

# 50 ideas to change science



## Part two

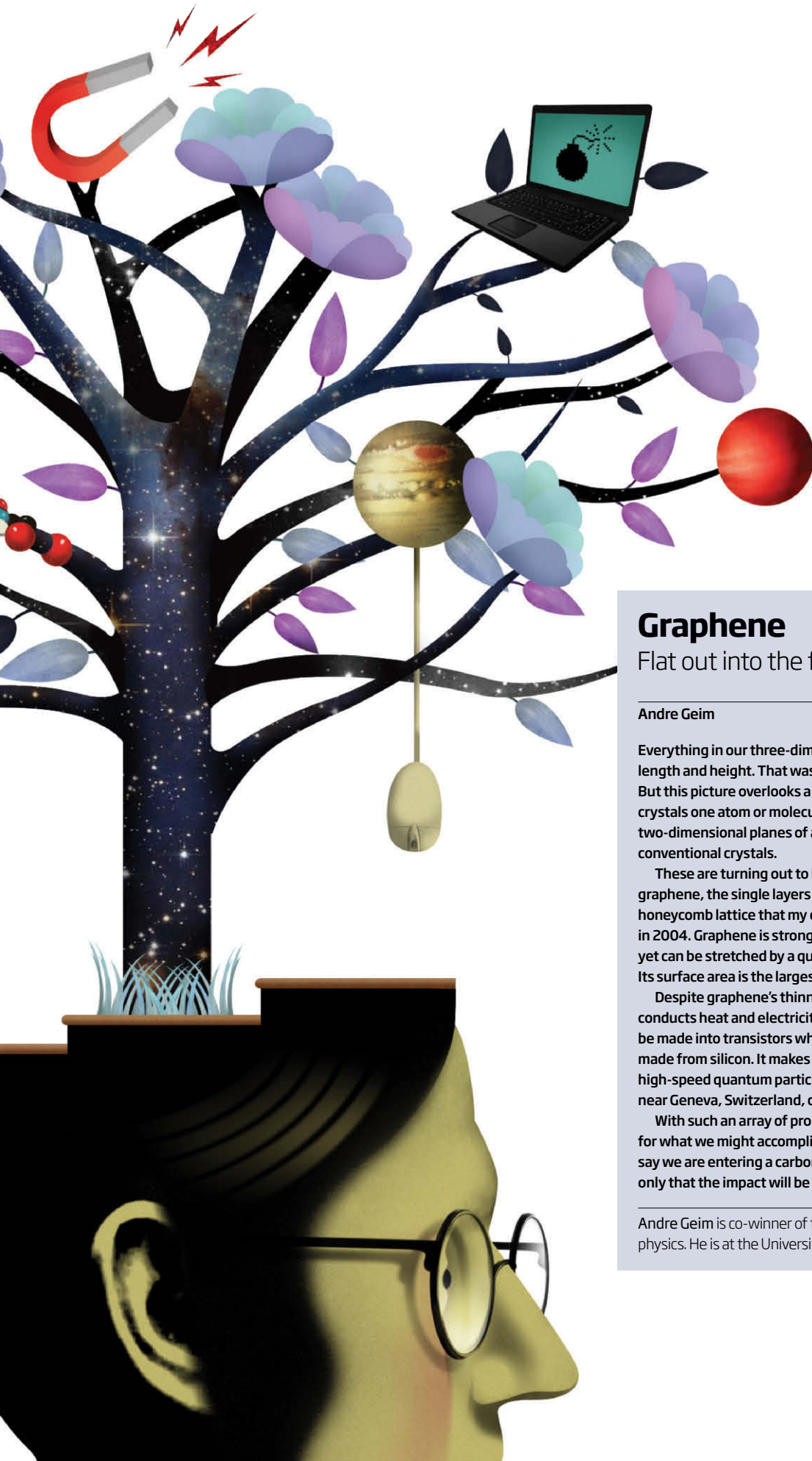
## Physics, space and technology

In the second part of our special report on the game-changing ideas of science, it is the turn of nature on its smallest and grandest scales. From new ways to probe the quirks of the quantum world to the computing technologies of the future to the latest thinking on the workings of the cosmos, what ideas, projects and trends are shaking up the worlds of physics, space and technology?

It is your turn, too. Which of the 50 ideas from this week and last do you think is the biggest? To nominate your favourite, turn to page 40 for details of our prize competition



BRETT RYDER



## Graphene

Flat out into the future

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Andre Geim

Everything in our three-dimensional world has a width, length and height. That was what we thought, at least. But this picture overlooks a whole class of materials: crystals one atom or molecule thick, essentially two-dimensional planes of atoms shaved from conventional crystals.

