CS5027: Fifty Discoveries, Fifty Inventions

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Preface

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Part I

PART 1: LECTURES

1 Science, Mathematics, and Technology

This week's contents focuses on Singapore's history with regards to its scientific and technological advancements.

1.1 Singapore's Past

> "A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill."
>
> – Bush, 1945

When Singapore separated from Malaysia, its focus was put on survival as it was a nation with no natural resources. One such tool that would enable Singapore to survive was through Science: a necessary pre-requisite for industrial and technological advancement.

In February 1966, Deputy Prime Minister Toh Chin Chye[1] announced a proposal for forming a new statutory board: the **Science Council of Singapore**.

1.1.1 Science Council of Singapore (i.e., SCS)

This board was established in 1967 - the board would make reports and suggest recommendations on:

1. Scientific and technological research and developments.
2. Effective training and utilization of scientific and technological manpower in Singapore.
3. Establishing official relations with other scientific organizations.

In 1968, the board suggested establishing a science center in Singapore - this was suggested to the Minister of Science and Technology.

Shortly after, a special committee was appointed to come up with the preparatory work and submit proposals for setting up the center - this committee included:

1. A chairman: Ronald Sng Ewe Min

[1] He was a Physiologist and a Vice Chancellor of the University of Singapore.

2. Three members:

    1. Sng Yew Chong
    2. Rex Anthony Shelley
    3. Bernard Tan Tiong Gie

1.1.1.1 Science and Industry Quiz (i.e., SIQ)

The SCS thought that one way to popularize science and technology over the television would be to combine education with entertainment.

Secondary school students would form teams and participate in the SIQ. Each team would have four members: two members would participate in the quiz programme and the other two on standby.

There are two rounds to the SIQ:

1. **Preliminary Round**

    All competing teams had two sets of question papers: Set A and Set B.

    Set A had 100 questions; Set B had 50 questions. Each team had 15 minutes to answer both sets.

    The first preliminary round was held at the Raffles Institution Hall on 28 July, 1972. 54 Teams competed, but only 12 were selected for the Televised Series.

2. **Televised Series**

    There were three stages - the four Quarter Finals, two Semi-Finals, and a Final.

    Each of the televised series had four rounds. The first round was where each team would have a fixed amount of time to answer as many questions as they could.

    The second round consisted of questions being asked to each individual of a team. The question had to be answered within a minute and with no assistance.

    Round three posed a question to all team members - the team had to answer the question unanimously. The six questions posed in this round enabled problem-solving and teamwork skills.

    The fourth final round was a buzzer-style question triva session.

1.1.1.2 The Innovators

In 1979, the SIQ was replaced by The Innovators.

The Innovators was a series of six programs where JC[2] students would work with Radio Television Singapura producers to produce television programs that had a scientific or technological theme, but focused on innovation.

The top three programs included:

1. "…And Life Goes On"
2. "Food Encounters"
3. "The Miracle Gene"

These three programs were selected by a panel of judges - the student producers were awarded prizes too.

1.1.1.3 Opening of the Science Center

> "While formal educational institutions make sure we are raising a nation of "science literate people", Science Centre Singapore takes this to the next level.
>
> We make science accessible and engaging, creating an environment where Singaporeans are empowered to advance their own learning and, hopefully, are inspired to do something incredible with their futures.
>
> Admission (just to the Science Centre) is $6 for adults and $4 for children."
>
> – Science Center's justification

The Science Center aimed to be a place where "Science befriends and transforms the minds of millions".

Figure 1.1: Entrance to Singapore's Science Center

It also aimed to promote interest, learning, and creativity in science and technology via imaginative and enjoyable experiences (that contribute to Singapore's human resources).

[2]**JC** is short for **J**unior **C**ollege!

1.1.1.3.1 Redeveloping the Science Center

> "Many people whom I have spoken to remember the Science Center fondly, and can even name specific exhibits that have inspired them. The new Science Centre gives us an opportunity to do even more – to help our young learn through play and fun, to inculcate a love and wonder for science and technology among Singaporeans and to kindle a passion for lifelong learning and inquiry."
>
> – Mr. Koh

The above was mentioned by Koh Boon Hwee during 12 November, 2014.

1.1.2 National Science and Technology Board (i.e., NSTB)

This was formed in October 1990 (after the passing of the bill); and the enactment of the Science and Technology Board act the following month.

The NSTB was a statutory board under the **M**inistry of **T**rade & **I**ndustry (i.e., **MTI**).

The NSTB developed Singapore into a center of excellence in certain fields of science and technology to enhance national competitiveness in industrial and service sectors (i.e., industry-driven research and development).

1.1.2.1 A*STAR

On 5 January 2002, the NSTB was reorganized and renamed to the Agency for Science, Technology and Research (i.e., A*STAR).

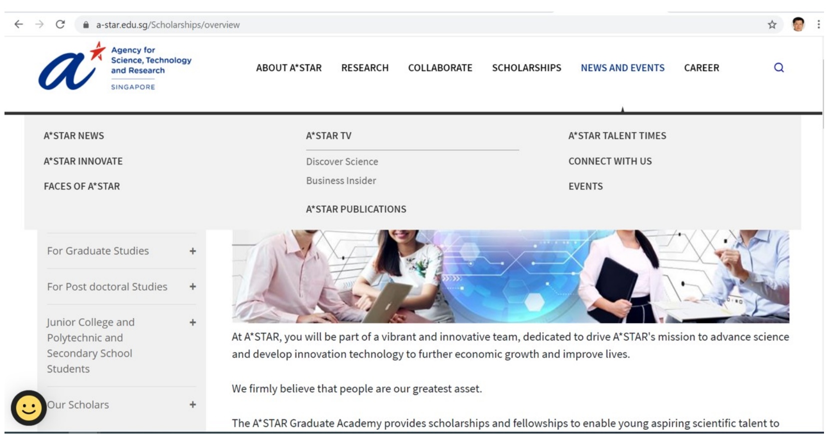

Figure 1.2: A*STAR's Homepage

A*STAR aimed to promote mission-oriented research that advances scientific discovery and technological innovations.

The agency got a portion of the national science and technology's budget as a show of support. Its facilities are currently located at Biopolis and Fusionopolis (at one-north).

