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Council Report
Graphene, physics in two dimensions
Foam as a geometer
Space-quest
Directory, summary and website

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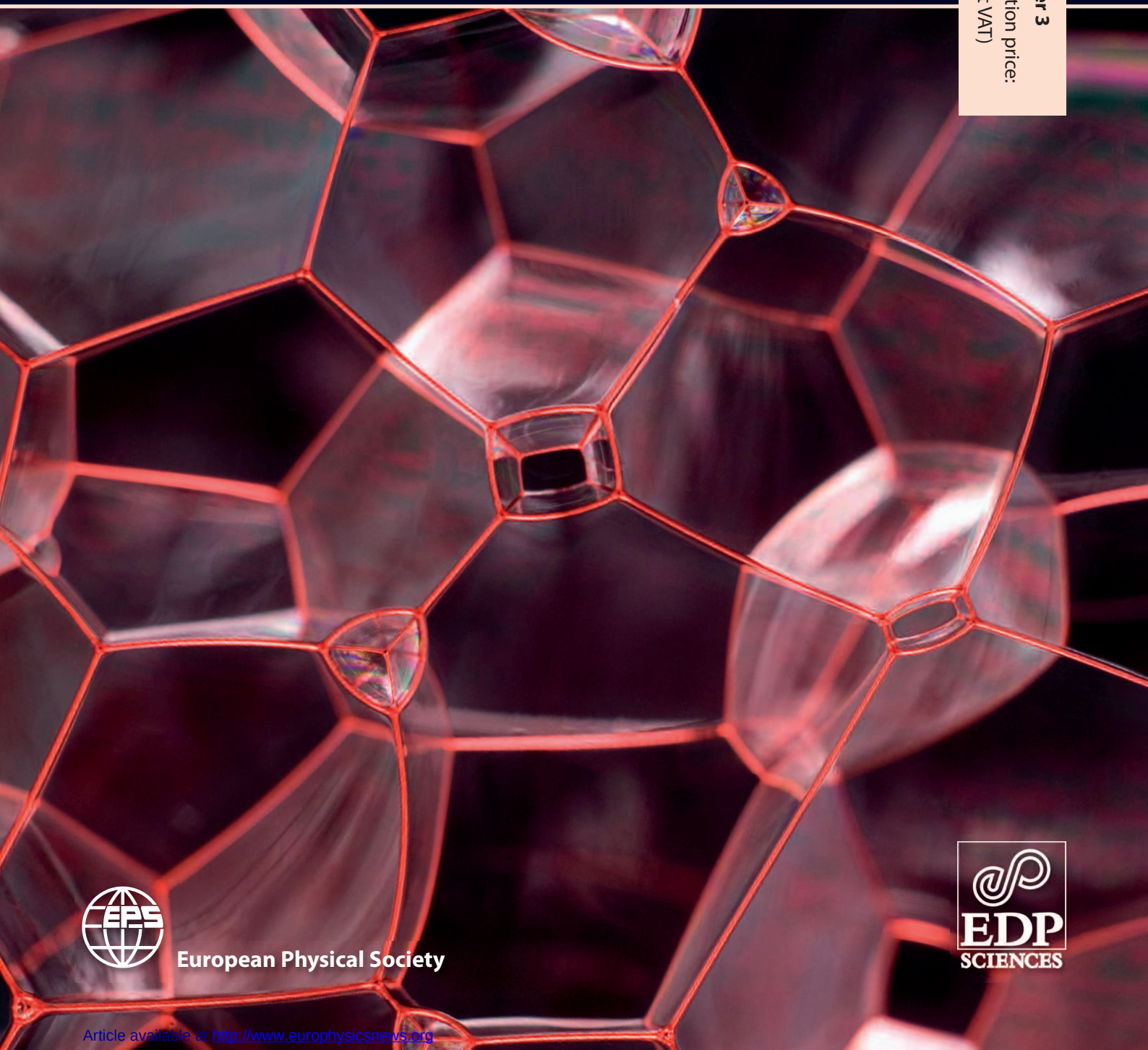

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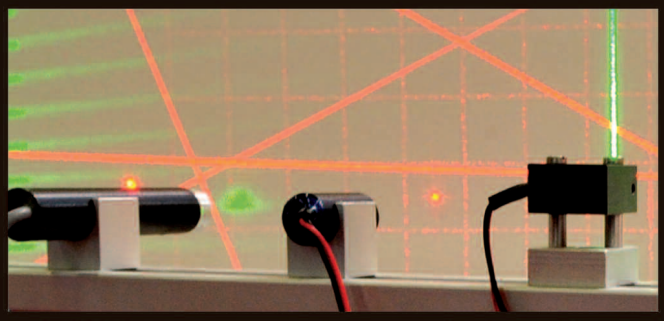

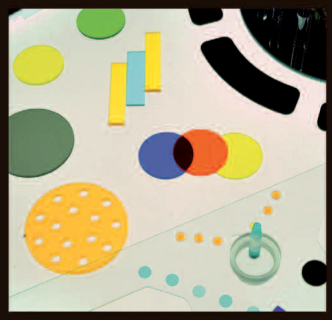

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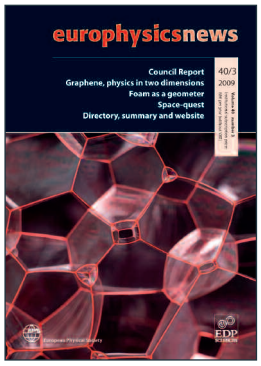

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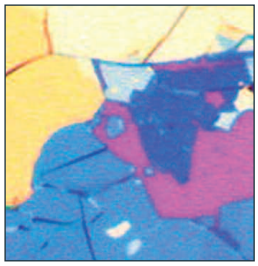
Cover picture: Closeup of the Iridescent surface of soap bubbles, made from red liquid, see *Foam as a geometer* p.21 © iStockPhoto



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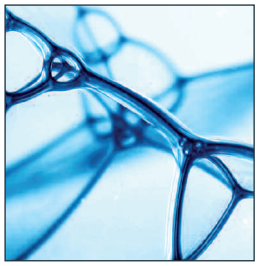
Graphene, physics in two dimensions



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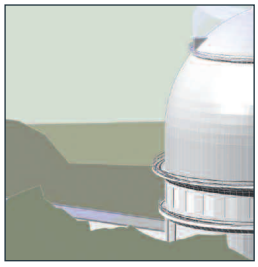
Foam as a geometer



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Space-quest, experiments in space

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THE EPS MISSION – VIEWS OF THE PRESIDENT

During the opening session of the EPS founding congress in 1968, G. Bernardini stressed the importance of making science a "source of widespread, deep-rooted culture". The other major topics of early EPS activity were:

- Support of European journals,
- The huge growth of the student population,
- The relation between pure and applied physics, science and industry.

Looking at G. Bernardini's first phrase in today's context, I would (modestly) paraphrase it: "Physics is a very important part of human culture, providing methods to understand or at least describe the Universe and being the basis for technology". The other topics seem to evolve reasonably well. Only "the huge growth" changed into "the deep decrease" of student population.

Our technical civilization (with its advantages and failures) and the current transition to information society was made possible in part by physics methods and discoveries. Ironically, this has led to a decrease in the visibility and understanding of physics. Like a User's Manual, physics provides too much detail, requires learning, and includes math. Classical physics is becoming background noise, dissolved in integrated science. It may seem that physics belongs to the past, and who cares about the past, glorious though it may be? Particularly during a crisis.

Our role is to show that physics is still important. Physics is forever young, solving new generations of problems (energy, environmental pollution and protection, nano, macro, black matter and Higgs etc) and looking deeper into the Universe. Methods, equipment and topics are changing. Difficult problems related with technical development exist and they cannot be avoided. However, only farther research and implementation of new methods are part of the solution. Progress of science and technology and the transition to a clean and environment friendly industry is not possible without physics and physicists. All diagnostic methods in medicine, biology, astronomy etc. are based on physics. This should be gently but constantly shown to the general public. The younger generation should be the main target of EPS promotion of physics. With a slight exaggeration, I would say that all EPS activities should serve to promote physics, science or technology.

The European Union has developed today to 27 member states and Europe's role in scientific research and policy has grown, e.g., through the framework programmes, European Research Council, European Research Area etc. The spectacular development in the Far East, particularly in China, means that it should play an important role in all domains, including science. This gives us broad and fascinating possibilities of activities and a variety of tasks. Moreover, the current serious financial crisis also starts to influence many of our initiatives.

Let's come back to EPS activities. The strategic task is constant:

EPS should be an active and visible policy - making society.

To achieve this goal let's divide the activity into six themes:

- **Education** on all levels (from curiosity to competition), trying to cooperate with teachers and educators
- **Professional physics activity**, building up the European Research Area, policy initiatives which favour the progress of science
- **Digitalisation of information** together with a revolution of the publication market
- **Worldwide alerts** *e.g.* clean energy and environmental protection
- **Cooperation with learned societies and associations**
- **Promotion and evolution of EPS**.

I will not go into details here, but the possibilities of diverse EPS bodies (Member Societies, Divisions and Groups, Committees, Associate Members, Collaborating Societies, Individual Members) give us a large capacity to act. They assure the effectiveness as well as usefulness of the Society.

Let me only mention three "principles":

- EPS activities should be "target oriented"
- Our current priorities need to be promotion, outreach and education
- Our obligation is to change the perceptions of physics from difficult and useless to exciting and professionally challenging and rewarding. Our image as physicists should also be improved from eccentric and poor to creative and interesting.

Any ideas (or financial resources) to this are welcome. ■

Maciej Kolwas, President of the EPS

COUNCIL REPORT

27-28 MARCH 2009, BAD HONNEF, GERMANY

Council 2009 provided an opportunity to review the activities over the past year, as well as introduce new elements that will go towards the development of future strategy. The meeting began on a sad note, commemorating the sudden and untimely death of J. Beeby in January 2009. P. Melville gave a touching tribute to J. Beeby's memory.

The President, F. Wagner, was heavily engaged on behalf of the EPS in 2008. He multiplied his visits to Member Societies, addressing key issues to better coordinate EPS/MS activities. In addition to the festivities at the last Council meeting, the EPS 40th anniversary celebrations in 2008 also included EPS14/CMD22 and the EPS General as well as a press conference at CERN.

He reminded the Council delegates that the EPS, through its Divisions and Groups is responsible for around 90 conferences and workshops per year. This shows the importance of the EPS and its Divisions and Groups in the dissemination of scientific results. Through the development of energy workshops, the EPS is bringing together the national energy groups to share experience. Moreover, the EPS, together with EuCheMS, the EMRS and the ESF will begin a new European Energy Conference Series, bringing together the physicists, chemists and materials scientists to look at the interdisciplinary aspects of energy research and development. The EPS also has a role in conference harmonisation and will work with Member societies and Divisions and Groups to enhance European conferences.

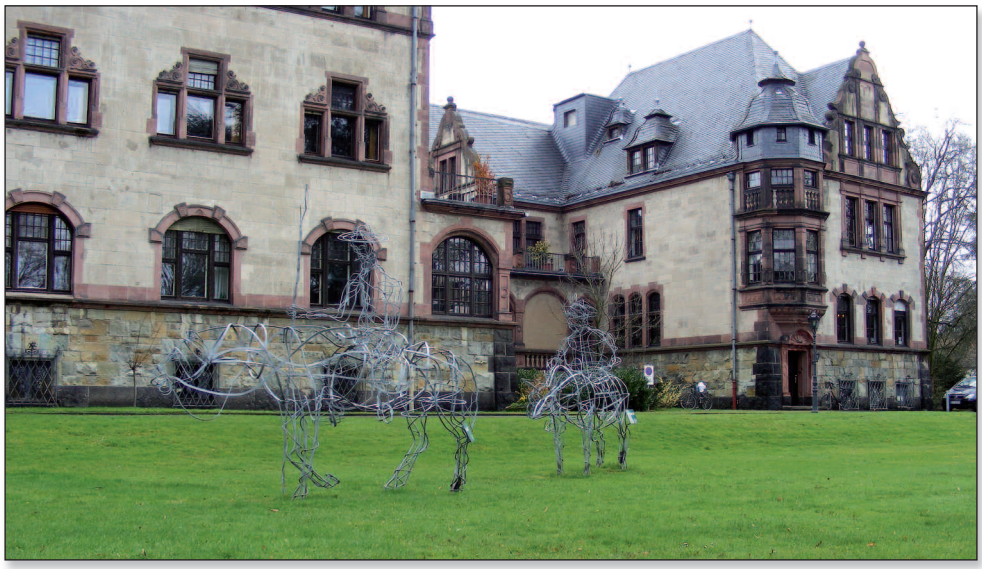
Although EPS Members were notified that a proposal would be made at Council 2009 to increase the membership fees, this proposal was withdrawn due to the current international financial situation. EPS finances remain sound.

With respect to publications, the EPS has been active, bringing together learned society publishers and publications to look at concrete measure to harmonise the European publishing landscape and how to make European publications more attractive to authors. One instance where more collaboration has been beneficial is EPL, which has developed in terms of visibility and impact through the association of the EPS, the French Physical Society, the Institute of Physics (UK) and the Italian Physical Society.

Together with 24 Member Societies, a study of the implementation of the Bologna Process in Physics Studies is currently being undertaken, financed by the European Commission. Questionnaires and curricula have been collected from over 100 universities. This shows the ability of the EPS to conduct Europe-wide studies, has created a network of individuals interested in physics education and has allowed the MS to enhance their contacts in the physics departments.

The EPS also hosted a meeting to look at how MS could increase their membership. Some of the conclusions from the meeting that help to increase membership include contacts to high school teachers, and high school students and good contacts among the university physics departments.

The EPS Executive Committee also explored the best way to become involved in scientific policy development at the European level. It participated, at the request of the IoP, in contacting policy makers at EU Parliament Committee on Industry, Research and Energy and the European Economic and



▼ Physikzentrum of the the University of Bonn in Bad Honnef (Germany), Headquarters of the DPG (German Physical Society)

Social Council to reconsider the MRI initiative, which would jeopardise the use of MRI techniques in the medical field.

F. Wagner was instrumental in launching the Large Facilities Technical Network. The LFTN will bring together research project leaders to create a network for the exchange of information and best practice in the scientific and technical management of large research projects.

The EPS has also begun working in new directions. A position paper on the contributions of physics and the need for a high quality physics education is under consideration. The EPS wants to be active in providing input for the development of Framework Programme 8.

M. Kolwas was confirmed as President of the EPS, and F. Wagner agreed to serve a further year as Vice-president. No elections were organised this year, though two new members of the Executive Committee were co-opted: Martina Knoop (replacing Françoise Masnou Seeuws), and Colin Latimer (replacing John Beeby). The other members of the Executive Committee are Marcin Auzinsh, Hendrik Ferdinande, Anders Kastberg, Ana Proykova, Klaus Wandelt, Victor Velasco, Angela di Virgilio. Council thanked F. Wagner for his hard work and dedication as President.

The EPS is still growing, and admitted the Association of Physicists in Luxembourg as the 41st Members Society of the EPS. Council also approved as Collaborating Societies EuCheMS (European Association for Chemical and Molecular Sciences); the AAPPS (The Association of Asia Pacific Physical Societies); and the EMRS (the European Materials Research Society).

Council approved the proposition to dissolve the Joint Astrophysics Division. The proposal was made by the JAD and was motivated by the lack of significant EPS acitivity in this field. The high energy particle and gravitational waves aspects of astrophysics would be included in future in the High Energy and Particle Physics Division.

Council approved the creation of a Solar Physics Division (S. Poedts, Chairman) as well as the creation of an EPS Energy Group (T. Hammacher, Chairman).

As part of this year's Council meeting, Sven Kullander from the Swedish Royal Academy of Sciences gave a remarkable presentation of current renewable energy sources and research. At the after dinner session, Berndt Feurbacher invited Council delegates on a trip through time and space.

The EPS Council was hosted on this year in the Physikzentrum Bad Honnef, which is run by the German Physical Society and supported by the University of Bonn and the state North Rhine-Westphalia. The PBZ is an impressive manor set in a wooded park, and is the EPS would like to express its thanks to the DPG and to V. Gomer and his staff for their efficiency and friendliness. ■

David Lee,
Secretary General of the EPS

PRIZES & AWARDS

The inaugural Walther Award

The Optical Society of America and the Deutsche Physikalische Gesellschaft (DPG) announce that their inaugural Herbert Walther Award is presented to **David J. Wineland**, of the National Institute of Standards and Technology (USA) for his seminal contributions to quantum information physics and metrology. The ceremony is in Munich during "LASER, World of Photonic" in June 2009.
For more, contact: Angela Stark, 202.416.1443, astark@osa.org and website www.osa.org.

King Faisal International Prize 2009

The King Faisal Foundation in Riyadh, Saudi Arabia announced that physicists Sir **Richard Henry Friend** and **Rashed Alievic Sunyaev** have jointly won the 2009 King Faisal International Prize for Science.

◄ Sir Richard Henry Friend

Rashed Alievic Sunyaev ►

The science subcategories cover physics, mathematics, chemistry and biology by rotation. The prize has a cash endowment of Saudi Riyal 750,000 (about US$200,000) to be shared equally. The winners have received their awards in March in a ceremony in Riyadh under the auspices of the King of Saudi Arabia.

