ICTS NEWS

INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

We, at the International Centre for Theoretical Sciences (ICTS), are proud to introduce our inaugural newsletter, *ICTS News*.

ICTS is a multi and interdisciplinary centre that brings together physicists, astronomers, cosmologists, mathematicians, biologists from all over the world under one roof to solve the most challenging questions posed by nature, to discover the underlying structures across the sciences and to strive for the unity of knowledge. ICTS endeavors to develop into a hub of scientific activity in the Indian subcontinent, and a centre for world-class research. ICTS also hopes to stimulate and harness the young minds of India and connect with members of the public who are interested in the latest developments of scientific research.

***ICTS News* will provide a glimpse into the science and events at ICTS. With each quarterly issue, we will learn about scientific research, discoveries, and ideas from the ICTS faculty, associates and visitors. There will also be updates on the recent news, programs and other activities.**

In this issue, we look back at 'Science at ICTS', the campus inauguration day and Strings 2015 which celebrated 100 years of Einstein's General Theory of Relativity. We also learn about Gravitational Wave-Astronomy and the proposed LIGO-India project from P. Ajith, faculty at ICTS, as well as Data Assimilation in the earth sciences from Amit Apte, faculty at ICTS.

UNIFYING BIG DATA WITH COMPLEX MODELS

AMIT APTE

Imagine standing on a beach near the edge of water, chatting with a friend, gentle waves caressing your feet every now and then. Now imagine that you two start playing a game of trying to guess whether the next wave that is coming towards you will reach you or will break before reaching your feet. If you are mathematically minded, you may want to guess the height up to which it will wet your feet, and if you are even more mathematical, you may want to give the probability of this event instead of a simple guess for no/yes/height of wet feet.

The game described above is qualitatively very similar to the task of those earth scientists that are trying to predict the weather or the climate. In fact, if you just think of waves of slightly (!) larger height and power, you will see that this problem is of critical importance to tsunami-prone areas. Additional examples of such questions are the predictions of the total Indian summer monsoon rainfall, the paths of hurricanes, the frequency of droughts in the final decade of this century, etc. It quickly becomes obvious that these problems are of immense importance for the society but I would also like to give a sense of their scientific and mathematical importance and challenge by describing how scientists study them.

The approach to the solution of these problems can be thought of as a symphony in four movements, one leading inevitably to the next: physical theories, models, data, and data assimilation, the last one being a later addition to the much older three-movement scientific method.[1]

Physical theories (the art of generalization from specifics): The atmosphere and the oceans are composed of fluids, interacting with the solid earth. The basic equations describing these fluids, based essentially on Newton's laws for a very large number of particles in these fluids, are the Navier-Stokes equations, along with the thermodynamic equations that describe the exchange of energy (heating and cooling) between different parts of the system, as well as processes such as cloud formation, reflection and absorption of light, and others. Thus a combination of thermodynamics, statistical mechanics, and fluid dynamics are, for the most part, believed to describe, with sufficient accuracy, the physical processes in the earth sciences. Of course, as the possibilities and need for accuracy increases, we also need theories for biological processes such as growth of phytoplankton, interactions of the atmosphere with vegetation, etc. (not to mention the social sciences to account for human activities and choices and their effects).

But the general physical theories do not tell us anything about our planet Earth, with about 70% oceans and 30% land (instead of no oceans as on Mars), 8000+ meters tall mountains (instead of the relatively level landmass of Venus), and a whole lot of distinguishing features. So here ends our first movement of understanding the physical principles involved.

All theorems are true. All models are wrong. And all data (even though extremely large in quantity) are inaccurate. So what are we to do?

Models (fall from the heaven of beautiful theories to the world of reality): In order to understand the oceans and the atmosphere of our specific planet Earth, we need to use these theories to develop models which now include observed facts such as the rate of rotation of the earth (one revolution per 24 hours), the topography and bathymetry (which are the measurements of the undulations of the earth's surface above and below water respectively, e.g., or simply put, heights of the mountains and depths of the oceans), the composition of the atmosphere (largely nitrogen and oxygen which decide its gas constant), and the variation of the amount of energy received from the sun (caused by a tilted rotation axis), and myriad other details. Modelling is an enjoyable activity for those who have an eye for the details and a disposition towards specifics, or just a boring chore for some others, but completely unavoidable irrespective of such preferences. The mathematical representation of these details is in terms of "parameters" of the system, and these are what distinguish the atmosphere of Jupiter from that of Earth. An important step in modelling is the use of approximations appropriate for a specific system, in order to simplify the equations involved in describing such a complex system, for example, using asymptotic methods, but I will not touch upon this aspect here.

In addition to the above details, there is a further complication that for such systems (or even much simpler ones), once we have set up the correct equations with all the details, it is impossible to solve these equations exactly. Hence we are forced to turn to computers in order to find numerical solutions, as best as we can. This task introduces further approximations, as well as further "parameters" which capture the details of how these numerical solutions are obtained.

As if all this is not enough, people such as Henri Poincaré and Edward Lorenz (and many others) pointed out that the solutions of the equations of such systems have a peculiar property called chaos: if you make a small error in specifying the state of such a system at any given time, this error grows very quickly (exponentially is the technical word). Thus if one modelling group includes a slight dip in temperature in Bengaluru on 25th April because of rains while the other one (using identical model) does not, the predictions made by these groups will look very different very quickly, e.g. the first group predicts low pressures over Chennai on 1st May while the other group does not. This is the essence of the title of a talk by Edward Lorenz: "Does the flap of a butterfly's wings in Brazil stir up a tornado in Texas?" [Lorenz, 1993]

This is as far as the second movement of modelling brings us and now we must start the next one on data.

Observations, and lots of them (also known as big data): In order to specify the state of the earth system in the model as precisely as possible, we need to obtain the data from the real system. There are several sources of such data: weather stations and balloons, aircrafts and ships, special research expeditions and observational missions, satellites, and many others. The number of observations from the atmosphere and the ocean are now close to a million or more every six hours, and the data size is increasing fast.

Even such large number of observations is not enough to specify the system state completely. For example, the profile of temperature from ground all the way to a few kilometers height in the atmosphere is available only at a few points around the globe. Furthermore, these data are noisy and simply using these observations will certainly lead to predictions which will not be accurate or precise or both. Another important characteristic of these observations is that they contain effects of physical processes which are not contained in the model at all – for example, localized rain over an area of a few thousand square meters.

Thus the third movement ends with this counterpoint between complex models and noisy, big but insufficient data.

Data Assimilation (how the data learn to live with the models): The set of mathematical techniques used for incorporating the noisy, partial and sparse, time-dependent data about a complex dynamical system into its incomplete model based on somewhat deficient knowledge of governing physical theories is known as Data Assimilation (DA) in the context of earth sciences.[2] Because of the need to represent the uncertainties in the model state and the observations, the use of probabilistic methods is quite common in DA. In this context, the focus is essentially on the so-called posterior probability distribution for the state of the system, which describes its probability conditioned on its observations. Such conditional distributions are obtained by the use of Bayes' theorem. [Apte et al., 2008]

A major obstacle to progress in DA is that the earth system is very high dimensional (with a large number of degrees of freedom) and highly nonlinear (with relevant solutions being chaotic). Thus most of the theoretical developments in nonlinear filtering theory are not directly usable for DA (because of high dimensions), and neither are the methods from the highly successful Kalman filtering theory (because of nonlinearity).

My current research focuses on developing particle filter methods in the context of DA and on applying ideas from dynamical systems theory to these problems. One of the recent representative results is that posterior distributions are concentrated on the unstable subspaces of the system, at least for a linear system. [Gurumoorthy et al., 2015] The generalization and use of such results for nonlinear systems is a promising direction of investigation because the dimension of unstable space is usually much smaller than the full state dimension.

A definitive treatment of many such aspects of assimilation is a challenge that still eludes us. The fourth movement has only just begun, but the future developments are sure to be exhilarating.

References

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Footnotes

1) The scientific method is not really a steady progression through these movements, but rather a process of repeating these movements, not always in order either. Thus all the movements described below are not finished works to be simply appreciated, but are evolving and growing continually.