1.1.2.1.1 A*STAR's Mission

A*STAR aims to develop Singapore's science, technology, and engineering capabilities to boost Singapore's economic growth via the three ways:

1. Developing the manpower required for the science and technology sectors.
2. Pioneering research and development to drive innovation and enhance the Singapore's knowledge-based economy.
3. Monetizing results in research and development.

Regarding the final point, A*STAR's commercialization arm manages its intellectual property and also helps apply its research to industry.

1.1.3 Lee Kong Chian Natural History Museum (i.e., LKCNHM)

The LKCNHM - formerly known as the **R**affles **M**useum of **B**iodiversity **R**esearch (i.e., **RMBR**) - was opened on 18 April, 2015 by Dr. Tony Tan Keng Yun: the president and chancellor of the National University of Singapore.

The museum strives to be a leader in Southeast Asian biodiversity in research, education, and outreach.

Mrs. Della Lee[3] donated enough money to enable LKCNHM to purchase three dinosaur skeletons.

1.1.4 NUS High School of Mathematics and Science

The school's mission was to shape the future of education in mathematics and science by producing future-ready pioneers, humanitarians, and innovators for the world.

The school's motto is: Experiment. Explore. Excel.

[3] She was Lee Seng Gee's - the Lee Foundation's chairman - wife.

1.1.5 Singapore National Academy of Sciences (i.e., SNAS)

In 31 July, 1967, scientists collectively formed the SNAS - a scholarly and professional body. The SNAS was meant to become the equivalent of the UK's Royal Society or the USA's National Academy of Sciences.

The SNAS was formed with the following objectives:

1. Promoting the advancement of science and technology in Singapore
2. Discussing scientific, technological, and macroeconomic problems (especially those that concern the nation)
3. Representing members' scientific opinions and fellows of the academy

1.2 Singapore's Return on Investment

This sub-section discusses some of Singapore's results with regards to its investment in science and technology.

1.2.1 Trends in International Mathematics and Science Study (i.e., TIMSS)

The TIMSS is developed and executed at the international level by the **I**nternational Association for the **E**valuation of Education **A**ssessment (i.e., **IEA**).

Rank (Grade 4)	Country	Average Score
1	Singapore	587
2	Chinese Taipei	557
3	Hong Kong SAR	554
4	Japan	548

Rank (Grade 8)	Country	Average Score
1	Singapore	567
2	Chinese Taipei	561
3	Japan	554
9	Hong Kong SAR	530

Figure 1.3: Singapore's TIMSS Results in Science

The TIMSS happens once every four years (the latest one was in 2019) - Singapore has partook in every study.

1.2.1.1 Scope of the TIMSS

The TIMSS gauges the mathematics and science knowledge of fourth and eighth graders (i.e., primary four and secondary 2 respectively). However, some countries only participate at the eighth-grade level.

The TIMSS allows for an international benchmark in three bands and along two dimensions - content and cognitive domains:

1. Average is higher than the US'
2. Average score is not measurably different from the US'
3. Average score is lower than the US'

Results may wildly differ between countries, but the reasons are attributed to students' attitudes, educational aspirations, school climates (e.g., violence in schools), school resources, and safety.

1.2.2 Programme for International Student Assessment (e.g., PISA)

The PISA is a study done once every three years and is run by the **O**rganization for the **E**conomic **C**ooperation and **D**evelopment (i.e., **OECD**).

Singapore's 15-year olds were ranked first in mathematics, science, and reading in 2015 (i.e., Singaporean students were the best in the world when it comes to working in teams to solve problems).

Hence, Singaporean students are very well equipped for the future's opportunities and challenges - they have a high ability to work well independently and together.

In 2018, Singapore came in second place in all three categories (China took first place).

1.2.3 Times Higher Education (i.e., THE) University Rankings

In 2019, NTU and NUS were ranked 51 and 23 on the THE world university rankings.

Subject	2019 Rank	2018 Rank	Institution
Architecture / Built Environment	8	10	NUS
Chemistry	7	7	NUS
Chemistry	9	11	NTU
Communication and Media Studies	8	12	NTU
Computer Science and Information Systems	10	10	NUS
Engineering – Chemical	7	9	NUS
Engineering – Civil and Structural	10	21	NTU

STEM in red

Figure 1.4: QS Rankings for NTU and NUS in 2019

The **Q**uacquarelli **S**ymonds (i.e., **QS**) rankings ranked NTU and NUS at 12 and 11 respectively - SMU was ranked at 500. Both NTU and NUS were ranked at 11 in the QS rankings in 2020 - SMU was at 477.

1.2.4 President's Science and Technology Award (i.e., PSTA)

The PSTA recognizes individuals with creative ideas who have made significant contributions to Singapore.

So far, over 60 men and women who have been singled out for this.

1.2.5 International Olympiads

This following sub sub-section lists Singapore's performances in the International Olympiads:

1. **Math**

59TH INTERNATIONAL MATHEMATICAL OLYMPIAD (IMO)

2. For starters, the Singapore team won **two Gold medals, three Silver medals and one Bronze medal** at the IMO held in Cluj-Napoca, Romania, from 3 to 14 July 2018. The IMO challenged students to apply high-level problem solving skills and present rigorous proofs to support their solutions. Singapore was placed 8th in a field of 107 countries/territories, featuring a total of 594 participants.

Gold medallists	• Ng Yu Peng, Hwa Chong Institution • Lee Ker Yang, Raffles Institution
Silver medallists	• Joel Tan Junyao, NUS High School of Mathematics and Science • Lucas Boo Tse Yang, Raffles Institution • Cheng Puhua, Raffles Institution
Bronze medallist	• Shi Cheng, Hwa Chong Institution
Led by	• Associate Professor Wong Yan Loi, Department of Mathematics, National University of Singapore • Mr Thomas Teo Teck Kian, Raffles Institution

Figure 1.5: Singapore's Performance in the International Math Olympiad (i.e., IMO)

The first math olympiad (i.e., IMO) was held in 1959 in Romania with 7 countries' participants. Over the years, 100 counries from five continents have participated.

The competition is overseen by the IMO board - they also ensure that each host country upholds the traditions of the IMO.