These are turning out to be wonder materials. Take graphene, the single layers of carbon atoms arranged in a honeycomb lattice that my colleagues and I first isolated in 2004. Graphene is stronger and stiffer than diamond, yet can be stretched by a quarter of its length, like rubber. Its surface area is the largest known for its weight.

Despite graphene's thinness it is impermeable. It conducts heat and electricity better than copper, and can be made into transistors which are faster than those made from silicon. It makes possible experiments with high-speed quantum particles that researchers at CERN near Geneva, Switzerland, can only dream of.

With such an array of properties, there are high hopes for what we might accomplish with graphene. Optimists say we are entering a carbon age. Even pessimists argue only that the impact will be somewhat less.

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Andre Geim is co-winner of the 2010 Nobel prize for physics. He is at the University of Manchester, UK

### Topological insulators

#### A new spin on electronics

For the time after electronics there is spintronics, in which information is transported and devices controlled not by currents of many electrons, but by the quantum-mechanical spins of individual electrons.

There are still a few obstacles on the way. One is that spin is a magnetic effect, but on the small scale of, say, a computer chip, we only really know how to manipulate electric fields.

That is where topological insulators come in, a new class of material only postulated in 2005. Quantum-mechanical effects within them allow the spins of electrons on their surfaces to be controlled directly by electric fields.

The result is an "electron superhighway" along which electrons flow in one-way "lanes" according to their spin. Collisions are suppressed and business is conducted altogether more smartly than on a conventional silicon chip, so they don't heat up as much as today's power-hungry chips. If the technique can be scaled up, the result could be cooler, faster spintronic devices for all.

### Mars rocks

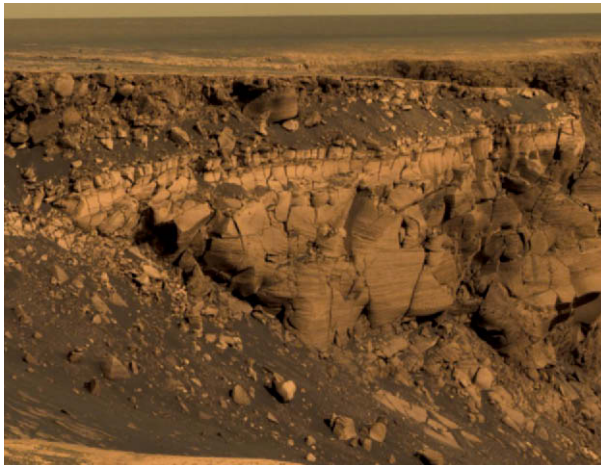
#### Raiders of the Red Planet

The moon rocks brought to Earth by the Apollo missions in the 1960s and 1970s represent almost unaltered material from the solar system's earliest days. They are the foundation stones of our theories of planetary formation.

Ideally, we'd like a load of rocks from elsewhere to check those theories. Previous probes have done some limited in-situ chemical analysis of the most obvious source, Mars, but a full battery of tests would mean bringing a chunk of the Red Planet back here.

That would also tell us about Mars's own development. How extensive was its early volcanism? Was it ever covered by an ocean? If life ever got started on Mars, do its rocks reveal how?

The answers will be a while coming, if they come at all. The US National Academy of Sciences is currently weighing a Mars sample-return mission against a mission to Jupiter. Even if the Mars mission is selected, it could be 15 years or more to blast-off, presuming the technology - to lift off against Mars's strong gravity field, for instance - is ready by then.



JPL/NASA

OLIVIER CULMANN/TENDANCEFLOUE



### The internet telescope

#### How the web gets beneath our skin

Duncan Watts

The fundamental question of social science, in a nutshell, is this: how can you throw a bunch of people together and end up with not just a bunch of people, but families, companies, markets and societies?

The answer, we have long thought, lies in the interactions between individuals and organisations. Measuring those interactions is at last becoming possible as hundreds of millions of people shift their social and economic activities online - to email and social networking services, search engines and e-commerce sites and, increasingly, smartphones. The net is becoming to social science what the telescope was to astronomy: a device for making a previously invisible universe visible.

We have used email and instant messaging to map out social networks running to hundreds of

millions of people, and shown through large-scale experiments how social influence generates hit songs. We have used search queries to predict the box-office revenues of movies or local flu trends, and mined Facebook updates to generate measures of a society's happiness.

These early successes do not address the "big" problems of social science, such as the origins of economic inequality or religious intolerance. But there is no reason why the internet data revolution should not change our understanding of ourselves, just as the data collected by early astronomers transformed our view of the cosmos.

