processes. In tropical Singapore, there is only one bitterly cold spot—the liquefied natural gas (LNG) plant on Jurong Island, where LNG exists at -162 degrees Celsius. Data centres could theoretically provide the heat needed to re-gasify it before it is bottled and sold, says Professor Tan. The expanding gas could even be used to drive turbines, which would further offset supercomputing energy requirements.

Combining the DataCentreX concept with high-performance InfiniBand networking would allow computing load to be redistributed depending on temperature conditions—between Northern and Southern hemispheres, for example, so that computing would always take place during the winter. But data security—as sensitive information is shared globally—remains a major hurdle.

LAYING THE GROUND FOR PARADIGM SHIFTS

It's easy to forget that throughout all this, Professor Tan has also built a successful career as a molecular biologist and bioinformatician, with a long-standing interest in vaccines and infectious diseases.

Professor Tan is also kept busy by his two teenage children, who grew up in NUS's Eusoff Hall where he was hall master—a job that involved "looking after 485 students who don't sleep till 4am".

Reflecting on what he sees as inevitable societal change, Professor Tan uses the example of how no one was willing to make data freely available in the early days of the Internet. Similarly, he is confident that what may seem outrageously daring today—locating a data centre next to a seemingly volatile LNG plant, for example—will eventually come to pass.

"It's only a matter of time, it may be another 10 to 15 years before mindsets change," says Professor Tan. "But we want to be 15 years ahead."

That mindsets do change, his family must surely be thankful. After more than 20 years of NUS campus living, in early 2014 Professor Tan finally moved them into their own home. A hyper-connected, energy-efficient one, no doubt.

Biomaterials 'Spin' Doctor

Teoh Swee Hin

By Grace Chua

As equipment beeps and whirrs around us in a Nanyang Technological University (NTU) laboratory, Teoh Swee Hin, a bioengineering professor there, shows off a spherical device about the size of a small watermelon, which churns about like the belly of a cement mixer.

This is a bioreactor he designed more than a decade ago to mimic the natural rough-and-tumble environment in which cells develop while in the body.

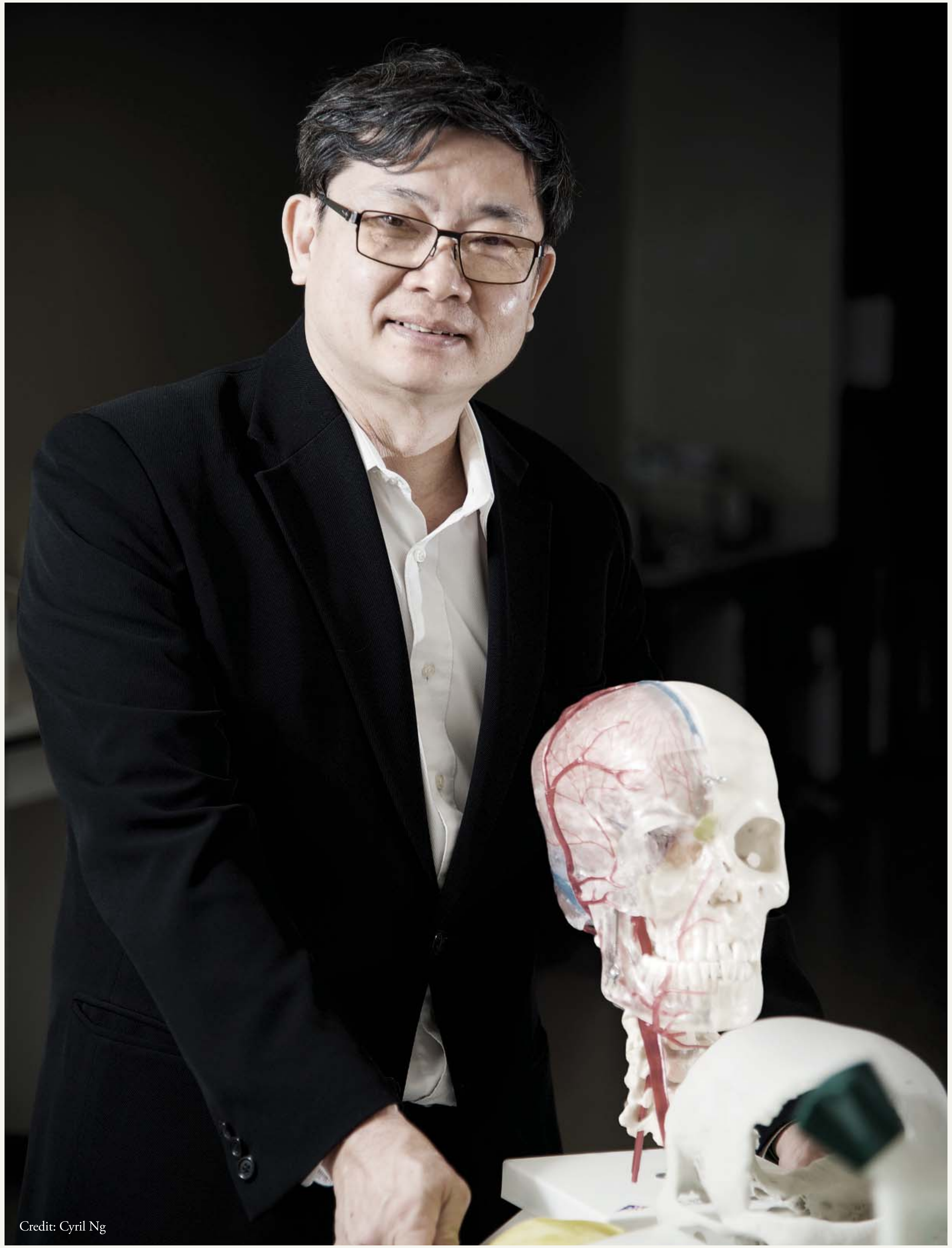
For more than three decades, Professor Teoh, 60, has been applying his engineering know-how to the biomedical field, seeking to: understand the forces that make stem cells and bone cells grow; and, with this understanding, develop devices to improve medical treatments.

