THE SCIENCE OF THINKING

...Europe's next policy challenge

Microsoft SCIENCE BUSINESS

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The Royal Academy of Science, Humanities and Arts, Brussels

LIST OF DELEGATES

On 19 September 2007, a group of leaders in European science, policy and industry gathered at the Royal Academy of Science, Humanities and Arts, in Brussels. The topic for discussion: How fundamental developments in computer science – among them, computational thinking – are changing the way we perform research, educate our children and set policy. Participants in this Science|Business Roundtable:

Jan Beirlant, Dean of Sciences, Katholieke Universiteit Leuven
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Jiri Plecity, Member of Cabinet of Vice-President Günter Verheugen, European Commission
Corrado Priami, President and CEO of the Microsoft Research - University of Trento Centre for Computational and Systems Biology
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André Richier, Principal Administrator, DG Enterprise and Industry, European Commission
Tom Rodden, Professor of Interactive Systems at the Mixed Reality Laboratory, University of Nottingham
Sven Schade, Policy Officer, Support for Innovation Unit, Directorate-General Enterprise, European Commission
Alexander Szalay, Alumni Centennial Professor of Astronomy, Johns Hopkins University
Kurt Vandenberghe, Deputy Head of Cabinet of Mr Janez Potočnik, Commissioner for Science and Research, European Commission
David White, Director, Life Long Learning, Education & Training Policy, DG Education, European Commission
Jeannette M. Wing, President's Professor of Computer Science, Carnegie Mellon University and Assistant Director, Computer & Information Science & Engineering Directorate, (US) National Science Foundation

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EXECUTIVE SUMMARY

No one doubts the importance of computers in all aspects of science, economics, business, government and policy. Now though, rather than playing merely a supporting role, computer science is transforming all other disciplines. In part this is a result of vast increases in low-cost processing power, making possible computational tasks that were previously too complex or expensive. But the most radical change comes from applying the methods of computer science – from the way data are organised to the way problems get solved – to other fields. This is already transforming biology, with computer modelling of chemical pathways and living systems now a major sub-discipline of the life sciences. It is similarly changing the way astronomers, epidemiologists, and economists work. Complexity theory depends on it. And climate change may be the first global problem to be recognised, analysed and solved by computer. There are many terms for this re-invention of the scientific process; "computational thinking" is one. To the traditional methods of "in vitro" and "in vivo", it adds "in silico".

For governments, this is important. It is critical that policy be framed to support the adoption of computational thinking to handle, manage and understand complexity. Action is needed internationally – but, given the importance of European universities and research institutes to global science, it's especially urgent to think through the policy implications in Brussels, London, Paris, Berlin and other European capitals. At stake is Europe's competitiveness in the 21st century.

This report is intended to raise awareness of the science, provide case studies to give a flavour of its potential across a range of disciplines, from public health to astronomy, and set out some recommendations for policy in general, and education in particular. It is based partly on a Science|Business roundtable discussion in Brussels on 19 September 2007, some 30 scientists, industrialists and policy makers came together to explore the implications of computational thinking. The meeting, and this report, was sponsored by Microsoft Corp. It follows a prominent Microsoft study, *Towards 2020 Science*, which elaborated the basic science involved.

From the Science|Business roundtable meeting, held at the Royal Academy of Sciences and Humanities in Brussels, several recommendations emerged:

- **Spend more on computer science**. Use public–private cooperation and public-sector procurement to drive development of Europe's ICT sector and increase understanding of the role that basic computer science plays in it.

- **Work together**. Develop a true pan-European market for science and ideas – the European Research Area advocated by the European Commission – to reduce fragmentation. Tap into pan-European funding schemes such as the Networks of Excellence. Ensure that the importance of computer science is recognised within the European Institute of Technology, the EU's new initiative to promote innovation.

- **Focus on the best**. Carry out international, rather than national, benchmarking to understand where the centres of excellence are, and where there is a competitive edge. Support these, rather than trying to fund everything across the board. Highlight the centres of academic excellence and encourage industry to connect with them.

- **Raise awareness** of the power of computational thinking – in schools, universities, the media and government.

- **For Europe's education system**, in particular, special recommendations emerged: delivering on the promise of computational thinking requires skills seldom taught at present. It will involve not only training computer scientists, but also imbuing the same thought processes in those working in other disciplines.

- **Reform the education system**. Invest in new models of primary/elementary teaching and learning. Highlight good practice, identify good programmes run by educational charities and leverage them. Make education a research zone. Develop closer ties between education and society, to make education more responsive.

- **Update the curriculum**. Teach computer science, not just computer technology. Provide relevant teaching material. Support development of the 21st-century equivalent of the child's "chemistry set" that inspired so many youngsters to take up science and engineering.

- **Work on image**. Try to end the "geek" stereotype of computer science. Make teaching a prestigious career choice for scientists.

I: THE SCIENCE

THE SCIENCE

How computers are changing the way we think ...and why that matters for Europe

Oil prices are up. Bread costs more. Minerals and metals are dear. In a world of scarcity and inflation, one resource – computer processing power – is abundant and falling in price. That has profound implications. Released from the need to use a scarce resource sparingly, computer scientists are applying this power in ways that are transforming the wider world of science, commerce, business and policy. But so far, outside the world of computer science, awareness is low about where this is heading.

That gap, between the future potential of computer science and public awareness of it, has profound policy implications. What's cooking in the IT labs are tools that change, not just the speed and efficiency with which economists can forecast, climatologists can model and biologists can cure disease, but also the way they work and even think. It permits collaboration, simulation, and analysis unthinkable only a decade ago. It changes how they plan an experiment. It provides their first tool to understand and control complex systems, from a human immune reaction to the structure of galaxies. In the process, computer science changes from a geeky form of engineering to a creative scientific discipline that all other researchers need to understand, in order to do their own work. It enables the progress of science and technology across an economy.

That means competitiveness in computer science matters, in Europe as much as anywhere else in the world. Yet funding for this field is limited; training is narrow; and political attention limited. That has to change if Europe is to compete. How and why it should change was the topic of a high-level gathering of policy makers, academics and industry executives in Brussels on 19 September 2007.

As a starting point, here are some perspectives from that meeting in Brussels:

> "The challenge is that the biggest change in computing itself is coming in the next four to five years, and to date there has been little preparation to deal with the majority of that change," said Craig Mundie, chief research and strategy officer of Microsoft. Computers will not only get faster still; but there will be a move to parallel computing that will increase the flexibility with which this increase in power can be applied.

"The challenge is that the biggest change in computing itself is coming in the next four to five years, and to date there has been little preparation to deal with the majority of that change..."

Craig Mundie, Microsoft Corp

> "Computer science is in a period of Renaissance," said another symposium participant, Muffy Calder, professor and head of computer science at Glasgow University. In computer science, "we are being reborn – at the same time as other sciences are being reborn by computer science."

The prime cause of all this is well known: the smaller, faster, cheaper cycle of the global computer industry. Infinite amounts of computer power make it possible to reflect and model the world around us in all its minute detail, from the exquisite machinations of a single cell, to the baroque feedback loops that are driving climate change. But the impact isn't just about applying more and more computer firepower to manipulate and query bigger and bigger data sets. Nor is it merely to do with collecting, maintaining and sharing information. It is about a different way of handling complex questions, in which the concepts and tools of computer science provide the framework for problem solving.