Duncan Watts directs the human social dynamics group at Yahoo! Research, New York, and is author of the upcoming book *Everything is Obvious (Once You Know the Answer)* (Crown, 2011)



## The AdS/CFT correspondence

### Superconductors from black holes

Jan Zaanen

Of all things in physics, black holes have possibly the most appeal. Mind-bogglingly extreme, they are abundant in the universe. In fact, there's probably one in a lab near you - although you will need one of the weirdest insights of recent physics to notice it.

This is the grandly titled "anti-de-Sitter/conformal field theory correspondence", or AdS/CFT for short. A result derived from string theory, it says that gravitational objects such as black holes are encoded in a very precise, albeit indirect, manner in the properties of exotic quantum matter probed in many physics labs worldwide.

Why does this matter? Because while quantum matter is largely a mystery even to the initiated, we have a pretty extensive tool kit for dealing with black holes and the like. With AdS/CFT, we can use the one to explain the other.

That might allow us, for example, to crack the 24-year-old riddle of high-temperature superconductors, materials whose quantum workings allow them to conduct electricity without resistance at temperatures well above absolute zero. If through that we can realise the dream of superconductivity at room temperature, we would rewrite the terms of the energy debate.

The grandest dreams of physicists, however, lie with what the AdS/CFT correspondence might deliver in another direction: could quantum-matter experiments be mobilised to obtain a deeper understanding of gravity, perhaps leading to a theory of quantum gravity that could unify all of physics? This promise captivates me and many others.

Jan Zaanen is professor of theoretical condensed-matter physics at Leiden University in the Netherlands

## Quantum Darwinism

### The fittest of all possible worlds

It has bluffed the best minds since quantum theory's inception. Quantum stuff can exist in several places at once, or spin clockwise and anticlockwise simultaneously. But when we make a measurement, we always get just one answer. Why?

Perhaps because of a Darwinian-style struggle for survival: quantum states compete with each other for our attention, with us only seeing the "fittest" state that influences its surroundings the most.

Experiments this year probing minuscule assemblages of electrons held in quantum dots seem to confirm some predictions of this "quantum Darwinism" (*Physical Review Letters*, vol 104, p 176801). If the idea proves right, it will confirm our suspicions that experiments can only probe a quantum system's impact on its environment, never the system itself.

## Slow light

### Lowering the speed limit

Light, the fastest thing in the cosmos, can be slowed to walking pace or even stopped in its tracks. Who would have thought it?

Actually, it is a sleight of hand: it is not the light that is slowed or stopped, but the information that it carries. Send an energy-tuned pulse of light into a cloud of supercooled atoms known as a Bose-Einstein condensate, and it resonates with the atoms of the condensate, allowing information to be transferred from the light to the atoms. A second laser pulse can then pull the information out of the atoms and carry it away.

This is good news. If we can master the fiddly details of the technique, the ability to store light-borne data indefinitely could usher in the age of super-fast optical computers that do away with cumbersome silicon components.