A BIOMEDICAL CALLING

Measured, soft-spoken and calm, Professor Teoh might have made an excellent doctor. Growing up in Ipoh, Perak, he aspired to be a doctor, but that ambition was thwarted at 14 when his father, a clerk in an ice factory, died.

Unable to afford medical school, Professor Teoh found an alternative far away. From odd jobs, savings and what little his father had left, he scraped together enough for a one-way ticket to Australia, where he studied materials engineering at Monash University, which was tuition-free at the time.

For his PhD there, he studied how the common plastic polyethylene—used in medical and domestic applications—stretches, breaks and tears under different conditions of manufacturing and usage. After that, he followed his wife, a Singaporean accountant, back home, signing on to teach mechanical engineering at the National University of Singapore (NUS).



Credit: Cyril Ng

Meanwhile, Professor Teoh never let his medical dreams go.

In the early 1980s Victor Chang, a renowned Australian cardiothoracic surgeon who also operated at Mount Elizabeth Hospital in Singapore, was looking for engineers to help him design better mechanical heart valves. Professor Teoh leapt at the chance. "At that time, to get a $5,000 or $10,000 research grant was a very big thing," he says.

Dr Chang fully funded the work and became Professor Teoh's first mentor. The latter helped study heart-valve failure for Dr Chang's multinational firm, Pacific Biomedical Enterprises, which made mechanical and tissue heart valves to replace those from organ donors. "He was the first one [who] I felt had a mission to combine clinical work with manufacturing, and that caught my attention," says Professor Teoh.

But the collaboration came to a tragic end after just eight years. In 1991, Dr Chang was fatally shot in a failed extortion attempt in Sydney.

BONE SCAFFOLDS AND BIOREACTORS

Dr Chang's untimely death deflated the team's research ambitions. "All our work on fatigue evaluation, mechanical and materials evaluation, also went with him," Professor Teoh says of his mentor. Starting over again "took a lot of stars to be aligned".

Not till a few years later, after conversations with surgeons and tissue-engineering experts such as Charles Vacanti, a US doctor, did Professor Teoh hit upon his next big breakthrough: plastic scaffolds for bone and other tissue.

Surgeons trying to repair jaw, skull or other injuries often struggle to get enough bone for procedures, either from their patients' own bodies or cadaver donations. For larger repairs, titanium plates or other synthetic materials can be used, but these may be rejected by the body after surgery.

Instead, Professor Teoh and his colleagues designed a technology that combined the best of both worlds. They made scaffolds out of a special plastic material called polycaprolactone, which degrades into carbon dioxide and water and is absorbed harmlessly into the body.

These scaffolds are first seeded with bone marrow stem cells that eventually grow into sturdy bone, and then implanted into the body. Initial application of this technology involved small discs of the material being used to plug the burr-holes in patients' skulls after brain surgery.

Later, the advent of 3D-printing technologies in the manufacture of scaffolds meant they could be custom-shaped and sculpted to whatever form was needed. "It's like building a tall building," Professor Teoh explains. "You have scaffolds which you remove later. In this case, you can't remove the scaffolds, so we have to design a bioresorbable that dissolves."

