SPEED

National Science and Engineering Week Seminar on Thursday 21st March

HOW TO MEASURE SPEED

Dr Michael de Podesta MBE
National Physical Laboratory

Michael de Podesta considering the possibilities of the NPL-Cranfield acoustic resonator – the most accurate thermometer in the world.

Measurement is the comparison of an unknown quantity with a standard amount of that quantity. So when we weigh 250 grams of flour to make a cake, we are comparing the mass of flour with the mass of the international prototype of the kilogram. When an engineer measures the temperature of steam to be 337°C, they are comparing the temperature of the steam with the temperature of the triple point of water. This simple idea, when applied with ingenuity and thoroughness, transforms our vision of the world.

Viewing the world through the lens of precision measurement brings our scientific vision into sharp focus. It allows us to see clearly the beautiful patterns in nature, and to compare them with our expectations – and so refine our model of reality. Measurement is a simple idea but one which is central to our scientific world view.

So let us look at precision measurement of speed. We describe speeds as 'fast' or 'slow', but these assignations are anthropocentric. By 'fast' we mean some measurable change has happened in a 'heartbeat' or a 'blink of the eye'. And by 'slow' we mean something which shows only a small change in a 'long' time, perhaps one 'year', one orbit of the Sun, or a 'lifetime' (hopefully) one hundred orbits of the Sun.

But we see phenomena taking place with a vast range of speeds. Things which appear instantaneous to humans are just 'very fast', and we find that tiny differences in ultra-fast speeds can be of profound significance. Similarly processes which are slow enough can appear to be stationary. But precision measurement can reveal even the slowest of motions – and the results can again be of the most profound significance.

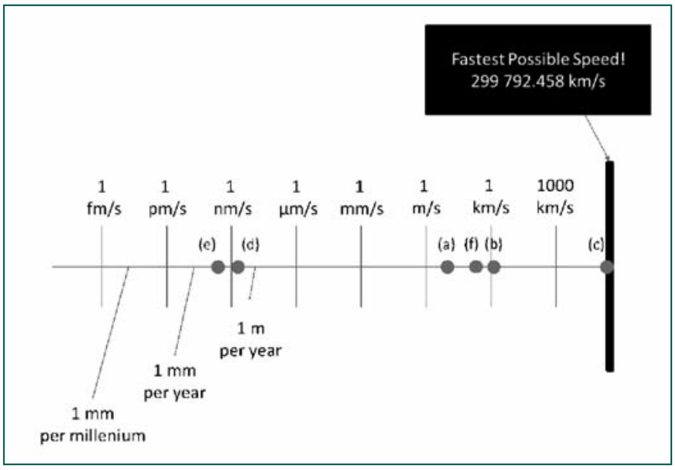
The figure shows the range of speeds which are significant for human beings – a range of over 18 orders of magnitude! Shown as dots are the speed of (a) sprinters, (b) bullets, (c) neutrinos, (d) bridges, (e) continents and (f) sound. We will look in turn at how each of these speeds is measured.

The timing of a sprint race is easy to understand. A starter fires a gun and the 'bang' is supposed to start the race fairly. However, sound travels through air at approximately 340 metres per second so that a runner on the far side of a 10 metre running track would hear the gun approximately 0.030 seconds later than the runner on the near side of the track. Such a gap – 30 milliseconds – is the difference between winning and losing in many races. For this reason, the starting 'pistol' is now electronic, and it triggers a sound which is played from a loudspeaker directly behind each runner. This 'pistol' also starts 'the clock'.

. . . difficulty in accepting that continents move . . .

The 'clock' is stopped by the first runner breaking a beam of infrared light shone across the finish line. This records the winning time but does not detect who has won! This is determined by a 'photo-finish' system of beautiful ingenuity. A camera captures a picture of the finishing line – just the finishing line –1000 times each second. The images of the finishing line are then stitched together to make an image that looks like a distorted photograph, but is in fact a technical record revealing the time at which each athlete crossed the line.

