Institute of Advanced Studies
Nanyang Technological University, Singapore

Editor-In-Chief: Prof Phua Kok Khoo
Director, Institute of Advanced Studies, NTU, Singapore

Panel Discussion: Science, Scientists and Society

Panel Discussion with Nobel Laureates at NTU

- 4th International Workshop on Solar Energy for Sustainability: Photosynthesis and Bioenergetics
- Memorial Meeting for Nobel Laureate Professor Abdus Salam’s 90th Birthday
FEATURES

3 | 4th International Workshop on Solar Energy for Sustainability: Photosynthesis and Bioenergetics
7 | Memorial Meeting for Nobel Laureate Prof Abdus Salam’s 90th Birthday
10 | Nobel Laureate Prof Abdus Salam’s Memorial Meeting — Reflections from High School Students
13 | 8th International Science Youth Forum with Nobel Laureates and Eminent Scientists in Singapore
17 | Science, Scientists and Society — Panel Discussion with Nobel Laureates at NTU
19 | The 2016 Singapore Sustainability Symposium: Unlocking Urban Opportunities
21 | IAS-ICTP School on Quantum Information Processing

CONFERENCES and WORKSHOPS

25 | Conference on New Physics at the Large Hadron Collider
28 | International Workshop on Evolution of Cells, Genomes and Proteins
31 | 2nd Workshop on the Chemistry of Energy Conversion: From Molecular Design to Advanced Materials

SPECIAL ARTICLES

33 | Discussing Singapore’s Culture of Science in View of the Discovery of Gravitational Waves
35 | LIGO’s Discovery and the Dawn of Gravitational-Wave Astronomy

FORTHCOMING EVENTS

Editor-in-Chief
Phua Kok Khoo

Members
Kwek Leong Chuan
Low Hwee Boon
Xiong Chi
Chris Ong
Louis Lim

Charlotte Wee
Maitri Bobba
Raymond Liu
Erin Ong
Sun Hui
For four days from 21 to 24 March 2016, an extraordinary collection of passionate and accomplished scientists from across the globe gathered in Singapore to celebrate past successes and future possibilities of photosynthesis and bioenergy research. The Institute of Advanced Studies (IAS) at Nanyang Technological University (NTU) hosted the 4th International Workshop on Solar Energy for Sustainability, an event organised in collaboration with the School of Biological Sciences and the Solar Fuels Lab (School of Materials Science & Engineering and Energy Research Institute @ NTU). The workshop was chaired by Prof James Barber FRS (Imperial College London) and co-chaired by Prof Phua Kok Khoo (Director, IAS).

Photosynthesis and bioenergetics research has proven to be a diverse, deep, and fecund field of scholarship. Over the past several decades many great leaps have been made, yet today much work remains in improving our understanding of natural processes that generate and maintain life on our planet. Technological applications were discussed as well — the hope is that the fruits of this study may be harnessed for the benefit of all. Many of the world’s most inventive and prolific scholars on the topic presented their scientific work and ideas for further exploration.

Among the many distinguished speakers were Prof Rudolph Marcus (Nobel Laureate in Chemistry 1992), Prof Sir John Walker FRS (Nobel Laureate in Chemistry 1997), Prof Leslie Dutton FRS (University of Pennsylvania), Prof Judy Hirst (University of Cambridge), Prof Neil
Hunter FRS (University of Sheffield), Prof Daniel Nocera (Harvard University), Prof Alfred Rutherford FRS (Imperial College London), and more.

The workshop was dedicated to Prof Jan Anderson FRS, who passed away in August 2015. The pioneering Jan Anderson left an indelible legacy during her fifty-year career in photosynthesis research. When Jan Anderson began her scientific work on photosynthetic membranes, the mechanisms by which they functioned were a mystery. Her daring hypotheses and industrious disposition empowered Jan Anderson to uncover the nature of these pathways. NTU President Prof Bertil Andersson delivered a speech in tribute to Jan Anderson. He described her as an inspirational character in his early career. Prof Bertil Andersson began work as her postdoctoral fellow in Canberra in 1979. Their collaboration yielded fascinating results, introducing evidence for molecular organisation with differentiated tiny molecular machines facilitating reactions. This led to the revolutionary discovery of photosystems I and II.

The event also served as an opportunity to celebrate the 75th birthdays of Professors Sir John Walker FRS and Leslie Dutton FRS, who have dedicated their lives and contributed much to the expansion of human understanding of natural processes. Sir Walker presented “Generation and Regulation of Rotation in ATP Synthase” on his investigations of the rotation of ATP synthases. X-ray crystallography and electron cryo-microscopy studies demonstrate that ATP synthase moves protons through a pathway composed of polar residues at a 30° angle with respect to the membrane, with the release of protons regulated by the binding of cardiolipin molecules. Curiously, the mechanisms for this activity in different organisms appear to be distinct, opening up possibilities for targeted drugs. Prof Dutton presented the first-principles computational studies of photosynthetic charge separation in “Structural Engineering of Natural Solar Energy Conversion”. His models demonstrated in a clear and elegant way that in order to achieve efficient charge separation and minimise losses via back reactions, a photosynthetic system must operate a chain of at least four successive redox-active cofactors arranged in a defined geometry. This basic knowledge may prove invaluable in the first-principles design of synthetic photosynthesis-inspired solar energy devices.

Photosynthesis and bioenergetics is a diverse field, and presenters discussed the research and approached the matter from different perspectives. In plants, photosynthetic processes occur in thylakoid membranes, which have a complex three-dimensional architecture. Prof Helmut Kirchoff (Washington State University) discussed the intriguing multiscale plasticity of these membranes — structural alterations in the membranes controlled by various molecular interactions enable plants to adapt to the demands of their surrounding environment. Prof Alexander Ruban (Queen Mary University of London) discussed the interactions and changes in the thylakoid membranes that protect the photosynthetic machinery from the damaging effects of...
excess light. Within the thylakoid membranes are photosynthetic units with light-harvesting and reaction center complexes. Atomic force microscopy and computational methods for exploring their supramolecular organisation were described by Prof Neil Hunter FRS. The primary light absorbing pigments of the photosynthetic complexes are several forms of chlorophyll. Prof Alison Telfer (Imperial College London) presented on research inquiring into the role of chlorophyll f in cyanobacteria, which appears to comprise ~15% of total chlorophyll and expands the light capture spectrum into the far red.

The first protein complex to engage in the process of photosynthesis is photosystem II (PSII). PSII captures photons from solar radiation to power the essential processes. Electrons are made available by splitting of water into oxygen and protons. The oxygen-evolving complex in PSII is vulnerable to irreversible damage by high intensity radiation. Prof Peter Nixon (Imperial College London) elaborated on a remarkable product of evolution — PSII has a sophisticated and highly specific repair cycle in order to synthesise and replace damaged components. The mechanism of this cycle has been further revealed by expressing mutant PSII complexes. Bicarbonate is a well-known regulator of PSII activity and an intrinsic part of the reaction center complex but its role in the PSII electron transport has been a mystery. A novel regulatory model was illustrated by Prof Alfred Rutherford FRS in which bicarbonate controls the redox potential of the quinone acceptor $Q_A$. Prof Gary Brudwig (Yale University) introduced research in which the $^{18}$O kinetic isotope effect (KIE) of PSII was analysed to provide clues into the mechanism of the water-oxidation reaction. This effect is a significant factor in the isotopic ratios observed in atmospheric $O_2$.

The other side of the world bioenergy economy is cellular respiration in mitochondria. Respiratory chain complex I (NADH-ubiquinone oxidoreductase) contributes to the proton flux needed for the generation of ATP. Dr Leonid Sazanov (The Institute of Science and Technology) shared results from research using X-ray crystallography and cryo-EM to reveal mechanistic details of a coupled process in which NADH and ubiquinone transfer electrons. Protons are pumped through hydrophilic networks in the structures of cytochrome c oxidase (COX) proteins. Prof Marten Wikstrom (Helsinki University) presented a review of 40 years of research that has revealed the mechanism of the catalysis of the reduction of $O_2$, while much remains to be discovered regarding how this process is coupled to the motion of protons through the hydrophilic channels. Investigations in mutated yeast COX has opened new questions into the function and regulation of these channels, presented by Prof Peter Rich (University College London).

Prof Marilyn Gunner (City University of New York) introduced molecular simulation methods to probe fundamental principles of coupled electron and proton transfer needed to generate and maintain the proton gradient. Prof Judy Hirst (University of Cambridge) detailed efforts to determine the mechanism of catalysis of respiratory complex I in mammalian mitochondria. Results from single-particle electron cryo-microscopy give clues into the energy-transduction processes by which protons are transferred across the inner mitochondrial membrane by oxidising NADH. Prof Anthony Moore (University of Sussex) discussed his research into the structure of alternative oxidases (AOX), proteins contributing to the mitochondrial electron transport chain in human parasites among other organisms. He has studied the ubiquinol-binding site by measuring the structure in the presence of inhibitors, yielding information including the presence of a hydrophobic channel essential to the mechanism of catalysed oxygen reduction.

The proton gradient across the mitochondrial or chloroplast membrane provides the energy used by ATP synthase in the generation of ATP. The workings of this molecular machine have been the subject of intense scrutiny and it was discussed at length in the workshop. A distinct feature is the rotor components F0 (the proton motor) and F1 (the chemical generator) that turn, bind,
and release protons through the course of step rotation. Prof Wolfgang Junge (University of Osnabrueck) has studied the mechanical coupling of the system components as well as protonic coupling. He discussed structural details that explain why some rotating domains are more stiff or compliant. Prof Rudolph Marcus illustrated a theoretical model analysing the relationship between the stall angle and the rate constant and the equilibrium constant, as well as the Brønsted slopes. Prof Marcus’ collaborator, Prof Sandor Volkan-Kasco (California Institute of Technology), elaborated with another single molecule experiment where the rotor experiences a slow controlled rotation, using a statistic method in which the finite experimental time resolution is removed. These computation experiments yield reasonable agreement with ATP and GTP binding experimental data. Prof Werner Kühlbrandt (Max Planck Institute of Biophysics) discussed high-resolution cryoEM results revealing structural details, including a horizontal helix oriented such that it allows protons to reach a critical binding site in the rotor ring. The mechanisms of action and biological variants of another molecular motor found in the plant cells that activates rubisco — the enzyme catalysing the photosynthetic reduction of CO$_2$ — was presented by its discoverer, Prof Oliver Mueller-Cajar (NTU).

