has recently launched Tata Nano, which is touted as a triumph of Indian ingenuity and world's cheapest car, costing just 100,000 rupees ($1,979; £1,366).

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Profiting from the Breakthrough:

Technology Commercialisation in the Global Age

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Abstract

Commercialising breakthrough technology is a complex and time consuming process. It is also an essential part of creating value from national science bases and contributing to continued economic development at both the national and international levels.

Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under or unexploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of new 'technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation.

The emergence of these breakthrough innovations is a global process with contributions from a geographically diverse network of participants. These innovations also draw on significant resources from both public and private sources, from the initial 'discovery' to eventual 'commercial application', yet the rewards from these emergent innovations are not as evenly dispersed.

This paper uses a case study of the development and commercialisation of liquid crystal display (LCD) technology to examine the geographical emergence of a technology. The paper compares the geographical contributions of both public and private participants in this emergence, with the eventual geographical position of the industrial development and commercial success of the LCD industry. This highlights the tensions between the goals of national policies supporting the development and commercialisation of science and the knowledge of where the ultimate benefits of this support may lie.

Keywords: Science-based commercialization, Liquid crystal display, Innovation, Science and technology policy

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Introduction

The commercialisation of breakthrough technologies are rare events, yet when they do occur they can have dramatic effects on the industrial landscape. When and where the next breakthrough technology will emerge is difficult to predict because the extent and reach of the disruptive capacity of a new scientific discovery is unknown, as too the range of applications that such a discovery can change or create.

Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under or unexploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of new 'technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation. However, the first few applications of a new technology are critical in setting the commercialisation path of these breakthrough technologies.

Public policy over the preceding decades has attempted to encourage the discovery of breakthrough technologies and accelerate the commercialisation of these technologies. The interest in following and trying to support these technology activities lies in their potential for value creation across a broad range of industries and applications (Maine and Garnsey 2006). These upside gains can outweigh the downside risks of commercialising radical innovation and the knowledge that most of these technologies will come to nothing. These gains have national effects as well. These new industries can have effects on export income and international competitiveness and increased knowledge based employment and living standards domestically. Governments invest heavily in the science behind these technologies, either through the training of the highly skilled staff that work in both public and private research and development (R&D) laboratories or through the subsidisation of R&D either through direct grants or subsiding private expenditure through tax credits and concessions.

This paper examines the development of one of the breakthrough technologies of the past fifty years – Liquid Crystal Displays (LCD) and reflects on the geographical spread of science and engineering activities associated with this technology. The development of the LCD industry is traced through knowledge generation activity, including patents, and the role of key personnel and firm activities and their geography. In presenting this single historical case study of technology emergence, two issues are highlighted. The first is the long timelines involved for the emergence of breakthrough technologies and the need for patient investment, and the second, is acknowledging the risks and uncertainties involved with the commercialisation processes of such technologies, which can see small and largely unforeseen events having a dramatic impact on the direction of the industry.

The LCD case study presented in this paper is one of eight case studies of breakthrough technologies commercialised in the past fifty years that are investigated in the *Funding Breakthrough Technology* project. This project, in turn, is part of a wider programme of research within the Cambridge Integrated Knowledge Centre (CIKC) into macro molecular materials in micro electronics. The combined result of these case studies is to provide an overall and comparative view of the commercialisation of breakthrough technologies and how this can inform policy and support for current breakthrough technologies in microelectronics that are in the early stages of commercialisation.

Context for this research

The value creation associated with the successful commercialisation of breakthrough technology means that analysis of commercialisation process is of immense interest both to governments and firms. In the United Kingdom (UK) the widespread experience and attitude towards science-based commercialisation is largely one of failure. That the UK has strengths in the production of basic science but poorly executes on the commercialisation of this basic science into technology and applications. Two quotes displayed below, separated in time by over 80 years, sum up the prevalence and long held nature of these views;

> *"These works reveal numerous cases in which members of the small band of British scientific men have made revolutionary discoveries in science; but yet the chief fruits of their work have been reaped by businesses in Germany and other countries..."*
> Alfred Marshall, Industry and Trade 1919, p.102

> *"The UK has a strong science base but lags in patenting and commercialisation..."*
> Michael Porter & Christian Ketels, DTI Economics Paper No.3 2003

National performance in terms of science-based commercialisation is difficult to capture in a quantitative way. The global nature of many large firms, who are at the forefront of commercialising such technologies, makes this a difficult story to unpack at the national level. This is one of the reasons why the case study methodology employed in this project is useful.

The International Monetary Fund publishes annual data on the balance of payment between nations including a category on payments for licences and royalties (IMF 2008). Such payments for licenses and royalties would include revenue earned by firms in the process of commercialising technology; i.e. licensing out patents or royalties on IP included in products and services. These payments also include royalties received by authors and musicians for their works. Therefore examining the performance of individual nationals in terms of this balance of payments is limited, it can only provide some indications of the activity of science commercialisation, but will not reveal the whole story.

Figure 1 shows the balance of payments for royalties and licenses received and paid out for the United Kingdom. On the basis of this chart the UK has maintained a surplus of payments throughout the data period (1970-2007) and since 2000 this surplus has been increasing. Figure 2 compares the differences in payments received and made in a number of comparative countries (US, Japan and Germany). From this figure we can see that whilst the UK and Japan have maintained surpluses in their balance of payments, these surpluses are dwarfed in comparison to the US. Germany throughout the majority of the data period has a deficit in its balance of payments for royalties and licences.
In this brief comparative examination of these figures it is difficult to draw conclusions for what this may mean for science based commercialisation, particularly when considering the aforementioned limitations of the data. It does however reveal that national performance in terms of commercialisation of science is not a straightforward matter, and that interpreting breakthrough technology requires an analysis of the underlying complexities developed over time both within and between nations and science fields.

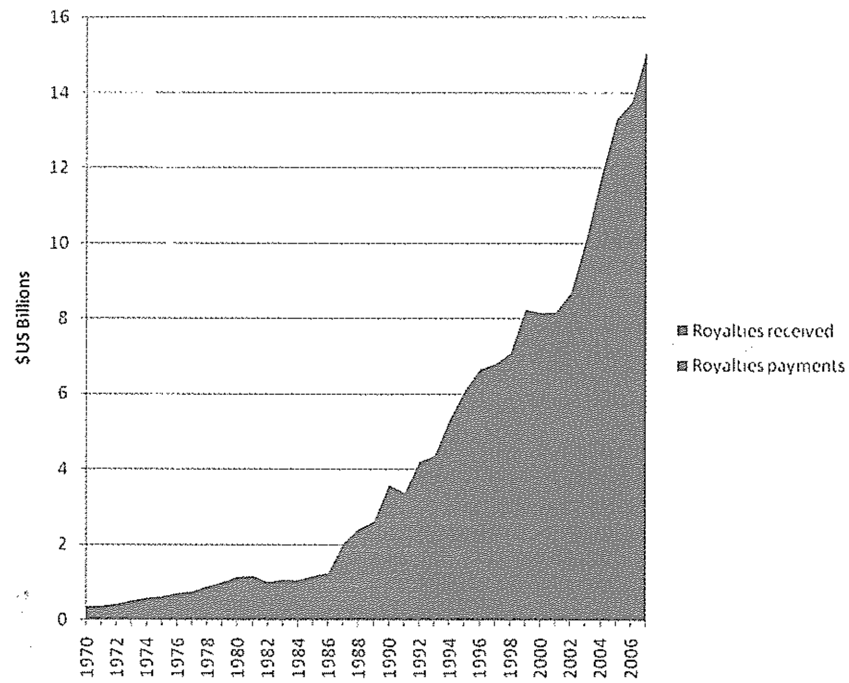

Figure 1: UK Import and export of royalty and licensing payments
Source: IFM, International Financial Statistics, Direction of Trade Statistics, Balance of Payments Statistics and Government Finance Statistics