## Agent-based modelling

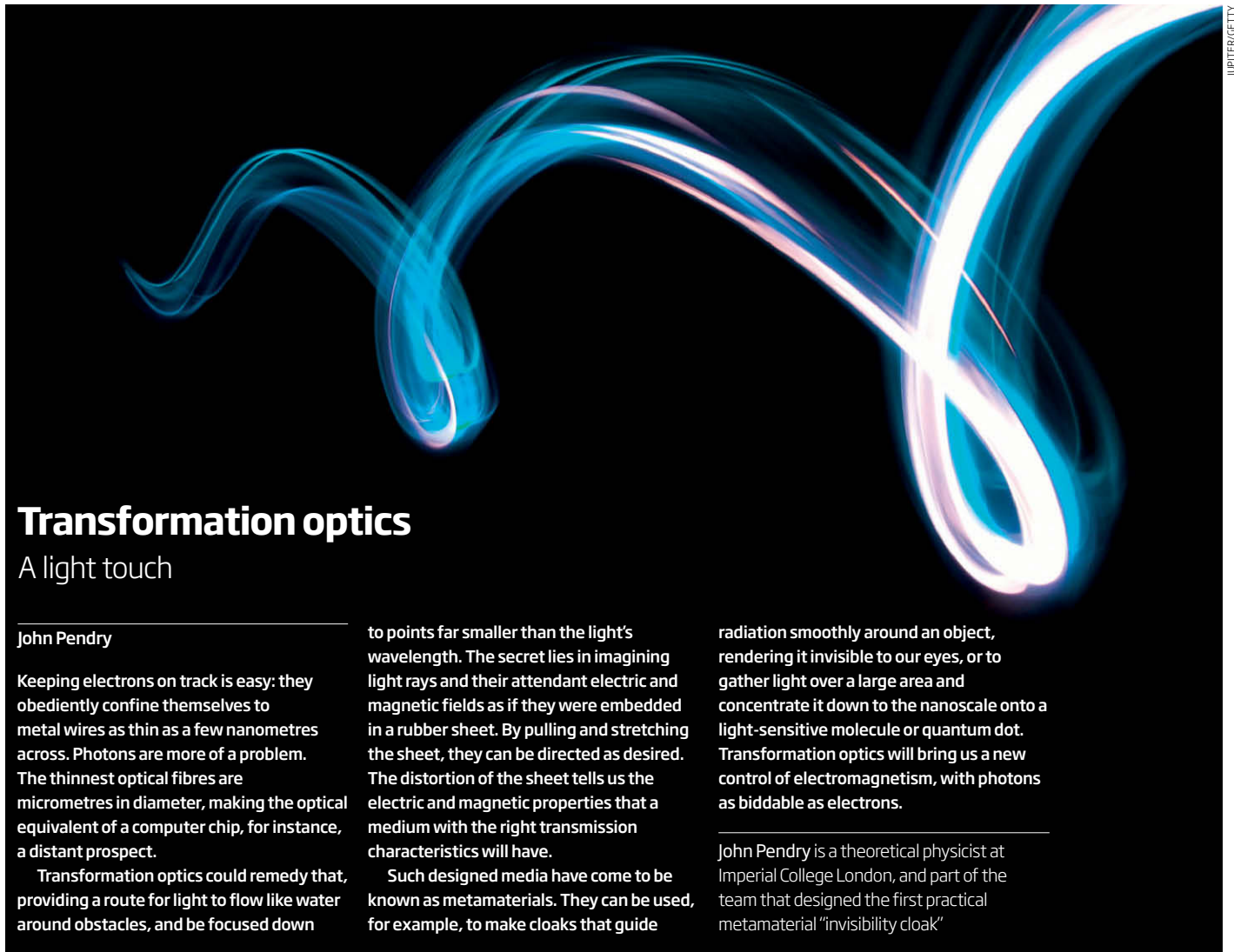
### It's a human world, after all

How do you model the evolution of a solar system? Simple, in theory: you program a computer with the equations that describe planetary motions and relevant numbers such as each planet or asteroid's mass, and soon you have a picture of your solar system in a billion years' time.

In practice, a solar system's myriad objects make things less simple. Imagine, then, the difficulty of simulating human interactions, where the number of players is so much greater, and their behaviour less easily described by a few equations.

Agent-based modelling circumvents this difficulty. Particle-like "agents" interact according to simple, global rules, and additional adaptive rules permit their behaviour to change in response to previous interactions. Complex real-world behaviours, deriving from millions of inscrutable individual decision-making processes, often quickly emerge.

That provides a powerful tool to crack tough nuts such as the origins of traffic congestion, epidemics and financial crashes. Now ambitious plans are afoot to create a model with 10 billion agents - one that can simulate the development of an entire planetary population.



JUPITER/GETTY

## Transformation optics

### A light touch

John Pendry

Keeping electrons on track is easy: they obediently confine themselves to metal wires as thin as a few nanometres across. Photons are more of a problem. The thinnest optical fibres are micrometres in diameter, making the optical equivalent of a computer chip, for instance, a distant prospect.

Transformation optics could remedy that, providing a route for light to flow like water around obstacles, and be focused down

to points far smaller than the light's wavelength. The secret lies in imagining light rays and their attendant electric and magnetic fields as if they were embedded in a rubber sheet. By pulling and stretching the sheet, they can be directed as desired. The distortion of the sheet tells us the electric and magnetic properties that a medium with the right transmission characteristics will have.

Such designed media have come to be known as metamaterials. They can be used, for example, to make cloaks that guide

radiation smoothly around an object, rendering it invisible to our eyes, or to gather light over a large area and concentrate it down to the nanoscale onto a light-sensitive molecule or quantum dot. Transformation optics will bring us a new control of electromagnetism, with photons as biddable as electrons.

John Pendry is a theoretical physicist at Imperial College London, and part of the team that designed the first practical metamaterial "invisibility cloak"

## Hořava gravity

### The end of space-time

Since Einstein published his general theory of relativity in 1915, space and time have been one: space-time. Almost a century on, they may be getting divorced.