In 2003, Professor Teoh and his team set up a firm, Osteopore International, to market and sell the bioresorbable implants.

He continues to study implants and materials from various angles, including research into: why implants might fail; and ways by which to improve cell growth around implants.

For instance, a phenomenon called delayed dehiscence—in other words, the breakdown of something weeks or months after it is implanted—can occur some time after any implant (not just the bioresorbable kind).

"It's a very strange phenomenon," Professor Teoh says. "When we put a jaw implant in, for instance, the mucosa might grow over it, the patient smiles, we think it's going to be successful—but then six months later, the whole thing falls apart."

He and his colleagues are seeking to understand why this occurs. He believes it is likely due to micro-motion—the implant shifting about almost imperceptibly and breaking down.

Meanwhile, the cell bioreactor, which mimics the physiologic conditions of the body under which cells grow, was a happy accident. A graduate student in Professor Teoh's laboratory was pregnant with twins. "She said, 'Prof, my babies are tumbling,'" he recalls. "We wondered why... so out of pure curiosity, we designed a bioreactor that rotates like a baby in the mother's womb. Suddenly, the cells grew four times faster."

"I began to realise that our cells are never static," he says. "If you take cells which are in constant motion from the first day in the mother's womb, experience tumbling and flow, and you put them in a static 2D environment... they grow in that unnatural environment and may not like your real body's conditions when you try to put them back in the body."

Bone grown in the reactor, which rotates on two axes, is stronger than that cultured on a plate and has fewer dead cells. The bioreactor technology has been licensed to Quinxell Technologies, a Singapore startup. While NASA studied a similar bioreactor which cultured cells in near-zero gravity, Professor Teoh's was one of the first in the world to rotate on two axes, and he believes that gravity's pull this way helps bone cells formation and growth.

"ENTREPRENEURSHIP WAS A DIRTY WORD"

When Professor Teoh and his team began to spin-off Osteopore International, "entrepreneurship was a dirty word," he says. The university frowned upon it, as though "you were using university facilities for your own profits… it was not in your KPIs [key performance indicators]. They made us do all kinds of record-keeping."

Today, Professor Teoh's firms are "just making ends meet", he says. He focuses largely on research and leaves the running of the businesses to executive teams.

His successes have helped turn around perceptions of university-based entrepreneurship, which Singapore's research institutions now promote.

Professor Teoh describes how his entrepreneurial instincts were nurtured as a child. To support the family, the youngest of five children resorted to selling encyclopaedias door-to-door during school holidays. He lugged the 12-volume set about the city on public transport in all weather, had doors shut in his face, and learned to sell by referral to friends' relatives.

The budding entrepreneur also bred and sold his orchid-enthusiast father's plants on the family's small plot of land in a rundown tin-mining neighbourhood in Ipoh. Buyers were charmed by the youngster's knowledge of *Phaelanopsis* and *Cattleya*, *Dendrobiums* and *Vandas*, and he soon learned how to bargain.

"I would greet them at the door so I could see what car they drove—whether it's a lorry or a Mercedes," he says. He knew when to market and price the plants as potted decorations or as "pieces of art". "Marketing is not book-learning alone, it is looking at the value proposition," he says. "It's helped me connect and translate research outside the lab, beyond the hospital."

Besides setting up firms and licensing technologies to increase their reach, the animal lover also sees a humane mission in some of his work. "I had two dogs," Professor Teoh says. "It's very painful for me to make use of animals for experiments. When it comes to saving human lives, I'll do it, but it's not for fun. Why use ten rats when five will do?" Growing tissue in bioreactors, for instance, decreases the need for grafts from animals.

RENAISSANCE AND BEYOND

Improving engineering education is another key objective for Professor Teoh, who has been director of NTU's renaissance engineering programme since 2012. The programme, started in 2011, rounds out top engineering students with training in business and the liberal arts; students also get a year to study abroad at select universities, such as the University of California, Berkeley and Imperial College London, to get a different perspective on their discipline, career and life. The objective is to provide them with a holistic education that combines sound engineering fundamentals with business savvy.

"Do you want more casinos or more engineers?"

For Professor Teoh, training graduate students at NUS and now NTU's school of chemical and biomedical engineering is a way of giving back to society. His first PhD students, Freddy Boey (see p.14) and Raj Thampuran, have now become, respectively, NTU provost and Agency for Science, Technology and Research managing director. "Part of the joy of being a professor is this: that our students are better than us and doing much more in areas that we never dreamed we could do ourselves," he says.