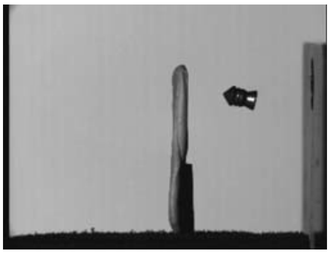
Bullets are faster than athletes but they are still timed photographically. Cameras not-so-different from those commonly used to capture movies at 30 pictures per second can be 'super-charged' to capture movies at up to one million frames a second. But each image needs lots of light to allow the passage of the bullet



. . . tiny differences can be of profound significance . . .

. . . brings our scientific vision into sharp focus . . .

to be recorded. It is at this point – where the apparently instantaneous pulse of a camera flash appears as a slowly brightening and fading light that we truly leave the realm of speed that is appreciable to humans.



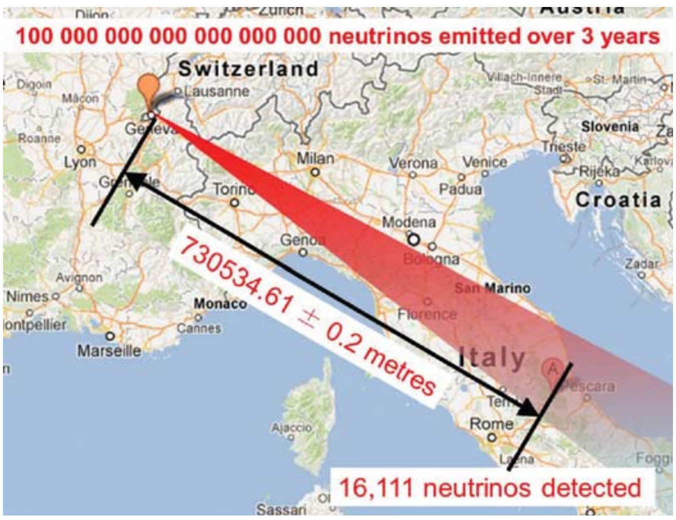
And so to the timing of neutrinos, possibly the oddest particles humans have discovered. They have a lower mass than even the electrons which whizz around every atom in the universe. Neutrinos interact so weakly with ordinary matter that they routinely travel through the Earth without anyone noticing. As a student I wrote an essay on the breath-taking experiment in which neutrinos were first detected! Now we can time neutrinos routinely. Recently it appeared as though neutrinos were travelling faster than 299 792 458 metres per second – the speed at which light travels through a vacuum.

The experiment in which this appeared to happen is complex. Protons (ionised hydrogen atoms) were accelerated in Switzerland and fired into a target which emitted neutrinos. The beam of protons was vaguely pointed towards the Gran Sasso laboratory in Italy, some 730.53461 kilometres away, a distance known with an uncertainty of 20 cm. Over three years approximately 100,000,000,000,000,000,000 neutrinos were emitted in well-timed bunches. This is a number so large that it makes the UK national debt look small!

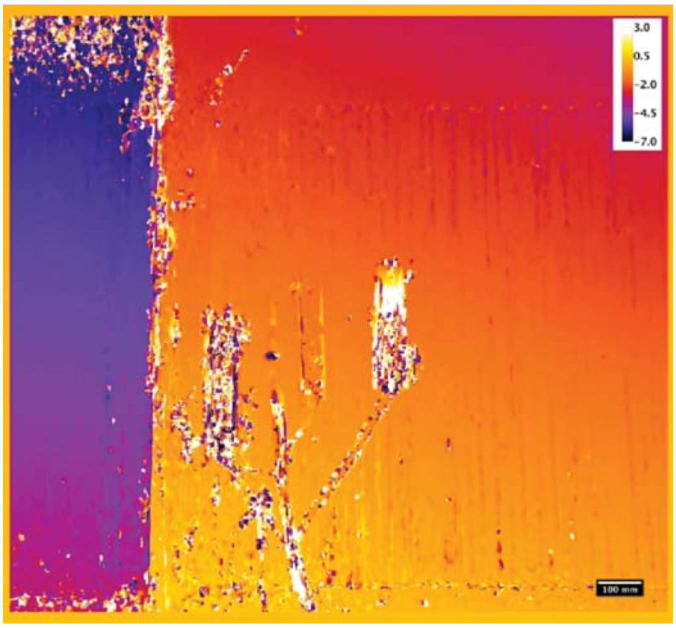
However, only 0.000 000 000 000 016% of the neutrinos were detected (16111). Nonetheless, instead of taking 2.436801 milliseconds to reach the detector – they took just 2.436741 milliseconds.