Thinking like a computer scientist

The term "computational thinking" has been coined to describe this new approach. Jeannette M. Wing, a Carnegie Mellon University professor who is currently assistant director of the US National Science Foundation's computer programmes, has a vision of it becoming a fundamental skill, ranking alongside reading, writing and arithmetic. "Imagine every child thinking like a computer scientist," she says.

In the case of systems biology, it means the ability to pull together the multiple abstractions that molecular biology has accumulated – the individual chemical pathways, protein structures, and receptors – and build holistic models of entire biological processes "in silico". Similarly, in astronomy, the sky becomes a vast database of star observations for modelling. In epidemiology, doctors can simulate the spread of disease and conduct experiments not possible in the real world. And the entire science of climate change simply wouldn't exist without computer modelling and the ability to handle multiple abstractions. "You can pull together many different pictures, rather than having to focus on one," says Malik Ghallab, CEO for Science and Technology at the French national computer lab, INRIA.

"Computational thinking is a fundamental skill for everyone, not just for computer scientists."

Jeanette M. Wing, National Science Foundation

One of Wing's favourite examples is a proposal from geophysicists to model processes from the Earth's core to its surface, and from the Earth's surface to the Sun. "And they want all the models to interact," says Wing. Boeing's 777 model was the first aircraft to be designed and tested without the use of a wind tunnel. "It relied completely on computational simulation and methods – which goes to show how much in engineering is predicted using computational methods," says Wing. Worldwide, symposium participants agreed, there needs to be more funding for basic research in computing, and for interdisciplinary research between computing and other fields.

An example of research across disciplines is a new $52 million programme at the US National Science Foundation, called Cyber-Enabled Discovery and Innovation. But that's just one of several American funding programmes for computer science. By contrast, the European Union spends roughly €150 million a year on all forms of fundamental computer science; to keep up with just the US civilian programmes would require at least a doubling of resources.

Fixing the system

But money isn't the only issue, notes Corrado Priami, CEO of a joint venture in systems biology between Microsoft Research and the University of Trento, Italy. "I would suggest more importance be given to better spending of the money, by selecting the areas in which Europe is the most competitive and which are starting up, so we can be in the lead." Furthermore, he says, a new

What is 'computational thinking'?

"Computational thinking is a fundamental skill for everyone, not just for computer scientists. To reading, writing, and arithmetic, we should add computational thinking to every child's analytical ability... (It) involves solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science....

"Computational thinking is thinking recursively. It is parallel processing. It is interpreting code as data and data as code... (It) is using abstraction and decomposition when attacking a large complex task or designing a large complex system. It is separation of concerns. It is choosing an appropriate representation for a problem or modelling the relevant aspects of a problem to make it tractable. It is using invariants to describe a system's behaviour succinctly and declaratively. It is having the confidence we can safely use, modify and influence a large complex system without understanding its every detail....

Computational thinking is thinking in terms of prevention, protection and recovery from worst-case scenarios through redundancy, damage containment, and error correction. ...
Computational thinking is using heuristic reasoning to discover a solution. It is planning, learning and scheduling in the presence of uncertainty. It is search, search and more search, resulting in a list of Web pages, a strategy for winning a game, or a counterexample....

From Wing, Jeannete M. *"Computational Thinking." Communications of the ACM, March 2006/Vol.49, No.3, pp33-35* system is needed for reviewing grants. "Referees are getting in the way. If you try to do something on the borders of disciplines, you just get handed over from one to the other."

The implications for education are broader, still – as it means a change in the way all citizens are trained, not just scientists and engineers. At present, only 20 per cent to 25 per cent of students complete their computer science courses successfully, noted Jan Beirlant, dean of sciences at Belgium's Katholieke Universiteit Leuven. Says Wing: "Introductory courses are not inspiring – especially to non-computer scientists – because they tend to be introductions to programming. The problem is we don't know how to teach computer science to kids: There needs to be a research programme to investigate the pedagogy of computer science."

Peter Buneman, professor of database systems at Edinburgh University, agreed. "We can't just go into schools and say how important computer science is. We need to inspire. We need to find the computer science equivalent of the chemistry set and get those into schools."

At present, the emphasis is on teaching computing as a tool rather than teaching the concepts that underlie it, says Martin Rem, director of ICTRegie, the Dutch government's ICT research agency. "We as computer scientists have a responsibility to come up with good, teachable concepts for young children."

The way ahead for computing

Microsoft's research and strategy chief on how computing is changing the way science is performed

The free lunch is over.

For the past 20 years the computer industry has grown on the back of ever-increasing clock rates. In line with Moore's law, coined by Intel co-founder Gordon Moore, advances in chip design have allowed performance to double every 18 months.

"But the clock rate can't go up any more," says Craig Mundie, chief research and strategy officer of Microsoft. "We find ourselves increasingly unable to remove the heat generated by denser and denser microprocessors. Yesterday, Gordon [Moore] predicted the demise of his law in 2020."

Parallelism has long been proposed as a way out of this bind, but few in the industry were prepared to invest in the field while processors were taking regular, massive, leaps in capacity. "We are now at the point where if we want computing to support all the things it is capable of, we need to deal with the issue of parallelism," says Mundie.

Now, says Mundie, it is up to the software community to rise to the challenge. In the immediate future this will necessitate the grooming of a cadre of programmers at ease with these architectures. It also calls for the development of newer, higher-level languages that can handle the complexity involved in parallel programming.

The move to a source of processing that is not only more powerful, but also far more flexible, has profound repercussions for all fields of science and commerce.

For a start, believes Mundie, it will transform the economics of computing. It will be possible to build parallel arrays of systems to handle what today would be an impossible data-mining exercise. "This will be at the heart of breakthroughs in science and business. It will, in fact, be impossible to make breakthroughs without computing," says Mundie.
Medicine will undergo its largest transition in decades, as it becomes a data-driven business. There will be a focus on prevention, not alleviation.

There are profound implications for computer science, itself. Older fields of engineering have always evolved by what's called "formal composition". Expertise is built up layer by layer, making it possible to attack larger and larger problems. For example, in civil engineering, design expertise is supplemented by knowledge of different or new materials, making it possible to build a longer bridge or a higher skyscraper.

"That's not the case in computing," says Mundie. "We haven't mastered programming in the same way as formal composition."

What's needed is a big advance in the formal methods of computer science. "This would move software from what is too much of an art form to a real engineering discipline," says Mundie. He noted that one of the leading European centres researching formal methods is the French state computer lab, INRIA, with which Microsoft Research is collaborating now.

Alas, funding for this kind of research is rare, Mundie noted. "Most governments are pulling back from basic research, and computer science was never regarded as basic. So there is a double whammy for basic research in computer science."

As the world's largest spender on software research, Microsoft started to move in the direction of parallelism six years ago. Researchers at the company's lab in Cambridge, UK, are devising new languages and architectures, and creating new strategies for writing programs. The first fruits should be on the market by 2012. "But it will take two product cycles to move this ecosystem forward," says Mundie.