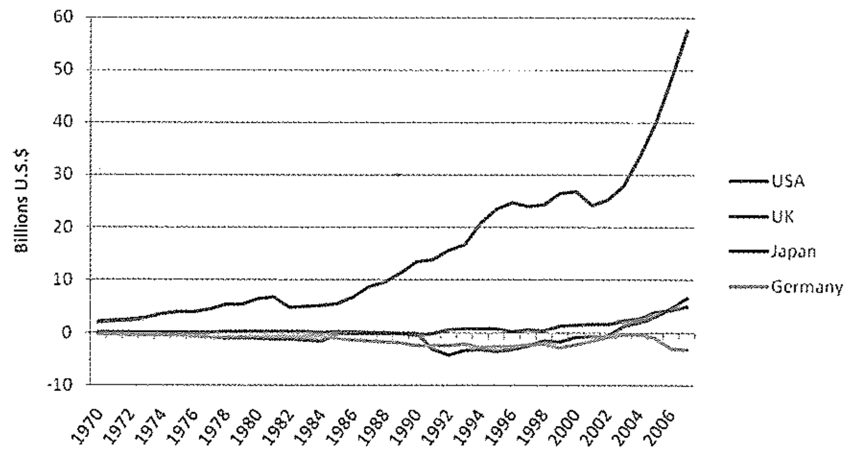

Figure 2: UK Import and export of royalty and licensing payments
Source: IFM, International Financial Statistics, Direction of Trade Statistics, Balance of Payments Statistics and Government Finance Statistics, author's calculations

Commercialisation of science-based innovations

The commercialisation of technology from the science-base is considered one of the key drivers of economic growth. This view is based on a combination of the recent US experience in micro electronics (the famous rise of Silicon Valley) (Chandler 2001; Kressel and Lento 2007) and the fact that discontinuous innovations have the potential for very large upscale profits (Maine and Garnsey 2006). A country's position in relation to prominent and successful breakthrough technologies can have a significant impact on their international competitiveness.

The problem however is that this position is determined by relatively small and often inconsequential (at the time) activities of a number of actors in the very early stages of the breakthrough technology's evolution – activities that are taken when the end result and any resulting profitable industry is a long way off.

How breakthrough technologies commercialise is difficult to predict, it depends how the science is applied to the existing knowledge base and how this is interpreted through to applications. This can be a quick process with the new technology attached to an existing knowledge base in a relatively quick manner and then rapidly linked to applications (and demand for applications) (Adner and Levinthal 2002). In other circumstances, although these breakthrough technologies have potentially revolutionary prospects for industrial development, the process of commercialisation is a long and slow one.

In this sense we can think of the commercialisation process in two phases – one in the science base where the new knowledge is link with the existing knowledge base. The second links the technological discovery with an application, market and market demand. Science-based applications tend to emerge from a 'technology push', rather than a 'market pull' mechanism. The functions and advantages of new science-based applications are unfamiliar to customers (Freeman 1982). Therefore this second phase can be as lengthy and complicated as the first.

These phases can occur in two places (geographically) and at two points in time (sometimes the points in time can be far apart). They both require different sets of decision making and actors. The second process is heavily dependent on the resources available at that point of time (financial, organisational and market) and place and other technological advances commercialising or being developed at the same time. These twp phases can happen independently of each another, and just because the first one happens does not mean the other one has to as well.

Historical case study methodology

This research uses a historical case study methodology. Earlier sections of this paper have alluded to the advantages of this approach. These include the ability to deal with the complexity of analysis of technological development; the many participants, organisations and geographies. Also, historical analysis allows us to deal with the long timelines involved in technology commercialisation.

Historical analysis of past technology commercialisation also has relevance to current considerations of science commercialisation. As Tosh (Tosh 1984) points out, "...We know that we cannot understand a situation in life without some perception of where it fits into a continuing process, or whether it has happened before...our sense of what is practicable in the future is formed by an awareness of what has happened – or not happened – in the past" (p.1).

Although the historical method allows analogies to be drawn between the different development paths of breakthrough technologies and the roles of different actors, organisations and government policies in these development paths, it is limited to describing and analysing what happened (or did not happen), not what could have happened if situations were different (NRC 1999). The method also analyses from a point of view of knowing the final outcomes of earlier events.

Government policy towards the commercialisation of science

In the past decade there has been a lot of attention by government's to accelerate and support the commercialisation process. The aim has been to speed up the process. This has been done in a number of ways including, encouraging universities to patent, license and commercialise science based discoveries that emerge from their research. Other countries have developed intermediate institutions that offer an incubation space between universities and industry. In the US the *Small Business Innovation Research* (SBIR) programme has used government procurement funding to offer 100% upfront development funding for technology applications that can address government stated needs, therefore providing funding but also demand pull for any emergent technological application. Governments across the globe have used their military, telecommunications and health departments as first customers to stimulate the development of many breakthrough technologies. Countries have also sought to increase subsidies available to firms to invest in R&D, and subsidies to firms and individuals to invest in risk based investment opportunities – which are typically new technology based firms.

The objectives of government policy need to be considered within the wider view of where government can effectively intervene. Governments, through their investments in universities, research laboratories, and the education of scientists and researchers, are typically best positioned to act in the science base and with the transfer of new knowledge into the science base. They are less well equipped in comparison with firms, to intervene in the second phase of commercialisation, the development of applications and products. Importantly, and as the following case study demonstrates, government intervention usually comes at a time when the long term success or not of a science discovery can not readily be determined from the time of the policy intevention.

Liquid Crystal display technology[1]

The Liquid Crystal Display (LCD) industry is an US$85billion industry (Hart 2008). LCDs have become the dominant display technology, surpassing plasma and light emitting diodes in modern electronic displays. Sales of LCD TVs overtook worldwide sales of cathode ray tube (CRT) TVs in 2007. LCDs account for 95% of all flat panel display (FPD) sales and thin-film transistor LCDs (TFT-LCD) account for 90% of these sales (Hart 2008).

The industry began in the 1960s in the corporate R&D laboratories of some of the US' leading corporations – including RCA, Westinghouse and General Electric, before rapidly transferring to Japan and companies such as Sharp, Canon and Seiko. LCD production then shifted, initially in search of lower manufacturing costs, and then because of the sophisticated fabrication investment required for LCD production, to South Korea, Taiwan, and increasingly in China. In 1996 over 95% of all TFT LCD production was made in Japan, but ten years later in 2005 Japan accounted for 11% of production, with South Korea and Taiwan producing approx 40% of the total global market each (Hart 2008).

To gain an overall picture of this global movement, and also the evolution of the industry, Figure 3 shows the global distribution of US granted patents in the technology class 349 (Liquid Crystal Cells, Elements and Systems) from 1969-2007. The first patent was granted in 1967 to RCA in the USA. Further patents to RCA, Westinghouse and IBM followed in 1970, with the early years of the LCD technology evolution progress confined to the USA.

Although the US played a prominent role in these early years, as signified by the patents, the field of Liquid Crystal research was an international one, by 1977, ten years after the first patent was granted to RCA, half of all patents granted by the US patent office were to foreign applicants.

This international distribution and contribution of individual countries by year is shown in Figure 4. Japanese activity starts in the early 1970s coinciding with the launch of the first LCD applications – the pocket calculator and then a few years later the digital watch. UK and European activity is also evident in the 1970s[2]. Japanese activity continues to strengthen throughout the 1980's and 1990's, whilst US activity decreased in terms of overall patenting numbers. There is a clear shift in the knowledge base of the technology to Asia. This is reinforced with the increasing activity of South Korea and Taiwan in the last decade.

[1] In writing this case study and the story of the technological emergence of LCDs three texts were key in providing the personal points of view to the technology's evolution; Castellano, J. (2005). Liquid Gold: The story of of LCDs and the creation of an industry. New York, World Scientific., Johnstone, B. (1999). We were burning: Japanese entrepreneurs and the forging of the electronic age. New York, Basic Books., Kawamoto, H. (2002). "The History of Liquid Crystal Displays." Proceedings of the IEEE 90(4): 460-500.

[2] The focus of much European work, particularly in the UK, was on developing effective liquid crystal materials. European firms have dominated the international market for basic LC materials Imakita, J. (1981). "A comparative market survey of liquid crystal displays: the United States, Japan and Europe." Displays October: 331-336.

