Practice in Communities: how engineers create solutions - the Bloodhound Guided Missile and the Hawker Harrier "jump jet".

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"Every aeroplane is different - a self-optimising shambles" Ralph Hooper, Harrier project designer

Aerospace engineers face the task of developing a project from overall design concept through to working prototype and on into sustained use. Engineers often work in small groups when developing an initial concept. Once the basic concept has been agreed they may work in similarly small groups, or as part of larger teams to develop key components of a system. At this stage key design tasks are defined and delegated and then the resulting components are tested and integrated to build a prototype (Vincenti, 1990). Individual sub-assemblies are usually developed in parallel. So, aeronautical engineering is often seen as a cyclical process of analysis and synthesis, although in practice it is seldom so neat and linear, as the opening quote from a leading practitioner, Ralph Hooper, illustrates.

The nature of engineering design is complex, with designers having to cope with many systems and components interacting in dynamic ways. The breadth and depth of knowledge required means no one person can carry out all the tasks of engineering design. Group or team working is essential. Engineering design is an innately social activity. However, mastering the specific skills of any one discipline, and also learning how to utilise the knowledge gained within the group or team, often depends on the abilities of key individuals. Some engineers are able to grasp more than their own specialism, and a few are able to grasp the implications of their work across most of the field. These individuals often provide the core leadership for teams, and it is the leadership of these types of people, as well as the way their teams operate, that we explore.

The focus here is on how task groups of engineers emerge and evolve over time while solving novel problems. The orthodox view is that engineering is carried out as a carefully managed project, following a strict and formal planning processes, characterised by Gantt Charts with regular and systematic reviews, proceeding inexorably to a perfect prototype which has already been extensively computer simulated prior to first flight. Providing these managerial tenets have been followed, the project will naturally be on time and within budget! Sapolsky's (1972) study of the management of the Polaris submarine programme, with its reliance on PERT techniques, is an exemplar of how this approach originated, but importantly shows it emerged not as a rational tool but as a 'boss dazzler', aimed at giving the engineers room to do what they needed while satisfying the more formal requirements of management bureaucracy. Note that Sapolsky's work focuses on the customer centered management of the project, rather than the day to day work of the engineering teams creating the technology. What is lacking is a clear understanding of how engineering design actually occurs in complex, large-scale projects, and how it is really managed.

Naive, linear accounts of engineering design contradict reality in two other respects. Firstly, we know from the Rayner report on the organisation of UK defence procurement (Cmnd.4641, 1971) which traced a large number of projects (National Archive, DEFE 13/368-371), that not one project followed the same development paths as any of the others, and indeed none followed the ideal path recommended, for example, by Downey (Ministry of Technology, 1967).

Secondly, detailed accounts of technology developments, such as early US jet engines (Scranton, 2006), reveal much trial and error, much cursing and swearing, and a rather messy and contingent development process which makes halting progress and suffers frequent reverses. As Scranton cautions (2008, 207) "real engineering at the edge is a gritty process laden with fixes, errors, cursing, and painfully-incremental steps towards something that works, much less works reliably and safely. There's no romance in that, so a more marketable story has long been routinely fashioned". In short, a more realistic account is needed of how engineering actually progresses. While Constant (1999) has addressed the issue of just how recursion *(which is where the cursing happens!)* is used by engineers, and Vincenti (1990) has looked at how engineering knowledge is generated, what has been lacking are detailed case studies of how engineering teams work, rather than just what it is they do or how they are formally organised. This paper aims to fill that gap.

Here we focus on the role of communities of practice. In this paper these are groups of engineers and technicians who coalesce around a particular design issue, recruit fellow engineers with related skills, solve the problem in hand and either disperse upon completion or persist for many decades, working in a similar fashion from problem to problem. Such teams of key individuals have been called communities of technological practitioners (Constant, 1980, ch.1) or communities of practice (Wenger, 1998). Within these communities there is heavy reliance on tacit knowledge, intuition and experience coupled with formal analytic procedures. In effect, these communities are the locus of learning and understanding about a problem and its possible solutions. The concept of communities of practice has recently been diluted by academic research that has moved away from a focus on context (Ash & Roberts 2008). In contrast, the cases here place these communities firmly in the context of problem solving in aerospace. We agree with Brown and Duguid (2001) that practice matters, and epistemic communities are distinctive and distinguish one firm, or division of a firm from another. There is variety in what we study. These communities of practice cover teams that were variously geographically dispersed and co-located, temporary and enduring. Despite these differences, the communities evinced very similar characteristics.

Our examples are drawn from two contexts: development of computer control for military and civilian use at Ferranti Automation and the early development of the Hawker Harrier jump jet. Use of historical case studies circumvents problems of military or commercial secrecy associated with current projects (MacKenzie, 1990, ch.1). Both projects were unequivocally successful in so far as they resulted in long lived and widely deployed weapons systems. Both examples focus on technical problem solving in organisations dependent upon the key skills of individuals who gain status and influence from creative solutions. [1]

We use the term communities of practice to refer to groups of engineers and technologists who come together to implement a novel technology, coalesce around a shared problem, recruit outsiders with relevant skills and then either leave to join another small community once the task in hand is complete, or continue working with the same group on an enduring task. Our premise is that communities of practice are a way of working that allows engineers to deploy skills and knowledge they have as individuals in an effective way within a group. In effect, knowledge is specific to the context in which it arises. The culture and values of an organisation shapes what it knows (Josefson, 1987).