Sameen Ahmed Khan,
Salalah College of Technology (SCOT),
Sultanate of Oman, rohelakhan@yahoo.com

2009 Walter Hälg Prize

Every two years the European Neutron Scattering Association (ENSA) awards the prestigious Walter Hälg Prize to a European scientist for an outstanding programme of research in neutron scattering with a long term impact on scientific and/or technical neutron scattering applications. The Prize of 10,000 Swiss Francs, is donated by Professor Walter Hälg, the founder of neutron scattering science in Switzerland.

◄ Dieter Richter

The selection committee is delighted to announce that the recipient of the 2009 Walter Hälg Prize is **Professor Dieter Richter** of the Research Center Jülich, Germany, in recognition of his coherent work towards understanding the dynamics of polymers and biological macromolecules using high-resolution neutron scattering techniques.

NEW MEMBERS OF THE EPS EXECUTIVE COMMITTEE

Martina Knoop (1965, Marseille, France)

Born in France, I lived in Belgium and different parts of Germany. I studied at the University of Tübingen, starting in 1984, and concluding with a diploma work in solid state physics. I took a new thematic start in 1991 with my PhD thesis in atomic physics at Université de Provence/Marseille where I have been working as a CNRS researcher since 1995. I am an experimentalist, my research activities and interests include storage of ion clouds and single ions in radiofrequency traps of various size, lifetime measurements, investigation of collisional effects with trapped ions, generation of different (laser) wavelengths and laser stabilisation techniques, manipulation of atomic states with laser radiation, and very recently we have started to look into the ion dynamics of various multipole traps.

I am a member of the French and the German Physical Societies. I have been involved in activities of the French Physical Society and I served on its council for three years.

Personally, one of my major concerns is the decline of interest in physics in the European civil society, being reflected among other things in the decrease of student numbers. I look forward to actively contribute to EPS' declared aim to promote physics and physicists in Europe. ■

Colin Latimer (1944, Belfast, UK)

Colin Latimer has been Professor of Physics at the Queen's University of Belfast since 1997 and has also held appointments at Rice University, Houston, Texas and Tokyo Metropolitan University.

He has held numerous positions at the Institute of Physics and is a former Chair of the Irish Branch. He is a member of Council, the current Honorary Treasurer and on numerous related committees. He is also a director of IoP Publishing and has served on the editorial board of Journal of Physics B for many years.

His current research interests lie in the area of atomic and molecular processes and interactions of fundamental, technological, and astrophysical interest. This involves experimental studies of state selected ion-molecule collisions and reactions, molecular fragmentation and dissociative photoionization phenomena, negative ion production, VUV/EUV spectroscopy, XUV instrumentation for synchrotron radiation studies, and heavy ion radiation damage in DNA. In recent years he has chaired the UK SR Science Advisory Committee, the Institute of Physics Atomic Molecular and Optical Physics Division and the UK EPSRC Network on Molecules and Synchrotron Radiation. He is currently a member of the EPSRC Peer Review College, the European ITSLEIF programme and a French SOLEIL Synchrotron Peer Review Committee. He has also written and lectured widely on physics teaching and the history of science.

Like John Beeby, Colin plans to take a special interest in EPS financial matters and the general running of the organization. ■

GERO THOMAS MEDAL 2009

The recipient of the 2009 Gero Thomas medal is Dr. Jaroslav Nadrchal, a computational physicist who obtained his degree at Charles University, Prague (CZ), has worked in the Institute of Physics of the Czech Academy of Sciences, was head of the Department of Computational Physics there and became deputy director of the Institute of Physics.

He is active also in computational physics education on Czech Universities. In 1972 Jaroslav started his work for EPS as founding member of the Computational Physics Group (CPG) and later on as secretary of the group. He was the principal organizer of a series of 14 Summer Schools on Computational Physics and was a chairperson of the EPS East West Task Force from the start in 1996 till 2007.

Laudatio by EPS President, F. Wagner

The prize ceremony took place at the EPS Council meeting last March in Bad Honnef (Germany). The President emphasized that he was happy this time the prize went to a representative from an Eastern European country and very coincidently during the Czech presidency of the E.C.
The citation reads: *"For his pivotal work in EPS as chair of the East West Task Force and co-founder of the Computational Physics Group, organizing a series of Computational Physics Summer Schools"*

Reply by Recipient, Jaroslav Nadrchal

"I want to mention what my activities in EPS have meant for me and to append shortly a few (maybe) remarkable experiences.
Until 1989 I lived behind the Iron Curtain and my contacts in EPS enabled me personal contacts with people on the other side! I have oriented my activities to intensive spreading of contacts between physicists from countries behind the Iron Curtain with their colleagues at meetings in Czechoslovakia: mainly at 14 Summer Schools on Computing Techniques in Physics in 1975 - 2004. Physicists who could travel only with problems, could meet colleagues from developed countries there.
The Summer Schools series was an event that could not pass unnoticed by the Secret Police –the Czechoslovak and others, esp. Russian. We had to be careful but for all that the atmosphere was open and friendly. The so-called pigs among participants were often easily detectable: they were registered by non-scientific institutions, they were not interested in lectures etc. Sometimes we succeeded in distinguishing pigs – *e.g.* by red briefcases.

▲ **J. Nadrchal (left) receiving the G. Thomas Medal from the President of the EPS, F. Wagner.**

After the collapse of the Iron Curtain I was happy to administer EPS grants in the East-West Task Force [EWTF] for 12 years. The number of colleagues supported was on average five times higher than last year after the termination of the Taskforce.
I have been a member or a co-opted member of the CPG Committee since its beginning. It was a very active Committee during many recent years. However, the first years were quite critical: The Group was founded in 1972 but the first chairman soon became seriously ill and died after 2 or 3 years. The committee was resuscitated after 2 years: a new chairman was elected but he, too, got ill soon and chaired meetings in lying position. Bad beginning – successful follow-up. The crisis was overcome!
In 1984, I was the treasurer of the General Conference in Prague. To gain experience, an excursion for several people was organized by a Czechoslovak travel agency to the previous Conference in Istanbul. It was an extraordinary opportunity! I remember a small funny experience: The conference dinner was served in a glass-walled garden pavilion. The setting of tables took longer than expected, and hundreds of hungry people observed the preparation through windows. The Executive Committee wanted to utilize the time and met for its meeting. The hungry mob plundered tables when the doors were opened an hour later – the unfortunate EC members found just empty tables!
I liked all the work in EPS, I liked the collaboration with fantastic and friendly colleagues. I am grateful to EPS Presidents for their goodwill and appreciate the effective and well disposed Secretariat workers, especially David Lee, Sylvie Loskill and Patricia Helfenstein.
I wish to express my appreciation for the attitude of Gero Thomas towards the specific problems of citizens and national physical societies in Communist countries. For me, this is also a point why the prize should be dedicated to his memory.
At the end I wish to thank the EC for the honour they have done to me. I wish the Executive Committee can always work in the best conditions – not being hungry or in another inconvenient condition at the meetings!" ■

H. Ferdinande,
Chair of the medal Committee

THE EPS COMPUTATIONAL PHYSICS GROUP

To mark the 40th anniversary of the EPS, we have written a brief history of the EPS CPG (Computational Physics Group) including some remarks on the history of CP itself. To keep the history brief, few references are included as all are easily found on the web.

The CPG is not quite as old as EPS. In Europhysics News [EPN], vol. 1 no. 8 (1970) it was announced that the CPG had been set up. The announcement included the farsighted statement: ***There is a very broad range of the kinds of use made of computers in physics. They are used to solve complex sets of equations, to handle large quantities of data, to simulate physical situations and devices or to control experimental equipment recording and processing data in real time. Advances in computer technology and programming may equally bring new ways of applying computers and open up new avenues of research which would otherwise not be feasible.***

For further details, see also EPN Volume 2 (1971).

Computational Physics, as the term is now understood, based upon the using of programmable electronic machines, has a history that starts sometime during the Second World War, but there was a very substantial pre-history: see for example the preface to Whittaker and Robinson's "The Calculus of Observations" which refers to Whittaker's lecture courses between 1913 and 1923 in the Mathematical Laboratory of the University of Edinburgh. There were also Herculean efforts on planetary (and lunar) orbits in earlier centuries.

One of the earliest post-war non-military electronic computers reported was the thermionic-valve based SSEM [Small Scale Experimental Machine] at the University of Manchester, on which the first successful run of a program was made on 21st June 1948, 60 years ago.

The first high-level computer language, FORTRAN appeared in 1957. Many other languages have come and gone since then, but it has continued to evolve, and is still much used.

The earliest identified use of the term "Computational Physics" was by Berni Alder, circa 1963.

By the late 1960s some of the larger Physics Departments in Universities had mainframe computers.

In 1965 Moore formulated his famous Law: that the number of transistors on an integrated circuit would double every 18 months or two years. This empirical law has proved remarkably accurate (see Wikipedia): in the 60 years since the invention of the transistor in 1948, the number of transistors on a chip has doubled some 30 times. Currently the number is over 2^{30}, *i.e.* 1GB.

A more general version of Moore's Law is that everything in computing halves or doubles every two years, so in the 40 year history of EPS, there has been a change of some 2^{20} times *i.e.* a million times. A change of that magnitude is so large that it may not be just a quantitative change, but may represent qualitative changes. Two examples are cameras and operational amplifiers. (1) Film cameras have been almost completely replaced by digital cameras. (2) In the early 1960s the cost of an operational amplifier was comparable with one's monthly salary, while for some time now the cost has been less than that of a cup of coffee. This means that operational amplifiers are comparable in cost with other circuit elements such as resistors, and one can, for example, construct a simple circuit with a few resistors, a capacitor and two op amps to simulate an inductor of as large an inductance as is needed, for a few pence.

By 1972 there had been further progress: the first scientific pocket calculator, the HP35 appeared. Its cost was about the same as the cheapest desktop computer in 2008. It was also possible for individual researchers to buy minicomputers, such as a PDP 8 or a PDP11, for their own research. To start such a computer, one had to enter the "bootstrap" program by operating a row of toggle switches. Such computers were minuscule by current standards, and were expensive. The maximum memory was about 56kb, and it cost about £1 per byte. That was in the days of magnetic core memory, all hand knitted! In 1976 the Rutherford Laboratory computer, one of the largest available to the scientific community in Great Britain was closed for a weekend while its memory was upgraded from 1MB to 2MB.

Programmable calculators and desktop computers, with graphics appeared in the mid 1970s: many will remember the Apple II. The memory available was measured in kilobytes, and in programs the variable names were usually A, B, C etc: longer names took up too much memory. The joy of being able to print out a graph, and not having to use tabs and linefeeds on a line printer with "+" and "x" etc!

We now have super computers, which use so much electric power that they require special cooling. Come to think of it, not everything has changed qualitatively in the past 40 years!

Conferences

The first conference organised by the CPG, the First European Conference on Computational Physics, with the theme "The Impact of Computers on Physics" was held in Geneva in April 1972. For details see EPN, 1971.

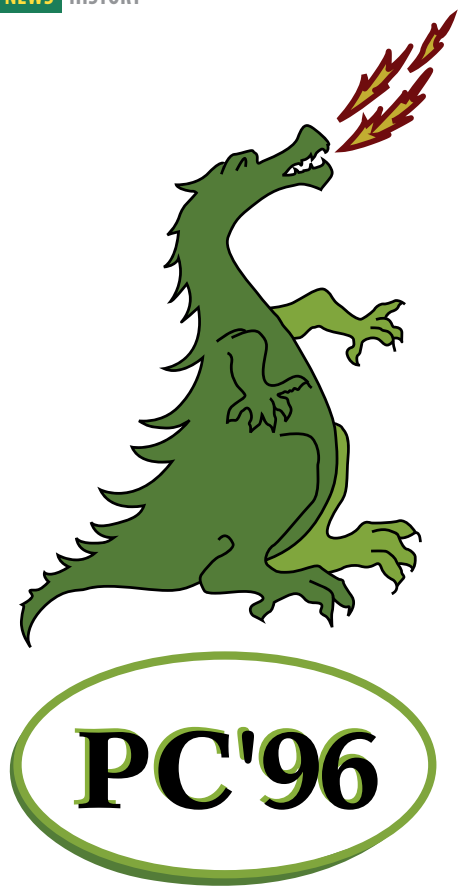
From the early 1970s CPG has organised a major Conference on Computational

Physics every two or three years. Initially these were European Conferences.
In 1986 the American Physical Society [APS] set up a Computational Physics Division [CPD], and from 1989 CPD and CPG collaborated in organising the Physics Computing [PC] conferences: odd years in America, even years in Europe.

Computational Physics in IUPAP

In 1993, the APS-EPS Steering Committee on Physics Computing Conferences was approached by the Chinese Computational Physics community with a view to having a fully international conference series. For some years there had been an International Conference on Computational Physics [ICCP] focussed on China. The Chinese approach was welcomed because it had been the original intention of the Steering Committee to bring together the whole international Computational Physics community.
It was agreed to approach the International Union of Pure and Applied Physics [IUPAP] to request that IUPAP create a Commission on Computational Physics [CCP]. The proposal was accepted by the triennial IUPAP General Assembly [GA] at Nara, Japan in September 1993 and a Working Group on Computational Physics [WGCP] was set up. Its aim was to establish the CCP by the next GA in 1996. To this end the Working Group was requested to investigate the issue and to present to the IUPAP Council a concrete proposal for a Commission on Computational Physics including its mandate and a proposal for members of the CCP.
The Working Group was chaired by Dr D Anderson from LLNL and Dr J Nadrchal from CPG was one of the members. It met during the conference PC94 at Lugano (Switzerland) in August 1994 and prepared the required materials for IUPAP Council that were sent to IUPAP on August 28, 1994. The proposed mandate of the CCP was:
To promote the exchange of information and views among the members of the international community of physicists in the area of Computational studies of problems originating in or relevant to physics, including
a) numerical and symbolic models and algorithms for the simulation of physical systems
b) computational control and data processing of experiments
c) programming and computational environments
d) the physical basis of computer machinery.
It had been hoped that IUPAP Executive Council would agree to create the CCP, C20 in 1994, but it was decided to consult C18, the Commission on Mathematical Physics, on whether there should be a joint commission or separate ones on Mathematical Physics and CP. This delay meant that IUPAP would not sponsor PC95 (Pittsburgh) nor PC96 (Cracow).
Jaroslav Nadrchal (see p.07 of this EPN issue) who was now chairman of the WGCP was invited to attend the meeting of the IUPAP Executive Council in Budapest in September 1995. The Executive Council agreed that the fields of interests of the proposed CCP and C 18 were sufficiently distinct, and there should not be a joint Commission, and decided to create immediately a new Commission on CP, C20. The following members were nominated to serve on the new Commission for one year: Chairman: **Dr J. Nadrchal** (Czech Republic), **Dr P. Borcherds** (UK), **Dr M. Bubak** (Poland), **Dr W. Camp** (USA), **Prof. Du X** (China) and **Dr J. Petersen** (Norway): of the six members four were on our Board!
The first task of the Commission was to decide on a name for the new conference series: after considerable discussion, the name "Conference on Computational Physics" was agreed, with the short form CCP1998. It was also agreed that the conference venue would rotate on a three-year cycle: Europe, then America, then Asia/Pacific under the auspices of EPS, APS and AAPPS.
The Commission and the Steering Committee cooperated in the preparation of PC96 in Cracow; however, the first IUPAP supported conference was in 1997, in California.
The first CCP conference was CCP1998, in Granada. Others in Europe have been CCP2001 in Julich, CCP2004 in Genoa, CCP2007 in Brussels. CCP2010 in Trondheim is now being planned.
It is impossible in such a brief history as this to report in any detail on the scientific content of the CPG Conferences and Summer Schools.

▲ Berni Alder presenting prize to Daan Frenkel



Let us instead highlight the splendid logo of the Cracow meeting PC96, based on the Cracow Dragon..

This meeting was also memorable for holding its Conference Dinner in a salt mine, surrounded by splendid sculptures in salt. For pictures, see the web

Prizes

CPG is fortunate that there are now two prizes awarded at CCP meetings in Europe. Each prize winner is expected to give a lecture, given at the end of the final session of the conference. They have proved an excellent way to round it off.

CECAM Prize: Centre Européen de Calcul Atomique et Moléculaire

In 1999 CECAM created a €5000 prize, the most prestigious European prize for computer simulation in statistical physics and physical chemistry, the Berni J. Alder CECAM Prize. The name of the prize honours one of the founding fathers of Computational Physics. It is awarded to distinguish a scientist who has made exceptional contributions to the field of microscopic simulation of matter. The first recipient was Giovanni Ciccotti: a member of the CPG Board.

In 2000 the CECAM Director Michel Mareschal approached the CPG Board to suggest that the prize be awarded at the CCP conference when it was held in Europe (anticipated to be every third year), and that the Prize Committee should include members of the CPG Board as well as members nominated by CECAM.

We are delighted that Berni Alder presented the award in 2001 to Kurt Binder, a member of the CPG Board, in 2004 to Mike Klein and in 2007 to Daan Frenkel.

IUPAP Young Scientist Prize in Computational Physics

In 2006 IUPAP set up the IUPAP Young Scientist Prize in Computational Physics as well as similar prizes for other Commissions. The recipients in a given year should on January 1 of that year have a maximum of 8 years research experience (excluding career interruptions) following the PhD. The recipient should be the principal performer of original work of outstanding scientific quality in Computational Physics. A previous recipient will not be eligible for another award.