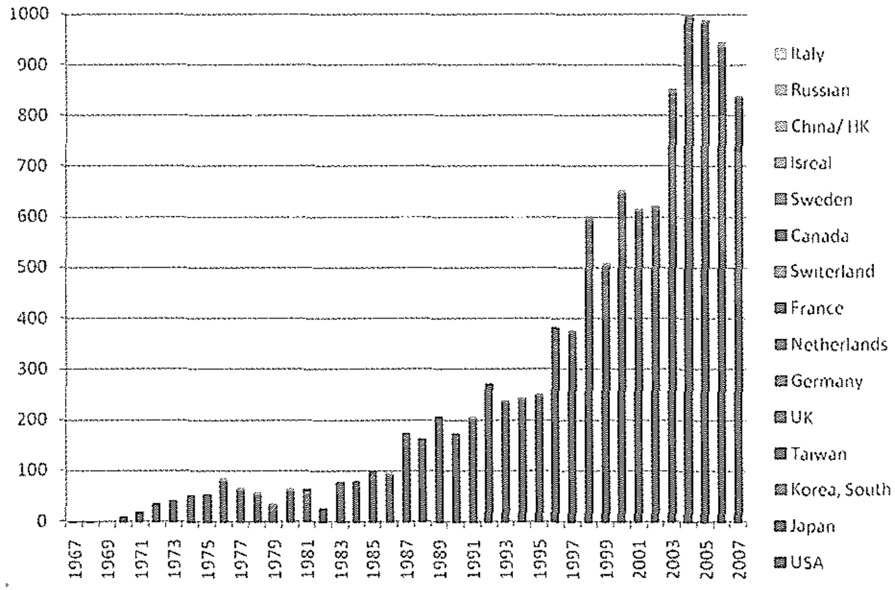

Figure 3: US patents granted in Liquid Crystals (class 349) by country (1st inventor) by year

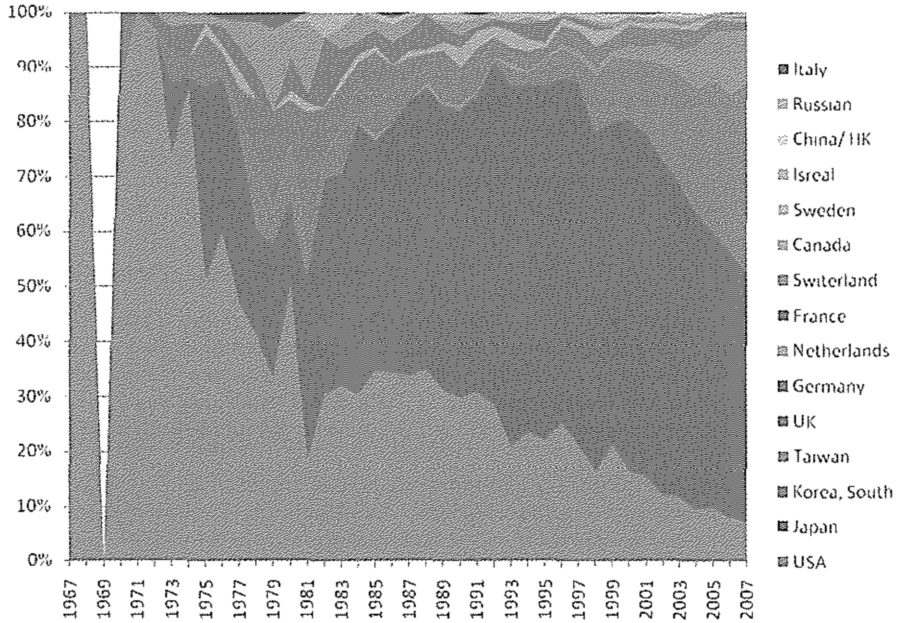

Figure 4: % contribution of LCD patenting countries (1st inventor) by year (US Patents)

The discovery of liquid crystals

The participation of a number of countries in LCD research and development reflects the international basis for the development of the science behind LCD. Liquid crystals were first discovered by a Czech scientist in 1888. Friedrich Reinitizer was working at the Institute of Plant Physiology at the University of Prague. He was conducting work on the cholesterol of carrots and found the material appeared to have two melting points, one at 145.5c, where the solid melted into a cloudy liquid, and then at 178.5c when the cloudiness disappeared to give way to a clear and transparent liquid.

Reinitizer's friend and physicist Otto Lehmann from the Technical University of Karlsruhe coined the term 'Flussige Krystalle' or 'Liquid Crystals' on noticing that the cloudy liquid had some properties of a solid crystal (regular structure of the crystals) and others of a liquid (no set shape). A French scientist Charles Mauguin first theorised the twisted nematic (TN) liquid crystal structure in 1911.

The TN structure formed the basis of liquid crystal technology and its application to displays, but this was a connection that would not be made for another sixty years. Liquid crystals continued to be researched for the next few decades in universities throughout Europe, but when no useful application could be found for the materials, their popularity waned to such extent that by the post WWII period LC research was virtually non-existent (Johnstone 1999).

Linking the science to applications

Two critical publications marked the beginning of the resurgence of liquid crystal research. In 1958 Glenn Brown[3], an American chemist published an article in Chemical Reviews on the liquid crystal phase that subsequently sparked international interest in liquid crystal research. Shortly afterwards, a leading scholar in liquid crystal research during this period, Prof George Gray of the University of Hull[4] published a book on liquid crystals. In an attempt to bolster interest in the field, Gray authored the first book in English on liquid crystals in 1962 called Molecular Structure and the Properties of Liquid Crystals. This book had the affect of codifying much of the scientific knowledge around liquid crystals and communicating the field to an audience beyond organic chemistry. As Joe Castellano[5] noted "...before its publication students of organic chemistry at most US universities did not know what a liquid crystal was" (Johnstone 1999, p.95).

Both Brown's and Gray's publications meant that when potential applications for liquid crystal materials in displays began to emerge in strength in the late 1960s researchers had ready access to the 'start of the field' information.

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[3] Born in Logan, Ohio, on September 10, 1915, Glenn received his BS (1939) at Ohio University, his MIS (1941) at Ohio State University and his PhD (1951) at Iowa State University. He taught Chemistry as an instructor at the University of Mississippi (1941-1942) and as an assistant professor at the University of Vermont (1950-1952). He then moved to the University of Cincinnati where he was promoted to associate professor and taught Chemistry (1952-1960). In 1960, he came to Kent State University as a professor to head the Chemistry Department where he successfully built a PhD program. He served as Chairman from 1960-1965, as Dean of Research from 1963-1968, and Director of the Liquid Crystal Institute from 1965-1983. He became Kent's only Regent's Professor in 1968 (Neubert 1995)

[4] George Gray started researching liquid crystals in 1947 as a lecturer at Hull University. He went on to receive his PhD from the University of London in 1953. He returned to Hull after completing his PhD and continued to research liquid crystals, writing *Molecular Structure and the Properties of Liquid Crystals* in 1962 and working with the MoD from 1970 onwards (Kawamoto 2002).

[5] Joe Castellano was a chemist at RCA in the period 1965-1975. He was part of the initial RCA team that completed early research of LCDs and their initial application in electronic calculators and watches. He went on to found a LCD start-up and an LCD technology consultancy. He authored the book Liquid Gold the story of an industry in 2005.

RCA and the discovery of LCD

At the same time as Gray's book was being published one researcher at RCA laboratories[6] (later known as the Sarnoff Centre after General Manager David Sarnoff) in Princeton, Richard Williams, began experimenting with liquid crystals and their electro-optical properties. RCA had a keen focus on television technology (having developed television in 1939 and colour television in 1953), and a long standing ambition to create a 'TV on the wall'. Williams was quoted by Johnstone (1999, p.95) "…the idea that there should be a flat display and that that would be a good idea was not a discovery, it was something that was obvious to anyone working at Sarnoff. The question was could anyone make one work?"

Williams' domain

Williams' experiments showed that the electro-optic characteristics of liquid crystals could generate an effect (stripe patterns) when voltage was applied. This effect was caused by electro-hydrodynamic instability forming in the liquid crystals – the effect came to be known as 'Williams' domain'. Williams posited that these effects could be used to create electrically operated displays, and wrote up his research and applied for a patent. The research was not published until 1963, and the patent granted in 1967. Shortly after the patent application was lodged Richard Williams left RCA New Jersey to take up a sabbatical at RCA's Swiss research facility. It was when he was in Switzerland that he was invited to give a presentation on liquid crystals to Swiss Watch Institute in Geneva (Johnstone 1999). This link to Switzerland would be reinforced by later Swiss work on liquid crystal displays, particularly with watch applications in mind.

