Prometheus, Vol. 18, No. 2, 2000

Entrepreneurship in Science: Case Studies from Liquid Crystal Application[1]

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ABSTRACT *Current UK policy on the knowledge-driven economy places a heavy weight of expectation on the fostering of entrepreneurial attitudes amongst university scientists. Interviews with the owner-managers of innovative companies in liquid crystal technology suggest that scientist-entrepreneurs are not simply scientists who have become imbued with the entrepreneurial spirit. They are also characterised by particular approaches to science and market intelligence. As scientists, they are fascinated by science-based effects (rather than science as a body of knowledge), knowledge of which tends to be acquired through interpersonal networks. Their knowledge of markets, similarly, tends to be acquired by networking with users. The result is a dynamic mental landscape in which application possibilities constantly churn against user needs to yield a stream of new product concepts, and in which there exists the possibility of insuring against the risks of career moves and strategic changes of direction. Assuming these findings can be replicated in further research, the implication is that the formation of scientist-entrepreneurs may need to foster 'concrete' attitudes towards science and a networking style of operation.*

Keywords: entrepreneurship, scientists, science, technology, new product development, risk.

Science + Entrepreneurship = Scientific Entrepreneurship?

It is widely accepted, especially in the UK, that there is a problem in connecting advances in applied science with the development of new products. Recognition of this lies behind a variety of initiatives at the structural level. Examples include the promotion of university science parks as a medium of technology transfer,[2] government funding for schemes of university–industry co-operation, such as the UK Foresight Programme,[3] and the Science Enterprise Challenge, which has made £25 million available for the development of Centres of Enterprise in UK universities (increased to £50 million in the March 1999 budget). Initiatives of this kind are essentially facilitative. That is, they aim to create the conditions under which individuals with the appropriate knowledge base and motivation are able to develop research-based new products. Measures of this kind do not, in themselves, ensure that the right individuals will come forward. Alongside these facilitative structures, therefore, there is an intention to promote entrepreneurial cultures and thinking within UK universities, and especially amongst university scientists. The Science Enterprise Challenge, for example, stipulates that the Centres of Enterprise should provide for the teaching of entrepreneurship in science curricula.

The considerable volume of research on the teaching of entrepreneurship suggests that the manner and matter of it is still controversial.[4] Supply-side experience from the

ISSN 0810-9028 print; 1470-1030 online/00/020133-15

one-time co-director of MIT's entrepreneurship centre suggests that contact with practising entrepreneurs is much the most effective form of teaching,[5] whilst research on the consumers' view indicates that fledgling scientist-entrepreneurs much prefer immediate practical instruction to generalised education.[6] However these debates ultimately turn out, it appears that some form of education in entrepreneurship is going to find its way into science curricula.

The study of the *modus operandi* of scientist-entrepreneurs (SEs) reported in this paper indicates that this policy may tackle only part of the problem. It assumes that the relationship between entrepreneurship and science is additive. That is, the scientist-entrepreneur is believed to differ from other capable applied scientists only in the possession or acquisition of entrepreneurial attitudes and skills. Against this, our data suggest that these individuals are also distinguished by a particular attitude to, and way of working in, science itself. Possibly because existing approaches to scientific entrepreneurship have been developed by social scientists and management academics, this aspect of the problem has been neglected.

Approaching Scientific Entrepreneurship

Science-based product innovation lies at the intersection of a number of research traditions. For some, the ability to envision new products in presently non-existent markets is an instance of entrepreneurship.[7] Framing the phenomenon in this manner opens it up to a number of well-established approaches. At the psychological end of the spectrum, there have been attempts to identify the personal characteristics of the successful entrepreneur,[8] while approaches which assign more weight to the social situation have studied such issues as the entrepreneur's use of information, or their management of relationships.[9]