Asked about his hopes for science and engineering in Singapore, Professor Teoh thinks that despite the successes of the renaissance engineering programme, the engineering profession needs an image makeover.

"When I set up a company, I employ a CEO, CFO, accountants, lawyers—but all of them rely on engineers," says the father of a robotics graduate student, a lawyer, and an investment banker.

"It's STEM [science, technology, engineering and mathematics] that brought Singapore through the first 50 years, and I hope that will remain," Professor Teoh says. He believes that Singapore's future growth should come from making things that benefit people: "Do you want more casinos or more engineers?"

WHAT'S DIFFERENT ABOUT ASIA?

JOHN WONG

By Shuzhen Sim

In 1985, a young Singaporean doctor sat outside the office of the chairman of the department of medicine at Cornell University. After graduating from the National University of Singapore (NUS), John Wong badly wanted to train with the best minds in the US.

But nobody there had heard of NUS; few even knew where Singapore is. Without confidence in his medical training, every programme he applied to had summarily rejected him. Cornell seemed like his last chance. "I went in and gave this fifteen-minute sell," he says. "The only difference was I offered to work for free."

The strategy worked. Cornell took him on as an intern, making it clear that he would be on the next flight home if he did not measure up. He went on to become chief resident in medicine at the New York Hospital-Cornell Medical Center.

Now a professor in medical sciences at NUS and chief executive of the National University Health System (NUHS), Professor Wong is a highly-regarded oncologist who has led significant efforts to understand and treat cancers that predominantly affect Asian populations. As an administrator, he has also been instrumental in shaping Singapore's biomedical sciences and academic medicine initiatives from their very beginnings.

A TREMENDOUS NEED AT HOME

"I never worked so hard in my life," says Professor Wong, of those first years at Cornell. All his colleagues—from the medical student who visited a patient at home just to make sure she was okay, to the resident who for every case would go to the library and find three relevant references to share with the team—made a big impact on him.

"It was illuminating to see that people could work so hard and love their work so much," says Professor Wong. "Their degree of professionalism was so intense. That was one of the biggest eye-openers for me."

Professor Wong returned to Singapore in 1992, when only a handful of cancer specialists were practicing in the country. Singaporeans of means, he recalls, would sometimes seek treatment halfway across the world.

Credit: Bryan van der Beek

"I came back to Singapore because I thought there was a tremendous need. There's no reason why Singapore can't have the same quality of medicine," he says, referring to treatments for cancer.

In the US, he had seen how top hospitals, by working with pharmaceutical companies to run clinical trials, obtained good drugs for their patients years before their commercial release.

One example in particular sticks with him. In the late 1980s, a drug called amonafide was found to be ineffective against breast cancer, except in the small number of Chinese-Americans enrolled in the trial (90% of patients in clinical trials at the time were Caucasian).

It turned out that amonafide needed to be acetylated (a chemical reaction that adds an acetyl group to the molecule) by the body in order to become active; this happens more quickly in Chinese than in Caucasians.

The drug's selective efficacy undermined its market potential in the West; the pharmaceutical firm decided not to pursue its development. "But just imagine if they did that trial in Singapore," Professor Wong says, noting that the drug might have been developed as an effective treatment for Asian patients.

How could patients in Singapore enjoy the same level of access to experimental drugs? While governments and philanthropic organisations are the main funders of initial research in drug discovery, venture capitalists and pharmaceutical companies typically bear the cost of late-stage drug development.

Given the high costs and risks involved—an estimated US$2.6bn is needed to bring a drug to market, with a success rate of about 10%—pharmaceutical companies would need compelling reasons to shift R&D away from experienced US medical centres to Singapore, a country with little experience in clinical trials.

UNDERSTANDING ASIAN CANCERS

Cancer is caused by genetic changes that affect how cells grow and divide. These changes may be inherited, or may be acquired over one's lifetime, either as a result of errors that accumulate as cells divide, or through exposure to carcinogens such as cigarette smoke or ultraviolet radiation from the sun.

The development of cancer involves a complex combination of such genetic and environmental risk factors—consider that not every smoker will develop lung cancer, while some non-smokers may. And, as the amonafide trial demonstrated, genetic factors can also affect how patients respond to cancer treatments.

Poring over data from the Singapore Cancer Registry, Professor Wong and his colleagues noticed that Singaporean women were being afflicted with lung cancer at almost the same incidence as in the West. However most of the cases in the West were associated with cigarette smoking, whereas most of the cases in Singaporean women were in non-smokers, suggesting that doctors here may be dealing with a different disease.