The ultimate ambition of photosynthesis research is to use this knowledge of natural processes for the benefit of all. Some potential future technological applications were presented. Protein engineering is a new and challenging field with enormous potential. All-atom design appears to be an almost impossible method for anything beyond the simplest polypeptides. Prof James Murray (Imperial College London) gave a presentation on a technique that may simplify this challenge using extensible protein scaffolds with protruding loops designed using a new all-atom method. Prof Daniel Nocera (Harvard University) discussed on an artificial leaf /microbial device which generates biomass and liquid fuel like natural photosynthesis with sunlight, water, and carbon dioxide. His method has achieved high yields of 10.7% for solar-to-biomass and 6.2% for solar-to-liquid fuel. The system consists of a silicon wafer and Mn, Co, and Ni catalysts paired with a bio-engineered bacterium to assist with the needed biochemistry. Prof Neil Hunter FRS discussed on attempts to use lithographic technology in order to construct 2D assemblies of natural light-harvesting and reaction centre complexes as well as engineered maquette and pigment molecules. This provides a surface from which new energy transfer and trapping schemes can be tested.

The workshop was characterised by a warm and amiable atmosphere, the result of decades of collaboration in scientific enquiry for many of those present. The presentations were complemented by a poster session featuring additional scientific work by other participants. Further scientific discussion as well as more light-hearted banter flourished at regular coffee breaks and dinner banquet. The final day included a tour of the vibrant island city of Singapore.
Memorial Meeting for Nobel Laureate Prof Abdus Salam’s 90th Birthday

Lars Brink  Chalmers University of Technology

Speakers and participants posing for a memorable group photograph.
On 29 January 2016, Nobel Laureate Abdus Salam would have been 90. Unfortunately he passed away far too young almost 20 years ago. Abdus Salam rose from modest conditions in the little village of Jhang in what would become Pakistan to become one of the most important scientists of the last century. After having broken all school records, even writing a paper in mathematics, he went to Cambridge to get his PhD in 1951. In 1957, he was called to Imperial College in London as Professor and there he built up a world leading group in theoretical physics. At the young age of just 33, he was elected a Fellow of the Royal Society.

From the beginning, he had a burning interest to help the third world to establish basic science and in 1964, he managed to establish one of his dreams: the International Centre for Theoretical Physics (ICTP) in Trieste, where over the fifty years that it has existed,
thousands of young scientists from developing countries have been trained and matured. One cannot overemphasise the importance of ICTP, now known as The Abdus Salam International Centre for Theoretical Physics. With boundless energy, he travelled the world to speak about the importance of science and in his home country, he set up all the necessary research infrastructure, organising among other things Pakistan’s Atomic Energy Commission.

Abdus Salam’s contributions to physics are huge. In his thesis, he finalised the proof of renormalisation of QED. He later introduced the two-component nature of the neutrino and during the 1960s, he developed gauge theory as the correct framework for the electro-weak theory, a work for which he shared the Nobel Prize in 1979 with Sheldon Glashow and Steven Weinberg. He was one of the first to understand the importance of supersymmetry and with Strathdee, he introduced the superfields. Even with his heavy international workload, he was always on top of what was happening in particle physics. A proof of his standing is the 44 honorary doctorates that he earned.

A conference to the memory of his 90th birthday was held at IAS, NTU from 25 to 28 January 2016. Many of his collaborators, students and friends came to give lectures. Four Nobel Laureates, David Gross (Physics 2004), Anthony Leggett (Physics 2003), Carlo Rubbia (Physics 1984) and Gerard ’t Hooft (Physics 1999) participated as well as many other famous physicists. The talks were partly historical in nature. Michael Duff (Imperial College London) talked about Abdus Salam and his life and career, and many of Salam’s old collaborators, such as Jogesh Pati (SLAC, Stanford University), Robert Delbourgo (University of Tasmania) and Lu Yu (Chinese Academy of Sciences), interfoliated their scientific talks with reminiscences. Many of Salam’s old students, such as Peter West (King’s College London), Ali Chamseddine (American University of Beirut) and Qaisar Shafi (University of Delaware), gave talks about their current work. One day was devoted to the present situation of particle physics with talks by Peter Jenni (CERN), Jim Virdee (Imperial College London), Carlo Rubbia, David Gross and Hirotaka Sugawara (Okinawa Institute of Science and Technology). ICTP was well represented with talks by the present director, Fernando Quevedo, and his predecessor, Miguel Virasoro. Around 120 participants took part in the conference that was held at the Nanyang Executive Centre in NTU.

The proceedings cum memorial book of Abdus Salam will be published by World Scientific.
Nobel Laureate Prof Abdus Salam’s Memorial Meeting — Reflections from High School Students

Sidharth Chambocheri Veetil, Yap Yi Tern, Elden and Seet Yong Sheng, Clive
NUS High School of Mathematics and Science

Abdus Salam was one of the most illustrious and prolific scientists of the 20th century. Born in a modest village in Pakistan, he rose to become one of the most influential particle physicists. He was also the first Muslim to win the Nobel Prize in Physics in 1979 for his contributions to electroweak theory, which is an important aspect in the Standard Model. He had made significant contributions and revolutionised the way we see quantum physics.

The Memorial Meeting, organised by the Institute of Advanced Studies (IAS) at NTU from 25 to 28 January 2016 comprised a series of sessions in which distinguished scientists shared their experiences of working with Prof Salam and their deep appreciation for his work. A few of the speakers were his colleagues at the Imperial College London, such as Professors Michael Duff and Chris Hull.

Prof Gerard ’t Hooft (Nobel Laureate in Physics 1999) delivered the lecture titled “Imagining the Future: How the Standard Model may survive the attacks”. His instructive lecture on developing new ways of thinking in order to be able to formulate considerable modifications and improvements in society was awe-inspiring. He discussed the significance of the Higgs mass, and as to why the value is so special. The new ideas that were
raised made the lecture interesting — such as the observing of particle physics at higher energy levels (approaching Planck energy), which most modern GUTs revolve around.

Prof Carlo Rubbia (Nobel Laureate in Physics 1984) presented his talk on “An Alternative Proposal of a Muon Cooled Higgs Factory” and discussed how a more refined understanding of the rather complex Higgs mechanisms would require accurate observations of other processes with electron-positron or muon-antimuon colliders.

Prof Michael Duff from Imperial College London gave a talk about Abdus Salam, and his contributions while at the Imperial College London, where he successfully unified the weak and electromagnetic forces. Nobel Laureate Sheldon Glashow had also formulated the same work, and the theory was combined in 1966. In 1967, Prof Salam proved the electroweak unification theory mathematically, and finally published the papers.

Prof Lu Yu (Chinese Academy of Sciences) shared his personal reminiscences of Abdus Salam’s legacy at Imperial College London. He also talked about Salam’s dream in China for condensed matter physics, and how the International Centre for Theoretical Physics (ICTP), set up by Professor Salam, was largely involved in the immense development of condensed matter physics in China.

Presenting a more technical lecture on “Symmetry and Geometry in String theory”, Prof Chris Hull (Imperial College London) enthralled the audience with his ideas on string theory. He lectured on duality symmetries and highlighted that they lead to an extension of geometry to allow for “non-geometric” solution, and also focused on string theory on Tori and T-duality.

Prof Kazuo Fujikawa’s (RIKEN) lecture on the “CPT Symmetry in an Extension of the Standard Model” discussed a concrete example of the Lorentz invariant non-local scheme of CPT breaking, which gave rise to different masses for the positive and negative energy solutions. Some other talks by other eminent speakers also gave us fresh perspectives about particle physics. ■

“It was truly a privilege to be able to see distinguished scientists from all over the world gathering at a conference meeting and sharing their extensive research. One of the talks that left a lasting impression on me was “An Alternative Proposal of a Muon Cooled Higgs Factory” by Prof Carlo Rubbia. He mentioned that in order to gain a deeper understanding of the complex Higgs mechanism, we will need more accurate observations of processes with either an electron-positron or a muon-antimuon collider. These novel ideas of creating new types of particle accelerators have sparked my interest in this topic. If such particle accelerators were really constructed, imagine the endless possible discoveries we can make. It will definitely unlock the mysteries in the field of Higgs mechanism.

What if I were to do this? What if that was to happen? I indulged myself in these questions during the talk. To me, science is about the discovery of new knowledge, one that will help us gain a deeper insight of the world in which we live in. In order to bring science, or more specifically physics, to a whole new level of understanding, we first need to construct novel machines that allow us to conduct deeper observations. The ideas discussed during Prof Rubbia’s talk are good examples of this. In essence, he has motivated me to continue exploring the unknown realms in physics, by observing experiments from different points of view.

Several other talks have also allowed me to realise that physics is such a broad topic and there is so much more that I do not know about. And it is through these meetings that we learn from one another and discover more. Being able to attend this series of lectures has also allowed me to see the true nature and spirit of science.”

- Yap Yi Tern, Elden
Year 3 student
NUS High School of Mathematics and Science
“Overall, I feel that the series of lectures have given me quite a bit of insight into the fields discussed, specifically particle physics and string theory. I was personally enthralled by Prof Gerard ’t Hooft’s lecture due to its uniqueness, for it proposed new methods of thinking. The lecture pushed me to think about what happens at higher energy levels.

CERN’s Large Hadron Collider (LHC) currently only enables us to go up to 13 TeV – but what would happen at larger energy scales? For such large energies, we would likely need new physics, and perhaps rely on more abstract theories, such as superstrings.

It was also on that day that I learnt about the invaluable contributions of Prof Salam in the field of particle physics in the 20th century. Prof Duff’s lecture provided me with quite a bit of insight into Prof Salam’s work, and made me realise how significant his contributions to physics were. The depth and importance of Prof Salam’s work also inspired me – the wide range of fields that Prof Salam had contributed to significantly over the course of his life is amazing.”

