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Can the Large Penrosian Firm cope with the Dynamics of Technology?*

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SUMMARY

Whilst knowledge is a growing feature of corporate competitiveness and growth, it will make firms increasingly dependent on outside resources (including public and foreign resources), and will be increasingly disruptive to their internal organisation. This is because knowledge is increasingly specialised in its production, and leads to periodic step-jumps in technical performance with potentially disruptive effects on corporate organisation.

1. Introduction

Edith Penrose is one of the few eminent economists of the 20th century who not only considered what happened inside the business firm to be important for economics, but also had interesting things to say about it. She rightly criticised the mainstream theory for its assumptions of perfect foresight and rationality amongst managers (1959), and - at the other extreme - the use of biological metaphors for the absence of any rationality whatsoever (1952). Anticipating the later work of Nelson and Winter (1982), she saw the usefulness of the concept of organisational "routines", recognised that much useful knowledge central to the diversification and growth of the firm is tacit and learned through experience, and thereby understood why the growth of firms is path-dependent. Section 2 of this paper argues that many of the tasks of corporate routines, whose purpose is to link advances in knowledge to product diversification and growth, are still the same as those described by Penrose in her various writings.

In the Foreword to the Third Edition of her book, written in 1995, Edith Penrose identified both the growth of knowledge and of networking as major features of the modern corporation. I shall argue in sections 3-5 that, whilst the importance to competitiveness and growth of firm-specific knowledge will continue to increase in future, business firms are likely to become both less self-contained and more dependent on outside knowledge sources, and more difficult to organise internally. This is because the nature and production of knowledge is increasingly specialised, and because the knowledge produced leads to periodic step-jumps in improved technical performance (the contemporary cases being information and communications technology - ICT, and biotechnology) with potentially disruptive effects on established organisational practices. The combined effects of these processes may increasingly undermine the nature and growth of established large firms in future.

2. Knowledge and Diversification

In the main Penrose book (1959), a sound corporate base of technological knowledge base is identified as a major source of product diversification and growth. As an example, the mechanical and mass production capabilities of *General Motors* are shown as major vectors of the company's product diversification. In her study of the *Hercules Powder Company* (1960), she also illustrates in depth a story of a typical chemical company diversifying on the basis of its mastery of organic chemistry. Similar stories can be told of electrical and electronic companies diversifying on the basis of their competencies in electromagnetism and radio waves (Reich, 1985), and now of telecommunications equipment and software companies by exploiting Moore's Law and digital compression[1]. Experience tells us that not all design and production competencies enable product diversification: the core competence of steel firms turns out to be ….. making steel. Nonetheless, pervasive technologies emerge periodically from knowledge-based, step-jump improvements in the performance of key productive inputs (e.g. materials, energy, transportation, machinery, information) that have potential applications in all sectors (Freeman and Louca, 2001). Firms developing and exploiting these opportunities have diversified and grown on the basis of an ever-widening range of applications, just as Penrose described.

[1] For reviews of the evidence, see Pavitt and Steinmueller (2001), and Tidd et al. (2001)

The continuing importance of knowledge-based product diversification has been matched by the continuing importance of specific managerial tasks, some of which were identified by Penrose.

- Integrating learning activities across specialised corporate functions, and particularly between R & D and marketing (Burns and Stalker, 1961)
- Dealing with an inevitably imperfect M-form organisation, given the impossibility of neatly decomposing technological activities with pervasive applications into established product divisions (Tunzelmann, 1995)
- Coping with the difficulty of *ex ante* evaluation of R & D activities, given the high levels of technical and market uncertainties (Mansfield et al., 1972; Schnaars and Berenson, 1986). As a consequence, firms tend to oscillate between judgement-based systems (which fail because it is difficult to distinguish between good judgement and luck), and rule-based systems (which fail because rules inevitably simplify, and may miss critically important variables)
- Keeping technological practice ahead (but not too far ahead) of underlying scientific theory, by developing new engineering disciplines - most recently, software engineering, and by exploiting major scientific breakthroughs - most recently, in molecular biology (Rosenberg and Nelson, 1994; Constant, 2000)[2].