As an alternative to the entrepreneurship approach, the SE may be viewed as an instance of the creative or innovative individual. As with entrepreneurship, creativity may be studied as a personality trait[10] or as the correlate of more contextualised behaviour, such as the management of information.[11] A third approach derives from the fact that the SE typically operates through the medium of a small firm. This means that some of the literature on SMEs is relevant, especially that which is concerned with entrepreneurship or creativity as a characteristic of organisations, as opposed to individuals. Within this organisational-level literature, too, there are parallels to both the psychological and socially situated approaches to entrepreneurship and innovation. While the first, broadly speaking, emphasises the internal resources of companies which make for entrepreneurship or innovation, the second stresses their external relationships. Exemplifying the first approach are studies of the influence of their founders' experience on the success of small entrepreneurial firms.[12] Exemplifying the second are studies of the use of information in entrepreneurial firms,[13] of their motives for co-operation,[14] and of a number of aspects of their external strategies.[15] For the innovative company, there are catalogues of necessary internal assets,[16] and studies of their external research linkages.[17]

Existing approaches to scientific entrepreneurship, then, can be placed in six categories. The phenomenon can be identified as either entrepreneurship or innovation, the unit of analysis can be the individual or the organisation, and the correlates of the phenomenon may be either internal or external to that unit. Not all studies, of course, fall unambiguously into one of these categories. With some justification, many authors move freely between the individual and the company level of analysis, while others include both internal characteristics and external relationships within their analyses. Less justifiably, perhaps, there is a tendency to conflate entrepreneurship and innovation.

These overlaps and ambiguities mean that the categorisation is best understood as a grid against which most previous approaches to the SE can be located.

Taking Science Seriously

Our approach lies a little to one side of this grid. Instead of treating the SE as a sub-species of the entrepreneur or innovator, our starting point, both methodologically and conceptually, was their mode of involvement with applied science. Because the authors are conversant with liquid crystal technology, our research proposal to the UK Design Council was that we would investigate the role of the design imagination in developing new products based on this technology. The interviews reported in this paper are with the managing directors of three companies with a record of developing successful new products based on the thermochromic (colour-changing) properties of liquid crystals. Both the managers and their companies have been given pseudonyms for reasons of commercial confidentiality. Because we wanted the approach of these SEs to science and new product development to emerge in its own terms, the interviews were open-ended. In the event, no other approach would have been possible. The interviewees themselves took charge, each of them beginning with a detailed and vivid narrative of the advances in applied science and the product applications through which their careers and the fortunes of their companies had progressed.

Creating an immediate impression of irrepressible enthusiasm, this is the language of people who spontaneously think of science in terms of product concepts. The descriptions of scientific effects, which featured so prominently in their conversation, were consistently *embedded*, both functionally and socially. That is, the effects had been produced, and had been encountered, in the context of specific product applications. As Gibbons *et al.* have argued, the production of scientific knowledge in dispersed contexts of application (mode 2 knowledge production) is increasingly supplementing traditional models of discipline-based scientific research (mode 1).[18] Conceptualising scientific effects in terms of potential applications, the SEs were evidently adapted to the world of mode 2 knowledge production. The thought that such a mindset might also be a condition of survival in a field of rapid scientific advance and short product life-cycles led to a second difference between our approach and the methodologies prevalent in studies of entrepreneurship and innovation. In place of a theoretically open empiricism, which would aim to identify discrete attributes of the SE, we have argued for their systemic and adaptive nature. We have made the hypothesis, in other words, that the qualities of the successful SE constitute a syndrome, and that this syndrome is an adaptation to fields of rapid technological change and short product life-cycles. We argue, for example, that the dual focus on applied science and product applications enables the SEs and their companies to survive discontinuous changes in either. At the same time, it demands that they keep up with new science and user-needs as these emerge, a demand which encourages a personal networking approach. The contacts made through this networking style of operation then create opportunities for alternative employment which act as a safety-net, so reducing the potential costs of risk-taking behaviour.

The reliance on interview data to support a hypothesis of adaptation raises a methodological problem. It is that the interviewees' qualities and behaviour on the one hand, and their account of their environment on the other hand, are not independent. They interact both at the level of perception and fact. At the level of perception, the interviewees perceive their world largely through their actions within it, while at the level of fact, it is a world which has been made, in part, by people like themselves. On the one hand, this difficulty arises as a cost of eschewing decontextualised psychological approaches, in that there is no independent metric of the SEs' personal characteristics. On the other hand, it is a consequence of the inaccessibility of the SEs' habitat. While it might be desirable in theory to have an independent account of the scientific fields and product markets in which they operate, no outsider is going to understand this better than the SEs themselves.