General relativity provides an explanation for the force we call gravity. But it is not a quantum theory, unlike the theories describing the other three forces of nature. Last year, though, the Czech physicist Petr Hořava worked out that by allowing space and time to change independently of one another, gravity becomes susceptible to quantum theory's advances.

A marriage of the two would represent the greatest breakthrough of physics - a "theory of everything" to answer questions such as what happened at the big bang, when microscopic volumes met intense gravity. More complex proposals such as string theory are already attempting the same coup, and are equally unverified by experiment. Time alone will tell which approach is right.

"The marriage of relativity and quantum theory would be the greatest breakthrough of physics - a 'theory of everything'"

## Lifelogging

Digital immortality available now

Gordon Bell

In 1945, American engineer Vannevar Bush introduced the idea of a person's memex - "an enlarged intimate supplement to his memory" - that would store, search and retrieve a lifetime's books, records and communications. Fifty years later, Bill Gates wrote that "someday computers will store everything a person has ever seen and heard".

That day is now here. Since 2001, Jim Gemmell and I have demonstrated many aspects of complete "lifelogging", storing letters, papers, photos, videos and voice recordings associated with my life in an annotated and searchable database. Terabyte memory storage coupled with digital cameras, biosensors and GPS means we can now log everything about an individual in real time, from their location to aspects of their physical state such as energy expenditure, heart rate and stress levels.



Utopian vision, or dystopian nightmare? That will depend not least on the laws and norms we establish on privacy. What rights do we have, for example, to record our interactions with others? But lifelogging's beneficial potential is immense. In 2009, researchers in the UK showed how lifelogging with a time-lapse camera can aid those suffering from memory loss to regain control of their lives (*Journal of Neurology, Neurosurgery & Psychiatry*, DOI: 10.1136/jnnp.2008.164251).

For social scientists, extensive lifelogging will mean an unprecedented flood of data to further our understanding of human behaviour. For each of us, it could mean a chance for a little, limited immortality.

Gordon Bell is a computer scientist at Microsoft Research in Redmond, Washington

## Claytronics

Matter shaped as you want it

Imagine shape-shifting grandma into a piece of furniture. Fanciful, perhaps, but the potential of claytronics does not stop far short.

It involves building up materials from tiny, wirelessly programmable blocks dubbed catoms, which can be instructed to bind together in any three-dimensional arrangement. In their latest incarnation, catoms are millimetre-sized curled-up strips of conducting material that respond to remotely controlled electrostatic forces.

It is early days, and present research is concentrating on ways to bind catoms together more firmly, while still keeping them detachable. Eventually, though, the possibilities range from chairs that morph on command into a table or bookcase, to a form of videoconferencing in which a realistic copy of the other speaker is in the room while you chat.

## The Square Kilometre Array

Probing the dark universe

There is a part of the universe that conventional telescopes do not reach. To see what went on in those far-off times, in the "dark ages" before stars and galaxies formed, we need an instrument the likes of which we have not seen. The Square Kilometre Array (SKA) will consist of thousands of radio telescopes spread across a continent - whether Australasia or southern Africa will be decided in 2012 - acting in concert to produce the equivalent of a single, gargantuan dish a square kilometre in size.

SKA will spy out radio waves emitted by ultra-distant hydrogen atoms and chart their disappearance as the atoms are dismembered by ionising light from the first celestial objects. It will help to pin down the properties of our apparently accelerating universe, probe general relativity around black holes and look into the origin of cosmic magnetic fields. In short, it will open our eyes to the invisible cosmos.

## Magnetic monopoles

Electromagnetism's missing link

Break a bar magnet in half and, like the broom in Disney's *The Sorcerer's Apprentice*, you get two new magnets, each with two poles. Can you ever have just one pole - a monopole?

Yes, say physicists. Magnets are described by the theory of electromagnetism. The "electro" side involves attractive and repulsive forces and isolated positive and negative charges, so symmetry demands that the attractive and repulsive forces of magnetism should also be accompanied by isolated poles. What's more, our best theory describing the earliest moments of the universe requires monopoles to exist.

So for the past 80 years we have been combing through environments as diverse as moon dust, cosmic rays and the debris of collisions in particle accelerators to find them. We've just started seeing things that fit the description in highly specialised crystals known as spin ices. But the question is still whether we will ever spot one in the wild.

## Memristors

### Missing link to an artificial brain?

The building blocks of electronic circuits are resistors, capacitors and inductors. Oh, and memristors. These devices - "resistors with memory" - were predicted to exist 40 years ago, but it was only in 2008 that a material with memristive behaviour was finally found (*Nature*, vol 453, p 80).