3. Knowledge and Networks

However, this is only part of the story. Already in the 1970s, G. B. Richardson (1972) argued that individual firms were not isolated but heavily networked in co-operative agreements with

[2] For an illustration of how these two features have combined to revolutionise the practice of drug development in the pharmaceutical industry, see Nightingale (2000).

their suppliers, customers and other institutions. Accessing knowledge has become an important purpose of these corporate networks (Hagedoorn, 1992). Established products have to incorporate an increasing range of advancing technologies. Firms in all sectors have to cope with the increasing range of specialised bodies of knowledge that are becoming useful, given the advantages of specialisation in knowledge production foreseen by Adam Smith (Pavitt, 1998). Compare the bodies of knowledge in the loom in the early 19th century (almost exclusively mechanical) with today's version (now also including electrical, electronic, aerodynamic and software knowledge). Note also that today's carmakers must master and incorporate electronics and software technologies in their products and design processes, if they are to remain competitive.

Of course, the typical business firm does not need to develop competencies in all fields of technological knowledge. Some may be irrelevant (e.g. biotechnology in the production of electronic chips); others may be incorporated in purchased hardware (materials science in better steel); and yet others may be provided through a modular and simple interface (e.g. electricity through a plug connection). Furthermore, Arora and Gambardella (2001) have argued more generally that the tacit component of knowledge is becoming less important, and that the increasingly important codified component can be recognised, protected and traded. Under these conditions, one might expect those firms would have technological profiles that are more specialised than their production profiles. However, this is not the case.

- The *first* characteristic of the technological competencies in large firms is that they are spread over a wider range of fields than those associated with their core product competencies. They all include technologies associated with production machinery, control instrumentation, and organic chemistry (Granstrand et al., 1997).

By way of explanation, Brusoni et al. (2000) have argued that some in-house technological competence in the firm without associated production is necessary under two conditions. First, when new product development involves a complex array of interdependent components or elements (e.g. automobiles, chemical processes) the interactions between which cannot be predicted: under these conditions, the firm requires the capabilities to test and improve a fully assembled product. These will include knowledge of the technologies of components, sub-systems, production machinery, and chemical processes, which is precisely what the evidence shows.

Firms also need to know more than they do when - even with simple modular interfaces - imbalances in performance are caused by uneven rates of change in the performance of components, and sub-systems: for example, the effects of the introduction of jet engines on airframe design (Mowery and Rosenberg, 1982). This helps explain the second characteristic that we can observe over the past 30 years in the world's leading firms (Granstrand et al., 1997).

- *Second*, over time, an increase in the spread of competencies within large firms, particularly into fields like materials, ICT and biotechnology.

This increase in spread of corporate technological competencies over time reflects corporate search processes associated with the evaluation of new, potentially rich and fast-changing fields of technical change. For example, Miyazaki (1995) has shown how Japanese firms went through an extensive period of search, trial and error, before identifying the potential application of advances in opto-electronics that they were capable of exploiting commercially. Similarly, Prencipe (1997) has shown how aero-engine firms have progressively accumulated in-house capabilities in the fields of new materials and ICT that have become critically important in engine component performance and control systems. In the case of Ericsson's successful diversification into the development of mobile telephone systems, Granstrand and his colleagues (1992) have shown how this required the following: first, a marked increase in the range of technological fields in which the company needed in-house competence: second, an increasing interaction with outside sources of technological knowledge and related products: and third, a marked *increase* in the R & D expenditures required to co-ordinate and integrate activities in a wider range of fields of technological knowledge.

This helps explain what we can observe over the past 20 years in the world's leading firms: the apparent paradox of both an increased number of inter-firm alliances, and *increasing* spread of in-house technological competencies in the same fast-changing fields: information and communication technology (ICT), biotechnology and materials. The reason for these alliances is not the conventional one of cost-cutting through out-sourcing, but of learning and exploiting new competencies related to their established ones.