"We are now at the point where if we want computing to support all the things it is capable of, we need to deal with the issue of parallelism,"

Craig Mundie, Microsoft Corp.

CASE STUDY: SYSTEMS BIOLOGY

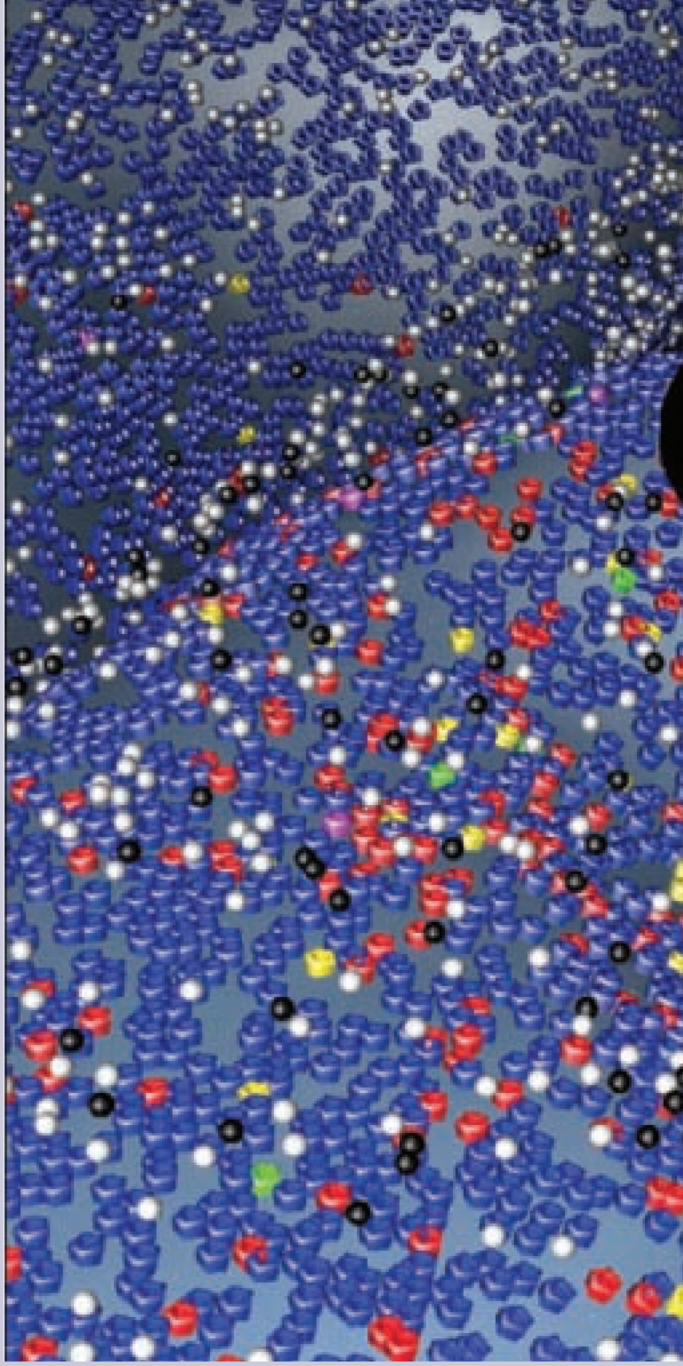
Biology – like football – is all about how the component parts interact

You can't capture the thrill and excitement of a football match by describing the individual players. Similarly, it is not possible to understand biological processes and pathways by looking just at the component parts.

"Biology is a science of interactions and complexity. Looking at its individual components doesn't tell you about the system as a whole," says Corrado Priami, President and CEO of the Microsoft Research–University of Trento Centre for Computational and Systems Biology.

In the past 40 years the reductionist techniques of molecular biology have provided deep insights into thousands of individual actors – membranes, hormones, enzymes, genes, and their associated kinetics – that are involved in the functioning of organisms. But living creatures aren't a bundle of chemical bits. "They behave in a given way due to the interaction of components," says Priami.

Understanding this requires a fundamental shift towards viewing biology as an information science. Seen from this

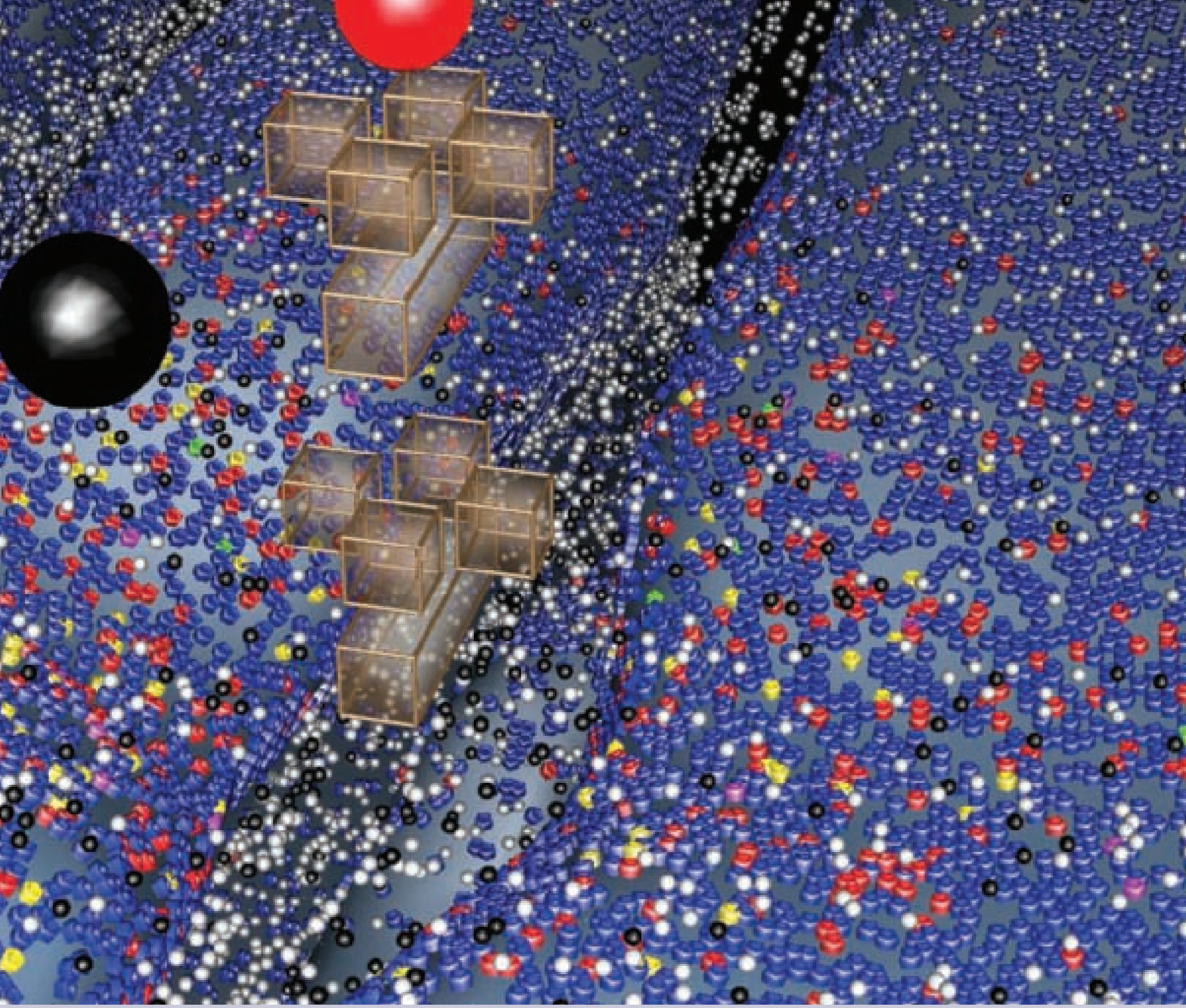


Corrado Priami: the research model has to change.

perspective, computer science and systems biology share the same conceptual challenges. "They both need to handle complex systems that are inherently highly parallel," says Priami.

