The role of intellectual property in influencing the success of innovations
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Contents

1. My background

I am a patent attorney and have worked for over forty years in major international organisations. I have a first degree in physics and was awarded a PhD in law and technology by the University of London for my multidisciplinary research into the dynamics of innovation. I have also gained a Diploma in Management Studies from the Polytechnic of Central London, now the University of Westminster. I am a Fellow of the Chartered Institute of Patent Attorneys, of the Institute of Physics and of the Institution of Electrical Engineers.

I commenced my career in research and development and gained sixteen patents for my inventions relating to the early silicon chips. I was employed by the British Technology Group for eighteen years and prepared and filed the patent applications on the University of Southampton [Mears, Payne, Poole and Reekie] invention of the erbium-doped fibre optic amplifier, one of the major inventions of the twentieth century and a foundation of the modern information economy.

I am currently a Senior Visiting Fellow of the Queen Mary Intellectual Property Research Institute (QMIPRI) and have taught and examined students for the MSc in Management of Intellectual Property since 1990.

2. Executive summary

At QMIPRI, I have recently completed a multidisciplinary study of the dynamics of innovation based on a number of inventions which have resulted in major expansion of the global economy. The subjects included the incandescent filament lamp and the electricity industry, cable and wireless communications and the thermionic valve, the transistor and the integrated circuit, personal computers and the associated software.

The attached case studies of these innovations show how they formed the foundation for growth of the economy. They are analysed in *Patents, Inventions and the Dynamics of Innovation* which will be published by Edward Elgar Ltd in February 2007 (ISBN 978 1 84542 958 4). The initial chapters of this book set out the context and highlight factors which could change the evolution of technological paradigms. Subsequent chapters take illustrations from the case studies to draw out the characteristics of individual factors of invention and to predict the likely success of an innovation. Appendices and relational databases on which my analysis was based are also attached to this evidence.

3. Issues pertinent to the role of IP in the dynamics of innovation

Schumpeter revealed that innovation is characterised by a short, disruptive conception (the A-phase), in which discrete and random advances occur spontaneously, followed by a longer period of consolidation (the B-phase), in which improvements are of a steady and asymptotic nature. There is no clear picture of which factors contribute to success, but modern observers consider that, in order to provide useful information, a study needs, at least, to take into account historic, scientific, technological, economic and legal viewpoints, personal psychology, social needs, communications, finance and marketing.

Jewkes examined details of the history of different innovations, but discovered no common pattern. One suggestion by Julius Wolf, later taken up by Schmookler and others, was that, ultimately, the possibilities for innovation in a technological field become exhausted. This may be because the physical limits of processes are reached. Kingston noted that cross-fertilisation of ideas may postpone any reduction in the rate of innovation, as does the ‘sailing-ship effect’. However, Wolf’s theory is contradicted by the example of the automobile industry, which is based on mature technology, but continues to innovate. Integrated circuit manufacture provides a test for the proposition, since the limits of current technology are only about three technological generations (about ten years) away.

Opposing views of the origins of invention are that either they are the conception of great men or they are the inevitable product of socio-deterministic pressures – a consequence of the needs of an époque. Under the latter theory, they will just have a window of opportunity during which the socio-economic environment is favourable for their exploitation.

Various authors have observed that progress by fits and starts, initiated by sporadic flashes of inspiration and inhibited by obstacles such as the need to develop new materials, finds a parallel in biological evolution. The opportunity cost of re-working an abandoned idea is greater than that of developing the current technology. This is manifest in the binary nature of technological choices and gives rise to innovation paths which resemble phylogenetic trees.

A significant corollary of the biological analogy is that the distinction between micro-mutations and macro-mutations, advanced by Goldschmidt, leads to a corresponding dichotomy between micro-inventions and macro-inventions, a concept which is useful when modelling innovation dynamics. However, whilst the comparison provides useful analytical tools, it is merely a model and should therefore not be regarded as set in stone.

Occasionally inventions will be made by purely by chance – erroneous observations may have felicitous consequences. A newly-discovered material may have ideal properties for a particular application or an unplanned discussion between two individuals may resolve an apparently insuperable problem.

Taton noted that, even if inventions do not require great men for their genesis, they will be influenced by the personal characteristics of individual inventors. The ability to observe is one significant quality. Perseverance and attention to detail are others. The inventor’s path is hard and he needs strength of purpose to act as product champion. An inventor also needs to have the right sort of mind, which may be stimulated by cross-fertilisation of ideas from other disciplines. Different environments suit different inventors – some prosper in institutional environments, whilst others like to plough a lone furrow.

Innovation is, at times, inhibited by the need for some enabling invention or other event, such as the development of a material having suitable physical characteristics or the enactment of legislation which removes regulatory barriers.

Firms need to innovate to keep up with competitors. Often, however, resistance to change – a universal trait – manifests itself in the Not-Invented-Here (NIH) syndrome, in which it is difficult for an outsider to get his ideas accepted. Skills are not always home grown. Sometimes their acquisition takes the form of predatory activities such as hiring inventors employed by rivals or taking over companies to gain access to their technology. Information sharing by cross-licensing is an alternative means. This brings incremental revenue and there may be other benefits. Informal know-how trading also spreads the knowledge base and may take an innovation to its critical mass or speed a company's progress up the learning curve.

4. Is the process of intellectual-property-law-making designed to produce effective results?

The nature and extent of the monopoly provided by intellectual property rights varies from industry to industry. This is due partly to the particular way monopoly impinges on the technology and partly to the haphazard way the law develops. The established view is that statutory monopolies provide a temporary respite from competition to enable innovation to become established. However, the origins of the modern patent system (the 1623 Statute of Monopolies), for instance, militate against the proposition that it will be an effective tool to foster innovation. Empirical evidence gathered by Taylor and Silberston supports this contention, as does a rational financial risk analysis. However, Kingston pointed out that patents do serve a useful purpose as a form of currency for technology marketing. Isolated periods (such as the Netherlands and Switzerland in the nineteenth century and the USA in November 1917), when certain countries abandoned or suspended patents, provide a vehicle for study of the utility of the system.

Market structure exerts a dominant effect on the propensity to innovate. For instance, inertia in market dynamics may create opportunities for an innovator, whilst market power, which can be generated intrinsically by a firm's own efforts, may be used to reduce the countervailing strength of buyers. Informal distortions of a market may be generated by trade secrecy and *de facto* standards. Response time delays, which were highlighted by von Hippel, create a temporary monopoly which can assist an innovator in controlling a market. Marketing requirements, which possess both physical and psychological components, are a stimulus for research and development and, hence, invention.

Governments may be a major influence in controlling the progress of innovation. On the one hand, they can stimulate it by direct procurement or fiscal incentives, whilst, on the other hand, they can control the power of innovators by competition laws or direct regulation or the application of national or international standards.

Finally, finance is important because innovation is accompanied by the absolute certainty of negative cash flow, whereas the prospect of an innovation rent is highly uncertain. The anticipated return will depend on risk assessment, which is also a very imprecise procedure. Why then should capital be forthcoming? Comfort for the capitalist may be supplied by intellectual property rights, but cyclic variations in the economy will also affect the magnitude of the income. The cost of market entry may be reduced by using others' R&D through the medium of a licence which will usually be obtained at marginal cost.

Historical experience illustrates the sporadic nature of paradigm-changing invention and its uneven evolution under the control of a multiplicity of determinants. This leads to the hypothesis that the influence of the factors of invention is both hierarchical and dependent on the timing of their incidence. In consequence, although a given invention may appear on one or more occasions, it will have a limited window of opportunity for successful development and will not achieve a critical mass if conditions are unfavourable.

Adoption of Kuhn's concept of the scientific paradigm enables developing technologies to be viewed as phylogenetic trees, which highlights their transient nature. Due to the variable characteristics and incidence of the factors, a study must be multi-disciplinary, rather than follow the methodology of many previous authors who assumed that only one factor at a time need be considered.

Typical of the contributory determinants is the inventor's role, which has its own sub-set of influences. It may, for example, be postulated that *when* an inventor makes his invention is significant, since the corollary of the concept of a variable propensity to invent, is that certain stages of life will be more fruitful than others.

Second-order vectors are cartels, statutory monopolies, war and government regulation. The temporal phasing of their influence will vary both on a micro-economic and a macro-economic scale.

Case studies of major innovations, based on chronologies derived from patent office records, provide a framework for the identification of response patterns, the creation of comparison benchmarks and the extraction of paradigm optimisation strategies. This permits, firstly, the main hypothesis concerning the importance of the hierarchical nature and significance of its temporal context for the success of invention to be tested and, secondly, a challenge to be made to the contention that it is reasonable to investigate the dynamics of innovation from a unitary, usually purely economic, viewpoint. It will also lay a foundation for maximising the advantages of innovation in the business environment and for possible changes in public policy to increase the efficiency of industrial change.

In an evolving economy, firms need to innovate in order to survive. A steady flow of obstacles to be overcome will provide an opportunity to do this. A literature survey confirmed that to produce meaningful results, a study of the dynamics of innovation needs to be multi-disciplinary. Jewkes searched for a universal pattern but this proved fruitless. Other authors attempted to explain this failure, but their assumptions are open to question.

There are opposing views on the origins of invention. It may be the inevitable consequence of the environment, the product of great minds or, simply, serendipity. Market structure is a dominant factor in shaping the evolution of innovation and this may be distorted by influences, some of which can be controlled by the innovator. Intellectual property is not necessarily the stimulus that it is usually held out to be. Government intervention, particularly at the early stages, may promote or inhibit it as may the laws of physics and the properties of materials. Good communication, however, is an essential component. The role of finance is significant because cash is a consumable and, if the rate of consumption is constrained by the rate of supply, it can inhibit progress or even stifle the innovation completely.

One school has used biological analogies as an analysis tool. My research has shown that it is likely to be helpful to represent technological paradigms as phylogenetic trees because technological innovation involves a succession of paradigm shifts which fulfil the role of biological mutations. Case studies which examine the reasons for the choices made therefore, by corollary, throw light on the hierarchy of the factors of invention.

5. Conclusions from case studies

5.1 The invention of the incandescent filament lamp– influences on the development of the electricity industry

The key to the development of the incandescent lamp industry was Volta’s invention of the voltaic pile which, for the first time provided a reliable source of continuous electric current. Humphry Davy, during his tenure of the Royal Institution, was provided with a powerful battery composed of these cells and, with this, he demonstrated the electric arc, the incandescent filament and the luminous gas discharge, precursors of the three main technological paradigms for conversion of electrical energy to light.