> "I think the quality of our own talent, our students and our young faculty—they're easily as good as anywhere else in the world. But what our talent needs to do is to be hungry."

In 1996, Professor Wong's team collaborated with James Bishop, an oncologist at the Sydney Cancer Centre, to run head-to-head trials of a docetaxel and carboplatin regimen—common chemotherapy medication—for non-small-cell lung cancer in Singapore and Australia.

The results were striking—the response rate in the predominantly Chinese Singaporean population was double that in the largely Caucasian Australian. It was one of the first studies to show an effect of ethnicity on response to chemotherapy. It turned out that the drugs were metabolised more slowly in Chinese patients, giving them more time to work their effect.

Importantly, the data allowed doctors to make ethno-specific dose recommendations. But it also caused disgruntlement. "I remember when I presented this data in Boston; this lady in the audience got up and called me a racist," Professor Wong recalls.

These studies also drew the attention of pharmaceutical companies eager to tap into the growing Asian markets for therapeutic drugs. The US Food and Drug Administration (FDA) and National Cancer Institute (NCI), which had little data on non-Caucasians, were also keen to collaborate on clinical trials.

In 1997, capitalising on this interest, Professor Wong founded the Cancer Therapeutics Research Group (CTRG), a consortium of researchers from around the Asia-Pacific region. Still active today, the CTRG carries out clinical trials of treatments for cancers that predominantly affect Asian populations, including nasopharyngeal, gastric, and liver cancers.

BUILDING PROGRAMMES AND RECRUITING WHALES

In the late 1990s, Professor Wong, by then vice-dean of the NUS School of Medicine, was a key member of the team that strategised Singapore's biomedical science initiative.

The study of diseases that disproportionately affect Asians, they knew, would be an important niche for Singapore. Its three major ethnic groups—Chinese, Malay and Indian—are representative of much of Asia. Rather than competing directly with much more established Western medical centres, Singapore could instead work with them on comparative studies.

Professor Wong recalls helping write the concept paper for what was then termed the Singapore Genomics Programme (SGP)—aimed at understanding Asian and Caucasian genomics—in one caffeine- and junk-food-fuelled night, holed up in someone's kitchen.

The SGP needed a leader. At a CTRG meeting in Hong Kong in 2000, Professor Wong mooted the idea to Edison Liu, then director of the division of clinical sciences at the US NCI.

"We were staying at such a cheap hotel that there was no place to sit—we had to sit on the floor near the elevators," says Professor Wong. "We talked all night about Ed moving to Singapore."

In 2001, in a recruiting coup for Singapore, Professor Liu became the founding executive director of the SGP, later renamed the Genome Institute of Singapore (GIS). He would go on to head GIS until 2011, building it from a skeleton crew of three people into a thriving institute of nearly 300. GIS researchers now study the genetic basis of diverse human diseases, including cancers, infectious diseases, eye diseases, and neurological disorders, and have identified genes associated with susceptibility in both Asian and Caucasian populations.

BRIDGING THE GAP

Medical innovations in areas such as vaccine development or organ transplantation often arise through close partnerships between medical schools and hospitals. In Singapore, however, for years administrative structures did not support this integration of clinical care, research, and education—termed academic medicine.

For decades, the NUS School of Medicine and the National University Hospital (NUH) had been administered separately. "If you wanted to translate [apply] anything from NUS into a patient, you needed to make a case firstly to NUS and then to NUH," says Professor Wong.

Professor Wong played a major role in linking NUH and the NUS schools of medicine, dentistry and public health under a unified governance structure. NUHS—Singapore's first academic medical centre—was established in 2008.

The challenge, he says, is that the link between clinical care, research and education is often not intuitive. Singapore needs to integrate the three in order to develop solutions to its own particular set of health problems. Convincing the public of this is a constant uphill battle, but an important one. "You can't expect Western taxpayers to develop solutions for dengue or the diseases we face," Professor Wong says.

"It's been very rewarding to see the quality of science and the opportunities in science now completely transformed from what it was ten or fifteen years ago," says Professor Wong. This is also true for clinical care—it is now rare for Singaporeans to seek second opinions overseas, he adds.

His biggest concern, however, is drive: "I think the quality of our own talent, our students and our young faculty—they're easily as good as anywhere else in the world. But what our talent needs to do is to be hungry."

He encourages mentees to visit top medical and research centres in other countries, such as the US, to experience their level of intense professionalism.

Professor Wong now devotes the majority of his time to running NUHS. He also sees patients, some of whom have been with him for twenty years.