2. **Informatics**

30TH INTERNATIONAL OLYMPIAD IN INFORMATICS (IOI)

8. The Singapore team secured **1 Gold medal, 2 Silver medals and 1 Bronze** medal at the IOI held in Tsukuba, Ibaraki, Japan from 1 to 8 September 2018. During the competition, students faced challenging computational problems which tested their ability to design and implement efficient algorithms and data structures. Singapore was placed joint 9th in a field of 87 countries/territories with 341 participants.

Gold medallists	• Gabriel Goh Kheng Lin, NUS High School of Mathematics and Science
Silver medallists	• Jacob Teo Por Loong, NUS High School of Mathematics and Science • Jeffrey Lee Chun Hean, NUS High School of Mathematics and Science
Bronze medallists	• Teow Hua Jun, Hwa Chong Institution
Led by	• Dr Steven Halim, School of Computing, National University of Singapore • Dr Daren Ler Shan Wen, National Junior College

Figure 1.6: Singapore's Performance in the International Olympiads in Informatics (i.e, IOI)

The IOI is an annual competitive programming competition for secondary school students - the first IOI happened in 1989 in Pravetz, Bulgaria.

The contest consists of two days of computer programming and problem-solving in algorithms.

3. **Biology**

29TH INTERNATIONAL BIOLOGY OLYMPIAD (IBO)

3. The Singapore team also garnered **three Gold medals and one Silver medal** at the IBO held in Tehran, Iran, from 15 to 22 July 2018. The students went through a diverse range of Biological tasks, including the dissection and identification of the internal structure of the Persian leech, purification of a bacterial protein and investigation of the behaviour of fruit fly larvae. Singapore was placed joint 3rd in a field of 68 countries/territories, featuring 261 participants in all.

Gold medallists	• Shermane Lim Yun Wei, NUS High School of Mathematics and Science • Isaac Chan Xu Rui, Hwa Chong Institution • Justin Ng Wei Jun, Hwa Chong Institution
Silver medallist	• Ong Jia Xin, NUS High School of Mathematics and Science
Led by	• Dr Ng Ngan Kee, Department of Biological Sciences, National University of Singapore • Dr Chen Zhong and Dr Beverly Goh, National Institute of Education, Nanyang Technological University • Ms Lim Yan Ling, Singapore Institute of Biology • Mr Marcus Chan Boon Peng, Ministry of Education

Figure 1.7: Singapore's Performance in the International Biology Olympiad (i.e., IBO)

The IBO is a competition that tackles Biological problems and deals with Biological experiments (i.e., testing them). The IBO challenges and stimulates participants to expand their talents and to promote participants' careers as scientists.

4. **Chemistry**

50TH INTERNATIONAL CHEMISTRY OLYMPIAD (ICHO)

5. The Singapore team secured **two Gold medals and two Silver medals** at the IChO held in Bratislava, Slovakia and Prague, Czech Republic, from 19 to 29 July 2018. To commemorate the 50th anniversary of the IChO, students were provided with preparatory problems that exposed them to the Chemistry behind oscillating reactions. Singapore was placed 6th in a field of 76 countries/territories, boasting 300 participants in total.

Gold medallists	• Marvin Dragon Choo, NUS High School of Mathematics and Science • Fong Khi Yung, Raffles Institution
Silver medallists	• Lim Hur, Raffles Institution • Miao Jiapei, NUS High School of Mathematics and Science
Led by	• Dr Zhang Sheng, Department of Chemistry, National University of Singapore • Dr Tan Wee Boon, Department of Chemistry, National University of Singapore • Mr Marcus Yip, Anglo-Chinese Junior College • Mdm Ng Yu Rui, Ministry of Education

Figure 1.8: Singapore's Performance in the 30th International Chemistry Olympiad (i.e., IChO)

The IChO is an annual Chemistry for a nation's most talented high-schoolers. Nations send a team of four students who are tested on their Chemistry knowledge and skills in a five-hour laboratory practical and five-hour written theoretical examination that are both held on different days.

31ST INTERNATIONAL YOUNG PHYSICISTS' TOURNAMENT (IYPT)

4. Competing against 31 other countries/territories, the Singapore team emerged **overall champion** at this year's IYPT held in Beijing, China, from 19 to 26 July 2018. The IYPT is organised around "physics fights", that mimic discussions at research conferences, where participants present their research and provide constructive feedback on the work of other teams.

Team members	• Fu Xinghong, Raffles Institution • Jerry Han Jiatao, Raffles Institution • Hu Yongao, Raffles Institution • Liu Haixuan, Raffles Institution • Russell Yang Qi Xun, NUS High School of Mathematics and Science
Led by	• Dr Koh Teck Seng, School of Physics and Mathematical Sciences, Nanyang Technological University • Mrs Lim Siew Eng, Raffles Institution • Mr Chan Khai Mun, Ministry of Education

Figure 1.9: Singapore's Performance in the International Young Physicists' Tournament (i.e., IYPT)

5. **Young Physicists' Tournament**

   The IYPT (sometimes called the "Physics World Cup") is a team-oriented competition for secondary school students.

   Participants present their solutions to scientific problems they have prepared over several months and then discuss their solutions with other teams.

6. **Astronomy and Astrophysics (i.e., IOAA)**

   The IOAA promotes interest in astronomy and similar subjects by developing "international contacts" between different schools to promote Astronomy and Astrophysics in schools.

1.2.6 Singapore's Scientific Pioneers

The book shown above contains information on 25 individuals who laid foundations for Singapore's scientific achievements.

All of these scientists were born prior to Singapore's independence, but have made exceptional contributions to Singapore's engineering, medical, educational, and scientific sectors.

Some of these people include:

1. **Benjamin Henry Sheares**

   He was the father of Obstetrics and Gynaecology in Singapore. He has a procedure named after him and was one of the top graduates of the King Edward VII College of Medicine.

   He was also Singapore's second president - he also has a bridge named after him: the Benjamin Sheares Bridge (which is one of Singapore's most famous landmarks).

Figure 1.10: A Book on Singapore's Scientific Pioneers

2. **Shih Choong Fong**

   Shih was the president of NUS from 2000 to 2008 and also the founding president for King Abdullah University of Science and Technology (i.e., KAUST) in from 2008 to 2013.

   Shih got a PhD from Harvard in 1973 and led the Fracture Research Group at the GE Corporate Research Lab in the US. In 1981, he joined Brown University. He was appointed University Professor by NUS in 2013 and was inducted into the Honorary Membership by NUSS in 2001.