- Sidharth Chambocheri Veetil
Year 3 student
NUS High School of Mathematics and Science

“Prof Spenta Wadia (Tata Institute of Fundamental Research) provided an engaging talk for students like me, since he narrated how Abdus Salam assisted him in his research journey in university, providing me with invaluable insights regarding graduate life in the field of theoretical physics.

Prof Jordan Nash’s (Head of Department of Physics, Imperial College London) talk left the most lasting impression on me. During his speech, he explained about his COMET (Coherent Muon-to-Electron Transition) experiment as well as his research at CERN. This was the talk that best grabbed my attention as his speech touched more on his practical experiment instead of the mathematics involved in theoretical physics. This has allowed me to gain a better understanding of his research.

His presentation has further inspired me to pursue my dream to be a particle physicist. He enlightened me on how the field of particle physics is filled with mysteries, such as new high energy particles, etc., which requires tremendous work and many experiments to be solved. The detailed descriptions of his research and experiments at CERN also inspired me to set my sights on working at CERN one day.

In conclusion, this talk has provided me with insights on various areas of theoretical particle physics. Not only had it sparked a strong interest in me about particle physics, it had also given me an idea of how an international conference of expert physicists is like.”

- Seet Yong Sheng, Clive
Year 3 student
NUS High School of Mathematics and Science
8th International Science Youth Forum with Nobel Laureates and Eminent Scientists in Singapore

Sun Yudong and Lim Zheng Theng  Hwa Chong Institution

The 8th International Science Youth Forum (ISYF) was successfully held from 17 to 21 January 2016. It was jointly organised by the Institute of Advanced Studies (IAS) at Nanyang Technological University (NTU) and Hwa Chong Institution, with strong support from the Agency for Science, Technology and Research (A*STAR) and the Ministry of Education. Once again, this ISYF has brought students from all over the world together to share their passion for science and deepen their knowledge through insightful dialogues with scientists from various fields.
We were privileged to host seven Nobel Laureates: Prof Anthony Leggett (Nobel Laureate in Physics 2003), Prof Carlo Rubbia (Nobel Laureate in Physics 1984), Prof David Gross (Nobel Prize in Physics 2004), Prof Ei-ichi Negishi (Nobel Laureate in Chemistry 2010), Prof Jerome Isaac Friedman (Nobel Laureate in Physics 1990), Prof John Robin Warren (Nobel Laureate in Physiology or Medicine 2005) and Prof Sir Tim Hunt (Nobel Prize in Physiology or Medicine 2001).

The theme for this year’s ISYF was “Communicating Science”, which sought to generate meaningful discussion on how to facilitate and improve communication between the scientific community and the general public.

Scientific research is about discovering our world and developing innovations to improve our lives. Yet to the ordinary man, scientific knowledge and understanding is often esoteric and abstract. Hence, despite our use of products harnessing these breakthroughs on a daily basis, the public’s understanding and appreciation of scientific research have often remained quite superficial. Thus, the challenge is to balance simplification without oversimplification; and to connect science to the general population so that it is both meaningful and fascinating to the layperson.

A total of 117 participants and 36 educators from around the world gathered in Singapore to experience Singapore’s advanced research facilities, beginning with a trip to A*STAR. At the various research institutes, the delegates witnessed the cutting-edge technologies and modern scientific equipment in the laboratories. They were also introduced to the role of A*STAR in Singapore – a key contributor to the development of the science and research industry.

Participants also had the opportunity to visit NTU and her various schools, namely the School of Biological Sciences (SBS), School of Physical and Mathematical Sciences (SPMS), School of Computer Engineering (SCE), School of Mechanical and Aerospace Engineering (MAE), School of Electrical and Electronic Engineering (EEE), and the Lee Kong Chian School of Medicine (LKCSoM).

At the various schools, they were treated to a spectrum of engaging hands-on activities, such as “Medieval Dynamics” with self-constructed catapults and miniature wooden forts. In addition, participants embarked on a tour of various research facilities such as the Robotics Research Centre and the Luminous! Centre of Excellence for Semiconductor Lighting and Displays.

“Scientific research is about discovering our world and developing innovations to improve our lives. Yet to the ordinary man, scientific knowledge and understanding is often esoteric and abstract...The challenge is to balance simplification without oversimplification; and to connect science to the general population so that it is both meaningful and fascinating to the layperson.”
Pinxi Tan from NUS High School of Mathematics and Science presented his poster to the Nobel Laureates in the Research Poster Competition final.

Dr Anand Kumar Andiappan from Singapore Immunology Network (SiGN) at A*STAR interacting with ISYF participant Gigi Lam from Hong Kong during the dialogue session.

ISYF delegates showcasing the cultures of their countries at the Cultural Exhibition.
Currently in its second year, the Research Poster Competition saw a wide variety of entries covering different fields of science by both local and foreign participants alike. Scientists from A*STAR were invited as judges, critiquing the projects based on their creativity, data collection and interpretation, as well as poster presentation. After the preliminary round, four groups were selected for the final judging by four Nobel Laureates, Professors David Gross, Ei-ichi Negishi, Jerome Friedman, and John Robin Warren. Participants from Cite Scolaire Internationale (CSI) Grenoble, France and National Junior College, Singapore emerged the winners. The winning team from France presented their project on charging a cell phone with solar cells made with compounds in fruit juice, while the winner from Singapore shared his project on the role of irisin on skeletal muscle.

One of the main highlights of this year’s ISYF was the intellectual exchange between the students, Nobel Laureates and other eminent scientists through the masterclass and dialogue sessions. The Nobel Laureates and A*STAR scientists shared their research experience with the young, aspiring scientists. During the masterclasses, the scientists explained the concepts behind the discoveries in their scientific fields, augmenting the students’ levels of interest in their niche areas. In the dialogue sessions, students had the rare opportunity to interact closely with the Nobel Laureates. They asked questions ranging from career options to casual topics such as their hobbies.

The penultimate day of ISYF was another fulfilling one for the delegates, with both the Cultural Exhibition and Nobel Forum Grand Ceremony. In the morning, delegates set up booths in Hwa Chong Institution (College) to showcase the distinctive cultures of their countries, including games and food. Participants and students from Hwa Chong Institution alike forged friendships and gained a deeper understanding of each other’s cultures.

The focus of the afternoon was the Nobel Forum Grand Ceremony. Chaired by Prof Bertil Andersson (NTU President), it brought together four Nobel Laureates in an engaging discussion – Professors David Gross, Ei-ichi Negishi, Jerome Friedman, and John Robin Warren. The Laureates addressed a range of questions, from the teaching of science in schools to embracing one’s curiosity in the realm of research. The ceremony was graced by Ms Indranee Rajah, Senior Minister of State, Ministry of Finance and Ministry of Law. In her speech, she emphasised the need for clear, effective, and responsible communication of scientific research with the public. She also highlighted how good science communicators, such as Isaac Asimov, have increased the allure of science in the eyes of the common man.

Five days of interaction with fellow delegates, Nobel Laureates and other eminent scientists culminated in the Closing Ceremony at the Mandarin Oriental hotel. The ISYF has provided a platform for students to interact with like-minded peers from all over the world, and offered an opportunity for them to further their interest in science while appreciating each other’s diverse cultures. Through the activities over the course of ISYF, participants have connected on a deeper level, and the memories woven over the week will remain etched in their minds for a long time.
The panel discussion with Nobel Laureates on “Science, Scientists and Society” organised by the Institute of Advanced Studies (IAS) was held on 19 January 2016 at the School of Art, Design, and Media in NTU. Chaired and moderated by NTU President Prof Bertil Andersson, the distinguished panel of speakers comprised three Nobel Laureates, Professors Carlo Rubbia (Physics 1984), Arieh Warshel (Chemistry 2013) and John Robin Warren (Physiology or Medicine 2005). The panel discussion is a partner event of the 4th Global Young Scientists Summit organised by the National Research Foundation Singapore.

It is important for scientists to communicate their ideas and results effectively to non-scientists and the layman in society, especially how best to achieve good
communication of science to students who may be interested in studying science. This was one of the many questions discussed during the panel discussion.

There is no doubt that advances in science have changed human lives. Yet, not all curiosity-driven scientific discoveries have found social or economic impact. Some may take a long time to find an application, but possibly one of very high impact, while others may never reach that point. Furthermore, certain discoveries can also be double-edged swords, with potentially both positive and negative impacts on human lives and societies. There is therefore a constant debate on the public funding of basic scientific research when compared to applied research, as well as on the relationship between scientific research, ethics and morals. Also discussed was whether it is possible to strike a balance between research, ethics and morals and the roles scientists play in connecting science with the society at large.

About 400 people attended the panel discussion, comprising faculty, staff and students from universities, students from various junior colleges and polytechnics such as NUS High School of Mathematics and Science, Hwa Chong Institution, Jurong Junior College, Ngee Ann Polytechnic, and other interested members of the public. There were also 50 postgraduate participants from the IAS-ICTP School on Modern Topics in Quantum Information Processing who attended the panel discussion. Many people who attended found the discussion with the experts stimulating and interesting.
The 2016 Singapore Sustainability Symposium: Unlocking Urban Opportunities

William Clune  Policy Director, Sustainable Earth Office, NTU

The third annual Singapore Sustainability Symposium (S3) was co-organised by the Institute of Advanced Studies (IAS) and Sustainable Earth Office (SEO) at NTU with strong support from the Ministry of the Environment and Water Resources (MEWR). The event was held at the Grand Hyatt, Singapore from 27 to 29 April 2016.