The IUPAP Prize was presented for the first time at CCP2007. The winner was Stefano Sanvito, now at Trinity College, Dublin.

Summer Schools on Computing Techniques in Physics

The CPG has been involved in two series of summer schools.

From 1975 until 2004 the CPG (in cooperation with Czechoslovak Institutions) organised a biennial summer school.

There were 14 schools covering such topics as Clusters for Computing in Physics, Parallelization of Algorithms in Physics, Teaching Computational Physics, Microcomputers, Graphics in Physics, High-Performance Computing, Databases, Software Engineering, and Computing in Theoretical Physics.

Until the collapse of the Iron Curtain these schools were very important for computational physicists on the wrong side of it. It was very difficult for them to participate in scientific meetings in other countries, and to have contact with colleagues abroad. The invited speakers at the summer schools were mostly leading scientists from reputable scientific institutions and universities. Participants coming from non-Communist countries helped their colleagues through informal discussions.

The schools were very popular: the number of participants was about 100, but many applicants had to be rejected owing to the capacity of lecture theatres and accommodation. Participants could obtain funding through mutual official exchange programmes between universities and academies of science.

After the collapse of the Iron Curtain in 1989, the more open atmosphere and greater freedom of movement meant that the schools lost their primary purpose, and funding dried up. The organisers tried to modify the orientation of the schools, but in 2004 took the decision not to continue with them.

The CPG owes a great debt to Jaroslav Nadrchal, who was the organiser of all these summer schools for their whole 30 year history. Jaroslav was also very much involved with the East-West task force organised by the European Physical Society from 1995 until 2007 for helping to fund physicists from Eastern Europe to attend EPS sponsored meetings.

For many years Joaquin Marro has organised computational physics summer schools in Spain. Since 1998 these have been sponsored by EPS.

Conclusion

In a recent issue of CSCnews (3/2007), published by the Finnish IT Center for Science, our eye was caught by an intriguing headline "Tearing paper for information about earthquakes". This brings us back to that farsighted statement at the start of our history: "Advances in computer technology and programming may equally bring new ways of applying computers and open up new avenues of research which would otherwise not be feasible." ■

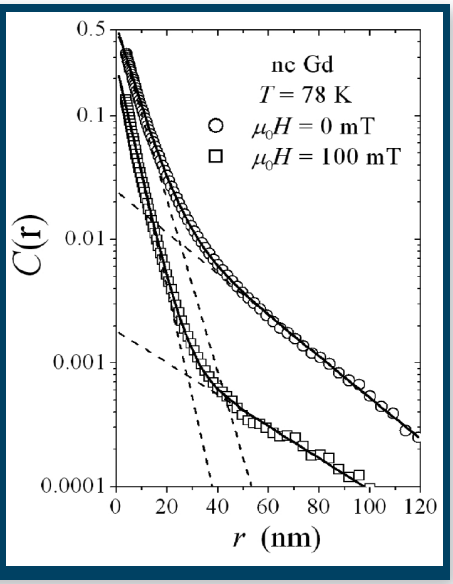
Acknowledgement

"The support of CPG Board Members in writing this is gratefully acknowledged"

Peter H. Borcherds,
University of Birmingham (UK)

Spin disorder at **Gd grain boundaries**

The macroscopic magnetic properties of a solid are largely controlled by lattice imperfections on a local microscopic scale. Magnetic neutron scattering is a particularly powerful technique for studying this correlation, because neutrons probe the spin structure in the bulk and on the relevant nanometer scale.



► Correlation function C(r) of the spin misalignment of nanocrystalline ^{160}Gd (log-linear scale). Average crystallite size of the nc Gd sample is D = 21 nm. It is seen that C(r) contains two characteristic length scales, as indicated, respectively, by the dashed lines. Solid lines: fit to a sum of two decaying exponentials.

By computing the autocorrelation function C(r) of the spin misalignment from experimental magnetic-field-dependent small-angle neutron scattering data, we were able to "visualize" the defect character of internal interfaces (grain boundaries) in the nanocrystalline rare-earth metal Gd.

The figure displays C(r) of nanoscaled Gd at two applied magnetic fields. From the decay of the spin-misalignment correlations, we infer the existence of at least two characteristic length scales in the spin system: the smaller length scale is of the order of 5 nm and is attributed to the perturbation caused by the defect cores of the grain boundaries, whereas the larger length scale, of the order of 25-35 nm, is associated with the magnetic anisotropy field from within the bulk of the individual crystallites. The results demonstrate the sensitivity of magnetic small-angle neutron scattering for detecting fine-scale spin inhomogeneities in magnetic microstructures and may have important repercussions for quantifying the strength of the exchange coupling across interfaces. ■

F. Döbrich, M. Elmas, A. Ferdinand, J. Markmann, M. Sharp, H. Eckerlebe, J. Kohlbrecher, R. Birringer and **A. Michels**,
'Grain-boundary-induced spin disorder in nanocrystalline gadolinium', *J. Phys.: Condens. Matter* **21**, 156003 (2009).

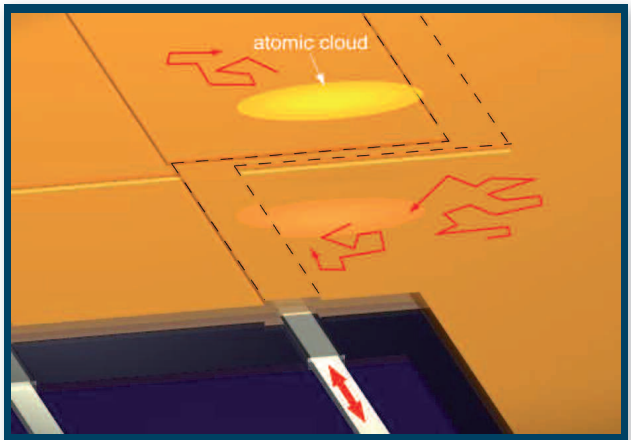
Trapping lifetime at a cold metallic surface

In atom-chip experiments, cold atoms are trapped in magnetic field gradients created by microfabricated current-carrying wires. By adjusting these fields, the atomic cloud can be manipulated in a versatile manner. When the atomic cloud is brought close to the surface of the chip, the confinement by the potential wells becomes very tight. This paves the way to quantum control of the atomic motion.

In these conditions however, new loss mechanisms are observed. They originate mainly from Johnson-Nyquist and technical noise currents in the trapping structure. They produce magnetic-field fluctuations in the MHz range at the position of the trapped cloud, inducing transitions towards untrapped states.

The cryogenic atom-chip group at ENS Paris has now shown that the Johnson-Nyquist noise is reduced by cooling down the atom-chip to cryogenic temperatures, resulting in very long trap lifetimes close to the atom-chip surface. For superconductors, the current noise is expected to be dramatically smaller. Furthermore, the use of permanent supercurrents makes it possible to get rid of technical noise fluctuations. By these means, unprecedented trapping times and coherent manipulation of the atomic cloud at small distances to the atom-chip surface are within reach. ■

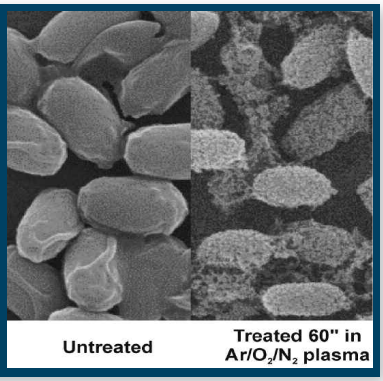
A. Emmert, A. Lupa, G. Nogues, M. Brune, J-M. Raimond and **S. Haroche**,
'Measurement of the trapping lifetime close to a cold metallic surface on a cryogenic atom-chip', *Eur. Phys. J. D* **51**, 173 (2009)



▲ Representation of a cold atomic cloud in the vicinity of the atom-chip surface. The atoms are captured in a magnetic trap created by an electric current through the superconducting Z-shaped wire (dashed lines) and a homogeneous magnetic bias field. Technical noise current in the wire, and thermal current fluctuations in the gold layer are represented by red arrows. They induce spin flips towards untrapped atomic sublevels

Sterilization of medical instruments **by plasma**

Cleaning, sterilization and decontamination of medical equipment are fundamental steps in health care facilities. However, the techniques currently used are often insufficient to guarantee complete inactivation or elimination of various pathogens; this represents a serious problem with respect to the possible transmission of diseases or onset of immunological events by the residues left after incomplete decontamination. Therefore, there is a demand for developing alternative decontamination methods allowing entire elimination of all biological residues from the surfaces of medical tools.



▶ Bacterial spores before (left) and after (right) plasma treatment in $Ar/O_2/N_2$ ternary mixture

One of the options that gained attention recently is the application of low-pressure, non-equilibrium plasma discharges, capable either to inactivate biological pathogens (*e.g.* spores sterilization by UV photons, which induce alteration of their DNA) or remove them from surfaces through etching (e.g. by O atoms) or chemical sputtering combining the effects of radicals with impact of energetic ions. For effective and universal process, both inactivation and elimination have to be combined. However, as demonstrated, intense UV radiation and high fluxes of etching gases and ions cannot be reached simultaneously in binary discharge mixtures.

In order to overcome this limitation, a plasma discharge based on a ternary mixture composed of Ar, O_2 and N_2 has been tested and its capability both to emit intense UV radiation and produce high fluxes of O atoms and ions has been investigated. The results show that discharges sustained in ternary mixture combine advantageous properties of plasma discharges operated in O_2/N_2 mixture - emission of intense UV radiation - and Ar/O_2 mixture optimal for the etching of biological pathogens. The treatment time necessary for safe processing of medical tools is significantly shortened, thus limiting undesirable damages of treated objects. ■

O. Kylián and **F. Rossi**,

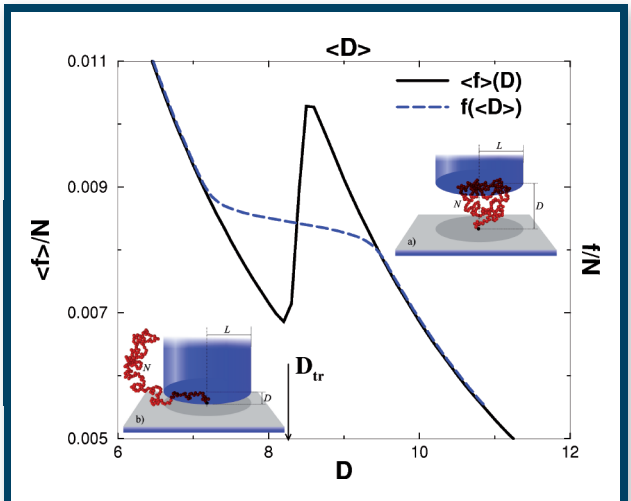
'Sterilization and decontamination of medical instruments by low-pressure plasma discharges: Application of $Ar/O_2/N_2$ ternary mixture', *J. Phys. D: Appl. Phys.* **42**, 085207 (2009)

Escape Transition of a Squeezed Polymer

Polymers undergo an escape transition when a flexible macromolecule with contour length Na and unperturbed gyration radius $Rg \propto aN^{\nu}$, end-grafted on a flat repulsive surface under good solvent conditions, is compressed by a piston of circular cross-section with radius $L > R_g$. Beyond a critical distance $D_{tr} \propto (Na/L)^{\nu/(1-\nu)}$ where $\nu \approx 0.587$ is the Flory exponent, the conformation of the confined chain changes abruptly from a compressed coil to an "escaped state". The latter consists of a tether, stretching from the grafting site to the piston border, and an expelled fraction of the coil outside of the compressing piston. We investigate this transition by both Molecular Dynamics computer simulations and a Landau free energy approach, based on a suitably derived (global) order parameter. Using D as an independent control variable, the statistical average of the force $\langle f \rangle$ on the piston is measured. One can also use the conjugate statistical ensemble where the force is fixed and $\langle D \rangle$ is recorded. While a plot of f vs. $\langle D \rangle$ is monotonous, $\langle f \rangle$ vs. D exhibits a sharp loop with a region of negative compressibility. We present evidence that in the transition region these two ensembles are non equivalent even in the thermodynamic limit. The observed ensemble non equivalence can be traced back to the effective long-range interactions which are induced by topological connectivity of repeat units in the linear chain. ■

D.I. Dimitrov, **L.I. Klushin**, **A.Skvortsov**, **A. Milchev** and **K. Binder**,

'The escape transition of a polymer: a unique case of non equivalence between statistical ensembles', *Eur. Phys. J. E* **29**, 9-26 (2009) DOI 10.1140/epje/i2008-10442-0.)

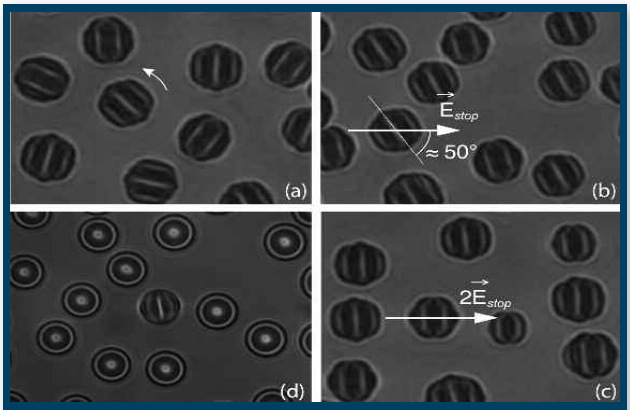


▲ Force vs. distance curves for Na/L=5 at the thermodynamic limit in the two ensembles. The simulation snapshot (a) shows an "imprisoned state" and (b) shows a snapshot of an "escaped state" The threshold piston height, D_{tr}=8.25a, is denoted by an arrow.

Lehmann effect in cholesteric liquid crystals

In 1900, Otto Lehmann observed the continuous rotation of cholesteric droplets when heated from below. This thermomechanical phenomenon was explained 68 years later by Leslie from symmetry arguments. According to the theory, the director experiences a torque proportional to the temperature gradient. The proportionality constant is called the Lehmann coefficient.

So far, this coefficient has only been measured close to the compensation point of very special mixtures (see the references in the article). It was thus important to extend such measurements to more usual cholesterics. In this context, we



▲ Cholesteric droplets observed in natural light. Without electric field, they all rotate in the same direction (a). When a large enough electric field is applied they stop rotating (b). At large field, the bands are perpendicular to the field (c). The droplets change texture and stop rotating below a critical size (d).

used a standard nematic liquid crystal (eutectic mixture of cyanobiphenyls 8CB and 8OCB) doped with a small amount of the chiral molecule R811. We observed the Lehmann rotation of cholesteric droplets subjected to a temperature gradient.

This experiment — not reproduced to our knowledge since Lehmann's original work — showed that the angular velocity of the droplets strongly depends on their size and on the concentration of chiral molecules. To estimate the Lehmann coefficient, three different methods were used. The first one consisted of measuring the droplet angular velocity as of function of the droplet size. The second one consisted of applying an electric field to stop the droplet rotation. The last one consisted of observing below which critical size the drops stop rotating because of a textural change. The three methods led to consistent values of the Lehmann coefficient at the clearing temperature. In addition, it was found that the coefficient is proportional to the concentration of chiral molecules. ■

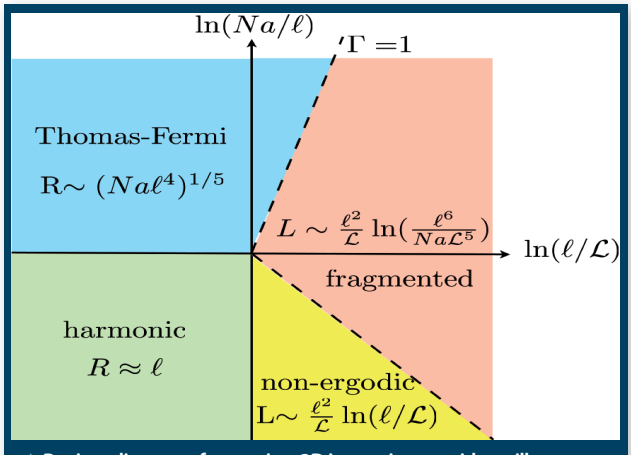
P. Oswald,
'Lehmann rotation of cholesteric droplets subjected to a temperature gradient: Role of the concentration of chiral molecules', *Eur. Phys. J. E* **28**, 377 (2009)

Effect of disorder **in Bose gases**

Non-interacting bosons condense at a single-particle state with the lowest energy. In a homogeneous system it leads to a coherent quantum state known as the Bose-Einstein condensate. Bose-Einstein condensation still persists when a small amount of disorder is added to the system. But in a random environment and in the absence of interaction, all Bose-particles fall into the lowest localized single-particle state. Such a ground state is non-ergodic since its energy and spatial extension depend on a specific realization of the disorder. An arbitrary small repulsive interaction redistributes the bosons over multiple potential wells and restores ergodicity. Hence, contrary to the fermionic case, the perturbation theory with respect to the interaction strength is invalid.