The prospect is that one discipline will feed off the other: understanding the parallelism of biology will be used to build better tools in computer science. The ultimate vision is to use living systems as computers: in effect, organisms are processing systems with all the essential properties of a highly efficient computer.

The focus of Priami's own research is this convergence of life sciences and computer science. The aim is to develop new computational tools to enhance understanding of the evolutionary processes that are responsible for the large-scale properties and dynamics of biological systems.

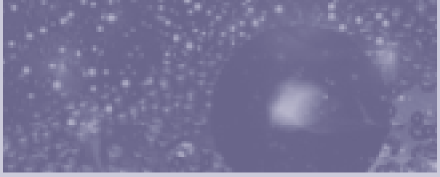


Concurrently, he is building a better understanding of how biological systems process information. This reverse engineering is underpinning the development of new, more powerful, more reliable programming languages that will be used to develop the software of the future. “We are trying to exploit computer science as an enabling technology to enhance life science at large, and capitalise on the new knowledge to enhance computer science,” says Priami.

This then, is the vision. At a practical level systems biology involves many different disciplines. “And once you have built a multidisciplinary team you need a common language – different sciences use different words to talk about the same thing,” says Priami. A further implication is that the basic model of research has to change. “It should be targeted and interdisciplinary – and you should make it iterative, not linear.”

Computer simulation of neurotransmitter molecules releasing from a vesicle (red). The image was created by MCell (Monte Carlo cell), a program that uses spatially realistic 3-D cellular models and specialised Monte Carlo algorithms to simulate the movements and reactions of molecules within and between cells.

Image courtesy Joel R. Stiles, MD, PhD., Director, National Resource for Biomedical Supercomputing, Mellon College of Science & Pittsburgh Supercomputing Center, Carnegie Mellon University.



CASE STUDY: ASTRONOMY

Too much data, not enough time

Information overload first hit Alexander Szalay in the early 1990s. Szalay, now Alumni Centennial Professor of Astronomy at Johns Hopkins University, realised that unless he came up with a way of organising the vast amounts of data he was acquiring, “I would find myself unable to do my work.”

This sparked his interest in the design of databases for handling astronomy data, and led subsequently to Szalay being appointed to lead the design of the relational database for the Sloan Digital Sky Survey, one of the most ambitious projects ever undertaken in astronomy.

The survey is creating detailed optical images covering more than a quarter of the sky, and a three-dimensional map of about a million galaxies and quasars.

The project uses a dedicated, 2.5-metre telescope on Apache Point, in New Mexico, equipped with two powerful special-purpose instruments. The 120-megapixel camera can image 1.5 square degrees of sky at a time, about eight times the area of the full moon, while a pair of spectrographs can measure the distances to more than 600 galaxies and quasars in a single observation. A custom-designed set of software pipelines keeps pace with the enormous amounts of data flowing from the telescope.

Alexander Szalay: an embarrassment of data riches.

One aim of the Sloan survey was to provide evidence in support of one of the central tenets of astronomy, the Big Bang theory. This posits that all matter and energy originated 13 billion years ago in a “singularity” of intense heat and pressure, and ever since the Universe has been expanding out from that central point, cooling as it goes.

Szalay likens this massive survey to astronomy’s version of the Human Genome Project. When it is completed later in 2008, the project will have collected 40 terabytes of data.

Central region of the Perseus cluster of galaxies, including the prominent elliptical galaxy NGC 1275, a powerful radio source.

Image courtesy R. Lupton and the Sloan Digital Sky, Survey (SDSS) Collaboration, www.sdss.org

In the face of such leaps in data volumes, it is not enough just to add more processing power, says Szalay. "You need algorithms to do the thinking. When you classify galaxies you have to rethink how you do the statistical analyses, because the techniques used previously are based on an era when data were in short supply."

Szalay compares the rate of data acquisition in the Sloan survey to the volumes of genomics data currently being generated by high-throughput gene chips. A similar explosion in volumes of data is happening in environmental sciences, where a proliferation of sensor networks are now automatically monitoring air, water and soil quality, and so on.

In the case of environmental sciences it is not only large data sets that have to be managed and digested. "There are also a lot of little data sets. The trick is to put them together to yield new insights," he notes.

The embarrassment of data riches is, says Szalay, "leading to a paradigm shift everywhere I look". Domain scientists can no longer manage and interrogate their own data; they need computer scientists to do this for them.

Those responsible for managing the Sloan data have solved the problem of communicating with the wide range of disciplines they serve by asking individual scientists to pose the 20 questions they would like their data to answer. This then informs the design of the database to deliver the answers.

The Sloan website is open for public access and has received 350 million hits. "There are only ten to fifteen thousand professional astronomers in the world, so the bulk of users are not academics," says Szalay. "It's important to note we are not teaching astronomy on this site, we are teaching computer science – in other words how to extract information from a database."

In June 2007 Szalay helped to create a new project that called on the many amateur astronomy enthusiasts to take part in a census of one million galaxies captured by its telescope. The website www.galaxyzoo.org was conceived by astrophysicists at Oxford University in the UK as a fast route to classifying the images into spiral galaxies (like the Milky Way) or elliptical galaxies.

"It's not just for fun," says Kevin Schawinski, an astrophysicist at Oxford University, where the data are being analysed. "The human brain is actually better than a computer at pattern recognition tasks like this." The aim of the census is to shed light on how different kinds of galaxies are distributed across the sky.

Szalay says the response has been overwhelming, with more than 10,000 taking the online tutorial to enable them to take part. "People are fascinated that they can contribute to science. They are looking at brand new data, and they are contributing in the process of science."

The virtual world yields insights into the real one

As a behavioural epidemiologist Nina Fefferman studies the people, not the bugs, in a disease outbreak.

"I'm interested in how you keep the public calm and keep them healthy." She says. "How secure people feel about health measures and how they react to them govern how disease spreads."

Fefferman is co-director of an infectious-disease modelling effort at Tufts University, an Assistant Research Professor at Rutgers University – and has turned to computers to learn things about epidemics she couldn't otherwise begin to study.

Existing computer models of how people behave when threatened by disease rely in part on historical examples, in particular the experience of Canada in the 1918 flu epidemic, where measures such as mandatory reporting and isolating patients at home were not only unenforceable, but were often seen as discriminatory. They did not prevent the spread of the disease.