A latent demand for electric lighting had been created by the luminous flame. Before artificial lighting became economically viable with the development of coal gas and the bats’ wing and fishtail burners and the portable kerosene lamp, the workman had been constrained by the availability of daylight. He rose with the sun and retired at dusk.

The gas flame was not an efficient source of light. It relied on incomplete combustion to create illumination – the gas mantle was not invented until towards the end of the nineteenth century. The gas itself was smelly and potentially explosive. There were therefore many incentives to replace it provided a sufficiently cheap alternative could be found.

Although the battery provided a source of steady current, the primary cell consumed zinc, which was an expensive fuel. A cheaper alternative became available when Gramme and others perfected dynamos for conversion of mechanical energy into electricity. The power of steam generated by combustion of readily-available coal, or of water flowing from high reservoirs, could then be harnessed.

As soon as electricity was viable, it was used to drive the carbon arc lamp. Early developments, such as hard carbons made this practicable and refinements such as a clockwork mechanism for automatically maintaining optimum spacing of the arc could be established using extant technology. Moving parts were eliminated when Jablochkoff introduced his ‘Candle’ and this might have proved to be a fruitful line of development had the arc not been displaced by the incandescent filament. Improvement to the arc lamp went on long after its successor was established – a manifestation of the well-known ‘sailing ship’ effect.

The arc lamp was noisy and it produced a huge amount of light – far more than was necessary for domestic purposes. 'The subdivision of the light' therefore became an objective for researchers in this field. Davy and others had experimented with incandescent wires as a source of light. Platinum was the most widely used because it did not oxidise when heated in air, although other noble metals were pressed into service. These materials were, however, not satisfactory because the temperature at which they became white hot was very little below their melting points. With the poor regulation of early power supplies and non-uniformity of wires due to crude metallurgy, this meant that filaments frequently fused and failed.

Heinrich Göbel was the first inventor to make a working light from a refractory material – carbon. His lamp exhibited many of the characteristics of the later devices of Swan and Edison. It had a glass envelope and a carbon filament glowing in a vacuum. However, Göbel lacked the skills of communication and commerce necessary to crown his invention with success. Edison and Swan, on the other hand, in their very different ways, were able to marry their skills with those of others to exploit the invention effectively.

The carbon filament lamp was the direct result of the combination of improvements in vacuum technology effected by Sprengel and others with the serendipitous discovery of the technique of 'running on the pumps' for removing adsorbed gases which had previously been a cause of destruction of the carbon. Once Edison and Swan had shown the way, many others, including Lane Fox, Maxim, Sawyer and Man were immediately able tread the same path. Intellectual property rights were the tool by means of which the pioneers were able to suppress the competition. Edison and Swan demonstrated the truth of the adage 'United we stand' by combining their resources to turn a weak patent into one that was invincible. They exploited the common law system of precedent to establish a monopoly which remained absolute until their original patents expired. By this time patterns of trade had been firmly established and the market was closed to newcomers.

Swan demonstrated the truth of the statement that a little knowledge is a dangerous thing. On the basis of his previous experience of the patent system, he delayed filing an application on the carbon filament lamp. As a result, his rival Edison, who operated on the principle of file first and enquire later whether the invention is patentable, pre-empted important features of Swan's patent.

Edison believed strongly in a vertically-integrated manufacturing system. He set up plant to make all of the components of his lighting system, from generators to supply cables and meters. His philosophy persisted in his successor company, General Electric, up to the end of the twentieth century.

Patent protection bred complacency. The metal filaments which superseded the carbon filament were developed by third parties who were trying to break into this lucrative market. It was of little avail. The market power resulting from being first in the field permitted the original companies to purchase the new technology, whilst retaining their market dominance.

Swan and Edison represented opposite ends of the spectrum of the process of innovation. Swan would select his goal and work steadily towards it, picking off useful peripheral ideas such as the miners' lamp and artificial silk along the way. He believed in the *keiretsu* method, harnessing the independent resources of fellow workers including R.E. Crompton and C.W. Siemens. Edison, on the other hand, adopted a scatter-gun, bull-in-the-china-shop approach. He squandered the profits of the quadruplex telegraph on trying unsuccessfully to develop a sextuplex version. Although his initial attempt at 'subdivision of the light' was based on a meticulous study of the economics of gas lighting, he financed expensive expeditions to seek natural sources of carboniferous fibres without any consideration of the prospects of an adequate return. A large number of his inventions failed, lacking a sound technological foundation, whilst many of those which succeeded, did so mainly because of manufacturing and market power. He failed to recognise the importance of alternating as opposed to direct current and was unsuccessful in developing wireless communications although he had all of the necessary inventions to hand. As well as being the inventor of the carbon filament lamp, the phonograph and the quadruplex telegraph, he was also the proponent of the odoroscope, the tasimeter, the pyromagnetic generator and vacuum 'preservation' of meat. His most significant innovation was of the concept of the industrial research laboratory, although he viewed it merely as an extension of his personal skills, frequently taking the credit for the work of others. His career exhibited a classic Gaussian profile of the propensity to invent, peaking in his early thirties and tailing off with increasing age, with subsidiary peaks corresponding to new enthusiasms and troughs resulting from extraneous distractions.

The course of litigation highlighted an important plank of innovation strategy, so-called forum-shopping. Edison and Swan had separately patented important elements in the manufacture of the carbon filament lamp — the use of a vacuum, an all-glass enclosure, a thin carbonised filament. In opposition, they could have destroyed one another. They therefore settled their differences and combined to litigate against third parties. In common law jurisdictions, an increasingly invincible series of precedents was built up against weak opponents. The combination of deep pockets, multiple actions and retention of the leading advocates was employed to ensure victory. In jurisdictions where there was an inquisitorial system of justice, they did not prevail and the corresponding market became fragmented.

Evolving public attitudes to private monopoly were a major influence on the international structure of the electrical industry. The choice of an inappropriate precedent — the Tramways Act 1870 — for the first Electric Lighting Act to control the installation of infrastructure for generation and distribution of electricity in the UK set back British industry ten years and allowed US and German rivals to gain a commanding lead. It was only the creation of international cartels and the existence of the imperial preference that permitted British companies to play a subsequent part on the world stage.

Once the regulatory regime was structured satisfactorily, finance ceased to be an important influence. Although needs ranged from the modest requirements of experimenters like Swan to social capital for the creation of the infrastructure necessary to establish the electricity industry, the greed of speculators ensured that resources were forthcoming. Marketing techniques were relatively unsophisticated, but the modern exponent of this art would recognise the use of public figures, exhibitions and learned societies to mould opinions. Some approaches, such as Edison's use of his rival Westinghouse's alternating current generator to power the electric chair as a means of promoting the use of direct current, do not accord with modern ethics, but were effective in achieving publicity.

Early forms of artificial lighting, through the medium of discrete sources, such as the fire brand, tallow dip and candle, stretched back into pre-history. The motive force behind the first paradigm change – from the individual flame to the continuous illumination of the centrally-produced coal gas – was purely economic. It used, in an entirely predictable manner, only those technological resources which were already available. Financial returns were assured and capital was therefore forthcoming. On two occasions, inventions reinforced this paradigm. The first was the dilution of coal gas using petroleum-vapour-enriched water gas, which reduced input costs, and the second was the introduction of the gas mantle, which delayed the move to electric lighting.

When limelight was invented, a decade after the introduction of coal gas, it provided the prospect of a great increase in luminosity, but this could not be harnessed because conventional gas burners did not give a hot enough flame unless they were supplied with pure oxygen to aid combustion. No viable means of generating this oxygen was available. (At that time, pure oxygen was produced by relatively costly chemical processes rather than the present-day technique of fractional distillation of liquefied air.) In any event, pure oxygen when mixed with coal gas is potentially explosive and, for safety reasons, would probably not have been acceptable. Indeed, if modern safety criteria had been prevalent at the beginning of the nineteenth century, it is questionable whether gas would have been taken up as a universal energy source.

Sixty years elapsed from Drummond's invention of the limelight burner before a clever and resourceful inventor – Carl Auer von Welsbach – devised a means of harnessing the luminosity of refractory oxides. His gas mantle, which was impregnated with, *inter alia*, [radio-active] thoria, found immediate acceptance and remained in general use for another seventy years or so. There is no apparent reason why this invention could not have been made forty or more years earlier, if someone had decided to carry out research into improved burners to raise the temperature of refractory oxides in coal gas flames sustained by air rather than pure oxygen. The time and environment were ripe. It was only the invention that was lacking. The inference is that the problems of gas lighting technology did not attract sufficiently smart thinkers.

The genesis of electricity as a power source was serendipitous, but it required Volta's perspicacious interpretation of Galvani's observation, to turn the discovery into a viable innovation. Volta's ideas, in turn, needed a receptive environment – which he sought in London rather than his native Italy – to provide the resources for the discovery, development and dissemination of basic forms of electric lighting.

The drawbacks of gas – including poor luminosity, hazardous operation and pollution – created a strong latent demand for a better alternative. The first to be developed was the arc, which could be made to operate reasonably satisfactorily using extant technology developed in a logical, extrapolative manner. The negative features were that it was noisy, that the level of light from an individual burner was very high, that the spacing of the electrodes required continual and precise adjustment and that it was very sensitive to variations in the electrical power supply.

The incandescent filament, the principle of which was established by Davy at the same time as the arc light, overcame these problems, but its immediate take-up was inhibited by the unsuitable properties of available materials – noble metals, such as platinum and iridium did not oxidise, but melted if they were overheated; carbon did not melt but oxidised, even when encapsulated in a sealed chamber. Early workers who tried carbon did not succeed until Sprengel's and Geissler's more efficient vacuum pumps for creating better vacua and the serendipitously-discovered technique of 'running on the pumps' solved the latent problem of occluded gases. This was the last step in the jigsaw. The floodgates opened and other potential makers were able to commence manufacture.

Patents were the key to control of the market. Combination of Edison's and Swan's resources to assemble a portfolio of key inventions created a dominant position. Patterns of trade established by this monopoly persisted after expiry of the patents. Innovation followed the classical Schumpeterian model. Eventually, a paradigm-changing invention came from without, but the market power of the original monopolists enabled them to acquire the substitute technology.

Once the incentive was created by Swan's and Edison's invention of the carbon filament lamp, there was no insuperable obstacle to the establishment of the massive infrastructure needed to support this innovation. Vertically and horizontally integrated business models were equally appropriate for this development. Problems were solved as they were encountered, over a very short time interval, by using adaptations of existing technology on an *ad hoc* basis. Sometimes this created long-lasting *de facto* standards such as the Edison screw and the bayonet cap lamp holders.