R&D labs

> *"During these golden years of the 1950's and 1960's, both labs (GE and Westinghouse) did very good basic research. Just as good, if not better than, their researchers like to think, than of any university"* (Johnstone 1999, p.98)

The industrial research and development of the US in the post WWII period was a watermark period in the history of micro electronics – during this period the semiconductor was created along with host of other micro-electronic developments that were the predecessors of many of technologies that are ubiquitous to us today. The major labs were AT&T's Bell Labs ("undisputedly top of the ladder" (Johnstone 1999)), RCA's Sarnoff Centre, and the R&D labs of major corporate such as Westinghouse, General Electric (GE), Texas Instruments and International Business Machines (IBM).

Interdisciplinary research was also a new concept. Until the early 1950s R&D had usually progressed through fields of research, rather than interdisciplinary teams. The Manhattan Project (US effort to develop and build the first nuclear weapons during the Second World War) has been referred to as "the first time that physicists, chemists and engineers worked together for a common goal" (Castellano 2005, p.9). The early stages of LCD research also benefited from this interdisciplinary interactivity between organic chemists, physicists and electrical engineering (Heilmeier 1976).

Guest-Host and the dynamic scattering mode (DSM)

A young scientist at RCA, George Heilmeier[7], seeking to work on something big[8] switched from solid state microwaves to the field of organic semi-conductivity (Heilmeier 1976). Heilmeier continued research into William's work and completed further experiments in 'doping' the liquid crystals with dichotic dye. This 'doping' enabled with the application of voltage, immediate and dramatic cell changes on a display. This became known as the Guest-Host-Effect.

The Guest-Host effect was imperfect. The liquid crystals and the dyes were not stable over long periods of time; they were sensitive to surface effects and required heating to maintain the nematic state (Kawamoto 2002). This led to two avenues of further work at RCA. Firstly in applying a field-effect that was effective in reflecting light, the Dynamic Scattering mode (DSM) being the end product. Secondly in producing more stable, room-temperature liquid crystal materials (organic compounds referred to as Schiff's bases were the most effective), which was also achieved by RCA scientists. This allowed the first LCD prototypes to be created; an electronic clock, LC cockpit display and liquid crystal readout display (Kawamoto 2002).

Heilmeier was quoted discussing his discovery "You take two pieces of glass with a transparent conductive coating on them and you put the liquid crystal between the two pieces of glass, with a thickness of, say, 25 microns. Then you apply an electric field, and lo and behold: very interesting things happen," he says, "I thought 'This might make this a very interesting display device.' By golly, you could change colours with a relatively low voltage - which would suggest that integrated circuits could do the addressing" (Metz 2009).

A prototype device was built, tested and displayed to RCA senior management. Management deemed the LC research to be confidential and therefore no more publications were to be written on the research or discussions to take place with external parties with the RCA scientists until 1968, when RCA launched liquid crystal displays to the worldwide media.

"When RCA announced, the world listened. The corporation was famous for its great leaps forward. There had been the television itself, unveiled by David Sarnoff at the 1939 World Fair in New York. Fifteen years later came the colour TV, launched in 1953 with a media blitz that included enormous print advertisements and lavish special broadcasts on RCA's own network NBC….on the 28th May 1968 some fifty reporters, photographers and network camera crews crowded into the conference room in the RCA building at 30 Rockefeller Plaza to behold the unveiling of the television of the future" (Johnstone 1999:p8)

RCA's announcement elicited an immediate response from firms around the world. Liquid research programs in the US, Europe and Japan were commenced, or reinvigorated, as a direct result of the RCA announcement. The case study now turns attention to some of these other critical parties.

[6] RCA – Radio Corporation of America was founded in 1919 by General Electric (GE) as a publicly held company with GE as the controlling shareholder. The company was formed to create a monopoly on radio technology in the US through government support and navy radio assets, the purchase of the US operations of UK based Marconi Wireless and cooperation from AT&T, United Fruit and Westinghouse in pooling their patents in radio technology Aitken, H. (1985). The continuous wave: Technology and American Radio 1900-1932. Princeton, NJ, Princeton University Press.. The end result was government created monopolies in radio for GE and Westinghouse and telephone for AT&T. RCA Laboratories was established in 1941 in Princeton, New Jersey. Technologies such as colour television, the electron microscope, CMOS based technology, video cassette recorders and LCDs

[7] George Heilmeier completed his PhD at Princeton University 1961 while working at RCA Laboratories. Heilmeier left RCA in 1970 to become a White House Fellow, becoming a special assistant to Secretary of Defence, then in 1975 running DARPA (Defence Advanced Research Projects Agency) and then CTO for Texas Instruments in 1983.

[8] Heilmeier was described as an ambitious, young scientist, "…unlike Williams, who was something of a loner, Heilmeier was out to make a name for himself beyond scientific circles" (Johnstone 1999.p: 97). He moved into research on Liquid Crystals after working in solid-state microwave devices, looking for a more 'fascinating and risky' (Kawamoto 2002.p:465) field of research and attracted to the experiments of Richard Williams.

Other players in LCD research

Kent State and the Liquid Crystal Institute

Kent State University in Ohio established the Liquid Crystal Institute in 1965 under the directorship of Dr. Glenn H. Brown, author of the critical 1958 paper on liquid crystals (Kent State University 2009). The Institute started with one graduate student and $21,000 in annual funding (Neubert 1995) and further grants from the National Institutes of Health, the National Science Foundation, and U.S. defence agencies. The Institute held the first International Conference on liquid crystal research in 1965.

James Ferguson[9] who was researching liquid crystals at Westinghouse, initially for use as thermal sensors, was heavily influenced by the RCA 1968 announcement and Richard Williams' work and Ferguson switched his attention to displays. When Westinghouse stated they were not interested in display applications, considering them to be outside of their core offering (heavy electrical equipment) Ferguson joined the Liquid Crystal Institute at Kent State University[10].

Ferguson was not to remain at Kent State for long, the late 1960's university campus was politically active and "industrial applications" were dirty words (Johnstone 1999)[11] particularly if they were sponsored by US defence agencies, as was the case for his work. However the research Ferguson conducted during his time at Kent State would become one of the turning point advances in liquid crystal display technology – the twisted nematic structure. The twisted nematic structure refers to the orientation of the liquid crystals, by rubbing the glass in which the liquid crystals are sandwiched between, one of the sheets of glass is then 'twisted' 90 degrees, so the LC molecules form a helix, and light can be switched on and off by twisting around the helix (Johnstone 1999).

Ferguson left Kent State after a shooting incident at the university (see note 11) and founded a start-up company – ILIXCO. He had already completed and documented his experiments regarding the twisted nematic (TN) LCD structure, whilst at Kent State University. He did not file a patent application for the TN discovery until February 1971. This delay marked a controversial period in LCD development. Two researchers Wolfgang Helfrich[12] and Martin Schadt at Hoffman La Roche in Basel, Switzerland filed a patent application for the TN LCD structure with the Swiss patent office in December 1970. They published their research in a paper in *Applied Physical Letters* four days later. Ferguson's delay in applying for a patent, despite his detailed record keeping of his experiments dating back to 1969 led to an extensive legal fight over ownership of the patent. This was complicated further by Kent State University claiming a right to Ferguson's patent because part of the research was completed when he was still at the University. A legal battle between a multinational and a small start up is always going to be a one-sided affair. The dispute was settled out of court with Hoffman La Roche purchasing Ferguson's patents. However, according to Ferguson La Roche only made one of the promised two payments, but Ferguson's company ILIXCO was unable to fund further legal action (Kawamoto 2002).

The UK Liquid Crystal Programme – new LC materials and reverse tilt, reverse twist discovery

RCA's 1968 announcement of LCD was a turning point in the UK liquid crystal research community. As with many other researchers RCA's announcement showed the potential of what had up until this point been only of interest out of academic curiosity. This is highlighted in the following quote by Prof. George Gray and his research, "This (RCA's announcement) changed the attitude of the University towards his research (Gray's). His research became a shining example of collaboration; it was not 'blue sky' research any more, but its success owed everything to the earlier 'blue sky' research on materials, before devices were conceived" (Kawamoto 2002, p.478).

Although the RCA announcement was a boost for LC research globally, a more specific issue was at the core of the first UK government sponsored LC research program – the high cost of royalties the UK paid to RCA for shadow-mask colour TV tube as recounted in the quote below (Kawamoto 2002). In 1967, the new Minister of State for Technology, John Stonehouse[13] made his first visit to the Royal Radar Establishment (Rothaermel and Boeker 2008), the technology research arm of the British Armed Forces at Malvern UK.