In both cases, firms "know more than they can do": they maintain in house technological competencies, even when they outsource the related production, in order to be capable of co-ordinating in-house product and process change with changes in the supply chain and in emerging technological opportunities (Brusoni et al., 2000). Corporate R & D consequently now has three faces rather than the two identified by Cohen and Levinthal

(1989): innovation, imitation and the co-ordination of external changes in the supply of artefacts and knowledge. This last function is often called “systems integration”.

This "systems integration" capability (Prencipe, 2000) is likely to grow in importance in future, because of the nature of contemporary changes in technology itself. In particular, the rapid pace of change in ICT is increasing external co-ordination in knowledge and physical production through three mechanisms:

- The emergence of new product markets through new combinations of knowledge (e.g. mobile telephony, with electronic chips essential in handsets)
- The digitalisation of information which has led to the increasingly systemic nature, not only of manufacturing production, but also of commercial exchange (e.g. banking, retailing) and of consumption (e.g. digitised consumer electronics).
- More rapid international communications with component suppliers, increasing the possibilities of offshore contract manufacture (Venables, 2001).

4. Reliance on Public (and Foreign) Knowledge

Increasing internationalisation and external dependence are also consequences of the growing reliance of business firms on public knowledge and related skills produced in the universities. This publicly produced knowledge is an important source of new entrepreneurial opportunities, and has been particularly important since the emergence of the chemical and electrical industries. It used to take the form of links between researchers and graduate students in university departments and in the central laboratories of large firms in these industries: Carrothers and Dupont in the development of nylon is one of the classic examples (Hounshell and Smith, 1988).

Over the past 20 years, the form of the linkages appears to have been changing. Corporations have cut back their central laboratories, and are increasing their formal agreements with university departments, and also with small firms emerging from universities in fields such as biotechnology and ICT (Zucker and Darby, 1996; Mahdi and Pavitt, 1997; Koumpis and Pavitt, 1999). In these fields, major theoretical breakthroughs (e.g. genetic manipulation) and reductions in the costs of experimentation (e.g. simulations) have increased the range of technological opportunities emerging from universities, but also the associated uncertainties about commercial success. Multiple formal agreements between large established firms, on the one hand, and university-based research and spin-off firms, on the other, allow early exploration and experimentation by corporations, without premature commitments to increasingly uncertain outcomes (Pisano, 1991).

Contrary to a common assumption amongst economists (Arrow, 1962), accessing this public knowledge is far from costless (Callon, 1994). Firms are mainly interested in the tacit knowledge and know-how behind the papers published by academics (Hicks, 1995). This is why frequent personal contacts between like-minded professionals are essential for effective research links with universities. As a growing body of empirical studies show, physical distance and language matter (Jaffe, 1989; Narin et al., 1997). Corporations find it more difficult to access foreign "public" knowledge than foreign proprietary and commercial knowledge (Arundel et al., 1995).

However, uneven international patterns of development of university research (with the USA in the lead) are forcing companies to increase their dependence on foreign sources of public knowledge. As Penrose observed in 1996 large firms are increasingly establishing foreign R

& D laboratories for the expressed purpose of accessing more effectively the local, tacit and commercially important knowledge emerging from universities. Amongst the earliest and most spectacular examples were the agreements signed between the large German chemical firms and public research institutions in the USA, in order to access the research and related skills in molecular biology that they could not then find in German public institutions (Sharp, 1991). The considerable increase in the 1990s of foreign corporate R& D in the USA, particularly in biotechnology and ICT, has had similar causes. (Florida, 1997). This important change loosens the links, that are often assumed to be exclusive in national systems of innovation, between university-based research and locally controlled business firms (Patel and Pavitt, 2000)

This trend may be the beginnings of wider changes in the international location of corporate R & D. Until recently, such R & D was amongst the least internationalised of the functional activities of large global firms (Niosi, 1999). In product development, there have been clear advantages, for internal co-ordination and for accessing external skills, of physical proximity of most corporate R & D to corporate headquarters; foreign corporate R & D was typically done simply to adapt products and processes to local markets. In the future, developments in ICT could possibly increase the degree of internationalisation of corporate R & D further: first, increasing use of virtual meetings could increase the transfer over long distance of tacit knowledge, and speed up decision making in product development; and, second, the inherent characteristics of software - its ease of transmission and modular nature - could facilitate the international dispersal of software development, especially when there are acute world shortages of software engineers.