Swan worked selectively towards his goals but Edison adopted a scatter-gun approach, throwing money at problems. Edison's concept of an industrial research laboratory enabled him to maximise his efforts. He *missed* many opportunities through lack of focus, but *created* many more as a result of his free thinking. His propensity to invent changed through his life, following a skewed gaussian distribution.

Edison's and Swan's differing methodologies were equally successful in initiating innovation. Edison, however, did not hesitate to punch below the belt if it would help him to achieve his objectives. He also consumed more resources, both physical and mental. Swan, on the other hand, always adopted a strictly ethical approach. The former's more robust stance succeeded better in business. If one contestant adopts a 'no-holds-barred' attitude and the other is playing by the rule book then clearly the former will be at an advantage.

The conduct of litigation highlighted another important feature of innovation strategy. Edison and Swan had both patented the important combination of elements in the manufacture of the carbon filament lamp – the use of a vacuum, an all-glass enclosure and a thin carbonised filament. In opposition, the two patentees could have destroyed one another. They therefore settled their differences and combined to litigate against third parties. In common law jurisdictions, an increasingly invincible series of precedents was built up by initiating proceedings against weak opponents. The combination of deep pockets, multiple actions and retention of the leading advocates was employed to ensure victory. In jurisdictions where there was an inquisitorial system of justice, they did not prevail and the corresponding market became more fragmented.

In most territories, markets evolved into oligopolies, often with overt cartels, such as the British Electric Lamp Manufacturers Association. The Phoebus Organisation, controlled by the US General Electric Company, regulated international trade. Early competition law was ineffective against these trusts. Indeed, the strong industry which they engendered was viewed with favour in Germany and Britain. Absence of a patent system in Holland and Switzerland permitted small manufacturers to establish themselves, but, in the long term, they were either absorbed by larger businesses or joined them in an oligopolistic market.

Direct regulation can have a disproportionate influence on a developing industry. An infelicitous choice of legislative precedent which, although reflecting public attitudes, did not take sufficient account of the need for adequate financial return and almost strangled the juvenile British electrical industry at birth.

The dissemination of Davy's findings stimulated research elsewhere and led to improvements in battery technology, but energy produced in this way could not supplant that produced by coal as it was three orders of magnitude more costly. In 1831, Faraday, Davy's successor at the Royal Institution, discovered a means of converting mechanical energy to electricity and hence of harnessing the low cost and ready availability of coal, but it was another forty years before a reliable dynamo was developed. The move from battery to generator as a source of electric current was analogous to the paradigm shift from the candle to the gas flame – from a discrete to centralised power supply.

Advances in power sources led to improvements in lighting. Better light sources created a demand for more electric power and the two paradigms advanced in a stepwise manner.

Von Welsbach's contribution to the improvement of gas lighting through the invention of the oxide-charged gas mantle, with its vast increase in efficiency over the bats' wing and fishtail burners, led directly to Nernst's development of an electrical analogue. This could well have spawned an alternative train of development, a different phylogenetic tree, but another of von Welsbach's inventions, the extruded, sintered osmium filament lamp, set in motion the introduction of other refractory metals, vanadium, tantalum and tungsten, which exhibited a greater luminous efficiency and product life. Stanley Mullard's Point-o-lite, a sealed tungsten arc lamp, might also have been the source of another fruitful line, had it appeared three decades earlier. Both Nernst's and Mullard's inventions demonstrate the need for felicitous timing as a component of success.

One major paradigm shift, from direct to alternating current, was conceived theoretically and reduced to practice by a 'great man' (Tesla). He combined with a 'man of vision' (Westinghouse) who had the resources to bring the idea to fruition and the experience to transfer the technology effectively. Although it evoked a Luddite reaction in Edison, this negative response was no more effective in delaying progress than a similar reaction was in delaying the transition from a cylindrical to a disc-shaped sound recording medium some years later.

5.2 The development of electronic communications

Early communications were driven by military requirements. The semaphore held sway for many years and the advance of the electric telegraph was delayed by the cessation of hostilities between England and France. The advent of the railways provided a commercial incentive and also the wayleaves to lay cables from city centre to city centre. Once the cables had been installed, the explosion of commerce that accompanied the industrial revolution ensured their viability.

The telephone was invented in America. Edison and Bell both set up service companies in Britain which posed a threat to the General Post Office's monopoly of communications. Although the Telegraph Act was invoked in a landmark case, *Attorney-General v. Edison Telephone Co. of London* **6 QBD 244**, to restore control to the state, the prospect of growth in the telephone system was not taken seriously because, in the words of the Sir William Preece, Chief Engineer to the Post Office, 'We have a super-abundance of messenger boys.'

Starting with the modest beginning of a cable under the Thames, Britain pioneered underwater communications cables. As well as the burgeoning demand of trans-Atlantic commerce, there was a need to communicate with the outposts of Empire, which provided the political incentive to undertake the massive investment required. As a maritime nation, Britain had rope-making technology available and it was readily adapted, but cable construction was a new art. Suitable materials had to be discovered by trial and error. Gutta percha, a product of the rubber industry proved to be a suitable insulator. This led to Britain, with its imperial sources of raw materials becoming a leader in cable-based communications. This eventually inhibited the progress of wireless in Britain because, by the First World War, when wireless was beginning to expand, there had been a huge investment in the cable infrastructure and, it was thought, the power of the Royal Navy would prevent these cables being cut, so there was no need for an alternative form of communication – an echo of the decision a century earlier on replacement of the semaphore. Even before the laying of the first trans-Atlantic cable, the telegraph companies had formed a price-fixing cartel. This remained effective throughout the latter half of the nineteenth century.

There were many pioneers of wireless communications, including Hertz, Lodge, de Forest, Marconi and Slaby. Even Edison had tried his hand and, indeed, had made inventions which would have laid the foundations for a successful development. He, however, was fully occupied with the exploitation of the electric light and lacked the motivation to drive the inventions through to commercial viability.

With wireless, Marconi was the man of vision. Lacking support in his native Italy, he emigrated to the home country of his wife, where he received the patronage which supported his early experiments.

The early operator-based detectors of wireless signals were many, various and crude, but were universally based on the creation of an audible signal which was translated by a trained operator. J.A. Fleming, scientific consultant to Marconi, suffered from progressive deafness and could not use these techniques and was forced to seek an alternative. He adapted apparatus on which he had worked two decades earlier to invent the thermionic diode detector. As a consequence of the English common law of master and servant, he assigned his rights to his employer, the Marconi Company. Lee de Forest, in the USA, extended Fleming's work and made a more sensitive detector by adding a third electrode to the diode. At the time, he did not realise that he had made an amplifier, but he later exploited the invention to the full. Wehnelt, von Lieben and Reiβ in Germany mirrored the work of Fleming and de Forest to develop a thermionic relay valve.

De Forest was a difficult character, who fell out with his business associates. Shortly after his invention of the triode valve, he underwent a period of financial stringency, as a result of which he was unable to maintain his foreign patents. He became involved in litigation with Marconi and again, due his nature, was unable to reach a settlement. This led to a stand-off in the US thermionic valve industry which was not resolved until the suspension of patent monopolies during the first world war. The Fleming diode patent was eventually (in the 1940s) held to be invalid by the US Supreme Court, but, by then, its role in shaping the structure of the industry had been fully played out.

The upheaval caused by the war allowed the lamp manufacturers to gain control of the manufacture of thermionic valves. The industry was ruled by cartels which paralleled those of the lamp manufacturers. The demarcation of national boundaries was enforced by the adoption of non-tariff barriers such as the use of mechanically-incompatible valve bases for devices with similar electrical characteristics. In this regulated environment, the rate of technological development was slow.

The need to communicate with ships was the economic driver which stimulated the early expansion of wireless communications. Marconi adopted an aggressive commercial stance and threatened to gain a monopoly. Other nations were antipathetic and adopted countermeasures to prevent Britain gaining the degree of control of wireless which it enjoyed in cable-based telegraphy. Germany convened international conferences at which it fought for its national interests. Britain's support for Marconi was half-hearted, partly as a result of the Post Office monopoly. In the USA, commercial interests closed ranks and set up the Radio Corporation of America (RCA) to prevent Marconi gaining access to the Alexanderson alternator which would effectively have given him a monopoly of trans-Atlantic wireless.

The broadcast entertainment industry was a by-product of the wireless communications revolution, but this was completely regulated by cartels. Patents were pooled and *de facto* standards created by a need for a *lingua franca.* There was therefore little incentive to innovate other than in response to consumer demand for advances such as colour television.

Although Volta's battery made the electric telegraph feasible, existing technologies did not yield viable systems. The enabling step was Oersted's discovery of the magnetic effects of an electric current, but even so, the electric telegraph did not become widespread until there was a strong commercial demand initiated by railway mania.

In the nineteenth century, Britain had long been a maritime nation and possessed appropriate industries to service naval activities. British manufacturers became dominant in cable manufacture because they could adapt established rope-making techniques and had exclusive access to suitable raw materials through trade with the Empire. Commercial demands attracted many new suppliers, but, almost as soon as a regular service was established, the cable operators found it necessary to set up a price-fixing cartel to maintain profits.

Technological limitations at the time of the invention of the telephone inhibited its immediate acceptance. It posed a potential threat to telegraphy, but lack of a means for compensating for transmitted signal degradation blocked an early paradigm shift. In the legal environment, statute law did not keep pace with technology, but judge-made law, based on the legal fiction that the telephone was a telegraph, enabled the government to retain its monopoly of operations.

Like the luminous flame before von Welsbach's invention of the gas mantle, cable construction techniques did not inspire successful lateral thought. Until the invention of the fibre optic light guide towards the end of the twentieth century, there was no fundamental re-appraisal of cable communications technology which remained wedded to the copper wire.

The evolution of wireless followed the classical path of theoretical proposal, followed by proof of concept, development of crude practical systems with commercial utility and, ultimately, supersession by more refined systems. As with the electric lamp, although many inventors were capable of making the enabling inventions, the one who succeeded (Marconi) also possessed the necessary business acumen. The new paradigm destroyed the economic viability of its predecessor (cable communications) and Marconi used this as a threat to gain access to the cable operators' local delivery network. Like Edison and Swan, he employed a domino strategy to eliminate or marginalise competition, picking off his opponents one by one. He used patents to control the market, whilst his contemporary Lodge, who had a similar command of the technology, was timid in enforcing his rights.

Development of long-distance wireless communications was frustrated by conflicting national interests and reluctance of governments to come to terms with private monopolies when they, themselves, were not prepared to commit to investment in infrastructure or write off outmoded cable systems. Political considerations over-rode technological ones.