2) The use of observations in data assimilation for obtaining the state, in a given model, of a particular solution that best represents the reality must to be contrasted with the more traditional use of observations in most areas of sciences for building theories for describing a whole class of systems or even models for describing specific systems.

Amit Apte is a mathematician and a faculty member at ICTS-TIFR.

CAMPUS INAUGURATION EVENT: SCIENCE AT ICTS

The ICTS celebrated the inauguration of their new campus at Shivakote, Hesaraghatta Hobli in north Bengaluru with a day-long event named Science at ICTS on June 20, 2015.

This event marked the culmination of a process begun six years ago when the campus foundation stone was unveiled by CNR Rao in the presence of David Gross and Michael Atiyah during 'Science without Boundaries' held in December 2009.

Science at ICTS began with an invocation by Carnatic vocalist Srimatha Ramanand followed by a series of ceremonial speeches by a distinguished panel of lecturers.

In their speeches the panel recalled the history of ICTS, commented on the role it is poised to play as a catalyst in Indian and international science and gave advice to the institute for the road ahead.

These talks were followed by the ceremonial planting of saplings by a group of academics and friends of ICTS. The group included Nima Arkani-Hamed, S. Batni, Manjul Bhargava, M. Bhaumik, Vivek Borkar, S. Bhattacharya, Avinash Dhar, Michael Green, David Gross, Kris Gopalakrishnan, Ravindra Kumar, Andrew Millis, Roddam Narasimha, Ashoke Sen, Boris Shraiman, Subir Sachdev, E.V. Sampathkumaran, Director DCSEM, Fernando Quevedo, Cumrun Vafa, K. VijayRaghavan, Spenta Wadia, Bernard de Wit and others.

SPEECHES

DAVID GROSS
KITP SANTA BARBARA AND CHAIR, ICTS INTERNATIONAL ADVISORY BOARD

What a wonderful day. What a journey. What a dream.

I was here two years ago when the foundations were just beginning to come up. As I arrived today I was just overwhelmed with joy and a sense of great accomplishment. Perhaps this is the end of the beginning of this marvellous new institute. Let me say a bit about my involvement in this journey, which goes back to about a decade. It was 2005 when I was on a long visit to India – I visited my colleagues in various universities and institutes and all I heard were complaints about the government, the administration, the lack of support, the woeful state of Indian science. I really got angry and I thought this was crazy – India has a great tradition of respect for science, it has great scientific institutes, it has a history. It can easily take advantage of its traditions and culture, respect for excellence to overtake the Chinese who were then pouring enormous resources into science. Everyone said, yes yes but it's the government's fault and we can't do anything.

After talking to some of the people in the government, I realised that this wasn't the case. They were beginning to have resources and wishing to invest in science. But there was very little leadership on the ground, except for a few people. Among them is my very good friend Spenta Wadia, with whom I had many conversations. He told me of his dream to build in India something like the Kavli Institute for Theoretical Physics – the KITP in Santa Barbara. An institute devoted to the theoretical sciences that would serve both the local community – bringing scientists from all over India to work the frontiers of sciences – as well as scientists, colleagues from all over the world. And four years later, in Bangalore, we inaugurated the International Centre for Theoretical Sciences. Some people have alluded to how difficult it is to create a new institution in India. And indeed, I think it was nothing short of a minor miracle that all this happened in a short period of four years. Six years later the campus exists. What a journey, what a dream, what a success.

This has happened with the help of many institutions, people, and colleagues here and abroad. The Tata Institute of Fundamental Research, of course, of which this is an off shoot. The Atomic Energy Commission, the IISc in Bangalore, the other government institutions, also the Simons Foundation. Many dedicated, sacrificing theoretical scientists working in India and abroad. When Spenta asked me to chair the International Advisory Board, I agreed of course. Most of the members of the IAB are here today and you will be hearing from them later. Some of them will give lectures in the afternoon. All of them have been very helpful and wonderful. We meet often over phone from around the world. Some of the members have already rotated off and new ones have joined. I must say it has been an absolute pleasure to help the establishment of this institute. There is so much goodwill among the academic colleagues, so much self sacrifice and effort that has been poured in to create this place. There is so much hope, so many dreams exist in the construction of this institution that it has been an enormous pleasure to serve as the chair of the IAB.

But the real tribute of course, as already mentioned, must go to Spenta. He has devoted ten years of his life, a good part of what could have been his research to creating this institution. His extraordinary energy and vision – but most importantly because it is India his persistence and patience – has really achieved a miracle. But this is at best the end of the beginning. And now that the foundation has been set, we all hope that all of this effort and dreams will start to materialize in a way it has been alluded to before. But I would like to make a special point – there is something special about an institute of this kind devoted to the theoretical sciences. First of all theorists are natural unifiers, interdisciplinary animals.

Experimentalists, central as they are to science, work by necessity and within very narrow domains because that's where they do their experiments, in well-defined laboratories. Whereas theorists see a broader scope and are able to cross interdisciplinary boundaries. So an institute like this which is able to bring together theory-minded scientists from mathematics to physics to computer science, astrophysics, to theoretical biology can serve a function that cannot be achieved in any other fashion. India has excellent theoretical capabilities and an institute like this, we all hope, will amplify and magnify that excellence manifold. But this is just the end of the beginning and to realise those dreams is needed. So among the younger theoretical scientists who have joined the ICTS, who will benefit from it, much hard work and sacrifice will be required. But in addition to the contribution of scientists in scientific institutions, I do believe that society, private society and especially the elements in Bangalore who have profited so much from the application of science and technology and have turned Bangalore and the rest of India to a technologically growing country should start giving back. Giving back to the academic institutions from which they emerged, giving back to culture, to science, to the advancement of fundamental theory.

This has been a wonderful day, it's been an incredible journey. And it is such a pleasure to see the end of the beginning and the beginning of the future.

Thank you.

SPENTA R. WADIA
DIRECTOR, INTERNATIONAL CENTRE FOR THEORETICAL SCIENCES OF TIFR

Distinguished members on the dais, colleagues, friends and guests, it is my great pleasure to welcome you all to the inauguration event of the ICTS campus, which we have called 'Science at ICTS'. I would like to thank you all for coming here today, especially those of you who have come from far away and have landed only a few hours ago.

Over the last five and a half years, since the 'Foundation Stone Ceremony' in December 2009, ICTS has travelled a long way. At that time I had presented a brief history of how the ICTS came about. Let me briefly say that the idea that one can build a top-class facility in India was inspired by my visit to the Infosys campus in Bangalore in 2001 with Edward Witten who wanted to visit the 'modern temples of India'. Also the NCBS campus was an inspiration. The conception of the ICTS, its mission and how to go about creating the Centre happened in a long meeting in Santa Barbara with David Gross (Director KITP) in 2004.

To sum it up the campus is almost done and moving in will begin within the next month. The ICTS campus has facilities to carry out its mission: in-house research, programs, schools and discussion meetings and outreach activities.

I would like to recall that in his speech during the inauguration of the new TIFR buildings on 15 January 1962, Homi Bhabha the founding Director of TIFR clearly stated that:

"The building itself is only a shell to make possible the work that is done inside it. It is by the quality and volume of its scientific work that an institute like this must be judged, by the extent to which it has helped to explore and push back the frontiers of knowledge."

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The first phase of **faculty** induction is almost over and the present faculty is engaged in various areas of research and programming activities. We keep in mind that 'institutions are built around individuals'.

In-house **research** is presently organized in 3 broad categories:

Complex Systems: non-equilibrium statistical physics, fluid turbulence, condensed matter, physical biology, nonlinear dynamics and big data assimilation

Gravity and Elementary Particles: astrophysical relativity, gravity waves, string theory and quantum gravity and cosmology

Mathematics: Fluids and experimental mathematics, differential geometry and partial differential equations

Even in a short time several excellent research contributions have come from the faculty and I hope this trend will continue and gain momentum once they are all settled in their new home...here!