Much of what engineers know is tacit knowledge. Tacit knowledge is defined by Smith (2001) as practical, action-orientated knowledge or know-how, typically acquired by personal experience and seldom expressed openly. Tacit knowledge is not codified and cannot be easily shared or transmitted. Members of design communities pool their tacit knowledge (Howells, 1996) and experience, focusing on solving problems of engineering design. Howells (2010) asks where is tacit knowledge located? He sees the "knowing self" as someone who can assemble knowledge, combined with beliefs, and communicate information in a social context. Learning and problem solving in technology is a process of social participation by individuals who draw on their own personal, practical experience and their technical training – the knowledge of familiarity.

Communities of practice also allow knowledge that is not necessarily tacit to be used in a parsimonious manner. To outsiders, much knowledge may appear tacit. In reality it is simply efficient working in a group that does not need to overtly state what is already understood between its members. Familiar technical principles and commonplace facts go without saying. Almost every member of the Ferranti Automation teams had at least one engineering degree, which helped make many complex ideas common knowledge. Nevertheless, although this knowledge may not be tacit, it may not be readily replicable between individuals in the group, or explicable to those outside the group. By looking in detail at how such groups work these issues are drawn out more clearly.

As Wegner argues social practice is the fundamental process by which "we get to know what we know" as we pursue a shared enterprise over time. Or, in other terms these communities are a locus of knowledge and places where tacit knowledge is not only shared, but accumulates. Since tacit knowledge cannot be captured in drawings or operating manuals, it has to reside in the minds of practitioners who have learned together while focussing on a shared problem. It also requires a great deal of tacit knowledge to understand what Blackler (1995) calls encoded knowledge such as a design blueprint, or a computer simulation programme (Baynes and Pugh, 1981).

Some of these communities of practitioners are short-lived, focussing for instance on an anomaly demanding a solution – the inaccuracy of analogue computers as a means of directing a radar dish on the Bloodhound 2 missile, for instance. Some communities were long lived, such as the 50 year culture of design for the Harrier jump jet at Kingston, Surrey. In this way a stock of knowledge accumulates within the milieu of the community, increases and develops as problems

get resolved, and may be lost if the group disperses and individuals begin to forget or find new jobs.

Assembling teams is a basic management role. This suggests formal management procedures. But in practice, communities can be spontaneous, ad hoc assemblies that draw in interested or competent individuals, or groups of friends – "a coalition of the willing". The design team that was officially responsible for Bloodhound Mark 2 Ground Equipment relied upon members of the missile team to resolve the central difficulty of steering the radar dish. Implementation of computer control at a soda ash plant at Fleetwood, Lancashire required personnel from both Ferranti and their customer, ICI, to implement the scheme. In this fashion tacit (and explicit) knowledge is drawn in from outside the formal task team or firm.

The working environment, or "group culture", of communities of practitioners is crucial (Figure 1). They share a method of working that is at once both tightly focussed and loosely organised: Tightly focussed on problem solving, these task groups usually have clear objectives, a budget and a time frame for completion. Yet, at the same time, they are loosely organised in the sense that such groups are often self-assembling, democratic and unorthodox in approach. This tight-loose paradox runs through our two stories of successful development. This tight-loose method of working can be seen as being both the mark and the substance of a community of practice in the engineering of complex systems. Other formal organizational structures are possible (and can be 'worked round' if so desired). There are other, more structured ways of working too. But it is the day to day working practices and habits of the group that identify and define it as a community of practice. Figure 2 illustrates the variety in the cases described here, despite their being similar communities of practice.

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Figure 1

Communities of practice in engineering and technology

1. Members coalesce around an agreed aim, problem or task
2. Clear recognition among participants of who belongs – an "in group" and recognition of local "heroes" - with mutually defining identities and styles of behaviour
3. Sustained mutual relationships—usually harmonious, sometimes conflictual
4. A shared understanding and tolerance of differences, providing they produce results
5. Rapid flow of technical information and gossip and scandal
6. Absence of introductory preambles - conversations pick up where they left off
7. Quick setup of a problem to be discussed
8. Knowing what others might know, what they can do, how they can contribute and how far they can be trusted
9. Professional ability to judge technical solutions and fixes
10. Specific tools, techniques, software, drawings and representations and shared understanding of their use and meanings
11. Local lore, shared "war stories", insider jokes