A conflict of interest affected the British Government's stance. On the one hand, it wished to encourage national interests, but on the other it wanted to maintain the Post Office's monopoly of communications. Other nations fought their own corner vigorously.

For ship-owners, investment in wireless for safety purposes was a 'distress purchase' and compliance had to be enforced by diplomatic agreement – a very slow process. It was, furthermore, an inelastic market determined precisely by the volume of shipping.

The broadcast entertainment industry was a by-product of the wireless communications revolution. Radio broadcasting excited public interest. It grew organically over many decades (and is still growing) interrupted only by the precedence accorded to the demands of military communications for limited resources, particularly during periods of war.

When broadcasting got under way, Marconi repeated the strategy he had used with maritime wireless and set out to establish a dominant patent portfolio by original invention or by acquisition of other people's. As with cable, a cartel was established to further the interests of the principal suppliers. Patents were pooled and *de facto* standards created in response to a need for a inter-working of products from different manufacturers. Pool licensing conditions created artificial constraints on receiver design and marketing. There was therefore little incentive to innovate other than to reduce manufacturing costs and to respond to consumer demand for novelties such as colour television. A radio receiver manufactured in 1955 differed little from one made in 1935, apart from the substitution of physically smaller valves with all-glass bases (albeit performing identical functions).

With the thermionic valve, there was considerable borrowing from incandescent lamp technology. Fleming's diode was a direct consequence of an unexpected (and ignored) observation by Upton and Edison two decades earlier. De Forest's discovery of the amplification by his Audion valve was also serendipitous – for a long time, he thought that he had merely made a more sensitive detector.

In the main, technological advance in valve construction techniques went hand-in-hand with progress in communications technology. The early innovations were empirically-based. One early paradigm shift was the result of a chance contamination of materials but, once the fundamental principles of the thermionic valve had been established, subsequent advances were made by developments in electrode materials and mechanical construction to enhance the emission characteristics and optimise the internal electric field topography.

Due to their relatively short lifetimes, the replacement market for valves was profitable. This influenced the pricing structure of component supplies to original equipment manufacturers, which was designed to gain access to these lucrative later sales. Non-tariff barriers were erected to protect national markets.

War provided increased focus and direction for innovation. In the British Empire, because there was a highly developed cable communications network which was not considered vulnerable due to the strength of the Royal Navy, little effort was expended on radio. German cables, on the other hand, were constantly cut, so great strides were made there in transmitter and receiver design to improve long distance wireless communications. War also encouraged long uniform production runs and standardisation. To this end there was exchange of know-how between manufacturers and suspension of patent monopolies. Eventually it created a vast post-war surplus market which fed pioneering amateur enthusiasts and entrepreneurs. War stimulated demand, but peace switched it off again, with wireless as it had done with the electric telegraph at the start of the nineteenth century.

Paranoia about freedom-to-use created a cross-licensing culture when monopolies intersected. This was often accompanied by an overt or implicit agreement to respect exclusive territorial rights to markets – for example, Philips exchanged licences with RCA and kept out of the US market. There were also complementary cross-holdings of shares in competing companies. Personality conflict was a significant determinant of the structure of the electronics industry because this paranoia was a direct consequence of de Forest's lack of willingness to compromise in his conflict with Marconi, which created a hiatus in the industry's progress.

5.3 The invention of the transistor – influences on the development of the semiconductor industry

A three-electrode semiconductor amplifying device was first invented in the 1920s by Julius Lilienfeld. He proposed device structures which were brought to practical realisation some 30-40 years later. His inventions were patented, but not developed commercially because the materials available to him were not capable of sustaining the minority carrier charge flow necessary for viable operation. Although his ideas were soundly based, Lilienfeld did not have the resources or perseverance to push them through to fruition.

Hilsch and Pohl revisited the concept of a solid-state amplifier in the 1940s. They did not succeed because they tried to simulate a thermionic triode structure in an ionic crystal. Although they achieved a measurable current gain, the properties of the materials inhibited operation at frequencies which would have been commercially useful.

Wartime activity, in particular at Purdue University, was responsible for the development of the materials which provided the springboard for the discovery of the transistor effect. Another essential component was the existence of a culture in the Bell Telephone System which permitted the expenditure of substantial funds on a programme of fundamental research. Although such research could conceivably lead to the holy grail of a solid state replacement for the unreliable thermionic valve, there was no requirement for it to be so targeted.

The Bell Laboratories were a centre of excellence, and the team which was assembled was of the highest quality. It was also multi-skilled, including theoretical and applied physicists, chemists, metallurgists and electronic engineers. As befits a major US corporation, it was well-briefed legally and performed a thorough job of protecting the intellectual property generated by the research.

Constraints which had arisen from anti-trust actions prevented the Bell System from exploiting the invention of the transistor in the most direct way – by making and selling the devices. An imaginative licensing programme was therefore introduced by seminars which provided a taster of the significance of the invention. This was followed up by well-organised transfer of know-how to the licensee organisations. Success was further assured by inviting only companies of substance to participate.**[1965] RPC 335**

An artificial situation existed initially as an anti-trust consent decree effectively forced Bell to pass on its semiconductor know-how to others. The transfer of know-how was soon reinforced by movement of personnel as Shockley and Teal, who were members of the original team, sought pastures new. Another early influence was Shockley's irascible personality. Scientists and engineers who had joined his Palo Alto start-up, found that he was impossible to work with, and left to create their own companies. This was the beginning of the 'Silicon Valley Effect' – technology transfer through the founding of new companies.

There was a great *cameradie* amongst the Californian semiconductor community, which shared technical knowledge, oblivious to the proprietary nature of the know-how. The semiconductor manufacturers possessed a vast core of technical skills. As soon as a new idea was made public, many rivals were in a position to exploit it, a factor which is confirmed by the short lead time between seminal patents and daughter inventions. Patents were either cross-licensed or ignored so the lead-time advantage of innovation was negligible.

Although the first wave of manufacturers was drawn mainly from the ranks of those who made thermionic valves, the predecessor product, by the time the industry was ten years old, many of these had fallen by the wayside and newcomers, such as Texas Instruments and Fairchild, had taken their places. The Not-Invented-Here syndrome was probably playing a significant part.

During the fifteen years after the initial discovery, the dominant manufacturing technology changed every three to four years. The point contact was superseded by the grown junction, which was more robust. The alloyed junction, which followed, reduced manufacturing waste and parasitic collector resistance. Silicon replaced germanium to make devices less sensitive to the effects of high temperatures, whilst the associated double-diffusion and mesa etching processes gave much better high frequency performance. Planar surface passivation techniques introduced long-term stability and permitted the use of plastic encapsulation. Finally epitaxy gave rise to flexibility in device topography and presaged the fabrication of complex integrated circuits.

Advances in device technology were governed by properties of materials and the materials scientists and metallurgists were the unsung heroes who made the industry viable. Silicon took over from germanium partly because it had a wider band gap, but mainly because it had a stable glassy oxide which provided surface passivation. Alloyed junction transistors were predominantly *pnp* devices, despite the fact that electron mobility was of the order of three times that of hole mobility, because indium, an acceptor dopant, was ductile and alloyed readily with germanium. Complementary *n*-type dopants, antimony and arsenic, were brittle and volatile at alloying temperatures. They had to be used in conjunction with an inert metal carrier such as lead, which did not wet the surface of germanium as well as indium did. The post-alloy-diffused transistor was made possible because donor impurities had higher diffusivities than acceptors, whereas the segregation coefficients, which were important for alloying, were higher with the *p*-type dopants. Gallium arsenide, which had a wider band gap and higher minority carrier mobility than silicon, did not supersede it because it was difficult to fabricate. Eutectic bonding processes, such as bird-beak and nail-head or ball bonding, used for external lead attachment were a serendipitous consequence of the metallurgy of gold and aluminium. (A counter influence, which caused many catastrophic failures until its mechanism was well understood, was 'purple plague', a non-conducting intermetallic compound of gold and aluminium which formed at high temperatures.)

The commercial potential of the transistor was apparent, even before a practical implementation was developed. It was a salesman's dream – a product capable of satisfying a huge latent need. In the early days, when the volume of sales was low, the cost of market entry was commensurate. Potential participants either possessed the skills and equipment necessary, or could acquire them with very little outlay. Later, as markets increased in size, specialist equipment suppliers emerged and device manufacturers relinquished in-house equipment construction. The industry was a technological meritocracy. Companies with the most efficient processes succeeded; those which did not adapt to change, went to the wall.

The transistor and the *pn*-junction diode were the mainstream components of the semiconductor paradigm, as the thermionic triode and diode had been during the first age of electronics. Other thermionic and gas discharge devices also had their semiconductor analogues. Thus the thyristor was the equivalent of the thyratron, whilst the unijunction transistor and the four-layer diode played the role of the gas discharge tubes. The vertical junction field-effect transistor was able to mimic the electrical characteristics of the pentode valve and the zener diode provided a voltage reference as did the neon tube in valve circuits. The existence of so many comparable devices is indicative of the methodology of circuit design during the genesis of the semiconductor industry. The general approach was to attempt to translate the equivalent valve circuit by substitution of an appropriate semiconductor component. It was not until the invention of the integrated circuit and the move from analogue to digital electronics that engineers truly began to think in new terms.

As with the electric light and cable and wireless communications, the technological origins of the transistor may be traced to discoveries made some fifty to a hundred years earlier. Again, like the light and cable and wireless, it was invented at least twice before its time. The transistor finally got off the ground, mainly as a result of wartime research which produced new and suitable materials, but also due to the assembly of a polytechnic team of scientists of the highest calibre – analogous to Edison's laboratory at Menlo Park – by a company which allocated sufficient resources to a management which, in turn, had the creative vision to see the project through to a successful conclusion.

The transistor was developed as a result of a well-directed, broadly based investigation, which was carried out from first principles by a high-calibre, multi-disciplinary team. The discovery of the point contact transistor effect was a chance consequence of rigorous, comprehensive and thorough experimental procedure, but it provided a huge fillip to the project. The team leader, William Shockley, had developed the theoretical basis for the transistor over long period of time and was annoyed when Bardeen and Brattain stole his thunder with the fortunate discovery, but the cognitive dissonance which this engendered, resulted in the conception of a viable alternative by Shockley.