His packed schedule leaves him with little time for outside pursuits. But a good doctor practices what he preaches—Professor Wong at least attempts to get enough exercise and sleep, just as he asks of his patients.

Beach-comber, Wave-watcher

Wong Poh Poh

By Grace Chua

Sturdy in his Bermuda shorts and rubber clogs, Wong Poh Poh, retired associate professor of geography at the National University of Singapore (NUS), emerges from around a corner in the garden of his rambling Hougang home holding a potted plant: *Avicennia marina*, a robust, common species that, belying its name, thrives even inland.

Professor Wong admires the versatility of the grey mangrove, as it is more commonly known. It provides animals with food; humans with burning fuel; and coastlines with shelter from high-energy waves.

"You want some mangroves in your garden, you just come and collect them," he says. "The day I'm no longer around, these seedlings will be my standing testimony that mangroves can grow in my garden."

Like the grey mangrove, the 70-year-old has thrived across a range of roles. He is most noted for being a coordinating lead author of the seminal work by the Intergovernmental Panel on Climate Change (IPCC), the international body of scientists that reviews and reports on the latest climate-change data for policymakers.

In 2007, IPCC and Al Gore, former US vice president, shared a Nobel Peace Prize for disseminating knowledge on man-made climate change.

It was the highlight of a four-decade career studying coasts—specifically, how human activity such as tourism reshapes the coastline, and how the coastline itself influences human activity.


Credit: Cyril Ng

THE ACCIDENTAL GEOGRAPHER

Coastal geomorphology is a field that chose Professor Wong. As a student at the University of Singapore, he did so well in geography classes and so enjoyed the subject that the department, short of Singaporean lecturers, sent him to McGill University in Canada for a PhD.

But what exactly would he study? "Singapore has no big rivers, no forests, no deserts, no glaciers, and no mountains," Professor Wong laughs. "The only thing left was beaches."

But by the 1970s, when he returned, most of Singapore's natural beaches had vanished beneath reclamation, so Professor Wong looked to other field sites, for example studying how monsoons affected beaches on Malaysia's east coast.

Shortly thereafter, he was inspired to apply his hard-science skills to coastal tourism. The Association of American Geographers had just published a path-breaking paper on the geography of tourism. "Tourism used to be at the fringe of serious studies," Professor Wong says. "Nobody studied it except at business school."

His interest was in the interplay between resorts and coasts—how the geomorphology of a coast affects the layout, nature and management of a resort; and subsequently how resort development affects the coast.

> "Few Singaporeans call themselves islanders when our country is small and is indeed an island."

As one of the first geographers to carve out a niche in coastal tourism, Professor Wong surveyed resorts around Asia, including beach resorts on rocky shores that had hauled sand in to create artificial beaches; resorts which had installed their own corals; and resorts with manmade freshwater and marine swimming pools along the coast. In 1992, he wrote a research article on the impact of sea level rise on coasts.

In 1997, the Singapore government asked him to review IPCC's *Regional Impacts of Climate Change* special report. He was invited to be a lead author for IPCC's third assessment report in 2001, and for the fourth report in 2007—which ultimately won the Nobel —he was a coordinating lead author. He reprised his role as a coordinating lead author for the fifth report published in 2014.

Success has cemented his faith in unconventional pursuits. "Don't pick areas which too many people are working on," Professor Wong advises budding researchers. "Pick areas that are new and interesting, where you can contribute."

DISAPPEARING BEACHES

Singapore, of course, became a fascinating case study in coastal development. From 1965 till today, the country's land area has grown by almost 25% from 580 sq km to 720 sq km.

Singapore has only a few natural coasts remaining, such as on Pulau Ubin and a rocky shore at Labrador Park. "The government wanted it [reclamation], so we had no choice," he says, without rancour.

What's more important is to make sure the reclamation does not have adverse impacts, he thinks. For example, sediment moves through Singapore waters roughly from east to west; a large reclamation project at Changi, such as for the airport terminals, blocks the natural movement of sediment and results in erosion at East Coast, of which he despairs.

Singapore's coasts are certainly vulnerable to long-term environmental shifts. For one, some of the reclaimed land has subsided and the breakwaters have to be raised. Meanwhile, to safeguard against the threat of rising sea levels, Singapore has drawn up new coastal regulations. For instance, some of the existing reclaimed land on which Changi Airport's Terminal 5 will be built must be heightened to at least 2.25-metres above the highest recorded tide.

In order to properly guard against climate change, says Professor Wong, Singapore needs to share more of its coastal-vulnerability information with citizens to properly guard against climate change. This includes data obtained by LiDAR (light detection and ranging) systems, which use remote laser measurements to make detailed topographic maps.