"His conversation with RRE Director George MacFarlane ranged over many topics including the financial returns from inventions. MacFarlane pointed out that the UK paid royalties to RCA on the shadow mask colour TV tube which were more than the development costs of the Concorde. Early the next morning, he (Stonehouse) rang the director saying he was convinced that the UK should mount a program to invent a solid-state alternative to the shadow mask tube" (Kawamoto 2002, p.478).

At the Minister's insistence a working party into solid state research was established. The director of this program was Cyril Hilsum[14]. He was determined that any flat panel display research program should included LCD research. The flat panel display working party supported research on LEDs, electroluminescence and LCDs[15]. Two years later a consortium program was established for firms interested in making and using liquid crystals. Prof George Gray at the University of Hull was offered a two-year contract with the Ministry of Defence to work on "substances exhibiting liquid-crystal states at room temperature" with a budget of £2177 per annum (Kawamoto 2002). The Hull/RRE program started in 1970 with Prof Gray and one post doctoral student, and quickly expanded to include two other scientists, Peter Raynes and Ken Harrison, who

[9] James Ferguson first started working with liquid crystals at Westinghouse Research Laboratories in Pittsburgh, using LC for temperature sensors which had some initial applications in breast cancer diagnosis. After Westinghouse were not interested in progressing LCD research, Ferguson moved to the new Liquid Crystal Institute at Kent State University. He left Kent State in 1970 to found a start-up company ILIXCO to develop TN LCs for digital watches. Ferguson has over 500 patents in the LC field.

[10] Westinghouse was also to turn down another major technological advance in LCD, researcher T. Peter Brody built the first active matrix driven LCD, but this would be commercialised by Japanese firms.

[11] Kent State University was the site of the 4th May 1970 shooting of students by the Ohio National Guard – 4 died and 9 were injured. Students were protesting about the Vietnam War, particularly the recently announced incursion of US troops into Cambodia, announced by President Nixon on the 30th April 1970.

[12] Wolfgang Helfrich had immediately prior to his work at Hoffman La Roche, been employed at RCA in the LC team. He acknowledged that much of the thinking for his TN work occurred at the time when he was located at RCA, who at the time where winding down their LCD program, but it was only when he started work with Martin Schadt that they put the concept together.

[13] Shortly after Stonehouse initiated the LC research program, his clothes were found on a beach in California. He was considered to have committed suicide by drowning, only later to be discovered living with his former secretary in Australia. He eventually found himself in jail for having confiscated funds from a company of which he had served as one of the directors. (Kawamoto 2002).

[14] Cyril Hilsum was born in 1925. He completed his B.Sci at university College London in 1945, and then joined the Royal Naval Scientific Service. He moved to the Admiralty Research Lab in 1947, then to the Services Electronic Research Lab in 1950 and then the Royal Radar Establishment in 1963, where he remained for twenty years. In 1983 he was made Director of Research at GEC Hirst Research Centre. His time at military R&D labs, Hilsum was credited with supporting LCD research in the UK and bringing in £100m in government support over the three decades of LCD development. The British Liquid Crystal Society awards the Cyril Hilsum medal annually to the British candidates for overall contributions to liquid crystal science and technology.

[15] Cliff Jones, interview with author June 2009.

were based at the Royal Signals Research Establishment (RSRE) at Malvern.[16]

Gray's work at Hull was focused on developing new liquid crystal materials while Raynes' work theorised about important elements of liquid crystals in the TN structure. Raynes work lead to two important discoveries that increased the effectiveness of how the TN structure works; the reverse twist and reverse tilt. Raynes designed a solution to correct the twist and tilt (which had the effect of increasing the contrast of a display), as well as an equation which predicted the necessary properties of the LC mixture.

These discoveries were critical to the success of liquid crystals as a display technology. Together with the new LC materials (cyanobiphenyls) being synthesized by Gray and his team at Hull, it genuinely made liquid crystal displays a viable commercial prospect. "Hull and RRE were conscious that they had control of something with commercial value. The consortium documents were immediately marked 'commercial-in-confidence' and code words were issued to describe the materials (Kawamoto 2002, p.479).

In 1972 the Hull/ RRE research team took the first steps towards commercialising their research. Members of the research consortium were keen to access the new cyanobiphenyls developed by the Hull team and demand soon outstripped their ability to produce them. The British Drug House (BDH) was approached to manufacture the compounds under licence for the research program. BDH agreed and delivered their first sample in early 1973. As with many research and development programs, the operation of the liquid crystal materials in the lab differed to that when commercial production quantities were involved. BDH, and particularly Ben Sturgeon, worked at the materials and made improvements that increased their effectiveness and made them more manufacturable[17].

Even with this external manufacturing arrangement demand from consortium members for the new liquid crystal materials increased rapidly. Soon BDH was struggling to keep up with orders from the consortium for materials as well as approaches from several other manufacturers to produce the chemicals under licence. The situation was complicated further in September 1973 when BDH was sold by its parent company Glaxo to the German firm to E. Merck of Darmstadt. The Ministry of Defence was immediately concerned that BDH's sale to Merck would jeopardise the LC research and its commercial production. Merck had its own LC research group and sold their own LC compounds. Despite these concerns it was market difficulties rather than issues with new parent company Merck that plagued BHD.

Despite the demand for materials from the consortium partners, actual sales to other firms did not eventuate as expected. Many of the international display manufacturers that were producing LCDs had specific processes relating to their mixtures and they were reluctant to change, hoping that they themselves could resolve the deficiencies with their own mixtures rather than buy in new ones and have to change all the other associated manufacturing processes. In the first six months only 150g were sold in the USA and slightly less in Japan. One scientist noted, "Ironically persuading people to buy something clearly superior to anything they had used previously seemed very difficult. For scientists the commercial world is most strange" (Kawamoto 2002, p481).

[16] RSRE, initially the Royal Radar Establishment and founded in 1953, it merged with the Signals Research and Radar Establishment in 1976 to form the Royal Signals and Radar Establishment. This in turn became the Defence Research Agency (DRA) in 1991. IN 2001 DRA was split into two organisations; a government agency – the Defence Science and Technology Laboratory (DSTL) and a company later privatised, called QinetiQ. QinetiQ went on to complete new research into zenithal bi-stable liquid crystals.

[17] Cliff Jones, interview with author June 2009.

The focus of the RRE/ Hull team turned from discovery and development of the liquid crystal materials to supporting the marketing effort of BDH in selling the materials. The sales team at BDH was not familiar with the physics problems presented by LCD (Kawamoto 2002). By this time the focus of the LCD market had moved from the US to Japan, therefore securing the Japanese market was critical. By 1975 Sharp was using the cyanobiphenyls, having signed an agreement to purchase 1 tonne of the materials per annum. The following year they introduced a pocket calculator based on cyanobiphenyls in the TN mode. Seiko soon followed suit using the materials in their digital watches.

Despite a slow start with establishing market traction and developing the reputation of their LCD materials by 1977 BDH was the largest manufacturer of LC materials in the world and biphenyls were their best selling product. The cyanobiphenyls were also licensed by the UK MoD to Merck in Germany (despite their initial concerns) and Hoffman La Roche in Switzerland. BDH's leadership position in the market for LC material was to be short lived; the cyanobiphenyls were soon displaced by LC materials developed by Merck.

Super-twisted effects

The twisted nematic patent was owned by Swiss firm Hoffman La Roche. They were working in partnership with Brown Boveri and Company (BBC)[18] who had an active liquid crystal research program. In 1978 researchers at BBC developed the 'supertwisted bi-refringement effect' LCDs, which became known as the STN-LCDs[19] (Castellano 2004).

At the same time Peter Raynes, Colin Waters and V. Brimmell from RSRE were also investigating super twisted structures, initially for the 'Guest-Host' effect (discovered by Heilmeier at RCA) which they completed and patented in 1982. In this patent they also noted that this super twisted effect could be applied to nematic structures as well. The UK work predates the Swiss work by some 12 months; BBC applied for their patent in 1983. Controversy erupted over which team should be credited for the initial discovery of the super twisted effect.

Castellano (2004) and other cite the BBC team as the inventors because they came up with the first practical working device (Castellano 2004, p.151). Indeed BBC researcher Terry J Scheffer, was awarded the Society for Information Display's 'Jan Rajchan prize' in 1993 for the STN-LCD. However the RSRE super twisted effect patent by Raynes, Waters and Brimmell is the largest royalty generating single patent for the UK government[20], suggesting that the intellectual property leadership came from the UK.