"But you can't grasp all the complexities by looking at single outbreaks," says Fefferman. The utility of historical outbreaks is further limited by vastly different circumstances now – in particular the growth of international air travel.

Nina Fefferman: modelling epidemics.

Instead Fefferman and her colleague Eric Lofgren hit on the idea of using the virtual world of an online game as a real-time laboratory to study contemporary human behaviour in an epidemic. They were inspired by "Corrupted Blood" – a virtual plague that infected characters in the online computer game the World of Warcraft.

"This has nine million players, including a core group which has a big investment in the game. We watched how people responded to the outbreak and found it closely mimicked what you might expect in a real-world pandemic," says Fefferman.

As the Corrupted Blood disease moved from the virtual jungle in the online game to urban centres, infected "people" – avatars representing the players – started to

die. Social chaos ensued. Some gamers left the uninfected areas to go for a "quick look" at an infected area. Others tried to help sufferers even though this put their own avatar at risk. "In other words, it provided a new laboratory setting for studying the epidemiology of disease," says Fefferman. "And if you tweak it you can see how responses differ. That's something you couldn't possibly investigate in a real-world setting."

Looking at how people reacted in the virtual world of the game, is now informing Fefferman's computer models of pandemics. For example, it has given her insights into what she terms the "Stupid Effect" of people taking gratuitous risks.

"There were people outside the game calling each other and saying there's something cool going on. This encouraged others to log on, even though it meant their characters dying," says Fefferman.

Entrance to the World of Warcraft (www.worldofwarcraft.com): an online game becomes a real-time laboratory.

This also provided an explicit parallel with how people react in real-life situations, such as exposure to sexually transmitted diseases. "People think it won't happen to me."

"It also brought home the sheer diversity of human response and the challenge of how to reflect this [in models]."

Fefferman concludes: "This is a fascinating example of how computer science changes the way science is done – it shows scientific computing is not just number crunching. It also highlights that in general we are failing to tell a good story about modern computer science."

II: THE POLICY

How to keep Europe competitive in computer science

Scientific computing and computational thinking have the potential and the power to transform every other area of science and engineering. But there are also obstacles to progress. One is funding. The European Commission puts about €150 million per annum into basic computer research. That's less than half the US government's spending on civilian IT research – and it pales beside the resources of the American IT industry. For instance, on basic research, Microsoft alone spends about three times what the Commission spends, according to Mundie.

The underfunding has many causes. For instance, the IT industry in Europe simply isn't as big as that in the US – and so has less weight when seeking public research funding, suggests Ulf Dahlsten, Director of Emerging Technologies and Infrastructure, in the Commission's Directorate-General for Information Society. Further, he notes that while there may be enormous scientific computing capacity in place in the continent's e-science grids, what's also needed is the capability to use it.

Another problem: the fragmented nature of funding. The EU R&D programmes constitute just 5 per cent of total government research funding in Europe, reducing their impact through lack of coordination. Moreover, grant systems typically fund for the short term, rather than sustaining long-term projects. The money available is usually salami-sliced into many small grants to spread the wealth, rather than identifying and supporting excellence.

And the programme definitions are skewed. When computer scientists do apply for research funding, the system forces them to demonstrate the potential practical applications of their research. For fundamental research, this represents a contradiction in terms. "While practical applications are clearly the ultimate goal of fundamental research, requirements for demonstrating the applications should not be imposed. Fundamental research is above all a time when discoveries are made that have unforeseeable applications in future markets," argues Xerox Research Centre Europe Laboratory Manager Christopher Dance.

The money problem

Some of the obstacles to funding:

1. Not enough money overall.

2. A weak ICT industry means there is a low level of investment by Europe's companies. Much of Europe's ICT industry consists of small companies providing applications and services, rather than industrial powerhouses.

3. Compounding the low level of funding for computer science is a fragmentation of effort.

4. While there is widespread appreciation of the value of applying computer power as a tool, there is scant understanding that computer science needs to be funded as a basic science.

5. As a result, national funding programmes do not reflect the importance of the discipline, either as an end in itself, or as a critical element in other fields.

6. Different disciplines are funded through grant silos. It is very difficult to get grants to carry out interdisciplinary research.

7. What money is available is salami-sliced, making it difficult to carry out long-term projects and build excellence.

"Fundamental research is above all a time when discoveries are made that have unforeseeable applications in future markets,"

Christopher Dance, Xerox Research Centre Europe

Of course, the whole question of how much funding should be for basic research and how much for applied remains open.

"It's difficult to say we need a lot of funding for computational science itself," muses Kurt Vandenberghe, deputy chief of staff to EU Science and Research Commissioner Janez Potočnik. "What you need is to have this computational thinking in all the other areas of research. So it's difficult to say how much money is going into computational science. One important development: we now have this European Research Council (for basic research). If computational science is really important, then I'm confident that it will come up in all their research projects – computer science or not. Look at the ERC grants in two to three years' time. That will be the benchmark for the success of computational thinking in Europe."

A final problem is that in Europe computer science had its roots in university mathematics departments – not an area that traditionally gets high levels of grant funding. Contrast this with the position in the US, where the discipline's origin in electronic engineering confers a different status on computer science today. Further, while politicians recognise the importance of computing as a tool for business and commerce, they do not appreciate that computer science needs to be funded on its own as a scientific discipline.

In short, computer science has a status problem. It is seen as a route to generating skills and services for Europe's computer users, not as a basic scientific discipline.

Some possible answers, suggested by roundtable participants:

1. Mobilise the public sector

The public sector in Europe does not have the tradition of scanning the horizon to see where it wants to be in the future or how it can hone and improve its services. Indeed, much of the public administration, notably in healthcare and social services, remains uncomputerised. Persuading bureaucrats of the power of computational methods to change the way the system operates could dramatically improve services and efficiency.

Coordinating procurement, regulation and other public-sector powers is another solution. In January 2008, EU Vice President Günter Verheugen announced plans for a "Lead Markets Initiative" to do just that: in a few fields, such as computerising patient records, the Commission will encourage national health agencies to develop common EU-wide technical standards, buy the standardised products and services, and adjust their internal regulations and working practices to make use of them. That approach – a coordinated public–private effort to pull an emerging technology to market – was behind the success of the European GSM mobile-phone standard in the 1980s and 1990s.

Another model is in defence procurement. Funded by the public purse, the armed forces invest in basic research and have a huge interest in technology transfer. The development cycles may be protracted, but private companies have the confidence to invest, driving technology transfer and the sector's commercial development.

2. Fund long term and critical mass

Europe needs to get away from its egalitarian forms of funding, with which everyone who makes the grade gets a small grant for a short time. "Don't fund one or two people for two years, but ten people for six years," says Tom Rodden, Professor of Interactive Systems at the Mixed Reality Laboratory at Nottingham University. The system needs to pick winners and back them.

3. End fragmentation

The objective of the European Research Area, a Commission campaign to get more researchers collaborating across Europe, cannot be delivered soon enough. Fragmentation carries an enormous cost, both in terms of duplication of grant-giving bureaucracies, and of the research that is carried out. Many researchers are not aware of what their colleagues elsewhere are trying to achieve. Europe needs to develop joint programming, so that funds can be spent strategically. Too many national systems are suboptimal; there is no excellence and no competition.