"In other countries they share information openly," he says. "Coastal vulnerability studies are paid for by the taxpayer and should not be restricted to press releases or announcements in parliament."

Such information would be useful to insurance firms, developers and, most importantly, ordinary people who live near the sea. Singapore needs to prepare for climate change, and not just by raising land reclamation levels and building seawalls. For example, it will have to decide what space should be given over to coastal ecosystems as sea levels rise and they retreat further inland.

And it needs laws to govern so-called "managed retreat", he adds. "There's a lot of interest from lawyers. If you have a piece of land which is under water in 10 or 20 years, what are your property rights—are they on land or in the sea? Who will compensate you?"

TALES FROM THE FIELD

Professor Wong, of course, knows a thing or two about nature's ferocity. He was once caught in the middle of the US's worst pre-Katrina hurricane.

In 1969, as a graduate student, he spent a few months at a field site called Santa Rosa Island, a sandy island with dunes off the Florida coast. When Hurricane Camille hurtled through Florida at more than 200 kph, he and his colleagues hunkered down in a local hotel. "You could see pebbles being blown horizontally," he says. "In the hotel, we had to tape down the glass doors with sticky tape to make sure that they wouldn't shatter into small pieces if they broke."

The hurricane deposited shells and marine animals along the beach. Professor Wong, a "*kampung* boy" who had grown up fishing and swimming at Changi and Pasir Ris, was loath to waste a perfectly good source of food. "So I looked for things that were closed, and found a lot of pen shells," he says. "I took a knife and opened them up and cut off the muscles, boiled them and ate them."

That hardiness came in handy when he was stranded in Bintan while doing some surveying in the 1990s, before it had developed. "We were in a place called the Pasir Panjang coast, towards the eastern side of Bintan," he says. "It was dark, and we didn't have water or food. But I had a penknife, and we managed to scrounge and find two old coconuts which we opened up and shared."

YOUTH OUT OF TOUCH WITH NATURE

Unfortunately, he says, most young Singaporeans do not share his familiarity with nature. His three sons are lucky enough to have grown up in a house with a large garden, hibiscus plants, one chiku tree and many banana trees, but most young people are not—and in the process an intrinsic geographic identity has seeped away.

"Few Singaporeans call themselves islanders when our country is small and is indeed an island," laments Professor Wong. "I have been to many island nations, some bigger than Singapore, and their people are proud to be islanders. We're proud to be a world port but forget that it is based on the coastline and water."

To resuscitate our island consciousness and general nature awareness, Professor Wong has many suggestions. These include maintaining Pulau Ubin's rural environment; introducing compulsory gardening and gardens in schools; extending gardening schemes in housing precincts; and encouraging nurseries to stock seeds and potted seedlings of vegetables and fruits (and not just flowers).

At a larger level, he believes Singapore needs more "non-hype" outreach by the likes of the Botanic Gardens and the Zoo. "We spend one billion dollars on the Gardens by the Bay and yet it cannot teach the average Singaporean kid about our nature," he says. "Something is seriously wrong here."

For his part, Professor Wong has recently introduced mangrove planting to local schools. He has also recently initiated a project to set up mangrove restoration sites in South-east Asian countries such as Cambodia, Indonesia and the Philippines. These sites would serve as fish nurseries, storm surge buffers, and help stem coastal erosion. They would also become a source of livelihood for villagers, who could manufacture mangrove-planting modules from coir or jute, and benefit from eco-tourism.

The self-described "professional beach bum" has made a career out of going to the beach. Now, it is time to give back, he says. "The more satisfying thing is contributing something back to the coastal community."

TIMELINE

1965

Singapore separates from Malaysia and becomes an independent and sovereign state.

1968

The Ministry of Science and Technology is established to develop science and technology policies, build up manpower and infrastructure, and promote economic growth.

The Science Council of Singapore is formed to oversee the implementation of science-related policies and programmes.

A severe drought leads to a ten-month water rationing period across Singapore.

1977

The Science Centre, first mooted in 1969, is officially opened.

1980

The National University of Singapore (NUS) is formed from the merger of the University of Singapore and Nanyang University.

1981

The Ministry of Science and Technology is closed, with its various functions re-assigned to the Ministries of Education, Trade and Industry, and Health.

1985

Singapore suffers its first recession, which lasts for one year.

1986

The Institute of Molecular and Cell Biology (IMCB), one of the first research institutes in Singapore, is established at NUS.

1991

Nanyang Technological University (NTU) is formed from the merger of Nanyang Technological Institute and the National Institute of Education.