In the end this discrepancy was resolved by the discovery of a loose cable which delayed a signal by seventy nanoseconds in a way which no one had considered possible. But the lesson of this experiment is that precision experiments test our expectations of the world. It is only because of precision measurement that anyone dared to check our expectations that nothing can travel faster than light. And if they had been right, the textbooks would have had to be re-written, and our conception of the entire universe would have changed. So, although that didn't happen, that is the power of precision measurement – to make, or break, our most strongly-felt convictions about the world.

So let us now consider something at the opposite end of Figure 1 – something we generally consider to stationary: Bridges. However, if you have ever stood on a motorway bridge while a lorry passes you



The path taken by neutrinos fired from CERN towards the Gran Sasso Laboratory in Italy.



A colour-coded photograph of two concrete components on a bridge showing that the slab on the left (purple) has moved approximately 7 mm with respect to the slab on the right.

will realise that bridges move all the time. And temperature changes cause bridges to change shape too. Both vibrations and environmental changes cause bridges and other civil engineering constructions to change over time – something which is of obvious interest to engineers concerned with the safety of such structures.

Once again photography comes to our aid. Photographs taken from precisely the same location days, months or years apart can detect the slow motion of structures – a few millimetres a year of motion can be quickly detected. This is simpler and cheaper than installing and monitoring arrays of strain gauges and allows the detection of movement in unexpected places.

We appreciate that bridges move, but the idea that continents can move is more challenging. And the story of how we came to understand that not only can they move, but that they are still moving now is no less astounding. From early suspicions based on the shapes of the facing coast of Africa and America; through research showing matching rock and fossil types; to our modern theories of plate tectonics. This gives us a real insight into how science advances.

The fundamental difficulty in accepting that continents move is because their motion is so slow compared with a human lifetime – and the moving parts are so large compared with human perceptions. There is no way we could become directly aware of this motion. Or so it seemed.

Radio telescopes listen to periodic signals from rotating stars called pulsars. A beam of radio waves from such a star

. . . sound travels through a gas at a comfortable rate . . .

sweeps past the Earth every second, and these signals are analysed by radio telescopes around the Earth. When the signals from widely separated radio telescopes are compared, a small adjustment must be made for the delay as the beam sweeps from one telescope to the other. Analysis of this delay shows that the time difference is changing because the position of radio telescopes is changing as the continents on which they sit are moving.

The movement is slow – typically 20 mm per year or one tenth the speed at which hair grows – but it is real and can be monitored week by week.

My own measurement speciality is the speed of sound. In contrast to the extremely slow and the extremely fast events described earlier, sound travels through a gas at quite a comfortable rate. Fast enough that we are not conscious of the delay as someone speaks, but slow enough that we can hear 'echoes' in large rooms. What is often not appreciated is that the speed of sound in a gas is directly proportional to the average speed with which the molecules of the gas are moving. And because the temperature of a substance is related to the speed of motion of its molecules, a precise measurement of the speed of sound in a gas can enable a measurement of its temperature.

For the last 6 years, my colleagues and I at NPL have been working to make such a measurement. Our measurements – the most accurate ever – will enable a new definition of the units of temperature (the kelvin and the degree Celsius) in the near future. This will link the unit of temperature to measurements of molecular speed and energy – and provide a foundation for future improvements in temperature measurement.

SPEED

FAST HORSES, ROBOTS AND NEUROTECHNOLOGIES: Discovering how to go fast on legs

Dr Andrew Spence
Lecturer in Biomechanics, Structure & Motion Laboratory,
Royal Veterinary College

Understanding how animals move is one of the grand challenges of modern science. It has broad impact on society: it affects our ability to explain the biological world, to treat human and animal disease, and to aid those recovering from injury. The more we know about how biological systems control their movement, and how different organs contribute to locomotion, the better we will be able to treat those with neurological disorders or musculoskeletal injury, and to inspire new technologies, such as legged robots.