At low average density or weak enough interaction the particles fill deep potential wells of the random potential whose radius and depth depend on the characteristics of the random potential and the interacting gas. This localized state is the random singlet with no long-range phase correlation. We give a geometrical description of the remote weakly coupled fragments and their distribution in space. At a critical density the increasing tunneling of particles between fragments leads to a transition from the random singlet state to the coherent superfluid. We calculate the critical density in terms of the geometrical characteristics of the noise and the gas. The theory is extended for atoms in harmonic traps. Four different regimes are found and only one of them is superfluid. ■

G.M. Falco, T. Nattermann and **V.L. Pokrovsky**,
'Localized states and interaction induced delocalization in Bose gases with disorder', *EPL* **85**, 30002 (2009)



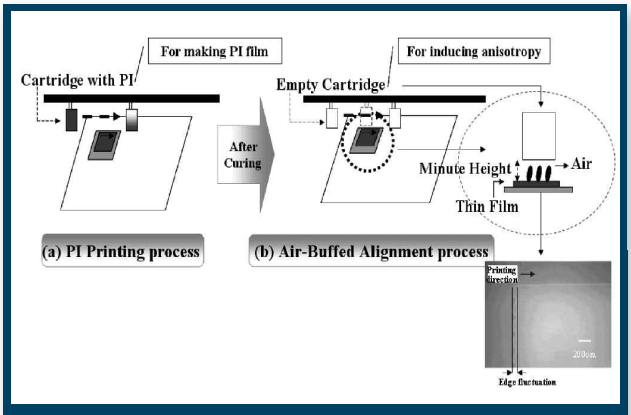
▲ Regime diagram of atoms in a 3D isotropic trap with oscillator length ℓ for uncorrelated disorder characterized by Larkin length $\mathcal{L}$. R denotes the size of the single existing atomic cloud while L is the size of the cloud of fragments. The interaction between atoms is described by the scattering length a and N represents the number of particles. The transition from the localized state to the superfluid state occurs where the dimensionless quantity $\Gamma \sim \ell^6/Na\mathcal{L}^5$ approaches 1.

Liquid crystal alignment on some polyimide surfaces

We have found that liquid crystal (LC) can be aligned on an inkjet printed and air-buffed (AB) polyimide (PI) surface. The surface anisotropy is introduced by the inkjet printing and air blowing from the polyimide ink cartridge and an empty cartridge of an inkjet printer, respectively. LC molecules align on the polyimide surfaces with the nano-scale grooves, which are validated with atomic force microscope (AFM) images. The pre-tilt angles of the liquid crystals could be varied from 0° to 90°, by controlling the composition of a mixture of homogeneous and homeotropic PIs.

In this paper, we describe a new non-rubbing LC alignment method, using the inkjet printed and air-buffed (AB) alignment to thwart the problems posed by the rubbing alignment. The two-step method is first by using an inkjet printer to print a thin layer of PI and create a nanostructured surface. This step is followed by blowing air from an empty inkjet cartridge to create surface anisotropy on the PI layer. The advantages of this inkjet printing and air-buffing induced alignment over the other techniques are a non-contact alignment and a high air blowing only the surface layers are affected so the damage to the PI film and charge build up are circumvented. Furthermore, the inkjet printing method is well known to the electronics manufacturing community and compatible with a clean room environment. The surface contact angle measurements, pretilt angle measurements, surface morphology of the alignment films, and electro-optical properties of LC cells are discussed. ■

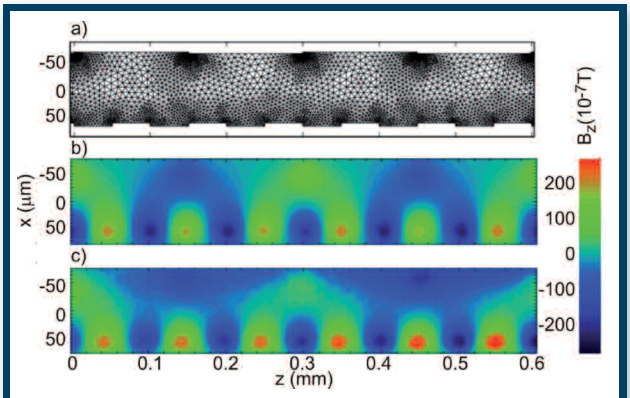
Jeoung-Yeon Hwang and **Liang-Chy Chien**, 'Liquid crystal alignment on inkjet printed and air-buffed polyimide with nano-grove surface', *J. Phys. D: Appl. Phys.* **42**, 055305 (2009)



▲ The principle of the air-assisted alignment method: (a) PI printing process, and (b) AB alignment process.

Atom chips made by femtosecond laser ablation

Since their inception, atom chips have revolutionized experiments with ultra-cold gases. This has been achieved primarily through the use of microscopic wires in which currents flow to form magnetic trapping potentials for atoms very close to the conductors. While the precise engineering of these potentials has benefited from the know-how of the electronics micro-fabrication industry, it typically requires highly demanding multi-step approaches including: electron beam lithography for mask creation, ultraviolet photolithography and wet etching for micro-wire fabrication, electroplating for wire thickening and ion beam milling for edge cleaning.



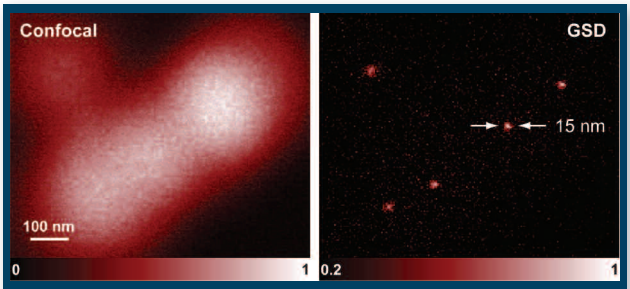
▲ (a) Sculptured wire design for BEC beam splitter array, (b) the finite element calculation (c) the magnetic field topology measurements.

The work reported by Wolff and co-workers has recently demonstrated the fabrication of micro-wires using a pulsed femtosecond laser to carefully ablate insulating grooves in an atom chip. To fabricate an atom chip typically takes only a few hours and is essentially a single step process. The laser is focussed to a submicron spot and the chip is translated by computer control drawing insulating grooves like a microscopic etch-a-sketch. Using a magneto-resistance microscope the magnetic potential landscape above a straight wire was measured indicating a potential roughness below the microscope noise floor. The ablation method was also used to sculpt a periodic array of symmetric BEC 'beam splitters' (Fig.). The results of this paper indicate that atom chips can be simply machined with femtosecond laser ablation. ■

C.H. Wolff, **S. Whitlock**, **R.M. Lowe**, **A.I. Sidorov** and **B.V. Hall**, 'Fabricating atom chips with femtosecond laser ablation', *J. Phys. B: At. Mol. Opt. Phys.* **42**, 085301 (2009).

Fluorescence nanoscopy **of diamond color centers**

Since the end of the 19th century it has been commonly accepted that the resolution of any light microscope using conventional lenses is largely limited to about half the wavelength of light. However, in 1994, the invention of stimulated emission depletion (STED) and ground state depletion (GSD) microscopy [V. Dose, "Peer review", *EPL* **86**, 10000 (2009)] revealed that, at least in fluorescence microscopy, the limiting role of diffraction can be overcome by exploiting basic transitions in a fluorophore, specifically of transitions that on-off modulate the emission of fluorescence. In the present article, Eva Rittweger, Dominik Wildanger, and Stefan Hell report on two elegant and effective implementations of GSD microscopy. Applying it to the imaging of fluorescent crystal defects in diamond, the authors routinely discern individual color



▲ Comparison between a confocal and a subdiffraction resolution GSD microscopy image of fluorescent color centers in diamond. While the diffraction-limited confocal recording of ~200 nm maximum spatial resolution fails to discern individual crystal defects, the GSD image, here at 15 nm spatial resolution, resolves every color center individually in space.

centers that are just a tiny fraction of the wavelength apart. Their experiments demonstrate a resolving power down to 7.6 nm, corresponding to 1/70 of the 532 nm wavelength used. Since it is theoretically no longer limited by the wavelength, the resolution of GSD microscopy can be further augmented down to a fraction of a nanometer, thus setting the scene for another thrilling quest. ■

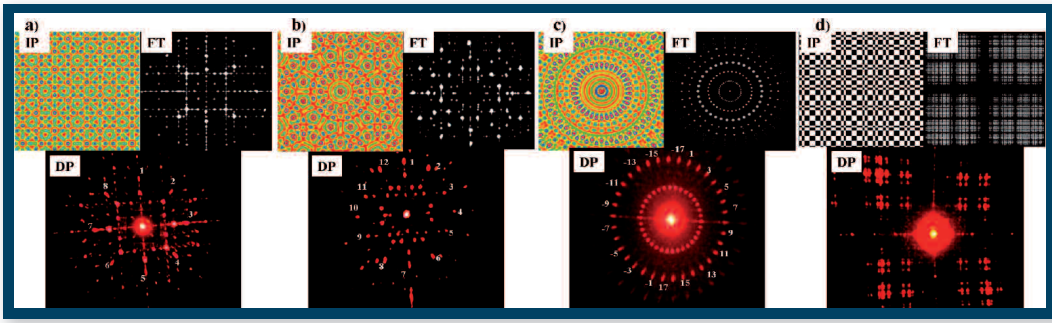
E. Rittweger, **D. Wildanger** and **S. W. Hell**, 'Far-field fluorescence nanoscopy of diamond color centers by ground state depletion', *EPL* **86**, 14001 (2009)

Quasi- and a-periodic photonic **bandgap structures**

We demonstrated that quasi-periodic structures of high rotational symmetry require proper tiling to exhibit photonic bandgaps (PBG) at low index contrast (*e.g.* 0.4 for 8-fold symmetry). Correspondingly, we developed a powerful single-beam holographic technique, with which we can obtain 2D patterns of any complexity. These results may have a large impact in the rapidly growing world of PBG based devices. The low index contrast required by our PBG structures allows to exploit soft materials like polymers and liquid crystals to realize low cost tunable photonic devices. Our computations proved that, if wide PBG are to be obtained at low index contrast, tiling is more important than symmetry, and hence accurate control of the fabrication parameters is mandatory.

Usual holographic techniques to make photonic structures control much more easily the overall rotational symmetry than tiling, since tiling depends dramatically on the delicate balance between all the beam parameters. Thus, we developed a diffractive single-beam technique able to accurately control both symmetry and tiling of photonic structures. Our technique, based on a programmable Spatial Light Modulator (SLM) encoding Computer-Generated Holograms (CGH), is versatile, robust and simpler than competing ones. We fabricated quasi-periodic structures (see figure) with rotational symmetries as high as 23-fold with different tiles and even aperiodic patterns not achievable using N-beam interference, like the 2D Thue-Morse pattern. Our structures were realized by induced photo-polymerization of liquid crystal-polymer composites. Nevertheless, our SLM-CGH technique might be applied to other photosensitive materials. ■

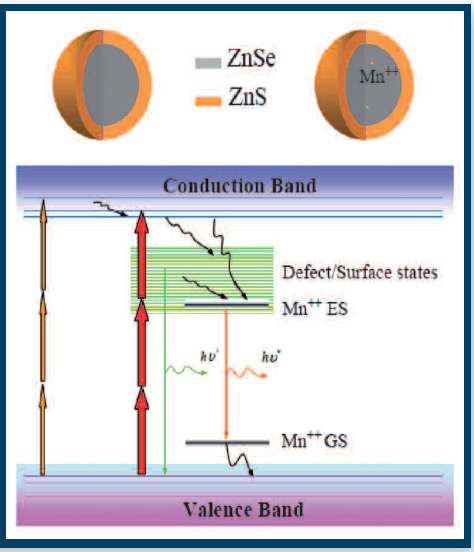
G. Zito, **B. Piccirillo**, **E. Santamato**, **A. Marino**, **V. Tkachenko** and **G. Abbate**, 'FDTD analysis of photonic quasicrystals with different tiling geometries and fabrication by single-beam computer-generated holography', *J. Opt. A: Pure Appl. Opt.* **11**, 024007 (2009)



◀ (a) to (c) examples of 8-, 12-, 17-fold quasi-periodic patterns; (d) aperiodic 2D Thue-Morse pattern. Top left: computed irradiance profile (IP); Top right: 2D Fourier transform (FT) of the irradiance profile; Bottom: experimental diffraction pattern (DP). Notice the good agreement between each DP and the corresponding computed FT.

3-photon absorption in Mn-ZnS/ZnSe quantum dots

Three-photon absorption (3PA) in colloidal quantum dots is of great importance to multiphoton microscopy [*e.g.* Michalet *et al.*, *Science* **307** 538 (2005)] which produces three-dimensionally resolved fluorescence imaging of living cells and tissues. Three-photon microscopy features attractive advantages, including deeper penetration depths in absorptive media and higher spatial resolution.



► Schematic diagrams of ZnSe/ZnS quantum dots and electronic structures

To improve the small cross-sections of 3PA, normally found in intrinsic semiconductor quantum dots, we investigated an enhancement mechanism in transition-metal-doped quantum dots. We found that 3PA should be enhanced greatly if extrinsic semiconductor quantum dots are chosen in such a way that the excitonic energy matches to the three-photon energy and the energy difference between the ground states and the dopant states is equal to the two-photon energy (see Fig.). Our investigation showed a remarkable enhancement of 100-fold for Mn-doped ZnSe/ZnS core-shell quantum dots at light wavelength of 1000 nm. Furthermore, Mn-doping in ZnSe/ZnS quantum dots gave rise to an increase of one order of magnitude in photoluminescence efficiency compared to un-doped ZnSe/ZnS quantum dots. In the process of three-photon-excited photoluminescence, either 3PA or photoluminescence plays an equally important role. Both enhanced 3PA and efficient photoluminescence in Mn-doped ZnSe/ZnS quantum dots make them extremely promising for fluorescence imaging of bio-samples through three-photon excitation. ■

X.B. Feng, **G.C. Xing** and **W. Ji**,
'Two-photon-enhanced three-photon absorption in transition-metal-doped semiconductor quantum dots', *J. Opt. A: Pure Appl. Opt.* **11**, 024004 (2009)

X-ray studies of sub-monolayer organic thin films

The structural investigations of model organic systems like pentacene in the monolayer regime is very important for fundamental understanding of the initial nucleation process together with the electronic performance of transistor devices. The fact that the transistor performance saturates after deposition of some monolayers of the active organic material motivates a basic investigation of the sub-monolayer and monolayer regime in more detail. In this paper a method for the evaluation of the island formation and the island growth within the first monolayer is introduced. The method is based on X-ray scattering under grazing incident condition by means of specular X-ray reflectivity and off-specular X-ray scattering. From the specular reflectivity the electron density can be obtained which is directly correlated with the coverage of a sub-monolayer.

Within the presented experiment, coverage ranging from 7% up to 97% could be identified and are in excellent agreement with atomic force microscope results. Lateral information on the islands is obtained by rocking curve and detector scan measurements under grazing incident condition. The observed correlation peaks are evaluated by using Distorted Wave Born approximation, whereby mean island sizes ranging from 300nm to 1.5µm and mean island separation of about 2µm could be determined for the various samples. The obtained results encourage the use of this type of investigation for in-situ growth experiments to obtain a better understanding of the first monolayer formation. ■

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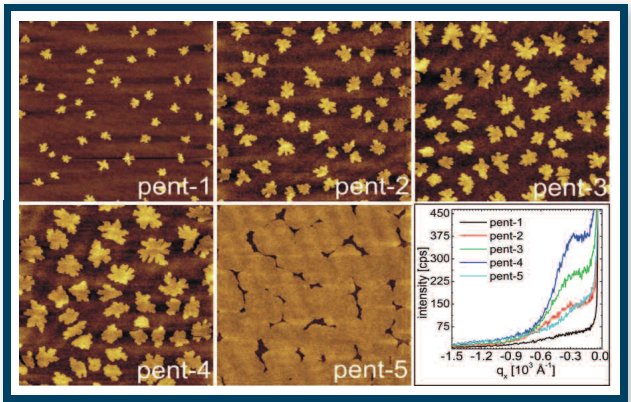
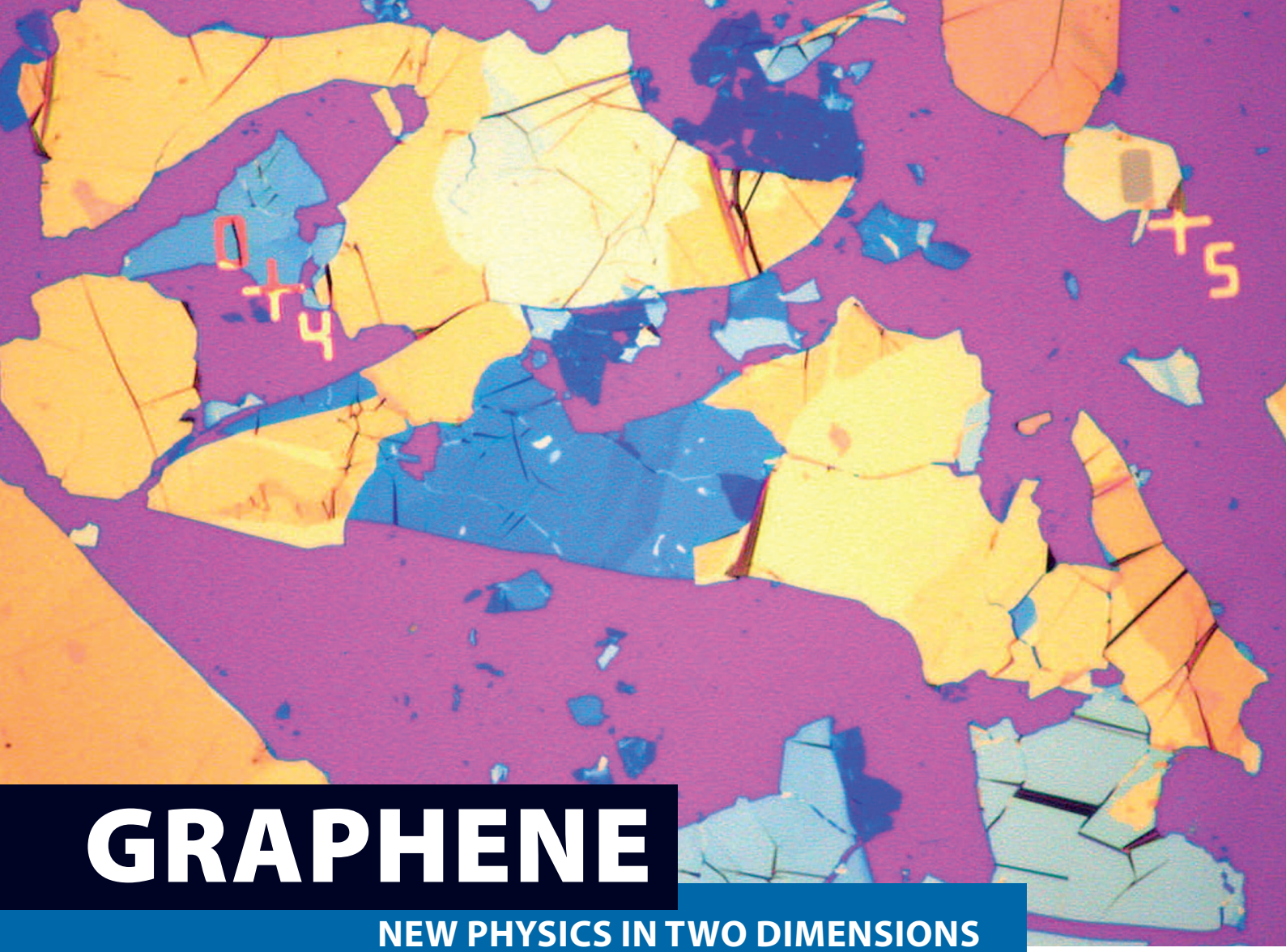


▲ Atomic force microscopy height images of pentacene submonolayers (pent1 – 5) and respective X-ray scattering results.