3. **Tay Eng Soon**

   Soon was more well-known as a politician. He was a minister of state in the Ministry of Education from 1980 until he died in 1993.

   Soon worked hard to develop polytechnics and ITEs.

   His speciality was in nuclear energy and nuclear power.

Figure 1.11: The Shears Bridge in Singapore

1.3 What is Science?

> "Science is a voyage of intellectual exploration, and an expression of the human spirit."
>
> – Henry Stommel, 1989

In 1834, William Whewell[4] (1794 - 1866) coined the term "scientist"[5].

He was also the master of of Trinity College at Cambridge; he was also a founding member and a president of the British Association for the Advancement of Science.

1.3.1 Scientific Worldview

The world is seen as such by a scientist:

1. The world is understandable
2. Scientific ideas can change
3. Scientific knowledge is everlasting
4. Science cannot answer everything
5. Science is an enterprise

Science is a blend of logic and imagination - logic is used to understand why things happen while one's creativity is used to recognize the meaning of something unexpected.

1.3.1.1 The World is Understandable

Stuff that happens in this world have a consistent pattern that can be seen through close observation.

By using one's intellect along with instruments, people can find all sorts of patterns.

The universe is a system where the basic rules are the same.

1.3.1.2 Scientific Ideas can Change

New observations can challenge existing theories, in which case, new theories may be needed to explain the observation.

Science is humanity's attempt at explaining how the universe works.

Testing, improving, and discarding theories is an ongoing process in Science.

[4]He was a philosopher of science and a Cambridge University historian

[5]Prior to this term, scientists were known as "men of science" or "natural philosophers"

1.3.1.3 Scientific Knowledge is Everlasting

Modifying ideas (instead of rejecting them) is a norm in science. Powerful constructs survive and grow more precise so that they are more widely accepted.

Einstein did not reject the Newtonian law of motion, but only showed them to be a limited application with a more general concept.

1.3.1.4 Science Cannot Answer Everything

Many beliefs fall into this category (e.g., supernatural forces, true purpose of life, etc).

In some cases, science may even be seen as irrelevant by people hwo have certain beliefs (e.g., fortune tellers)

1.3.1.5 Science is an Enterprise

Science is a complex, social activity that involves many individuals of many backgrounds.

Scientific research is also competitive in that researchers compete for funding - committees meet up to decide which topic(s) should be focused on.

1.3.2 Components of Science

Science has certain elements:

1.3.2.1 Scientific Enquiry

Science demands evidence; scientists focus on collecting accurate data (which are verified by others).

1.3.2.2 Making Observations

To make observations, scientists must use:

1. Their five senses
2. Instruments that enhance those senses
3. Instruments that go beyond the human senses

1.3.2.3 Attitudes

Scientists need to be willing to work hard, to have courage, and to embrace openness (i.e., be willing to change).

1.3.3 Ways of Observation

Scientists…

1. Observe passively (i.e., watch things happen without interefering)
2. Make collections (i.e., collecting samples)
3. Actively probe the world (e.g., conducting clinical trials, etc).

Otherwise, they also…

1. **Explain and Predict**

   Scientists use observations to construct explanations for them.

   These hypotheses should also fit additional observations.

2. **Identify and Avoid Bias**

   Scientific evidence can be biased in how scientists choose to report those facts (or the kind of data collected to begin with).

   A scientist's nationality, sex, age, and other factors may cause them to look for one kind of evidence or interpretation.

   A possible safeguard against this is to have many different people involved working on the same problem.

3. **Realize that nobody is omniscient (i.e., all-knowing)**

   No scientist had the right to decide for themselves what is "true".

   Scientist whose observations do not align with mainstream ideas may encounter vigorous criticisms - these scientists may also have difficulty garnering support for their research.

1.3.4 Creative-Failure Methodology

> "A basic truth that the history of the creation of the transistor reveals is that the foundations of transistor electronics were created by making errors and following hunches that failed to give what was expected."
>
> – William Shockley

William Shockley - inventor of the transistor - started with a concept of the tubeless radio and used trial and error to make his invention.

1.3.5 Communication and Organization in Science

Science can be communicated in a variety of ways, some of which include:

1. **Communicating with the Public**

   Science is too important for the public to stay in the lab.

   Many scientists too feel a need to inform the public about potentially dangerous misconceptions or to counter misinformation from numerous quarters.

Science is also organized into content disciplines - it is a collection of scientific fields (that provide a foundation of research).

Different fields in science also spill into one another (e.g., Biochemistry, Biophysics, etc).

1.3.6 A "Right" Way to Perform Science

There are ethical principles to conducting science - competition has led to unethical practices such as:

1. **Scientists withholding information and falsifying findings**

   These violations damage science, the scientific community, and the funding agencies.

2. **Treating live subjects**

   For instance, human subjects should only be used for a study if they consent to it. Part of this also means disclosing the risks and intended benefits of research.

3. **Scientists as Experts and Advisors**

   Scientists partake in public affairs as specialists and as citizens.

   Scientists help the public and its representatives to help understand what most likely happened.

1.3.7 Why is Science so Important?

Science is so important (and specialised) that the President of the United States has a 25-member panel, known as the "National Science Board" to serve as advisors to him and the Congress on policy matters related to science and engineering, and education in both fields.

The National Science Board has its members drawn from industry and academia. Vannevar Bush was the first Presidential Science Advisor, and also head of the Office of Scientific Research and Development (OSRD). He oversaw most of America's scientific research during World War II.

1.3.8 Science in Courtrooms

An increasing number of legal disputes involve the principles and tools of science. Properly resolving those disputes matters not just to the litigants, but also to the general public – those who live in our technologically complex society and whom the law must serve.

The decisions of the judges should reflect a proper scientific and technical understanding so that the law can respond to the needs of the public

1.4 Mathematics and Science

Mathematics is the science of patterns and relationships For some, especially professional mathematicians, the essence of mathematics lies in its beauty and its intellectual challenge these people talk about "elegant" solutions to mathematical problems

For scientists and engineers, the value of mathematics lie in its ability to solve problems that originate in the world of experience

Mathematics also find application in "non-technical", fields, e.g., business, music, politics, sports, and social sciences

1.5 Technology

Technology extends our abilities to change the world: to cut, shape, or put together materials; to reach farther with our hands, voices, and senses.