Once again quoting from Bhabha at the annual meeting of the National Institute of Science of India (later renamed the Indian National Science Academy) in October 1963, he spoke at length about the challenges of setting up a scientific institution:

"I feel that we in India are apt to believe that a good scientific institution can be established by Government decree or order. A scientific institution, be it a laboratory or an academy, has to be grown with great care like a tree. Its growth in terms of quality and achievement can only be accelerated to a very limited extent. This is a field in which a large number of mediocre or second rate workers cannot make up for a few outstanding ones, and the few outstanding ones always take at least 10-15 years to grow."

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ICTS has striven to create an excellent and modern **administrative and technical support** staff to manage its various activities, given that ICTS conducts a large number of programs and a very large number of visitors spend varying times at ICTS.

On this too, quoting from Bhabha in the last speech he gave before his death in 1966, he expressed his view of the kind of administration that is needed in an institution of fundamental research:

"The type of administration required for the growth of science and technology is quite different from the type of administration required for the operation of industrial enterprises, and both of these are again different from the type of administration required for such matters as the preservation of law and order, administration of justice, finance and so on."

Clearly differentiating between the government support and government control, he felt strongly that administrative practices should be aligned with the specific objectives of an institution.

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From its inception ICTS has been guided in its academic planning by a very dynamic and demanding Advisory Board chaired by Prof David Gross and a Program Committee consisting of distinguished scientists in various areas of research, many are present here today. Their involvement and commitment are crucial in making ICTS an internationally happening place.

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What we envisage for the future and what we will need to fulfill the mission of ICTS:

We envisage one of the best theory Centres in the world in the service of science especially science research and education in India. ICTS is a hub where people from the world over congregate to research, teach and learn. Hopefully our Centre will contribute to solving some of the important problems of science and concomitantly enhance the education of our students.

ICTS needs the continuing support from the Tata Institute and the DAE in human resources and financial grants. There needs to be an appreciation that the ICTS is an important catalyst for Indian science in research and education.

Also, given the present situation ICTS needs non-governmental involvement to carry out its mission in a sustained manner. I am extremely happy that this need has already been recognized, and given our initial performance, the Simons Foundation of USA has awarded us a modest institutional grant to carry out our various activities. I am also glad that Prof. Andrew Millis of the Simons Foundation is here with us on the dais.

ICTS also recognizes the value of communicating the excitement of science to school and college students and members of civic society, and hence its faculty and facilities are also geared to various outreach programs. This is part of a broader engagement of our scientists with civic society that we would like to foster. Kris Gopalakrishnan co-founder and ex-CEO of Infosys, now a member of the Advisory

CAMPUS INAUGURATION










Board, is helping ICTS establish and strengthen this direction.

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I would like to thank the TIFR and the Department of Atomic Energy of the Govt of India for the grant of almost 140 crore to build this campus. We look forward to their continued support to fulfil the mission of ICTS.

We are very thankful to NCBS for handholding us these past many years in so many ways; it is an extraordinary example of institutional help within the TIFR system. I would especially like to thank K. VijayRaghavan.

ICTS is over the past five years functioning from the Indian Institute of Science under the aegis of a joint ICTS-IISc program. We thank IISc for hosting us and look forward to a fruitful interaction in the future which will be mutually beneficial.

The ICTS project required extraordinary work and commitment of many people:

First, I would like to thank Prof Avinash Dhar who has worked side by side with me since the creation of this Centre, in all aspects: academic, administrative, architecture, construction.

I would like to thank the entire ICTS staff for their dedication and enthusiasm to work for a fledging institution.

Ms Mukesh Dodain in-charge of administration at ICTS without whose boundless energy and courage we could not have come so far.

Thanks on behalf of ICTS to all the members of the DCSEM team especially the Director Mr Gabhane, Engineers Mr Sharma and Mr Jakate for their continuous contribution to project. It is also unlikely that the campus could have reached where it has without the tireless persistence of Mr Prasanna, on site project engineer from DCSEM.

The campus has many unique architectural features that have been specially designed for a lot of interactive spaces and visitor comfort. It has been a great pleasure to know and interact with Ravindra Kumar our architect from the firm of Venkataramanan and Associates (VA). Also thanks to Naresh Narasimhan of VA and Jahnvi Ashar and Venu who did the detailed design.

The construction company JMC Pvt Ltd (India) has executed the project very well: high quality and cost effective. I would like to thank the JMC team Mr Kamath, Mr Rajasekhar, Mr Alex and others and the senior management of JMC, especially Mr Hemant Mody, Mr Reddy and Mr Santhakumar and all the engineers, and the hundreds of workers who have toiled hard for very modest wages to build this campus.

Today gathered here are also family members of ICTS faculty and staff. I would like to thank them for their support to the ICTS members during this nascent period of ICTS.

EXCERPTS OF SPEECHES

For full versions of all the speeches please visit https://www.icts.res.in/science-at-icts

E.V. SAMPATHKUMARAN
DIRECTOR, TIFR

Today, with this inauguration we are poised for a new start. The ICTS has already made a name for itself, both nationally and internationally, with a number of high quality programs and workshops, which have drawn some of the leading practitioners from around the world.

RATAN KUMAR SINHA
SECRETARY, DAE AND CHAIRPERSON, AEC (SPEECH READ OUT BY SPENTA WADIA)

With the unique resources at the Centre, including the faculty and the students, I think ICTS should go further, through its outreach activities, with the objective of creating a scientific temper and aptitude for theoretical sciences in the educational institutions in the country, with particular focus on those in the neighbourhood. I would like to conclude by saying that the DAE is fully behind this new initiative of Indian science and will support it so that it fulfils its mission.

SABYASACHI BHATTACHARYA
TIFR & PRESIDENCY UNIVERSITY, KOLKATA

There ought to be a place that will break down the silos between institutions, between disciplines, between modes of research. Finally, as an experimentalist, who has a record of never having written a single paper in theory, I would like to say that unfortunately we have a divide between theory and experiment. This has helped neither theory nor experiment in my opinion, in my judgment after all these years. It would be great, and I know it has been very much on the mind of the builders of this institution, to bring in people of my sort here.

RODDAM NARASIMHA
JNCASR & MEMBER, ICTS INTERNATIONAL ADVISORY BOARD

ICTS is in the first place multi- and inter-disciplinary but, with the inclusion of earth sciences and computer science as well, the choice of subjects of research for the Centre goes beyond the mathematics, physics and biology that have formed the core of basic science for long. I confess to a bias for those relatively rare entries, but I must say that India badly needs a high-level initiative there; by bringing these subjects under one roof, ICTS has taken an extraordinary initiative. The triad of earth sciences, computers and mathematics (with ideas from physics and biology) is a powerful combination that is essential for achieving progress in earth sciences, because of the complexity of the subject: the problems are scientifically challenging, and nationally and globally important. And the greatest advances in these subjects are actually happening at the borders between these disciplines. There is as of today no Indian general circulation model, in spite of the extraordinary importance of the monsoons to our economy. ICTS has taken a path-breaking initiative by putting people from the 'triad' under one roof.

K. VIJAYRAGHAVAN
NCBS-TIFR AND SECRETARY, DEPARTMENT OF BIOTECHNOLOGY, MINISTRY OF SCIENCE AND TECHNOLOGY, SECRETARY, MINISTRY OF EARTH SCIENCES & MEMBER, ICTS MANAGEMENT BOARD

And that really is a challenge we have – how can we take basic science from a situation where it is today – in which we take the best problems that the world has defined and try to be really good at that – to a situation where we in addition also define the best problems that the whole world addresses. Those kinds of new questions in basic science can come both from interacting with our colleagues all over the world but also by taking new problems from our environment – be it ecology or climate, epidemiology. All of which can raise basic questions that are embedded in our context also.

ANDREW MILLIS
COLUMBIA UNIVERSITY AND ASSOCIATE DIRECTOR FOR PHYSICS, MPS-SIMONS FOUNDATION

We at the Simons Foundation are proud to provide financial support to the ICTS and I just want to tell you briefly why. Our job, our mission in the mathematics and physical sciences division of Simons Foundation is to foster excellence in the theoretical sciences

radiating from mathematics. I think it's obvious to all of us that the outstanding high calibre of the members of ICTS, the focus that ICTS has in the connections between different areas of science and the key role it plays in forging links between scientists both across India and India with rest of the world, marks ICTS as one of the world's premier institutions in this area. One which is an honor and a privilege for the foundation to support. So I will conclude very briefly here that I congratulate Spenta Wadia and the ICTS on the occasion of the inauguration of their new campus. We all look forward to be part of many years of exciting science to come.