GRAPHENE

NEW PHYSICS IN TWO DIMENSIONS

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Graphene was discovered in 2004 at the Centre for Mesoscopic and Nanotechnology of the University of Manchester, U.K., directed by A.K. Geim [1,2]. This new material is a true two-dimensional system made solely of carbon atoms. The carbon atoms form a two-dimensional honeycomb (hexagonal) lattice, such as that represented in Fig. 1, where the spheres represent the carbon atoms. One can view the lattice of graphene as a number of benzene rings glued together.

How is graphene isolated? The original method of graphene production is based on micro-mechanical cleavage of graphite surface – the so called *scotch tape method*. In very simple terms, a piece of graphite – the material from which pencils are made – is gently rubbed on a piece of ordinary scotch tape. This produces carbon debris. The scotch tape with the debris is then pressed against a slab of oxidized silicon (of 300 nm width). As a consequence the debries move to the oxidized silicon – see Fig. 2. Using an optical microscope one can identify small crystallites of graphene on top of the oxidized silicon. This low-tech procedure induced a revolution in condensed matter physics.

Chemical bonding

A carbon atom has six electrons distributed in the atomic orbitals as $1s^2\ 2s^2\ 2p^2$. The 1s electrons are essentially inert and do not contribute to the chemical bond. In graphene, the 2s, $2p_x$ and $2p_y$ orbitals combine – or 'hybridize' – to form three new planar orbitals called sp^2 (which will originate the sigma bonds in the solid), each containing one electron. These orbitals are directed along lines with angles of 120 degrees, and are responsible for the hexagonal lattice structure of graphene. The chemical bonding of the carbon atoms in graphene is maintained by these three orbitals, and the mechanical properties of graphene are determined by the rigidity of the bond.

▲ FIG. 2: Optical-microscope picture of graphite debries on top of oxidized silicon produced by the scotch tape method. Image courtesy of A.K. Geim

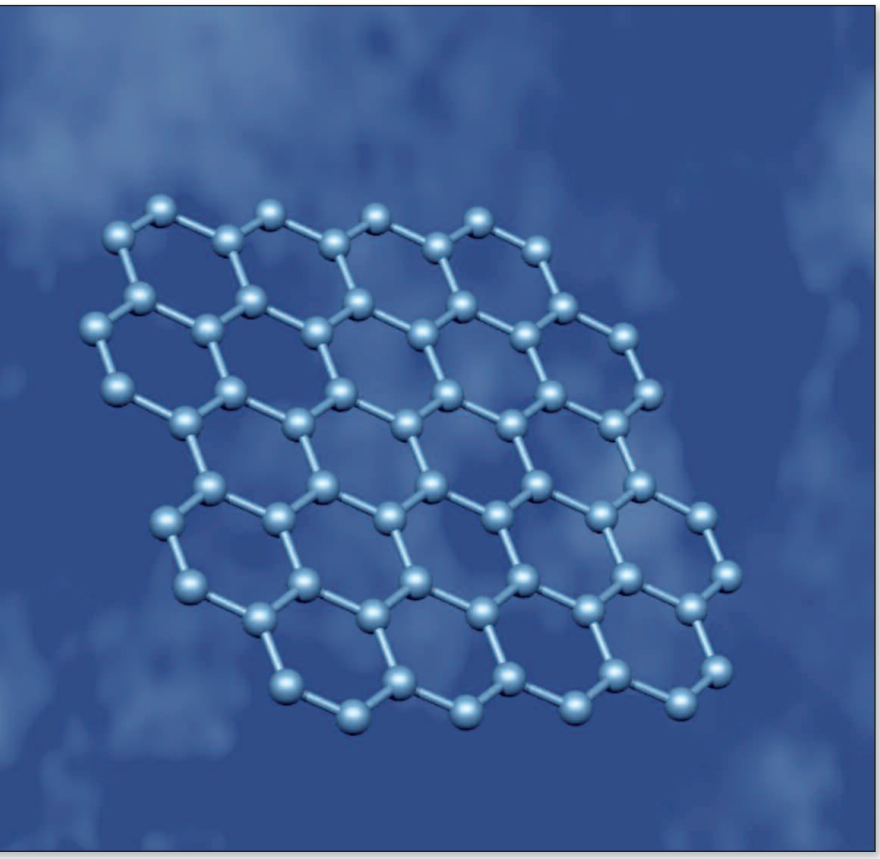
The reader certainly noticed that one orbital remained, the p_z orbital with one electron. This orbital is perpendicular to the plane formed by the carbon atoms. As in the case of the 2s, $2p_x$ and $2p_y$ orbitals, the p_z orbitals of different atoms combine to form the pi-bonds. Each p_z orbital contributes with one electron, and therefore graphene is a system with one electron per lattice site (the carbon atoms define the sites in the lattice). This is called a half-filled system. The pi-orbitals are responsible for the unusual electronic properties of graphene.

Graphene offers the **possibility** to study **relativistic effects** in **table-top experiments**

It should be noted that graphene can be considered the raw material for other existing forms of pure carbon. For example, graphite is a stack of graphene planes weakly coupled; carbon nanotubes are made of rolled-up graphene; and fullerenes are made of wrapped graphene, by introducing the right amount of pentagons to give the required curvature [3,4].

Lattice structure and band structure

As already mentioned, graphene is a two-dimensional hexagonal lattice made of carbon atoms. The hexagonal lattice is not a Bravais lattice. Instead it can be viewed as two interpenetrating triangular lattices, each containing one set of equivalent carbon atom sites – the A and B carbon sites (see Fig. 3). One should note that from a chemical point of view the two carbon atoms are exactly identical. Since the unit cell contains two carbon atoms, one A and one B, the energy spectrum originating from the pi-orbitals has two energy bands - a valence band (at lower energies) and a conduction band (at higher energies). As said before, graphene is a half-filled system and therefore the valence band is completely filled. In condensed matter physics, the electronic properties of a system are determined by the nature of the spectrum close to the last filled states, the energy of which defines the Fermi level. Therefore, the physics of graphene is determined by the nature of the energy spectrum close to the top of the valence band and to the bottom of the conduction band. The interaction of the pi-electrons with the hexagonal lattice gives graphene a very unusual energy spectrum. Both the valence and the conduction bands are represented in Fig. 4. A number of very interesting and peculiar features emerge from this figure. First it is clear that the valence and the conduction bands touch each other at a number of finite momentum values. The momentum values at which the two bands touch are termed Dirac points (there are two in the Brillouin zone). As a consequence, graphene's spectrum does not have an energy gap. On the other hand, since the bands only touch at two momentum points the density of states is zero at the corresponding energy. Therefore, graphene is sometimes termed a zero-gap semiconductor with vanishing density of states at the Fermi energy.



▲ **FIG. 1:** Artistic view of the hexagonal lattice of graphene. Notice that the graphene lattice has two types of edges: zigzag **(top and bottom edges)** and armchair **(right and left edges)**. Image obtained from: http://news.thomasnet.com/IMT/archives/.

Even more interesting is the form of the valence and the conduction bands close to the Dirac points. They show a conical shape, with negative (valence) and positive (conduction) energy values. In fact, the energy spectrum of graphene close to the Dirac point is well represented by the relation

$$E = \pm v_F p \qquad (1)$$

where v_F is the Fermi velocity, p is the momentum, and E is the energy. The value of v_F is $c/300$, where c is the speed of light. The energy given by equation (1) resembles that of ultra-relativistic particles (sometimes one says that electrons loose their mass in graphene).

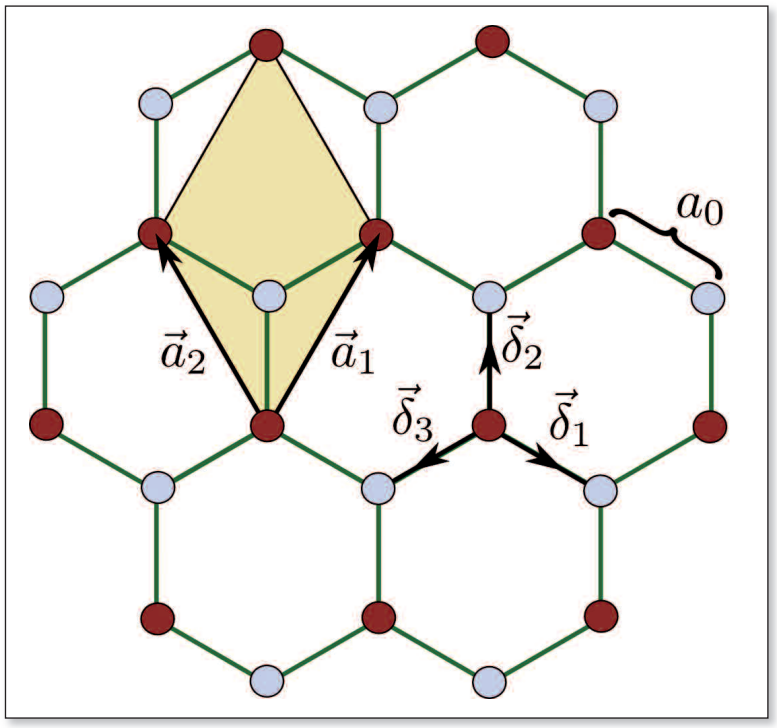
This is a truly amazing result: as a consequence of the interaction between the lattice and the pi-electrons, an effective theory emerges where the electrons (or better: the quasi-particles) are massless Dirac electrons. This is a good example of complex emergent behavior, in the spirit of the classic article of P.W. Anderson [5].

The result of equation (1) should be contrasted with the electronic spectrum of an ordinary metal or semiconductor, which is given by $E = p^2/(2m)$, where m is the effective mass of the electrons inside the material (in a semiconductor m can be different for holes and for electrons, with m being negative for holes). The dependence of the energy on the square of the momentum is an indication that the Schrödinger equation is the appropriate one to describe the physics of these systems at low energies.

Note that in graphene the primary quantum problem is described by the Schrödinger equation with two terms: the kinetic energy and the periodic potential produced by the carbon atoms arranged in the hexagonal lattice. This formulation describes the physics at all energy scales (within the pi-bands). However, the important physics of graphene takes place close to the Dirac point, where the Fermi energy is located. It can be formally shown [6] that, close to the Dirac point, the equation describing the low-energy physics is not the Schrödinger equation but the massless Dirac equation in two-dimensions, as one would guess from the fact that the energy in equation (1) is linear in momentum, with positive and negative energies. So one moves from electrons interacting with a periodic potential to free massless Dirac particles moving at the effective velocity of light v_F. As a consequence, the electronic wave-function in graphene is not a scalar field[1] but has a spinorial nature, where the spinor has two entries, reflecting the fact that the original lattice has A and B types of carbon atoms. Graphene therefore offers the possibility of studying relativistic effects in table-top experiments. Since traditional condensed-matter physics knowledge for describing the electronic properties of materials is based on the properties of solutions of the Schrödinger equation, graphene opens a new research frontline, since the electronic properties of systems described by spinorial solutions of the Dirac equation is lacking. In fact, the electronic properties of Dirac electrons are different from those of Schrödinger electrons.

Some properties of Dirac electrons in graphene

Graphene has a number of fascinating properties from both elastic and electronic points of view. For example, the stiffness of graphene has been proved to be extremely large, with a Young modulus E=1.0 TPa, making it the strongest material ever measured. This is a consequence of the sigma-bonds and not of the fact that the low-energy physics is described by the massless Dirac equation. Furthermore, the material is chemically stable and almost impermeable to gases. In addition, the material has high thermal conductivity, can withstand large current densities [1], has ballistic transport over submicron scales, with very high mobilities in its suspended form [1] (in the first experiments the electronic properties of graphene were measured with the material on top of oxidized silicon; more recently the substrate was etched away leaving graphene standing free). Finally, it shows ambipolar (electron and hole) behavior, one of the first properties to be measured [1]. This latter property is a direct consequence of the massless Dirac nature of the pi-electrons in graphene. The density of charge carriers in graphene can be tuned by the field effect using a backgate [1]. This setup allows tuning of the Fermi level above or below the Dirac point. When the Fermi level is tuned *below* the Dirac point the valence band is filled with holes; when the Fermi level is tuned *above* the Dirac point the conduction band is filled with electrons. These two possibilities give graphene its ambipolar nature, with the Hall effect measurements giving direct evidence on the charge of the carriers.



▲ **FIG. 3:** Graphene hexagonal lattice made of two interpenetrating triangular lattices. The nodes of each triangular lattice define the carbon atoms of type A **(red)** and B **(blue)**. Also represented are the unit cell vectors a_1 and a_2.

At large magnetic fields another amazing consequence of Dirac electrons in graphene kicks in: the chiral quantum Hall effect [7,8], where the origin of the name stems again from the fact that electrons in graphene are described by the massless Dirac equation. Contrary to the traditional quantum Hall effect observed in the two-dimensional electron gas, the quantization rule of the Hall conductivity is given by

$$\sigma_{\text{Hall}} = \pm 4e^2(n+1/2)/h,\ n = 0, 1, 2, \ldots \qquad (2)$$

where e is the electron charge and h the Planck constant.

note

[1] We are not considering the electron's real spin

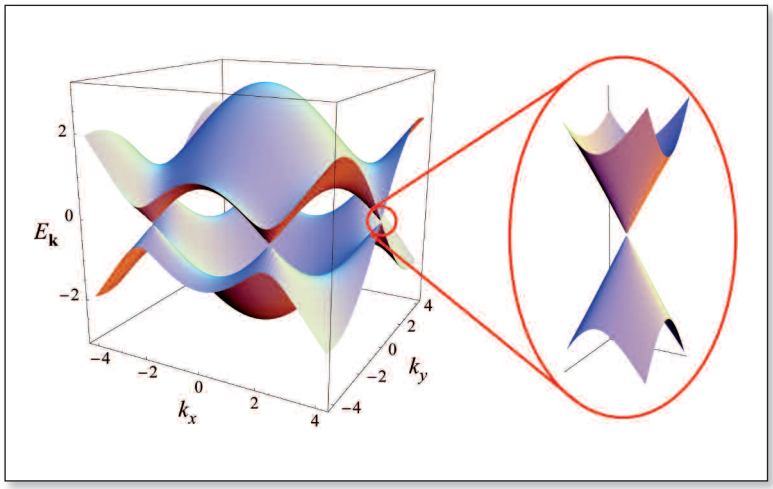
How can we interpret equation (2)? The number four in front of the equation is in fact the result of a factor two due to the spin degeneracy and another factor two due to the two Dirac points. The integer number n determines which energy levels are contributing to the charge transport in the system. Finally, the term ½ is the signature of the presence of Dirac electrons in the system [9], and does not show up in the case of Schrödinger electrons.