5. Knowledge that disrupts Organisational Practices

Finally, the dynamics of technology have also been disruptive to the internal organisation and routines of large, established firms. Some analysts argue that such firms are intrinsically incapable of coping with radical new technologies, and that new entrants always do better (Utterback, 1993). The empirical evidence suggests that there is no universal law preventing large firms from exploiting new technologies (Methe et al., 1996), but that - over the longer term - major new technologies often lead to major new entrants (Louçã and Mendonçã, 2001). In the past, the conventional explanation of such processes of "creative destruction" was the inability of large established firms to master radically new fields of technological knowledge (e.g. from the horse-drawn carriage to the railway). But contemporary evidence shows that large firms have learned how to evaluate and assimilate new fields of knowledge through their corporate R & D departments (Mowery and Rosenberg, 1989; Granstrand et al.,1997).

The causes of failure are to be sought instead in the difficulties that large firms have in coping with the *organisational* implications of major technological changes. These implications are often difficult to identify at the time. With the benefit of hindsight in the examination of several cases, we can group them as follows.

- The unexpected emergence of new products and customers, with which established companies are unfamiliar. An example of the former is the personal computer in the late 1970s, and of the latter are the computer and military as customers for semi-conductors in the 1950s. In this context, C. Christensen (1997) has spoken of "disruptive technologies" and Levinthal (1998) of processes of "speciation".

- Mismatches between the level of innovative opportunities and corporate routines for allocating resources to innovative activities. Thus, the UK-based firm GEC changed over a 25-year period from heavy engagement in high-tech electronics to becoming a routine military arsenal, through the rigorous adherence in its investments to those with short-term profitability, and a refusal to spend money on exploring technological options (Aris, 1998).
- Changes (particularly reductions) in the costs of experimentation, requiring adjustments in routines for decision-making (or processes of learning) in product development. See for example, the difficulties of *IBM* in coping organisationally with the personal computer, compared with its mastery of complex and costly mainframes computer.
- Changes in sources of technological knowledge, requiring new skills, networks, critical interfaces and boundaries of the firm. Compare, for example, the success of established firms in the US radio industry in dominating the emerging TV market, with failure of established firms in valves to dominate the emerging semi-conductor market (Holbrook et al., 2001; Klepper and Simmons, 2001). In order to be competent in TV, radio firms had only to master the technology of the relatively well known cathode-ray tube; otherwise customers, product development and manufacturing skills, and regulatory regimes were the same. However, in order to be competent in semiconductors, valve firms had the much more challenging task of mastering quantum physics, new and demanding manufacturing technologies, and the emergence of major new markets. See, also, the emergence of a major "technological fault line" as the basis of the de-merger of the UK chemical firm ICI (Owen and Harrison, 1995).
- The emergence of major new specialised competencies, engendering scepticism or hostility from those with competencies that have been successful in the past, are powerfully entrenched at present, and are potentially obsolete in future. Examples

include "mainframers" versus PC nerds in computing firms, and biologists versus chemists in pharmaceutical firms. Leonard-Barton (1995) has described how "core competencies" can become "core rigidities"[3]. More recently, Scarbrough and Swan (2001) have described how IT professionals have colonised the "knowledge management" movement: "new" is not always "better". Either way, novelty engenders conflict.

6. Conclusions

The growth of the large firm continues to be based on the exploitation of its own knowledge and skills. But the experience of the past 20 years shows that large established firms have had a rougher ride than many would have predicted before then. This paper has argued that two features of the dynamics of technology have made this inevitable and likely to continue in future: first, the success of increasing specialisation in producing useful knowledge; second, the particular characteristics of recent revolutionary improvements in ICT and biotechnology.

