Lord Broers

Reith Lectures 2005: The Triumph of the Technology

Lecture 2: Collaboration

When I returned to this Engineering Department from the USA in 1984 my wife and I bought an historic and wonderful house some ten miles south of Cambridge. It was built around 1520, a date that could be substantiated to within a decade by the form of the oak beams that comprised its floors and ceilings. These had been shaped by iron blades that only lasted about ten years. Being someone of the present rather than the past I had not previously been much preoccupied with history but living in the splendid oak structure - like a fine sailing vessel that had gone aground - inspired me to wonder what had preoccupied the technologists and scientists of that age.

In my search I discovered that on 24 August 1563 a 'conjunction' took place of the planets Saturn and Jupiter. The two appeared so close together in the sky that they seemed to merge together. This rare occurrence was of great importance in an era when it was widely believed that exceptional astronomical events both influenced and predicted worldly happenings.

The problem was that the very best minds of the period, in Europe at least, were quite unable to calculate exactly when the conjunction was to take place. Some calculations were at least a month out. The best were inaccurate by days. Given the science and technology of the period, such inaccuracy is easy to understand. There were no reliable and accurate clocks. And without astronomical telescopes, robust celestial observation was to a great extent impossible. And besides, how many of us could do this calculation today?

The importance of overcoming such problems was not just a matter of shoring up the credibility of astrologers. Upon fine and accurate astronomical observation, and upon accurate timekeeping, depended reliable navigation, and the possibility of fruitful voyaging in the coming centuries. Measurement, the development of observational instruments and accurate clocks, complex calculations: all these came together in the ensuing centuries. Technology was of importance and gained support and the process by which these advances was achieved perfectly illustrates the productive connection between science and technology. The latest manifestations of this are the Global Positioning System, which I shall describe later, and its European descendant Galileo.

We think of such support as a modern phenomenon, but in fact - in Europe at least - governments have supported scientific and technological research for centuries. Such support was commonly tied to the fulfilment of contemporary needs, for example in the development of accurate systems of navigation to overcome the shortcomings we have just glimpsed.

Most modern technologies are created by bringing together and evolving capabilities which already exist. The genius lies in the way they are brought together and improved. There are innumerable examples to illustrate the process. The long sought mobile phone was made a reality by bringing together mathematical concepts of cellular networks, advanced ultra high frequency radios, low power microprocessors, and improved batteries. It was not invented, although buried within it are innumerable inventions, and several of the genii who design the world's best cell-phones do so just south of Cambridge. The hybrid car combines the efficient modern internal combustion engine with pollution free electric drive and systems that recycle the energy dissipated in braking. The modern jet airliner combines innumerable individual capabilities in mechanical design, aerodynamics, jet engines, electronic communication and navigation systems, and the airports that they serve are wonders of modern civil engineering. Other examples easily come to mind; the modern dental surgery, flat-screen TVs, medical scanners, the ubiquitous scanning electron microscope developed in this laboratory, electronic stock exchanges, Dyson's vacuum cleaner, the apparatus used to decode DNA, the IPod, and so on. All of these new technologies came about through a process in which established capabilities were evolved and combined in new ways. They were the result of engineers seeking solutions to practical problems and human need.

When fundamentally new materials or ideas are available the potential is even greater but the route to useful products is longer and the commercial risks higher. Such is the case, for example, with the polymer semiconductors that have emerged recently in the Cavendish laboratory that offer no less than a revolution in computer displays and in low cost electronics.

In this second Reith lecture I explore the origins of modern technologies. I believe that today collaboration is essential for success because it brings both global awareness and the ability to gather together diverse capabilities. It is rare that individuals or groups working in isolation possess all that is needed. During my time at Cambridge I concentrated on extending the bridges that provided global awareness and enabled collaborations - with industry, with universities, with government. Without joining with others, one quite simply does not have the resources to be internationally competitive nor does one have the 'spirit level' that reveals whether or not one is even in the race - complacency and smugness easily set in.

Mind you there are dangers in collaboration, especially in the security of ideas - patents can protect ideas but necessarily give away the details when they are published. Individuals have this dilemma. They need to be a part of the larger world and communicate with it, but the moment they reveal their ideas, they have to be ready to run fast or competitors will out-speed them. I will return to this question in my third lecture.

The process of collaboration has been vastly enhanced by modern communications. The World Wide Web, which Tim Berners-Lee originally developed to allow physicists to work together, now allows creators of technology in every corner of the earth to work together - or to compete. And it is amazing how the efforts of creative engineers lead to advances and novel concepts that could not have been imagined by those who carried out the original research.