What this means at the level of theory is that evidence of adaptation from the interviews should be read as evidence of adaptation at the level of perception. The SEs, we would argue, are adapted to their environment as they perceive it. At the level of practice, the difficulty may be more apparent than real. If the aim is to identify individuals with SE potential, for example, the view could simply be taken that they are people who 'sound like' those in our interviews.

A more mundane methodological problem concerns the limitations of our data. While our decision to concentrate on product applications of liquid crystals meant that we could explore relatively esoteric issues in applied science, the downside was a severe restriction of the relevant population of SEs. Apart from a large firm which supplied the base technology, the three SEs interviewed in this paper manage a significant proportion of the UK effort in the thermochromic applications of liquid crystals. Allowing that these three gave generously of their time—the interviews amounted to approximately 12 hours in total—our conclusions are still based on only three cases and should be regarded as provisional.

Three Scientist-Entrepreneurs: a Biographical Sketch

Mathew

Mathew is managing director of PenKo UK and holds a B.Sc. and Ph.D. in chemistry. He began work as a chemist for a well-known multinational, then moved to the major UK supplier of liquid crystals, where he worked for about 5 years in a business development position. Sensing that his career was blocked, he left, without first obtaining another job. Subsequently he joined PenKo, a US company. Mathew set up PenKo's UK operation in 1992, with one employee, then moved back to the UK in 1995 to become director of the UK company. This now achieves an annual growth in sales and profits of about 20% and employs 12 people. PenKo operates in niche markets for applications of liquid crystal thermochromics. Most of the competition is from other small companies, though a multinational company has also attempted to penetrate this market, albeit with limited success so far.

Mark

Mark is managing director of Med E Quip. Having trained as a metallurgical engineer, he then worked for MedCo, a company specialising in liquid crystal thermochromics (thermography). Mark encountered the application of this technology to mapping the temperature of the human body at a medical conference, and suggested to the MedCo directors that the company should go into this. When they refused, he left MedCo in 1982 to set up Med E Quip, a company which initially marketed thermographic systems manufactured to the company's specifications in the USA. Subsequently the company developed a range of devices to aid the circulatory system, and currently employs 15 staff in the UK. Med E Quip is now part of a US company which has achieved a compound annual growth of 29% over the past 10 years. Within this company, the Med E Quip range is a star performer, having achieved a growth in sales of 37% in the year 1997–1998. In several countries, it is a market leader in circulation technology.

Luke

The managing director of ScienceCo, Luke took science A-levels and a business degree. His first post was in marketing, then, with a partner, he set up a company to do promotional work. He became involved in liquid crystals in the mid-1980s through their use in promotional products. In 1991, his company merged with a liquid crystal company specialising in scientific applications. Having realised the technical and cost limitations of liquid crystals, the merged company added alternative thermochromic chemicals to its capabilities. In recognition of the innovative nature of its product range, the company received four UK government awards. Having grown to 20 people, the company now supplies thermochromic devices to the expanding domestic, medical equipment and promotional packaging markets. Its customers include major power supply, retail and food manufacturing companies.

Characteristics of the Scientist-Entrepreneur

The Balance of Technological and Product Innovation

As we have argued previously there is a temptation for companies operating in fields of advancing technology to become fixated on the solution of technical problems, to the neglect of *product* innovation.[19] Successful new products need to be innovative from the point of view of the user,[20] rather than in the technology on which they are based. Noticeably, the user perspective was prominent in the interviews given by the SEs. Luke, for example, tells the story of his company as a history of product concepts.

> ScienceCo–LcCo was two companies brought together about 5 or 6 years ago. LcCo began about 18 years ago with government grants from the military, making thin unbreakable control panels which gave colour changes. The company then started developing into other areas, like fridge thermometry, baby care and so on, and was also doing quite well with thermometry for industrial uses. ScienceCo started about 12 years ago, and were mainly involved in thermometry for promotional usage, on packs of nappies or baby foods. For instance, we had a sticker banded on the outside of a cornflakes pack which would change colour when a child touched it.
>
> Luke

The prominence of user applications in the thought processes of these SEs implies that much of their success has been based on their abilities as product designers, not in the sense of detailed functionality, but in the sense that they are capable of generating innovative, and practical, product concepts. The actual process by which this occurs, however, depends as much on the SEs' absorption in the technology as on their involvement with the community of users. For the SEs, there is an aesthetic dimension to science-based effects, even those which presently lack a practical application.