KRIS GOPALAKRISHNAN
CO-FOUNDER AND FORMER CEO OF INFOSYS AND MEMBER, ICTS INTERNATIONAL ADVISORY BOARD

My endeavour has been to try and create an eco-system here where the scientists and researchers can collaborate and they don't need to travel outside the country. That's one of my projects – to get the scientists here in Bangalore connect with each other, create the platform for them to interact, get them to collaborate. So basically leverage the eco-system that exists here. ICTS in some sense represents this – global collaboration.

MICHAEL ATIYAH
UNIVERSITY OF EDINBURGH AND MEMBER - ICTS INTERNATIONAL ADVISORY BOARD

The ICTS, whose inauguration we are celebrating today is a branch of the Tata Institute in Mumbai. I have visited the TIFR many times over the years and got to know the key mathematical figures there, including S. Chandrasekharan, M.S. Narasimhan and C.S. Seshadri. Many of their students came to work with me in Oxford and Princeton, notably the brilliant mathematician Vijay Patodi, whose life paralleled that of Ramanujan, dying at the early age of 32.

I also got to know a young physicist, Spenta Wadia (happily still alive), who has been the driving force behind the establishment of the ICTS. The fact that I had physics friends is an indication that the frontiers between disciplines were breaking down, and this has become the main feature of our times. The old rigid disciplines of the past are giving way to a much more fluid scene, which is why the ICTS is the right body for the future.

The future belongs to the young and the science that is now emerging will affect the lives of everyone on the planet. The ICTS has a noble task, that of providing the right atmosphere to inspire the next generation of scientists. When I was a young man in 1954, I heard the great German mathematician Hermann Weyl eulogize the Fields Medallists by saying that their work showed that the "old gnarled tree of mathematics was still full of the sap of life". I am happy to end on that cheerful note.

ACADEMIC SESSION

The afternoon session comprised scientific lectures on topics ranging from a possible low energy derivation of the Veneziano amplitude as the unique consistent classical completion of gravity, the role of higher spin particles and symmetries in inflation and string theory, the universality of fluctuations in the neighborhood of third order phase transitions and the mathematical modelling of the evolution of the flu virus. The speakers were Boris Shraiman, Satya Majumdar, Subir Sachdev, Rajesh Gopakumar and Nima Arkani-Hamed.

CHAIR
Vivek Borkar
Indian Institute of Technology,
Bombay, India

SPEAKERS
BORIS SHRAIMAN
Emergent simplicity of evolutionary dynamics and the possibility of predicting evolutionary future

SATYA MAJUMDAR
Top eigenvalue of a random matrix: Tracy-Widom distribution and third order phase transition

CHAIR
FERNANDO QUEVEDO
ICTP, Trieste, Italy

SPEAKERS
SUBIR SACHDEV
Exploring quantum matter in the high temperature

RAJESH GOPAKUMAR
Simplifying String Theory

NIMA ARKANI-HAMED
Quantum Mechanics and Spacetime in the 21st century

POETRY, DRUMMING AND MATHEMATICS

In the evening, Field's Medal winner Manjul Bhargava (Princeton University) delivered a public lecture titled "Poetry, Drumming, and Mathematics" at the Christ University auditorium. In his lecture

Manjul Bhargava during his public talk at Christ University on June 20, 2015.

Bhargava described remarkable mathematical advances that were made over two thousand years ago by classical Sanskrit poets and musicians who attempted, for instance, to count the number of distinct rhythms that can be encoded in a given number of beats. This lecture was delivered to an enthralled audience of almost 1000 people. The day ended with a celebratory dinner at Christ University.

For all details please visit https://www.icts.res.in/science-at-icts

BETWEEN THE SCIENCE

Founding director of ICTS, **SPENTA WADIA**, handed over the directorship to **RAJESH GOPAKUMAR** on August 1, 2015. Spenta Wadia will remain at ICTS-TIFR as Emeritus Professor. Gopakumar completed his PhD from Princeton University. He was a postdoc at Harvard University and a long-term visiting member at the Institute for Advanced Study, Princeton. His area of research is theoretical physics with a focus on Quantum Field Theory and String Theory. Before joining ICTS, he was a faculty member at the Harish-Chandra Research Institute in Allahabad.

SIVARAM AMBIKASARAN joined ICTS-TIFR on July 30, 2015 as a Junior Faculty. Before joining ICTS, he was an assistant professor at the Courant Institute of Mathematical Sciences, New York University. His research interests are in Fast Algorithms, Numerical Linear Algebra, Discrete Mathematics, Approximation Theory, Inverse Problems, Data Analysis and Assimilation, Filtering.

VISHAL VASAN (previously with the Department of Mathematics, Pennsylvania State University, USA) joined ICTS-TIFR as a Junior Faculty in July 2015. His research interests are in Applied Mathematics, Partial Differential Equations with an emphasis on the theory of surface waterwaves and interests in related boundary-value and inverse problems, Analytical and numerical methods to investigate partial differential equations.

ANUPAM KUNDU joined the ICTS Faculty in May 2015. He was a Feinberg Research Fellow at the Weizmann Institute. His research interests are broadly in the field of non-equilibrium statistical mechanics, in particular fluctuations in non-equilibrium systems, transport of energy across materials, structural and extremal properties of Brownian trajectories.

SAMRIDDHI SANKAR RAY joined as a Faculty member at ICTS. His areas of research are Turbulence, Non-equilibrium Statistical Mechanics, and Fluid Dynamics.

SHASHI THUTUPALLI (now a HFSP Cross Disciplinary Fellow at Princeton University) will join ICTS-TIFR at a Joint Faculty position later this year. He will join the National Centre for Biological Sciences as a regular faculty member at that time. His research interests are in collective behavior and emergent self-organization, mainly in non-equilibrium and non-linear systems.

KARTHIK GURUMOORTHY, Amazon Development Centre, Bengaluru, is now an ICTS Associate. His research interests are in dynamical systems and data assimilation, density estimation and image analysis.

R. LOGANAYAGAM is now a member of the ICTS-TIFR Faculty. Before joining ICTS in October 2015, he was a member at the Institute for Advanced Study in Princeton. His research interests are in String theory, Black hole physics and Quantum field theory with a focus on real time, finite temperature quantum field theory.

EINSTEIN'S WAVY MESSENGERS

PARAMESWARAN AJITH

Celebrating its birth centenary this year, the General Theory of Relativity propounded by Albert Einstein is the cornerstone of our understanding of high-energy astrophysics and cosmology. General Relativity describes gravity as the curvature of spacetime, caused by the mass and energy content in the spacetime. Whenever these mass-energy concentrations change shape, the theory predicts that oscillations in the spacetime curvature would propagate at the speed of light as *gravitational waves.*

Although his theory predicts their existence, Einstein himself doubted the existence of gravitational waves in the physical world. Indeed, the field equations of General Relativity admit wave-like solutions. But the question was whether these were 'physical' waves that carry away energy, or an artifact of choosing wave-like coordinates. In the height of skepticism, Arthur Eddington famously declared that "gravitational waves propagate at the speed of thought."

The theoretical community eventually reached a consensus on the physical nature of gravitational radiation by the 1960s, thanks to a large body of mathematical work in General Relativity that took place in the previous decade. However, what finally settled this debate was the discovery of the first binary pulsar system by Russel Hulse and Joseph Taylor in 1975. This is a system of two neutron stars with an orbital period of about 8 hours. The loss of orbital binding energy and angular momentum due to gravitational radiation causes the orbital separation to decrease. The corresponding decay in the orbital period was measured using a few years of radio observations, which agreed precisely with the prediction of General Relativity as due to gravitational radiation. In the coming decades, radio observations of several binary pulsars corroborated this, providing a strong body of indirect evidence of the existence of gravitational waves.

