Chapter Three

Replicating the TEA-Laser: Maintaining Scientific Knowledge(1)

It is the 'easy' cases of replication — cases where the murine rules present few problems and where orderly action is most readily achieved — which are the most mysterious. So long as it is thought that easy science is really an easy matter, it will be hard to see it as the social accomplishment that it is. For this reason I start the empirical work of this book with an analysis of the case of laser building, a piece of straightforward 'normal' science where no one doubted that the phenomenon could be replicated.

The TEA-laser

A laser produces a beam of powerful 'coherent' radiation, often visible light, that can be focused very finely and can therefore damage the small spot upon which it impinges. The radiation is generated by putting energy into the molecules of the lasing substance — it might be a piece of ruby, or a gas — and then releasing all this energy in a synchronized way. The TEA-laser uses a gas as the lasing medium and produces infra-red radiation rather than visible light. If properly focused this radiation can vaporize concrete or burn the silver from a mirror. However, the crucial part of this story turns not upon what happens after the gas molecules give up their energy, but on how these molecules are energized in the first place.

The TEA-laser uses Carbon-Dioxide (CO_2) as the lasing medium. This is mixed with quantities of helium and nitrogen. The gas is held in a glass or perspex tube and is energized by passing an electrical discharge through it. When a gas is energized in this way it glows. A neon display tube, such as is used in shop signs, is a tube of electrically energized neon gas. The colour of the glow depends on the nature of the gas. Red is the characteristic of neon whereas the TEA-laser gases produce a pleasant pinkish/whiteish/blueish glow.

A standard gas laser is like a neon display tube in that the enclosed gas is energized by passing a high-voltage current through it between electrodes placed at either ends of the tube. A laser is made by using the appropriate gases and voltages and making suitable arrangements of optical windows and mirrors at the ends of the tube. With such an arrangement, however, a uniform glow discharge can only be obtained in lasers (and display tubes) if the gas is at a very low pressure, a very small fraction of atmospheric pressure. As the gas pressure inside such a tube is raised it is harder and harder to 'force' the electricity through the gas. Higher and higher voltages are required, and at 'high' pressures the current will only pass along a narrow path and only with a sudden jump. This is what we see as a 'spark', or an 'arc' breakdown, of which lightning is an example on the largest scale. But a glow discharge is needed for a laser.

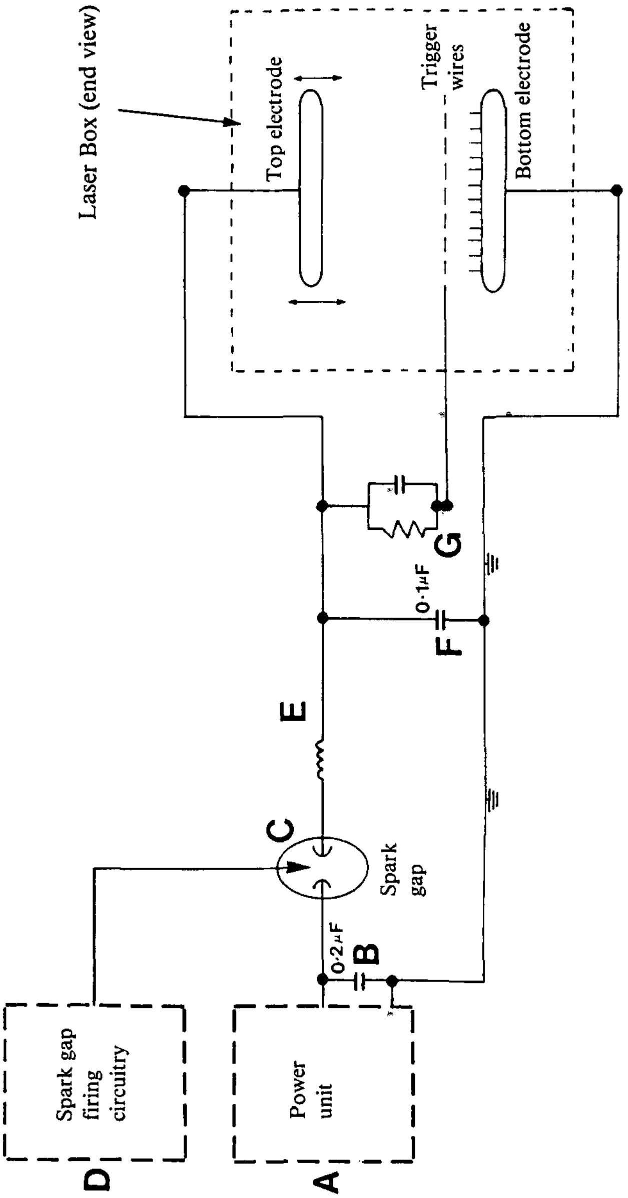
The power of a gas laser is proportional to the amount of gas that can be energized, and the amount of gas in a container of given size is proportional to its pressure. Thus the power of gas lasers was initially limited by the low pressure of the lasing medium made necessary by the need for a glow discharge. It is this barrier that the TEA-laser broke through. The TEA-laser uses gas at atmospheric pressure. It generates a glow discharge in this 'high pressure' gas by using very high voltages, by placing the electrodes at either side of the tube rather than at either end, so that the path between them is shorter and so that their area can be increased, and by discharging in pulses rather than continuously. That is why it is called the Transversely Excited Atmospheric pressure CO_2 laser. The difficulties in building such a device lie in the electrode structure, the electronics which shape the pulses of electricity, and the high voltages. These will be the main features in the discussion which follows.

Appearance and construction

The gas tube on the TEA-laser models that I saw ranged in size from about three aerosol cans placed end to end up to the size of a golf bag. The small, early devices used round glass tubes, whereas 'Jumbo', one of the more powerful lasers to be discussed later, used a perspex box of square cross section. Since the gas was at, or fractionally above, atmospheric pressure no special care needed to be taken in preparing the gas vessel against leaks, implosion, and so forth. Indeed, the first article in *New Scientist* to reveal the existence of the laser drew attention to the relative simplicity of the gas vessel by giving it the headline 'plywood-laser'.

The electrodes (the positive 'anode' and the negative 'cathode') are easily visible, running along either side within the tube. The design of these changed considerably as the state of the art developed between 1969 and 1979. The early models were known as 'pin-bar' lasers because one electrode took the form of a plain bar, and one a series of pins. Later devices, such as Jumbo, used artfully curved plates of metal at one side, and a flat or finned plate with a row of 'trigger wires' just above it on the other.

Electrical Circuit Diagram for the TEA CO_2 Laser



The electrical system of such a device includes a 'power unit' (A in the figure above) capable of building up to around 60,000 volts which is usually an 'off the shelf' item. The power unit charges a 'primary-capacitor' or capacitors (B in figure above). The latter are required to dump their charge across the two electrodes once they are fully charged, and for this purpose a special 'spark gap' switch is needed (C). This is itself a small gas filled tube that can be made to conduct electricity by creating a spark within it. An ordinary automobile spark plug can be used for this purpose but some additional circuitry (D) is required to fire it.