Source: Adapted from Wenger (1998, pp. 125–126) and Amin and Roberts (2008, p.354)
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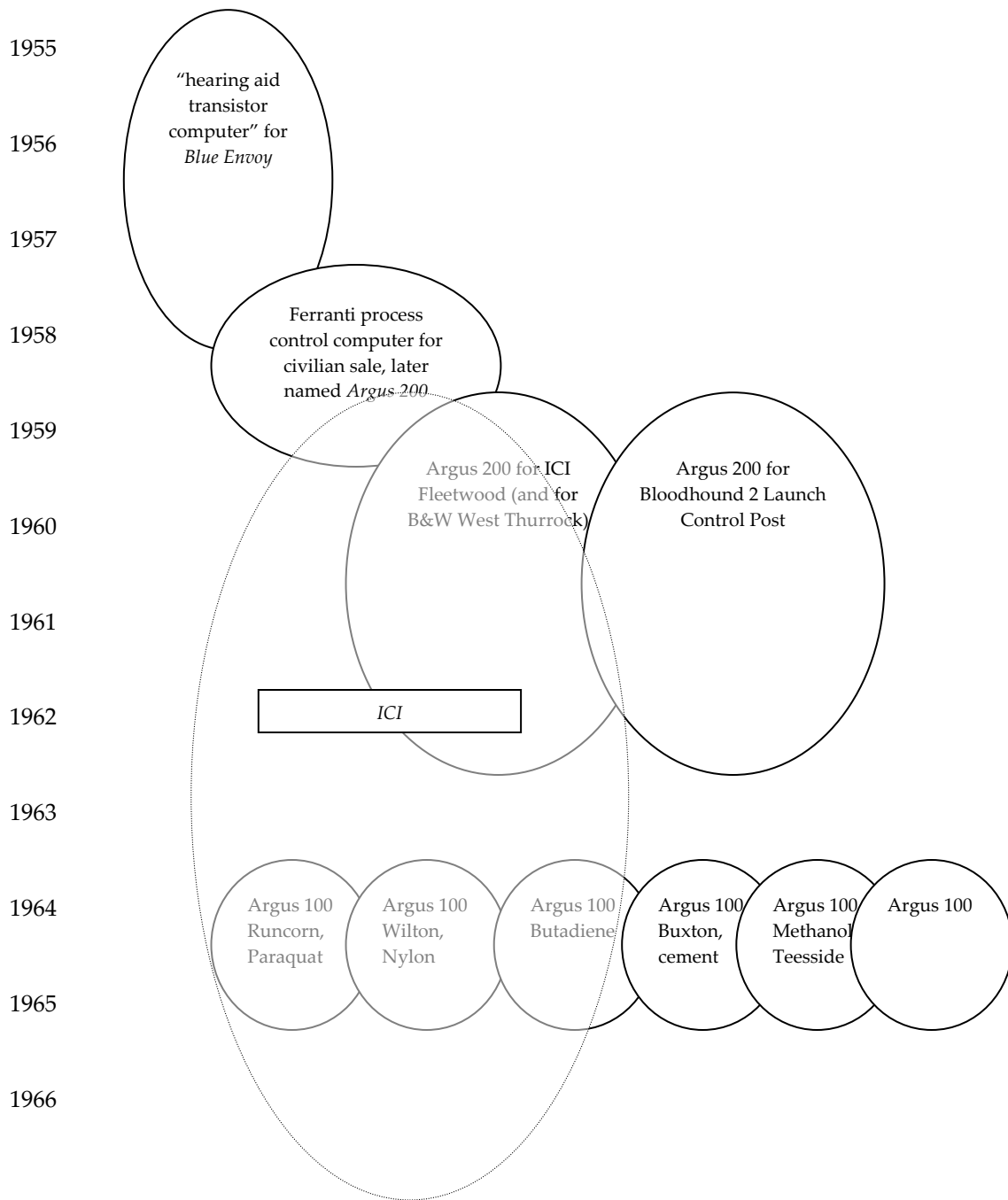|	Formal Organisation	Duration
Argus	project teams	typically two years
Harrier	functional/matrix/project teams – *changing over time*	long (decades)

Figure 2 Characteristics of the two cases: although differing in formal organisation type and duration and technology, the two teams adopted a similar community of practice approach

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Group cohesion around a common goal is reinforced by long hours of technical effort, the inevitable reverses, and struggle towards an agreed outcome. A strong feeling of community is reinforced in the defence world by signing the Official Secrets Act. Participants in defence projects cannot talk about their work outside of the plant, but can talk openly to others bound by the same Act. At the same time, the Official Secrets Act explains why knowledge was sticky within these communities at the height of the Cold War and did not "fission" out of these design groups to receptive rivals working in the same field or even the same company.

Gossip and scandal play a central role in maintaining communities of practice. As Gluckman (1963) recognises, shared gossip builds links within communities. He suggests the more exclusive the group, the greater will be the amount of gossip within it and an important part of gaining membership of any group is to learn its scandals. Above all gossip and scandal unite a group within a larger society, or against another group. So, gossip brings clear recognition of who belongs to a community and serves to identify the local heroes and the excluded villains. War stories about past triumphs and failures bring a shared identity.   This mutual history reinforces swift exchange of technical ideas and development of a common language to express engineering developments with precision and parsimony. Shared language and slang helps the easy flow of technical information. Common understanding helps support rapid shifts in conversation whereby issues can be picked up where they left off and new problems quickly set up and analysed. All this is true of the larger community at Kingston and the small communities developing Argus and Bloodhound at Wythenshawe, where research interviews for this paper were redolent with delicious and nuanced gossip worthy of Jane Austen's *Emma*, despite a distance of more than 40 years.

None of this implies communities of practice are always harmonious. In the case of the Harrier the Chief Designer of Hawker was notoriously critical of his designers, touring the drawing boards each morning and criticising poor detail design with some acerbic put-down such as "It look like mother done it – all pots and pans", but defending the group strongly against outside criticism (Hooper 1991). [2]

Figure 3 The Evolution of Communities of Practice at Ferranti Automation, Wythenshawe

1955

1956

"hearing aid transistor computer" for *Blue Envoy*

1957

1958

Ferranti process control computer for civilian sale, later named *Argus 200*

1959

Argus 200 for ICI Fleetwood (and for B&W West Thurrock)