Another noticeable effect of Dirac electrons in graphene is the transparency of the material to light [10]. It is found experimentally and explained theoretically that the transmissivity T (percentage of light passing through the material) of graphene is given by the simple relation

$$T = 1\text{-}\pi\alpha \approx 98\% \qquad (3)$$

where α is the fine-structure constant. That is, the transmissivity of graphene depends only on fundamental constants, with no reference to any of the material parameters. This is a rare situation in condensed matter physics, with parallels only in the quantum Hall effect, the flux quantization in superconductors or vorticity quantization in superfluids, and conductance quantization. Again this result is a consequence of equation (1). The high transmissivity of graphene (98%) and its metallic behavior opens the possibility of using graphene in the solar cell industry and in gateable displays as transparent metallic electrode.

Since the original work of Klein [11] it became clear that Dirac electrons respond differently from Schrödinger electrons to electrostatic potentials. In fact, massless Dirac electrons pass through a potential barrier with probability one at normal incidence, at odds with its Schrödinger counterpart. This result became known as Klein tunneling. In technical terms, this can be explained using the concept of chirality. This concept introduces a new quantum number that is conserved in massless Dirac particles. The head-on collision of the Dirac electron with the potential barrier has to conserve this quantum number and this implies tunneling with probability unity [12]. This, in turn, has observable consequences in the transport properties of electrons in graphene [13].



▼ FIG. 4: Band structure of graphene as a function of the momentum k_x and k_y. One notices the valence band (at lower energy) and the conduction band (at higher energy). A zoom-in shows the bands close to the point where they touch each other.

Conclusions

We have surveyed only some of the many interesting properties of graphene. There are many more fascinating aspects of graphene that can not be covered in such a short space and the interested reader can pursue his/her readings in some of the reviews listed in the references list [4,6,12]. A physicist working in graphene is required to have notions of condensed matter, elasticity, high-energy physics, and material science. Therefore, graphene physics is an interdisciplinary research field with new fundamental physics and several promising applications [4], making it a truly exciting research area. ■

About the author

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Acknowledgments

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Foams are found everywhere: in nature, in technology, in our home. They are examples of ***cellular materials****: assemblies or clusters of cells (from Latin* ***cella****: a small compartment or enclosed region) packed together so that they fill space without gaps. Foams come in different kinds. Ordinary liquid foam is an experimental system that solves some difficult geometry problems.*

FOAM

AS A GEOMETER

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▲ **Organic cellular abstract in blue with white background. ©iStockPhoto**

If the walls bounding the cells are solid, and their contents liquids or gases, we are dealing with a *solid foam* or a *cellular solid*. These are common in nature: wood, cork, sponge and coral are examples. Mankind has made use of cellular solids for millennia, as witness artifacts retrieved from the pyramids of Egypt. More recently, we have turned to producing our own cellular solids, tailored to specific purposes. At the simplest level there are honeycomb-like materials, made up of parallel, prismatic cells, which are used for lightweight packaging and structural components. More familiar are the polymeric foams, found in everything from the humble disposable coffee cups to modern car bumpers and thermal insulation layers in buildings and refrigerated vehicles. Techniques now exist for foaming not just polymers, but also metals, ceramics and glasses. Metal foams are finding applications as shock absorbers in the automotive industry, whereas ceramic and glass foams, because of their good biocompatibility, can be ingrown by living tissue, thereby aiding the integration of dental and bone implants coated with them [1].

On the other hand, a *liquid foam* consists of a mixture of two fluids, and yet behaves as a solid if subjected to only very small stresses. When one of the fluids is air, the cells are usually called bubbles. Typically the thickness of a wall separating two bubbles is much smaller than the linear size of a bubble, and the walls can then be idealised as curved surfaces, which meet on lines, which in turn meet in vertices. This is the limit of a perfectly dry, or mathematical, foam. In two-dimensional (2D) perfectly dry foams we have only lines (cell walls) which meet in point vertices. Real foams, by

contrast, all have a finite liquid volume fraction which can be as high as 30%; these are wet foams (see figure 1). Most of the liquid resides in the channels along which films meet, called Plateau borders; in 2D these coincide with the vertices. A real foam may be called 'dry' if its Plateau borders (in 2D) or Plateau borders and vertices (in 3D) are of negligible size; this corresponds to a liquid area (in 2D) or volume (in 3D) fraction of a few percent [2].

One aims at **delivering drugs** in **such a way** that they **react** only after **reaching** some **specified location**

Traditional applications of liquid foams include drinks such as beer and sparkling wines; foodstuffs such as whipped cream and chocolate mousse; household cleaning products such as oven cleaner and limescale remover; and toiletries such as shaving cream. Various industrial separation processes also utilise the properties of foams. In fractionation, a solute that is adsorbed at the bubble surfaces can be removed from solution. In flotation, metal-rich, hydrophobic particles stay in the foam, while metal-poor hydrophilic ones drain out. Fire-fighting foams perform an all-out attack on the three ingredients necessary to sustain a fire: they exclude oxygen, lower the temperature, and trap fuel vapour. Finally, in enhanced oil recovery, foam acts as a surfactant carrier for flushing oil out of the interstices in reservoirs.

The behaviour of a dry foam with a low-viscosity liquid phase (*e.g.*, an aqueous foam, as opposed to a polymeric foam) is dominated by surface tension. The films tend to contract in order to minimise their surface area and hence their energy. This is opposed by the pressure difference across the film separating bubbles i and j, according to Laplace's equation:

$$p_i - p_j = \gamma \left(\frac{1}{R_{ij}^{(1)}} + \frac{1}{R_{ij}^{(2)}} \right) \qquad (1)$$

where γ is the film tension, $p_i(p_j)$ is the pressure inside bubble $i(j)$, and $R_{ij}^{(1)}$, $R_{ij}^{(2)}$ are the radii of curvature of the surface between bubbles i and j. The rules for the equilibrium of such a foam are embodied in Plateau's laws, discovered experimentally in the second half of the 19th century [3] and later proved [4] to be necessary conditions for stability. They are:

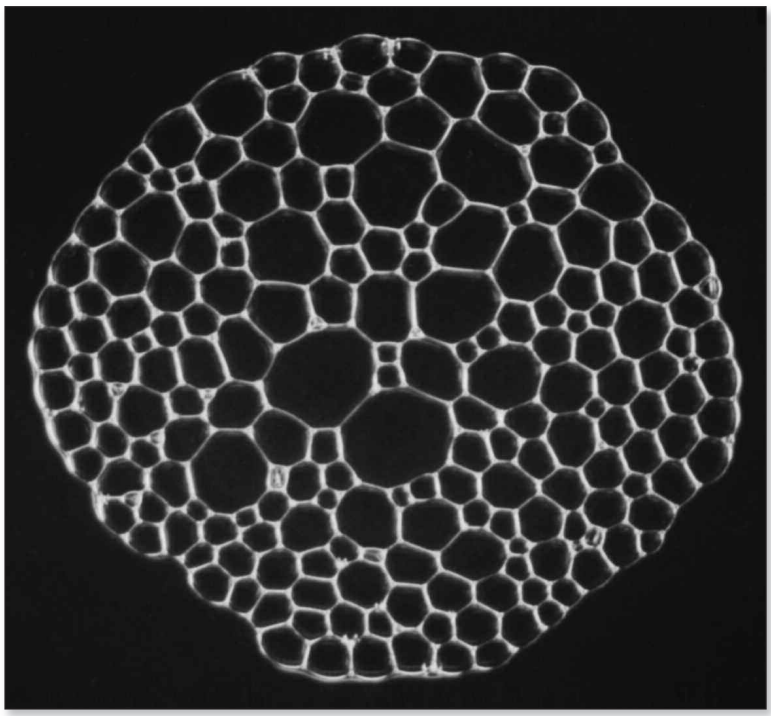
1. Films meet three at a time, at 120°-angles, along Plateau borders.
2. No more than four Plateau borders may meet at a vertex, where the angle between any two of them is the tetrahedral angle, 109.5°.
3. Film curvatures sum to zero at a vertex (from Laplace's law).

In 2D there is one additional rule (which also follows from Laplace's law) that the films must be arcs of circle (since there is only one radius of curvature and this must be constant).

Unlike a solid foam, a liquid foam is inherently unstable and will eventually disappear, though there are recorded instances of foams surviving weeks or even months, if kept in sheltered conditions. The mechanisms for foam instability are three:

- **Drainage:** under gravity, liquid will drain out until an equilibrium state is reached. This occurs on a timescale of the order of one minute.
- **Coarsening:** diffusion of gas between bubbles causes some to grow and others to shrink, leading to an increase in mean bubble size. The timescale is about 10 minutes, but may vary.
- **Film rupture:** foam films that are too thin and weak will rupture, and eventually the whole foam will collapse and disappear. The timescale for these processes is hugely variable.

In what follows we shall be interested in timescales of a few minutes, for which the foam has had time to drain dry but gas diffusion is negligible, as is experimentally borne out by the fact that bubble sizes do not change appreciably. Under such circumstances, a dry foam can be seen as a structure that realises a partition of space into cells of given volumes for a minimal expense of surface area. When the cells all have the same volume, this is known as the *Kelvin problem* – by analogy with the Kepler problem of how to pack spheres so that they take up the least amount of space [5]. Kelvin was interested in using foam as a model for the luminiferous

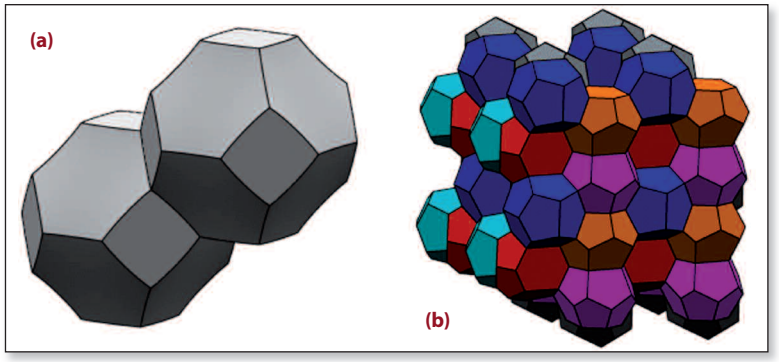


▼ **FIG. 1:** A moderately wet 2D foam cluster. (Image by M. Fátima Vaz, Instituto Superior Técnico, Lisbon.

aether of electromagnetic theory, which was motivated by the need to find a material that would have zero compression modulus and therefore not support any longitudinal waves, as it was by then already known from experiment that electromagnetic waves were strictly transverse. The structure Kelvin came up with – a packing of identical 14-sided truncated octahedra, or, as he called them, orthic tetrakaidecahedra [6] (see figure 2a) – turned out to be a very good candidate for the division of space into equal volumes with minimal partitional area, until it was dethroned by the Weaire-Phelan, or A15, structure in 1994 [7] (see figure 2b). Unlike Kelvin's, this fills space with cells of two different shapes (but equal volumes), a dodecahedron and a 14-sided polyhedron. It beats Kelvin's by a slim 0.3%.

However, there is no formal proof to date that the Weaire-Phelan structure, which was found by numerical minimisation of the energy of competing structures, is the lowest-energy geometry of a 3D foam. Indeed, formal proofs are very hard to come by in this field. Consider a related problem, known as the *double bubble conjecture*: given two volumes, V_1 and V_2, what is the surface that circumscribes these two volumes with the least surface area? Not until 2002 was this proved to be two bubbles joined at a single film [8] (see figure 3); if $V_1 = V_2$, the film is flat.

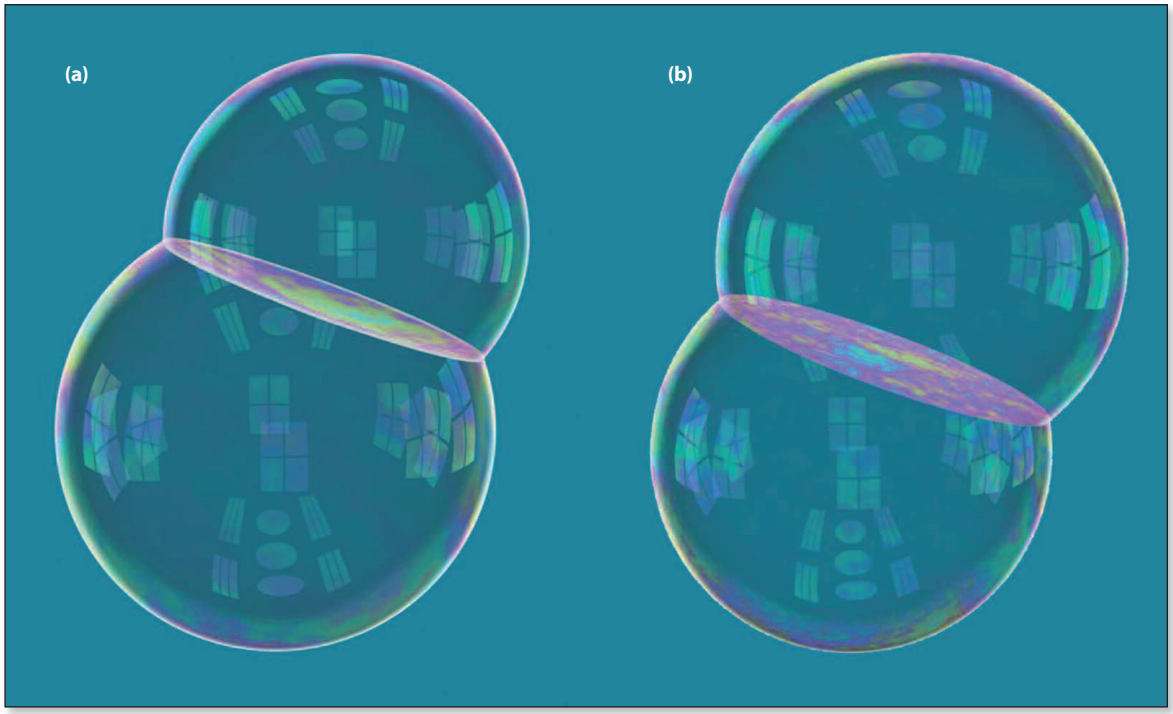
The 2D version of the Kelvin problem concerns the minimum partition of the plane into regions of equal area. That it is the tiling by regular hexagons (or honeycomb) seems obvious, and yet stood as a conjecture since classical antiquity [9]; its formal proof has been given only recently by Hales [10].



▲ **FIG. 2:** **(a)** The Kelvin structure. **(b)** The Weaire-Phelan structure. (Images by Kenneth Brakke, Susquehanna University.)

In this article we discuss some of our own recent results relating to surface minimisation in 2D foams. The general strategy is to draw competing structures and compare their energies; these can be worked out analytically in some cases, more generally numerically by solving a small set of non-linear algebraic equations that implement Plateau's laws. In the spirit of Kelvin, we offer no formal proofs.

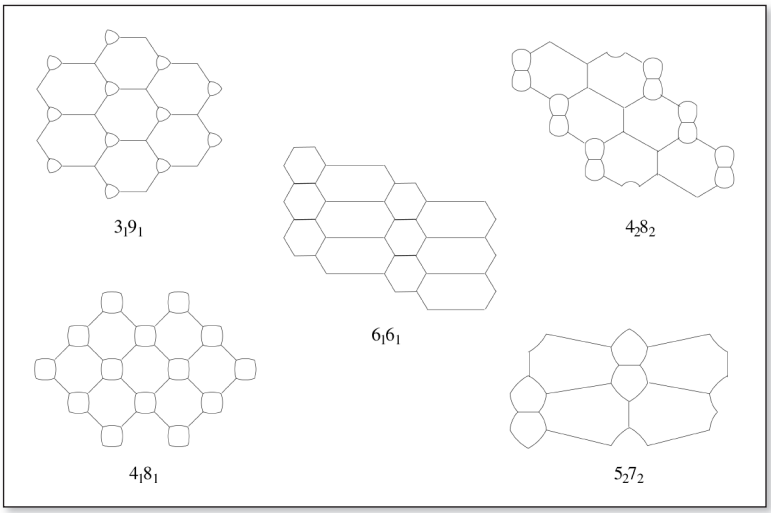
Besides contributing towards the solution of an intriguing (and, in our view, aesthetically pleasing) riddle of discrete geometry, what do we expect to achieve by this? Many solid foams, traditionally viewed as a distinct subject, are actually formed by freezing of vitrifying liquid foams. The mechanical properties of solid foams, such as their Young and shear moduli, and their yield strength, are paramount in many of their structural applications, and are known to depend sensitively on their topology [1]. Knowing the topology and geometry of the percursor, liquid foam composed of cells of given sizes and number of sides would therefore allow a more accurate prediction, and thus enable tailoring, of the properties of the final cellular solid. Other possible applications will be discussed below.



◀ **FIG. 3:** The double bubble. **(a)** Unequal volumes. **(b)** Equal volumes. (Images by J. Sullivan, TU Berlin.)

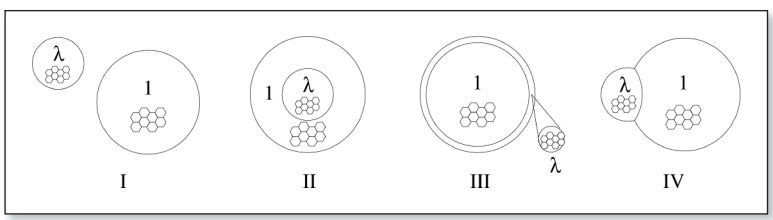
How to pave a plane with two types of tile?