- Increasing specialisation in knowledge production has increased the dependence of even the largest of business firms on external sources of technological knowledge. Advances in revolutionary technologies have accelerated this trend. They have also increased large firms' dependence on sources of public knowledge, and have forced them to

[3] It is not a new problem:
" ..there is nothing more difficult to carry out, nor more doubtful of success, nor more dangerous to handle, than to initiate a new order of things. For the reformer has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new order … arising partly from fear of adversaries … and partly from the incredulity of mankind, who do not truly believe in anything new until they have actual experience of it." Machiavelli, *The Prince*, p.21.

- internationalise their R & D activities, in order to benefit better from localised sources of tacit knowledge.
- Revolutionary technologies have also disrupted established routine in large firms, generated important new specialised skills and competencies, and have threatened (and thereby engendered resistance from) established ones.

Thus we have the paradox that, as knowledge becomes an increasingly important feature of corporate competitiveness, and is recognised as such, it will make firms increasingly dependent on outside resources, and will be increasingly disruptive to their internal organisation. In her later writings, Edith Penrose was well aware of these shifts, especially the trend towards increasing networking and internationalisation, stimulated by the search for knowledge and capabilities (1996). However, she was perhaps less alert to the implications of the specialised and differentiated nature of knowledge-based entrepreneurship, of which there are at least three.

First, it can be argued that entrepreneurship in practice cannot be separated from the particular knowledge on which it is based. Both Silicon Valley and an Arab street market are entrepreneurial, but they know about and sell different things, including new things. Similarly, there are differences in entrepreneurship between chemical firms and electronic firms. Both are knowledge-based, but they exploit different bodies of specialised knowledge, and explore new knowledge in different directions. Knowledge-based entrepreneurship is not therefore a general-purpose management skill that can be deployed in all places at all times.

Second, entrepreneurship involves assimilating new specialised professionals, sometimes at the expense of established ones, especially in periods of step-jump improvements in technological opportunity. It involves orchestrating and changing the balance between specific and specialised professionals. For this reason, a reading of Machiavelli may be more important than management textbooks, and knowledge-based firms will continue to live in turbulent times.

Finally, the major new opportunities for knowledge-based entrepreneurship emerge less from "managerial slack" than from major technological breakthroughs, which themselves are increasingly based on publicly funded research in the universities, and on the related training of high-level specialists. Corporate entrepreneurship therefore depends increasingly on academic entrepreneurship, the purpose of which is not to launch financially rewarding new products, but academically rewarding new disciplines (Rosenberg, 2000).