The small size and low power consumption of memristors makes them perfect for storing and manipulating information. A single memristor can do the work of up to a dozen transistors in a CPU chip, and the first chips to use the technology are due on the market in 2013.

But memristors offer still more. One idea is that they reproduce the behaviour of synapses, the conducting gaps that ferry electronic signals between neurons. Developing memristive circuits that simulate the architecture of the brain on a chip might enhance our understanding of our own circuitry, or even help to develop next-generation artificial intelligence.

## Nuclear transmutation

### Blasted waste

Nuclear reactors provide about 14 per cent of the world's electricity. They also generate 12,000 tonnes of waste each year, some of which will remain dangerously radioactive for millennia. The current plan for dealing with this poisonous legacy is to seal it in underground repositories and put a "Keep out" sign up to ward off future generations.

There is another way, inspired by the radioactive reactions that forge heavy metals in a supernova: blast the spent fuel with neutrons. Harmful radioactive isotopes absorb these neutrons, become unstable and decay into something somewhat less problematic.

The most troublesome forms of plutonium, uranium and other actinides can require hundreds of thousands of years to become harmless, but this "nuclear transmutation" can slash that to a more manageable 500 years. Experiments in Europe and Japan will test the idea in the next few years. If industrial-scale projects can clean up high-level nuclear waste properly, many more countries could be saying "yes please" to nuclear power.



PATRICK LANDMANN/SCIENCE PHOTO LIBRARY

## Supersymmetry

### The window to a new reality

John Ellis

The standard model of particle physics is both wildly successful and manifestly incomplete. When we consider what might extend and deepen our understanding of nature's most basic workings, there is often a one-word answer: supersymmetry.

Supersymmetry is like a wonder drug. It helps to unify the various fundamental interactions of nature. It plays a pivotal part in quantum theories of gravity based on string theory. It could even explain what the dark matter that fills the universe is made of.

At its heart is a simple idea: that all known particles have a heavier "superparticle" partner with a different quantum-mechanical spin.

Particles and superparticles are mathematically linked through a "superspace" whose dimensions - and this is where things become a little hard to envisage - are the square roots of dimensions in our normal space.

Physics, technology and even philosophy were revolutionised when Einstein's relativity taught us to regard time as a fourth dimension. Could the idea that the familiar dimensions of space-time have square roots be as revolutionary? As the Large Hadron Collider at CERN, near Geneva, Switzerland, searches for the first traces of supersymmetry, we are about to find out.