A straightforward generalisation of the Kelvin problem in 2D is to ask ourselves: What is the minimum-perimeter partition of the plane into regions ('cells' or 'bubbles') of *two* different areas? Without loss of generality we take the area of the cell with fewer sides to be unity; the other cell will then have (non-dimensional) area λ, the ratio of cell areas. Again we consider *perfectly dry foams*, *i.e.*, whose liquid content is close to zero: these obey Plateau's laws [3] in 2D, as above, with the only difference that films (which must be either straight lines or arcs of circle) meet at 120° angles at vertices. Plateau's laws are *necessary* conditions for perimeter minimisation, but do not uniquely determine the (stress-free) geometry of a tiling of given topology and given cell area ratio λ. In this first approach we restricted ourselves to periodic tilings with at most two cells of each area per repeating unit, and such that all cells of the same area are equivalent (*i.e.*, have the same neighbourhood). Under these restrictions there is a finite (and fairly small) number of possible arrangements. Figure 4 shows the five that are minimal, *i.e.*, that have the lowest energy in some range of λ. Their characteristics are summarised in table 1. We use a simple notation to label them, *e.g.*, 3_19_1 is a tiling with one 3-sided cell and one 9-sided cell per repeating unit, etc. In addition to these, there are four others that are never minimal: 2_110_1, 2_210_2, 3_29_2 and 6_26_2.



▲ **FIG. 4:** The five tilings that have minimum perimeter in some range of λ, the cell area ratio [11].(With kind permission of The European Physical Journal (EPJ).)

▼ **FIG. 5:** The four sorted arrangements of honeycombs (I, II, III, IV) of cell sizes 1 and λ [11]. (With kind permission of The European Physical Journal (EPJ).)



Interval of λ	Minimal tiling
0.645-1	6_16_1
0.268-0.645	5_27_2
0.108-0.268	4_18_1
0.041-0.108	4_28_2
0-0.041	3_19_1

◀ **TABLE 1:** Minimal (*i.e.*, lowest-energy) tilings *vs* λ [12]. (With kind permission of The European Physical Journal (EPJ).)

It is seen that when cell sizes are very different (*i.e.*, for small λ), their numbers of sides are also very different. As λ increases the two types of cells become more similar; for λ>0.645 they are both hexagons, and we go continuously to the monodisperse honeycomb limit as $\lambda \to 1$.

Mixing *vs* sorting

What happens if we now allow the cells to de-mix, *i.e.*, separate into two regions each composed of cells of just one size? And what if we are dealing not with an infinite foam, but with a (more realistic) finite cell cluster? We now need to consider, in addition to the five minimal tilings of figure 4, the four sorted arrangements of figure 5. Sorting is of course always into two honeycombs, since each contains only cells all of the same size.

Besides the 'bulk' energy of each tiling, we must estimate the energies of the outer boundaries of the clusters, and of the boundary between clusters of different-sized cells; the latter we approximate by that of a wall of dislocations between mismatched honeycombs. This we do for each cell area ratio λ and for each number N of bubbles of each size. Our results are summarised in figure 6: note the alternation between mixed and sorted states, where the winning sorted arrangement is always IV in figure 5 ('partial wetting' of one honeycomb by the other).

Smaller clusters want to be mixed because of the high relative cost of forming interfaces; as N increases, 'biphasic' regions appear. However, convergence to the $N \to \infty$ limit [11] is slow, and has not quite been reached for N=104. Two further remarks are in order. Firstly, the limit of a monodisperse honeycomb is again approached continuously as $\lambda \to 1$, as expected (since in this limit 6+6 and 6_16_1 become indistinguishable). Secondly, and more intriguingly, the size of the 'biphasic' regions increases with increasing λ, *i.e.*, as the two types of cells become *more similar*. This behaviour is opposite to what one normally expects in a binary mixture, where miscibility is usually favoured by particle likeness.

But why should we care whether cells/bubbles mix or segregate? More recent applications arise in the emerging field of *discrete microfluidics* [13]. Here one aims to

control the transport and mixing (or sorting) of individual droplets of liquids for, *e.g.*, the delivery of minute quantities of reacting chemicals, as in tests of many different formulations of a novel drug or consumer product. Ideally one would like to be able to feed different reactants through the same channel(s) in such a way that they would not react until reaching some specified locations at specified times. Recent work [14] suggests that this might be achievable by encapsulating the chemicals in the bubbles of ordered foam structures that are then pushed through appropriately designed channel geometries. At low flow rates where viscous dissipation is negligible, whether bubbles mix or sort is governed by surface tension minimisation. In view of our results, careful selection of bubble sizes could therefore lead to the bubbles (and chemicals) self-assembling into the desired configurations, with no need for outside intervention.

Outlook

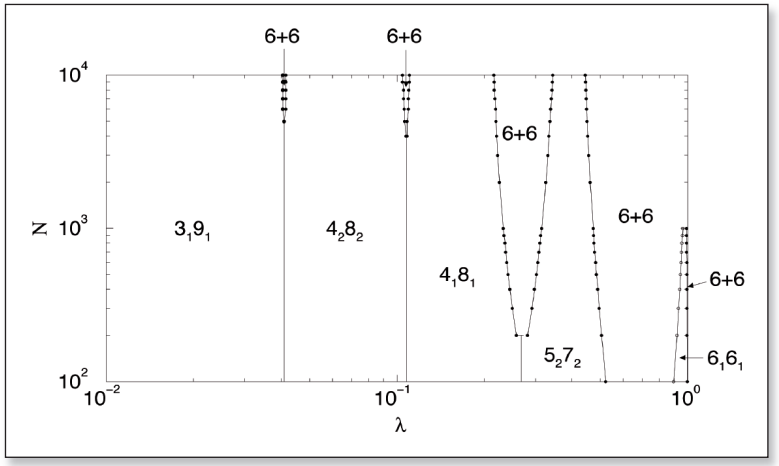
The work presented here can be extended in a number of directions.Our analysis of bidisperse tilings of the plane is admittedly rather restrictive. Ideally one would like to include a much larger set of possible arrangements, both periodic and aperiodic.

When addressing the competition between mixing and sorting Erreur ! Source du renvoi introuvable.we investigated just the special case of equal numbers of bubbles of each area. Moreover, we restricted our set of allowed mixed arrangements to those discussed above. The more general problem of finding the minimal configuration of clusters of bubbles of areas 1 and λ in any proportion would lead to the full phase diagram of 'bubble alloys'. One such diagram has been obtained by Likos and Henley [15] for a binary mixture of hard discs (in the $N\to\infty$ limit), using a 'zero-temperature approach' which, like ours, neglects the entropy. Their results for 1:1 clusters are in rough agreement with ours, the main differences being that they find an interval where a 'random tiling' wins, *two* intervals where 5_27_2 wins, and they did not consider the 4_28_2 tiling.

We have left out entirely the many issues pertaining to foams out of equilibrium, namely their rheology. These are currently the focus of much research, particulary with respect to the rigidity loss and flow of wet foams in relation to their topology. This and the applications to microfluidics alluded to above will probably be the most active fields of foam research in the coming years. ■

Dedication

This article is dedicated to the memory of M. A. Fortes, originator and prime mover of the research.



▲ **FIG. 6: 'Phase diagram' of 1:1 cell clusters in the (*N*,λ) plane. (Adapted from [11]. With kind permission of The European Physical Journal (EPJ).)**

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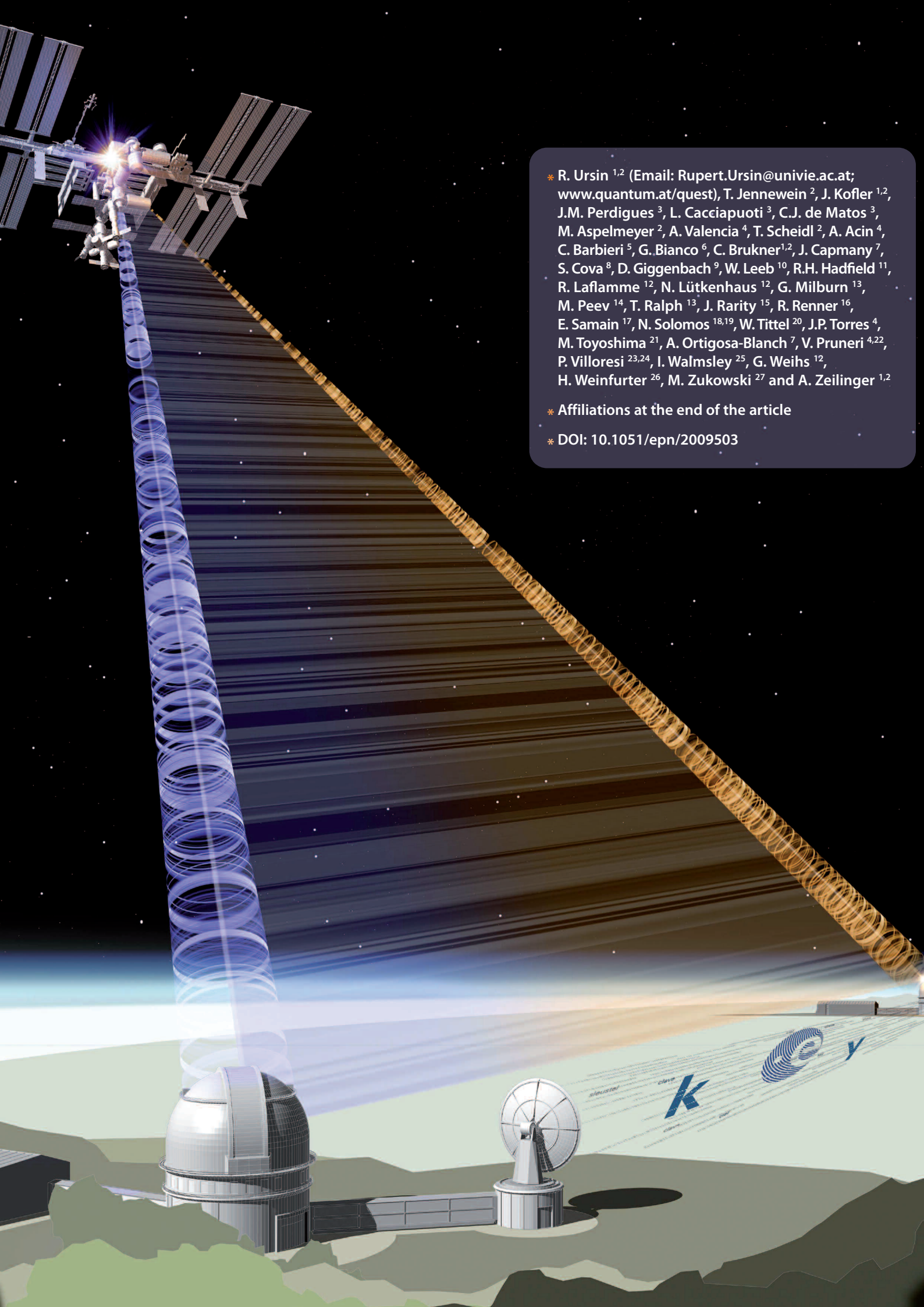

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SPACE-QUEST

EXPERIMENTS WITH QUANTUM ENTANGLEMENT IN SPACE

Quantum entanglement is, according to Erwin Schrödinger in 1935 [1], the essence of quantum physics. It inspires fundamental questions about the principles of nature. By testing the entanglement of particles, we are able to ask fundamental questions about realism and locality in nature [2]. Local realism imposes certain constraints in statistical correlations of measurements on multi-particle systems. Quantum mechanics, however, predicts that entangled systems have much stronger than classical correlations that are independent of the distance between the particles and are not explicable with classical physics.

It is an open issue whether quantum laws, originally established to describe nature at the microscopic level of atoms, are also valid in the macroscopic domain such as long distances. Various proposals predict that quantum entanglement is limited to certain mass and length scales or is altered under specific gravitational circumstances.

Testing the quantum correlations over distances achievable with systems placed in the Earth orbit or even beyond would allow verifying both the validity of quantum physics and the preservation of entanglement over distances impossible to achieve on ground. Using the large relative velocity of two orbiting satellites, one can perform experiments on entanglement where – due to special relativity – both observers can claim that they have performed the measurement on their system prior to the measurement of the other observer. In such an experiment it is no longer possible to think of any local realistic mechanisms that potentially influence one measurement outcome according to the other one.

Moreover, quantum mechanics is also the basis for emerging technologies of quantum information science, presently one of the most active research fields in physics. Today's most prominent application is quantum key distribution (QKD) [3], *i.e.* the generation of a provably unconditionally secure key at distance, which is not possible with classical cryptography. The use of satellites allows for demonstrations of quantum communication on a global scale, a task impossible on ground with current optical fiber and photon-detector technology. Currently, quantum communication on ground is limited to the order of 200 kilometers [4]. Bringing quantum communication into space is the only way to overcome this limit with state-of-the-art technology.

Another area of applications is metrology, where quantum clock synchronization and quantum positioning [5] are studied. Furthermore, sources of quantum states in space may have applications in the new field of quantum astronomy.

◀ **FIG. 1:** Distribution of pairs of entangled photons using the International Space Station (ISS). Entangled photon pairs are simultaneously distributed to two separated locations on Earth, thus enabling both fundamental quantum physics experiments and novel applications such as quantum key distribution. (Image courtesy ESA/GSRP

The proposed experiments

We propose to ESA to perform these experiments in space by placing a quantum transceiver on the external pallet of the European Columbus module at the ISS (see Fig. 1). The entire terminal must not exceed the specifications given for pallet payloads as provided by ESA. The requirements are: size 1.39×1.17×0.86 m^3, mass < 100 kg, and a peak power consumption of < 250 W, respectively. A preliminary design of a satellite-based quantum transceiver (including an entangled photon source, a weak pulse laser source, single photon detection modules together with two transceiver telescopes) based on state-of-the-art optical communication terminals and adapted to the needs of quantum communication has already been published in [6] (see Fig. 2).

The entangled photons are transmitted to two distant ground stations via simultaneous down-links [7], allowing a test on entanglement and the generation of an unconditional secure quantum cryptographic key between stations separated by more than 1000 km.

Additionally, such a quantum transceiver in space is capable of performing two consecutive single down-links—using the entangled or the weak pulse laser onboard the satellite—establishing two different secure keys between the satellite and each of the ground stations (say, Vienna and Tokyo). Then a logical combination of the two keys (*e.g.* bitwise XOR) is sent publicly to one of the two ground stations. Out of that, an unconditionally secure key between the two ground stations can be computed. Using such a scheme would allow for the first demonstration of global quantum key distribution.

An important step towards the applicability of quantum communication on a global scale is to extend single QKD links to a quantum network by key relaying along a chain of trusted nodes using satellites as well as fiber-based systems. Furthermore, the efficiency of quantum networks can be improved employing quantum percolation protocols [8].

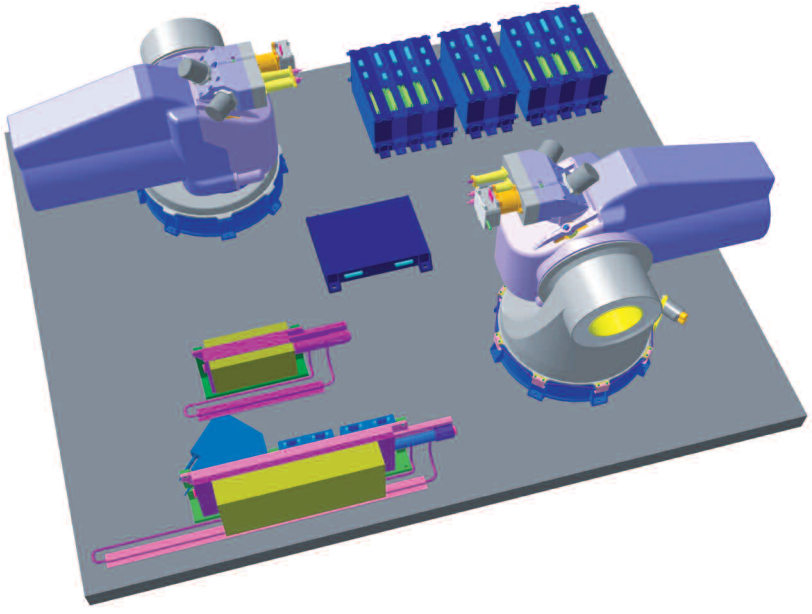
It would be favorable to include in parallel to the QKD down-link from the ISS a high-speed communication link providing several Gigabit per second bandwidth [9].

Proof-of-principle experiments

As an important step towards quantum communication protocols using satellites various proof-of principle demonstrations of quantum communication protocols have already been performed over terrestrial free-space links. One experiment was carried out on the Canary Islands using a 144 km free-space link, between the neighboring islands La Palma and Tenerife (Spain), where ESA's 1-meter-diameter receiver telescope, originally designed for classical laser communication with satellites, was used [10, 11] to receive single photons (see Fig. 3).

In a second experiment the Matera-Laser-Ranging-Observatory (Italy) was used to establish a single photon downlink from a low-earth orbit satellite [12]. A satellite-to-Earth quantum-channel down-link was simulated by reflecting attenuated laser pulses off the optical retro-reflector on board the satellite Ajisai, whose orbit has a perigee height of 1485 km.