S3 has now become an international platform for thought leadership on urban sustainability solutions. It helps in connecting the nation’s university and research capacity to Singapore’s sustainability and planning priorities. It highlights and enriches multidisciplinary perspectives in the dialogue of urban sustainability challenges and opportunities. It aids in promoting a systems approach to sustainable solutions, through a format and discussion process that emphasises the connections between disciplines, stakeholders, and topics. It also serves as an early input and support for Singapore’s World Cities Summit and its Mayor’s Forum.
The third S3 kicked off on a Wednesday night with a roundtable discussion panel, graced by the Guest-of-Honour, Minister for the Environment and Water Resources, Masagos Zulkifli. The panel included Ambassador Chang-Beom Kim (Ambassador for International Relations to the Seoul Metropolitan Government), Mr János Pásztor (Senior Advisor to the UN Secretary-General on Climate Change), Mr Simon Upton (Director, Environment Directorate, OECD), Dr Claude Martin (Chancellor of the International University of Geneva) and Mr Anders Karlsson (Vice President, Elsevier). The discussion was moderated and chaired by Ambassador Keng-Yong Ong (Executive Deputy Chairman, RSIS, NTU; Director, Institute of Policy Studies, Lee Kuan Yew School of Public Policy, NUS).

The theme of this year’s symposium was “Unlocking Urban Opportunities” and categorised into three sessions, each focussing on the different aspects — Technology and Innovation; Laws and Governance; and Economics and Financial Incentives. Each session was chaired by experts in the field and followed a format similar to previous years, with a focus to create interactive and generative dialogue sessions. After 3 to 4 short presentations at the beginning of each session, a moderated discussion with all attending delegates followed. The participant delegates were representatives from many disciplines and perspectives, from academia, government, the private sector, and civil society.

The positive reaction of speakers and participants to this year’s symposium was gratifying. The high quality of speakers and session chairs played a major role in garnering close to 200 delegates attending and participating in the symposium.

A few key themes and topics that emerged from this year’s presentations and discussions included:

1. Civic Engagement and Public Participation are Essential to the Success of Urban Sustainability Projects. From greater transparency, more inclusive governance, and improved access to better information, to more effective communications strategies and using technology and social media to improve connectivity, cities are undergoing a transformation in how they reach, react to, and harness the collective sustainability potential of citizens.

2. Sustainability Education at All Levels is Key to Improving and Connecting Government and Corporate Leadership with Engaged and Capable Citizens. Real sustainable development progress and more effective civic engagement are possible when inspired and highly trained leadership is matched by the high expectations and commitment of a fully informed and invested public.

3. Clusters are a Key Operational Level for Urban Sustainability Planning and Design. Just as communities of life (animals, plants, bacteria) are significantly different from individual or single cell organisms, cities are highly complex and networked spaces. Whether regarding technology development and test-bedding, or for considerations of economic connectivity or creating better governance structures, a cluster or scale-up focus, from building to block to neighbourhood, is equally important for the sustainable development of cities.

4. Small and Medium Enterprises (SMEs) are Essential to Supporting the Sustainable Development of Global Cities. Collaborative and long-term relationships between cities and the wide variety of their small and medium sized enterprises are increasingly important to shaping a future of opportunities and sustainability solutions for global cities. Many urban adaptation and environmental challenges require local talent and applied solutions. In addition, innovative, entrepreneurial, and disruptive enterprises play crucial roles in defining the productive potential of cities to stay economically competitive and socially vibrant.

As we look forward to next year’s S3, which is scheduled for late April or early May 2017, we hope many more enthusiastic participants will join in for yet another successful and engaging symposium.
The Institute of Advanced Studies (IAS) at the Nanyang Technological University (NTU) and the Abdus Salam International Centre for Theoretical Physics (ICTP) jointly organised the School on Modern Topics in Quantum Information Processing in Singapore. It was held from 18 to 29 January 2016 at the Nanyang Executive Centre, NTU.

A total of 85 international participants from various developing countries such as Thailand, Malaysia, India and China attended the School. There were also students hailing from Australia, Korea and United Kingdom. The topics covered in the first week revolved around quantum algorithm and quantum computers, topological quantum computation, Majorana fermions. In the second week, the main topics were experimental aspects of quantum computation and quantum information, fundamentals concepts like entanglement, matrix product states, tensor network and quantum correlations, quantum metrology and interferometry.

The Opening Ceremony was graced by IAS Director Prof Phua Kok Khoo, who spoke about the close collaboration between ICTP and IAS. He also highlighted the immense contributions of Abdus Salam in setting up ICTP.

The two-week School was filled with quantum information talks as well as public lectures by three Nobel Laureates on three separate occasions, namely Prof Anthony Leggett, Prof Serge Haroche and Prof Gerard ’t Hooft.

Prof Anthony Leggett (Nobel Laureate in Physics 2003) gave a lecture on the prospects of topological quantum computing using physical effects in condensed matter. He showed mathematically how non-Abelian systems can be topologically protected, and he discussed at length the Fractional Quantum Hall Effect (FQHE) in torus geometry and elaborated on the Kitaev model for spin half system in honeycomb lattice. He also touched on p-wave Fermi superfluid of Helium-3 in two dimensional geometry with pairing in spin triplet. Finally, he highlighted the issues and limitations of the optical lattice systems for use in quantum information technology as compared to superconducting qubits.
In his talk about quantum metrology with nonclassical atomic Rydberg states, Prof Serge Haroche (Nobel Laureate in Physics 2012) showed how one could achieve precision measurement below the Standard Quantum Limit (SQL) and approach the Heisenberg Limit (HL) by entangling the Dicke states in the angular momentum of Rydberg atom with linear Stark effect. The precision technique involves the use of the Schrodinger’s Cat State (SCS), the Ramsey technique and dynamical quantum Zeno effect.

Prof Gerard ‘t Hooft (Nobel Laureate in Physics 1999) talked about cellular automaton. He introduced a novel idea of quantum cells that contain quantum information of all interrelated events from the past. The insight of the idea may stem from the 3-point correlation function. He also alluded to the connection with conformal symmetry. According to him, quantum field theory contains all quantum correlations that arise naturally.

Prof ‘t Hooft also delivered a second public lecture at the National University of Singapore (NUS) on 27 January 2016. It was jointly organised by the Netherlands Embassy and the Department of Physics at NUS. He discussed the roadmap and exploration towards colonisation of the planet Mars. Apart from the high-end technology involved in the realisation of this project, Prof ‘t Hooft also mentioned issues like the cost of such a plan and the funding required for advanced robotic and information technologies, the feasibility of using transit vehicles to land on Mars, and the possibility of survival on Mars as a “Living Unit”, listing down specific problems such as weight, food and water supply.

The lecture series on quantum information processing were given by several experts at the School.

Prof Matthias Troyer (ETH Zurich) talked about the computation and numerical aspects of quantum algorithms. According to him, the performance of quantum computers demonstrated by D wave is not exponential as expected in theory nor is there any quantum speedup, even though Google is moving towards quantum computing with ambitious “save the world” aspirations. There is a lot that can be learned. He also discussed the potential weaknesses and possibilities of improvement in connection with quantum Monte Carlo simulation and quantum annealing involving Ising spin glass. The necessary ingredients include not only quantum algorithm, but also quantum software engineering or programming language.

Prof David DiVincenzo (Institute of Theoretical Nanoelectronics) showed that superconducting qubit is promising for quantum computer due to its high fidelity. He also discussed the double well system in 2DEG with one single and three triplet states, which somewhat reminds us of the four states of 1s2s in atomic helium. He highlighted that it is also possible to lift quantum degeneracy via introduction of defects and electron tunnelling.

Prof Ady Stern (Weizmann Institute of Science) talked about the topological state of matter and Majorana fermions. The lecture covered multifold degeneracy from fractional quantum Hall to topological quantum computation. He gave an in-depth introduction to the quantum Hall effect and discussed the emergence of fractional spins. He also defined the topological sector, the edge state as 1D system with anomaly and the disordered quantum Hall state.

Prof Jiannis Pachos (University of Leeds) discussed topological phases from a more abstract point of view, explaining the braiding and fusion rules of anyons and the constraints the latter have to obey. He showed in a specific example how certain braiding rules will encode non-trivial quantum gates for quantum information processing, which furthermore are protected from environmental noise due to their topological nature. He discussed in detail the Toric code — a specific model of spin $\frac{1}{2}$ degrees of freedom on a square lattice, which hosts two types of Abelian anyons. He also discussed the topological entanglement entropy which witnesses the presence of topological quantum memory.
Prof Andreas Winter (Universitat Autònoma de Barcelona) presented the concept of entanglement using the entropic approach, especially the Shannon entropy in connection with classical communication channels and made use of the bounds of inequality relations.

Prof Jeremie Roland (Université libre de Bruxelles) talked about the recipes in quantum computations and discussed the thermodynamics aspect of quantum information in terms of quantum gates.

The lecture given by Prof Xin Wan (Zhejiang University) touched on the materials, devices and algorithms used for the development of a FQHE-based topological quantum computer. He showed how FQHE can be observed in two-dimensional electron system such as GaAs quantum wells or in high mobility graphene. He also introduced the model of anyons (theory of a two-dimensional medium with a mass gap, where the particles carry locally conserved charges) as well as the Moore-Read state. He showed how interferometric experiments could be demonstrated, how current technology could be harnessed to create anyons and how they could be manipulated to achieve braiding. The final session was about the algorithms in the compilation of topological quantum gates. He ended the lecture with an interesting remark that the Chinese characters may contain some topological information.

Prof Vadim Smelyanskiy (Google) elaborated on the theory of rf SQUID as superconducting qubit and the detailed physics of flux associated with the magnetic fields and the underlying tunneling, diffusion and noise phenomena. He presented the experimental implementation of quantum computation, particularly quantum annealing with flux qubits.

The lecture by Prof Frank Verstraete (University of Vienna) covered the topics of entanglement, matrix product states and tensor networks. He introduced a concept called the monogamy of entanglement followed by the translational invariance, area law and local singlets as the criteria to minimise the energy of the systems. AKLT model was used to study matrix product states wavefunction which fulfilled the previously mentioned criteria. He then presented the fundamental theorem of multipartite state and related it to Cauchy-Schwarz inequality. He also introduced and analysed RVB states which have applications in topological quantum computation.