The pulse of electricity dumped by the capacitors has to be the right 'shape'. For example it has to rise quickly and steadily and not be too 'jerky'. The pulse is shaped by being passed through an 'inductance' (E) and a 'secondary capacitor' (F). In more sophisticated lasers a portion of the charge goes to the trigger wires through the 'resistance-capacitor (rc) circuit' (G). The figure above represents a simplified circuit diagram for one of the more sophisticated lasers.[2] The cross section of the top electrode in such designs is shaped in what was called a 'Rogowski profile'. Designs such as this, which start their discharge with a small trigger pulse between the trigger wires and the bottom electrode, are known as 'double-discharge' lasers. The triggering pulse is designed to generate a small area of 'pre-ionization' of the gas within the tube.

Replication of the early lasers: the transmission of knowledge

Early in 1970, when no one else had yet achieved successful gas laser operation at pressures above about half an atmosphere, a Canadian defence research laboratory, which I will call 'Origin', announced the TEA-laser. In fact, the device had first been operated early in 1968, and a more sophisticated version had been built by the autumn of that year; but both generations of laser were classified as secret for two years.

In 1971 and 1972 I decided to talk to scientists who were trying to build copies of the device in Britain, and to find out what they did in order to replicate the original experimental finding.(3) In the summer of 1971, I located seven British laboratories which had built or were building TEA-lasers; I visited six of them.(4) This was eighteen months after the first news of the device came from Origin. In the autumn of 1972 I visited the five North American laboratories which had been involved in the transfer of laser building knowledge to British sites.

The seven British laboratories comprised two government-run laboratories and five university physics or applied physics departments of physics or applied physics. The five North American laboratories comprised two government-run establishments (both Canadian), one American university department and two separate research laboratories belonging to the same American firm.

I found that the transmission of the ability to build a TEA-laser was not a straightforward matter. The flow of knowledge between the laboratories was constrained in a number of ways. There were some constraints, which are of interest but of only small significance for this study, which emerged out of what seemed to be competition among laboratories. Thus many communication links that could have proved useful to the less advanced centres were never realized, even though their potential was understood (Collins, 1974). A second constraint caused by competition affected the communication links that *had* been actualized. In some cases the knowledgeable institution would not be completely open with members of the learning institution. Thus one scientist reported of a visit to another laboratory:

> They showed me roughly what it looked like but they wouldn't show me anything as to how they managed to damage mirrors. I had not a rebuff, but they were very cautious.

A more subtle tactic used was that of answering questions, but not actually volunteering information. This maintains the appearance of openness while many important items of information are withheld; their significance will not occur to the questioner. One scientist put it:

> If someone comes here to look at the laser the normal approach is to answer their questions, but... although it's in our interests to answer their questions in an information exchange, we don't give our liberty.

Another remarked succinctly:

> Let's say I've always told the truth, nothing but the truth, but not the whole truth.

The more significant constraints, as far as this book is concerned, operated where there was no conscious attempt to conceal information. The first point is that no scientist succeeded in building a laser by using only information found in published or other written sources. Thus every scientist who managed to copy the laser obtained a crucial component of the requisite knowledge from personal contact and discussion.

A second point is that no scientist succeeded in building a TEA-laser where their informant was a 'middle man' who had not built a device himself. The third point is that even where the informant had built a successful device, and where information flowed freely as far as could be seen, the learner would be unlikely to succeed without some extended period of contact with the informant and, in some cases, would not succeed at all. The extended contact might come through exchange visits of laboratory personnel, or regular cooperation, or a series of visits and telephone calls. Typically, a laboratory visit might be followed by an attempt to build a laser which would not work, so another visit would follow, and if success was still elusive, a telephone call, or perhaps several, would follow. In at least one case, even this type of sequence resulted in failure, and the unsuccessful laboratory eventually abandoned its attempts to build a device.

In sum, the flow of knowledge was such that, first, it travelled only where there was personal contact with an accomplished practitioner; second, its passage was invisible so that scientists did not know whether they had the relevant expertise to build a laser until they tried it; and, third, it was so capricious that similar relationships between teacher and learner might or might not result in the transfer of knowledge. These characteristics of the flow of knowledge make sense if a crucial component in laser building ability is 'tacit knowledge'.

Tacit knowledge

Tacit knowledge is the name given by Michael Polanyi (1958, 1967) to our ability to perform skills without being able to articulate how we do them. The standard example is the skill involved in riding a bicycle. No amount of reading and study in the physics and dynamics of the bicycle will enable a novice to get on and ride immediately. On the other hand, the skilled rider is usually quite unable to describe the dynamics of balance involved. Does one turn the handlebars to the right when one feels oneself falling to the right? Or is it that one shifts one's weight when one senses approaching disequilibrium? The rider simply does not know. All the rider does is 'ride a bike'. The experience of riding rarely involves the anticipation of an imminent fall which must be avoided by a deliberate act of balancing (except perhaps at very low speeds). Even the early learning process does not seem to be aided by attempts to articulate what is required to stay balanced. It is a matter of trying over and over again until the skill, whatever it is, has been mastered.

Tacit knowledge usually finds its application in practical settings such as bike riding or other 'skilled' occupations. However, it is equally applicable to mental activity. Thus, to return to an earlier example, the member of a social group who has the ability to continue the sequence '2,4,6,8' with '10,12,14,16' as a matter of course, without even thinking about it, also possesses something that the stranger to our culture and the newborn do not. This is sometimes referred to as 'social skill' but we can call it tacit knowledge without doing too much violence to the term. It forms the foundation upon which formal learning rests. If I am taught some new algebraic manipulation in school, and the teacher tells me to do it the same way next time, I can say that it is my tacit knowledge which tells me what counts as the next instance of the same problem as well as what is meant by proceeding in the same way. (Remember the fundamental ambiguity of such an instruction as discussed in chapter one.)(5)

Two models of learning

This discussion suggests two models of learning. One model rests upon a notion of knowledge as a set of formal instructions, or pieces of 'information', about what to do in a variety of circumstances. This model views knowledge as the sort of information that enables a computer to carry out its programmer's intentions — I will call it the *algorithmical model.* The other model looks upon knowledge as being like, or at least based on, a set of social skills. It is what the child or the stranger must know before they understand what it means to go on in the 'same way', whether the same way is what is required at a cocktail party or required of an audio-typist or required of a member of the communities of physicists, mathematicians, parapsychologists or laser builders. This I call the *enculturational model.*

If a crucial component of laser building ability is tacit knowledge, then it should come as no surprise that written information turned out to be an inadequate source. Likewise, one would not expect that a 'middle man', who had not mastered the skill himself, would be able to pass it on. Further, since laser building skill, just like bicycle riding skill, is invisible in its passage and in its possession scientists who thought they knew how to build the laser discovered that they did not know how — this is no more surprising than if an expert in dynamics, having never ridden before, were to fall off a bicycle. Finally, it ought not to be surprising that the passage of the skill is not *completely* determined by the extent of the personal contacts between scientists; after all, as with other skills, the most lengthy training does not guarantee mastery. All these are the predictable consequences of the enculturational model of learning and communication; they do not follow from the algorithmical model.