Merck and the development of phenyl cyclohexanes

Merck has been involved with LC since 1907, but again it was the RCA announcement in 1968 that kicked things off for Merck as well. Merck, being a pharmaceutical company was interested in the LC compounds and in 1970 they produced room-temperature LC mixtures for display applications. A decisive breakthrough came in 1976 with the

[18] The twisted nematic and super-twisted LCDs were a big success for BBC, but they were not to remain in the LCD market for long. They exited the LCD business in 1984, apparently "scared off by the size of the opportunity" (Castellano 2004, p.151). They sold their interest in *Videlec*, the joint LCD manufacturing company that it formed with Philips in 1980.

[19] Super twisted nematic displays are a type of monochrome passive matrix LCD. They have more contrast than a TN display. This is achieved by twisting the liquid crystal molecules from 180 to 270 degrees. STN-LCDs require less power, are less expensive to manufacture than TFT-LCDs, although they have poorer image control and refresh speeds lower than TFT driven LCDs.

[20] Cliff Jones, interview with the author June 2009.

synthesis of a new LC family – phenyl cyclohexanes. These were similar to the cyanobiphenyls that were being made by BDH (which Merck acquired in 1970) but these materials were superior in that they had a lower viscosity (rapid time response) and smaller bifringent effects. These materials were used in TN mode LCD and later in active matrix TFT displays.

In the 1990s Merck would again develop a further family of liquid crystal materials with faster response times. These new materials would maintain Merck's position within the market for liquid crystal materials in the commercialisation of active-matrix LCDs.

The development and production of these liquid crystal materials meant that Merck was one of the few companies to truly profit from the LCD revolution. Cut throat competition in consumer electronics and economies of scale increasing the size and scale of display production meant that although display manufacturers invested billions in plants and employed thousands of people, actual profits were relatively small in terms of the scale and risk of investment. Merck as a component manufacturer and also 3M (manufacturer of specialist polarised films for the LCD glass panels) were protected from this end consumer competition and had dominance in their repective component manufacturing, allowing them to profit[21].

First wave of commercialisation – calculators and digital watches

The first mass market application of liquid crystal display technology was the electronic calculator. As has already been noted the 1968 RCA announced of the LCD progress had spurred many other competitors into LC activities or increased company's focus on their current activities. The Japanese watch manufacturer Suwa Seikoswa[22] was one of the first firms to negotiate licences to use RCA technology.

With the advances both in the TN structure and the liquid crystal materials, commercialisation of LC into applications progressed quickly in two areas; pocket calculators and digital watches. In both cases it was Japanese firms who were at the forefront in bringing these products to market.

RCA, despite playing a major role in establishing the early technological base of LCDs and ensuring it captured the display industry's imagination faced a major decision with regard to its continuing participation in research and development on liquid crystal displays. RCA held the dominant market position in cathode ray tubes (CRT) and had major investments in silicon based technologies. RCA's commitment to LCDs had up until this point in time focused on research, and much of this government sponsored research (through DoD, Navy, Air Force). In order to develop a product, serious resources would need to be committed to develop pilot manufacturing capability.

The reasons for RCA's reluctance to continue in the LCD arena are varied. Some members of the RCA LCD research team noted that management was worried about LCD potentially taking revenue away from the CRT market. According to Heilmeier "The people who were asked to commercialise (the technology) saw it as a distraction to their main electronic focus (CRT)" (Wall Street Jour. 1993)

Others acknowledged that they simply could not dedicate the resources that full commercial applications would demand. Richard Williams, when recalling the early days, has said "If it had continued that work, RCA would have never achieved a commercial

[21] Cliff Jones, interview with the author, June 2009.
[22] Suwa Seikosha was an affiliate of Hattori and Co (now Seiko Corporation). The firm developed and launched the first quartz watch launched onto the Japanese market in 1969.

success. It had to await the development of liquid crystal materials and amorphous silicon (a-Si) technologies, both of which were yet to come from Europe. Those developments altogether have taken a quarter of a century" (Kawamoto 2002, p.468).

Executives from Sharp Corporation[23] visited RCA labs to examine the LC research and assess its potential for use as a display in a pocket electronic calculator. Sharp Corporation asked RCA to go into production of DSM LCD pocket calculators, even offered to pay for the development, but RCA was only interested in using DSM LCDs for digital watches in partnership with Timex Corporation. If Sharp was to use liquid crystals for their pocket calculator they were going to have to make them, Sharp launched their LCD research program in 1970 (Castellano 2005).

Sharp set up a special team of researchers to develop the pocket calculator – the multidisciplinary team was given 18 months (instead of the usual 3-5 years standard in Sharp for new product development (Johnstone 1999) to develop a working prototype. In April 1973 they completed the project on time, and in May 1973 Sharp launched the Elsi-Mate EL-805 pocket calculator. The calculator was an immediate success and the first commercial application to successfully use a LCD.

Watches

In addition to working on calculator products Sharp also considered LCD to be suitable completed for other small area displays – such as those in watches. Light emitting diodes (LED) had been used previously in watch applications but proved disappointing, with high power consumption and users needing to press the LED light to illuminate the watch every time they wanted to look at the time.

Of all of the early LCD applications RCA investigated digital watches in the most detail. They entered into a partnership with Timex to develop a pilot manufacturing of digital watches based on DSM. The partnership did not last long, and RCA exited LCD manufacturing, selling all of their manufacturing assets to Timex. The early 1970s marked the period when the original RCA LCD research team began to break up. Heilmeier left RCA to become a White House fellow[24], Louis Zanoni left to found a start-up Optel Corporation with a number of other RCA researchers to commercialise digital wrist watches (which they achieved in 1971) (Castellano 2005).

Other early attempts to manufacture digital watches based on the DSM were not a success; there were reliability issues with the LC materials (they degraded quickly) and the DSM. Commercial success would have to wait for displays based on the twisted nematic (TN) mode. In 1973 Seiko became the first to market with a TN watch when they announced the digital LC watch 06L. These watches were the first commercial success for LC in the watch market. Reliability of the digital watches was increased when the LC cyanobiphenyls from the UK became widely available, "with the TN mode and the cyanobiphenyls the LC watch industry took off" (Kawamoto 2002, p.485).

[23] Sharp Corporation (originally Hayakawa Metal Industrial Laboratory) was founded in 1912. The firm is one of Japanese oldest consumer goods manufacturing firms. Inventor and founder Tokuji Hayakawa gained commercial success with the invention of the immensely popular mechanical pencil called 'Ever-Sharp'. The firm was all but destroyed in the 1923 Great Kanto Earthquake and only re-established and incorporated in the late 1920s, when development started on Japan's first domestically produced crystal radio. In the 1950s Hayakawa introduced the first commercial television set under the brand name 'Sharp' in acknowledgement the earlier mechanical pencil. In the 1970 Hayakawa resigned from day-to-day operations. In the same year the company reorganised, changing its name to Sharp Corporation and the establishment of Sharp's massive R&D lab – Tenri. Sharp went on to become the world leading in LCD technology.
[24] US Government training scheme for external experts to become White House Advisers

The active matrix – The TV on the wall

The next major technological advance in the LCD industry was concerned with the power supply of the LCDs. The active matrix would bring together LCD with amorphous silicon thin film transistors (TFT). These TFTs would replace the bulky CRT and enable the vision of the 'TV on the wall' to be achieved (Florida and Browdy 1994).

The first LCD driven by TFTs was developed by T. Peter Brody[25] at Westinghouse Research Laboratories in 1972. By this time Westinghouse was one of the only large US corporate still actively pursuing LCD research. RCA was winding its research program down, as were GE, Hughes Aircraft Company and IBM. Westinghouse's interest was not to last long, the firm was already feeling the effects of competition on their semiconductor and television businesses. Senior management found the technology development timelines of developing the TFT LCD too long, a management committee decided to end the TFT-LCD program in 1979 (Florida and Browdy 1994)[26].

Brody decided to commercialise TFT-LCD himself, founding Panelvision with \$1.5m of investment from 3M[27] and \$4m from a group of venture capitalists (Florida and Browdy 1994). This allowed Brody to set up a manufacturing facility. The venture capitalists also installed three new managers to help Brody run the company. The company experienced many of the early difficulties of high technology firms; difficulties in finding the right management team mix, identifying customers and developing suppliers. However by 1984 the firm was selling products and had eighty customers. Panelvision had received a further \$13m in venture capital investment over 6 rounds.