John Ellis is a theoretical physicist at CERN and King's College London

## Random matrix theory

### Not all randomness is equal

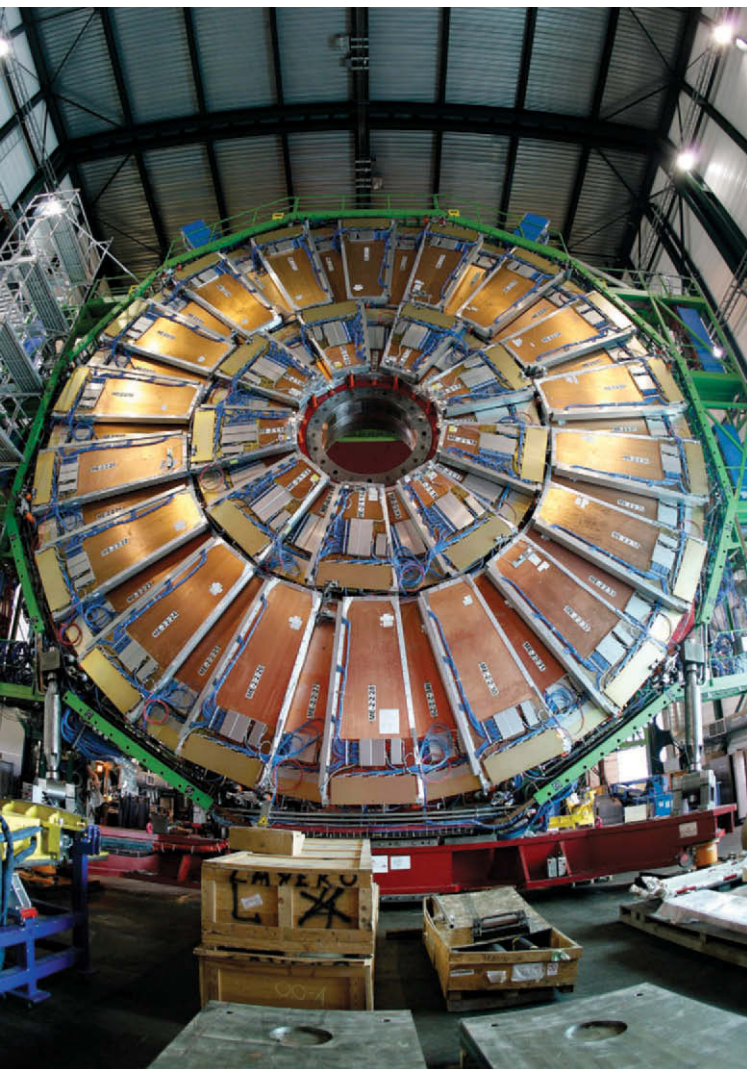
Marcus du Sautoy

Randomness often does not seem random. In a lottery such as the UK's National Lottery, in which six balls are plucked from 49, numbers clump: half the possible draws contain two consecutive numbers.

That's traditional randomness. But a new, non-clumping form of randomness now seems to be

cropping up in data all over mathematics and science, the signature of a mathematical curiosity called random matrix theory.

A matrix is a rectangular array of numbers that can be used to encode spatial transformations. The stretching or shrinking produced by a matrix in key directions of space is given by the matrix's associated "eigenvalue". Random matrices are



AP PHOTO/KEystone, MARTIAL TREZZINI

## Verified software

### My computer won't fail me

Web-browser crashes are annoying, but as far as software malfunctions go, the consequences are mild. With a plane's autopilot or the control room of a nuclear power station, it's another matter. As our lives become ever more saturated with computers, how can we know they won't fail?

Currently, we systematically test all conceivable scenarios under which they might. A better insurance might be logic. A computer program is a sequence of statements and commands that ultimately boil down to logic. Logic can be reduced to mathematical theorems that can be proved correct with an otherwise unattainable certainty.

The mathematical techniques to check software using formal logic have existed since the 1960s, but faster computers, better algorithms and clever theorem-checking programs are now making "verified software" commercially feasible. Software that is logically watertight is also less vulnerable to malicious attack, making this one innovation that could leave us all more secure.

## Anyons

### The fillip that quantum computing needs?

Some human tribes have been encoding numbers in knots for millennia. The tribe known as physicists has recently discovered that quantum particles can encode numbers too. Now they are tying the two ideas together, using particles' convoluted trajectories to represent bits of information.

The study of knots is known as topology, and topological quantum computing could create a revolution in number-crunching. The particles involved are not your average electrons or atoms, but non-Abelian anyons, ghostly entities that exist only as the product of the motion of other things. If you want the eye of a storm, you first need a storm; if you want non-Abelian anyons, you first need to create and control particular electron movements in disappearingly thin two-dimensional crystals.

That is still presenting a knotty problem, but success could see us finally harnessing supercharged quantum computing power.

## Zettaflops

### My new computer is zippier

Today's supercomputers are pretty awesome. But they aren't half as good as we would wish. Even the world's most powerful computer, the Cray Jaguar at Oak Ridge National Laboratory in Tennessee - capable of over 1.7 petaflops, or  $1.7 \times 10^{15}$  calculations per second - lacks the oomph for the most challenging simulations. Dreaming of recreating the universe's first few seconds, or predicting the planet's future climate in unparalleled detail? Dream on.

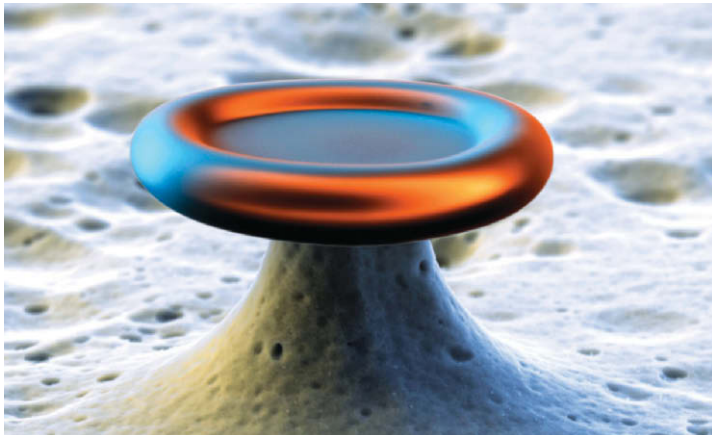
Don't forget to set the alarm, though. By 2030, ultrafast, low-power chips coupled with high-speed optical connections should have given rise to the zettaflop machine - at an industrious  $10^{21}$  calculations per second, the equivalent of a trillion present-day PCs. That will be a tipping point in our predictive capabilities, allowing us to model the effects of new drugs on the human body, the response of societies to climate change or how colliding galaxies give birth to new solar systems.

matrices filled with randomly chosen numbers, and it is the patterns of their eigenvalues - which are randomly distributed, yet without clumping - that we now see everywhere.