REFERENCES

Aris, S (1998) *Arnold Weinstock and the making of GEC*, Arum.
Arora, A. and A. Gambardella (2001), *Markets for Technology: the economics of innovation and corporate strategy*, MIT Press.
Arrow, K. (1962) "Economic Welfare and the Allocation of Resources for Invention", in R. Nelson (ed), *The Rate and Direction of Inventive Activity*, Princeton: Princeton University Press.
Arundel, A., van der Paal, G. and Soete, L. (1995) *Innovation Strategies of Europe's Largest Industrial Firms*. PACE Report, MERIT, University of Limbourg, Maastricht.
Brusoni, S., Prencipe, A. and Pavitt, K. (2000) "Knowledge Specialisation and the Boundaries of the Firm: why do firms know more than they do?", SPRU Electronic Working Paper No. 46, University of Sussex. www.sussex.ac.uk/SPRU/publications/imprint/sewps/sewps46.pdf
Burns, T. and Stalker, G. (1961) *The Management of Innovation.* London: Tavistock. (republished in 1994 by Oxford UP)
Callon, M. (1994) "Is Science a Public Good?" *Science, Technology and Human Values*, 19: 395-424.
Christensen, C. (1997) *The Innovator's Dilemma.* Boston: Harvard University Press.
Cohen, W. M. and Levinthal, D.A. (1989) "Innovation and Learning: the Two Faces of R & D", *Economic Journal*, 99: 569-596.
Constant, E. (2000) "Recursive practice and the evolution of technological knowledge" in Ziman, J. (ed.) *Technological Innovation as an Evolutionary Process*, Cambridge, Cambridge University Press.
Florida, R. (1997) "The globalization of R & D: results of a survey of foreign affiliated R & D laboratories in the USA", *Research Policy*, 26: 85-103.
Freeman, F. and F. Louçã (2001) *As Time Goes By: The Information Revolution and The Industrial Revolutions in Historical Perspective*. Oxford University Press, Oxford.
Granstrand, O., E. Bohlin , C. Oskarsson and N. Sjorberg (1992), 'External Technology Acquisition in Large Multi-technology Corporations', *R & D Management*, 22.
Granstrand, O., Patel, P. and Pavitt, K. (1997) 'Multi-technology corporations: why they have 'distributed' rather than 'distinctive core' competencies', *California Management Review*, 39: 8-25.
Hagedoorn, J. (1992), "Trends and Patterns in Strategic Technology Partnering since the Early Seventies", *Review of Industrial Organisation*, 11: 601-616.
Hicks, D. (1995) "Published Papers, Tacit Competencies and Corporate Management of the Public/Private Character of Knowledge", *Industrial and Corporate Change*, 4:401-424.
Holbrook, D., W. Cohen, D. Hounshell, and S. Klepper (2001), "The Nature, Sources, and Consequences of Firm Differences in the Early History of the Semiconductor Industry", *Strategic Management Journal* 21: 1017-1041.
Hounshell, D A and Smith, J K (1988) *Science and Corporate Strategy: DuPont R&D 1902-1980,* Cambridge: Cambridge University Press
Jaffe, A. (1989), "Real Effects of Academic Research", *American Economic Review*, 79: 957-970.
Klepper, S and K. Simons (2001), "Dominance by Birthright: Entry of Prior Radio Producers and Competitive Ramifications in the U.S. Television Receiver Industry", *Strategic Management Journal*, 997-1016.
Koumpis, K. and Pavitt, K. (1999) "Corporate Activities in Speech Recognition and Natural Language: another "New Science"-based Technology", *International Journal of Innovation Management*, 3: 335-366.
Leonard-Barton, D. (1995), *Wellsprings of Knowledge*, Boston, MA, Harvard Business School Press.
Levinthal, D. (1998) "The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change", *Industrial and Corporation Change*, 7: 217-247.
Louçã, F. and S. Mendonçã (2001) "Steady change. The 200 largest US manufacturing firms throughout the twentieth century", www.business.auc.dk/Druid/conferences/nw/paper1/Louca_Mendonca.pdf.
Machiavelli N. (1950 edition) *The Prince*, Modern Library College Editions, London, Random House.
Mahdi, S. and K. Pavitt (1997) "Key National Factors in the Emergence of Computational Chemistry Firms", *International Journal of Innovation Management*, 1: 355-386.
Mansfield, E., J. Raporport, J. Schnee, S. Wagner and M. Hamburger (1972) *Research and Innovation in the Modern Corporation*, Macmillan, London.
Methe, D., Swaminathan, A. and Mitchell, W. (1996) "The Underemphasized Role of Established Firms as Sources of Major Innovations", *Industrial and Corporate Change*, 5: 1181-1203.
Miyazaki, K. (1995) *Building Competencies in the Firm: Lessons from Japanese and European Optoelectronics*, Macmillan, Basingstoke.

Mowery, D. and N. Rosenberg (1982) "The Commercial Aircraft Industry." In Nelson R. R. (Ed.), *Government and Technological Progress*, New York: Pergamon Press.

Mowery, D. and N. Rosenberg (1989) *Technology and the Pursuit of Economic Growth*, Cambridge University Press.

Narin, F., Hamilton, K. and Olivastro, D. (1997) "The Increasing Linkage between U.S. Technology and Public Science", *Research Policy*, 26: 317-330.

Nelson, R. and S. Winter, (1982) *An Evolutionary Theory of Economic Change*, Cambridge MA: Harvard University Press

Nightingale, P. (2000) "Economies of Scale in Experimentation: Knowledge and Technology in Pharmaceutical R & D" *Industrial and Corporate Change*, 9: 315-359.