Movement is critical to health and quality of life. The total NHS spending on musculoskeletal and neurological disease in 2007 was £7.4bn (Featherstone, 2010; www.policyexchange.co.uk). Circulatory problems and mental health together cost the UK £17.2bn, and a significant fraction of this cost will have its roots in mobility; movement is central to maintaining both good circulation and mental health (Halliwell, 2005; Mental Health Found. London). We hope to lay the foundation for medical advances that improve our ability to treat those facing a lack of mobility, increasingly important as our population ages, and thus have a huge impact on the quality of life of many millions of people.

Locomotion is the signature behaviour of animals. In the face of an unpredictable environment, noisy signals from sense organs and noisy forces from muscles, animals are able to move with speed, dexterity and robustness. Yet for one of the most important types of movement, fast terrestrial locomotion on legs, we do not know how sensory information is used to stabilise the body, or how we manage our noisy muscles. Stability may be largely handled by the mechanics of the body; sensory input may still be incorporated, but on longer time-scales; or, rapid locomotion may be constrained by motor noise.

We are working to uncover the mechanisms by which animals (including humans!) achieve their extraordinary feats of dexterity, in the face of these constraints. To do so, we employ advantageous techniques and technologies from diverse fields: robotics, computer science, mathematics, zoology, evolutionary and cellular and molecular biology. If we can discover the mechanisms that enable legged animals to go fast, robustly and economically, it will have a dramatic impact on medicine, technology, and our understanding of the world around us.

A COMPLEX, DYNAMIC PROBLEM

When a horse gallops at 20 metres per second its hooves may be on the ground for as little as 90 milliseconds (Fig 1). This is not enough time for signals to come from sense organs on the horse's leg up into the spinal cord (or brain!), for the nervous system to perform a corrective computation, and for signals to be sent back out to muscles, to develop forces that compensate. This means that fast moving animals face a big challenge: can they use this feedback in the next step? Can they use it to change what other legs do? Or are they forced to ignore it altogether?

Exciting hints to how they remain stable have come from basic biology. In a famous experiment, Jindrich and colleages (Journal of Experimental Biology, 2000) perturbed fast running cockroaches by placing a small cannon on their backs, and firing it as they ran quickly. They discovered that the cockroaches recover not through reflexes, but through mechanical tuning of their bodies, legs, and overall locomotion. Just like a car having a tuned suspension to absorb the impact of potholes, evolution can tune the mechanics of fast moving legged animals to handle perturbations with the animal's "chassis," or body! This has major implications for our understanding of the control of fast locomotion, and how animals must overlay feedback on their tuned mechanics.

But this presents a major obstacle to our understanding of how the nervous and musculoskeletal systems work together to produce locomotion. For us to interpret accurately what the role of each of these subsystems is, we need to examine independently and manipulate each subsystem, in an intact, freely behaving animal, in an ethical way. Understanding how each subsystem works in the context of all of them is important not just because history teaches us that linking across subsystems is a reliable way of gaining insight into the whole system, but because disease and injury frequently affect only one of these subsystems, or organs within a subsystem, at a time.

AN INTEGRATIVE, MULTIDISCLINARY, SYSTEMS APPROACH

So called "systems" approaches, where scientists think about how phenomena occur in a broader context, as opposed to drilling down to smaller and smaller constituent parts, are not just proving critical to our understanding of cells and molecules. They are accelerating our understanding of how whole organisms, including humans, move and behave. And they may provide the key to overcoming the problem of understanding the coupled, complex phenomenon of fast legged locomotion.

. . . seeking to build prosthetic limbs . . .