> … although the infra-red imaging was very exotic and highly technical and great fun, it could never be used as a routine clinical tool, it was always going to be an expensive piece of laboratory kit.
>
> Mark

This 'collector's' view of science-based technologies means that they tend to be recalled to consciousness without conscious volition. It is this process which generates ideas for new products.

> All the time we think of new ways we can use these things. Your brain is constantly thinking of different things driving up the motorway. You're constantly ticking over new ideas.
>
> Luke

The idea may need the additional stimulus of user interest in order to set in motion the new product development process.

> … because you're involved in this most of the time, you think, 'Oh, maybe this can be used to do that'. Very often we don't have time to play around and see how possible it really is, and so forth, until actually a client comes in the right field, or actually says to us 'Can you do this?', and we say, 'Well, yes you could. We've actually been thinking about this for some time'. And they provide the impetus for doing it.
>
> Luke

Although the SEs take the user's view of applied science, in as much as they deal in product concepts, it is also important that they have remained scientists and technologists. Their grasp of the underlying science gives them important competitive advantages in the assessment of new ideas and the ability to carry through the necessary development work.

> The people who compete with us basically rely on their raw material suppliers to provide them with technical support. None of them really had the capability to develop anything that was out of the ordinary … We managed to produce a label using conventional technology, which is a sheet, and it worked. So now the issue is how to make five million of these things every month. How are you going to apply them automatically to cartons? The ideal thing is to print them directly on the cartons, but that wasn't really practical because of the coating thickness and speed of drying. As the project goes onto the next stage, we ought to start working with people to try and improve the characteristics of the liquid crystals, so that it might be possible to print directly onto the cartons. Right now the immediate problem was to produce something that was on a roll that could be applied automatically. And we managed … it's not the easiest thing to do because we had to go back to a new liquid crystal mixture which we could use on our proprietary web coating process up there in our Buffalo plant.
>
> Mathew

Secondly, the survival of a small firm in a field characterised by rapid and sudden advances in neighbouring technologies can depend on the SEs' awareness of these advances, and on their ability to acquire them. Thus the flexibility needed to cope with a turbulent environment, depends on the SEs' ability to keep in touch with the underlying science.[21]

> Liquid crystals go to sort of bright greens and blues, but if you want other colours, it isn't possible, which is why we have gone into these other areas. For example, we have a glass which we developed last year for Sunglop. Sunglop said, 'Our slogan is "The sun always shines when it pours". Can you can make us a glass which changes colour, so you pour your Sunglop in over ice, and it makes the sun shine?' And they said, 'Unless you can make the sun go orange, it's no good'. And, of course, you can't do that with liquid crystals.
>
> Luke

A by-product of these sideways moves into neighbouring technologies, also important in dynamic competition, may be the opening up of new areas of application.

> We've also got a number of photochromic chemicals which change colour with ultraviolet light, and have produced special cards which tell you whether you've been in the sun too long.
>
> Luke

The Dialectic of Application and Science

The SEs' dual focus on applied science and user application was reflected in their personal biographies. As told in the interviews, these were stories of movement, between companies, markets, technologies and locations—often continents. Metaphorically speaking, the mode of locomotion in these narratives could be described as two-legged, with the stationary foot standing, at any one time, on either a technology or an area of application. Movement by searching for alternative applications of a given technology was evident in Mathew's account of the origin of his company.

> PenKo originally started off as a pen company. In 1974, they started to add desk sets to their range, and they stuck a liquid crystal strip on them. So one of the first uses of the newly invented liquid crystal thermometer back in the early '70s was as an accessory to desk sets, sort of an executive gift with a thermometer on it. And then they got into wall thermometers, as retail items. Then they got into room and fridge thermometers. In the late seventies the forehead thermometer was invented.
>
> Mathew

At other times, it was the SEs' involvement in a network of users which formed a basis of stability from which they could then search for other technologies which might be adapted to these users' needs. Mark describes how an involvement with the network of pain specialists, originally established through marketing surgical applications of cryogenics, led him into the scientifically unrelated field of liquid crystals.