Production versions of the point-contact transistor were based on existing, well-established diode manufacturing technology, but they were soon replaced by the first junction transistors which were fabricated by a brute-force method and, like Edison's tar-putty incandescent lamp, were little more than a proof of the concept. This was, however, sufficient to stimulate enthusiastic work on circuit applications. As with the metallic incandescent-filament lamp, many major paradigm shifts came from without and were based on combinations of materials with felicitous physical, metallurgical and electrical properties

The use of single crystal material rather than polycrystalline germanium which was more readily available for the development work, was an early, informed decision based on theoretical principles. Materials were chosen and their properties orchestrated to construct device topographies yielding desired electrical characteristics. Paradigm shifts were the mechanism by which this procedure was optimised.

The key to the successful initial development of the transistor was a polytechnic research team. Contributions were often made by scientists from different disciplines bringing their particular heritage as a contribution to the feast. Materials scientists chemists and metallurgists made major breakthroughs, but received scant praise for their efforts. Many technological barriers were surmounted *ad hoc* as they were encountered. This did not require unduly creative thinking, merely meticulous attention to detail and mastery of the underlying scientific principles.

The combination of many companies, employing strong R&D teams and enjoying free exchange of information meant that new advances could potentially come from any quarter. If successful, they would be rapidly adopted universally. Some new paradigms offered the prospect of commercial advantage, but, after a brief period of exploitation by the single company that introduced them, they were abandoned and that company reverted to the technological path being followed by the remainder of the industry. Not all technologically elegant solutions proved to be commercially viable. However, due to the underlying economic growth pattern of the industry, it was possible to try, then abandon, them if they were unsuccessful.

Electronic circuit applications for the new transistor expanded rapidly as new fabrication techniques yielded devices with ever improved characteristics. The result of the impact of the classic cash-flow J-curve associated with technological paradigm shifts was cyclic profitability and zero or negative average net profit. This caused many participants to quit – market growth of the order of thirty percent per annum, easy access to know-how and low cost of market entry in the early days attracted many newcomers to the industry. Market leaders came and went with the introduction of new manufacturing methods. Cyclic profitability and zero average year-on-year net profit caused many of them to quit. Research and development were also stimulated because the military potential of the new development attracted a large provision of funds by the US Government.

The most obvious choice of materials for device manufacture, from the point of view of desirable electrical characteristics, was often *not* adopted because alternatives were either easier to fabricate or produced devices which exhibited greater reliability. Silicon, which became the universal material of choice for the mainstream semiconductor industry was a compromise based on these alternative considerations.

As experience increased, threats turned into opportunities. For instance, 'deathnium' which destroyed many early transistors, was found to be caused by deep-trap impurities, iron introduced by contamination from the manufacturing furnaces, and the phenomenon was harnessed to make faster switching transistors for computers. Planar integrated circuits arose from treatment of a threat (formation of a surface oxide layer to counteract pollution) as an opportunity (use of the oxide layer as support for interconnections). This methodology was applied twice in one company – Fairchild – which, as a consequence, became the dominant company in the industry for a while.

The subject chosen for this case study provided a particularly apt example of change for technological reasons in the Schumpeter A-phase because (a) there was always a strong demand for the end product (b) an extremely high rate of growth year-on-year which meant that the payback from paradigm shifts was quick, and (c) mistakes could be abandoned without significant penalty. Change was also facilitated by formal and informal exchange of know-how within the industry.

This case study also provided a unique example of the influence of competition law at the start of a new development rather than when it is mature (which is the usual situation.) Because a Consent

Decree was already in force when the transistor was invented, Bell Telephone System was forced to license all comers. To generate income, it provided know-how to permit the licensees to become established in the new industry. Potentially, this could have resulted in a completely different evolutionary characteristic for the innovation because the sanction was applied from the outset. However, in the long run, the market leaders which emerged were those companies which were responsible for significant paradigm shifts. In the absence of this competition law influence, these actual market leaders may well have been different, but the overall structure of the industry would, in all probability, have been the same, because it was determined by a meritocracy of innovations which offered a technological advance. New innovations came from without, possibly as a result of the 'not-invented-here' syndrome. Absence of response-time monopolies, which would have permitted the advantages of technological paradigm shifts to be pressed home, and freedom-to-use paranoia, which cancelled out the effect of intersecting patent monopolies, allowed competitors to play catch-up in characteristic ologopolistic fashion. Patents played little part because the dominant technology changed rapidly and was superseded before patents were granted or they were either ignored or negated by cross-licensing.

Ultimately, the universal adoption of planar diffusion and epitaxial deposition manufacturing techniques, and the transition from discrete devices to integrated circuits, marked the end of the gestation of the semiconductor industry. By this time the thermionic valve precursor was effectively dead, surviving in only a few niche applications and in price-sensitive markets where it still offered a financial advantage because it was a mature product and all costs were fully amortised. The next springboard was very large scale integration (VLSI), the so-called silicon chip, which was the subject of the next case study.

5.4 Very-large-scale integrated circuits – the silicon chip

The development of very large scale integrated (VLSI) circuits was the inevitable consequence of Jean Hoerni's invention of the planar process and Bob Noyce's development of etched metallic film interconnections. As with many major breakthroughs, the underlying concepts were also identified by others – notably Frosch and Derick at Bell Labs – but the successful company was the one which pushed them through to a well-thought-out conclusion. The received wisdom was to etch away the oxide diffusion mask. Fairchild left it on as a surface passivating layer.

There *were* changes in the fabrication technologies during the Schumpeter B-phase. Processes such as ion implantation and molecular beam epitaxy provided greater precision in the placing of impurities in the semiconductor wafers, but they achieved, in essence, the same end result as the less-refined, early processes of thermal diffusion and chemical vapour deposition. The principal economic consequences resulted from new applications of these fabrication technologies, notably, to the memory cell and the microprocessor.

The personal computer was an obvious application of the microprocessor, but it was of major importance because it permitted bipedal advance. New software could be developed on old processors and migrated easily when a new processor was introduced, giving the innovation an immediate user base. Bill Gates succeeded because he was in the right place at the right time – which was *not* flying his aeroplane over San Francisco bay, the preoccupation of his rival, Gary Kildall who might well have dominated computing with his CP/M operating system software.

Intel was founded by entrepreneurial characters who were not content to work for others. It set out to provide a product which the market needed (semiconductor memory). As with the incandescent lamp and the transistor, the decision to go for a latent market created by an alternative, but flawed, technology (magnetic core memory) made success of the memory chip inevitable, provided the product could be made satisfactorily. Backing three horses to be sure of being first to the winning post was the successful strategy adopted by Intel, which simultaneously developed three separate potential manufacturing processes.

Its first leap forward was the dynamic random access memory (DRAM) chip, the result of an enlightened trade-off – the addition of a cheap power supply gave an order of magnitude performance improvement. The erasable, programmable read-only memory (EPROM) chip, on the other hand, was the serendipitous recognition of the opportunities offered by a physical effect. The opportunity was, however, a manifestation of Pasteur's prepared mind syndrome, since both the initial discovery and the later development were identified as a result of painstaking investigation. The microprocessor, like the integrated circuit, was a logical extrapolation of a proven product (the

DEC PDP-8 computer) – make it smaller, make it in on a single chip. The skill lay in reducing the idea to practice and this was driven by the need to make best use of scarce resources.

The success of Intel was founded on the lucky choice of its 8088 processor to power the first IBM PC. However, this was an example of the successful making their own good luck. The reason that the 8088 was chosen was that the necessary peripheral chips were readily available and the next-generation processor (the 8086) was already in prospect.

By definition, start-up companies are starved of resources. Intel lacked a cash cow which was sufficiently fruitful to meet the demands of the expansion engendered by the runaway success of the IBM PC. Fortunately IBM was in a position to play fairy godmother by taking an equity stake at the appropriate time. Fortunately, also, IBM was so frightened by the prospect of anti-trust proceedings that it failed to exact the full price of exclusivity which it could reasonably have demanded.

Recognition of when to quit is an important component in achieving commercial maturity – Intel left the memory chip market when it became unprofitable and very quickly abandoned a foray into digital watches. (For years after, Gordon Moore, Intel's chairman, wore one of the watches, telling anyone who asked, that it cost $15m.) Another reason that Intel succeeded was because it made full use of the legal process. Like the politicians who rejected Edison's vote counter, it recognised the importance of delay, which, for Intel, amplified the effects of response-time monopoly. Intel was not afraid to hit below the belt if that would achieve an appropriate result. The name of the game was domination and legal filibustering was one of the tools available. Intellectual property monopolies were another. *Sui generis* rights could be created by exerting the right political influence. Market power coupled with the characteristics of the learning curve could be used to control the cash flow of competitors and maintain a quasi-stable monopoly indefinitely.

However, either timidity engendered by lack of confidence or possibly naïvety regarding intellectual property matters in a start-up organisation resulted in failure to establish a dominant patent position with memory circuit chips. The consequence was that competition increased, these products became commodities and the markets ceased to yield viable returns. With the microprocessor, Intel failed to establish the absolute monopoly that patents would have provided. In that case, it succeeded because it won a captive market which was created and supported by IBM. George Westinghouse laid the foundations for Tesla's ac machines in an analogous manner.

A positive management decision to go for a market- rather than a production-led approach resulted in the creation of a legacy-system evolutionary model, which maintained Intel's initial hold and locked customers into its products. This tactic, which was embraced as a result of failure of a proposed ground-breaking product to meet a critical development timetable, was supplemented by a willingness to exploit the legal process to enhance response-time delays, thereby emasculating competitors by controlling their cash flow. Not until the industry was well established did Intel turn to the use of patents and trade marks to reinforce its control of the market. It did, however, exhibit a prudent and opportunistic political attitude. It lobbied effectively to obtain enactment of *sui generis* intellectual property rights (semiconductor mask protection legislation) and, while its predatory techniques in the market place were not dissimilar to those of Microsoft, it reacted in a conciliatory manner and compromised with the authorities on anti-trust matters, whereas Microsoft was more confrontational and became involved in major litigation with the US Justice Department. It is too early to say whether this difference will have any long-term effect, but it did, in the short term conserve resources and allow Intel's management to concentrate on the primary role of developing the business.

Intel succeeded because of the hare and tortoise syndrome. Success comes not to those who make rapid advance, necessitating a fresh start each time, but to those who make an incremental change and build on an existing foundation – like Newton standing on the shoulders of giants. To some, the decision to make each generation a superset of its predecessor was reactionary, but for Intel it delivered a cohort of users who could be up and running immediately.

The rise of Intel was largely a matter of luck, albeit supplemented by a responsive and sometimes cynical management whose decisions, on balance, proved to be correct more often than they were wrong.

The case study demonstrated that the path of evolution of the industry was determined by specific events. The progress would clearly have been different without the influence of IBM, or if Intel had used patents to establish a monopoly over memory chips and the microprocessor.