4. Introduce international benchmarking

This change in funding should be underpinned by international benchmarking, believes Andrew Herbert, Managing Director of Microsoft Research Cambridge. "You may decide to duplicate something for strategic reasons or not, but you need to know the global landscape to inform your programmes."

5. Link centres of excellence with industry

What international benchmarking has been done indicates that Europe does have some strengths, including research into parallelism and formal methods. These should be publicised and the centres made prominent to attract connections with industry.

6. End risk aversion in research funding

Innovative ideas are inherently risky and funding systems are inherently risk-averse. "The end result is we fund work that is lukewarm," says Alexander Szalay, Alumni Centennial Professor of Astronomy at Johns Hopkins University. "It has got to be okay to fail."

7. Spread the message

Scientific computing and computational thinking are changing the world. They are having a huge and inspiring impact in many fields. "We need to get the message out there of the power of computer science," says Muffy Calder, Professor and Head of the Computing Science Department at Glasgow University.

"It's difficult to say we need a lot of funding for computational science itself... What you need is to have this computational thinking in all the other areas of research."

Kurt Vandenberghe, European Commission

Policy View: Make it virtual

A senior EU official on the growing importance of virtual networks for science

By Ulf Dahlsten

Global virtual research communities linked by high-power computing grids are revolutionising science. The European Commission has been instrumental in this movement.

The grid revolution was led by high-energy physicists who started building models for simulations in computers thirty years ago, lighting the way for this community and other groups of scientists to exploit distributed computing grids to create virtual research communities.

At its formation in 2003, the pan-European grid infrastructure for physicists (DATAGrid) aggregated the computing power of around 1,000 processors in 20 different sites.

By 2006, there were 50 virtual research communities across Europe processing 15,000 jobs per day in the enlarged multidisciplinary European grid. A year later, more than 200 virtual research communities were processing over 100,000 jobs a day using 45,000 processors all over the world.

This is fomenting a revolution in the practice of science. That these 200 virtual research communities have been initiated and led by European scientists shows Europe is an excellent nurturing ground for this new way of doing science, promoted by the intensive use of e-Infrastructures.

Some of these virtual communities are rudimentary, some developed. Some European, others global. The largest have sprung from high-energy physics, bioinformatics and radio astronomy, with organisations such as CERN, EMBL and ASTRON at the core.

Virtual research communities are enabling scientists to participate in global research challenges, unhindered by the geographical or institutional barriers.

In this new world of research – some call it eScience, some Research 2.0 – virtual research communities will be increasingly important. We should strive to make Europe the driver for this paradigm shift. An ambitious goal would be for Europe to be the hub for some 50 of the top 100 global virtual research communities. This would change the landscape of research, and we have a historic opportunity to make it happen.

More of the same?

There are those who fail to recognise the revolution that is taking place. They see the increasing use of computers as just another tool moving "Research 1.0" into "Research 1.1". That is also how e-Infrastructures are seen in the European Research Area Green Paper.

Abstraction and the use of algorithms is nothing new, many claim. And they are partly right.

So what is new? First, the sophisticated simulation models running on grid infrastructures have dramatically increased productivity. Second, high-bandwidth communication backbones and advanced middleware allow collaboration among geographically separated colleagues, federating remote resources spread around the world.

It is no longer simply theory and experimentation. The creation of virtual laboratories introduces a new element – models (biologists call them systems) that are representations of the world, in which it is possible to do actual research that often could not be done in the physical world. In the virtual laboratories you are creating and gaining knowledge: the research model has now shifted to theory, simulation and experimentation.

Of all papers published in high-energy physics today some 90 per cent are based on Research 2.0. Given the explosion in the use of the European Grid it is a reasonable prediction that in five years' time 80 per cent of all papers in natural sciences will be based on research done in this form.

Mr. Dahlsten was director of emerging technologies and infrastructures, in the European Commission's Directorate-General for Information Society. He is now on leave from the Commission as a commissioner with Postcomm, the UK postal regulator.

"An ambitious goal would be for Europe to be the hub for some 50 of the top 100 global virtual research communities. This would change the landscape of research and we have a historic opportunity to make it happen."

Ulf Dahlsten

“Europe has a very strong tradition in some of the more theoretical aspects of computer science; and that’s particularly important when you’re thinking about the reliability of software.”

Andrew Herbert, Microsoft Research

So what does Europe do well?

Microsoft’s European research boss on the strengths of European computer science

In the global village, goes the standard economic theory, every region should have its own set of specialised skills to trade with the rest of the world – an inventory of talents and resources at which it excels and earns its keep. So what is Europe’s niche?

When it comes to computer science, Europe’s strengths are in its culture and traditions, believes Andrew Herbert, managing director of Microsoft Research’s European lab, in Cambridge, England.

As head of one of Microsoft’s five worldwide research labs, the British computer scientist oversees a research staff of 100, and more than 250 inter-disciplinary research collaborations across Europe – for instance, in systems biology at the University of Trento, and in software security and information interaction with the French national computer lab, INRIA. As such, he has had to make his own mental map of which skills are on offer in Europe. Herewith, a glimpse of that map, as explained in an interview with Science|Business’s Richard L. Hudson.

Q. What are Europe's strengths in computer science?

A. Europe has a very strong tradition in some of the more theoretical aspects of computer science; and that's particularly important when you're thinking about the reliability of software. As we depend on software more and more for things in everyday life – transport, mobile phone systems, medical systems – I would like to be confident that the software works. Now, because computer science in Europe has never had the same level of funding as in the US, people tended to go more for theory. Also, mathematics has a stronger tradition in Europe than in the US. So when we are building these large, complex computer systems, we have the ability in Europe. Software reliability is also something that comes with the fact that a lot of the European IT industry has been in safety-critical things like aerospace: real-time safety and industrial automation.

Another area where there is strength is in machine learning and computer perception. That grows out of the mathematical tradition – the use of very advanced statistical techniques for image processing, handwriting recognition. Modern computers have the horse power to run demanding algorithms that can achieve near human levels of "perception".

Two other things: Europe is a multi-cultural society, and there's a very strong emphasis on design. One thinks of Italian fashion, Scandinavian furniture. There's quite a lot of European strength in the field of human-computer interaction. I think of consumer electronics companies like Philips: very design-led. Then you think about European leadership in the mobile phone markets, led by companies like Nokia.

And there's strength in the computational science and "e-science" field. The US has been focused on connecting supercomputers. In Europe, we've been looking more at scientific collaboration, helping people work together. We've used computers as a collaboration technology, to overcome the fact that we're very fragmented, that university departments are often small. The flagship for this is what CERN does with the European physics community – creating networked virtual organisations pulling groups together.

Q. What's the obstacle to a stronger European computer science effort?

A. There is a problem that computer science has in Europe: it is often perceived as a service, rather than as a discipline in its own right. People only bring in computer scientists when they want some programming done. The realisation that a computer scientist with a good background in computer science theory (what some call "computational thinking") could work jointly with someone in biology, and produce something better than either could do on their own – that's not well established. Computer scientists get frustrated about this. They are expected to do a lot of "training" for other subjects, since many computer sciences departments grew out of university data processing departments. The contribution computer scientists can make to basic science, engineering and technology is not so well understood, but if every computer scientist went on strike tomorrow, a lot of industries would say: "We'd better pay attention."