Which brings me to the laser. Few now remember that the laser was an adaptation of the earlier maser. The maser, an acronym for Microwave Amplification by Stimulated Emission of Radiation, was a device devised by Charles Townes to meet the need for an electronic oscillator that would operate at very high radio frequencies. It was an electronic device. Townes proposed that a similar device should be possible that operated at optical frequencies and two years later Theodore Maiman demonstrated the first laser. The laser uses the same principles as the maser but operates at optical frequencies, hence the acronym Light Amplification by Stimulated Emission of Radiation.

It was predicted in 1960, when the laser was first demonstrated, that it would revolutionise optical imaging systems and make holograms feasible, but no-one could have imagined the breadth of applications that were to emerge. No one could have foreseen that lasers would be used to transmit the majority of the world's telephone and television signals, or to record and play back sound and vision using plastic disks, let alone the plethora of other applications that now benefit everyone. These were subsequent accomplishments of technologists.

Telephone and television, and indeed all forms of electronic communications, are now carried around the world by beams of light that are channelled down glass fibres. The light beams are generated and modulated by solid state lasers that are so fast that a single beam can, for example, carry tens of thousands of simultaneous phone calls. A metal wire can carry about a hundred. An essential component in these optical systems is the Erbium amplifier which allows the light signal to be amplified directly without first converting it back to an electronic signal. This key advance was made by British engineers.

The technology of optical communication had its earliest origins in science but through most of its development it was a technologist's technology progressing through a series of intellectual advances that outweigh those of the original researchers. The achievements have been extraordinary - it has connected the world in a way that engineers would have thought impossible thirty years ago and avoided a log-jam in the Internet that people predicted twenty years ago.

These advances involved many people in many laboratories. One model says that ten times the effort needed in the original research must be expended in developing a prototype technology, and ten times this effort is needed to produce the manufactured product. The idea that a single person can 'invent' a new technology, is out of the question in these cases. Creative ideas of course come from individuals but their ideas must fit into the matrix of creativity being generated by individuals and teams all over the world.

I have discussed only two of the unexpected applications of the laser. I could have told similar stories about its applications to materials processing, such as the re-shaping of the lenses in our eyes, high quality welding, or precision measurement. Even some of the humble and reliable printing devices attached to our home computers apply low power lasers in an unforeseen manner. The successful applications of the laser far exceed the most extravagant predictions made in the 1960s.

The process of improving existing capabilities and adapting them to new applications relies on something that we do not need to teach, something that is inherent in the way the best technologists operate. Creative engineers are, by nature, problem solvers, always seeking ways to employ advances in technology in new and better ways. It is an extraordinarily exciting activity. Look back to the era of the first European ocean voyagers, the lack of reliable time-keepers to determine longitude, the reliance on crude devices such as the cross-staff to make astronomical observations. The navigators' achievements were astonishing, but consider where we are by contrast today.

GPS, the Global Positioning System, because it built on the vast technological achievements of humankind, belittled previous accomplishments. GPS had its origins almost exclusively in technology. It uses principles related to those of land based navigational systems but with the signals coming from satellites rather than ground based transmitters.

The idea of building a satellite-based location system emerged when a number of quite separate developments coincided. The cost of launching satellites became finite; advances in microelectronics allowed the necessary electronics to be packed into a small satellite and the receivers to be compact and reasonably priced; and finally, it was seen that such a system could have military significance making available the billions of dollars necessary to put up the twenty three satellites. This technology grew out of space research and microelectronics and was funded by the military.

At the time it was decided to build the Global Positioning System, I suspect that few would have foreseen that within a decade tens of millions of receivers would be sold and that they would not just be used for navigating ships and planes. Farmers would use them to guide their tractors, taxi fleets would be managed using GPS data, the arrival of trains and buses would be announced, and authorities would keep track of criminals on parole with GPS ankle bracelets. Standard cars would carry GPS-based navigational systems and these would not only tell people where they were, but just as importantly perhaps, the location of the nearest Indian restaurant.

But stop to wonder a moment about this technology. A GPS receiver contains up to a dozen individual receivers each of which automatically searches the frequency spectrum to find the tiny synchronised signals from the satellites. The receiver's computer knows the exact position of each satellite, and from the time delay between the signals it calculates its own position in three dimensions to an accuracy of a few metres. A modern receiver takes a few seconds to locate the satellites, make these measurements, and fix its position. And less than five centuries ago humankind could not even reliably predict a rare astronomical event.