That there was a tacit component of TEA-laser builders' knowledge was apparent to some builders. Thus the invention and state of knowledge concerning the 'Double Discharge' laser in 1972 was described to me by its inventor as follows:

> First of all we had rows of fins instead of pins, but this didn't work too well. We thought this might be because the field uniformity was too great so we put a row of trigger wires near the fins to disturb the field uniformity. Then we started finding out things. It did improve the discharge but there were delays involved. It definitely worked differently to the rationale we had when we first made it ...
>
> Even today there is no clear idea about how to get this thing working properly. We are even now discovering things about how to control the performance of these devices, which are unknown ...

> I have four theories (for how they work) which contradict each other ...The crucial part (in getting a device to operate) is in the mechanical arrangements, and how you get the things all integrated together. In the electrical characteristics of the mechanical structures ...This is all the black art that goes into building radar transmitters.

Again, the misleading quality of some of the formal information available in 1972 can be seen in different laboratories' beliefs and actions regarding the proper shape of the electrodes: one source laboratory provided information in the form of a set of equations for the so-called 'Rogowski profiles', along with the impression that machining tolerances must be small. The difficulties involved in making the electrodes were found by another laboratory to be insuperable. In the meantime, another British, laboratory had produced the shapes roughly from templates and a filing operation, while an American laboratory had simply used lengths of aluminium banister rail, both with complete success. The capriciousness of the knowledge flow is obvious, since even those who had succeeded in building a laser and making it work did not fully understand it!

Laser building in 1974 and 1979

What follows is a far more detailed examination of one scientist's attempts to replicate another laser. A physicist and expert in non-linear optics, Dr Bob Harrison (then at the University of Bath) set about building a TEA-laser of the double discharge design in early 1974. Harrison had previous experience of working with a laser of this design, and he had excellent contacts with a major laboratory where similar devices were in regular use. He visited this laboratory regularly. I was able to persuade him to keep a diary of his work and I regularly visited his laboratory and helped out with work on the laser.

Harrison eventually moved to another university, taking his working laser (nicknamed Jumbo) with him. In 1978–9 he built a near identical copy of Jumbo and I was able to be present, and help out in the crucial last session of development, from the first trial nearly up to the moment that the device finally worked. A description of this passage of work forms the latter part of this chapter.

Building Jumbo

In spite of Harrison's experience and excellent contacts it took him six months from the assembly of the parts to the final ironing out of the faults to make Jumbo work. There were some uncontrollable outside delays, such as those involved in the return and repair of faulty manufactured parts and repairs to a leaking laboratory roof. However, a large part of the time was spent on 'debugging' the device, or as I would prefer to say, developing the relevant tacit skills. A full account of the building of Jumbo has been published elsewhere (Collins and Harrison, 1975) and I will report only that part of the work which bears on the major thesis of this book.

Jumbo had parts in common with the lasers that Harrison had worked with before. Indeed, the laser cavity and one of the electrodes was supplied by Harrison's contact laboratory. Jumbo was intended to differ in design from these models only so as to make the layout of the electrical components slightly more tidy, since Harrison wished the whole unit to be easily portable. Thus, the high voltage components were arranged on a moveable trolley beneath the laser cavity itself. Harrison (henceforward 'H') described the general principle of the lay-out as follows:

> . . . with high voltage stuff, keep everything well apart . . . I knew working orders — breakdown in air is 30KV per centimetre at atmospheric pressure — that plus a kind of intuitive feel. But that's a hard thing to work out — is it breakdown between two flat surfaces or two points? — so actual distances are much bigger than this rule of thumb would imply . . . I just made sure that I had a 500% or 1,000% safety factor . . . Just keep things well spaced out — who needs trouble?

Arc breakdowns among the components

The first set of problems to be encountered was to do with arc breakdowns (enormous sparks at around 60,000 volts) among the various electrical components in the trolley. In particular, some 'arcing' occurred between earth points and other earth points which should have been at the same — zero — voltage!

> For example, I would have from the capacitor earth connection, an earth lead, and that lead would perhaps touch the housing of the capacitor which of course is meant to be at earth, and there would be a breakdown between the earth lead and the capacitor housing where it was touching, as far as one could see.

H also found arc breakdowns between components separated by much more than one centimetre for every 30,000 volts — the 'rule of thumb' distance. H knew that this could be explained if the components had sharp points, giving rise to 'dark field emissions' which may eventually break down suddenly when the voltage gets high enough. The dark field emissions prepare a path for the arc breakdown by pre-ionizing the air.

> But you 'wave hands' at this point because it's a subject that's been going on a hundred years and is still pretty difficult to understand, except under controlled physical conditions where, say, you have two flat surfaces and perhaps a point. But where you have a few curves and edges and you're not really looking at it, anything can happen . . . but remember when we had that really enormous breakdown, that was from a High Tension lead to

> earth, and that just didn't make sense rationally because there was a bloody foot separating them, or something ridiculous, and it looked as though it was arcing to wood!

H solved these problems in the most pragmatic way: wherever there was a breakdown between earth and earth he insulated with polythene sheet and wherever there was a breakdown between a high tension component and earth he covered any points and edges with cut up polythene bottles. I helped in this process of firing the capacitors, spotting the devastatingly loud and bright breakdowns, insulating, firing again, insulating again, and so on. Eventually, H had to drape most of the components in polythene sheet.

H discussed the earth-to-earth breakdowns with a colleague, and they agreed that it was probably a phenomenon associated with 'transient currents'; these could arise from differences in potential between common conductors where the rise time of a current pulse is very fast.

> It's intuitive evidence — 'beware my lad when you go to short, high voltage stuff -- transients and odd things creep in'. It's word of mouth. It's a technology that's evolved, people just give you guidelines and say, 'well, this is to be expected', without really full qualifications ... [the transient currents hypothesis] proved to be sensible but clearly only sensible because there was no other plausible reason.

Probe coil

When at last this programme of trial and error insulation had succeeded, H encountered problems within the laser cavity proper. He could not achieve the desired glow discharge, only sparks and arcs. After trials with different electrode separations he concluded that the pulse profile (see above) must be wrong. He therefore decided to monitor the shape of the discharge pulse, using a technique he had picked up earlier. This involved probing in the area of one of the high tension leads with a small inductive coil monitored by an oscilloscope. H soon found that his coil picked up so much radio frequency noise from the laser that the pulse shape information was completely masked. He spent some time moving the probe coil about, shielding the wires, using a Faraday cage on the oscilloscope, and so on; eventually he had to give up, as none of these precautions could sufficiently reduce the noise. At this point H remarked that he was:

> ... fairly desperate — I thought 'where the hell can I go from now?' I rang up 'D' [H's main contact] and he said 'it's a joke'. There are enormous problems trying to do it [the probe technique] ... Although — the bugger — I'd rung him up before and he'd told me how to do it and hadn't told me that it was a bloody virtually impossible thing to do. I'm sure of this — so I had a go and couldn't believe the things I was getting.

H then decided to visit his contact laboratory.

Leads and tubes

> I was then in a situation of — well, what shall I do with this damn laser? It's arcing and I can't [monitor the discharge pulse] so I thought well, let's take a trip to [the contact laboratory] and just make sure that simple characteristics like length of leads, glass tubes [these are part of the lower laser electrode] look right. If they're hopelessly wrong let's correct them.