> … I used to work for a company called MedCo, and we had a range of products which were temperature-based: cryosurgery (that's freezing bits off instead of cutting them off), and cryo-analgesics (that's freezing nerves). So we got quite interested in pain. Pain was a very interesting phenomenon. There was no diagnostic test for pain. You relied on what a patient told you. It's an area of great subjectivity. So, I was looking for new products at the time, and I saw a paper given at a congress, a pain congress. And they were talking about the use of thermal imaging to monitor a variety of pain syndromes.[22] And I was fascinated by this, and I thought this would be a very useful tool in the pain clinics that we were talking to. So I went over to the States, to visit a company in New York, a company called RadCo, who were very big in radiology. They were interested in anything that formed a picture the radiologists could use. And one of their founders was a radiologist, who was very interested in thermal imaging. He had been responsible for developing a simple, low cost liquid crystal system, and it was at this stage that I got really interested … So I went over, and I negotiated on behalf of MedCo the distribution rights [to the liquid crystal system] for the UK and Europe.
>
> Mark

This ability of the SEs, and their companies, to change direction, either on the basis of a given technology or area of application, has a defensive, as well as an offensive aspect. It has proved its worth as a survival characteristic in fields of rapid change, in which technologies can run into unexpected problems or be leap-frogged by rival technologies. When technical problems appeared in Mark's liquid crystal applications, for example, it was his involvement with the network of users which enabled him to survive by developing and marketing an alternative product.[23]

> And then we ran into a catastrophe. We'd been going for about 2 years, and the detectors with their liquid crystals started to … I suppose the only way to describe it is grow fungus. The cholesterol esters are a highly organic media, and because they were in a closed box, if any sort of disease got in then you would get a culture growing on the detectors. And you'd get these sort of measles spreading and growing, which is fairly horrid stuff, and immediately of course we were in a recall situation. We'd got all this defective product out there. The Americans tried for ages to solve the problem, and couldn't come up with a solution. And there was us, a one-product company, and we were totally dependent on it. And we got into really deep trouble.
>
> Mark

What eventually saved the company was its connection with the user network. An acquaintance with the broad range of problems faced by the cancer specialists, who were using liquid crystal thermography as a means of screening, enabled the company to develop a profitable, if decidedly low-tech, alternative product.

> One particular problem was hair loss during chemotherapy. And they'd been using cold bags, bags of peas, gel packs on the scalp, basically to constrict the circulation to keep the chemotherapeutic drug from getting to the hair roots. This was hopelessly impractical, so we developed a cooling cap through which coolant was passed and it worked a dream. Most oncology centres in the country now use it, and we've more or less saturated the market and passed it on to another company.
>
> Mark

Failure: its Meaning and Significance

Inevitably, in a rapidly moving field of applied science, products sometimes fail. The continuation of Mark's story (above) is instructive because of the light it throws on the SEs' response to failure, and on the general significance of the failures which litter the field. Whatever R&D effort Mark threw at the problem of contaminated liquid crystals, it is clear that the company survived because he walked away from failure in time. This means that the SEs need to be able to recognise and accept failure. As scientists involved in the mode 2 production of knowledge, with its attendant commercial pressures, they cannot afford the mode 1 researcher's obsessive engagement with intractable problems, and this may be an important limit to the applicability of mode 2.

The preference for tactical retreat in the face of difficulty, however, does not mean that these SEs lack attachment to their chosen fields of applied science. Mark retained his interest in liquid crystal thermochromics, despite the apparent insolubility of the contamination problem. It is clear from the interviews that the SEs continue to take pleasure in scientific effects, even when the products based on them have failed, and this aesthetic dimension to their involvement with science can be an important resource. Thus, Mark's continued connection with the liquid crystal thermochromics network paid off when the news broke that US researchers had developed microencapsulation as a means of overcoming the contamination problem. He was able to react quickly.