The presentation by Prof Rainer Dumke (NTU) was about the advances in quantum information technology with cold and trapped neutral atoms in magnetic trap. He presented the utilisation of neutral atoms in clocks, interferometers, magnetometers, atomtronics, many-body physics, etc. He also mentioned the Divincenzo criterion, which includes the five criteria that any candidate quantum computer implementation must satisfy and another additional two criteria for quantum communication. He showed that it is possible to realise qubits using neutral atoms and presented the traps for neutral atoms as well as the gates and architectures with similar system. According to Rainer, qubits can be encoded in the vibrational states of atoms in tight traps. He also showed mathematically and schematically how the atoms are being trapped using magnetic fields and the problems that may arise during the experimental realisation. Experimental data from relevant literature was also shown.

Prof Vlatko Vedral’s (Oxford University and Centre for Quantum Technologies, NUS) lecture was about quantum correlations. He gave an introduction to entanglement as defined by Schrodinger using the “Mean King Problem” as a case study. He emphasised that Local Operations and Classical Communications (LOCC) cannot increase entanglement and that if local unitary is done on two parties, then the entanglement should remain constant. He also showed mathematically...
that the entanglement of a separable state is zero. The final part of his lecture was about majorisation and the higher forms of correlations (discord and coherence) which brought us to the topic of quantum macroscopicity.

Prof Tomasz Paterek (NTU) introduced the laws of quantum communication which encompass information gain, information causality and entanglement gain. Using concepts in quantum information theory, Tomasz mathematically proved an indisputable law of communication, that is, information gain is bounded by the communicated information. The 2nd law, Information Causality, states that information that a receiver can gain about a previously unknown set of data from his sender, by using all of his local resources and m classical bits from the sender, cannot be greater than m. Information Causality excludes no-signalling (information cannot be transmitted faster than light) correlations which give access to too much remote data. Tomasz ended the session with the 3rd law which states that the increase of relative entropy of entanglement between two remote parties is bounded by the amount of non-classical correlations of the carrier with the parties as quantified by the relative entropy of discord.

The School ended with the lecture given by Prof Shau-Yu Lan (NTU). He presented something completely different yet exciting which is the utilisation of techniques in quantum optics, atom optics, and laser cooling and trapping for precision measurement of various fundamental constants in classical physics such as Newton’s gravitational constant G. He showed photos and schematic diagrams of how the experiment was done in other research groups and what his group is currently working on. According to Lan, the precision measurement method that he studies is currently the most precise and accurate measurement of G ever present.

Some feedback from the participants:

“The School happened to take place at a very crucial time in my life when I am shifting my research focus towards Quantum Information theory. It allowed me to discuss and interact with many people from different aspects of Quantum Information theory. I am very happy to have attended the School and I hope to make good use of the knowledge gained.”

- Chandrashekar Radhakrishnan
Researcher from New York University

“I have a bachelor degree in materials engineering but I have been thinking about shifting my research direction towards theoretical physics. This School gave me an excellent overview of quantum information and quantum computation with great breadth and depth. It motivates me to take my first step to start working on quantum information. I have also met a lot of interesting young researchers and PhD students during the School. I really enjoyed having interesting conversations with them about physics, life and culture. I appreciate this unforgettable opportunity provided by the organising committee. Thank you very much!”

- Junye Huang
Researcher from ERI@N

Enthusiastic students participating actively in the discussion.
Conference on New Physics at the Large Hadron Collider

Harald Fritzsch  University of Munich

From 29 February to 4 March 2016, an International Conference on New Physics at the Large Hadron Collider was held at the Institute of Advanced Studies (IAS) at the Nanyang Technological University in Singapore, organised by Professors Harald Fritzsch (University of Munich) and Phua Kok Khoo (IAS, NTU). Both new theoretical ideas and new experimental data were discussed at this conference.

The Standard Theory of Particle Physics describes very well the observed phenomena in particle physics. But most physicists think that the Standard Theory will not be valid at very high energies. The discovery of neutrino oscillations, which imply masses for the three neutrinos, was the first evidence for the new physics beyond the Standard Theory.

Thus far not much is known about the details of the mass spectrum of the three neutrinos — the neutrino oscillations give only information about the neutrino mass differences. The masses must be very small, probably much less than one electron volt.

The next-generation experiments of neutrino oscillations will determine the neutrino masses and the CP-violating phase. It might be that the neutrino masses are not normal masses as the mass of the electron, but Majorana masses. This will be investigated by the neutrino-less double beta decay experiments.

At the conference, new results from the IceCube detector were discussed. IceCube is a particle detector at the South Pole. It is the world’s largest neutrino detector, encompassing a cubic kilometer of ice. It searches for...
neutrinos from the most violent astrophysical sources: events like exploding stars, gamma-ray bursts or collisions of black holes. The neutrinos, studied by IceCube, have energies, which exceed those produced by accelerator beams — several neutrinos have been observed with energies above 1000 TeV.

The new accelerator at CERN, the Large Hadron Collider, started in 2009. In 2012, a new scalar boson was discovered, which decays e.g. into two photons or into two weak bosons. This boson might be the “Higgs Boson”, which generates the masses of the weak bosons and of the leptons and quarks due to a spontaneous symmetry breaking. The experimental results agree with the theoretical expectations.

But this new boson might also be an excited weak boson. In the Standard Theory, the weak bosons and the photon are elementary gauge bosons. Excitations of a weak boson exist only, if the weak boson is a bound state, similar to the rho-meson, which is a bound state of a quark and an anti-quark. If this is the case, one should discover soon other excitations, e.g. bosons with spin one or spin two. The masses of these bosons cannot be calculated precisely. The spin-two boson should have a mass between 0.5 TeV and 0.8 TeV.

In 2015, one has observed at the LHC two high energy photons, which might come from a decay of such a boson. It will take at least one more year, until the existence of such a boson is confirmed.

If weak bosons are bound states, also the quarks and leptons might be bound states of smaller constituents, which are called “haplons”. Then it should be possible to excite a lepton or a quark. Such excitations would decay e.g. into a photon and a lepton or a quark. With the LHC, one has searched for such effects. Nothing has been found. The mass of an excited lepton or quark must be larger than 4.4 TeV.

Theorists also speculate about new symmetries, which could be present at very high energies, e.g. supersymmetry. This symmetry would imply that for each particle in the Standard Theory, there exists another particle with a different spin. For example, the

Prof Albert De Roeck (CERN) explaining in detail the “Search for New Physics at the LHC”.

The conference banquet was held concurrently with the Institute of Physics Singapore Awards 2016 Presentation at Chui Huay Lim Club.
supersymmetric partner of the photon is a photino, which has spin \( \frac{1}{2} \). The supersymmetric partner of the electron is a scalar particle, the selectron. Thus far nothing has been observed in the LHC-experiments. The energy scale at which supersymmetry becomes relevant must be higher than 1 TeV.

If other new particles are observed at the LHC, one has to study the details of their decays. This cannot be done at the LHC. One is planning to build a linear collider, where electrons and positrons are accelerated, e.g. the International Linear Collider (ILC), which might be built in Japan. At the ILC the new particles are produced directly, thus the decays can be investigated in detail.

Another possibility is to build a muon collider. The mass of a muon is about 200 times larger than the electron mass, thus muons can be accelerated in a ring without losing a lot of energy by synchrotron radiation. But they have only a small lifetime and must be accelerated very quickly. A muon collider might be constructed at the Fermi National Accelerator Laboratory near Chicago.

Some time ago, it was observed that the expansion of the universe does not become slower in time, but it accelerates in time. This phenomenon might be related to the dark energy in the universe, e.g. given by the cosmological constant, introduced by Einstein in 1917. But it is still not clear, what kind of physics is behind the acceleration of the expansion.

Most of the matter in the universe is not nuclear matter, but dark matter. It is still a mystery, what the dark matter is. It is observed only by gravity. It might be due to the existence of a stable neutral particle. Such a particle could be produced in pairs in the collisions, studied with the LHC-experiments. Thus far nothing has been found.

Now the Large Hadron Collider has reached its highest energy of 13 TeV. In the coming years, the new physics beyond the Standard Theory should be discovered.
International Workshop on Evolution of Cells, Genomes and Proteins

The International Workshop on Evolution of Cells, Genomes and Proteins was organised by the Institute of Advanced Studies (IAS) at NTU from 1 to 6 February 2016. It was co-organised with the Swedish Royal Academy of Sciences, with strong support from NTU President’s Office and the Knut and Alice Wallenberg Foundation (Sweden).

The meeting was chaired by Prof Charles Kurland (Lund University). The co-chairs for the workshop were Dan Andersson (Uppsala University), Julian Gough (University of Bristol), Ajith Harish (Uppsala University), Michael Levitt (Stanford University), Mikael Oliveberg (Stockholm University), Lars Nordenskiöld (NTU), Phua Kok Khoo (IAS, NTU) as well as Antonis Rokas (Vanderbilt University).

The workshop discussed and tried to provoke answers and discussions to the fundamental biological problem — asking what sort of organism the universal common ancestor of modern life really was. Molecular evolutionists are now enlisting the help of palaeontologists to try to discover the answer to this question. Traditionally, it was assumed that the ancestor of the modern tree of life is a minimalist first cell that evolved by accumulating increasingly numerous and diverse coding sequences to reach the complexities of modern genomes. In fact, the root of the modern tree of life seems to be quite complex. The only sure thing now is that the common ancestor was not an archaeon or a bacterium or an eukaryote, but that it did encode many of the protein domains of all three superkingdoms. Studying protein domains between all three superkingdoms, i.e. Archaea, Bacteria and Eukaryotes, actually now suggests that the organellar proteomes have a common ancestor with both Bacteria and Archaea. Databases containing the coding sequences of thousands of genomes and the atomic resolution 3D structures of tens of thousands of proteins are transforming phylogenomics as well as refreshing the ways that cellular evolution is studied.