In 1992 I had the privilege of visiting one of the Royal Navy's nuclear submarines. It had an electronic navigation system that performed similar functions. It occupied an entire six foot high rack of electronics, cost a large fraction of a million pounds and took five minutes to give a fix with an accuracy of a few hundred metres. One of today's hand-held GPS receivers gives a ten times more accurate fix in a hundredth of the time at one ten thousandth of the cost. This is a triumph of technology.

To create technologies like GPS, and indeed to make progress in any advanced technology, engineers must be familiar with the full spectrum of technologies and know what is hindering further progress. To do this they must be working at the frontiers of development. If they are not then they cannot concentrate their resources efficiently and their efforts will not be competitive. Working from first principles is not effective as it opens up too many alternatives.

Obviously, progress is most rapid when the factors impeding progress are known. This does not make the problems easy to solve, and indeed with most modern technologies the solution generally requires an intimate knowledge of the science that underpins the technology, but without knowledge of these factors focus is lost. Let me trace the evolution of electronics as another example.

Electronics began with J J Thomson's identification of the electron in Cambridge in 1897. One could go back even earlier and seek the origins of scientific methodology but let me start at the time that Thomson proposed that the 'rays' which Europe's physicists had been experimenting with for many years were in fact streams of sub-atomic particles, 'corpuscles', later called electrons. J J Thomson used a glass bottle in which he had embedded a cathode from which the electrons would emerge, and an anode that attracted them. This was in effect a primitive cathode ray tube as used in television sets although there was in fact some residual gas in the tube and there were ions as well as electrons, but the simple analogy is none the less useful.

This primitive electron tube was adapted a few years later by John Fleming and used as a 'detector' for weak electromagnetic signals in the earliest experiments in long range radio transmission, that had been pioneered by Marconi. Fleming's diode was superceded by the triode of De Forest. De Forest's third electrode allowed amplification and created a universal electronic amplifier which was to become known as the vacuum valve in the UK and the vacuum tube in the US. The technology of electronics had been born and it was the vacuum valve that gave rise to most of the electronic systems that we are familiar with today, including computers. But engineers were not satisfied with the valve and following the second world war a search for a better alternative began, which eventually led to the transistor.

The first transistor was developed by John Bardeen, Walter Brattain, and William Shockley at Bell Telephone Laboratories in New Jersey in December of 1947. They were seeking an alternative to the vacuum valve that was cheaper, lower power, and less fragile: an electronic device that operated like the valve but did not have to operate in a vacuum. Their device turned out to be perhaps the most important single technological development of the 20th century; but these three pioneers could never have imagined what was to come. By early in the twenty first century more transistors would have been built than characters printed since the beginning of time. I will bring this story up to date in the fourth lecture when I will discuss nanotechnology, which had its origins in this laboratory.

Following the contribution of JJ Thomson, who was clearly motivated by the desire to understand the universe, the development of electronics followed the route of most successful technological developments. The engineers and scientists who made the remarkable breakthroughs were not being driven by science, and a wish to understand nature, their aim was to find useful applications for their knowledge.

Today, the fledgling electronics, that started with the elementary two electrode valve, has reached extremes. A chip manufacturing plant costs several billion dollars and if you have problems that delay the production of a new chip for six months you may have lost 50% of the profit from that chip. And this industry is not alone in its magnitude and complexity. The situation is similar in many other fields, certainly in aerospace and in the automobile industries, and the resources needed to be successful in the pharmaceutical industry are just as great and the adherence to schedule even more critical.

By now it should be clear why it is not only difficult but impossible to make progress in this sort of high technology if you are not already at the frontiers of development. If you are not, then you have no means of knowing where to concentrate you efforts. It is possible with a relatively small team to tackle new technologies but only if the team is fully aware of the international competitive situation and is linked in with partners that have the ability to proceed at a competitive pace. There can be no half-hearted commitment

Advances equivalent to those of past centuries are extremely unlikely to be achieved in the same way today, by the separate endeavours of often amateur researchers and technologists. James Joule, working in a private laboratory attached to his father's brewery; Michael Faraday, brought up as a bookbinder's apprentice and educated through studying the books that passed through his hands; Thomas Newcomen, an ironmonger and blacksmith: these and other giants of past ages made their achievements partly alone and largely by happy chance. Such a course is probably impossible today, but the excitement and thrill of achievement are just the same. There are few more satisfying activities than the creation of new technologies for the benefit of humankind. Creative engineers may not receive the recognition they deserve in this country but it rarely troubles them - the satisfaction they derive from their jobs is unsurpassed.