It is an extraordinary time to work in the neuromechanics of movement, because several new fields of science are converging to make possible more rapid progress. First, we are beginning to formulate quantitative, predictive mathematical models of how animals move, that integrate from molecular processes in the brain and spinal cord, through muscles and the skeleton, all the way out to the forces that limbs exert on the outside world. We are in the early stages, but the fact that we have mathematical models that make testable predictions, despite the complexity of the problem, means that we have a solid foundation to work from.

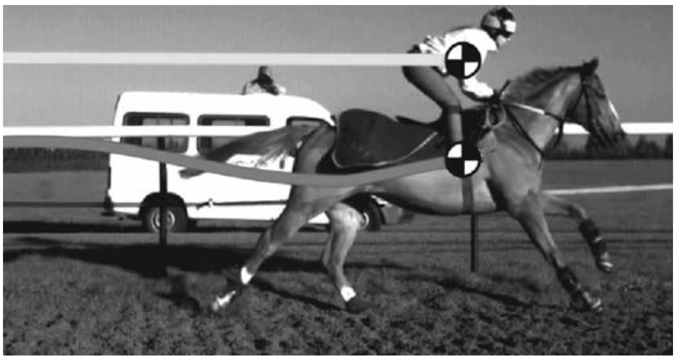


Figure 1

Second, legged robots have matured to become fantastic physical models of moving animals that can bring unprecedented insight into the mechanisms underlying locomotion (Fig 2). Two of the major limitations in animal locomotion research are that 1) the experimenter cannot control the behaviour of, or systematically the body conformation of, the animal, and 2) it can be unethical to perturb freely running animals to the point at which they are likely to fall over, even though this is the most important point for helping with, eg, understanding how humans fall over.

Robots can overcome these limitations. Using legged robots that we know move in a similar manner to animals (like the RHex robot seen in Fig 2, a six legged, dynamic running cockroach inspired robot), we can programme them to use exactly the type of controller that we hypothesise the animal is using, and therefore control the behaviour of the "animal." We can bolt on different legs, or add mass to different parts of the robot, to understand their effects on locomotion. Furthermore, we can then perturb the robot to the point of falling, and in doing so without using animals, we are contributing to the three R's of animal welfare: replace, reduce, refine. Where our robots are decent models of moving animals, they can completely replace the need for animal experiments.

Third, slow motion video cameras have become cheap, and open source libraries for automatic tracking and analysis of video using computer vision software have matured. This means we can gather and analyse large data sets of more and better quality motion than ever before. These technologies allow us to explore and model the extraordinary feats of animals that escape the naked eye.

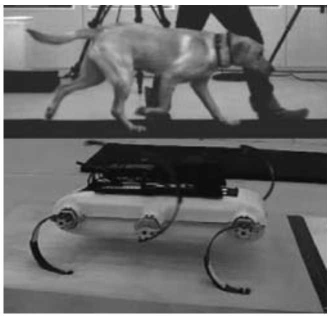


Figure 2

A BRIGHT FUTURE

A fourth and final technology is driving a revolution in neuroscience, and we are working to bring about another one in the neuromechanics of animal locomotion. It is called optogenetics, and in many ways it is the stuff of science fiction.

With optogenetics, specific sets of neurons can be switched on or off very quickly using light. By using genetic tools, we can specify which sets of neurons express these light switches. One of them, Channelrhodopsin, allows us to make neurons fire when we shine blue light on them. Another, Halorhodopsin, allows us to silence neurons with yellow light.

To understand the neuromechanical basis of locomotion, we need to turn on and off specific parts of the nervous system on the millisecond time scale. The extraordinary, revolutionary capabilities of optogenetics mean that, for the first time in human history, we have the technology to do this.

Furthermore, we can do it in our close mammalian cousin: the mouse. It is revolutionising neuroscience because it allows us to study the function of parts of the nervous system in a causal manner. Optogenetics and movement are a perfect combination because optogenetics can work quickly and reversibly. By combining optogenetics with a neuromechanical approach to locomotion, we can see an exciting future ahead in which we can really tease apart how different systems (neural, mechanical) contribute to locomotion.