The workshop began with Prof Charles Kurland giving an introduction to the meeting scope. After the opening address by NTU President Prof Bertil Andersson, Prof Sydney Brenner (Nobel Laureate in Physiology or Medicine 2002) gave an inspiring lecture titled “Reconstructing the Past from Contemporary Genomes” to kick-start the workshop.
The workshop was conducted in two-fold: a public open event and a closed-door event. The public open event was held at NTU, Singapore from the 1 to 3 February 2016, with invited talks from specialists in various fields related to the topic of the workshop. The closed-door event for the invited speakers was held from 4 to 6 February 2016 at Bintan, Indonesia. This in-depth meeting allowed the speakers to have several detailed presentations, formal and informal discussions and deliberations on the latest findings in the field.

The workshop was attended by about 60 participants, including researchers from other Singapore universities and research institutes. A total of 36 eminent scientists spoke at the workshop.

On the first day of the workshop, participants heard Prof Christine Orengo (University College London) speak on “Domain Structure Classifications and What they Reveal about Protein Evolution”, Prof Julian Gough (University of Bristol) on “Which molecular characters for phylogenetic analysis?”, Prof Charles Kurland (Lund University) on “Modular Protein Domains Track Genome Evolution”, Prof Mikael Oliveberg (Stockholm University) on “Protein stability inside live cells”, Prof Shelley Copley (University of Colorado, Boulder) on “Enzyme promiscuity: what it is and why it is important” and Prof Florian Hollfelder (University of Cambridge) speak on “Multiple Catalytic Promiscuity in the Alkaline Phosphatase Superfamily: Rules and Tools”.

The highlight of the day was the talk by Prof Michael Levitt (Nobel Laureate in Chemistry 2013) on “Fun and Games in Computational Biology”, which was split into three sections. The section on “Solving Large & Difficult Structures with Less Experimental Data” presented new methods for solving structures of large macromolecules by combining several technologies. The following section on “Hybrid Multiscale Models for Simulating Functional Motion in Macromolecular Complexes” discussed his new work on simulating the motion of large macromolecules by Torsional Normal Mode and Natural Move Monte Carlo sampling. The final part on “Birth & Future of Multiscale Modelling of Macromolecules” described the early origins of computational structural biology, from back when computers were not yet advanced enough to perform the complex operations required for computational structural biology, and went on to discuss the current state of technology and its future applications for this field.
On the second day, speakers spoke on varied topics. It began with Prof Brigitte Regenberg (University of Copenhagen) speaking on “Extrachromosomal circular DNAs are common copy number variations in eukaryotic cells”, followed by Prof Dujon Bernard (University of Cambridge) on “Inside the yeast genomes: progressive and regressive evolution” and Prof Antonis Rokas (Vanderbilt University) speaking on “The relationship between gene trees and species phylogenies”. After lunch, the talks included Prof Alex Liu’s (University of Bristol) talk on “Evaluating the fossil record of major evolutionary transitions”, Prof Michael Gray (Dalhousie University) on “Mitochondrial Evolution: What, How And Why”, Prof Ajith Harish (Uppsala University) on “Genomic Origins of Eukaryotes: Is the Endosymbiotic Model Still Relevant?”, Prof John Roth (University of California) on “Mutation and Selection — The gain and loss of genetic functions (and protein folds)” and Prof Mans Ehrenberg (Uppsala University) ending the days’ session speaking on “The bacterial proteome: errors, adjustments and evolution”.

The last day of the workshop was a half day event with speakers Prof Richard Vilems (University of Tartu and Estonian Biocentre) speaking on “Mother Tongue, Fatherland And Demographic History Of Modern Humans: Different Stories Told By Our Matrilineages, Patrilineages And Autosomes”, Prof Valerie Daggett (University of Washington, Seattle) on “Dynamomics: From Simulation of All Protein Folds to Amyloidosis to the Design of Amyloid Inhibitors and Diagnostics” and Prof Lars Bolund (Aarhus University) on “Selection in human populations and somatic cell systems: Search for “wellness” genetic/epigenetic variants conveying resistance to disease processes”. The floor was then open for discussion. Speakers and participants engaged actively in conversation about the topics that were showcased over the two and a half days.

Other eminent speakers who participated in the workshop included Professors Aare Abroi (Estonian Biocentre), Alexey Murzin (University of Cambridge), Andrea Scaiewicz (Stanford University), Dan I Andersson (Uppsala University), David Roy Smith (The University of Western Ontario), Emmanuel Levy (Weizmann Institute of Science), Emmanuelle J Javaux (University of Liège), Gavin Sherlock (Stanford University), Janet Thornton (European Bioinformatics Institute), Lucy Colwell (University of Cambridge), Owen Rackham (Duke-NUS Graduate Medical School), Patrik Björkholm (Uppsala University), Philip Donoghue (University of Bristol), Stefan Bengtson (Swedish Museum of Natural History), Vincent Daubin (CNRS / Université de Lyone) and Yehuda Cohen (NTU).

For those who wanted to know the latest research and experimental outcomes about the evolution of cells, genomes and proteins, the public meeting at NTU provided an excellent opportunity to listen to these eminent experts divulge new findings in the field.
Sunlight is the most basic component in many chemical conversions occurring in nature. Plants are able to harness sunlight to convert it into energy. To replicate such a conversion, scientists have worked earnestly to combine lab-created synthetic nanoscopic and molecular components to produce fuel. Similar chemical energy conversions are imperative to the transformations of energy systems into a sustainable future. In the current days when carbon emissions are significant, the chemistry involved to create, regulate and maintain utilisable energy levels will need to be tailored with techniques that have high standards of scalability, sustainability and stability.

The Institute of Advanced Studies (IAS) and the School of Physical and Mathematical Sciences (SPMS) at Nanyang Technological University (NTU) jointly organised the workshop from 23 to 24 May 2016. This workshop is the 2nd in the series. The first workshop was held in July 2014. This year, the focus was on sustainable chemistry and its advancement in new materials design and development. Eminent speakers shared their valuable insights and perspective to the development of materials and discussed the recent findings in the field.

The workshop was graced by nine overseas speakers and nine local speakers. Chaired by Prof Peidong Yang (University of California, Berkeley) and co-chaired by Prof Phua Kok Khoo (Director, IAS), the workshop ran successfully over two days with a total of eight sessions. Every 30 minute lecture was followed by a 10 minute Q&A session, where students and professors took active interest in discussing and sharing further developments in the fields.

This year the workshop garnered about 60 participants and 20 poster presentations. A total of four poster awards were presented. The posters were judged by the distinguished speakers over the two days of the workshop. Two posters were also awarded the Honourable Mention award for their outstanding efforts.

The workshop began with an opening and welcome address by the chairman, Prof Peidong Yang. Prof Hongjin Fan (SPMS, NTU) started Session 1 speaking on the topic “Organo-Lead Trihalide Hybrid Perovskites..."
Solar Cell Powered Devices”. He was followed by Prof Kyung-Byung Yoon (Sogang University) who spoke on “Electrochemical and Molecular Approaches for Artificial Photosynthesis”. Session 2 had Prof Bin Liu (SPMS, NTU) speaking on “Improving Electron Transport in Nanostructured TiO2 Electrode” and Prof Haw Yang (Princeton University) on “Steering Self-Propelled Active Micro-Swimmers and Insights into Biological Locomotion”.

After the group photo and lunch, the preliminary round for poster presentation judging took place. Prof Zong Yun (Institute of Materials Research and Engineering) opened Session 3, speaking on “Development of Durable Rechargeable Zinc-air Batteries” followed by Prof Chris Chang (University of California, Berkeley) speaking on “Hybrid Molecular, Materials, and Biology Approaches to Solar-to-Chemical Conversion”, and ending with Prof Yi Ying Wu (Ohio State University) on “Molecular Analogs of MoS_2 Edges for Hydrogen-Evolution Electrocatalysis and their Applications in Dye-Sensitised Solar Fuels”. Session 4 had Prof Jim Yang Lee (National University of Singapore) discussing “Application of Redox Targeting Principles to the Design of Rechargeable Li-S Flow Batteries”. The day ended with Prof Guangshan Zhu (Jilin University) on the topic “Targeted Synthesis of Porous Aromatic Frameworks: From Structure Design to Advanced Application”.

Session 5 on day 2 opened with Prof Peidong Yang speaking on “CO_2 + H_2O + Sunlight → Chemical Fuels + O_2”. Prof Bengang Xing (SPMS, NTU) showcased “Cutting Edge Photon-converted Rare-earth Nanostructures for Precise Regulation of Cellular Functions and Localised Thermaotics” followed by Prof Jeff Long (University of California, Berkeley) on the topic “Natural Gas Storage in Metal-Organic Frameworks”. Session 6 had Prof Han Sen Soo (SPMS, NTU) elaborating on “Artificial Photosynthesis by Light Absorption, Hydrogen Evolution, and Biomass Valorisation”, followed by Prof Hongkun Park (Harvard University) speaking on “Integrated Optoplasmonics for Solid State Computing”. After lunch, the final judging for the poster presentations was carried out. In Session 7, Prof Tze Chien Sum (SPMS, NTU) highlighted the “Halide Perovskites: The New Wonder Photovoltaic Material” followed by Prof Mark Green (National Institute of Standards and Technology) speaking on “Solving Structures of Energy Materials” and Prof Zeng Hua Chun (National University of Singapore) on “New Preparation Methods for Integrated Nanocatalysts”.

The last session had Prof Rong Xu (School of Chemical and Biomedical Engineering, NTU) speaking on “Metal-Organic-Framework Derived Photo/electro-catalysts for Energy Conversion”. The workshop ended with the poster award presentation ceremony and closing remarks. It was a fruitful exchange of research and findings in the field of energy conversion.
Discussing Singapore’s Culture of Science in View of the Discovery of Gravitational Waves

Phua Kok Khoo  Founding Director, Institute of Advanced Studies, NTU

Einstein’s theory of general relativity hypothesised the existence of gravitational waves, temporal fluctuations transmitted at the speed of light. A form of perturbation of the space-time curvature, it travels in the form of waves transmitted outward. The US National Science Foundation and the European Gravitational Observatory held a press conference in January 2016 where researchers announced the first direct detection of gravitational waves. The waves originated from the collision of two black holes 1.3 billion years ago. The perturbation caused by the merger of these two large masses reached Earth on 14 September 2015 and was detected by the Laser Interferometer Gravitational-wave Observatory (hereafter referred to as LIGO). This meant the last missing piece of the “puzzle” of Einstein’s theory of general relativity had been found and was verified. After the announcement, gravitational waves became headline news and was the subject of much attention and frenzy in mainstream Western media.

