**Exploring innovation in action: The dimming of the light bulb**

In the beginning....

God said let there be light. And for a long time this came from a rather primitive but surprisingly effective method – the oil lamp. From the early days of putting simple wicks into congealed animal fats, through candles to more sophisticated oil lamps people have been using this form of illumination. Archaeologists tell us this goes back at least 40 000 years so there has been plenty of scope for innovation to improve the basic idea! Certainly by the time of the Romans domestic illumination – albeit with candles – was a well-developed feature of civilized society.

Not a lot changed until the late eighteenth century when the expansion of the mining industry led to experiments with uses for coal gas – one of which was as an alternative source of illumination. One of the pioneers of research in the coal industry – Humphrey Davy – invented the carbon arc lamp and ushered in a new era of safety within the mines – but also opened the door to alternative forms of domestic illumination and the era of gas lighting began.

But it was not until the middle of the following century that researchers began to explore the possibilities of using a new power source and some new physical effects. Experiments by Joseph Swann in England and Farmer in the USA (amongst others) led to the development of a device in which a tiny metal filament enclosed within a glass envelope was heated to incandescence by an electric current. This was the first electric light bulb – and it still bears more than a passing resemblance to the product found hanging from millions of ceilings all around the world.

By 1879 it became clear that there was significant commercial potential in such lighting – not just for domestic use. Two events occurred during that year which were to have far-reaching effects on the emergence of a new industry. The first was that the city of Cleveland – although using a different lamp technology (carbon arc) – introduced the first public street lighting. And the second was that patents were registered for the incandescent filament light bulb by Joseph Swann in England and one Thomas Edison in the USA.

Needless to say the firms involved in gas supply and distribution and the gas lighting industry were not taking the threat from electric light lying down and they responded with a series of improvement innovations which helped retain gas lighting's popularity for much of the late nineteenth century. Much of what happened over the next 30 years is a good example of what is sometimes called the 'sailing ship effect'. That is, just as in the shipping world the invention of steam power did not instantly lead to the disappearance of sailing ships but instead triggered a whole series of improvement in that industry, so the gas

But electric lighting was also improving and the period 1886-1920 saw many important breakthroughs and a host of smaller incremental performance

improvements. In a famous and detailed study (carried out by an appropriately named researcher called Bright) there is evidence to show that little improvements in the design of the bulb and in the process for manufacturing it led to a fall in price of over 80% between 1880 and 1896 (A. Bright, The Electric Lamp Industry lighting industry consolidated its position through incremental product and process innovations.
Examples of such innovations include the use of gas instead of vacuum in the bulb (1913 Langmuir) and the use of tungsten filament.

Innovation theory teaches us that after an invention there is a period in which all sorts of designs and ideas are thrown around before finally a 'dominant design' settles out and the industry begins to mature. So it was with the light bulb; by the 1920s the basic configuration of the product – a tungsten filament inside a glass gas-filled bulb – was established and the industry began to consolidate. It is at this point that the major players with whom we associate the industry –Philips, General Electric (GE), Westinghouse – become established.

## Technological alternatives

Although the industry then entered a period of stability in the market place there was still considerable activity in the technology arena. Back in the nineteenth century Henri Becquerel invented the fluorescent lamp and in 1911 Claude invented the neon lamp – both inventions which would have far-reaching effects in terms of the industry and its segmentation into different markets.

The neon lamp started a train of work based on forming different glass tubes into shapes for signs and in filling them with a variety of gases with similar properties to neon but which gave different colours.

The fluorescent tube was first made commercially by Sylvania in the USA in 1938 following extensive development work by both GE and Westinghouse. The technology had a number of important features including low power consumption and long life – factors which led to their widespread use on office and business environments although less so in the home. By the 1990s this product had matured alongside the traditional filament bulb and a range of compact and shaped fittings were available from the major lighting firms.

## Meanwhile, in another part of the world...

Whilst neon and fluorescent tubes were variations on the same basic theme of lights, a different development began in a totally new sector in the 1960s. In 1962 work on the emerging solid state electronics area led to the discovery of a light emitting diode – LED – a device which would, when a current passed through it, glow in red or green colour. These lights were bright and used little power; they were also part of the emerging trend towards miniaturization. They quickly became standard features in electronic devices and today the average household will have hundreds of LEDs in orange, green or red to indicate whether devices such as TV sets, mobile phones or electric toothbrushes are on and functioning.

Development and refinement of LEDs took place in a different industry for a different market and in particular one line of work was followed in two locations – a university department in Nagoya and in a small Japanese chemical company supplying LEDs to the major manufacturers like Sony. The Nagoya University team (Isamu Akasaki and Hiroshi Amano) were working on new structures for semiconductors based on gallium arsenide and in 1986 were able to grow crystals of the substance. They found it had interesting optical properties, glowing when subjected to the energy from their electron microscope.

In 1988 Shuji Nakamura working at Nichia Chemical began a programme of research on a type of LED which would emit blue light – something much more difficult to achieve and requiring complex chemistry and careful process control. Eventually they were successful and in 1993 produced a blue LED based on gallium arsenide technology. The firm then committed a major investment to development of both product and process technology, amassing around 300 patents along the way. Their research culminated in the development in 1995 of a white light LED – using the principle that white light is made up of red, green and blue light mixed together.