Argus 200 for Bloodhound 2 Launch Control Post

1960

1961

1962

ICI

1963

1964

Argus 100 Runcorn, Paraquat

Argus 100 Wilton, Nylon

Argus 100 Butadiene

Argus 100 Buxton, cement

Argus 100 Methanol Teesside

Argus 100

1965

1966

Blue envoy guidance computer: Gribble, Butler (+ Blue Envoy team)
Hearing Aid Transistor to Process Control: Gribble, Butler, Eyre, Evans, Senior
Argus 200 for Fleetwood:
  Phase 1: Sales agreement: Morley, Thompson, Corin, Gribble
  Phase 2: Development and installation: Evans, Moss, Rushton, Leece, Gossling, Thompson, +ICI man
Argus 200 for Bloodhound 2: Fensome, Calveley, Thomas, Smith, Whitehead

Ferranti was a major British defence contractor who developed the highly successful *Bloodhound* ground-to-air guided missile in collaboration with the Bristol Aircraft Company (Adams, 1976; Wilson, 2000). "Bloodhound may be seen as an archetypal Cold War weapon system; its development, deployment and eventual withdrawal in 1991, covering the entire span of the Cold War" (Cocroft *et al.*, 2003, p.155). Guided missile development was based at a purpose built site composed of laboratories and final assembly facilities at Wythenshawe, Manchester opened officially in June 1954.

Technical development at Wythenshawe followed the standard pattern of aerospace engineering. The overall missile was broken down into packages for individual design teams to develop. In turn, these packages were devolved into sub-assemblies. The Launch Control Post for Bloodhound was one key sub-assembly. As a respondent describes: "Frank Fensome conceived the whole thing . . . from scratch. He then parcelled it out to three or four of us to develop our bits of it" (Whitehead, 1st Feb. 2011, Heald Green.)

Our concern here is one part of Ferranti's defence related activity, the development of the Argus computer at Wythenshawe, Manchester. Digital computers for process control went on sale in the UK and the USA at the end of the 1950's. The Ferranti Argus was among the first computers worldwide used for direct digital control of industrial equipment. Announced by Ferranti as the "process control transistor computer" in November 1958, Argus came into civilian and military use in 1962. The Ferranti Argus computer had its origins in a "hearing aid transistor computer" developed from 1956 onward by Maurice Gribble for another guided missile project, Blue Envoy (Butler, 1958). Blue Envoy has been described as "possibly the most enigmatic project in the field of 1950's United Kingdom weapons development" (Gibson, 2005).[3] But there was no secret about the Argus series of computers that went on to became a mainstay of industrial process control, selling some 1,263 units by May 1979.

The Argus computer is a classic boundary object. Design coalesced around the digital opportunities it afforded. Each team within Ferranti saw the computer in a different way – as a set of problems to be solved, as a commercial opportunity, a source of employment, or a focus of manufacturing effort. Argus was developed simultaneously in military and civilian contexts by small communities of practitioners at Wythenshawe. The common novel focus of these efforts was direct, real time digital control of processes. In one case, this was automation of a complete soda ash chemical plant at Fleetwood for ICI. In another case, it was use of digital control to direct a radar dish in the nose of a guided missile. Ironically, the civilian adoption of Argus was purposive and single minded, with ICI as a lead customer. The switch to digital control on the military side owes more to personal friendships and the shortcomings of arithmetic calculation on analogue computers.

While communities of practice reinforced group cohesion within Ferranti Automation, this may have strengthened hostility to outside groups. Wythenshawe had contacts with the Ferranti assembly facilities in Moston, north-east Manchester and circuit production at Gem Mill, Oldham. But there was no interaction whatsoever with the Ferranti Computer Department at Gorton, Manchester just nine miles away, even though they were working in exactly the same

field – digital electronics – and working on exactly the same problems, such as memory storage or interrupts at exactly the same time, and despite their common origins in Moston during the early 1950's. Practice can build barriers within an organisation as well as surmount them. Ferranti was a set of feudal kingdoms – or, as Brown and Duguid (2001) suggest, a balkanised firm.

Communities of practice did however straddle the divide between top secret military activity and civilian projects during the Cold War. It was open innovation in a closed world. Syd Evans is an example of this career transition [Syd Evans, 25th November 2010, Cumbria]. He was one of four or five engineers working on mid-course guidance for the Blue Envoy missile until 1957. He then became a trouble shooter on technical development of the Argus computer, before leading the civilian ICI project from 1961. This fluid movement from one overlapping community to another was typical of the career paths of Ferranti development engineers. The inventor of Argus, Maurice Gribble, was the ultimate boundary spanning individual, moving freely in and out of both communities.

Typically, a community of practice at Ferranti Wythenshawe coalesced around five or six core participants (figure 3.) Groups were supported by less experienced engineers, a couple of technicians and secretaries. So the formal team was bigger than the core group of developers. But even major projects occupied very few people. According to Bruce Calveley who was in charge, The total development programme for Ferranti's share of the Bloodhound Mark 2 covering the whole of the missile forebody and the complete launch control post centered on "less than 10 people, out of a total of perhaps 16 or 17". Surviving minutes of "Ground Equipment Progress Meetings" show approaching 20 people were entitled to attend, but interview evidence persistently re-iterates the importance of the same five or six key individuals (Ferranti, 1959).

Even in this formal workplace, communities of practice were often self-assembling. This is not to deny the formal organisation of Ferranti Automation with its purpose built Laboratories at Wythenshawe and its functional management structures (Wenger, 1998, chapter 11). But a community of practitioners relates to those who actually deliver the goods rather than a formal organisation diagram. In the case of Ferranti, those in charge did not necessarily know what was going on. They were not the locus of innovation. As Maurice Gribble, the inventor of Argus says "I was given free reign. No one ever told me what to do. . . no one quite understood what I was doing. No one ever questioned." [interview 14th March 2008, mid-Wales].