Under the current paradigm, Moore's Law serves as a predictor of the growth of the semiconductor industry, but other factors will increasingly come into play. At present Keynesian influences drive suppliers along the path of technological development. Eventually, physical parameters, such as the magnitude of the charge on a single electron and optical limits on the ability of lithography to reproduce ever smaller feature sizes, will provide an endpoint to further increases in packing density. As time passes, economic constraints will exert greater influence.

6. Factors which influence the dynamics of innovation

A prerequisite to predicting the course of future events is the creation of a model which leads to an understanding of the interrelationship of the factors which moulded the shape of the past and present. Thus armed, one can approach the task of developing a strategy for the future which is based on the knowledge of those factors most amenable to control and, equally importantly, the most propitious time to exert an influence.

The concept of modelling of dynamically changing systems is based on the premise that certain mathematical relationships provide appropriate descriptions of observed characteristics. Manipulation of those relationships will then lead to an understanding of how those systems develop under different conditions and this will provide tools for adapting those systems to meet pre-defined criteria.

Analysis of a system is assisted by the process of model building. This permits relationships between the components to be developed using established mathematical methods to gain a greater understanding of the process and, possibly, also predictability of its future course.

My principal hypothesis was that it was not possible to treat the components of innovation separately. This therefore set an objective of creating an holistic model which took into account the need to consider the collective influence of all of the elements.

Like the evolution of biological species, innovation has a phylogenetic tree structure. Methodologies appropriate for biological systems are, therefore, also applicable for innovation. In the process of analysis, formulation of a problem is followed by qualitative description. Input-output diagrams are then used to illustrate signal flows and develop equations for the model.

Innovation may be regarded as a singular system which interacts with the socio-economic environment by means of a series of flows. Subsystems are identified, together with the relevant variables and control parameters.

As certain variables are inaccessible, the system may be treated as a black box. In such a model, the practice used in accountancy may conveniently be followed – revenue flows are distinguished from transfers of capital. Dimensional integrity is maintained through the separation of these flows into elementary constituents such as cash, materials and know-how. Variables comprise infrastructure, work-in-progress and market structure and control parameters include the laws of physics, facilitators and the legal regime. Not all of these components are measurable using currently available metrological techniques.

Timing *is* important. Invention occurs in cycles – the wheel *is* re-invented at periodic intervals. Its success at a particular genesis will, however, be entirely dependent on the then current environment.

Innovation is a socio-economic process which follows a binary decision tree. Progress is contingent on the existence of enabling technologies and potential demand, both of which may be time-sensitive.

An invention which is before its time cannot succeed – in the 1920s, Lilienfeld's proposal for the transistor failed because semiconductor materials' technology was immature; the carbon filament lamp succeeded because, not only did Edison (in the words of James Swinburne) 'make a noise about it', he also set up the necessary infrastructure to meet the pent-up demand which had been created by the imperfections of the luminous flame as a light source. An invention which emerges successfully today may be irrelevant at a later date and would fail if it were to be introduced then. Inventions which succeed as solutions to a current problem are no longer required when that problem goes away.

Success in innovation arises from maximisation of the capital flows. This is a consequence of the optimisation of the revenue flows which result from interactions between the state variables and control parameters of the individual system.

Within this model, individual innovations emerge, wax and wane. During their existence, they influence the evolutionary path of other innovations as well as contributing to the general accretion of wealth. If the innovation is treated as a black box, a number of system variables will exhibit temporal changes in characteristics over the innovation's lifetime. These variables will be influenced by intrinsic and extrinsic control parameters as well as their mutual interaction. Some parameters, such as the laws of physics and the properties of materials are immutable, although efficiency of exploitation of those properties may improve as experience is gained. Other parameters, such as patent monopolies, will be ephemeral and, indeed, their propensity to control will be different at various stages in the innovation life cycle.

The logistic equation of each innovation is unique. It must therefore be constructed individually on the basis of observation. Since many variables are incommensurable, relationships can only be established qualitatively. Curve fitting will permit the derivation of a degree of mathematical predictability, but the associated uncertainty will be great.

Analysis of the effects of an innovation is complicated by the fact that, initially, at least, its influence is small and will be obscured by much greater socio-economic changes in the environment which are taking place concurrently.

7. General conclusions

From the initial observation that the process of technological advancement is not a uniform progression, my research set out to produce a model by means of which an innovator could optimise his use of resources and speed the achievement of his goals, whilst governments could apply its lessons to attain more effective implementation of public policy.

Rejecting the more customary approach that it was sufficient to study the dynamics of innovation from a unilateral viewpoint, the chosen starting premise was that many contributory factors should be taken into account. The value of this contention was demonstrated by multifarious examples of interactions between system variables and parameters to control capital and revenue flows between an innovatory system and its environment. These showed that, not only are there many elements which are part of the equation, but that the timing of the interactions is also significant.

A consequence of coming from a multidisciplinary standpoint was that it led to the conclusion that methodologies developed to solve problems in other fields of endeavour could be applied to analogous problems in the study of the development of innovation. Mathematical analysis and modelling techniques which are useful in biology were chosen because innovation, too, is a process of survival of the fittest, with paradigm shifts taking the place of genetic mutation to create the phylogenetic tree structures which are characteristic of the evolution of biological species.

A series of case studies, in which the factors of innovation were examined iteratively over a period of two centuries, provided insights into macro-economic changes. Notable amongst the observations was the vacillation of public policy towards private monopoly. During the latter part of the nineteenth century, opinion was strongly against private ownership of utilities which existed to serve the public. This resulted in legislation which, whilst recognising the right of private capital to introduce innovations, took the assets into public ownership when they became commercially viable. These attitudes persisted for around half a century, giving rise to such laws as the 1847 and 1871 Gasworks Clauses Acts, the 1868 and 1869 Telegraph Acts, the 1870 Tramways Act and the 1882 and 1888 Electric Lighting Acts, and judicial decisions, such as *Attorney-General* v. *Edison Telephone Company of London*, **6 QBD 244** which put the public policy into practice.

By the end of the 1800s, cartels were beginning to emerge. The reaction was one of opposition in the United States but one of official approval in Germany. In Britain the cartels initially remained covert, but there were later attempts to justify their existence. (*quaere* – why was Germany in favour of cartels, but antipathetic to patents?) In the United Kingdom, opinions which were hostile at the end of the nineteenth century changed to such an extent that, by the 1930s, judicial approval was given to dominant suppliers in a series of High Court decisions on the compulsory licensing of patents relating to the manufacture of tungsten filament lamps, thermionic valves and wireless broadcast receivers. **[1915] RPC 202, [1929] RPC 457, [1929] RPC 479** Even whilst this was happening, the next swing of the pendulum in the other direction was commencing.

In the New World, embryonic opposition to cartels had emerged in the shape of the 1887 Interstate Commerce Act and the Sherman Anti-Trust Act of 1890. At first, the electrical industry was able to render this legislation nugatory. General Electric and thirty-four other companies circumvented the effects of a 1911 prosecution by re-grouping and producing mere paper acquiescence. By the latter half of the twentieth century, however, a number of anti-trust cases had given rise to Consent Decrees which re-shaped the progress of development and caused industry to be much more circumspect in its conduct. However, British industry has, until the present time, still been cocking a snook at authority and continuing along its own sweet way, despite adverse Monopolies Commission reports.

The influence of regulatory, intellectual property and competition laws was subservient to the driving force of market economics and the constraints and opportunities presented by the properties of materials. As the case studies show, Edison, General Electric and Microsoft support the proposition that, if your purse is deep enough, you can circumvent the will of the legislators, whilst Swan and IBM are a cautionary tale of the dangers of paying too much attention to the perceived interpretation of statutes. On the other hand, the delays of the legal process (as in the case of Fleming's invalid US diode detector patent and Intel's filibustering), the consequences of legal etiquette or an inexperienced judge in creating precedents in a common law system (Edison's UK litigation), an inappropriate legislative precedent (the Tramways Act 1870) or suspension of the patent system during hostilities (USA in World War 1) can have the effect of changing the structure of an industry.

The mechanics of invention also changed, partly as a result of Edison's development of the concept of an industrial research laboratory. In the nineteenth century, solitary inventors were *de rigueur*, but, by the end of the twentieth century, many, if not most, patents had multiple inventors. With the effective demise of the heroic inventor as part of the ever-increasing trend towards collaborative research, this is a change which is not likely to be reversed.

When Edison and Swan first invented the incandescent carbon filament lamp, the need for a cheap and reliable source of artificial lighting was universal. However, although communications were reasonably good, each pursued the development along his own lines. In particular, Edison constructed his lamps from bamboo fibres, whilst Swan quickly moved to structureless filaments fabricated from extruded cellulose. Separate companies were set up in each territory and, despite the fact that they combined forces in Britain for pragmatic reasons concerned with the conduct of patent litigation, the partnership was not pursued elsewhere.

In the Victorian economy, trade was highly protectionist, jealously guarded by means of tariff barriers and the Imperial Preference. During the first half of the twentieth century, major companies operated internationally, but this was done through the medium of individual subsidiaries in each country. Towards the end of the 1960s, triggered by liberalisation of trade through the agency of the General Agreement on Tariffs and Trade (GATT), and by the establishment of new technologies which required huge investment and operated to universal standards, industries began to organise on a global basis. Led by the semiconductor integrated circuit and automobile industries, manufacturers set up plant in territories chosen because labour costs were low, they were convenient for their markets or local governments created incentives which distorted the normal economic rules of supply and demand. A political parallel to the classic structures of market economics evolved and the world technological scene moved from a regime dominated by America to one in which Japan, Europe and the tiger economies of the Pacific Rim played a major role. Again, this change is unlikely to be reversed because the economies of scale resulting from global operations preclude the establishment of industries which operate solely on a national basis.