Gravitational-wave astronomy: A new window to the Universe

While the radio observations mentioned above measure the *effect* of gravitational radiation on its source, several energetic astrophysical or cosmological events are expected to produce gravitational waves that can be *directly* detected from the Earth. Large international scientific collaborations are involved in an exciting quest for the direct detection of gravitational waves on a variety of fronts. Some collaborations aim to detect gravitational waves by measuring tiny distortions in the space by employing kilometer-sized laser interferometers, some aim to measure the effect of gravitational waves on the arrival times of radio pulses from millisecond pulsars (which are extremely precise clocks provided by the nature), some aim to detect the signature of gravitational waves on the cosmic microwave background radiation – the first light from the early Universe.

The first direct detection of gravitational waves is expected to happen in the very near future, and this decade will witness the emergence of a new branch of astronomy. Gravitational-wave signals carry information that is complementary to that carried by electromagnetic signals, and are the only messengers suitable for directly probing certain astrophysical and cosmological phenomena, such as binaries of black holes or very early Universe. Gravitational-wave observations will corroborate, complement, and perhaps challenge our understanding of the Cosmos gained from electromagnetic, neutrino and cosmic-ray astronomy. Apart from enabling us to perform precision tests of General Relativity in a regime currently inaccessible to astronomical observations (where gravity is strong and nonlinear effects are apparent), gravitational-wave observations will enable us to answer some fundamental questions in physics, astrophysics and cosmology.

Gravitational-wave observations will corroborate, complement, and perhaps challenge our understanding of the Cosmos gained from electromagnetic, neutrino and cosmic-ray astronomy

Gravitational-wave signals will carry imprints of the properties of their astrophysical source. For example, from the observed signal from a binary system consisting of black holes, we can make accurate measurements of the source properties – such as the masses and spin angular momenta of the black holes, the location of the source on the sky and the distance to the source, etc. Such observations will also allow us to carry out precision tests that will tell whether these objects are indeed black holes described by General Relativity as opposed to more exotic objects. Major science goals of gravitational-wave astronomy include direct observations of astrophysical black holes and understanding their nature, measurements of the masses and spins of black holes and neutron stars and inferring the mass and spin distributions of astrophysical populations, providing evidence of intermediate-mass black holes, obtaining equation of state of dense nuclear matter from tidal deformation of neutron stars, understanding the central engine of gamma-ray bursts and internal processes in core-collapse supernovae, mapping the merger history of galaxies and supermassive black holes, and proving independent estimates of cosmological parameters. In addition, gravitational-wave observations might also uncover some completely unexpected phenomena; all new astronomical windows have brought us big surprises in the past!

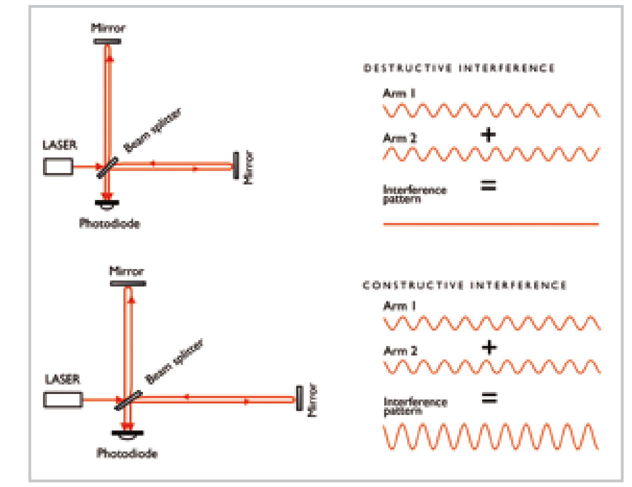


Figure 1: In a Michelson interferometer, a laser beam is split by a beam splitter and sent in two orthogonal directions. These beams are reflected back by two mirrors, which are in turn recombined to produce an interference pattern. Gravitational waves induce a relative length change between the two orthogonal arms, which produces a change in the interference pattern.

Figure 2: Aerial photograph of the LIGO-Livingston observatory in Louisiana, USA. LIGO observatories are sophisticated Michelson interferometer that have arm lengths of 4 kilometer

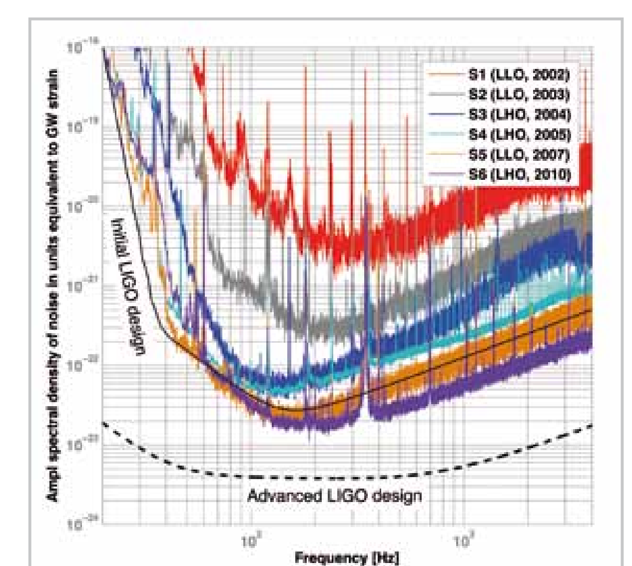


Figure 3: Evolution in the sensitivity of the Initial LIGO observatories during different science runs starting from year 2002. Also shown are the design sensitivity of Initial LIGO and the expected sensitivity of Advanced LIGO. Achieving a strain sensitivity of 2.5×10^{-23} amounts to measuring differential changes of the order of 10^{-19} meters in the arm-length of the 4 km-long LIGO interferometers.

Gravitational-wave detection using laser interferometers

At large distances from their source, gravitational waves can be viewed as tiny time-dependent oscillations on the geometry of space. The spatial deformations could be measured by means of large Michelson interferometers (see Figure 1). Since the expected values of the gravitational-wave amplitude from realistic astrophysical phenomena are of the order of 10^{-22}, even kilometer-scale laser interferometers should have the sensitivity to measure changes of the order of 10^{-19} meters in their arm length (see Figure 2). Laser interferometer technology has been tailored for the specific purpose of gravitational-wave detection during the past two decades, which helps the modern interferometric detectors to beat a number of fundamental and technical noises that affect the measurement at this sub-nuclear length scales. Experimental efforts for gravitational-wave detection have been driving the precision measurement science for more than two decades.

Several first-generation interferometric detectors (in particular, three LIGO detectors in the USA) have completed several science runs after achieving their designed sensitivity (see Figure 3). The non-detection by these observatories is consistent with our expectation of the rates of the astrophysical phenomena that produce gravitational waves of detectable strength. The upgraded second-generation instruments (Advanced LIGO) have started their operation in September this year, and are expected to approach their design sensitivity by around 2018-2019. These advanced detectors will provide a factor of 10 improvement in the sensitivity as compared to their first generation counterparts, and hence will result in a factor of 1000 improvement in the rate of detectable gravitational-wave sources. Even after considering the (known) uncertainties in the astrophysical event rates, the advanced gravitational-wave detectors are expected to make their first discoveries in the next few years, thus opening a fundamentally new branch of observational astronomy.

LIGO-India: The Indian participation in Advanced LIGO

Laser interferometric gravitational-wave detectors are nearly omnidirectional instruments. This is, at the same time, a blessing and a curse. While this enables us to observe the entire sky using a small number of instruments, single detectors do not have the ability to extract the sky-location of transient signals. Sky localization of the source is achieved by combining data from geographically separated detectors, using different techniques. The simplest technique of *triangulation* makes use of the fact that gravitational waves travel at the speed of light. This allows us to reconstruct the sky-location of the source from the arrival times of the signal at multiple detectors. Localizing gravitational-wave sources accurately on the sky is crucial for astronomy, since several gravitational-wave sources (such as the merger of binaries involving neutron stars) also produce electromagnetic counterparts. 'Multi-messenger astronomy' – combining observations from multiple astronomical messengers – will provide a more comprehensive picture of the astrophysical phenomenon.