CONCLUSION

Over 100 types of peripheral neuropathy have been identified, and many of these illnesses predominantly or exclusively affect the sensory (viruses and bacteria, including shingles, cytomegalovirus, and the Epstein-Barr virus) or motor (spasticity, essential tremor, autoimmune disorders such as multifocal motor neuropathy) nerves. More and more, we are seeking to build prosthetic limbs that interface directly with the patient's body. Thus, the more we understand our bodies and the signals that the nervous system uses to control them, the more we can help people with neurological problems or injury. An exciting aim indeed.

SPEED

SPEED – OF COMPUTERS

Professor Alistair Fitt
Pro Vice-Chancellor (Research & Knowledge Exchange), Oxford Brookes University, and Council member, Institute of Mathematics and its Applications

The majority of people alive today cannot remember life without computers. They know that computers dominate our lives, affect most of our everyday actions, and allow us to connect to the world via the internet and live digitally-dominated existences. They also know that, within their living memory, computer speed and storage have always increased, device size has always decreased, and nothing has ever looked like stopping the relentless advance of computer technology. Current petaflop machines (capable of performing over 10^{15} floating point calculations per second) allow us to make calculations of hitherto undreamed-of speed and accuracy, and the technological advantages of being able to perform such calculations are legion.

For more than 40 years the predictions of increasing computer power supplied by the famous "Moore's law" have served us well, but is there a limit to the march of computing progress, and what are the current important challenges? The huge energy consumption of modern computers is one real issue, which will assume increasing importance as the industry approaches exascale (10^{18} Flops) capability. As increases in basic CPU clock speed falter, ever more complicated technology is needed to ensure that Moore's law still holds, and this will require huge future investment in research and skills. Ultimately, theoretical physics (and in particular quantum theory) places limits on what may be achieved.

Finally, and possibly most intriguingly, will computers ever "wake up"? The possibility of a so-called "technological singularity" where computers become so powerful that they develop a kind of consciousness has engendered serious academic debate, and cannot be ruled out. If this were to happen, would it prove to be a blessing or a curse for humankind?

COMPUTERS ALWAYS GET FASTER

We can all argue about the identity of "the first computer". The Chinese abacus of 200BC, the 1822 Babbage difference engine, the enigma-cracking Bletchley Park COLOSSUS of 1943 and the 1944 Los Alamos ENIAC machine that calculated the details of the Hiroshima atomic bomb all have their claims to being "the first proper computer". One thing that we all agree on is that computers always get faster.

How do we measure how fast computers calculate? Computing speed is usually measured in Flops (Floating Point OPerations per Second), and historical increases in speed have been awesome. The NASA Gemini guidance computer of 1963 ran at a peak speed of 7,000 Flops (7 KFlops), the first megaflop (10^6 Flops) machine was the CDC 6600 in 1965, the CRAY2 of 1985 was the first gigaflop (10^9 Flops) computer and the 1996 INTEL ASCI RED boasted a peak speed of over a tera (10^{12}) Flops. The November 2012 speed champion is the Oak Ridge CRAY XK7, with a peak speed of over 27 petaflops, giving an awesome 27,113,000,000,000,000 sums per second. Figure 1 shows the increase in computer power over the years: the "N=1" line gives the speed of the world's most powerful computer at that time, the top line gives the sum of the power of the top 500 computers, and the third line traces the evolution of the speed of the world's 500th-fastest computer. The figure also compares supercomputing speed with our current familiar devices: for example, it takes an average of only 6-8 years for the world's most powerful machine to become relegated to 500th place, and my current laptop would have been the world's most powerful machine in late 1993.

What can we do with all this computing power? Many important calculations that were completely beyond us just a few years ago can now be carried out. Highly sophisticated climate change models can help to predict what we need to do to conserve our planet. The calculations carried out by the Large Hadron Collider to confirm the existence of the Higgs boson require the interpretation of mind-boggling amounts of data, and the power of current CFD (Computational Fluid Dynamics) calculations mean that F1 racing teams now rely more on simulation than wind tunnel testing to inform car design. The current capabilities of computational biology and medicine mean that important experiments can be carried out not in vitro or in vivo, but instead "in silico". Bioinformatics (including gene sequencing), social science data analysis and the processing of digital classics assets all require the huge computational power that is now at our fingertips. Our everyday devices are now so powerful that an HTC mobile phone recently won a grandmaster chess tournament. These are all wonderful achievements, but they beg an obvious question, namely whether or not this relentless technological advance can continue, and if so, for how long.