H knew that the leads from the capacitors to the electrodes had to be short, and the glass tubes flat, but had not given any quantitative consideration to these matters. In designing and building his laser he remarked that he:

> . . . had to support God knows how many pounds of capacitors — I knew that they had to be close, just how close I hadn't really [bothered to think about too seriously], so I put them as close as they could comfortably go in an upright position that was convenient for housing them: so, it was convenience — I know they've got to be close, at the same time we don't want to frig around with too much framework. . .

These leads were about eight inches long in the laser as first built, which, as H remarks, is 'short by any standards'. As regards the glass tubes, H knew they had to be flat from his earlier days. He says:

> In fact I had a communication way back in those days from a chap in Livermore, who was over here working, not in TEA-lasers but knew a few people who were, and he sent me some information. At that time . . . we didn't know how flat, we knew flat, and he wrote back to me giving me all these values, and the implication was they had to be incredibly flat. So this was always in the back of your mind — get things as flat as you can get them. That was really the criterion all along.

When H went back to the source laboratory, he noticed things he had not 'seen' before. He found that their capacitor leads were considerably shorter than his, and there was 'no limit to how short they should be, just as short as possible'; this had involved the scientists in inverting their capacitors to reduce the lead lengths. H had not noticed this before. As he said, there was no reason why he should be building one exactly like that of the source laboratory down to the detailed positioning of the electronic components.

Upon H's return he took the bottom electrode apart to check on the glass tubes, which he had seen were very flat indeed in the functioning model. He found that his tubes did not fit the bottom electrode properly: they were slightly too large, and thus were not held properly flat in their wells. After some trouble, he managed to fit flatter tubes in the bottom electrode, and to have the capacitors mounted upside down so that the leads were still shorter.

When the laser was reassembled, H tested it again and found that it was *still arcing* between the electrodes. All these modifications had not cured the basic problem.

Anode marking

H then telephoned his contact laboratory for advice on another troublesome problem to do with the spark gap. He chanced to remark that the arc discharges between the electrodes were marking the anode; he knew that other TEA laser systems left marks on the electrodes, and was not at all surprised to find the effect on his anode, so he added this comment 'by the way'. However, it prompted the experimental officer to suggest that H check the polarity of his power source; the officer had seen marks on the anode on an occasion when the electrodes were accidentally connected up the wrong way round.

H didn't completely dismiss this possibility, though he thought it rather unlikely; nevertheless, a quick check with a meter showed that in fact his power unit was delivering +60,000 volts, instead of −60,000 volts. Upon rearranging the connections to the electrodes and sorting out a few minor arcing problems, H found that he was at last able to obtain the desired glow discharge in the laser cavity.

H remarked at the time that if it had not been for a lucky telephone conversation he would certainly have continued to spend time and effort checking blind alleys, perhaps until some other fortuitous event caused him to notice the elementary polarity-reversal error.

This account confirms the findings of the network study regarding the nature of communication of TEA-laser building ability. It is difficult to explain H's problems by reference to any shortfall in his information sources. His informant laboratory was a place where he had worked; what is more, he had worked there at the early stages of the very same design of laser that he was now building. He maintained a continual consultancy relationship with the laboratory, visiting them regularly. And, far from being competitive or secretive, his source had loaned him some £1,500 worth of equipment to help him build the laser. Nevertheless, deliberate transfer of the requisite knowledge proved extremely difficult.

It is clear that there were long periods when, though he did not have laser building ability, *H did not know* that he did not have it except by reference to the fact that the laser did not work. During these times he expected Jumbo to function but it did not. In the end, one crucial piece of knowledge seemed to be only accidentally transferred. Sometimes these failures of communication seem to be simply a matter of poor understanding of the laser parameters — length of leads, flatness of glass tubes — and sometimes it seems that H was just making mistakes — polarity reversal. There is little doubt that H felt rather silly that his laser had failed because of such an elementary mistake and yet, as he said at the time, it is probable that most of the other things would have had to be set right anyway, so little time was lost on the polarity reversal alone. Nevertheless, as we shall see, being 'wise after the event' is an almost inescapable feeling in scientific work.

Building the Heriot-Watt laser

Bob Harrison started to build his second TEA laser at Heriot-Watt University, in Edinburgh, in the middle of 1978; he was ready to test fire it for the first time at 12.10 pm on 15 March 1979. I was able to be present at Heriot-Watt on 15 and 16 March; this turned out to be the whole period between first testing the laser and the moment of successful operation with the exception of the final two hours work. These were done on the morning of 20 March. Bob Harrison gave me an account of these two hours by telephone on the same Monday afternoon.

The material presented here comes then from an initial telephone discussion in January 1979, two days spent in the laser laboratory at Heriot-Watt recording events by tape recorder and notebook, tape recorded discussions on the evening of 16 March and notes made from a telephone call on 20 March. During the 15 and 16 March I was able to participate, and make occasional useful suggestions.

The account here is very unusual from the point of view of the knowledge transfer perspective. H had already built Jumbo, so the relationship between teacher and learner was one of identity; they were both Bob Harrison. There was certainly then, no shortfall in H's sources of information! The other unusual feature is that H had a working laser — Jumbo — alongside the new one he was building. Jumbo had been performing reliably for a number of years in H's new laboratory. Thus, immediate comparisons were readily made between the old and the new devices and parts could be easily interchanged between the two.

Finally, and this again makes the setting particularly pertinent to the thesis of this book, H intended to make the new laser as nearly as possible the same as Jumbo. The only difference that H wanted to build into the new laser was a higher repetition rate for its pulses of power. Jumbo could produce a pulse every six seconds but the new laser was to produce a pulse every two seconds. This difference was to be accomplished by changes in 'off the shelf' units.

The reader should now turn back to the explanation of the laser, and the simplified circuit diagram given in the figure. The major components in Jumbo and the new laser were all discrete and visible large objects; their size and separation was made necessary by the very high voltages being used — up to 60,000 volts. All except the secondary capacitor were installed in a metal box about six feet long and four feet square upon which the laser cavity and gas container rested. The secondary capacitor was housed alongside the laser box so that the leads from it to the laser main electrodes could be as short as possible.

The laser itself, marked in the dotted square to the right of the circuit diagram, consisted of a perspex box about five feet long and one foot square section with gas inlet and outlet. The top electrode was a bar of aluminium about four feet long, six inches wide and half an inch deep milled to a 'Rogowski profile'. The bottom electrode was the same length but about an inch narrower, and had eight deep grooves milled in its upper surface running the length of the electrode. In these grooves sat eight glass tubes containing 'trigger wires' (marked in the circuit diagram as dashes above the bottom electrode). The top electrode could be adjusted until it was exactly parallel with the bottom one. So far the new laser was the same as Jumbo except that in the former there were two secondary capacitors side by side instead of one. With improvements in capacitor technology the same capacitance can be fitted into one unit.

The laser works as follows: the power unit charges the primary capacitor up to a potential which is pre-set on a dial — for example, 45,000 volts. On command (this is what pressing the button amounts to), the spark gap is fired and the primary capacitor charges the secondary capacitor through the inductance. This in turn is supposed to discharge across the laser electrodes.

As explained above, a uniform discharge rather than an arc is required. To accomplish this, part of the charge in the secondary capacitor is fed to the trigger wires through the resistance-capacitance (rc) circuit; this should pull electrons from the bottom electrode, which will 'pre-ionize' the gas in the cavity, facilitating uniform main discharge. In these circumstances, pre-ionization is visible as a faint pinkish glow just above the bottom electrode, and the main discharge fills the space between the electrodes with pinkish light. The laser then makes a sound like a loud 'ping'. An arc discharge makes a blinding flash at one point in the box and a ringing 'crack'.