An important component in space-based quantum communication is a source for entangled photons that is suitable for space applications in terms of efficiency, mass and power consumption. A source fulfilling the payload requirements based on highly efficient down-conversion crystals which deliver the necessary numbers of photon pairs has been published in [13].



▼ FIG. 2: Image of the preliminary design of a transceiver suitable for the external pallet of the European Columbus module at the ISS. The terminal contains a source for entangled photons as well as for decoy laser pulses, the onboard electronics and two transmitter telescopes. (Image courtesy Oerlikon.)

Topical team

In 2007, the formation of a Topical Team for supporting the Space-QUEST experiment comprised of researchers from academia actively involved in relevant scientific fields was initiated by ESA and currently consists of 38 members from 10 countries. This team will support the proposal with their individual scientific and technical expertise and also aims to increase the research community's interaction with industry. The present programmatic roadmap of Space-QUEST is compatible with a launch date by end of 2014 [14,15].

Conclusions

We emphasize that the space environment will allow quantum physics experiments with photonic entanglement and single photon quantum states to be performed on a large, even global, scale. The Space-QUEST proposal aims to place a quantum communication transceiver containing the entangled photon source, a weak pulsed (decoy) laser source and single photon counting modules in space and will accomplish the first-ever demonstration in space of fundamental tests on quantum physics and quantum-based telecom applications. The unique features of space offer extremely long propagation paths to explore the limits of the validity of quantum physics principles. In particular, this system will allow for a test of quantum entanglement over a distance exceeding 1000 km, which is impossible on ground. &&■

Acknowledgments

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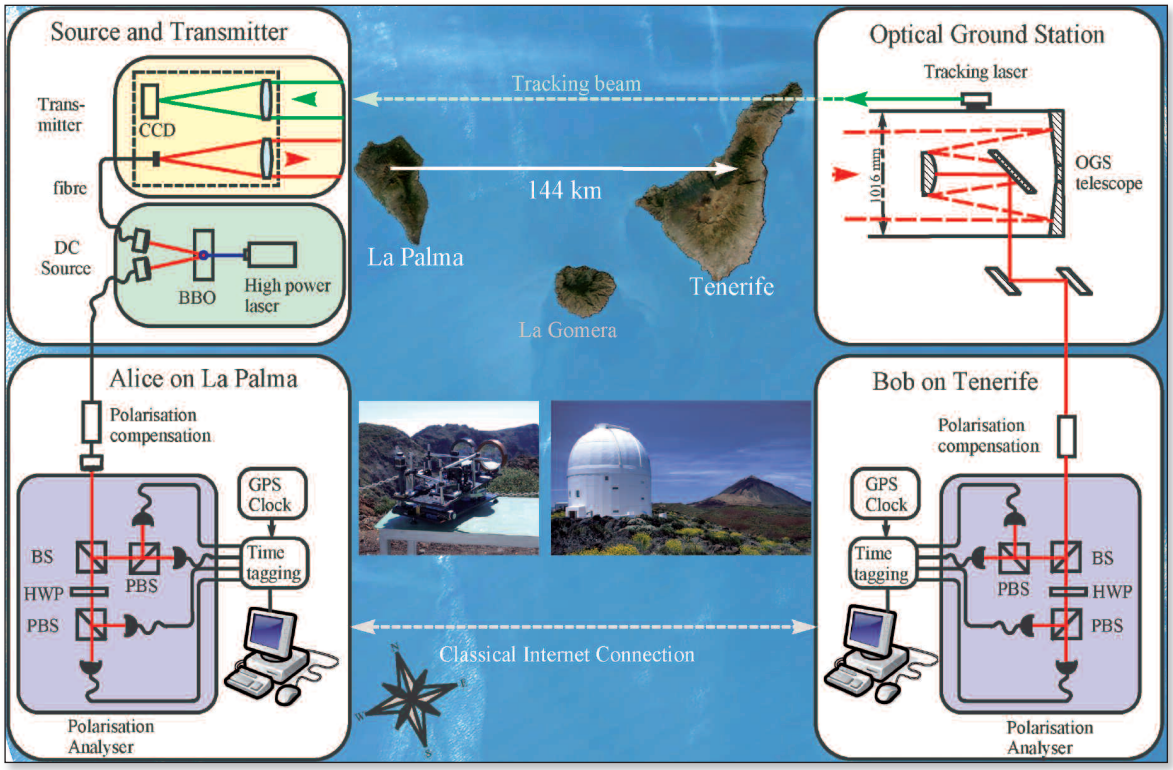

◀FIG. 3: Proof-of-principle inter-island quantum communication experiment between the Canary Islands La Palma and Tenerife over a 144 km free-space link. The receiver on Tenerife was the Optical Ground Station of ESA, which contains a 1 m telescope. This system is used for optical communication with satellites, and was adapted as a quantum communication receiver (from Ref. [11]).

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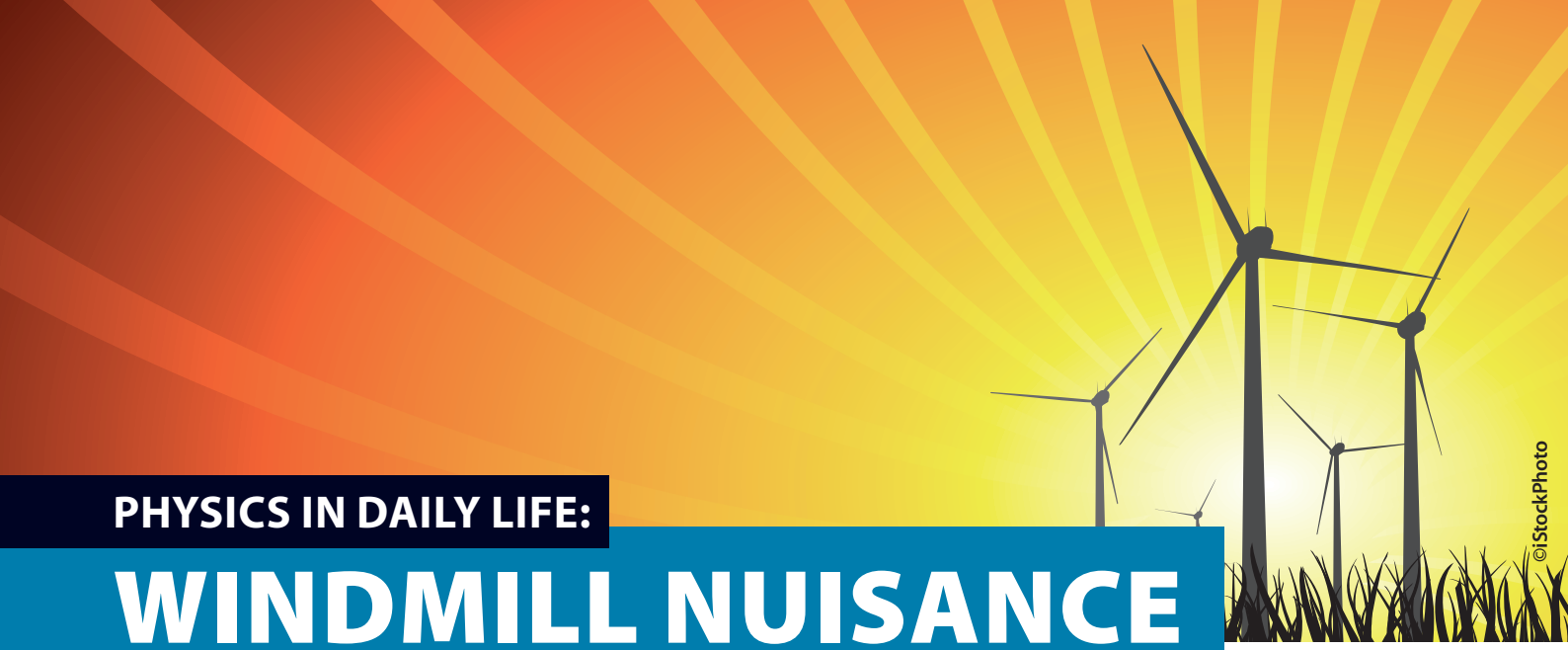

PHYSICS IN DAILY LIFE:

WINDMILL NUISANCE

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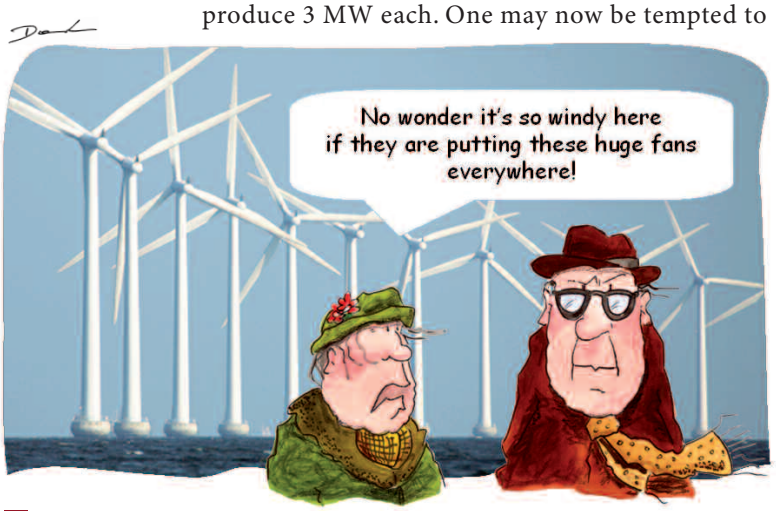
Many people dislike them, and some find them downright awful: it's the wind turbines scattered all across Europe these days. And let's be frank: there is nothing quite like the relentless droning of rotor blades to spoil the peace and tranquility of the countryside. Why do we put those things all over the place? As physicists we realize that wind power is proportional to v^3, with v the wind speed. So it may not be such a great idea to put those turbines on land, let alone in the middle of continental Europe where wind speeds are typically low. Why not put them off-shore where winds are strong, in the North Sea or the Baltic, for example? A few off-shore wind farms have already been put into operation recently, and a number of others are planned. Shouldn't we forget those monsters on shore altogether?

Let us have a closer look at the two options. First: wind turbines at sea. How many do we need, to begin with? Let us assume we want to have the equivalent of, say, 1500 MW, which is typically the electricity output of a large conventional or nuclear power plant. Modern wind turbines with a rotor diameter of 90 meters can produce 3 MW each. One may now be tempted to conclude that we need 500 turbines. Wrong. We have to include the load factor, *i.e.*, the average output divided by the maximum output. This is 30 to 33 % for wind turbines at sea (and up to 25 % on shore). So we need about 1500 turbines of this type for 1500 MW.



How much space would such a large number of turbines take? Here we have to account for the fact that a reasonable spacing is required. If wind turbines are too close, they will spoil each other's wind profile. This not only decreases the power of the wind turbines downstream, it also puts extra strain on the construction as a result of turbulence. It turns out that a spacing of 7 rotor diameters is a reasonable rule of thumb for wind farms. So the total area required is about 800 km^2. This is consistent with a rule of thumb saying that wind farms at sea generate, on average, between 1 and 2 MW per km^2, depending on type and location. This is, in first approximation, independent of the rotor diameter, since both turbine power and spacing scale with the square of the diameter. Large turbines obviously take advantage of the fact that the wind speed increases with altitude. Given the size of the seas around Europe, 800 km^2 does not sound unreasonable. So we should opt for off-shore wind power? Perhaps, but off-shore wind turbines have a drawback: building and maintaining them at sea is cumbersome. This makes them roughly twice as expensive as turbines on land. Economically speaking, we would be better off with wind power on shore. Such turbines, if placed wisely, are almost comparable to traditional power plants. And their 'energy pay-back time' is less than a year. Sounds great, but it does not address our aesthetic objections.

One may wonder: How did our 17th century ancestors perceive the windmills that we find so charming in the Dutch landscape today? Interesting question. But the answer… is blowing in the wind. ■

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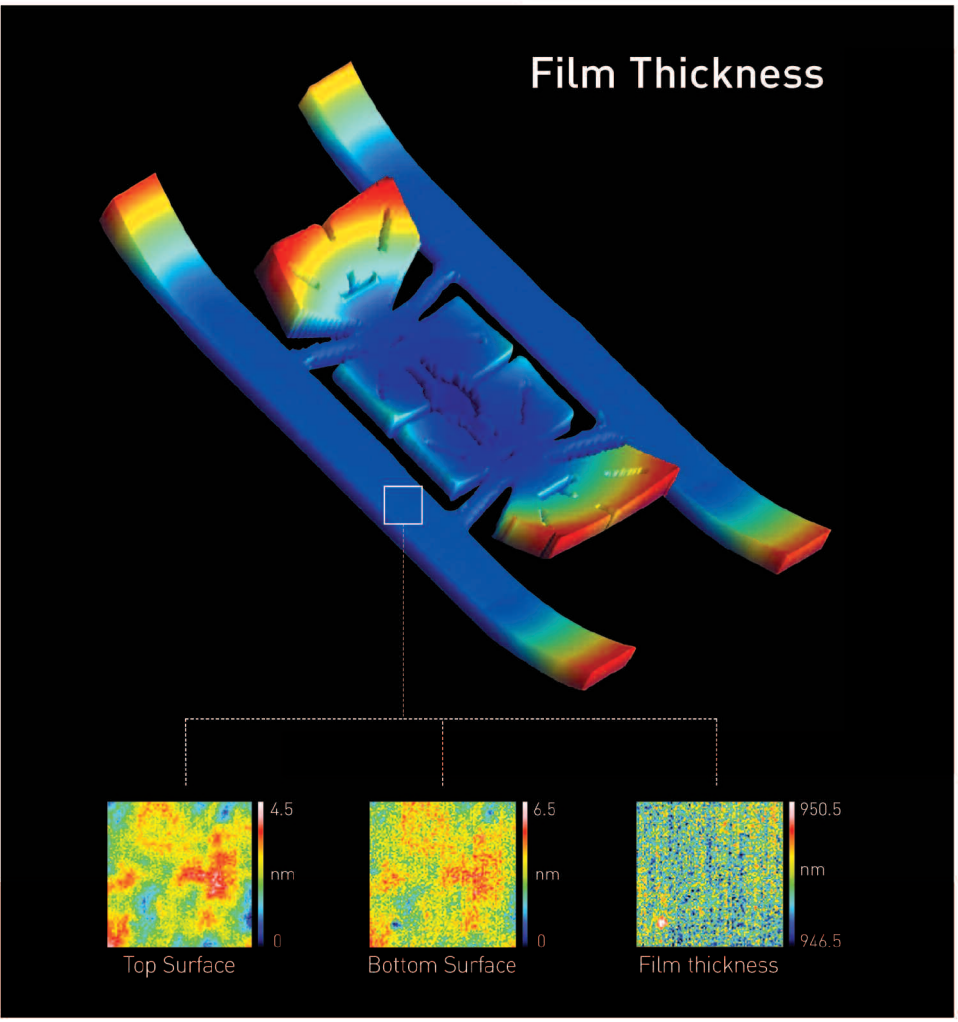

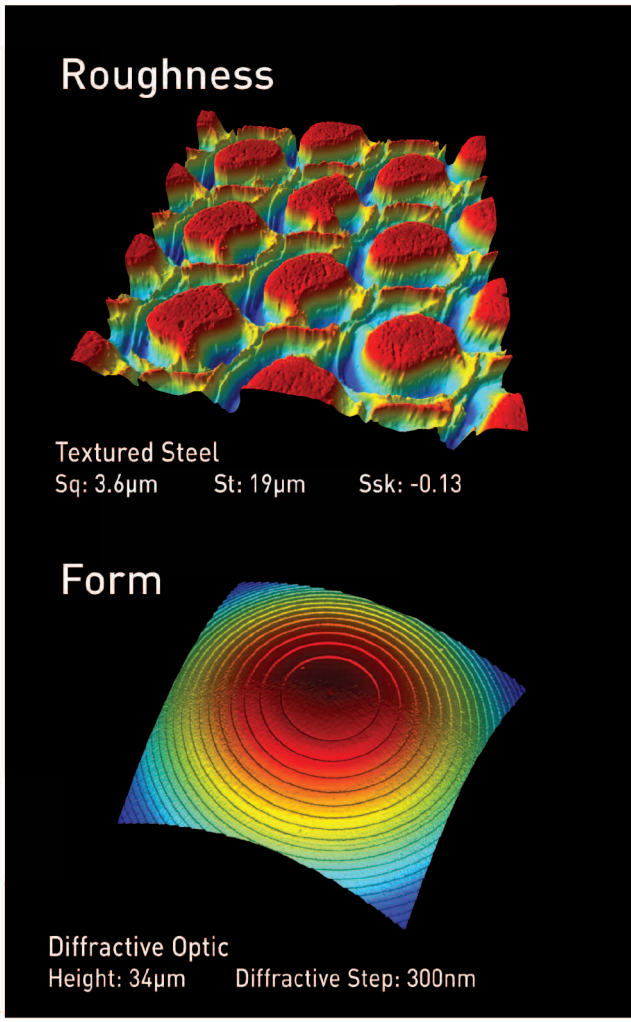

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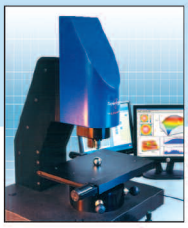

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