So what? The significance of this invention may not be instantly apparent – and for a long time the only products which could be bought utilizing it were small high power torches. But think about the implications of this discovery. White LEDs offer the following advantages:

- 85% less power consumption
- 16 times brighter than normal electric lights
- Tiny size
- Long life – tests suggest the life of an LED could be 100,000 hours – about 11 years , compared with 1000 hours for an incandescent bulb and 10,000 for a fluorescent one
- Can be packaged into different shapes, sizes and arrangements
- Will follow the same economies of scale in manufacturing that led to the continuing fall in the price of electronic components so will become very cheap very quickly.
- Unlike fluorescent bulbs they contain no mercury and so offer less of a problem in disposal

**Looking forward…**

If people are offered a low-cost, high-power, flexible source of white light they are likely to adopt it – and for this reason the lighting industry is feeling some sense of threat. The likelihood is that the industry as we know it will be changed dramatically by the emergence of this new light source – and whilst the names may remain the same they will have to pay a high price for licensing the technology. They may try and get around the patents – but with 300 already in place and the experience of the complex chemistry and processing which go into making LEDs Nichia have a long head start. When Dr Nakamura left Nichia Chemical for a chair at University of California, Santa Barbara, sales of blue LEDs (light-emitting diodes) and lasers were bringing the firm more than $200m a year and the technology is estimated to have earned Nichia nearly $2bn.

Things are already starting to happen. Many major cities are now using traffic lights which use the basic technology to make much brighter green and red lights since they have a much longer life than conventional bulbs. One US company, Traffic Technology Inc., has even offered to give away the lights in return for a share of the energy savings the local authority makes! Consumer products like torches are finding their way into shops and online catalogues whilst the automobile industry is looking at the use of LED white light for interior lighting in cars. Major manufacturers such as GE are entering the market and targeting mass markets such as street lighting and domestic applications, a market estimated to be worth $12bn in the USA alone.

**…and looking back**

We wrote the original case study in 1997 and it stopped at that point, looking forward to a bright future for LED lighting. Now, nearly 20 years later, we can see the pattern playing out as a classic example of innovation adoption and diffusion. What began as a niche product offering advantages in the market for small torches or in traffic lights has grown to a global industry worth, on current estimates around $50bn.

The technology has matured; for example the illumination efficiency (measured in lumens of light per watt of power input) has reached 300 as compared with 16 for incandescent light bulbs and 70 for fluorescent tubes. This has far-reaching potential effects on sustainability since around one quarter of global electricity usage is in illumination. And the prediction about lifetime for the bulbs has been confirmed; LEDs routinely have lives in excess of 100,000 hours.

Of course innovation diffusion is not just about technological improvement; a number of external forces have shaped this innovation. In particular concern about global warming and the need to rethink energy consumption has led to a range of legislation forcing the old technologies of incandescent bulbs out and bringing in a new generation of more efficient sources. LEDs comprise a growing share of this market, especially since technology research has enabled combinations of phosphors to allow for 'warmer' white light which is more suited to domestic applications.

On the market side the experience of early adoption was helped by the visibility of LEDs – the 'seeing is believing effect'. People could see these sources were bright, even in daylight and this helped change minds in favour of the new technology. Niche markets gave way to mainstream applications and LEDs are now a core feature in most vehicle lighting systems and increasingly in the street lighting on the roads on which those vehicles travel. According to a recent report from the research firm Navigant, installation of LEDs in street lighting worldwide is expected to grow from 13.2 million bulbs in 2014 to more than 116 million in 2023.

Domestic lighting is changing dramatically as the potential flexibility of LED technology opens up the idea of light being used to create atmosphere rather than just provide illumination. (There is a detailed case study on the Portal of Philip's work in this area describing way in which a mainstream lighting provider changed its whole approach – see http://www.innovation-portal.info/resources/philips-2/)

Price was a major barrier to early adoption and LEDs are still more expensive than traditional lighting sources but the costs are continuing to fall. Estimates suggest that in 2014 LEDs were at the point of becoming the largest revenue share of all lighting technologies.

A research project at the Technical University of Eindhoven has been exploring futures with new lighting sources and more details of their work and the wide range of applications for LED technology can be found at http://www.ili-lighthouse.nl/Index.html

Other applications emerge with significant social value. For example LED lighting opens up the possibility of bringing safe illumination into homes of the 1.5 billion people who have no access to electricity grids. The low power consumption means they can be battery powered or use accumulated power from solar cells. (There is a case study – Lifeline Energy – on the Portal, which explores this area of application). There is even research around using ultra-violet LEDs to enable water sterilization in regions where lack of fresh water is a problem.

Overall the world market for lighting is expected to reach around €100bn by the year 2020, according to a major survey by McKinsey consultants; of this LEDs are expected to have the major share of around 60%. Another study by the US Department of Energy suggests that by 2030 this will be 75%.

**A bright future…..?**

In 2014 the Nobel Prize for Physics was awarded to Akasaki, Amano and Nakamura for their contribution to a technology which is changing the world. As the committee suggested in their citation, "Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps". It's interesting to reflect that when the trio travelled to Stockholm to collect their prize the headlamps on the cars their rode in, the streetlights on the way to the city and the lights in the windows along the streets were all lit by LED technology.