H had deliberately built the new laser to resemble Jumbo as closely as possible in all essentials because he wanted to waste as little time as possible on irrelevant details. However, he had bought the most suitable 'off the shelf' components currently available. Thus, both capacitors in the new model were much smaller in size for the same capacitance, the spark gap was very much smaller; and the power unit was different as was the spark gap power supply with its transformer. The perspex box of the laser was identical to Jumbo's and both had been supplied by H's contact laboratory with whom he retained good relations.

Similarities and differences

When I arrived at Heriot-Watt at 10.30 am on 15 March I discussed these similarities and differences with Bob Harrison. The point was to determine *what counted as a difference* for H and what might subsequently be taken to account for failure of the laser. We noted the fact that the gap between the electrodes was the same in both lasers to the fraction of a millimetre. We remarked that in the new laser the tungsten wires emerging from the glass rods had snapped off, leaving only very small stubs which had been connected to their joint cable with electrically conducting glue; in Jumbo the wires were screwed into a brass connecting block. H remarked that he was not sure if the new method would work but that it should do so. Another change was that the glass rods in the new laser were held in place by elastic bands rather than a perspex clip. This seemed unlikely to affect performance. The connections to the electrodes were different, too, with only one connection to each electrode on the new laser, but four to each Jumbo.
H commented:

> ...so that could be slightly different again because we still really don't know whether it's important that you make only one connection or whether you try to distribute the charge across the whole electrode.

H remarked that the new capacitors, though smaller, were likely to work better. However, he also remarked that he was 'very suspicious' of the very small new spark gap and he did not think that it was going to work. He pointed out that the complex spark gap in Jumbo had been replaced with a single box, plus a tiny transformer to convert 350 volts to 35,000.

Another difference pointed out by H was that the new laser's bottom electrode had been made in two parts and bolted together, but he did not think that this would be important.

> That bottom electrode may be a bit worrying because its made in two sections — look, you can see the joint — and we've just got to see whether that's going to cause arcing. I suspect it won't. I think that will probably be all right.

I asked about the flatness of the glass tubes which at one time had seemed to be a crucial parameter in Jumbo, but H seemed unconcerned about this. Finally he commented:

> Everything else is identical ... and [jokingly] I guarantee that it won't work first time.

After some discussion we checked on the gas flow through the laser. The box is filled with a mixture of eight parts helium, two parts $C0_2$ and two parts nitrogen. The gas has to be turned on in advance of any trial so that it has time to purge air out of the system, as air will cause arcing. H controlled the values of the gas cylinders, while I read out values on a flow meter in the gas line bolted to the side of the main frame of the laser.

The first trial

At 12.05 H had a cigarette preparatory to the first test of the laser. A small crowd assembled for the button-pressing and the usual nervous jokes were exchanged. After switching on, it was found that the power unit was dead because the cable that connected it to the mains was missing! This was soon rectified. The first proper trial proved that the spark gap was firing a visible flash but there was no sign of life in the laser box even when we closed the doors and turned off the light. H put the laser through a number of trials, increasing the voltage each time until there was a very loud bang indeed accompanying an arc discharge somewhere in the electronic components.

H summed up the results of this first set of trials:

> So what's wrong ... the trigger works, the spark gap seems to work, the charging of the first capacitor seems to work but it doesn't seem to get to the second one.

Further examination of the circuits revealed that both of the capacitors had been connected the wrong way 'round; these new capacitors had a preferred polarity. H was slightly troubled in case they might have been damaged by being charged incorrectly.

At 12.30 we tried the laser again. Once more the spark gap fired but there was no discharge in the laser. H tested the bottom capacitor by discharging it to earth with a wire. This produced a satisfactory spark showing that it was indeed holding charge. He then tried all the components of the electronics with an 'Avometer', a device that would check that resistances and connections were correct. Again summing up, H remarked that the spark gap seemed to be working and that the indicated capacitor voltage was falling to about half its predischarge value, which fitted in with the behaviour of Jumbo.

The next step was to check the polarity of the spark gap, and try it out with the polarity reversed; H was not sure whether the trigger power supply gave a positive or negative impulse and the manufacturers had been unable to tell him!

By 1.15 the polarity on the spark gap had been reversed and it was time for another trial. A sequence of trials was made at higher and higher voltage. At first the spark gap fired, but nothing else happened.

H increased the voltage even more but still nothing happened in the laser cavity. Eventually we went for lunch.

More trials

After lunch H left me to work with two graduate students. The first thing we did was to check out the characteristics of Jumbo. We found that we could see pre-ionization in Jumbo at voltages as low as 30,000, whereas we had seen nothing up to more than 40,000 volts in the new device. We also tried moving the electrodes of the new laser closer together, to no effect. Then we disconnected one terminal of the secondary capacitor, and by earthing it, generated a spark which proved that this capacitor too was being charged when the spark gap fired.

The next hypothesis was that the pre-ionization circuit was not working properly. We decided therefore to disconnect the pre-ionization circuit in Jumbo, to see what happened when that laser was disabled in that way. We found that the disabled Jumbo was completely quiescent up to at least 38,000 volts; this was consistent with the hypothesis that the pre-ionization was causing the trouble in the new laser.

Next, on H's return, we tried closing the electrode gap further, but the top electrode fell from its mounting and it was discovered that the minimum gap attainable was about 4 centimetres. First trials with the 4 centimetres configuration also produced no effect. We tried hard to reduce the light level so that even the minutest flicker would be visible but there was nothing to be seen. Eventually in some frustration H turned the voltage right up. There was a very very loud crack from an arc in the electronics and the spark firing mechanism blew up. This was rather depressing, and little more progress was made that day.

16 March

As we drove home I remarked to H that I had noticed that the trigger wires in the new laser were of much thinner gauge than those in Jumbo. He had not noticed this, but on the following morning confirmed it.

The plan for the following day was to exchange components one at a time between the new laser and Jumbo. Each component from the new laser would be tested in Jumbo, and if Jumbo still worked, then that part could be replaced in the new laser with confidence.

The first part to be exchanged was the rc circuit. After some trouble this was made to work perfectly in Jumbo. Next the new glass tubes containing their trigger wires were put into Jumbo. Before trying them H was quite confident that Jumbo would work with the new set in spite of their smaller diameter and different method of connection.

He was right; Jumbo did work with the new trigger wires, which were put back into the new laser.

Next, two of the leads between the capacitor and the top electrode were disconnected and Jumbo tried again. It worked without problem so the extra three leads were disconnected from the bottom electrode. Again Jumbo worked perfectly. It seemed that the number of connections and the distribution of charge were not problems and so it was assumed that the single connections on the new laser would be adequate.

We were now running out of things to test. We had tested the components in the laser box — that is, the single connection configuration, and the trigger wires — and we had tested the rc circuit. The new capacitors were much smaller but similar, and even better according to the manufacturer's specification. Nevertheless we were by now considering switching them to Jumbo, but because of the discrepancy in the physical size of the two sets, and the very short leads, this might prove difficult. Difficulties of a similar sort attended the mooted exchange of the bottom electrodes.