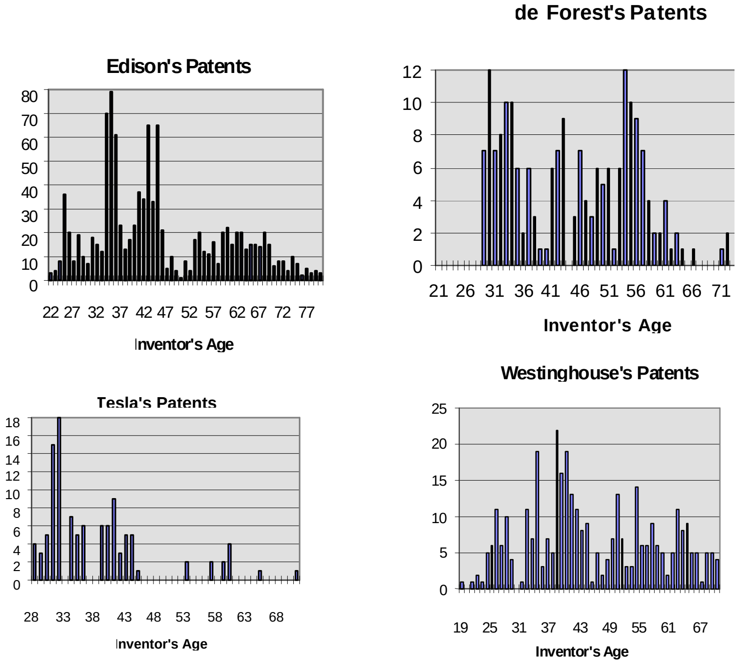
The time taken for changes in laws to follow socio-economic developments is measured in decades and for international harmonisation of legislation in centuries. Intellectual property law has been in the vanguard, but the movement which began with the Paris Convention in 1883 has still not achieved complete unison, partly due to American reluctance, for constitutional reasons, to adopt measures which are readily accepted elsewhere. The stand-off, in the first part of the twentieth century, between Marconi and de Forest with the Fleming thermionic diode and the de Forest Audion patents arose because the USA did not, at that time, have renewal fees for maintenance of patent rights and thus the impecunious de Forest's US patents did not lapse for non-payment as they had overseas. Edison and Swan dominated the US and British markets for incandescent lamps because the common law system gave them strong patents which they were not able to obtain in territories with inquisitorial legal codes which took into account inventive merit in the determination of patentability.

With the current pressures for harmonisation of laws and the development of global industries, it is unlikely that any country will henceforth diverge significantly from the common path. The reason for this is that, if a country attempts to do something which is out of line, economic pressures will place it at a disadvantage. Of course, there will be the occasional aberrant judicial decision, as in the Raytheon case on patentability of software-related inventions, [1993] RPC 427 but such divergence will only be transitory. (Commercial interests immediately started lobbying for a change in the law to negate the effect of this judgement.)

The overall trend to universal harmonisation will be followed more strongly in the future. The main intellectual property laws of patents, trade marks and copyright had diverse national origins and therefore needed to be brought into mutual conformity. New intellectual property laws to protect developments in technology, such as semiconductor masks and databases, are enacted as *sui generis* rights in internationally agreed format, or, at least, following a common precedent, so that, in the future, there will be no delay whilst laws are aligned, although there will still be uncertainties resulting from differing judicial opinions and national prejudices.

The main limitation of my investigation was that it attempted to devise stochastic rules by analysis of what are, essentially, unique deterministic systems. Although certain state variables and control parameters were taken as a basis for model building, their selection was predominantly an intuitive choice rather than a generalisation from first principles. There was, however, an underlying objectivity, since the model construction was based on an extensive case study. In support of the choice, there is no counter-indication to suggest that the conclusions reached are not broadly applicable. Because it is based on socio-economic needs, innovation in biotechnology, for instance, will be governed by the same financial incentives and general constraints as innovation in electronics. It is merely the relative importance of the variables and parameters which will differ. Patents for chemical compounds, for example, create an absolute monopoly, whereas, in electronics, patent monopolies intersect; pharmaceuticals are manufactured under stringent regulatory regimes which have the effect that they take around eight years or more before they reach the market place, whereas in the brown goods market, *caveat emptor* and product liability laws, which are only useful against gross misdemeanours, provide the protection for consumers.

A major problem in the study of the dynamics of innovation is the length of the time scales involved. It takes about thirty to forty years for a new development, such as digital television or the transistor, to become an essential part of the everyday life style. In radio, for example, amplitude modulation broadcasting began in the second decade of the twentieth century, frequency modulation started to take over in the 1950s and we are just now commencing the changeover to digital standards. With such slow evolution and with so many variables and interactions in an innovatory system, it is very difficult to identify contemporary causes and effects. Retrospective analysis is simpler, but a changing macro-economic environment, with different time scales for different control parameters, means that history will not repeat itself exactly, even if there is a cyclic element to the temporal dependency.



Variation of heroic inventors propensity to invent with age

A unique aspect of my research is that the initial hypotheses were based on my personal experience of making inventions which satisfied the statutory criteria of novelty and non-obviousness, pre-requisites for the grant of patents. Viewed four decades later, which permits them to be assessed contextually, this provided a special insight into the process of invention.

Although the finding might be expected, because many natural phenomena have a skewed gaussian distribution, it was interesting to observe from their patent filings that heroic inventors have a propensity to invent which changes throughout their lifetimes in such a manner. Within the overall gaussian envelope, there were individual spurts of activity as new projects and ideas occupied the inventors' minds. There was also a dip during early middle age, possibly due to the conflicting demands of other interests at that time of life.

The semiconductor industry provided an excellent exemplification of the influence of innovation on the ebb and flow of market dynamics. Different phases of economic development were well illustrated – the Schumpeter A-stage passed through characteristic changes as the different dominant technologies evolved. In 1959, the transition to the B-stage took place. The basic manufacturing technologies of planar diffusion, epitaxial deposition and ion implantation were then adopted universally and have only undergone improvements in details ever since. During this evolution, various market characteristics were apparent. Using a biological analogy, markets were identified as having lion, hyena and vulture phases with the rich feast of exclusive access to a fresh invention, the shared spoils of a mature market and the picked bones of a superseded product. On occasion, there was even a phoenix stage when a market rose from the ashes, as did gas lighting when invention of the gas mantle caused the postponement of the paradigm shift to electric lighting. In an expanding market, such as the one which existed immediately after the invention of the transistor, at any given moment in time, individual companies operated in an instantaneous oligopoly, but, in the long term, emerged, prospered and failed – surfers and sinkers in a market which emulated an ocean wave. The forward progress was inexorable, but the participating firms waxed and waned as their proprietary technological contribution first found universal favour and then was abandoned. In this environment, patents were ignored because the technology moved on before legal disputes were resolved or even initiated. Technological decisions were often a compromise with non-optimal performance being accepted because a particular raw material was easier to work – silicon with its lower charge carrier mobility but stable oxide was adopted in preference to germanium for integrated circuit manufacture.

As well as the statutory intellectual property monopolies, informal response-time and *de facto* monopolies were important in the creation of ultimate market structures. Feedback in this process had a stabilising effect in oligopolies, where initiatives tend to elicit a countervailing response from other market participants. In markets with a bipedal structure based on two advancing technologies, such as personal computer hardware and software or integrated circuits and photolithography, the possibility of overall positive feedback was identified. This gave rise to characteristics similar to those of a relaxation oscillator and created an 'anti-duopoly' or 'flip-flopoly'. In the analogous electronic circuit, output grows until limited by the impedance of the feedback loop. With the VLSI integrated circuit, consumer demand for 'killer' software applications controls growth and the magnitude of the charge on the electron and size constraints of photolithographic imaging will provide the asymptotic limit.

The concept of Moore's Law, which was expounded by Gordon Moore on the basis of extrapolation of three empirical observations of successive generations of integrated circuits, was demonstrated to be a special case which arose in the evolution of bipedal markets. The relationship was generalised and a new 'Moore's Parameter' introduced. In software development, an effect similar to Parkinson's Law was identified, where the size of programs expands to fill the computer memory available.

The emergence of global markets gave rise to the political analogues of monopoly and oligopoly – the terms monocracy and oligocracy were used to describe their characteristics. The USA practises a form of technological imperialism. Its government forced semiconductor mask protection rights on its trading partners and refused to grant export licences for 128-bit encryption software in an endeavour to retain an ability to maintain surveillance of communications on the Internet, whilst its companies colonised the world with products such as Microsoft Windows software, Intel integrated circuits and Ford cars. ('You can choose any colour, so long as it is black.')

In constructing a model of the innovation system, a key perception was that derived inventions have a separate character from that of seminal inventions. The former play the part of state variables, whilst the latter are parameters controlling the overall envelope which constrains the development potential.

Bipedal markets hold the potential for faster growth than single-technology innovations. In particular, the strategies employed by Intel, following its initial felicitous development of the microprocessor, led to its domination of this section of the semiconductor market. Its finances exhibit underlying chaotic characteristics, which Intel has managed to harness to its advantage. The progress of Motorola in the microprocessor market and of the semiconductor-memory-chip manufacturing oligopoly are tied to the technological features of Intel's strategy. A further aspect to such a study is the ancillary role of Cyrix and AMD as alternative suppliers in the mainstream microprocessor market – could AMD jump ahead of Intel, with the early introduction of devices such as the K6 processor, or must it, because of Intel's market power, remain a follower? The demise of Mostek – an early pioneer – and the relegation of Zilog, which had a product (the Z80) superior to that of Intel's first viable eight-bit processor (the 8080) – to the role of supplier to niche markets are also worthy subjects.

Lessons may be learned from the decline and fall of the industry giants. On the back of demand for computing, IBM grew to be one of the world's most powerful companies. It was slow to adapt to the emergence of the personal computer and the rise of networking, which moved products more quickly, but had far lower profit margins. Apple came to prominence as a result of the development of the spreadsheet. It prospered because Steve Jobs opportunistically exploited the graphic user interface which was developed by the Xerox Palo Alto Research Centre, but not recognised as a potential winner by Xerox' management at the East Coast headquarters. It withered because it attempted to retain a proprietary hold over its operating system when the Windows system of its rival was accessible to all.

8. Supplementary Information.

Appended to this evidence are tools and background information used in the preparation of the case

Table 8.1

Structure of database used for preparation of case studies

Field	Data	Mandatory?
AccnNo	Unique accession number allocated on data entry to permit identification and separation of data	Yes
Check	*Aide memoire* that some further action is needed	
KeyDat	Key Date; this might, for example, be the priority date of a patent	Yes
PubCod	Publication Code for the source of the information in this entry	Yes
SrcPag	Source page number	
ActTyp	Activity Type - classifies the information, e.g. PAT = patent, GOV = government intervention	Yes
PrPty1	First party to the activity e.g. owner or assignee of a patent	
PP1Nat	Nationality of First Party (two-letter ICEREPAT country code e.g. GB, US, DE)	
STitle	Brief description (255 words) of the activity	
PrDat	Priority Date for patent applications	
PrCtry	Priority Country Code	
PrSerN	Priority Serial Number	
Comment	An *aide memoire*	
Weight	Importance on a scale 1-5	
StarRtg	Star rating – as previous field	
Invtr1	First inventor	
Invtr2	First co-inventor	
Invtr3	Second co-inventor	
Invtr4	Third co-inventor	
Invtr5	Fourth co-inventor	
GBPatN	British patent number	
DEPatN	German patent number	
USPatN	US patent number	
FRPatN	French patent number	
EPPatN	European patent number	
WOPatN	PCT (International) patent number	

studies. These comprise databases, from which information may be retrieved using industry-standard computer software, and narrative descriptions which expand specific aspects of the main analysis.