Another of the challenges for Europe is how to make sure talented people who aren't at the best known centres also have the chance to excel. It's easy to focus on the top 15 or 20 labs, but we should also be tracking and supporting the strongest individuals, and be a little less emotional about (supporting) the institutions. The job of the institutions is to attract the best individuals, not rest on their laurels.

Time to reform education

To stay competitive, Europe needs to improve its computer science education

Computational thinking requires skills not taught generally. It involves not only training computer scientists, but also imbuing the new thought processes and ways of approaching problem solving. Some of the possible solutions, suggested by roundtable participants:

1. Train the teachers

At present, teachers seldom have a good understanding of computing as a science, or as a way of thinking. As a result they are not able to teach children the true power of computing. Children can access data but they can't process information. "They don't know how to express what it is they want to get from a computer system," says Anne Blandford, Professor of Human–Computer Interaction and Director, UCL Interaction Centre, University College London.

2. Provide teaching materials

Jan Beirlant, Dean of Science, Katholieke Universiteit Leuven, notes that there is a dearth of suitable teaching material in schools in Belgium, a situation that is surely not limited to this one country. The lack of suitable preparation in schools is translating to a huge drop-out rate from computer science courses, with only 20 to 25 per cent completing their degrees in Belgium.

3. Young people need role models

Computer science has a geeky image in a world where children aspire to be celebrity entertainers and athletes. Computer science needs to find some role models. And the aspects of IT with which children are prepared to engage, such as computer games, should be used as stepping stones to wider understanding, believes Nina Fefferman, Co-Director of the School of Medicine, Initiative for Forecasting and Modelling of Infectious Diseases, Tufts University. “From gaming we can go on to show how computer simulations are serious scientific tools.”

4. Connect computational thinking to the rest of education

Children have such ready access to technology that they find school, with its traditional methods of teaching, boring. And rather than being excited by the potential of computers, these are so user-friendly that they inhibit critical thinking, says Elie Faroult, DG Research RDT, Directorate K, Social Sciences and Humanities, Scientific and Technological Foresight, European Commission. “In short we are inhibited by our tools.”

5. Fix primary/elementary education

Inculcating new modes of thinking means starting early, believes Martin Rem, Director of ICT Regie, the Dutch ICT research and innovation authority. “We as computer scientists have a responsibility to come up with teachable concepts for young children,” he says.

Mundie of Microsoft agrees, saying this is the most fundamental part of the educational challenge. “Everything is by the by, if you don’t fix elementary education.”

There needs to be a reform of the way children are taught. Now the system helps them acquire data. Instead, they need to be shown how to process data. As Rem puts it: “We are teaching computing as a tool, rather than teaching the concepts that underlie it.” He noted that there are approaches to teaching computer science concepts without using a computer.

Kurt Vandenberghe, Deputy Head of Cabinet of Janez Potočnik, Commissioner for Science and Research, European Commission, noted that the teaching of science in elementary schools is recognised as critical within Framework Programme 7. The Commission is also calling for the development of new models of teaching primary school science.

6. Engage with local schools

Universities should be prepared to work with local schools, organising lecture days for pupils and teachers, providing curriculum material, and giving help to structure lessons.

As things stand, Europe’s education system cannot keep pace with the fast-changing needs of the economy, argues Jiri Plecity, Member of Cabinet for European Commission Vice President Verheugen. “Our system is conservative and is slow to react to demands.” One way of making it more responsive is through external partnerships.

7. Get good scientists to teach science in schools

Malcolm Harbour, member of the European Parliament for the West Midlands, UK, believes there is a need for good scientists to get into teaching. “National governments need to do this; there need to be greater incentives.” He suggested also that doing outreach work in schools should be part of a scientist’s professional development.

This implies improving the status of teaching, as has happened in Finland. Surveys suggest many Finns regard teaching as an important job. A higher degree in teaching is required to do it. Teachers are expected to contribute to research.

8. Leverage the work of educational charities

There are some programmes out there that validate these suggested reforms of the education system, says Simon Cox, Professor of Computational Methods, Computational Engineering Design Research Group, School of Engineering Sciences, Southampton University.

"The challenge at a wide level is how educational charities could scale up, and how they could be supported to do this," says Cox. Most are nationally or regionally based and would not think of applying for European money.

9. Build networks of excellence

There are individual schools or programmes that stand as models for computer science education; the question is how to spread that knowledge of best practice across Europe. What is needed is a movement to translate local efforts onto a wider European stage, suggests Tom Rodden, Professor of Interactive Systems at the Mixed Reality Laboratory, University of Nottingham. This could be bolstered by the creation of dedicated channels for exchanging best practice.

Similar problems in education have been recognised by the US National Science Foundation's Directorate for Computer and Information Science and Engineering (CISE). The Directorate has set up a programme, CPath (CISE Pathways to Revitalized Undergraduate Computing Education). While it is for undergraduates currently, CISE Assistant Director Jeannette Wing says she would like to see the programme applied to schools too.

10. Putting the mechanisms into place

This agenda needs to be promoted at a European level, suggests André Richier, Principal Administrator in DG Enterprise and Industry, European Commission. An exemplar for how this could be done was the move to put personal computers into schools in Europe in the 1980s and 1990s.There needs to be a multi-stakeholder push. Any initiative should begin by identifying projects and objectives that will deliver results in the short term, to provide continuing momentum.

In total Europe spends 5 per cent of its gross domestic product on education, but only 0.05 per cent of its research budget is devoted to research in education. This needs to be increased and the research needs to be directed to developing new teaching methods. At present education is reactive. Its methods should be based on evidence of what works.

Why Johnny can't learn (computer science)

Some of the obstacles to getting computer science into schools:

1. Teachers don't understand the issue, and there is seldom enough continuing education for teachers.
2. There is no suitable course material. Computer science lacks the equivalent of the old-fashioned hobbyist chemistry set to excite youngsters.
3. Children don't know how to handle data. The often-poor quality of maths teaching means potential students of computer science are not mathematically capable.
4. The multimedia world in which we live encourages children to believe that computing is limited to applications.
5. School is boring to many children. They fail to develop intellectual curiosity. Hard science is unattractive.
6. Devices are too user-friendly, delivering everything on a plate and limiting critical thinking.

'...and how are his social skills?'

A senior EU official, on sweeping changes afoot in Europe's educational system

By David White

"Europe has set itself a number of targets for improving its educational system. One of theme is to increase the number of maths, science and technical graduates."

David White, European Commission

The European higher education system is seriously challenged.

We have a system that is rather good on equity. It is producing a very broad band of good quality teaching. But it is somewhat underperforming on brilliance.

There is a major sea change taking place in the way higher education is organised. There is increasing autonomy, which has been lacking in many of the highly diverse European systems. They are bringing in a much wider group of European stakeholders, and changing the financing to diversify and bring more sustainability. I speak in broad numbers: Microsoft's research budget is more or less the same per year as the (EU R&D) Framework Programme. This would be terrifying for Europe if it wasn't that we are doing rather different things with the money.