At this point, summing up the results achieved so far, H suggested that most of his suspicion hovered over the spark gap. He cited as evidence that the needle on the voltage indicator of the power supply had not been falling when the spark gap fired suggested that the primary capacitor was not discharging. There was some confusion here; earlier this needle had indicated the appropriate discharge.

We decided to try the new laser again before transferring the more difficult components. We would try working on the spark gap and firing it in new ways which bypassed the proper circuitry. This allowed us to test the laser without worrying about whether the circuit from the spark plug power supply, which included a dubious transformer (see note 6), was working. In this configuration that whole section of the circuit became redundant. Unfortunately, though the spark gap now worked, still nothing happened in the laser cavity even though the voltage was turned quite high.

Finally, short of anything else to do, at about 5:15 pm, H completely removed the connecting wire from the spark gap and tried again. Suddenly an arc discharge took place between the plates; a great cheer greeted it. Arc discharges continued as we increased the voltage and though we all felt relieved there was still no sign of pre-ionization and nothing that looked like a uniform discharge could be obtained. When I asked H to reconstruct the reasoning that led him to remove the trigger wire from the spark plug he commented:

> . . . so it seemed that as a final thing, if the trigger is not doing anything it might as well be disconnected — anyway why not do that, there may just be something that happens — that is obviously what must have been going

> through my mind, so I just knocked it off, and ... hey presto ... if anything it was a bit of intuition.

Though we were pleased that we had achieved some kind of discharge between the electrodes of the new laser we had only now reached a stage that had been reached, in the case of Jumbo, in the middle of October 1974; Jumbo had not lased for a further five months! Celebration would have been premature, but we pressed on with the work for another hour that evening with an increased sense of optimism. We tried changing the gas mixture, and changing the electrode separation, but nothing but arc discharges could be obtained.

At one point I noticed that the anode of the new laser was heavily marked by the arc discharges. I pointed this out, but H shrugged it off. It now seemed that anode-marking was a normal part of these lasers' operation, so what had once been the 'vital clue' was now a piece of erroneous information!

We finally left the laboratory at about 6.30 pm and drove to H's house, where he thought about things that could be checked on Monday morning. He would check the value of the inductance and he could try swapping the capacitors even though this was a difficult task. He could also try checking the length of cables even where the inductances of these could not imaginably affect the performance of the laser. I had noticed another difference between the two lasers that I decided not to mention. This was that the bottom electrode of the new laser was about twice as thick as that on Jumbo. The two piece construction aside, H described the two electrodes as *identical* but I thought they were different. H summed up the rationale and the conclusions from two days' work as follows:

> the reason behind duplicating a Jumbo system was that I wanted lasers as quickly as possible — high powered lasers to be able to get on with a lot of the research which we've been trying to do with one laser and to duplicate Jumbo was definitely the right approach ...
>
> ...the fact that we've had two days' efforts, and we still haven't got a duplicate system to work is a reflection of kinds of problems you could face if you had tried to build another kind of laser system where I could be in the same mess as I was with Jumbo which may involve a year's work messing around getting the damned thing right.

I now left the scene. On the morning of Monday 19 March H went back to the laboratory to continue work. He reported events to me by telephone, in the middle of that same Monday afternoon. H had managed to get a uniform discharge in the laser box after not more than about an hour's work.

Lasers and knowledge

There is no need to labour further the point about the capricious nature of laser building skill and its transfer, but two more major points should be mentioned.

The first of these concerns Harrison's own developing tacit knowledge, its nature and limitations.

Throughout, Bob Harrison and I had been discussing similarities and differences between the old and the new laser. I had noticed the different thickness of the wires and had suggested that this might be significant. One of the graduate students had agreed that the thinner wires would have a significantly reduced surface area which might prevent proper pre-ionization. Yet Harrison had failed to see this as a significant difference; as it turned out his *not seeing* the difference was the proper way to see things. They were in fact just 'wires'. One might say that H's tacit knowledge was developed to an extent that enabled him to not to see a difference that was not a difference in terms of the operation of the laser. We others, without that level of ability, saw difference where it was inappropriate. Our suggestion that the difference between the wires might be important was a kind of laser builders' *faux pas*. It was as though we had suggested to a racing cyclist that his bike might go quicker if it were painted red instead of black.

There were other differences that I noticed and that Harrison ignored, quite rightly as it turned out. For example he was quite right not to see the 'obvious' physical differences in the bottom electrodes; I could see that the new one was much thicker than the old. He saw the bottom electrode as a 'double-discharge TEA-laser electrode' whereas I saw it as a piece of metal.

Again, the different ways the trigger wires were connected struck me as a possible cause of trouble. Conducting glue seemed very different to screw connections into a brass block, but Bob Harrison was right in not seeing this as a significant variation. Furthermore, he had learned to ignore the once crucial 'anode marking' and the exact degree of flatness of the glass tubes. Without knowing how to ignore all these things we might have spent months checking them out just as months were spent when Jumbo was being built. None of the things that Harrison had learned to ignore would be obviously significant, or insignificant, on a circuit diagram or in a technical article. The range of things to be ignored is, of course, indefinitely long.

On the other hand, in developing his laser building skill Harrison had also learned to see significance where previously he had noticed nothing. For example, the wires between the capacitors and the electrodes were no longer to be seen just as 'wires'; henceforward their length was crucial. One of the qualities of those particular wires was 'length'. This was a quality possessed by none of the other wires belonging to the laser (outside of the trigger wires themselves). All his previous electrical socialization had taught Harrison that wires did not have lengths. A long wire was 'the same' as a short wire; it is only in a few areas of electrical society — notably electronics — that wires do have lengths.

One might say that learning tacit knowledge, or acquiring culture, is a matter of learning this indefinitely long list of what is insignificant and, *inter alia*, learning what is significant. It entails learning that what might seem to the unskilled, or the uncultured, as going on in a different way is in fact going on in the same way and that what might seem to the uncultured as going on in the same way is in fact going on in a different way. It was in this that Harrison's new expertise lay.

Nevertheless Harrison's taken-for-granted reality, was not absolutely secure; it was not, after all, a formal system of knowledge. His hunches were better than mine but, as troubles developed, that is, as the laser continued to refuse to work, shadows of uncertainty began to creep in. All sorts of things were tested in spite of the fact that tacit knowledge would normally exclude them from consideration. Harrison's preparedness to test out some of my 'half-baked' suggestions was something more than good manners. What is more, as we drove home on the Friday night, some of the plans we hatched were a little desperate. Disorientation and bold speculation characterize many areas of cultural and political life when taken-for-granted reality is seriously disturbed.

When is something working properly?

The second major point to be drawn, especially from the Heriot-Watt study, is the difficulty of testing both knowledge and apparatus by means other than by having them perform the specific task toward which they are directed. Again, bicycle riding is an appropriate analogy; one only knows if one can ride by trying to ride. It should by now be clear that Harrison's laser building ability could only be tested by his trying to build a laser; the same principle applies to specific parts of the apparatus.