We use technology to try to change the world to suite us better The changes may relate to survival needs such as food, shelter, or defense, or they may relate to human aspirations such as knowledge, art, or control.

But the results of changing the world are often complicated and unpredictable.

They can include unexpected benefits, costs, or risks.

1.5.1 Is it Practical?

Engineering combines scientific enquiry and practical values In its broadest sense, engineering consists of construing a problem and designing a solution for it.

Engineering shares many characteristics with science, but engineering affects the social system and culture more directly than scientific research.

1.5.1.1 There is No Perfect Design

There is no perfect design as accommodating one constraint leads to conflict with another.

All technologies involve control, e.g., in an iron (or an air-conditioned room, or a rice cooker), the temperature is controlled within a preset range.

Control typically requires feedback, logical comparisons, and a means for activating change

1.5.1.2 Side Effects

Technologies have side effects   what is one side effect of X-ray? personal computers? mobile phones? the Internet? photocopy machines? the automobile? social media?

Systematic risk analysis is used to minimise the impact of side effects (e.g., the side effect of X-ray is cancer)

There may also be unintended benefits / consequences:

1. **Suntan lotion**

   The main ingredient, titanium dioxide, mixed with water, results in hydrogen peroxide. This kills phytoplankton that nourishes fish and ultimately poisons the rest of the food chain.

Technology can also fail too (e.g., crashing of the space shuttle).

1.5.2 Issues in Technology

Issues have also emerged   overuse of fossil fuels, pollution, global warming, new bacterial strains that are resistant to antibiotics, digital divide, deforestation, extinction of plants and animals, strain on the soil and water systems, and more.

1.5.2.1 Pseudoscience

In prescientific times, any attempt to harness nature mean forcing nature against her will, Nature had to be subjugated, usually with some form of magic, or by means that were “above” nature – that is, supernatural.

Science does the exact opposite, it works “within” nature’s laws. The methods of science have largely displaced reliance on the supernatural.

The old ways persist, full force in primitive cultures, and they survive in technologically advanced societies too, usually disguised as science.

1.5.2.1.1 No Science! Column

In his book, Flim-Flam!, James Randi reported that more than 20,000 practising astrologers in the United States serve millions of credulous believers.

Science writer Martin Gardner reports that a greater percentage of Americans today believe in astrology and occult phenomena than did citizens of medieval Europe.

Few newspapers print a daily science column, but nearly all provide daily horoscopes.

1.5.2.2 Science Denialism

> Denialism refers to “the employment of rhetorical arguments to give the appearance of legitimate debate where there is none, an approach that has the ultimate goal of rejecting a proposition on which a scientific consensus exists”.
>
> – CS5027 Course Material

Mbeki Aids denial 'caused 300,000 deaths'

South African president's refusal to accept medical evidence of virus was major obstacle to providing medicine, say Harvard researchers

Figure 1.12: A Consequence of Thabo Mbeki’s Science Denialism

Thabo Mbeki’s (the second president of South Africa) denial of science has led to the deaths of many people.

2 The Innovation Process

This week's lecture focuses on the following pieces of content:

1. Stoke's research quadrants
2. Cha-cha-cha theory of scientific studies
3. Types of innovation
4. Characteristics of innovation
5. Seven sources of innovation
6. Innovation case studies

2.1 Stoke's Research Quadrants

Research is the main way by which knowledge is produced.

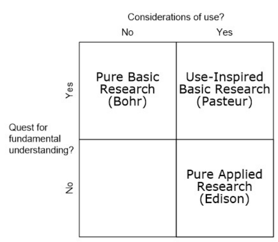

Figure 2.1: Stokes' Model of Research Quadrants

Stokes' 1997 model of research quadrants can be used to justify the kind of research that scientists conduct. A scientist is used to represent a particular kind of research[1].

2.1.1 Bohr's Quadrant

Research here is done for the sake of discovery (i.e., for knowledge purposes).

There is no attention to the research's practicality

[1]The bottom left quadrant has no scientist - that kind of research is non-existent.

2.1.2 Edison's Quadrant

> "Edison never allowed himself or those working with him in Menlo Park five minutes to consider the underlying side of the significance of what they were discovering in their headlong rush toward commercial illumination.
>
> The value and even the mark of true science consists, in my opinion, in the useful inventions which can be derived from it."
>
> – Gottfried Wilhelm Leibniz

Research in this quadrant is done for the sake of applications. When Thomas Edison invented the light bulb, he wasn't interested in the science behind the device, but the potential applications and revenue that could be generated from the light bulb.

2.1.3 Pasteur's Quadrant

This quadrant was a mix of both Bohr's and Edison's quadrants: research in this quadrant was a mix of both practical applications and discovering new knowledge.

Pasteur not only studied the disease that was ruining southern France's silkworm industry, but also anthrax, rabies, and fermentation and brewing in the beer industry.

2.2 Cha-Cha-Cha Theory

This theory states that scientific discoveries can be categorized into three types: **cha**rge, **cha**llenge, and **cha**nge.

CATEGORIES OF DISCOVERY

Problem that needed solving	Discovery	Discoverer	Category of discovery
Movement of stars, Earth, and Sun	Gravity	Newton	Charge
Structure of C_6H_6	Benzene structure	Kekulé	Challenge
Clear spots on petri dish	Penicillin	Fleming	Chance
Constant speed of light	Special relativity	Einstein	Challenge
Preventing heart attacks	Cholesterol metabolism	Brown & Goldstein	Charge
Crystals of D- and -L tartaric acid	Optical activity	Pasteur	Chance
Atomic spectra that could not be explained	Quantum mechanical atom	Bohr	Challenge
How DNA replicates and passes on coding	Base pairing in double helix	Watson & Crick	Challenge
Reagent "stuck" in storage cylinder	Teflon	Plunkett	Chance
Why offspring look like their parents	Laws of heredity	Mendel	Charge

Figure 2.2: Examples of Charge, Challenge, and Chance Discoveries

Charge solves problems that are obvious (e.g., cure malaria), but whose solutions must be seen from a novsel perspective.

Challenge discoveries are discoveries that arise from an accumulation of facts that cannot be explained by current science. A new concept or theory may be needed to explain the discovery.