They pop up in the distribution of energy levels in the nuclei of heavy elements like uranium, in the distribution of the zero values of the "Riemann zeta function", which determine how the prime numbers

are distributed, and even in the arrival times of buses in a town in Mexico where drivers determine their own timetables. Investigating why will be a fruitful new direction for mathematics and science.

Marcus du Sautoy is professor of mathematics and the public understanding of science at the University of Oxford



EYE OF SCIENCE/SPL

## Quantum optomechanics

Exploring the quantum-classical boundary

Markus Aspelmeyer

At the heart of modern physics lies a circle to be squared. Experiment tells us time and time again that the world at its most fundamental works according to the counter-intuitive laws of quantum mechanics. And yet the macroscopic world we live in seems solidly classical.

Quantum optomechanics could help us resolve this paradox. It uses the pressure of confined photons, the quantum-mechanical particles of light, to manipulate the properties of mechanical objects ranging from the nanoscale to the macroscale.

Recent experiments have, for example, demonstrated how laser cooling – a technique initially invented to cool clouds of atoms – can be used to curb the vibrations of small mechanical devices. This opens up the fascinating prospect of

mechanical resonators operating at the frigid temperatures where quantum effects come into play.

Such quantum resonators would have applications in sensing, metrology and quantum information processing, but what I find most intriguing is the possibility that an object visible to the naked eye can be put into a quantum superposition between two separated locations – so it is both here *and* there. Testing the predictions of quantum theory in a completely new regime of size and mass will bring fresh insights into where the boundary between the classical and the quantum worlds lies – and perhaps even to the great unfinished business of unifying quantum physics and gravity.

Markus Aspelmeyer researches the foundations of quantum physics at the University of Vienna, Austria

## Competition

### What's the biggest idea? Tell us and win a tablet PC

Which of the 50 ideas presented this week and last do you think is most likely to change the face of science? Go to [bit.ly/cogPmb](http://bit.ly/cogPmb) and explain your choice in not more than 140 characters. The most arresting entry will win an HP TouchSmart multi-touch tablet PC with a 20-inch screen and 500-gigabyte hard drive. Competition closing date is 31 October 2010 and the editor's decision is final.

## Nanogenerators

Power from the people

The idea is simple enough: put piezoelectric crystals in the soles of your shoes. They generate electricity when they are squeezed, so every step generates a little current. Channel it properly and you can charge your cellphone as you go about your day.

So far, zinc oxide wires just nanometres thick are the best piezoelectric performers. They can generate about 200 milliwatts per cubic centimetre (*Nature Nanotechnology*, vol 5, p 366). So far devices are so small that they only generate nanowatts, but those in the know say we'll be in the commercially crucial milliwatt range within five years. The benefits are not all as superficial as smartphones, either. People-powered energy generators might power medical implants that deliver drug doses or keep hearts beating to time.

## The semantic web

My computer understands me

Web search has its limits. Type a question such as "how many women have won more than one Nobel prize?" into a search engine, and you'll find the answer, but only after some clicking about and a little bit of reading.

That's because search engines don't know what words mean. In simple terms, they rank web pages by how frequently a queried word appears on it and how many popular sites link to them. They don't know that a Nobel prize is an award and that humans can win awards.

Semantic "metadata" now being infused into the web will help them do just that. A web-page author might tag the word "Nobel prize" with a link to a machine-readable database such as Dbpedia.org. There, "Nobel prize" might be linked to a number of names, each associated with a gender. Couple that with a search engine that has a basic understanding of human sentence structure, and web search might begin to find not just pages, but answers.

Such as, "One: Marie Curie".

## Terahertz radiation

After X comes T

Scan from the region of visible light towards the longer wavelengths of the electromagnetic spectrum and you'll find, sandwiched between microwaves and the infrared, a type of radiation that we have previously had little time for: terahertz rays, or T-rays.

Our tune is changing as we acquire the technology to produce and manipulate them easily. Like X-rays, T-rays can penetrate clothing and skin, but without the harmful side effects associated with prolonged X-ray exposure. The vibrational and rotational energy states of complex molecules are also uniquely susceptible to terahertz probing. Bombard a material with T-rays and the pattern of absorption and emission allows you to identify everything from drugs to explosives. The first full-body airport T-ray scanners are already being rolled out – along with profuse assurances that the intimate images they reveal will never be released. ■