For example, at one time we tried to measure the performance of the spark-firing transformer. This needed a complex network of measuring tools since the voltages involved were so high. Our initial conclusion was that the transformer was misbehaving because it seemed to be stepping up the input voltage by a factor of ten rather than the specified factor of one hundred. But we did not fully believe this. We suspected that there was some flaw in the network of testing instruments we had used. We were thrown back upon trying the transformer in the laser as a test of its functioning![6]

Most of the other tests we had done would have been immensely time consuming if there were no Jumbo to use as a facsimile test bed for the new laser. If we had been working with the new laser alone, it would have been impossible to be certain about which components, or even how many components, were broken down at any one time. It is possible to test certain components for their specified performance where this is a simple quantity; for instance, components can be tested for their electrical resistance with an 'Avometer' and similarly, connections can be tested by making certain that they have nil resistance and isolation can be tested by looking for infinite resistance. Other components can be checked by metering their output. The difficulty is that where components are being used in new ways — as in any new piece of apparatus — they will not necessarily perform in the desired manner even though they appear to meet specification. For instance, it will be remembered that Jumbo had troubles with arc discharges from one earth point to another during construction. Any simple meter test would see nothing but nil resistance between two such points. Consider also that the length of the leads between the capacitors and the top electrode was critical. Only the most sophisticated test could reveal the difference in inductance between eight-inch high tension leads and six-inch high tension leads, yet it was a difference of this order that was claimed to make a significant difference to the laser performance.

It would, of course, be possible to devise tests for such differences, but the tests would be of such complexity — they would have to test components' performance in the face of high tension surges of the same potential and time profile as used in the laser — that the apparatus for testing would come to resemble the laser itself. And, of course, the exact specification of the pulse profile of the laser was not known, and would have been very difficult to measure. (Remember the failure to measure the pulse profile of Jumbo using a probe coil.)

Similarly, it is almost impossible to think of a way the bottom electrode trigger wire assembly could have been tested without either fitting it to Jumbo, or making the new laser work. The same applies to the question of the number of connections to the electrodes.

H put some of these problems this way:

> . . . really to set something up under the same experimental conditions that you have from your laser is pretty difficult.
>
> . . . You always come away thinking 'well maybe that wasn't a completely conclusive test'.

Thus it seems fair to say that the operating laser *defined* the experimental conditions under which the components of the laser had to work. The desired component specification was embodied in the laser rather than in a set of performance figures.

The laser studies: five propositions

The two detailed examinations of the process of laser building make the findings of the knowledge transfer network study quite comprehensible. For example, it is easy to see that a laser builder might fail completely to make his laser work even where his knowledge sources were good. Harrison failed to make his first laser work for several months, even though it seemed to be a perfectly good copy of one that was functioning elsewhere. One can also see that it is important that one's source of knowledge is a competent laser builder. Harrison would not have been a lot of use as an informant at the beginning of his attempt to build Jumbo; there is no way that he could have informed anyone about the necessity of having the leads from the capacitor to the electrodes as short as possible, for example, since he did not realize the importance of this himself. *But*, he did not know that he did not know. These points can be represented as two propositions:

> *Proposition One:* Transfer of skill-like knowledge is capricious.
> *Proposition Two:* Skill-like knowledge travels best (or only) through accomplished practitioners.

Another thing to be noted is that it took Bob Harrison six months to make his first laser work from the moment of first test, whereas it took him only two days for his second device. Successful laser builders, then, are 'competent practitioners'. This means more than that they have built a laser. It means that they possess new skills and new knowledge which enables them to build another one faster. Working with H the second time, this became clear in the way he confidently ignored certain parameters that were once thought vital (flatness of tubes, anode marking) and in the way he overlooked differences between the lasers that I noticed and would have thought important: for example, the thickness of the bottom electrode, the glue and the wires. It was even evident in certain displays of more ordinary perceptual skill such as his ability to hear the quality of the sound made by an arc discharge and thereby know the discharge's characteristics. At the same time the fact that it did take H two whole days to sort out the problems and that a lot of what was done was a question of trial and error shows that H's new abilities did not lie (or at least not entirely) in new information.

> *Proposition Three:* Experimental ability has the character of a skill that can be acquired and developed with practice. Like a skill, it cannot be fully explicated or absolutely established.

From the three studies it seems firmly established that laser-building ability is something you do not know whether you possess until you have built a laser. Thus, laser building knowledge is invisible in its passage. There is no way, such as by examining the available range of information sources, or by making an inventory of items of information known, that will reveal whether a scientist has laser building ability.

> *Proposition Four:* Experimental ability is invisible in its passage and in those who possess it.

A closely related point is that the only indicator that someone has laser-building ability is his or her ability to build a laser. The correct functioning of the apparatus and the experimenter is defined by the output of the apparatus. This can be seen very nicely in the third study in respect of the various parts of the new laser; what counted as working properly was defined by ability to function first in Jumbo. That is, parts were defined as good parts, irrespective of other measurements, if they could take part in the process of lasing. It is important to note that it was extremely difficult, if not impossible, to think of any other way to discover their nature. Even where technical means appeared to be available, measurements were distrusted as surrogates for testing within the laser. Thus:

> *Proposition Five:* Proper working of the apparatus, parts of the apparatus *and the experimenter* are defined by the ability to take part in producing the proper experimental outcome. Other indicators cannot be found.

Crystallization of certainty

Finally, a more subtle conclusion may be drawn. This is that scientists are resistant to the sort of account of experimentation that I have just given. For example, it is tempting to think that if H had not been so stupid as to reverse the polarity in Jumbo, he might have had it working quite quickly. He himself was inclined to be 'wise after the event' and blame himself for his own stupidity. He felt it was a simple case of human error rather than a failure of skill.

The same applied to his eventual solution of the problems of the Heriot-Watt laser: The first thing Bob Harrison did on the Monday morning was to run both lasers on pure helium to see if this would make the discharge easier to obtain. He discovered that even Jumbo would only arc under these circumstances. Then, in adjusting the gas flows back to their proper values in the new laser, he noticed that the flow meter valve seemed to be hypersensitive; further examination revealed that the flow meter assembly was designed to pass only one litre of gas per minute rather than ten litres per minute. He changed this assembly, left the laser to flush with gas at the appropriate rate for a half hour, and then keeping the spark gap in the same configuration as we had used on the previous Friday evening, he found that he obtained a uniform discharge at 42,000 volts — consistent with the behaviour of Jumbo. After this, lasing is easily obtained by assembling the mirrors, and so forth. H reasoned that we had not been able to obtain a uniform discharge before because the gas flow had been so slow that the laser box had never been properly flushed of its residual air; this is what he now believed had been the cause of the continual arcing.

Bob Harrison reconstructed what had happened:

> The trouble with the system has been one of human error... Except for the trigger unit — that would have blown up anyway. Everything else was the fault of the experimenter. You always find this. There are too many things to think about, etc. There's a limit to how much checking of the system you are prepared to do before trying it out. You make your own assessment of the situation and draw the conclusion that at that stage you can learn a lot more about your system from trying it out rather than from over-checking before trying it out. Obviously if I'd been really thorough I'd have spotted the flow meter problem before trying it out.

I believe that H is being rather hard on himself here. There is no reason to suppose that even if the gas mixture had been correct the laser would have worked before 5.15 pm on the previous Friday when the first arc discharge was obtained in the laser cavity. Before then, so it seems, all the charge had been leaking away down the spark plug wire. But, with the laser working, the uncertainty which surrounded the laser on the Friday evening suddenly crystallized out. Physics and laser technology resumed their familiar sharp outline, so that the failures of the previous two days were now seen as a consequence of human error disturbing natural regularity. It is human to err, but we do not think that it is natural to err.