Chance discoveries are discoveries that arise out of chance (e.g., Pasteur's discovery of optical isomers).

2.3 Types of Innovation

> "Innovation distinguishes between a leader and a follower."
>
> – Steve Jobs

> "Leave the beaten track occasionally and dive into the woods. Every time you do so you will be certain to find something that you have never seen before."
>
> – Bell Labs' Motto

An **innovation** is a series of activities that begin when an idea is conceived. This idea then undergoes a series of research, development, engineering, design, market analysis, management decision making, and so on before ending at product realization.

Innovations are like creations and exploitations of new flowers.

> "Innovations, like flowers, start from tiny seeds and have to be nurtured carefully until they blossom, then their essence has to be carried elsewhere for the flowers to spread.
>
> Innovations can grow wild, springing up weed-like despite unfavourable circumstances.
>
> And some conditions - soil, climate, fertilizer, the layout of the garden - produce larger and more abundant flowers."
>
> – Professor himself

Innovations can be broadly divided into several categories:

1. **Product Innovations**

   This is the introduction of a good or a service that is new or is significantly improved in some way (i.e., technical specifications, components and materials, incorporated software, user friendliness, or other functional characteristics).

   Such innovations can be based on new ideas and technologies (or a combination of existing and new ideas and technologies).

2. **Process Innovations**

   These are the implementation of a new or significantly improved production or delivery method (which often includes changes in techniques, equipment, and / or software).

   Such innovations are often made to decrease unit costs, to increase quality, or to produce or deliver significantly improved products.

   These innovations also deal with the steps in making a product.

3. **Service Innovations**

Figure 2.3: Service Kiosks at McDonalds'

   These are intangible methods of serving users at a new level of performance - for instance, new service concepts.

4. **Radical Innovations**

Figure 2.4: The MP3 Logo

   These are big and major changes in products.

   The MP3 audio system is one major example. Prior to the invention of MP3, music was listened to communally.

5. **Incremental Innovations**

   These apply existing knowledge to improve products.

Figure 2.5: Transition from Mentos Mint Candy to Mentos Caramels

2.3.1 Innovation as Work

Innovation is the work of knowing, not doing. It's also an effort to purposeful, forced change in an enterprise's economic or social position.

> "I am not pleading with you to make changes. I am telling you you have got to make them – not because I say so, but because old Father Time will take care of you if you don't change. Advancing waves of other people's progress sweep over the unchanging man and wash him out. Consequently, you need to organise a department of systematic change-making."
>
> – Charles F. Kettering

Innovation requires knowledge, ingenuity, and boldness. If a person lacks persistence and commitment, then talent, knowledge, and ingenuity will not be useful.

> "Businessmen go down with their businesses because they like the old way so well they cannot bring themselves to change. One sees them all about - men who do not know that yesterday is past, and who woke up this morning with their last year's ideas."
>
> – Henry Ford

Innovation is a specific function of entrepreneurship, whether that be in the form of an existing business, a public service institution, or a new venture started by an individual.

2.3.2 Characteristics of Innovation

Kanter (1998) suggested the following traits of most, if not all innovations:

1. **Uncertainty**

   Sources of innovation may be unpredictable - the goal of innovation may have little to base itself off of.

   Innovations make progress in spurts in unforseen moments.

2. **A Long Journey**

   The costs of innovation may overrun and the results are highly uncertain.

   Analysts have estimated that it may take years for a business to see any returns on their innovations.

3. **Knowledge-Intensive**

   The innovation process generates new knowledge and in doing so, uses human intelligence and creativity. This learning curve is steep.

   Efforts during innovation are vulnerable to leaving because of the loss of knowledge and experience (i.e.,

4. **Controversial**

   Innovations are always competitive - they provide an alternative course of action.

   On several occassions, an innovation may be a threat to peoples' interests (whether that "interest" be a salesperson receiving high commissions or whatnot).

   Political problems are often the primary cause for the failure of new venture departments in corporations.

5. **Imperialistic**

   An innovation is also capable of crossing boundaries.

   There is also evidence that the best ideas or interdisciplinary (i.e., they benefit from broader perspectives and from information outside of the idea responsible for the innovation).

2.3.3 Example #1: Scrabble

In 1931, Alfred Mosher Butts was a young, out-of-work architect who was seeking a means of making money.

Butts was interested in anagrams and crossword puzzles (i.e., his source of inspiration) - after further analysis, he found that games of his generation fell into one of three categories:

1. Number-based games
2. Move-based games
3. Word-based games

Figure 2.6: People Playing Scrabble

He eventually created a game that used a grid and words. Butts wanted his game to have both skill and luck (with a stronger emphasis on skill). Butts also realized that of the 26 characters in the alphabet, that not all of them were used frequently.

To find out the relative frequencies, he painstakingly studied the front pages of the New York Times, doing letter-by-letter counts (i.e., innovation is knowledge-intensive).

This enabled Butts to assign values to each letter in his game.

From 1932 to 1938, Butts made the sets by hand and gave them to friends; most game manufacturers in the US turned down Butts' idea.

In 1943, Butts met marketing genius James Brunot - Brunot made some refinements to Butts' game.

Eventually, Brunot and his wife made an agreement with Selchow & Righter, a much more established game manufacturer to make the game (as Brunot could not keep up with game production himself).

Figure 2.7: The Irish Scrabble Association

By 1954, more than 4 million sets of the game had been sold; the game was also available in other languages (e.g., Spanish, Italian, French, etc).

In 1972, Selchow & Righter purchased the game and trademarked "Scrabble".

Hasbro now supports the National Scrabble Association (It was formerly Coleco, but they went bankrupt).

2.3.4 Example #2: Barbie Dolls

Figure 2.8: A Barbie Doll Holding a Plastic Video Recorder

In 1956, American businesswoman Ruth Handler was vacationing in Switzerland until she came across Bild Lilli: a prostitute doll with long legs and heavy makeup.

The first barbie doll came out in 1959.

2.4 Sources of Innovation

There are *seven* sources, some of which are inside or outside a company:

2.4.1 Inside a Company

These include:

Figure 2.9: A Bild Lilli Doll

Figure 2.10: A Stack of Post-it Notes

1. **Unexpected**

   Spencer Silver was trying to create a super strong adhesive, but instead discovered a weak adhesive that sticks to paper and can be lifted off without tearing the paper

   Silver told his colleague Art Fry about the new adhesive.