> Then we heard of another group in the States who had a lot of experience in liquid crystal microencapsulation. This means taking a little packet of liquid crystals and sealing them in a bubble, like a microcapsule, so each little capsule becomes its own thermal detector. If you can make these capsules lie down side-by-side in layers, you

> get a complete image formed. And the beauty of that is that it's sealed from the environment, so it cannot be contaminated. It's stable. So we beat a hasty path to Hickton, Nebraska, and a company there started manufacturing to our design, but to their liquid crystal technology and their detectors.
>
> Mark

The significance of the SEs' tendency to 'collect' presently-failing technologies is two-fold. First, these may turn out to be an important resource for product innovation, since it is always possible that their impracticalities will be removed, either by scientific advances in related fields, or by translation into new areas of user application. Secondly, it follows from this that failure is comparatively easy to live with, because it is always provisional and never final. The SEs' awareness of the complex and contingent factors which can lead to the failure of a product is illustrated in Mark's account of liquid crystal thermography for breast cancer screening.

> … we developed the NuTemp with fewer detectors because we didn't need as many because we were only looking at one bit of the body, which managed to get the price down. We sold hundreds of systems in Japan, which has a fashion market when it comes to medical products, and we sold a lot in France, where the breast was still fashionable. But it became increasingly clear that the technique was not diagnostic, and people weren't happy with something that required skill to interpret the data. There's no such thing as a thermographer, and the cost of training people is phenomenal. And if you don't train them properly, you get poor results. And if they get poor results they say it's a piece of junk. So you've got a relatively low cost product, which has a very high cost of sale because you've got to train people, but which could be very useful to them if they know how to use it. It was a product that could have carried on forever, I think, and we could have had a niche market, selling a few hundred each year, and the company would have stayed turning over a few hundred thousand. And we would not have had the funding to grow the business and develop other products. Meanwhile, we took on another product which had much greater commercial potential and clinical benefit and we decided that we would drop thermal imaging. So it's a technique that if somebody had got a lot of money to throw at it, you could actually relaunch again. I still love it, I think it's a brilliant product actually, we had a lot of good fun with it, met a lot of good people, and I think a lot of people benefited from it. But commercially it was almost impossible.
>
> Mark

This is undoubtedly a story of failure, but it is a failure tempered by an awareness that changes in the user environment or advances in related technologies might, at any time, unlock the potential of the underlying technology. In this sense, failed products in a field of advanced technology may possess the potential to be recycled. The catalyst is the SE's fascination with scientific effects, combined with a scanning of the changing technological and user environment. The sense of fluidity and lack of closure are captured in Mark's (provisional) obituary on the thermography venture as a whole.

> … it sometimes narks me that we couldn't really make a success of thermal imaging, but it's a bit of a physicist's dream. Now there's microwave thermography; have you heard about that? Yes? Well, the scope of that is mind-blowing in terms of complexity for image generation because there you can look at temperatures within the body as well [as on the surface]. Well that never really took off, but one day, who knows, one day somebody better than us with more money will be able to come back and crack it. Well, I hope so.
>
> Mark

Networking, Science and Know-How

Much of the capacity of the SEs in this study to develop science-based products is acquired through personal contact with other scientists. Mark's acquisition of the technique of liquid crystal encapsulation is a case in point. This networking style of operation appears to be related to the embeddedness of mode 2 knowledge production. First its integration with product development means that it is produced in dispersed sites. Secondly, the knowledge produced tends to be tacit and personal rather than codified and public, and is therefore embedded in persons.[24] This second aspect means that an important mode of knowledge acquisition is assembly by recruitment rather than development through research.

> PenKo started in 1981. They added a microencapsulation capability in 1982 when they hired a guy from [a competitor] in the Hickton area. They also hired another guy who was from Thermwrap in the States, doing these scans for medical thermometry. So he had some experience of novel liquid crystal formulations. Tim Rolland and I joined in '87 and we brought chiral nematic formulations and microencapsulation, which we'd been working on together at LcDisplay.
>
> Mathew

Even that knowledge which is acquired personally tends to be obtained through interpersonal networks and what is taken from them is a state-of-the-art knowledge of science-based effects, rather than the theoretical understanding which a mode 1 researcher would regard as the essence of the science. For the SEs, the underlying structures of scientific explanation function primarily as a language through which this state of the art can be communicated. This differs sharply from the approach of the traditional discipline-based scientific researcher, for whom the explanatory structure of science is an end in itself. This focus on effects (and on product applications) is evident in one SE's explication of liquid crystal thermochromics.