Communities of practice are *not* the same as a formal development teams since they transcend organisational boundaries and call upon outsiders. Communities of practice sometimes cut across formal organisational lines imposed by Ferranti. Derek Whitehead is a highly gifted engineer who worked across two communities, missile control and the launch control post. The Launch Control Post community included Derek Whitehead even though he was formally assigned to missile development, not ground control. He was a servo engineer but solved electronics problems.

Again, the practitioners for the civilian Fleetwood project encompassed both ICI and Ferranti personnel. ICI Alkali Division ordered an Argus 200 machine for an elderly soda ash plant at

Fleetwood, Lancashire ("Ferranti Argus . .", 1961; Thompson, 1965). ICI treated this Fleetwood plant as a commercial scale pilot plant. Adoption of Argus was effectively a giant R&D project [MacKeand, 9th March 2007, Delaware]. Ferranti wrote the software and provided the hardware (figure 4) But, ICI had the technical competence to develop the project by adding instrumentation, developing actuators to control valves and providing the communication links (Thompson, 1965); [Derek Hughes, 27th January 2011, Lancashire].

The project team for Fleetwood coalesced early in 1961 and was composed of four or five Ferranti people: Syd Evans, Frank Moss, Dave Rushton, Norman Leece and Tim Gossling, a mathematician who was their programmer. To this community may be added Allen Thompson from ICI along with his right hand man, making perhaps eight engineers in total at the heart of the development. Ferranti made frequent visits to ICI offices at Winnington: "we coordinated with them, spoke the same language" (Evans, 25th November 2010, Cumbria). All the ICI automation experience was with 2 and 3 term analogue controllers. By working in a cooperative way, ICI picked up knowledge of digital techniques embedded in their partners at Ferranti. In turn, Ferranti learned about prolonged real time control of industrial processes from ICI. So this community of practice was a form of knowledge exchange. In the event, there were problems to be overcome, such as the "noise" in the Fleetwood electrical circuits caused by spikes in the electric current in the mains. (The whole soda ash works was run on 440 volt direct current supplied by in house generating plant and from outside through mercury arc rectifiers - doubtless the source of the spikes.) They learned the hard way, the usual way to learn on these sorts of projects.
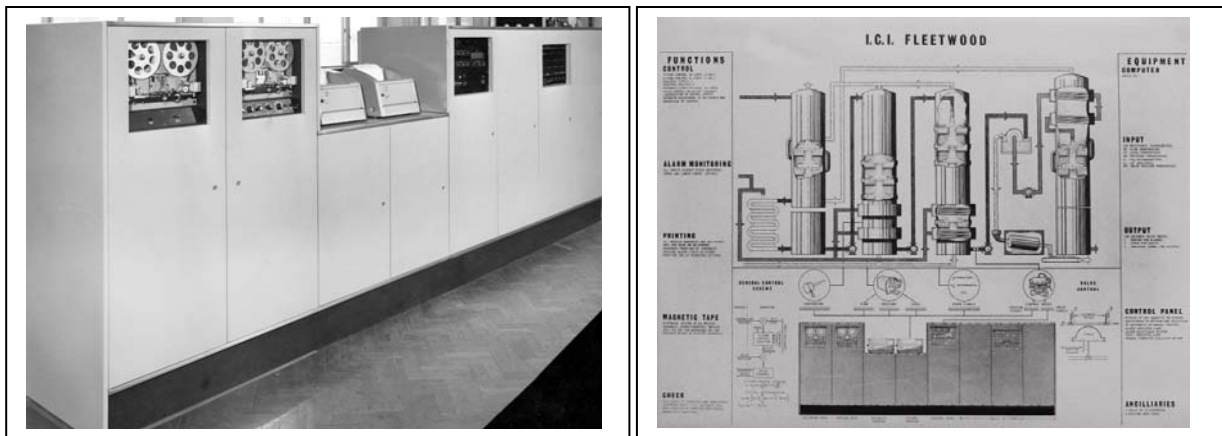

Figure 4   Argus 200 process control computer on test assembly in Ferranti's H2 Laboratory, Wythenshawe and mimic of the automation scheme at ICI's Soda Ash Plant at Fleetwood. Ferranti and ICI shared the problems of implementing this novel project, perhaps the first complete direct digital control of a chemical process worldwide

These communities emerge as surprisingly democratic and consensual with clear recognition of the respective talents of participants. (It is said that Syd Evans was selected by his fellows to lead the ICI team for Ferranti.) They were subject to little, if any managerial direction and conformed to group norms rather than, say, working hours laid down by the job: "It was an invigorating

environment, not a 9 to 5 job. . . . The view was 'we have interesting problems'." [Interview with Evans]

What really captures interest among a technical group is a situation where participants do not immediately understand a problem (Orr, 1996, p.95; Brown and Duguid, 1991). Here engineers differ from technicians. Technicians prefer work that is problematic but ultimately safe, where they can display their craft in solving a technical difficulty with little chance of disaster. Whereas development engineers are happiest on the edge. They find recognition among their peers for solving progress-blocking problem. The widespread respect and high status earned by Maurice Gribble and Derek Whitehead within Ferranti Automation derived from their ability to create solutions.