The detection of gravitational waves marks the beginning of a new era in astronomy and astrophysics; Man has opened a new window of observation in the universe. The discovery marks the first time we have observed a black hole binary system and black hole fusion. Theorists should use the data to develop and improve theories regarding the history of the universe and the Big Bang. The search for gravitational waves began with Einstein’s theory of general relativity and it took his successors a century to build the equipment and finally prove his theory. Important research processes in physics that resulted in the discovery of the God particle by CERN and the confirmation of the existence of gravitational waves through the work of LIGO all began with hypotheses proposed by theoretical physicists. Guided by the hypotheses, experimental physicists and engineers designed experiments, the results of which eventually verify and refine the theories proposed. Thus, the successes and results seen in basic science research are often achieved by the combined efforts of theoretical and experimental physicists, and engineers.

Prime Minister Lee Hsien Loong visited Silicon Valley in February 2016 and the Singapore government intends to introduce new talent programs to attract foreign professionals to undertake short-term work in Singapore. These professionals have plenty of job opportunities in Singapore, but when they face a choice of locations to work, many other factors influence their decision. These factors include the technological and creative environment of the location, the overall educational environment, and the cultural and artistic atmosphere (all collectively termed subtle factors). Basic science and technological innovation may be said to reinforce and support each other. Without first-class basic science, there would be no technological innovation which could revolutionise society and social processes.

When research funds are allocated in Singapore, the focus is usually on projects with practical applications; often those which solve real world problems are selected for funding. Many use practical products developed as
spin-offs from basic scientific research as measures of the value of the country’s investment in basic scientific research. If the recent LIGO experimental results were to be measured and judged by the same criteria, many may question the decisions of the US National Science Foundation administrators in the past. However, what LIGO experiments have developed, such as cushioning, laser and extremely low noise technology, may have very broad and important applications in the scientific community in the future.

Advancements in basic science promote the progress of human society. Without investment in basic science, there will be no widening of our vision, no truly innovative achievements and no qualitative leap. While the amount of research funds associated with large scientific projects that we are familiar with, such as CERN and LIGO, is astounding, not all basic scientific experiments require significant investment or expensive equipment. I think there should be more in-depth thinking and longer-term development plans when the government is considering investment in basic scientific research. Where the funds for investment in scientific research are limited, participation in international cooperative projects is an option that will improve project success rate, raise the overall level of scientific research and the influence of the research team on the international stage and achieve greater results. LIGO and CERN have cultivated large numbers of high quality scientific research, engineering and technical personnel for countries which have participated. Such talent will form the core of soft power behind their countries’ science and technology education.

At the same time, national education should focus on giving sufficient attention to the foundation of each discipline at its basic stage. When Chen Ning Yang and Tsung-Dao Lee won the Nobel Prize for Physics in 1957, they inspired countless young Chinese students who chose science as their career. Talent is the future of a country. National policy, social atmosphere and idols or the power of examples all subtly influence the choices of students. Singapore must pay attention to the sustainable development of scientific and technical personnel, because research and technological innovation are centred on humans. To promote scientific and technological innovation, we must first have a large number of highly qualified scientific personnel. Engineering faculties in local universities do not require students to have studied advanced level (A-level) physics in high schools or junior colleges, only O-level physics grades are required. Quantum mechanics and relativity are the two basic pillars of modern physics. Quantum mechanics, which has some 90 years of history, not only forms the basis of many branches of physics, but is applied in every aspect of modern technology, from semiconductors and electronic engineering to electronic equipment and nuclear physics etc. It can be said that quantum mechanics played a decisive role in the development of contemporary science and technology. Without quantum mechanics and modern physics, there would not be modern science and technology, and subsequently we would not have current standards of living. O-level physics does not give students the opportunity to learn the true spirit and skills of physics. If engineering students lack a solid foundation in physics and do not build sufficient stock of knowledge in physics, they may not really understand the cornerstone supporting modern science and technology – the essence of quantum mechanics. It is fair to say that future technology is more dependent on physics and mathematics than ever.

Whether it is the United States, Switzerland, Israel or Denmark, these countries have regarded science and innovation as a cornerstone of their nations. They have built an atmosphere that is conducive to the culture of science; this is something we should reflect upon and learn. The Singapore government needs to create an atmosphere that is conducive to the development of a culture of science. In addition to attracting Singapore talent who have left to return home, it has to attract more foreign talent and invest heavily in funding science and technology. I hope Singapore can develop a growing population of young people with a love for basic research and who are keen on technological innovation. Hopefully, this “little red dot” will contribute to the progress and survival of mankind as a whole.

The Chinese version of this article was printed in Lianhe Zaobao on 26 February 2016 (Page 27) and also appeared in China Xinhua News Network on 23 February 2016.
LIGO’s Discovery and the Dawn of Gravitational-Wave Astronomy

Alvin J. K. Chua (on behalf of the LIGO Scientific Collaboration)
Institute of Astronomy, University of Cambridge

Our present understanding of gravity not as an instantaneous force, but as an intrinsic property of spacetime itself, emerged in 1915 with the conception of Albert Einstein’s general theory of relativity. General relativity was subjected to an increasingly stringent list of checks and tests over the years, passing with flying colours each time. By the end of the 20th century, the only conspicuous omissions from that list were experiments designed to directly verify two of relativity’s most fundamental predictions: black holes and gravitational waves. The prospects for both of these phenomena were correlated, as merging black holes are a promising astrophysical source of gravitational waves — which in turn provide the sole means of directly observing the former.

Gravitational waves are a generic prediction of any modern theory of gravity. In general relativity, they are radiative perturbations in the curvature of spacetime, and propagate with two transverse polarisations at the speed of light. They were first predicted by Einstein shortly after the introduction of his field equations, and their physical reality became the subject of much theoretical debate over the next 40 years (with one of the doubters being Einstein himself, at least for a while). The growing understanding and acceptance of gravitational waves culminated at the famous Chapel Hill Conference of 1957, where several new insights on the challenge of their detection were achieved.

Pioneering attempts to detect the effects of gravitational waves on resonant bars were made by Joseph Weber in the 1960s, and eventually paved the way for the development of modern interferometric detectors such as the Laser Interferometer Gravitational-wave Observatory (LIGO). Contemporary to these efforts, Hulse and Taylor’s discovery of the inspiralling binary pulsar system PSR B1913+16 in 1974 lent support to the cause by providing indirect evidence for the existence of gravitational waves. A full account of this history is available elsewhere [1, 2].

As LIGO began its next observing phase in 2015 after five years of sensitivity and bandwidth upgrades, the question for those working in the field — and indeed many observers in the broader physics community — was not if, but when, the first direct detection would be made.

Nevertheless, it was business as usual until 09:50:45 UTC on 14 September 2015, when the twin LIGO detectors situated at both ends of the continental United States simultaneously recorded a transient gravitational-wave signal [3]. Over eight cycles in 0.2 s, the signal increased in frequency and amplitude from 35 to 150 Hz, indicating a binary source with a combined mass of 65 solar masses and a peak orbital frequency of 75 Hz. The only known objects with the measured mass and sufficient compactness to orbit at 75 Hz without contact are black holes. In essence, LIGO has made a pair of first detections: that of gravitational waves, and also the energy radiated directly by a black-hole system. The discovery is unequivocal.

Fig. 1. Schematic diagram of an Advanced LIGO interferometer, along with (a) the location and orientation of the two detectors in the US, and (b) the instrument noise for each detector near the time of GW150914.
and provides the best evidence yet for the last two major predictions of general relativity; that it should occur in the theory’s centennial year was by design, but with more than a bit of good fortune.

**Detection of GW150914**

The gravitational-wave signal, designated GW150914, was picked up by the Advanced LIGO detectors in Hanford, WA and Livingston, LA a mere two weeks into their first observing run. Each LIGO site operates an enhanced Michelson interferometer (see Fig. 1), which detects the miniscule stretch-and-squeeze effect of a passing gravitational wave on spacetime by measuring the phase difference of laser light in its orthogonal arms. Advanced LIGO is designed to search for gravitational waves emitted by the strongest expected astrophysical sources in the 30—1000 Hz frequency range. The upgraded detectors are three to ten times more sensitive than their initial LIGO predecessors, with a strain noise spectral density as low as $10^{-23} \text{Hz}^{-1/2}$ in the 100-300 Hz range. Further upgrades will bring them to full design sensitivity by the end of the decade.

To minimise the impact of photon shot noise at higher frequencies, the Advanced LIGO detectors employ Fabry-Pérot optical cavities to extend the effective length of the 4-km arms by a factor of 300, along with power recycling at the input to provide resonant buildup of the laser light and signal recycling at the output to optimise signal extraction at the photodetector. At lower frequencies, seismic noise in the detectors is suppressed by both passive and active vibration isolation systems in ultrahigh vacuum, while thermal noise is minimised through the use of materials with low mechanical loss in the test masses and their suspensions. Additionally, each detector site is equipped with environmental sensors to record any potential sources of transient noise.

The Hanford and Livingston detectors are separated by about 3000 km, with an inter-site light propagation time of 10 ms; as shown in Fig. 1(a), their orientations differ by around $\pi/2$, such that their responses to a passing gravitational wave will be out of phase by $\pi$. On 14 September 2015, the coincident signal GW150914 was observed first at Livingston, then at Hanford (correspondingly inverted and with a 7-ms delay). Advanced LIGO was in steady-state operation around the time of the event, and there was no evidence for any environmental or instrumental transients correlated between the two detectors and with the observed frequency evolution. The gravitational-wave strain measured by both detectors peaked at $10^{-21}$ — well above their base sensitivity — and is plotted in the top row of Fig. 2, with minimal filtering to suppress large fluctuations outside the optimal sensitivity range and to remove the narrowband instrumental noise seen in Fig. 1(b).