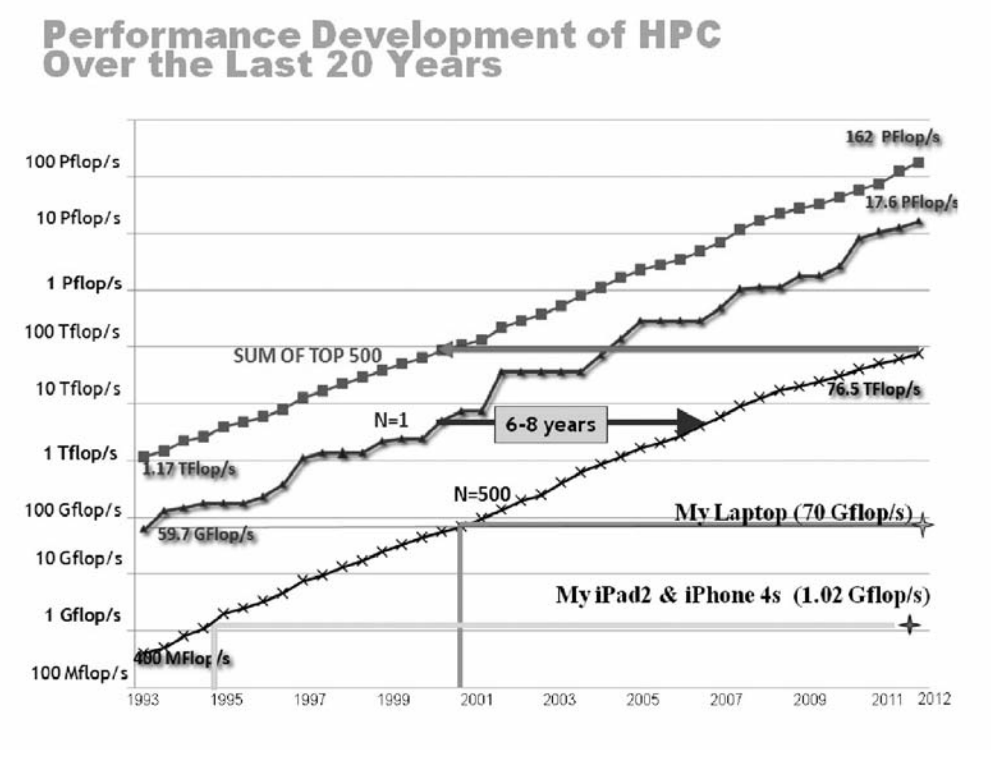
. . . mobile phone recently won a grandmaster chess tournament . . .

WILL COMPUTER SPEED ALWAYS INCREASE?

Many economists have debated what might happen if computer speed were to stop increasing, and the general consensus seems to be that a halting of the speeding-up process could have negative financial consequences, which could lead directly to a global recession. What are the most important barriers to continual speed increases? Many believe that the main things that we should be worrying about can be summarised fairly simply as energy challenges, infrastructure & skills, and natural limits.

First, modern computers use a great deal of energy. Put very roughly, CPUs expend energy doing two activities: floating point operations and moving data around. Though each of these in itself uses only minute amounts of energy, a petaflop machine does each of them in such vast quantities that its energy requirements are ferocious. The 2011 USA McKinsey/Uptime report on data centres estimated that the electricity consumption of an average data centre is equivalent to that of 25,000 households, and the worldwide data centre consumption doubled between 2000 and 2006. This leads to worryingly large carbon emissions: for example, the world's data centres currently emit more tons of CO_2 per annum than major countries such as Argentina and the Netherlands. If an exascale machine is to become a reality, this will require major advances in energy efficiency.