   Fry was singing in a church choir and had bookmarked his hymnal with little pieces of paper but when it was time to sing until they fell out. Fry thought that Silver's adhesive would be the ticket for a better bookmark.

   Fry went to work the next day, ordered a sample of the adhesive and began coating it on paper, carefully coating only the edge of the paper so that the part protruding from his hymnal wouldn't be sticky. Fry also realized that the bookmark could also be a note.

   In 1978, 3Mers descended on Boise, Idaho, with samples for what would later be called the "Boise Blitz". Boise was selected because it wasn't too big a city.

   Samples were handed out, and 3M discovered that more than 90% of the people who tried them would buy them.

   At the request of 3M marketers, Shirley Tholander (secretary to Lew Lehr, chairman of the 3M board) sent a letter to her executive secretary peers at Fortune 100 companies and enclosed a product sample.

2. **Incongruities**

   An **Incongruity** is an incompability - something that appears very different to the point of change.

   In 1912, Charles Franklin Kettering invented the electric starter.

   Before the electric starter, this boost was provided by a crank at the front of the car. Women and men of smaller stature had trouble working the crank without help. In addition, the crank was dangerous to operate, and some drivers were injured while cranking the car – this became a source of innovation.

   The impetus for the electric starter came from a realisation of the incongruity between the demographics of car buyers versus the demographic composition of the world at large.

   Without an easy way to start the car, car manufacturers were only selling to half[2] the population!

3. **Process Needs**

   SBS Transit's Iris NextBus and PostBox are good examples.

[2]The world has 50% men and 50% women.

4. **Industry Market and Structures**

   Industry structures can change, creating tremendous opportunities for innovation.

   In the past, photographic film needed to be "processed" in a dark room.

   In the digital world, processing can be self-serviced.

2.4.2 Outside a Company

These include:

1. **Demographic Changes**

   The graying of many societies is a demographic change that is looming.

   One impact of this will be the increasing need for robots to do routine housework (and so on).

2. **Changes in Public Perception**

   Cirque du Soleil (i.e., **CdS**) capitalised on the changes in public perception on the use of animals in circuses (in addition, the cost of the animals and their training, medical care, housing, insurance, and transportation was very high).

   Traditional circus shows have a series of unrelated acts, but each Cirque du Soleil creation has a theme and story line, somewhat resembling a theater performance.

3. **New Knowledge and Scientific Discoveries**

   There is a protracted time span between the emergence of new knowledge and its distillation into usable technology.

   Then there is another long period before this new technology appears in the marketplace in products, processes or services.

   To become effective, innovation of this sort demands not one kind of knowledge but

2.5 Innovation Case Study #1: Shipping Containers

The shipping container was invented by Malcolm Purcell McLean. MacLean was also responsible for founding pan-Atlantic services.

Figure 2.11: A Shipping Container

2.5.1 Prior to the Shipping Container's Fruition

Armies of ill-paid and ill-treated workers called **longshoremen** would help unload and load supplies onto merchant ships. The whole (un)loading process would take a day - shipping costs were hence expensive (i.e., a four-thousand mile voyage for a shipment might consume about 50% of its costs for just two ten-mile movements).

> "In the first forty months of World War II, the U-boats sank 2,177 merchant ships totalling 11,045,284 tons, while the number of merchant ships lost to all other causes was negligible in comparison."
>
> – Syrett, 1993, page 1.

Many German "U-boats" (i.e., submarines) also sank many merchant ships during the Battle of the Atlantic.

In response to this, the US navy built more than 2400 "liberty ships" between 1941 and 1945. These ships were small enough to avoid being sunk so that little cargo would be lost if the ship was sunk.

After the war, the US navy sold about 450 "liberty ships" to their merchant lines. However, these "liberty ships" were cramped and had odd dimensions - longshoremen needed to figure out how to fit cargo in these conditions. These "liberty ships" wasted time and money from the shipowners' perspectives.

2.5.1.1 More About Longshoremen

Longshoremen were individuals who saw themselve as tough, independent men who were doing a tough job. They had reputations as brawlers and drinkers.

The work that they did was brutal and physically dangerous, so much so that there were many injuries, and in some cases, fatalities.

Figure 2.12: Longshoremen Loading Bananas onto a Merchant Ship

Longshoremen would also work in all sorts of weather conditions and would also compete among themselves for work. This entire process meant kickbacks, flattery, and begging. Because of this, their income was irregular and longshoremen would be loyal to their co-workers, not the company that they were working for.

Strikes were also frequent due to poor pay and poor working conditions. In Britain alone, these strikes led to 1 million man-days lost between 1948 to 1951 and another 1.3 million in 1954. These strikes also led to two major problems:

1. Pilfering: longshoremen would end up stealing the cargo that they were supposed to load.
2. Resistance to anything that might eliminate jobs.

2.5.2 McLean's Background and Starting His Own Trucking Company

MacLean was born in Maxton, North Carolina. His mother first taught him how to do business by giving him eggs to sell on commission.

McLean graduated from high school in 1931 and started working at a grocery store to stock shelves. He eventually became the manager of a gas station in a nearby town.

McLean learned that drivers were being paid $5 an hour just to transport gas to the station.

2.5.2.1 McLean Trucking Company

In March 1934, McLean started the McLean Trucking Company. In 1935, he started off with two trucks and a truck trailer. He also employed nine truck drivers who owned their own rigs.

In 1940, he owned about 30 trucks and grossed about $230,000.

In 1945, he owned 162 trucks and in 1946, made a revenue of about $2.2 million.

In 1953, McLean noticed that the highways were becoming increasingly congested. He was also concerned that domestic ship lines were allowed to buy war-surplus cargo ships for a low price from the government.

In September 1955, McLean sold off his trucking company for about $14 million!

Figure 2.13: An Image of the Ideal-X

2.5.3 McLean's First Container Ship

On 26 April, 1956, 58 aluminium truck bodies were loaded aboard an ageing tanker **Ideal-X** that was moored in Newark, New Jersey. Ideal-X then sailed into Houston.

On 1 April, 1964, the **P**ort of **S**ingapore **A**uthority (i.e., **PSA**) was formed to take over the functions, the assets, and the liabilities of the Singapore harbor board.