The uncertainty with which a network of detectors can localize a source on the sky is proportional to the wavelength of the signal and is inversely proportional to the distance between different detectors forming the network. The gravitational-wave signals detectable by ground-based interferometers have rather large wavelengths – of the order of hundreds to thousands of kilometers. With the upcoming detector network (consisting of Advanced LIGO observatories in the USA and Advanced Virgo in Europe) accurate sky-localization of gravitational-wave sources will be challenging. The LIGO-India project is proposed to remedy this situation.

LIGO-India, a joint Indo-US project, proposes to relocate one of the three Advanced LIGO interferometers to Indian soil. LIGO lab in the USA, along with its international partners, will provide all the interferometer components such as the lasers, optics, suspensions and mechanical isolation systems. The Indian team is to set up the ultra-high vacuum system, assemble and commission the interferometer and operate it jointly with the LIGO lab. LIGO-India will significantly enhance the baseline of the international gravitational-wave detector network, and hence our ability to do astronomy using gravitational-wave observations. In addition, it will also give the Indian science the opportunity to play a major role in a research frontier that is expecting major discoveries in the near future. It will also facilitate the transfer of some key technologies and skills employed in precision measurements. The proposal, submitted in 2011, is still waiting for the final decision from the Indian Union Cabinet. The Indian scientific community hopes that the country will embrace this unique opportunity.

Parameswaran Ajith is an astrophysicist and a faculty member at ICTS-TIFR.

www.icts.res.in

STRINGS 2015

The Strings conference, held every year since 1995, is the most important yearly meeting of string theorists from around the world. The latest edition of this series – Strings 2015 – was hosted by ICTS in Bengaluru from June 22-26 this year.

Over the course of this meeting, speakers from around the world reviewed many of the most important developments in string theory research over the previous year in approximately 30 plenary talks, about an equal number of parallel session talks and three review talks. The lectures were on topics ranging from possible signatures of stringy physics in the cosmic microwave background, the prospects of new physics at the LHC, progress on the conformal bootstrap program, the role of entanglement entropy in the AdS/CFT correspondence, new exact results in quantum field theory and new developments in the theory of gravity.

The talks were held at the JN Tata Auditorium, on the Indian Institute of Science campus, on the first three days, in smaller lectures halls on the fourth day and in the Chandrasekhar Auditorium in the ICTS new campus at Hesaraghatta on the last day of the meeting. The final session of the meeting, on the afternoon of Friday the 26th of June, was a special celebratory session to commemorate a hundred years of general relativity. David Gross, Edward Witten, Peter Saulson, Francois Bouchet and Juan Maldacena presented talks surveying the accomplishments of the general theory over the last hundred years and looking towards the future.

On the morning of Saturday the 27th – the day after the strings meeting – Ashoke Sen and Nima Arkani-Hamed participated in an interactive session with students, fielding their questions on a range of subjects for over two hours. On the afternoon of the same day, Nathan Seiberg, Andy Strominger and Cumrun Vafa presented public talks at the Christ University Auditorium in central Bengaluru.

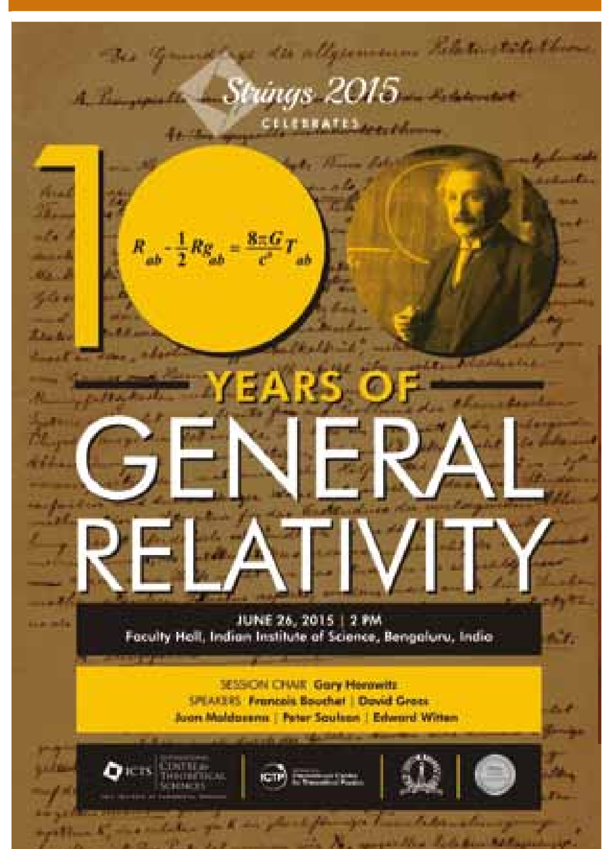
During the main conference banquet, professors John Schwartz and Tamiaki Yoneya delivered after dinner speeches recalling the historical birth of string theory. The speakers reminisced how string theory was originally developed as a candidate theory of the strong interactions but was then reinterpreted as a quantum theory of gravity in the 1970s. The post script to this story was written only with the discovery of the AdS/CFT correspondence in 1997, which made it clear that the same string theory can describe both a Yang Mills gauge theory and a quantum theory of gravity.

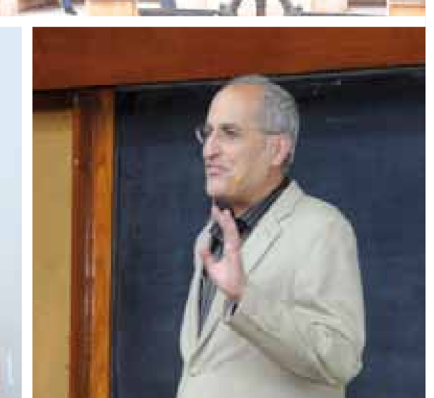
Strings 2015 appears to have been an extremely rewarding meeting, both for the approximately 300 string theorists who attended it as well as for members of the public and the larger Indian scientific community who were able to catch a glimpse of the excitement of the vibrant international string theory research program.

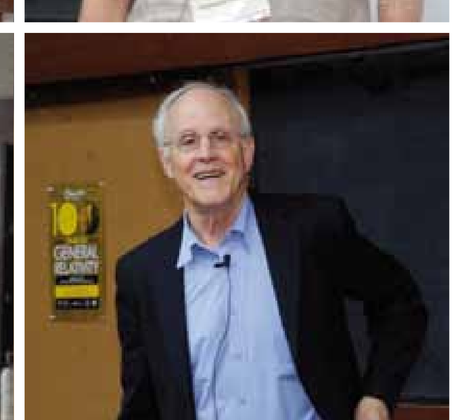
For details on Strings 2015 and associated programs please visit https://strings2015.icts.res.in/.

By Shiraz Minwalla, Tata Institute of Fundamental Research, co-organiser Strings 2015.