These communities had unorthodox ways of working. Derek Whitehead recalled the problem of getting the revolving radar dish in the nose cone of Bloodhound 2 stabilised in the face of a nutational frequency problem with a gyro [Derek Whitehead, 15th Feb 2008, Heald Green]:

> "John Waterworth and I were trying to get the gain of this dish servo up because I'd had experience training at University in servo mechanisms and John had a talent for it. And we were achieving no success at all. A very good theoretician called Tom Ingham . . . . came in one morning and then disappeared. At about half-past eleven he came out of the toilets with a roll of bog paper about that long covered in red crayon: What he had done, he had an idea while he had been sitting on the loo and he had written down all the equations of motion of this gyro/dish combination. He calculated if we did a certain thing it would stabilise it. . . . . . And it took John and I about a week to build a circuitry equivalent of this and it was rock solid, absolutely rock solid. "

Notice Derek Whitehead and John Waterworth actually built a circuit to prove Tom Ingham's theoretical calculations were correct. They quite literally turned scientific insight into practice with their own hands.[4]

Figure 5 The Argus 200 computer was also fitted into the Launch Control Post for the Bloodhound 2 Guided Missile (LCP to the left of Bloodhound – it would not have been so close when deployed in earnest!)

Group cohesion at Ferranti was reinforced by humour, play and idiosyncracy. Hours of technical effort and struggle towards a common goal encouraged specialised slang, catch phrases and jokes. Dave Senior speaks of the Fleetwood team coining the catch phrase "Orendisoakey" - an elision of "our end is ok" - a mickey-take of Norman Leece testing input-output circuits on the first Argus 200 in Lab H2 at Wythenshawe prior to delivery to ICI [Dave Senior, 5th January 2011, Herefordshire]. At an early stage, a "mini-Argus" was specially developed for ram jet trials at the Long Range Weapons Establishment, Woomera in Australia, a task due to be completed in six months and successfully achieved in seven. This small group used their boss Cliff Cundall to hasten progress in the workshops. On completion of the project, Cundall was awarded a presentation box by the workshop containing a wooden spoon, for stirring! The Argus 200 used ceramic ferrite pegs the size of pencil leads as part of a semi-permanent memory store. The delicate nature of the pegboards is part of the folk myth of the Argus 200 as a day's work could be undone by an inopportune jolt loosening the pegs, like sweeping a jigsaw off a table. To avoid frustrating accidents, the peg boards of the early machines were fitted with a transparent cover. Derek Whitehead recalled "we polished the lid of the peg board so the whole lot flew out on Pete Smith due to the static on the celluloid lid." [Derek Whitehead blames another member of the Launch Control Post team, Dave Shanks for the prank, 2nd June 2010, Manchester].

There was also a limited set of programmers for Argus, just five people in the early 1960's. Group cohesion was reinforced by daily completion of crosswords in all the newspapers. Typically, installation of the later Argus 100 series computer was devolved to just two key people, an engineer and a programmer supported by technicians – *wire mechs* – from Ferranti. Scilla Bretscher was given enormous responsibility for programming the Argus 100 at the No.2 Paraquat plant at the Pilkington-Sullivan Works of ICI Mond Division Works – "Pilks" as it was known locally [Scilla Bretscher, 5th January 2011, Herefordshire.] This was a highly dangerous plant! But she found support and advice among the programming group at Wythenshawe.

Group cohesion is an effective way to overcome official opposition, especially if it expressed outside the boundary of the community of practice. At one stage, Derek Whitehead proposed the Orange Yeoman surveillance radar system for the UK could act as a computer based system control centre for air defence across all guided missiles.[5] Derek took the idea of a system wide digital solution to the man responsible for all military radars in England, Norman Alder at RRE.

> "I was rather surprised I was able to get an interview with him because he was
> roughly equivalent to God . . . . And I took all this stuff in and I must have spent all
> of five minutes with Norman Alder because he listened to what I had to say and then
> he said "There is no place for digital computers in military systems and there never
> will be." [edited to spare Derek Whitehead's blushes, 15th Feb 2008, Heald Green]

Despite the official government position, the idea of direct digital control of missile systems was out of the box within Ferranti.

Ferranti also faced the problem of directing the radar dish on the new Bloodhound Mark 2 Guided Missile which was to use continuous wave radar for guidance. The radar dish in the forebody of the missile was locked for launch (the missile was subject to a force of some 30 g on take-off) but the dish had to point in the right direction to within 1° as soon as it was unlocked. There are perhaps only 30 seconds between unlock and hitting the target. When the dish was

unlocked in flight, two features were *crucial*: that the dish pointed in the right direction to find the target and the doppler gate was set to the right frequency to pick up the return from the illuminated aircraft.

Personal friendship with Maurice Gribble led Derek Whitehead to propose accurate digital calculation for the complex trigonometry required, despite opposition from RRE to digital schemes.

> "Maurice Gribble was developing a gizmo. He developed for a demonstration for the Duke of Edinburgh a scheme whereby you could effectively have a thing in space and something there and something here and you could turn one of the knobs and it did some trigonometry and it would track the thing that was moving, digitally. Wow!" [Derek Whitehead, 15th February 2008]

So Derek Whitehead and Peter Smith proposed to Bruce Calveley and then to Denis Best that the Argus 200 should be used for positioning the radar dish after launch on the Bloodhound Mark 2.

To sum up: These communities brought together people with considerable prior experience and previous patterns of cooperation and left a legacy of experts whose accumulated knowledge could be used on subsequent projects. As projects shifted towards software development, teams became smaller and women were given considerable individual responsibility. But, its main insight is the way in which just a few named individuals working in small communities, cutting across institutional boundaries, developed novel products that were not anticipated by higher management in an unconventional atmosphere characterised by long hours and much levity.