Despite revenue and continued VC investment, Panelvision had difficulty achieving profitability. It needed to manufacture on a larger scale to be worthwhile. A plan was devised to set up a large scale manufacturing facility; \$5m in development capital was required to build the facility. At the same time the Japanese firm Seiko introduced a colour pocket TV into the US even though they were infringing Westinghouse's original active matrix patent. This had the effect of scaring the investors[28] who were already weary of putting more money into the firm. Instead the investors decided to recoup their investment; Panelvision was sold to Litton Industries in 1985 who were seeking to develop and use the technology for aircraft cockpit displays.

Brody tried again to commercialise the active matrix LCD, founding a second firm; Magnascreen in 1988 but this again was thwarted by venture capitalists and Japanese competition. In retrospect, venture capital was an unsuitable method for financing a display manufacturing firm. The capital cost to development manufacturing capability that was commercially viable was large, and beyond what a VC would invest into a small start-up.

[25] T. Peter Brody joined Westinghouse Research laboratories in 1959 after completing his PhD in theoretical physics at University College London. Brody spent 12 years developing TFT technology for displays, firstly in electroluminescence, then LCD. Brody left Westinghouse in 1979 when decided against pursuing flat panel displays (Kawamoto 2002). He founded Panelvision in 1981 to commercialise AM LCDs with VC investment. Panelvision was sold to Litton Industries in 1985 by the VC investors.
[26] In this section I draw on extensively on Florida, R. and D. Browdy (1994). "The invention that got away." Technology Review 94(6).
[27] 3M were interesting in corporate venturing in LCD because they supplied the industry-leading polarising film for the display's glass panels.
[28] The threat of Japanese competition was cited by a number of firms as a reason for discontinuing their R&D programs and in each case does not seem to be based on empirical evidence.

Second wave of commercialisation – Televisions and laptops

A number of Japanese firms were also attempting to develop colour LCD driven by a TFT-LCD. Sharp, Daini Seikosha and Seiko Epsom[29] were all conducting research into TFT-LCD. Sharp followed the work of Spear and LeComber at the University of Dundee. The University of Dundee research team were developing amorphous silicon semiconductors (Madan 2006). Amorphous silicon had many advantages as a power source, it was more power efficient and operated at lower temperatures and could be fabricated on ordinary glass substrates, making it less expensive.

In 1981 LeComber demonstrated a TFT 7x5 inch array. In 1982 he visited Sharp in Japan to talk about the amorphous silicon technology, primarily to discuss its application to solar cells but the link to LCD was quickly made (Kawamoto 2002). Sharp quickly incorporated the technology into their work on TFT LCDs. Sharp announced the first 14-inch TFT LCD unit in June 1988. The TV on the wall was now a reality. At the time of this announcement Heilmeier was quoted in the Wall Street Journal, "I think you need to give the credit to the people who preserved and worked on LCDs for 25 years" (Wall Street Journal 1993).

The same technology would be integrated into portable laptop computers. With no US based LCD manufacturers US computer companies entered into production arrangements with Japanese manufacturers, Hoshiden made screens for Macintosh, Sharp for Texas Instruments and Toshiba Display technology for IBM (Florida and Browdy 1994).

Third wave of commercialisation – Large area displays

The next wave of commercialisation of LCD applications was around increasing the size of the displays. This required innovations in materials, manufacturing techniques and glass substrates, "Subsequent R&D has been focused on scaling the characteristic parameters of panel size, picture resolution, viewing angle, colour capabilities, weight, power consumption, ruggedness and manufacturing costs" (Stolpe 2002).

The early 1990s marked the start of this period of development of large screen displays. Large area displays now dominate the LCD industry. Japan enjoyed an early dominance in this market as well, with 95% of market share in the high volume, large format display industry in 1990 (Asakawa 2007). Japan's dominance has since reduced, currently it accounts for about 15% of the market with Taiwan and South Korea accounting for 40% each (Asakawa 2007).

There are various reasons used to explain Japan's decreasing market share of the large format LCD market. One of the most prominent is the Japanese recession in the early 1990s (which allowed South Korea into the market) and the Asian financial crisis in 1998 (which allowed Taiwan to enter the market) (Hu 2008). Both South Korea and Taiwan's entered into the large format LCD manufacturing industry with the assistance of Government programs aimed at 'catching up'. The most critical aspect of government support in these countries was financial support in setting up fabrication plants in Korea and Taiwan, rather than the assistance in knowledge transfer (Hu 2008). Japanese firms had well-established links with Taiwanese firms; Japan is the main source of foreign director investors into Taiwan in electronics, precision machinery and automotive industries (Wang 2006). This suggests that good knowledge transfer options already existed in the case of Taiwan.

[29] Dani Seikosha and Seiko Epsom were both subsidiaries of Hattori & Co (later Sharp Corporation in 1983)

Ongoing work in bi-stable passive matrix LCDs

Televisions and laptop computers rely on active matrix power supply driven by TFTs. The discussion on super twisted LCD effects highlight a group of passive matrix LCDs that had lower power consumption and manufacturing costs, but poorer image control and refresh speeds that TFT driven LCDs.

Passive matrix displays are not suitable for TVs and laptops as the images changes too frequently for the benefits to outweigh the disadvantages, but for displays where image control and high refresh speed are not priorities, passive matrix displays are ideal. Such applications include signage, screens and labelling.

DRA, the defence research agency in the UK, continued ongoing research into these types of bi-stable passive matrix LCDs through the 1990s. The research was largely funded by the royalty revenue from the STN patent. A major development was the discovery of zenithal bi-stable nematic LCDs. These displays use grated instead of rubbed layers on the glass substrate containing the liquid crystal material (Jones 2007). The technology was patented in 1995 with the first prototype devices developed in 1997. The technology is currently being commercialised by ZBD Solutions, a start up firm that spun out from DRA in 2000[30], just prior to DRA's split into a government agency and a private firm QinetiQ.

ZBD solutions products are zenithal bi-stable LCD for retail shelf labels. They are currently in final customer trials in different retail environments across Europe. The company has been funded by a consortium of UK venture capital funds including TTP Ventures and Dfj-esprit as well as from corporate sources; Dow Chemical Group and QinetiQ.

Conclusions

This paper has presented a case study of the development of liquid crystal display technology. The study focuses on the early technological development of LCDs in R&D laboratories in the US, primarily RCA. Much of this work was supported by military R&D contracts and the resources of (then) the US top corporations. Yet the US failed to capitalise in terms of industrial employment and exports, on their early scientific investments. This pattern was repeated again in the 1980s with the development of the active matrix driven LCDs.

The UK government also invested in the development of liquid crystal materials in the 1960s and 1970s (although not to the same level as the US). This led to a dominant position in the global supply of liquid crystal materials and the creation of key intellectual property relating to twisted and super twisted nematic structures. The global position in materials was overtaken by another European counterpart (and eventual parent company of the UK firm) Merck; who along with 3M have truly profited from the LCD revolution with their provision of superior quality component supply.

The UK LCD industry was primarily focused on military customers; highly specialised applications, low production quantities and high per unit costs. This meant that the UK LCD industry was never in a competitive position to enter the consumer

[30]ZBD Solutions spun out with much of the technical team involved in the zenithal bi-stable LCD program. In an interview with Cliff Jones, Director of R&D, he commented that ZBD Solutions may be the first civil service spin out company. The founding team had many difficulties in negotiating IP and equity stakes in the new spin out company because of their civil service status.

electronics market. Whether we can call this a failure of UK technological commercialisation is difficult to say, when success in the consumer markets was never the aim of the UK research programs, rather superior military applications, which were delivered. The UK situation highlights the importance of examining research programs within the context of their overall objectives, particularly government sponsored research, and eventual commercial outcomes of the research.

Japanese firms were the most successful in commercialising LCDs in the first and second waves of commercialisation (calculators, watches, TV and laptops). It is only recently, and in the third wave of LCD commercialisation, in large format displays, that Japan's position in manufacturing has been overtaken; by South Korea and Taiwan. Financial crises in Japan (recession and the Asian Financial crisis) allowed time for both these countries in turn to enter the large format LCD manufacturing market, and develop a stake. The success of Korean and Taiwanese firm to achieve this is attributed more to government support in accessing large amounts of financial capital rather than in supporting direct knowledge transfer. These three countries; Japan, South Korea and Taiwan have captured the most value out of the breakthrough technology, LCDs (Hart 2008).