100 YEARS OF GENERAL RELATIVITY







100 YEARS OF GENERAL RELATIVITY

PUBLIC LECTURES

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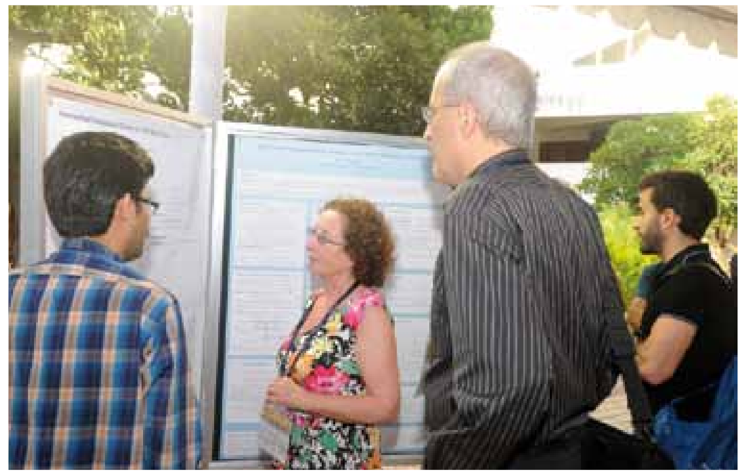
STRINGS 2015



PROGRAMS

MECHANICAL MANIPULATIONS AND RESPONSES AT THE SCALE OF THE CELL AND BEYOND

ORGANIZERS
Aurnab Ghose, Darius Koester, Roop Mallik, Satyajit Mayor, Thomas Pucadyil and Pramod Pullarkat
DATES
24 April-7 May, 2015
VENUE
NCBS and RRI, Bengaluru

The understanding of biological processes at a cellular and sub-cellular scale has made a big leap forward, thanks to the new tools that have made the advance from a qualitative to a quantitative description possible. The application of a wide variety of techniques to mechanically manipulate single molecules or multi-cellular cell composites has allowed scientists to address the question of how organisms react to controlled mechanical cues. This two-week long program introduced a bouquet of techniques to gain quantitative information of responses of biological material (at all scales) to perturbations of a mechanical nature, and explored how the combination of theory and experiments lead to a systematic deciphering of the physics of how living material engages with mechanical information. In addition, there was a discussion meeting, to discuss recent results in the field of Cell Mechanics. This was a joint program of ICTS with NCBS and RRI, Bangalore.

GDR DYNAMO 2015

ORGANIZERS
Emmanuel Dormy, Stephan Fauve, Samriddhi Sankar Ray, Binod Sreenivasan and Mahendra Verma
DATES
1-12 June, 2015
VENUE
ICTS-TIFR, IISc Campus, Bengaluru

Dynamo or self-induced magnetic field generation in nature and laboratory is a very important area of research in physics, astrophysics, geophysics and solar physics. The problem has remained largely unsolved for a century due to its nonlinear nature. This field is multidisciplinary with active involvement from theoreticians, experimentalists, and computational scientists. Considering the importance of this problem in various fields, a large number of complex large-scale simulations and experiments have been performed, which provide very valuable insights into dynamo mechanisms including dynamo reversals. Many simulations and several large-scale experiments have been planned for further exploration of dynamo processes.

ADVANCED STRINGS SCHOOL 2015

ORGANIZERS
Justin David, Chethan Krishnan and Gautam Mandal
DATES
11-18 June, 2015
VENUE
Physics Department, Indian Institute of Science, Bengaluru

Strings School 2015 introduced a wide range of basic background material for the latest developments in String theory, Quantum Field Theory and Gravity to senior graduate students and young postdocs. Another purpose of the School was to prepare young researchers for the Strings 2015 conference and bring about interactions and exchange of ideas among young physicists at a global level.

The areas chosen for the School covered most active areas of research in string theory over the last several years. The lectures, given by leading physicists, covered a selection of basic material as well as advanced topics at the forefront of current research.

SUMMER SCHOOL ON GRAVITATIONAL-WAVE ASTRONOMY

ORGANIZERS
Parameswaran Ajith, K. G. Arun and Bala Iyer
DATES
29 June-10 July, 2015
VENUE
ICTS Seminar Room, IISc Campus, Bengaluru

Albert Einstein's General Theory of Relativity, which is celebrating its centenary this year, predicts the existence of gravitational waves. Gravitational waves are freely propagating oscillations in the spacetime. The first direct detection of gravitational waves is expected to happen in the next few years by large laser interferometric detectors. Apart from the upcoming detectors in USA, Europe and Japan, there is an ongoing proposal to build a gravitational-wave observatory in India. This summer school on Gravitational Wave Astronomy aimed to train students and young researchers in the emerging area of gravitational-wave astronomy. The school involved four graduate-level courses on different topics of gravitational-wave astronomy. The lectures were given by five leading experts on these topics.

BANGALORE SCHOOL ON STATISTICAL PHYSICS - VI

ORGANIZERS
Abhishek Dhar, Sanjib Sabhapandit
DATES
2-18 July, 2015
VENUE
Raman Research Institute

This was a pedagogical school, aimed at bridging the gap between masters-level courses and topics in statistical physics at the frontline of current research. It was intended for PhD students, post-doctoral fellows and interested faculty members at the college and university level.

EXTRAGALACTIC RELATIVISTIC JETS: CAUSE AND EFFECT

ORGANIZERS
C. H. Ishwara-Chandra, Ajit Kembhavi, Preeti Kharb (Convener), Dharam Vir Lal, Anthony Readhead, Lakshmi Saripalli and C. S. Stalin
DATES
October 12-20, 2015
VENUE
ICTS-TIFR Campus, Bengaluru

Active Galactic Nuclei (AGN) are the luminous centers of galaxies that are believed to be powered by accretion of matter on to supermassive black holes. Bipolar outflows or jets that are launched from the accretion-disk black hole systems carry away angular momentum and impact the surrounding matter both inside and outside the host galaxies. Given the current computational power, AGN have become a test bed for general relativistic magnetohydrodynamics. AGN are sites of coalescing supermassive black holes, which are one of the primary science drivers of gravitational wave astronomy.

AGN jet astrophysics is at an important and exciting junction in time with the availability of ever-more sensitive multi-wavelength data and increased computing power. This program brought leading experts working on various aspects of AGN jet physics from around the world to Bengaluru. The program proved to be an invaluable opportunity for boosting AGN studies in India in time for India's participation in upcoming mega projects like SKA, TMT, LIGO-India, and ASTROSAT.

This program was organized in partnership with the Indian Institute of Astrophysics, Bengaluru.

NON-EQUILIBRIUM STATISTICAL PHYSICS

ORGANIZERS
Cedric Bernardin, Abhishek Dhar, Joel Lebowitz, Stefano Olla,
Sanjib Sabhapandit, Keiji Saito and Herbert Spohn
DATES
26 October - 20 November, 2015
VENUE
ICTS-TIFR Campus, Bengaluru

This program was organized as an advanced discussion workshop on some topical issues in non-equilibrium statistical physics. The aim of the program was to bring together active researchers to discuss outstanding problems. The main areas of focus in the workshop were:

- Heat and particle transport in low dimensional systems.
- Large deviation functions and fluctuations in non-equilibrium systems.
- Localization and thermalization.

AEI-ICTS JOINT WORKSHOP ON GRAVITATIONAL-WAVE ASTRONOMY

ORGANIZERS
Parameswaran Ajith, Bala Iyer and Bruce Allen
DATES
4-6 November, 2015
VENUE
ICTS-TIFR Campus, Bengaluru

This workshop on gravitational-wave astronomy was jointly organized by the ICTS and the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Hannover to mark the inauguration of the Max Planck Partner Group in Astrophysical Relativity and Gravitational-Wave Astronomy at ICTS. This workshop focused on issues related to the search for gravitational waves from coalescing compact binaries and spinning neutron stars. A special session was held on November 5 to talk about initiating collaborations between gravitational-wave astronomers and the core science team of the Indian multi-wavelength astronomy satellite project Astrosat in problems related to the search for gravitational-waves from accreting neutron stars.