III

The origins of the Harrier design team at Kingston go back to 1912 when T.O.M. Sopwith, a pioneer aviator, established his new aircraft company in the town with Harry Hawker as his company test pilot. By 1914 Sopwith had engaged a local schoolmaster as their first dedicated designer, based in a shed on the roof of the works (Davis 1999). That same year saw the firm expand its production floorspace with a new aircraft factory in Kingston to meet increasing demand from the British armed forces during the First World War. A series of combat aircraft were produced, such as the Sopwith Pup, Strutter and the Camel, which became the most successful Allied fighter of the war (Braybrook 1984).

In 1920 the Sopwith Aviation Company went into voluntary liquidation, in response to demands from the government to repay excess war profits, but reformed immediately as H.G.Hawker Engineering, with Sopwith still at its head. Hawker himself was killed in 1922 during an air race. In 1923 the first new aircraft designs emerged from the company (Mason 1991). By the mid-1930s the firm's success with its series of single-engined fighters and light bombers meant that the majority of RAF squadrons were equipped with its aircraft (Mason 1991). This success allowed Hawker to invest in the 'Private Venture' development of a new monoplane fighter, the Hurricane, in advance of government support. This aircraft became famous thanks to its central role during the Battle of Britain in 1940. Hawker designed and produced several other types of fighter aircraft during the war, with jet fighters following post-war, continuing their record of success.

In 1957 the British government announced a policy of equipping fighter squadrons with missiles in future, Blue Envoy and Bloodhound being paramount in these plans. For Hawker, a fighter specialist, this posed a serious threat. This led them to start work on vertical take-off 'jump-jet' concepts. Their first attempt, the P.1127, began in 1957 as a private venture. Hawker were not the most likely candidate to build such an aircraft, with its need for a light structure paramount, given their reputation for building structurally strong, heavier aircraft. The P.1127 prototype hovered for the first time in October 1960, with a long series of Harrier aircraft developed from it and manufactured in the following forty years, with many still flying.

In 1957 the initial design team at Kingston, known as the Project Office, numbered just 25 staff, out of a total in the Design Office of around 400. The Project Office looked after all the aerodynamic work for the company, including both new and existing aircraft and analysis of flight and wind tunnel test results [Williams Interview 26/04/2005]. Indeed, the Project Office was the location of all technical design work outside mainstream structural and mechanical design. This was in addition to their activities in new project design which required the generation of new concepts, writing proposals and liaising with suppliers and customers for such project designs. Staff in the Hawker Project Office tended to be young, with a mix of graduates and former shop-floor apprentices among their number. [Bore Interview 17/06/2005, Hansford Interview 02/12/2002, Williams Interview 26/04/2005]. The Chief Designer, Sir Sydney Camm, had a special interest in his 'Young Gentlemen' of the Project Office, being both their harshest critic and fiercest defender. The rate of 'turnover' in front line combat aircraft and related technology meant that it was clearly seen that the future of the company was directly linked to the work of the Project Office [Braybrook 1984, Hooper Interview 27/08/1996].

(Note: Rest of section based mainly on Dow and mix of interviews, references to be added)

The central innovation of the Hawker P.1127 was to use the same single engine to both lift vertically and then drive forward in flight, a system known as 'vectored thrust'. Other 'jump jets' designed in the UK relied on separate lift and propulsion engines for each flight regime, often installed by the half dozen or more. The origins of the vectored thrust engine lay in the work of a French designer, Michel Wibault, who approached NATO in Brussels with the outline idea in 1956. NATO officials saw the idea had merit, and passed the concept on to the Bristol Engine company in England, with whom NATO were already working.

At Bristol the idea of vectored thrust was simplified and made more practical, the work being led by a young engineer called Gordon Lewis. An essential part of this work was finding aircraft designers who could explore the issues raised by the new type of engine. Bristol were linked by cross-shareholdings to the Shorts aircraft company. But Shorts were more interested in the alternative lift jet system as they had a contract from the UK Government to develop a research aircraft using that approach. Shorts therefore used design work on vectored thrust as an opportunistic way to gain a meeting with NATO, where they put forward their own favoured type of lift jet design ahead of vectored thrust - hardly a way to gain popularity with Bristol. Design collaboration between the two firms ended immediately, a clear illustration that communities of practice which coalesce around a boundary object – such as vectored thrust – can divide off irrevocably from those with a different focus.

Since vertical take-off and landing jet aircraft were a 'hot topic', and as Hawker were desperate to secure their future after cuts in the UK fighter programmes, Camm wrote to the head of Bristol engines, Sir Stanley Hooker, to enquire about their work on the subject. A brochure on vectored thrust was passed back to the Hawker Project Office, but it was not initially seen as an attractive system. The brochure was initially picked up by Ralph Hooper, a project engineer at Hawker, who admitted he did so out of boredom with his main task of designing a flight control system on another project. He produced a few sketches of types of aircraft that could use the new vectored thrust engine, but none looked too promising. After a period of going back to his main work, he returned to the idea of the vectored thrust design and it was then that "the blinding flash of the obvious happened". The original Bristol brochure proposed that only half the engine's power would be 'vectored', limiting the weight it could support. Hooper realized that all the power could be vectored, allowing a much more useful aircraft design to emerge.