Europe has set itself a number of targets for improving its educational system. One of theme is to increase the number of maths, science and technical graduates. The number studying at European universities are of the order of four million at the moment – far above the level of America. And it is growing rather fast. We have a certain success there.

We have a Bologna Programme of reforms to curricula and structuring, to align the European approaches on a three-cycle system of bachelors, master and doctorate. This is going to give rise to much more transferability between the different systems and localities, so you can combine excellence in different areas and put them together. One of the most important reforms which has taken place is the development of a European qualifications framework, and a framework for higher education units and for vocational training units. As it comes into place it will give rise to a great permeability and mobility in learning outcomes, that will transform the system.

I'm struck by the areas of brilliances that are in European education. But also by the conservatism of the whole system. The reason the educational system is conservative is that this is an *acquis* of generations, and people are reluctant to throw away the major achievements of our society on the breeze of the latest development. It's a lever that you turn rather carefully. I don't think that's wrong. But the pressure for change within the system is striking and the support for it from teaching staff has been remarkable.

As for computer science, the system is certainly responding in the area of producing graduates. But I am convinced that the biggest, most crucial, areas of investment are pre-K [before kindergarten], and the very early laying-down of competences which make radical change later possible. I am still pretty terrified when an 8-year-old is so good at computing – and I ask myself: How are his social skills?

Mr. White is director of lifelong learning, in the Directorate-General for Education and Culture of the European Commission.

SCIENCE BUSINESS

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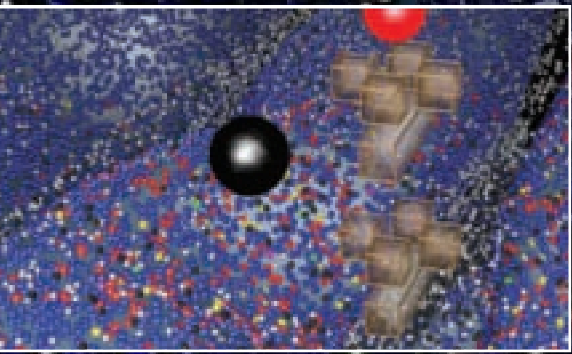

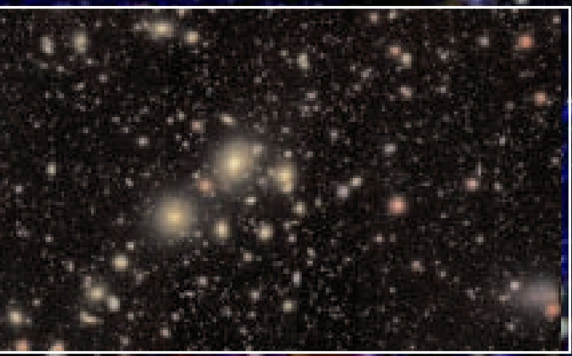

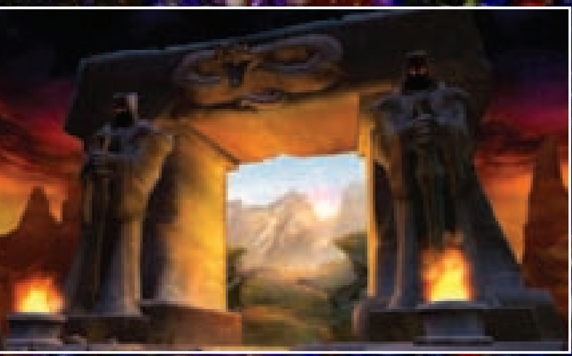

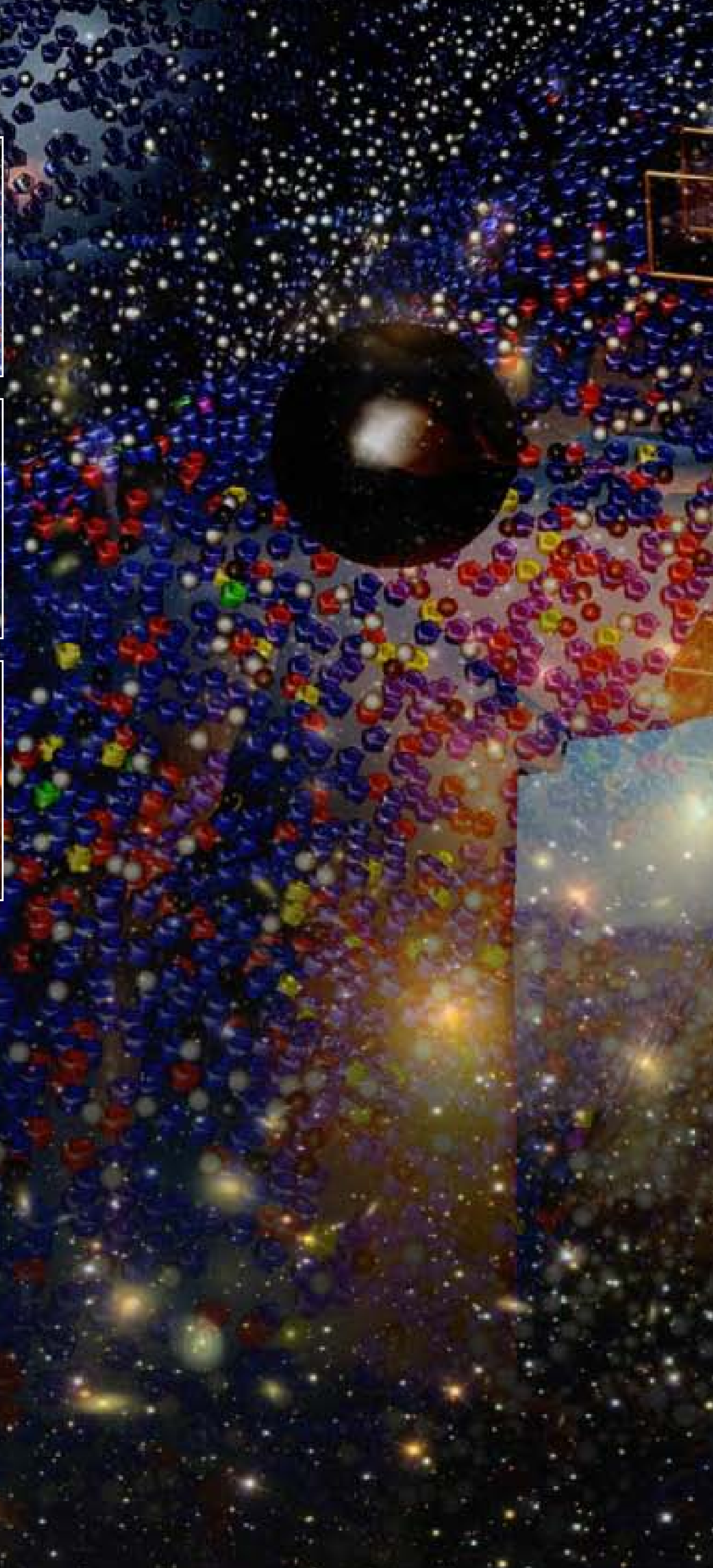

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