> It's a helix, and what we're basically doing is putting a number of components together to make that helix change its shape at different temperatures. So if we want something to be physically showing a green at 5°C, to show that the fridge is at the correct temperature, then the ratios at which those basic raw materials are mixed will then determine the temperature band.
>
> Luke

The SEs' interest in the practical potential of effects, rather than their implications for science as a body of knowledge, fits rather well with those fields of scientific knowledge in which the structures of explanation tend to lag behind the phenomena which can be produced. This is presently the case with liquid crystal thermochromics. Although the principles are well understood, the theory is not yet at the point where it can predict the temperature at which colour changes will occur. The extent to which this kind of theoretical lag typifies fields of advancing technology as a whole is difficult to determine, but its effect, where it exists, is to encourage an uninhibited freewheeling pragmatism.

> The industry around the world, it's founded really on empiricism. People go out and find a bunch of chemicals, and see what they'll do, but then mix them together or try to process them in some way or another. And the ones that work you keep, and the ones that don't you throw away.
>
> Mathew

> Everything tends to be self-taught. When the raw materials first started to become available a few years ago, we started playing with them. So there was quite a lot of trial and error. There's the usual sort of learning curve there. And once you have got that learning curve, you can always stay ahead of the game as it were.
>
> Luke

As the second quotation indicates, the pragmatic approach also has the advantage that it produces knowledge in the form of experience-based know-how rather than theoretical elaboration. Knowledge in this form possesses important competitive advantages: it is likely to be unique to its creators, and it cannot easily be detached from them.

> … if you go and search the patent literature or the open literature, there isn't very much written about anything that anyone does in the industry. There are patents there if you read the patents on liquid crystal formulations or microencapsulation, but that doesn't tell you very much. It tells you some rudiments, but there's nothing of any significance when you come to look interested in getting into the industry. So there's quite a significant barrier to entry based on the high level of empiricism that exists.
>
> Mathew

There are also advantages in career mobility and personal security which flow from the accumulation of this form of scientific know-how. Whereas conventional mode 1 science can be acquired through the normal media of the scientific journal or conference (assuming a basic infrastructure of competence), mode 2 know-how can be acquired only by recruiting, or otherwise enlisting, its possessors. This accounts for some of the confidence with which SEs approach apparently risky career moves. It is a confidence which is based in part on the possession of considerable personal intellectual capital.

Networking with Users

The SEs' knowledge of the market for applications, like their knowledge of science-based effects, is acquired through personal involvement with networks of users, rather than through the impersonal techniques of market research.

> We used to support the Pain Society, go to all the meetings. We knew everybody, I think, in the UK Pain Clinics, and—er—it was good fun. I did a huge amount of demonstrations, lecturing—all this sort of thing—how to use it for a whole range of things, and we learned a tremendous amount about how liquid crystal thermography could be used.
>
> Mark

This personal approach is in line with a considerable volume of research which indicates that proximity to the customer is important to the development of successful products.[25] Expressions of interest emerging from user networks, for example, can be an important stimulus to the further development of product concept, since they are a good indication that a market exists. The same can be true of wholesale moves into new technologies.

> Yes, well [a company] came along and said, 'Well, we want something which changes colour with ultraviolet. Can you do it for us?' So we did. We're developing a new range of photochromic ultraviolets for next year which we're going to link together with one of the charities for making sunshine indicators.
>
> Luke

And, as we have seen, the user network can be a major resource in enabling these small companies to change direction technologically, either as a means of expansion, or in response to problems with existing products.

Risk-taking Career Moves

Since all three of the SEs are managing their own companies, it follows that they have, at some stage, left secure careers in order to set up in business on their own account. The common precipitating factor was an awareness of opportunity built up through networking with users and scientific communities. The sense of potential product applications built up through this networking activity could lead to frustration when it was not recognised by employers.

> … I negotiated, on behalf of MedCo, the distribution rights for a thermal imaging system for the UK and for Europe. Went back, wrote a report for the Board, and the Board said, 'No, we think this is too experimental. We don't want to get involved in it'. And on a personal basis I'd got as far in that company as I could. So, amicably, I left, and, as I left, I said, 'Do you have any objections if I take this product with me, if you're not interested?' So I set up a company on my own and marketed it in the UK and also in Europe.
>
> Mark

The SEs' networking style of operation, in other words, encouraged the move out of secure employment. For those starting up a new business, it generated information on the product market which substantially reduced the perceived risk. For those leaving for a more uncertain future, it generated confidence in the marketability of their own expertise.