8.1 Databases

The case studies were based on a foundation of relational databases using either Borland Paradox or Microsoft Access software. Within the databases, the data which have been collected are stored in fields. For example, when the case studies were being prepared, an associated database included the separate fields listed in Table 8.1. This permitted the data they contain to be analysed and displayed in a multiplicity of formats. For example, although the collection of the data for the *Semiconductors* database took some thirteen months, extraction of relevant information may be performed in a matter of minutes. For example, using the Key Date field, the data may be sorted in date order to produce a chronology. Sorting first by date, with ancillary sorts by inventor and then by First Party (in this case the patent assignee) permits the employment history of an individual inventor to be extracted. The use of multiple fields for co-inventors allows patent data to be analysed to determine how many contributed to a particular innovation. (1013 inventions had a single inventor, 365 had two, 71 had three, 6 had four, 3 had five 1 had six and 1 had seven.) The Weight field permits the ready extraction of the most important activities e.g. the most significant inventions. Note, however, that this field entry is a subjective value judgement on the part of the compiler of the database.

The *Semiconductors* database was compiled using the US Patent Office Gazette. This journal is published weekly and gives bibliographic data, including names of inventors, priority date and country, on all patents granted in the USA. The patents are grouped by subject matter in accordance with the US Patent Office classification system. Each patent record contains the main patent claim and one of the drawings from the corresponding patent specification. In preparing the database, the author assessed all semiconductor patents published in the Schumpeter A-phase of this innovation. A 255-character (maximum) title, which encapsulated the essence of the patent, was prepared and the invention was assigned a star rating on a scale one to five. Five-star inventions were those which made a major contribution to the development of the paradigm, whilst one-star inventions were either mere paper proposals or non-workable. During the key decade of the 1950s, 1.1% of the inventions fell into the five-star category, 9.8% were four-star, 16.9% three-star, 69.1% two star and 3.1% were ‘also-rans’, a negation of the Pareto (eighty-twenty) rule.

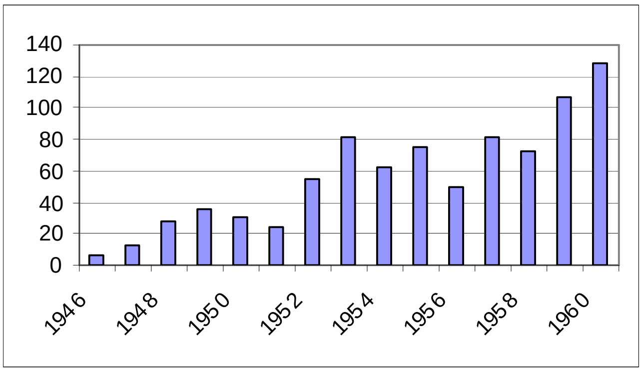


Figure 8.1

Number of semiconductor patent applications filed

By compiling these data as a relational database, information may be extracted in many forms. For example, the number of semiconductor patent filings, year-by-year, is shown in Figure 8.1. It is interesting to note from this database that the Bell Telephone System, the originator of the transistor, was the most prolific patentee, obtaining 168 patents. It licensed all serious potential manufacturers. Of these licensees, for example, Texas Instruments, which introduced the silicon transistor and the integrated circuit, obtained 89 patents, Radio Corporation of America, which developed the germanium alloyed-junction transistor, obtained 117, Fairchild, the source of the planar process which heralded the paradigm’s Schumpeter B-phase, gained 36 patents, IBM 63, Motorola 45, Philips 56 and Siemens 67.

Databases of key semiconductor inventors were extracted as sub-sets to permit a more detailed analysis of their contribution to be carried out.

Individual databases were also compiled separately for certain heroic inventors (Edison, Westinghouse, de Forest and Tesla). These databases included a field for the age of the inventor when the corresponding invention was made. These data were then extracted as a histogram showing the number of inventions made during each year of the inventor's life, thereby permitting conclusions to be drawn concerning age sensitivity of the propensity to invent.

This evidence contains the databases listed in Table 8.2.

Table 8.2
List of databases

Database File Name	Number of entries	Comment
Valve and lamp key events	619	Events which made a significant contribution to the evolution of the lamp, valve and communications industries
Semiconductors	1473	Inventions made during the Schumpeter A-phase of this innovation
Bardeen's patents	9	Inventions made by the co-inventor of the transistor
Christensen's patents	3	Bell Labs' materials scientist
Edison's patents	1101	Heroic inventor
Gibney's patents	3	Bell Labs' device engineer
Hall (RN)'s patents	15	Inventor of laser diode
Hoerni's patents	4	Co-inventor of planar process
Intel's patents	1519	Major integrated circuit manufacturer
Lilienfeld's patents	8	Inventor of pre-cursor of the transistor
Noyce's patents	9	Inventor of planar integrated circuit, co-founder of Intel
Ohl's patents	8	Bell Labs' materials scientist
Pankove's patents	17	Inventor of the alloyed junction transistor
Pearson's patents	10	Bell Labs' materials scientist
Shockley's patents	31	Inventions made by the co-inventor of the transistor
Teal's patents	5	Bell Labs' materials scientist
Tesla's patents	110	Heroic inventor
Theurer's patents	10	Bell Labs' materials scientist
Westinghouse's patents	356	Heroic inventor
Semiconductor patents rated 3-star plus	345	Significant inventions which contributed to the development of the Schumpeter A-phase of the semiconductor industry

8.2 Appendices

8.2.1 Appendix 1 – Invention in the early days of the silicon chip: the Author's personal perspective

At the start of his professional career, the author worked in research and development of the early silicon chips. During this time he made some sixteen inventions for which patents were granted in Britain, the USA and various other territories. Examination of the technological and commercial context in which these inventions were made, the mind set of the inventor and how it was formed by his background and education, gives a unique insight into the process of invention and provides a starting point for the wider-ranging investigation.

After four or five years in R&D, the author joined the Patent Department of International Telephone and Telegraph Corporation, which, at that time, was a multinational conglomerate and the ninth largest company in the world. In this post, he had responsibility for patenting inventions concerned with the manufacture of semiconductor devices and served on the ITT Worldwide Strategy and Action Committee which developed strategies to guide the corporation through the transition from national organisation to global operation during the late 1960s and early 1970s. For this work, he liaised with manufacturing plants and research laboratories in Germany, USA and the United Kingdom. He prepared a detailed survey of all UK patents concerned with the manufacture of semiconductor devices. At this time, the semiconductor industry was moving from the Schumpeter A-phase to the Schumpeter B-phase of development. This report therefore contained a useful epitome of inventions made by an industry in transition and gave an insight into the diverse contributions of different companies and inventors. It provided the background knowledge for the preparation of the third case study.

8.2.2 Appendix 2 – Chronology of the incandescent lamp and thermionic valve

This document was prepared from a variety of sources. (See 'Valve and lamp key events' relational database.) Starting in the seventeenth century, the chronology contains details of key technological and commercial steps which contributed to the development of the carbon filament lamp, the thermionic valve, the electric telegraph and wireless communications. It provides the framework on which the first and second case studies were built.

8.2.3 Appendix 3 Abridgement from Chapters 67-69 and 81-83 of *Menlo Park Reminiscences* by Francis Jehl

Francis Jehl was one of Thomas Edison's assistants. This narrative describes the development of the bamboo filament lamp. It illustrates the logistics of the transition from invention to manufacture.

8.2.4 Appendix 4 – Illustrated Catalogue of the Swan United Electric Light Company Limited, 1883

This document is a facsimile reproduction of Swan's lighting catalogue prepared when the incandescent lamp was in its infancy. It contains a description and price list of the lamp and its ancillary equipment, together with a description of a pathfinder installation of this innovation. It provides an indication of the then current state of development of the innovation some five years after its initial conception.

8.2.5 Appendix 5 – The Edison Filament Case by James Swinburne

Taken from *The Telegraphic Journal and Electrical Review* 6 August 1886 pp129-132, this is a contemporary critique of litigation which shaped the development of the electric lamp industry in the United Kingdom. The author was a lighting engineer and consultant who set up plant for Swan and pioneer organisations abroad.

8.2.6 Appendix 6 – US Patents naming Edison as inventor

Collated from biographies, this is a comprehensive schedule of inventions made or claimed by Edison. It contains such gems as a method of vacuum preservation of meat, which takes no account of anaerobic decomposition, a steam-powered lamp, which does not work because the physical principles on which it was based are flawed, and a vacuum pump, which was clearly designed by one of Edison's assistants. (See Chapter 4.)

8.2.7 Appendix 7 – Chronology of inventions and discoveries relating to semiconductor devices

This chronology, which is derived mainly from US patent specifications, includes all semiconductor device inventions made during the fifteen years following the discovery of the transistor effect at Bell Laboratories. The date given is the application date of the respective patent, the actual date of conception (where this can be ascertained) or the date of publication of a corresponding technical paper. Also listed are the assignee, the inventor(s) and a star rating which indicates the value of contribution made to the development of the art.

8.2.8 Appendix 8 – Personal Perspectives of Inventors

This appendix contains extracts from autobiographies and biographies of key inventors. It provides an indication of their thinking and motivation. The inventors included are John Ambrose Fleming, the inventor of the thermionic valve, Lee de Forest, the inventor of the first electronic amplifying device and a pioneer of radio communications, John Bardeen, Walter Brattain and William Shockley, winners of the Nobel Prize for their invention of the transistor, Gordon Teal, a materials scientist responsible for the first silicon transistor, and Marcian E. (Ted) Hoff, Federico Faggin and Masatoshi Shima, who invented and developed the microprocessor. (Bardeen was awarded a second Nobel Prize for his contribution to the understanding of the phenomenon of superconductivity.)

8.2.9 Appendix 9 – US patents granted to Intel

This is a schedule of patents granted to Intel during the period from its incorporation until it became the dominant company in the semiconductor industry.

8.2.10 Appendix 10 – Elements of chaos theory

An outline of basic concepts underlying chaos theory, some of which aid understanding of the dynamics of innovation.

8.2.11 Appendix 11 – The processing of VLSI integrated circuits

This is abstracted from *Integrated circuit fabrication technology* by David J. Elliott and provides a technological background to the third and fourth case studies.

8.2.12 Appendix 12 – The use of cross-correlation to identify data masked by noise

An example of how this mathematical technique may be utilised to extract relevant data.