Two independent classes of search were used to analyse 16 days of data from the Advanced LIGO detectors. For both classes, candidate events coincident at the two detectors within the inter-site propagation time were ranked according to some assigned detection statistic; the significance of each event was then determined against a population of background noise events, generated by artificially time-shifting one detector’s data with respect to the other. In the class of unmodelled searches (with minimal assumptions about the gravitational waveforms), time-frequency spectrograms of the data were used to identify generic transient signals with excess power. GW150914 was recovered as the strongest event with increasing time-frequency evolution, at a false-alarm rate of less than 1 in 22500 years and a corresponding significance of $> 4.6\sigma$.

The other class of search specifically targeted gravitational-wave signals from merging binary systems, through matched filtering of the data with model waveform templates. Waveforms in the region of parameter space containing GW150914 were generated using the effective-one-body formalism, which combines results from the post-Newtonian approach with those from black-hole perturbation theory and numerical relativity. In this class of modelled searches, the analysis recovered GW150914 as the strongest event across all searches (see Fig. 3); the high signal-to-noise ratio of 24 is reflected in the fact that the signal can clearly be tracked by eye in the

---

**Fig. 2.** The event GW150914 observed by the two Advanced LIGO detectors. The top row of plots shows the filtered gravitational-wave strain data; the middle row compares the best-fit waveform from numerical relativity to two waveforms reconstructed independently from the data; the bottom row shows the residuals after subtracting the numerical-relativity waveform from the data.
Implications and outlook
The detection of GW150914 provides new observational data for probing the validity of general relativity in the strong-field regime of gravity. Several tests of the theory’s predictions have been considered: an analysis of the residual data (obtained by subtracting the best-fit model waveform, as in the bottom row of Fig. 2) for consistency with noise; a search for generic deviations from general relativity in the post-Newtonian phase expansion for the pre-merger inspiral signal; and checks of the final Kerr black hole’s mass and spin against the properties of the progenitor binary, as well as the quasinormal modes of the post-merger ringdown. The observations also constrain the Compton wavelength of the graviton to $> 10^{16}$ m, which is consistent with bounds derived from galaxy-cluster dynamics and weak-lensing observations. All tests performed with the GW150914 data were found to provide no evidence against the predictions of general relativity.

Beyond its impact on the foundations of fundamental physics, LIGO’s discovery also has far-reaching implications in the field of astronomy. The existence of the GW150914 system establishes the fact that black-hole binaries can form in nature and merge within a Hubble time. This permits various models of black-hole formation from both isolated binaries and dense star clusters, provided that the metallicity of the stellar environment is lower than the Solar value. The rate of stellar-mass black-hole mergers in the local Universe is also constrained between 2 and 400 per Gpc$^3$ per year in the comoving frame, which allows predictions to be made about the detectability of other local mergers — as well as the gravitational-wave stochastic background from a population of such sources in the distant Universe.

The merger of two black holes is an extremely powerful event — a peak gravitational-wave luminosity of $3.6 \times 10^{49}$ W was achieved by the GW150914 system — but one that is not directly observable with traditional data. From the noise background considered, the event has a false-alarm rate of less than 1 in 203000 years, which corresponds to a significance of $> 5.1 \sigma$.

To obtain accurate estimates of the source’s astrophysical parameters, matched-filter analyses of the data with refined waveform models were performed. Some of the key parameters are listed in Tab. 1. Numerical-relativity waveforms generated using these parameters are an excellent match to waveforms reconstructed from the modelled and unmodelled detection searches, as shown by the middle row of plots in Fig. 2. The parameter estimation results confirm that GW150914 is the gravitational-wave signal from two black holes of 36 and 29 solar masses merging at a luminosity distance of 410 Mpc; most notably, they demonstrate the somewhat unexpected existence of binary systems comprising stellar-mass black holes above 25 solar masses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black-hole mass</td>
<td>$36^{+5}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Secondary black-hole mass</td>
<td>$29^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black-hole mass</td>
<td>$62^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black-hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180}$ Mpc</td>
</tr>
</tbody>
</table>

Tab. 1. Source parameters for GW150914. All parameter values are median values with 90% credible intervals. Masses are given in the source frame.
telescopes; whether it might be accompanied by indirect electromagnetic emission from any surrounding matter is unclear. No electromagnetic counterpart was detected by a follow-up search involving a number of partner collaborations (although the Fermi Gamma-ray Burst Monitor did report an X-ray transient occurring 0.4 s after GW150914 and lasting a full second [4]). The search was not helped by limited sky localisation of the source, with the 90% credible region encompassing a 600-deg² stretch of sky over the Southern Hemisphere (see Fig. 4) as the gravitational-wave signal was received by only two detectors.

Follow-up searches will be crucial when LIGO detects gravitational waves from compact mergers involving neutron stars, for which signatures across the electromagnetic spectrum are expected. A global network of detectors with overlapping bandwidth is the key to achieving improved source localisation. The LIGO Scientific Collaboration (LSC) operates the two Advanced LIGO instruments and the GEO600 detector in Hannover, Germany (which was neither in observing mode during the GW150914 event nor sensitive enough to detect it). Under an agreement with the European Gravitational Observatory, the combined LSC-Virgo Collaboration network also includes the 3-km Virgo interferometer in Cascina, Italy, which is currently offline for upgrades until later this year. Other observatories such as the underground Kamioka Gravitational Wave Detector (KAGRA) in Hida, Japan and the recently approved LIGO-India detector will add coverage from the Asia-Pacific region in the near future (see Fig. 5).

The first gravitational-wave observation of an otherwise invisible black-hole binary — and the prospect of finding many others like it — has given rise to a revolutionary new branch of multi-messenger astronomy. More high-frequency gravitational-wave sources will soon be observed routinely by the ground-based detector network and accompanied by successful electromagnetic follow-up, while pulsar timing arrays [5] are on track to detect the nanohertz gravitational waves from merging supermassive black-hole binaries within the next ten years [6]. In addition, the recently launched LISA Pathfinder mission [7] is testing vital technologies in preparation for proposed space-based interferometers such as eLISA [8] to search the source-rich millihertz gravitational-wave

Fig. 4. Sky location of GW150914, where the contours indicate deciles of probability. The view is from the South Atlantic Ocean with north at the top.

Fig. 5. Map showing the global network of present and near-future gravitational-wave detectors.
sky. With the reality of multi-band gravitational-wave astronomy on the horizon, the future of this nascent field is both imminent and profoundly rewarding.

**Asia-Pacific involvement**

The LSC-Virgo Collaboration is an international group of over 1000 scientists from 83 universities and research institutes in 15 countries. Around 150 members are based at various institutions across Australia, India, South Korea, and other countries in the Asia-Pacific region.

Over 60 researchers from the Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) played an important part in the discovery of GW150914, with contributions ranging from the design and implementation of key instrument technologies to the development and execution of data analysis techniques for gravitational-wave detection. The six ACIGA institutions are the Australian National University, the University of Western Australia, the University of Adelaide, Monash University, the University of Melbourne, and Charles Sturt University.

India’s role in the discovery, under the umbrella of the Indian Initiative in Gravitational-wave Observations (IndIGO), involved over 60 scientists from nine IndIGO institutions: CMI Chennai, ICTS-TIFR Bengaluru, IISER Kolkata, IISER Trivandrum, IIT Gandhinagar, IPR Gandhinagar, IUCAA Pune, RRCAT Indore, and TIFR Mumbai. These researchers performed seminal theoretical work on gravitational-wave source modelling and data analysis, as well as contributing significantly in areas such as detector technologies and electromagnetic follow-up searches.

The Korean Gravitational Wave Group (KGWG) also made a variety of important contributions to the analysis and interpretation of gravitational-wave data in LIGO’s discovery. This work was accomplished by around 15 scientists from five KGWG institutions: the Korea Institute of Science and Technology Information, the National Institute of Mathematical Sciences, Pusan National University, Seoul National University, and Hanyang University.

Other significant contributions from the Asia-Pacific region were made by a data analysis group based at China’s Tsinghua University, as well as an instrument research team from the Institute of Photonics Technology at Taiwan’s National Tsing Hua University.

The research of the LSC-Virgo Collaboration has also been supported in part by the following Asia-Pacific agencies: the Australian Research Council; India’s Council of Scientific and Industrial Research, Department of Science and Technology, Science and Engineering Research Board, and Ministry of Human Resource Development; the National Research Foundation of Korea; and Taiwan’s Ministry of Science and Technology.

**Acknowledgments:**

The author thanks Christopher Berry and David McClelland for helpful feedback. This article was compiled from information published by the LSC-Virgo Collaboration in the detection paper [3] and its companion papers, as well as official press releases from the various Asia-Pacific institutions. It has been assigned the LIGO document reference P1600117.

**References:**


19 July 2016
Workshop on the Standardisation of Chinese Physics Terminology
Taiwan

5 to 6 September 2016
IAS-Institute of Physics (IOP) UK Joint Workshop on Physics Education: Envisioning Physics Education for the 21st Century
Nanyang Executive Centre, NTU

19 to 20 September 2016
Tsinghua-NTU Joint Workshop on Quantum Materials
Tsinghua University

26 to 27 September 2016
IAS-CERN Joint Workshop on Collaboration with ASEAN Countries
Nanyang Executive Centre, NTU

23 October 2016
International Conference on the Modernisation of Chinese Medicine
Suntec Convention and Exhibition Centre

9 to 11 November 2016
TUM-NTU IAS Joint Workshop on Biomedical Imaging
TUM Institute for Advanced Study

1 to 2 December 2016
2nd International Institutes for Advanced Study Forum
Nanyang Executive Centre, NTU

15 to 19 January 2017
9th International Science Youth Forum with Nobel Laureates
Hwa Chong Institution & NTU

15 to 20 January 2017
5th Global Young Scientists Summit
(Organised by National Research Foundation, supported by IAS)
Singapore University of Technology and Design

23 to 26 January 2017
Conference on 90 Years of Quantum Mechanics
Nanyang Executive Centre, NTU

6 to 10 February 2017
Conference on Cosmology, Gravitational Waves and Particles
Nanyang Executive Centre, NTU