The case study highlights the long development trajectory of the LCD industry; twenty-five years plus from initial technological discovery to the commercialisation of the third wave LCDs (large format LCDs). All the decisions about technological development were made without the full knowledge of where the industry would ultimately capitalise on these advances. The majority of government support was also provided in this context.

> *"The history of LCDs is a story of hard work, disappointments, and successes of worldwide competition and cooperation that encompassed the US, Europe and Japan. Each industrial centre contributed its particular strengths; in America, it was the quickness of forming new ideas and demonstrating their feasibility; in Europe, it was the fundamental science and synthesis of basic materials; and in Japan, it was the process of perfecting implementation and moving it to the production line"* (Kawamoto 2002 p.461)

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Differentials in Endogenous Regional Employment Growth in U.S. Metropolitan Areas:

The Explanatory Role of Entrepreneurship and other Leadership and Institutional Factors

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Abstract

This paper uses data from a sample of U.S. metropolitan regions to examine the explanatory power of various factors related to endogenous employment growth. The factors included in the analysis are measures of resource endowments, market fit, leadership, institutional factors entrepreneurship. The interpretive part of the paper focuses explicitly on variables relating to entrepreneurship capital and other leadership and institutional factors\and the effects of metropolitan region size. Regression modeling shows how the importance of different measures of entrepreneurship varies by type of measure and by size category of metropolitan region.

Keywords: Endogenous growth, entrepreneurship, regional economic modeling, U.S. metropolitan areas.

Acknowledgements: The authors wish to acknowledge the financial support of the Australian Research Council Linkage International Scheme (grant #LX0346785) and the George Mason University Foundation for a research project on 'Regional Economic Development and Performance: Roles of Leadership and Institutional Factors in Endogenous Growth' on which this paper draws. We also acknowledge the contribution to that research of Maria Salazar, Alistair Robson, Scott Jackson, Jiamin Wang and Heifung Qian.

Introduction

Numerous writers refer to economic development as being both as a process and a product or outcome (see, for example, Blakely 1994; Stimson, Stough and Roberts 2006). It is a multi-dimensional phenomenon, involving many actors and influenced by many

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The twelfth Uddevalla Symposium 2009 was hosted by Politecnico di Bari, Italy and organised by University West, Sweden in co-operation with Politecnico di Bari, Italy, Jönköping International Business School, Centre of Excellence and Innovation Studies (CESIS) Royal Institute of Technology, Stockholm, Sweden and The School of Public Policy at George Mason University, Fairfax, VA, USA.

Preface

This anthology consists of fifty-two revised papers, first presented at the twelfth Uddevalla Symposium 2009.The overall theme was ***"The Geography of Innovation and Entrepreneurship"***. It took place at and was hosted by the *Politecnico di Bari* in Italy 11-13 June 2009[1].

The welcome address at this symposium was given by the professors *Salvatore Marzano*, vice-chancellor at the Politecnico di Bari, *Vito Albino*, Politecnico di Bari, *Gianfranco Viesti*, Regional Agency for the Research and Innovation Technology and Dr. *Gianluca Jacobini*, Director of the Business Department, Banca Popolare di Bari, Italy.

Twenty-one parallel paper-seminars were organized around the overall theme and nine subthemes. In total more than eighty papers were presented which made this symposium the largest ever with attendees from 16 different nations. The nine subthemes and chairing persons were:
I. Clustering in a Non-Industrial Sector: Physical and Networked Agglomeration in the Media Sector. Chair: Prof. *Robert Picard*, Media Management and Transformation Center, Jönköping International Business School, Sweden.
II: Proximity and Innovation, Chair: Prof. *Nunzia Carbonara*, Politecnico di Bari, Italy.
III: Innovation, Globalization and Agglomeration - Aggregate Trends and Micro-Level Evidence, Chair: Dr. *Martin Andersson*, Centre of Excellence for Science and Innovation Studies, Royal Institute of Technology, Sweden.
IV: The Geography of Rural Entrepreneurship and Growth. Chair: Assoc. Prof. *Johan Klaesson*, Research Unit for Rural Entrepreneurship and Growth, Jönköping International Business School, Sweden.
V: Cities, Service Industries and the Geography of Growth. Chair: Dr. *Lars Pettersson*, Urban Center Management, The Swedish Board of Agriculture, Sweden.
VI: Innovation and Entrepreneurship in Hospitality and Tourism. Chair: Prof. *Lena Mossberg*, BI Norwegian School of Management, Norway.
VII: The Dahmén Session: Commercialization of University Knowledge for Innovation and Entrepreneurship, Chairs: Dr. *Annika Rickne*, The Dahmén Institute & Gothenburg University, Sweden & Dr. *Olof Ejermo*, CIRCLE, Lund University, Sweden.
VIII: Regional Innovation Systems in Post-Transition Economies. Chair: Prof. *Ulrich Blum*, The Halle Institute for Economic Research, Germany and
IX: E-Geography of Innovations and Entrepreneurship. Chair: Assoc. Prof. *Elin Wihlborg*, Linköping University, Sweden.

Seven plenary keynote speakers gave their presentations; Professor *Ron Boschma*, Utrecht University, the Netherlands, Professor *Ulrich Blum*, Institute of Economic Research (IWH) Halle, Germany, Professor *Börje Johansson*, Centre of Excellence for Science and Innovation Studies (CESIS), Royal Institute of Technology, Stockholm & Jönköping International Business School, Sweden, Professor *Lucia Piscitello*, Politecnico di Milano, Italy, Professor *Robert Picard*, Media Management and Transformation

[1] Uddevalla Symposium is an international scientific symposium established in 1998 in Uddevalla, Sweden. The primary objective is to foster research collaboration and bring together leading-edge views between experts, researchers and insightful practitioners from various fields of regional science, international business, economics, entrepreneurship and small business economics as well as from regional economics, regional planning, economic geography/economic history/political science and sociology in order to increase the knowledge as regards research questions related to "Innovation and Entrepreneurship in Functional Regions".
For further information on the Uddevalla symposium, use the link: ***www.symposium.hv.se***

Center, Jönköping International Business School, Sweden, Professor *Robert J. Stimson*, the University of Queensland, Australia and Professor *Gianfracno Viesti*, University of Bari, Italy.

Two *Best Paper Awards* were announced. The winner of the Best Phd Candidate Paper was written by *Anders Broström*, Centre of Excellence for Science and Innovation Studies, Royal Institute of Technology, Stockholm, Sweden. The winner of the Best Paper Award was Dr. *Darrene Hackler*, George Mason University, Department of Public and International Affairs, Fairfax, VA, USA.

The Symposium was organised by the *University West*, Sweden and *Politecnico di Bari*, Italy, in co-operation with *Jönköping International Business School, Centre of Excellence for Science and Innovations Studies (CESIS)*, Royal Institute of Technology, Stockholm, Sweden and *George Mason University*, Fairfax, VA, USA. Except for these academic institutions the sponsors and partners were: *Centre for Innovation Systems, Entrepreneurship and Growth, (CISEG)*, Jönköping International Business School, Sweden. *Media Management and Transformation Center (MMTC)*, Jönköping International Business School, Sweden. *The Municipality of Uddevalla*, Sweden. *Nordic Section of Regional Science Association (NS-RSA)* and *Research Unit for Rural Entrepreneurship and Growth (RUREG)*, Jönköping International Business School, Sweden. Supporting local partners from Italy were: *Association of Industrial Manifacturers of the Province of Bari - Confindustria Bari, Banca Popolare di Bari* and *The Regional Agency of Technology and Innovation of Apulia - ARTI Puglia*, Bari. The organisers thank all sponsors who in different ways made this symposium possible.

Furthermore, the editor thanks the members of the *Scientific Committee*, the members of the *Organisation Committee*, especially *Dr. Nunzia Carbonara* at the Scientific Secretariat, *Rosella Moramarco, Rebecca Olsson* (also for editorial help) and *Daniele Rotolo*. The editor also thanks a number of individuals at University West, especially *William Jobe* for comments and editorial help.

Trollhättan, Sweden in November 2009
Department for Economics & IT, University West

Iréne Bernhard
Editor & Coordinator

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