One must distance oneself from the standard view of experimentation in science and escape from the railroad of common sense to see the conventional nature of this reconstruction of 'what really went on' in an experiment. I reserved the description of the solution of the Heriot-Watt laser problem to this late stage so that the reader could avoid being wise after the event for as long as possible.

The standard view of experiment is very much in accord with the view of the information scientist. Thus, once a scientist has mastered the basic skills of his trade he or she ought to be able to repeat any experiment using just what information is available from the usual sources. This is the initial 'murine' view as outlined by Popper and Dennis in Chapter Two. This view rests upon the notion that scientific facts are *testable* by 'independent replication'. The notion of independent testability ignores the active part played by man in seeing regularity rather than passively registering it. The point of Popper's third quotation is evident in the contrasting similarities and differences that Harrison and I saw in the two big lasers. The 'correct' way of seeing was only finally established after the laser worked. Prior instruction could not encapsulate these ways of seeing.

But, as soon as an experiment is successful — which in turn reaffirms the independent regularity of nature — any irregularity must be explained as arising out of human error. One experiences this sudden switch in perception in many practical activities. It is, as I have suggested, like a process of crystallization. One moment nature is obscure and recalcitrant, the next moment everything works and nature is once more orderly. The earlier obscurity and recalcitrance, which demanded so much human intervention to regulate, is then displayed as a *defect* in the human contribution.

I am certain that any working scientist will recognize all the elements in these stories from his or her own experience. And yet, it is so hard to maintain a degree of consciousness of such familiar happenings that it is almost impossible to see that they add up to a consistent story. Bob Harrison, as we noted, switched back in an instant to his picture of nature as orderly and cooperatively passive. This provides a sixth proposition:

> *Proposition Six:* Scientists and others tend to believe in the responsiveness of nature to manipulations directed by sets of algorithm-like instructions. This gives the impression that carrying out experiments is, literally, a formality. This belief, though it may occasionally be suspended at times of difficulty, re-crystallizes catastrophically upon the successful completion of an experiment.

It is this crystallization and re-crystallization that helps maintain existing scientific knowledge. Doubts, if they arise, last for only a very short time. In the chapters that follow we will explore the significance of Propositions One to Six for areas of less straightforward science.

Notes

1. There now follow three case studies. Case studies must be 'representative' if the conclusions drawn are to be generalized. The generalized conclusions of these case studies will be applied to science as a whole, and then to culture as a whole. For justification of the suitability of these studies and for a description of the fieldwork see the methodological appendix.
2. The cost of the equipment might be between £500 and £2,000, mostly for mirrors and ancillary equipment such as oscilloscopes and detectors which would be found in any laser laboratory.
3. In 1971, at the outset of these studies on lasers, the project was not envisaged as a study of replication but of knowledge transfer. For further discussion, see the methodological appendix.
4. The laboratories were found by a snowball technique: I asked at each location for the names of others making TEA-lasers. These laboratories were visited and one or more of the scientists involved centrally in the construction of the laser was interviewed at each site.

5. Polanyi writes as follows about tacit knowledge:

> Science is operated by the skill of the scientist and it is through the exercise of his skill that he shapes his scientific knowledge.
> ... the aim of a skilful performance is achieved by the observance of a set of rules which are not known as such to the person following them.
> ... from my interrogations of physicists, engineers and bicycle manufacturers, I have come to the conclusion that the principle by which the cyclist keeps his balance is not generally known. [and much more]
> An art which cannot be specified in detail cannot be transmitted by prescription, since no prescription for it exists. It can be passed on only by example from master to apprentice. This restricts the range of diffusion to that of personal contacts. (1958, pp 52-3)

There is some danger in completely identifying Wittgenstein's ideas and phenomenological ideas with Polanyi's tacit knowledge even though the term is useful and the consequences are similar. The formulation can be misleading for it tends to suggest that the only reason that knowledge cannot be formalized is because there is something *hidden*. Tacit knowledge could be converted into information, it seems to suggest; it is only time and ignorance that prevents us doing so. While it is true that the development of sciences does seem to involve a degree of explication of what was once only vaguely apprehended, the underlying model, it must be remembered, is the 'form of life' and it is incorrect to think that it could be eliminated if enough determination were put into the task.

A second danger is that Polanyi seems to take the idea of tacit knowledge much further than we would want to. For example, he believes that the solutions to scientific problems are somehow anticipated by scientists by virtue of their tacit knowledge. There may be some truth in this, evident in the way we solve chess problems and the like, by virtue of our ability to comprehend more of the context of a problem than we can articulate, but Polanyi's phrasing seems to suggest still more (eg see his 1966, pp 21-2).

The reason for continuing to use the term tacit knowledge, in spite of its undesirable connotations, is that there is no other way of referring to what we know by virtue of participation in a form of life, nor what is learned as one moves from being a non-participant to a participant. The Wittgensteinian model, as well as the phenomenological model, is set in an unchanging, undeveloping world (see Chapter One).

Ravetz (1971) draws on Polanyi to stress the craft aspect of scientific work. He describes scientific activity as having a 'peculiar' character 'as a special sort of craft work operating in intellectually constructed objects' (p 146). This leads him to stress the craft component in scientific method, the universality of pitfalls, the uncertain nature of criteria of adequacy in scientific assessment, and the interpersonal nature of some components of scientific communication.

The difficulty is that Ravetz' determination to treat the findings of science as 'objective' tends to obscure the sociological significance of his scholarly work. His argument is frequently qualified in surprising and seemingly inconsistent ways (eg, see p 178 and p 147).

6. No oscilloscope in the department could handle 35,000 volts so it was decided to test the output of the transformer by using a 'high voltage probe' that should step the potential down again by a factor of a thousand. The net result of a time consuming test, involving several pieces of apparatus (Jumbo's spark power supply, the transformer, the high voltage probe, and the oscilloscope), was the less than fully credible conclusion that the transformer was stepping up by only about ten times rather than a hundred.

To test our own measuring process, H decided to test an identical transformer in the same way. This produced the same result! Thus it looked as though the measuring process had gone wrong somewhere by a factor of ten, but we could not see how. The other alternative was that both transformers were wrong by a factor of ten when supplied by the manufacturer but this manufacturer only made this one type of transformer, so it was unlikely that units of the wrong value could have been supplied. At my suggestion, the transformers were tested again at a much lower input voltage by providing a few volts from a small pulse generator. On this test they seemed to work consistently and with a hundred-fold increase in potential. Then we tried to test the output of Jumbo's transformer, in order to test our initial measurements. Here however, we ran into great problems because we could not tap the potential without arcing problems. In the end, this whole series of tests was inconclusive and we were left uncertain whether the supplied transformers both worked properly at low voltage, but not at high voltage, or whether there was something wrong with our measuring techniques, or some piece of the measuring apparatus such as the high voltage probe. Only a test on the laser, with everything else working, would be completely decisive. Unfortunately, in this case, the transformer could not be fitted to Jumbo because the parameters of Jumbo's spark pulse generator and spark gap were different.