2.5.3.1 What is a Shipping Container?

A **shipping container** is an aluminum or a steel box that held up by rivets and welds - it has a wooden floor and two enormous doors at both ends.

The container cheapened transportation costs; it was also a part of a highly efficient and seamless system for shipping cargo across the world.

The container could also be loaded onto the Ideal-X in seven minutes (i.e., using a crane). The railroad and trucking business attempted to compete with McLean's shipping containers. Between April and December, 44 voyages were created; consequently, the tanker's capacity increased from 58 to 60 containers (before it increased to 62 containers).

2.5.4 New York's Decline

McLean's containers made New York ports obsolete. During the 1920s, the trucking industry had already made New York's ports obsolete.

In 1952, traffic leading to piers was so bad that pier-bound vehicles were banned from the Twelfth Avenue.

2.5.5 Social Impact of Shipping Containers

When the industry fled New York, the number of manufacturing jobs fell.

The Brooklyn Navy Yard closed in 1966, and Brooklyn residents abandoned the borough in droves. Brooklyn's population fell by 14% between 1971 and 1980.

Figure 2.14: A Group of People on Segways

2.6 Innovation Case Study #2: Segways

Kamen (i.e., the inventor of the segway) was at a local mall and was watching a man struggle to get his wheelchair over a curb. He was disturbed by what he saw. He thought: “we can put people on the moon and travel to the depths of the ocean, but we cannot get a wheelchair over a curb?”

The more he thought about the limitations faced by people in wheelchairs - no eye-level conversations, no trips to the beach or anywhere else without sidewalks, no reaching the top shelf at the grocery, no possibility of defeating the absolute barrier of stairs - the more he became offended as an engineer

2.6.1 Kamen’s Invention

Figure 2.15: The iBOT Project Started by Kamen

Fred-iBOT was a wheelchair that could roll through gravel and sand, go up curbs, and even climb stairs. It would change the lives of many.

The project was funded by Johnson & Johnson, but did not take off likely due to cost issues.

2.6.2 About Dean Kamen

He was born in Rockville Center, Long Island, New York, in 1951. He attended college at Worcester Polytechnic Institute in Massachusetts.

He also owned a business, Independent Prototype, and did a project for Cordis, a medical company, through which he met the founder, William Murphy. He made about $60,000 a year

Bart, a medical student at Harvard, suggested that he work on a drug-infusion pump.

From there, Kamen started a new company - AutoSyringe - where he designed the first portable insulin pump (which freed diabetics from their condition's limitations).

2.6.2.1 Starting a Family Business

Kamen's brother, Mitch and Mitch's friends became assemblers for the pump.

His mother tested circuit boards and kept the books.

His father drew the illustrations for the manual.

He enlisted the help of Worcester Polytechnic's students and professors to help him improve the design of his inventions.

Kamen also moved to New Hampshire to evade New York's high taxes.

Eventually, Kamen would sell the pump to Baxter Healthcare for about $30 million in 1982 (when Kamen was 31 years old).

Kamen would then go onto buy an airplane, a helicopter, and an island in Long Island Sound. He then founded his own R&D company DEKA (i.e., short for DEan KAmen).

Kamen's first spinoff company Teletrol installed climate control systems for large industrial and commercial buildings

2.6.3 Kamen's Attitude Regarding Failure

> "In study after study, of composers, basketball players, fiction writers, ice-skaters, concert pianists, chess players, master criminals," writes the neurologist Daniel Levitin, "this number comes up again and again.
>
> Ten thousand hours is equivalent to roughly three hours a day, or 20 hours a week, of practice over 10 years .... No one has yet found a case in which true world-class expertise was accomplished in less time. It seems that it takes the brain this long to assimilate all that it needs to know to achieve true mastery."
>
> – Dean Kamen

In 1987, Baxter Healthcare approached Kamen to improve its kidney dialysis machine - it was noisy, expensive, heavy (180 lb) and bulky!

Kamen urged his engineers not to limit themselves to what they thought was feasible, and he did not hold failures against his engineers if they learned something along the way.

His philosophy was that no experiments was useless.

2.7 Innovation Case Study #3: Bonsack Machine

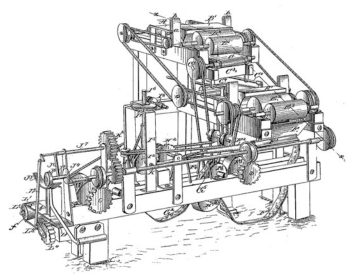

Figure 2.16: A Sketch of a Bonsack Machine

During 1876, **A**llen and **G**inter (i.e., **A&G**) were employing hundreds of girls as rollers. This was a problem as not only was it difficult to oversee such a vast amount of workers, but there would also be inconsistencies with the quality of labor.

A&G then offered a price of $75000 to anybody who could invent an automatic cigarette rolling machine.

2.7.1 James Albert Bonsack

On September 4, 1880, Bonsack - a teenager tinkerer - got a patent for his invention. His machine could turn out about 200 to 212 cigarettes per minute (roughly 40 to 50 workers' output).

2.7.1.1 Bonsack's Machine's Performance

A&G ultimately rejected the machine for the following reasons:

1. They feared that cigarettes were traditionally hand-crafted.
2. They feared that the machine would be too efficient, leaving them with mountains of unsold cigarettes.
3. Overall managerial timidity associated with the handling of the dismissals of unneeded workers.

Washington Duke and his son, James Buchanan Duke, decided to install Bonsack's machine in their factories. In 1889, Duke & Sons sold a billion cigarettes, and in 1890, formed the American Tobacco Company,

The machines brought about a tremendous reduction in the cost of manufacturing cigarettes.

By 1884, the Bonsack Machine was producing from 100,000 to 120,000 cigarettes per day, the equivalent of the production of forty to fifty hand workers.

Duke, like other producers, initially overcame any popular prejudice against the machines in a very simple way: he used them in the greatest secrecy and the public remained unaware of their widespread application for years.

The Duke company began to produce most of its cigarettes by machine in 1885, encountering little of the consumer resistance its rivals had anticipated. Duke's application of the Bonsack Machines revolutionized the business of making cigarettes; the profits of the Duke company rose during subsequent years.

This was also what happened to Leica.