LECTURE SERIES

CHANDRASEKHAR LECTURES

Random Matrix Theory and the dynamics of nonequilibrium interfaces
SPEAKER
Herbert Spohn
(Technical University, Munich)
DATE
27, 28, 29 October, 2015
VENUE
Ramanujan Lecture Hall, ICTS-TIFR

RAMANUJAN LECTURES

Understanding non-equilibrium: Some recent advances and a challenge for the future
SPEAKER
Giovanni Jona-Lasinio
(Sapienza University, Rome)
DATE
3, 4, 5 November, 2015
VENUE
Ramanujan Lecture Hall, ICTS-TIFR

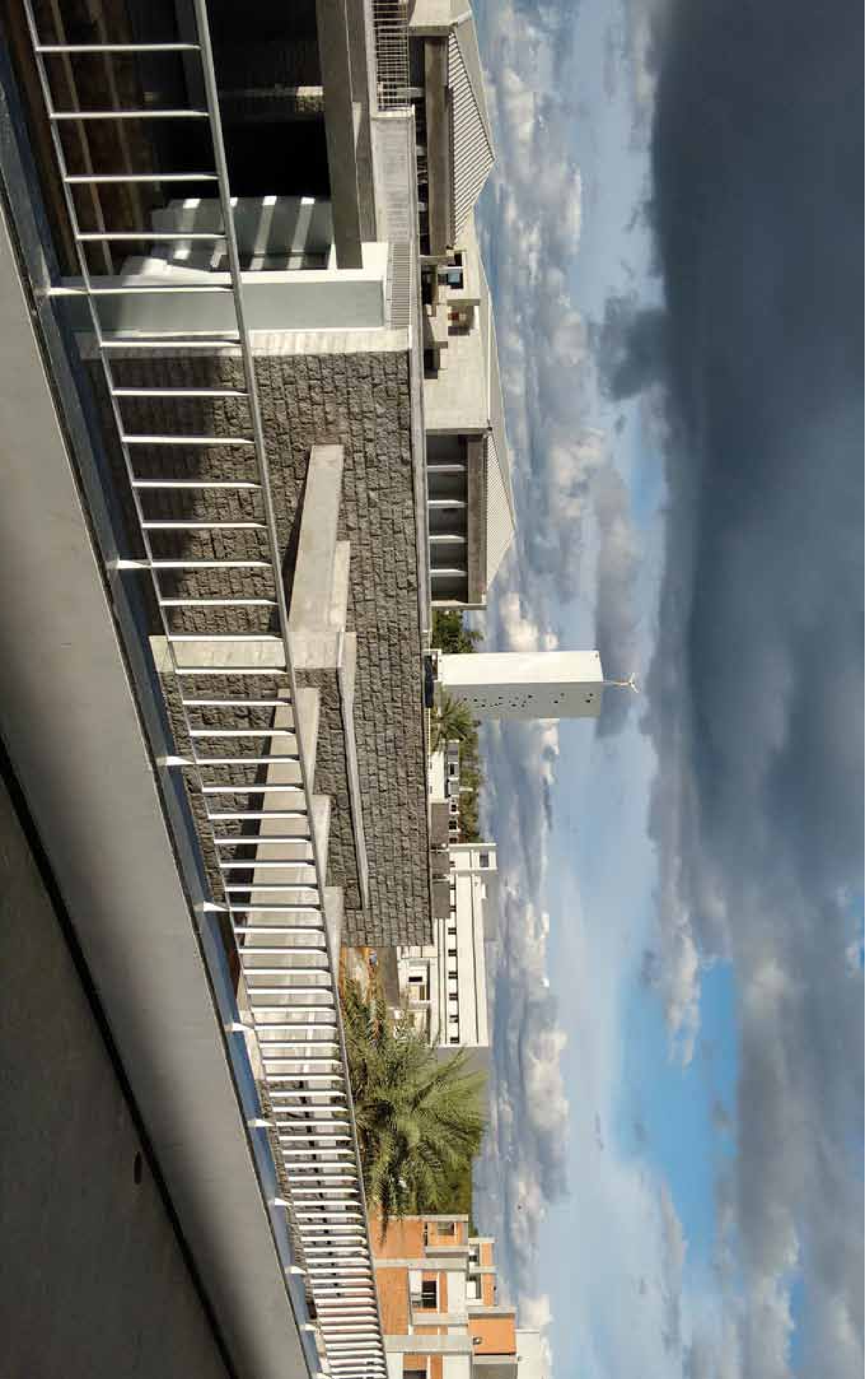
EINSTEIN LECTURES

Einstein's legacy, and the search for gravitational waves
SPEAKER
Bruce Allen
(Max Planck Institute for Gravitational Physics)
DATE
6 November, 2015
VENUE
Faculty Hall, Indian Institute of Science, Bengaluru

PUBLIC LECTURES

Astronomy, Big Data and Human Capital Development
SPEAKER
Bernard Fanaroff
(South African Square Kilometre Array)
DATE
16 October, 2015
VENUE
Chandrashekhar Auditorium, ICTS-TIFR

Time's Arrow and Entropy: Classical and Quantum
SPEAKER
Joel Lebowitz
(Rutgers University, USA)
DATE
10 November, 2015
VENUE
Chandrashekhar Auditorium, ICTS-TIFR



ICTS NEWS

International Centre *for* Theoretical Sciences

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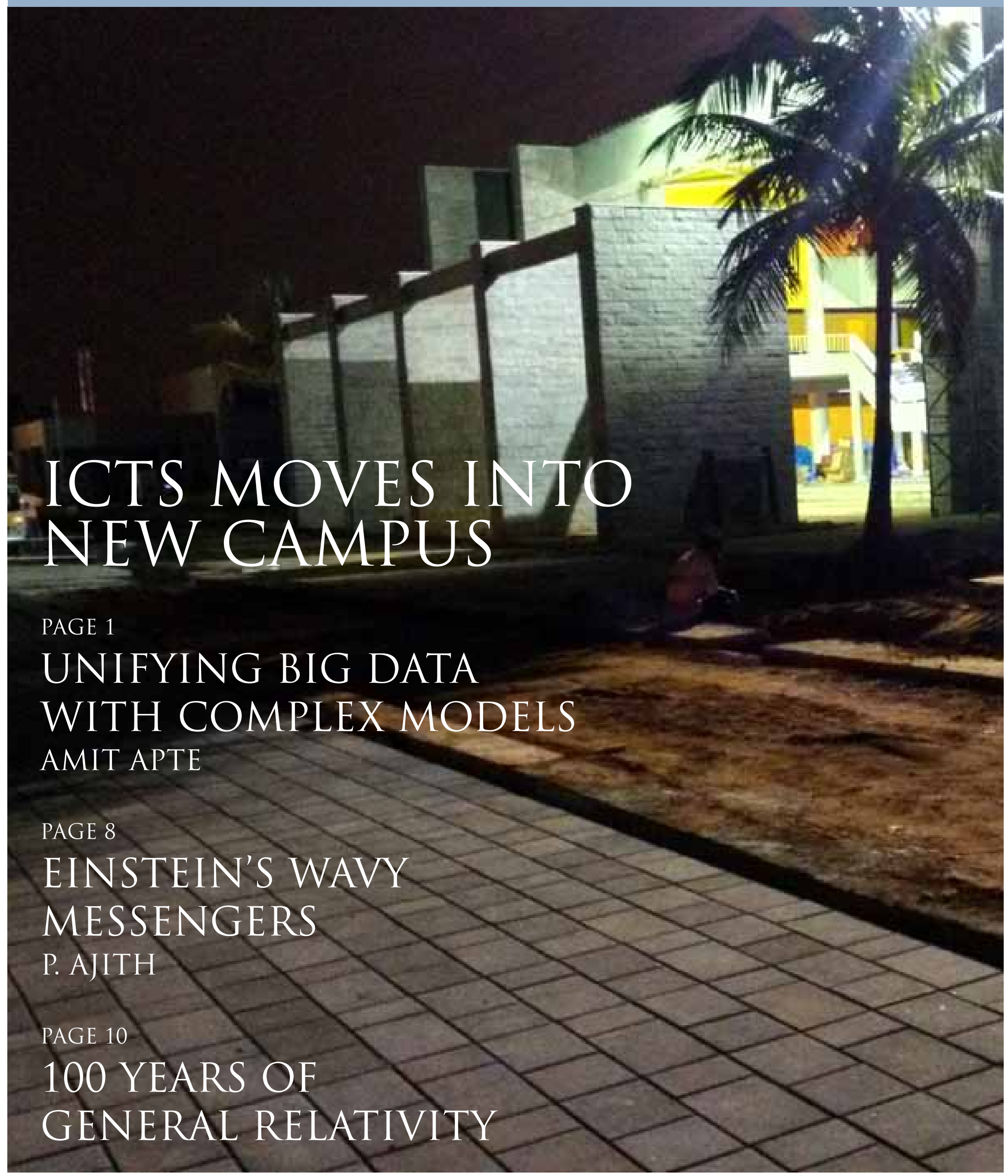
TATA INSTITUTE OF FUNDAMENTAL RESEARCH



ICTS MOVES INTO NEW CAMPUS