The often-misquoted Moore's law (an observation in a 1965 paper by George Moore, Intel's co-founder) says that the number of components in integrated circuits doubles approximately every two years. Though Moore's law has proved uncannily accurate for over 40 years, there is a great deal of evidence to show that this is unlikely to continue for much longer. As a result, some of our biggest challenges concern the provision of the necessary infrastructure and skills as Moore's law fails. Moore's law has held for many years essentially because of increases in underlying CPU clock speed, and that has now clearly stopped. As a result, Moore's law can only be achieved now via



(Courtesy of Jack Dongerra, Tennessee)

multicore processors, hyperthreading and the use of massively parallel architecture. Unfortunately much of industry uses legacy systems that have been developed over many years. The UK software business (worth over £3bn per annum) faces the huge challenge that almost *all* software will need to change to reflect the new architectures. Research and skills are crucial to these changes, and worldwide investment is urgently required.

> . . . worldwide investment is urgently required . . .

Inevitably, there are natural limits to what can be achieved. Nothing can grow exponentially forever, and we are already facing barriers imposed by basic physics. Transistors will soon have to be produced on a quantum scale and be just a few atoms large; circuit etching is limited by the 50nm wavelength of UV light, and hitherto unforeseen quantum complications such as the Heisenberg uncertainty principle and electron leakage from wires will have to be dealt with. The challenges are truly enormous.

"TECHNOLOGICAL SINGULARITY" – THE KRAKEN WAKES

Finally, it is worth debating whether computers will ever become "conscious". As humans we set great store by the fact that we are conscious, living beings – but what are the essential differences between our brains and a computer? Could it be that we are no more than extremely sophisticated robots? Many have debated this exotic question without coming to a conclusion. Nevertheless, eminent computer scientists regularly discuss so-called "Technological Singularity" theory, which countenances the possibility that, at some time in the near future, superhumanly intelligent computers that are in some sense "awake" will develop. Further, large computer networks and their associated users may combine to become an intimate and sentient, superhumanly intelligent entity. One result of this could be that biological science finds ways to improve on the natural human intellect. Some aspects of Technological Singularity theory are rather scary. Some of its exponents refer to the "post-human" era. It has been noted that there is no reason why a conscious, superhumanly intelligent computer should be friendly to humankind. Serious scientists across the world believe that it is only a matter of time before the singularity occurs.

CONCLUSIONS

For many years Moore's law and increased miniaturisation have combined to guarantee that computer speed and capacity increase. However, the days of the improvement via hardware are drawing to a close. We still need investment in supercomputer hardware and data centres, but even more we need investment in research, infrastructure & skills, and software development. The future is still rosy, but the strategic plan forward is becoming ever more complicated and the stakes could not be higher.

SPEED

National Science and Engineering Week Seminar on Thursday 21st March

We also heard from Lord Drayson (a previous Minister for Science) about his development of superfast electric cars. This included a film of him accelerating from 0-100mph in just over 3 seconds!

The final talk was from Professor Steve Jones (UCL), the well known geneticist and writer. He gave an amusing account about the rates of migration of snails (and hence their genes), and then segued into human populations, and in particular the surname "Jones".

AN OASIS IN THE DESERT – The growth of a Science Base in Qatar

Dominic McAllister
UK Science & Innovation Network (Gulf)

The UK Science & Innovation Network has recently appointed an officer to cover the Middle East Gulf region. Based at the British Embassy in Doha, Dominic McAllister covers UK S&I links with Qatar, Saudi Arabia, United Arab Emirates, Kuwait, Oman and Bahrain. He writes about his early experiences of Qatar. You can follow him on twitter @UKScienceQatar.

Coming to a new posting in the Middle East after three years in Seoul has been a big shift for my family. We aren't new to the region – my daughters are proud of the fact they were born in Riyadh. We had some expectations, but returning after 15 years has been an education. The rate of modernisation in Doha was the first revelation. A forward looking royal family, a relatively cohesive society, and a steady investment of income from gas and oil reserves are principally responsible. Doha is literally emerging from the desert (in many places the pavements are still sand). The traditional souk has been rebuilt, but is now air-conditioned. The