The National Science and Technology Board (NSTB) is established. It launches its first five-year National Science and Technology plan, which has been renewed every five years since then.

1997

DSO National Laboratories, established in 1972, is incorporated as a non-for-profit company limited by guarantee.

2000

The Defence Science and Technology Agency (DSTA) is formed as a statutory board under the Ministry of Defence.

The Biomedical Sciences (BMS) initiative is launched.

2001

NSTB is restructured into the Agency for Science, Technology and Research (A*STAR), overseeing biomedical sciences and physical sciences and engineering research entities.

2003

The Public Utilities Board (PUB) launches NEWater, Singapore's brand of ultra-clean, high-grade reclaimed water.

An outbreak of severe acute respiratory syndrome (SARS) in Singapore leads to the closure of Tan Tock Seng Hospital and 33 deaths.

2006

The National Research Foundation of Singapore (NRF), a department within the Prime Minister's Office, is established to set the national direction of research and development in Singapore.

2008

The National University Health System (NUHS) is established to unite the National University Hospital and the NUS schools of medicine, dentistry and public health.

2009

The Singapore University of Technology and Design (SUTD) is established. It is a collaboration between Singapore and the Massachusetts Institute of Technology in the United States.

2015

The Lee Kong Chian Natural History Museum, which traces its origins as the former Raffles Museum of Biodiversity Research (RMBR), is opened.

Singapore celebrates its 50th anniversary of independence. The book *Singapore's Scientific Pioneers* is published to celebrate the efforts of the scientific community over five decades.

NANYANG TECHNOLOGICAL UNIVERSITY

Photo credit: Hufton and Crow

Nanyang Technological University (NTU Singapore) has been a key pillar of Singapore's research and development activities, and is today ranked amongst the world's top universities. In the Nature Index 2015 Global, a ranking of the science output of 20,000 research institutions around the world, NTU is placed 40th globally and 8th in Asia for research excellence. It is also the highest-ranked Singapore institution on the list.

Young and research-intensive, NTU offers engineering, science, business, humanities, arts and social sciences, education, and medicine. Its medical school is set up jointly with Imperial College London.

Hub of research and innovation

NTU's research is interdisciplinary and covers high-impact areas such as sustainability, healthcare, new media and future learning. NTU hosts two national research centres of excellence, the Singapore Centre on Environmental Life Sciences Engineering and Earth Observatory of Singapore. It is also home to world-class institutes such as the National Institute of Education, S Rajaratnam School of International Studies, Nanyang Environment & Water Research Institute, Energy Research Institute @ NTU, and Institute on Asian Consumer Insight.

A leader in sustainability research, the university has won significant competitive research funding in this area since 2005.

NTU's scientific pioneers

Led by Professor Bertil Andersson, a world-renowned biochemist and recipient of Austria's prestigious Wilhelm Exner Medal, NTU has built on its strong foundations in engineering and technology laid by some of Singapore's pioneer scientists. These include NTU Provost Professor Freddy Boey, Chief of Staff and Vice President (Research) Professor Lam Khin Yong and former NTU Presidents Professor Su Guaning and Cham Tao Soon.

Among the internationally acclaimed scientists at NTU today are eminent geologist Professor Kerry Sieh, leading molecular biologist Professor Stephan Schuster, renowned microbiologist Professor Staffan Kjelleberg, top structural biologist Professor Daniela Rhodes FRS, global immunology expert Professor Philip Ingham FRS and materials science specialist Professor Zhang Hua, ranked by Thomson Reuters among the top 17 most impactful scientists in the world.

NTU continues to attract some of the best and brightest young researchers through the National Research Foundation's elite young investigator scheme and NTU's own premier young faculty recruitment scheme, the Nanyang Assistant Professorship.

A globally-connected university

NTU has more than 400 international partnerships. Its joint medical school is set up with Imperial College London and is addressing critical health challenges in Singapore and beyond through innovative medical education and cutting-edge clinical and translational research. The university's premier Renaissance Engineering Programme for top students offers a global curriculum that includes studies at University of California, Berkeley, or Imperial College London, and internships at Silicon Valley or in Europe.

In electromobility research, NTU has partnered Germany's Technical University of Munich (TUM) to set up the TUM-CREATE Centre for Electromobility and has also established the Future Mobility Research Lab with the BMW Group.

Through tie-ups with industry giants such as Rolls-Royce, Lockheed Martin and ST Engineering, NTU translates the latest research breakthroughs into useful applications. Its joint laboratories with major industry players on campus move high-tech solutions out of the lab and into the real world, to create real economic and social impact.

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