Niosi, J. (1999) "Introduction: The Internationalisation of Industrial R & D: From Technology Transfer to the Learning Organisation", *Research Policy*, 28: 107-117.

Owen, G. and Harrison, T. (1995) "Why *ICI* chose to demerge", *Harvard Business Review*, March-April: 133-142.

Patel, P. and Pavitt, K. (2000) "National Systems of Innovation under Strain: The Internationalisation of Corporate R & D", in R.Barrell, G. Mason and M. O'Mahoney (eds.) *Productivity, Innovation and Economic Performance*. Cambridge: Cambridge University Press.

Pavitt, K. (1998) 'Technologies, products and organisation in the innovating firm: what Adam Smith tells us and Joseph Schumpeter doesn't, *Industrial and Corporate Change*, 7: 433-51.

Pavitt, K. & W. Steinmueller (2001) "Technology in Corporate Strategy: Change, Continuity and the Information Revolution" in A. Pettigrew, H. Thomas and R. Whittington (eds.) *Handbook of Strategy and Management*, Sage (forthcoming). Now available at: www.sussex.ac.uk/SPRU/publications/imprint/sewps/sewps38.pdf

Penrose, E (1952) "Biological Analogies in the Theory of the Firm", *American Economic Review*, 42: 804-819.

Penrose, E. (1960) "The growth of the Firm - A Case Study: The Hercules Powder Company", *Business History Review*, XXXIV: 1-23.

Penrose, E. (1995) *The Theory of the Growth of the Firm*, OUP, Oxford (first published in 1959).

Penrose, E. (1996) "Growth of the firm and networking", in M. Warner (ed.) *International Encyclopedia of Business and Management*, Routledge, London.

Pisano, G. (1991) "The Governance of Innovation: Vertical Integration and Collaborative Relationships in the Biotechnology Industry", *Research Policy*, 20: 237-249.

Prencipe, A. (1997) "Technological Capabilities and Product Evolutionary Dynamics: a case study from the aero engine industry." *Research Policy*, 25: 1261-1276.

Prencipe, A. (2000) "Divide and Rule: Firm boundaries in the aircraft engine industry", Dphil Thesis, Brighton, University of Sussex.

Reich, L. (1985) *The Making of American Industrial Research: Science and Business at GE and Bell*, Cambridge University, Cambridge.

Richardson, G. (1972) "The Organisation of Industry", *Economic Journal*, 82:883-896.

Rosenberg, N. (2000) *Schumpeter and the Endogeneity of Technology*, Routledge, London.

Rosenberg, N. and Nelson, R. (1994), "American Universities and Technical Advance in Industry", *Research Policy*, 23: 323-348.

Scarbrough, H. and Swan, J. (2001) Explaining the Diffusion of Knowledge Management: The role of fashion. *British Journal of Management*, 12, 3-12.

Schnaars, S and C. Berenson (1986) "Growth market forecasting revisited: a look back at a look forward", *California Management Review*, 28:71-88.

Sharp, M (1991) 'Pharmaceuticals and biotechnology: perspectives for the European industry', Ch 13 in Freeman, C; Sharp, M and Walker, W (eds) *Technology and the Future of Europe*, London: Frances Pinter.

Tidd, J. J. Bessant and K. Pavitt (2001) *Managing Innovation*, (2nd edition), Wiley.

Tunzelmann, G.N. von (1995) *Technology and Industrial Progress: The Foundations of Economic Growth*. Aldershot: Edward Edgar.

Utterback, J M (1993) *Mastering the Dynamics of Innovation*, Boston MA: Harvard Business School Press

Venables, A. J. (2001) *Geography and international inequalities: the impact of new technologies*, http://econ.lse.ac.uk/staff/ajv/abcde3.pdf

Zucker, L. and Darby M. (1996) "Virtuous Circles of Productivity: Star Bioscientists and the Institutional Transformation of Industry", *Proceedings of the National Academy of Sciences*, Issue 23, November 12, Washington DC.