> I worked for PenKo for about 5 years. I took my career really as far as it could go there. Basically I resigned with no firm ideas about what I wanted to do. I explored the entrepreneurial nature of the industry, and before I resigned I felt fairly confident that I could get a job in the US, particularly as Tim had already left.
>
> Mathew

It would be wrong to minimise the element of risk-taking which has characterised the career-paths of the SEs, but it should also be recognised that risks have been taken on the basis of information which has substantially reduced these risks.

Conclusions

Data from semi-structured interviews with three scientist entrepreneurs whose companies have been responsible for successful product applications of the thermochromic properties of liquid crystals suggest that such individuals have adapted to rapid technological change in the following ways.

They think in terms of user applications, as well as fields of applied science. The result is a dual stock of knowledge and personal contacts which enables them, and their companies, to survive discontinuous changes in technology or in product markets. If, for example, their present technological base is rendered uncompetitive by advances elsewhere, their contacts with users enable them to develop alternative products based on different technologies. Alternatively, if one product market collapses, their knowledge of a particular technology enables them to develop alternative applications.

Because they are working in a rapidly advancing field of technology, they tend to acquire new science through networks of personal contacts rather than through personal research. As a side effect, this networking style of operation creates an extensive knowledge of the market for their skills and a 'safety net' of alternative employment opportunities. In combination, these serve as insurance against the risks which they typically encounter in creating new companies and new products.

Though they vary in the theoretical sophistication of their scientific backgrounds, the SEs' present orientation towards science is at the level of effects. This is well adapted to the networking style of operation, since this is better suited to the acquisition of knowledge at the level of effects, rather than theoretical understanding. In rapidly advancing fields, theory may lag well behind the phenomena which can be produced. This theoretical lag means that much of the scientific knowledge possessed by the SEs is pragmatic and experience based. Unlike theoretically elaborated science, this form of knowledge is difficult to separate from its possessors. This is important in a number of respects. First, it constitutes a considerable barrier to entry. Secondly, it is unique to its possessors so that the capabilities of the SEs' companies are unlikely to be exactly duplicated. Thirdly, it is a personal, rather than a company possession, so that it constitutes an insurance against failure, and encourages risk-taking.

The SEs' involvement with science takes the form of a 'collector's' enthusiasm for scientific effects, which is quite independent of their present utility. Paradoxically, this indiscriminate enthusiasm is a major resource for innovation since it means that scientific effects and application possibilities (from the network of users) are constantly churning in the SEs' consciousness. In addition, the impracticalities blocking the application of presently useless effects may, at any time, be removed by information on new developments flowing from the network of scientific contacts. The result is a highly dynamic body of information which generates a stream of ideas for new science-based products. These ideas tend to be set in motion towards the development stage in response to enquiries from the network of users.

The fact that apparently useless scientific effects may find eventual application through advances elsewhere means that failure, in a field of rapidly advancing applied science, is always provisional. This is important since the SEs will inevitably experience failure, and its lack of finality makes it easier to cope with. Looked at from another point of view, the failed applications which litter any field of scientific advance may be important as a source of new products if and when the reasons for their failure are removed by changes in science and user needs. It is the SEs' enthusiasm for these failures which ensures that knowledge of the underlying scientific effects remains available to the network.

In summary, the evidence from our interviews with scientist-entrepreneurs in the field of liquid crystal applications suggests that their attributes and modes of operation are systemically inter-related and understandable as an adaptation to fields of rapid scientific advance. If they can be confirmed by further research, the practical relevance of these findings is threefold. First, our characterisation of the scientist-entrepreneurs might serve as a template against which to assess candidates for positions in science-based innovation. Secondly, the experiences which have formed these scientist-entrepreneurs might serve as guidelines for the design of jobs in science-based companies so that they will develop people with the appropriate attributes and modes of operation. Thirdly, if students are to become entrepreneurs, they may need to develop a fascination with scientific effects combined with a 'what could you do with it?' attitude, as well as an ability to acquire scientific knowledge through personal contacts with other scientists.

Notes and References

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