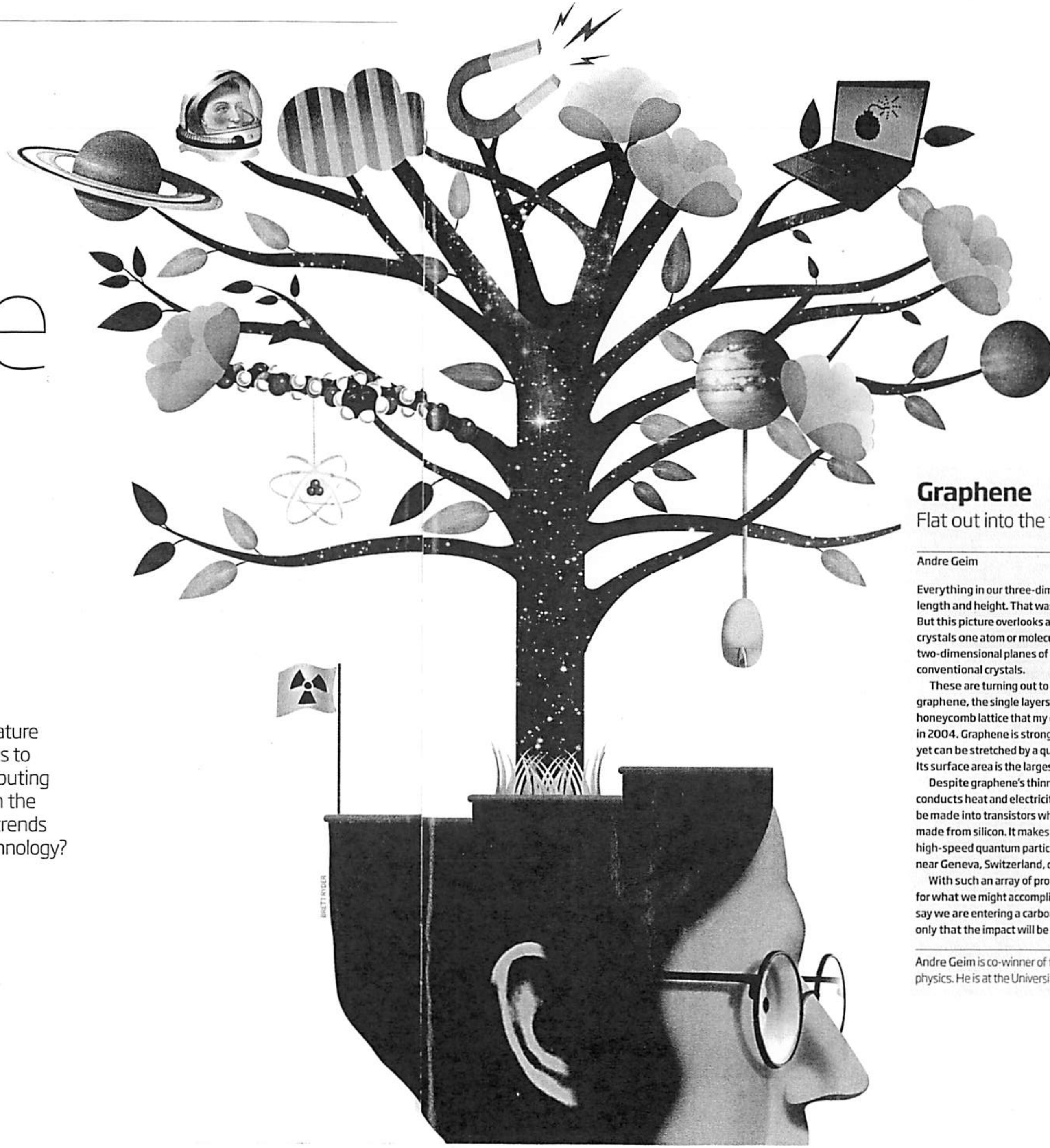
50 ideas to change science

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



Graphene

Flat out into the future

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.

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

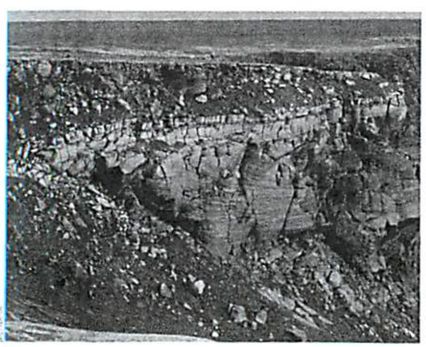
Raiders of the Red Planet

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.



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.