Hooper visited Bristol to discuss the idea with Lewis. It turned out that Bristol had anticipated the development Hooper outlined and put it into their engine's patent application, although the more detailed scheme Hooper created was also the subject of a Hawker patent. Despite this apparent conflict of interest, with Bristol fiercely defending their patent rights against other engine companies, they waived them with Hawker. This was a direct result of the design community that developed between Bristol and Hawker, with both feeding new ideas into the design of the engine and airframe over a period of several years. Many decades later it was impossible for participants to recall who had created what, and it was never a point of argument between them.. The design of what became the Harrier and its engine evolved over time through an informal process of joint working between Hawker and Bristol engineers (located 120 miles apart) with novel technical problems dealt with in a mutually supportive way – demarcation was neither technically nor organisationally desirable. This was a far cry from the often fractious relationship between other engine and aircraft companies, illustrated by a cartoon from the time:
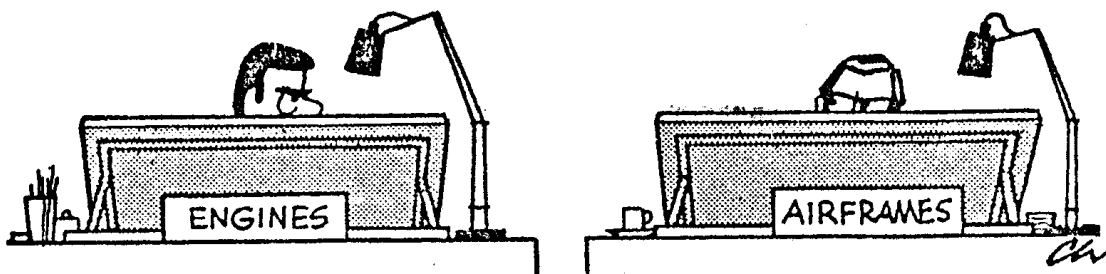
(Chris Wren)

Figure 6 Traditional animosity between jet engine builder and airframe designer illustrated here was absent between Bristol and Hawker in the development of the Harrier

An informal approach to working was supported by management – Camm and Hooker at director level having known and worked with each other for many years. In addition, within the two firms management trusted their project engineers to make decisions and act on them, and provided resources when needed. At a briefing for NATO it is reported that Lewis brought the wrong costing figures to win NATO funding for the engine. Too late to correct the mistake, and having obtained NATO approval at the lower costs presented, Arnold Hall, Bristol's director,

accepted Lewis's explanation and approved the significant additional spending the company would incur. A similar relationship operated with government – the Ministry of Defence ultimately funded the Hawker P.1127, but contract cover was only received a few months before the aircraft flew in 1960, with the design and manufacturing costs having been met by the company up to that point, a highly unusual state of affairs in the aircraft industry. However, Camm's reputation with the MoD meant that Hawker's directors were willing to place their faith in the innovative project his design team created. Such support 'greased the bearings' of the design process, and formed a vital part of the community that developed the Harrier.
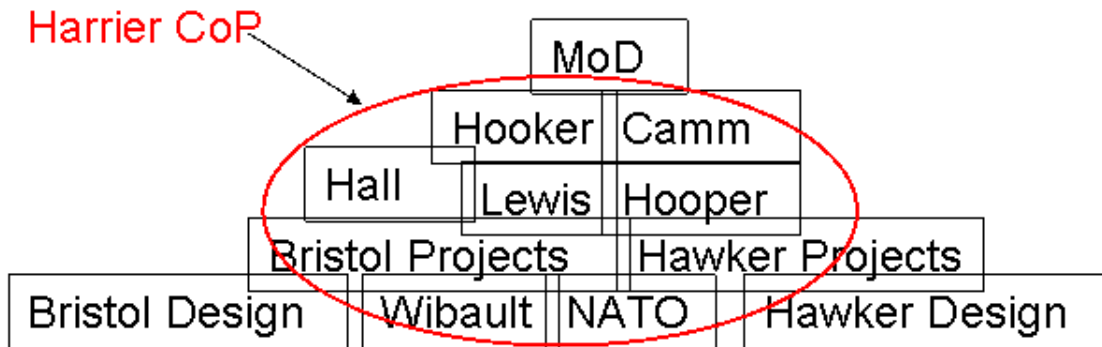

Figure 7 The joint development of the Harrier led to a long standing community of practice across Hawker and Bristol, fostered by the leadership of their respective designers (circa 1960)

Figure 8 The two men at the heart of the Harrier development and the original document that catalysed the formation of the community of practice across Hawker and Bristol

The role of the community in obtaining support and sustaining practices within the Harrier design team is highlighted by the difficulty those outside the community faced in understanding the engineering sense of the design. Many analytical studies were produced that 'proved' that the vectored thrust system produced the 'optimum worst' solution to vertical flight by jet aircraft. It was seen in these studies that the lift jet system provided a 'better' solution, with a hybrid of vectored thrust and lift jets producing the 'optimum' best. On the basis of these studies a number of aircraft were built in France, Germany, the UK and elsewhere. The Germans built an aircraft that used the optimum 'best' system, which turned out to be, in Ralph Hooper's words, "amongst the most expensive and useless of all time". The French had a similar experience, one of their lift jet equipped designs having the dubious distinction of crashing twice and killing two test pilots.

Central to the Harrier's success was that it was the simplest, most practical engineering solution to the problem. In large part, this was due to the community nature of the way the engine and aircraft designers worked together. Occam's razor shaped their way of working and the new fields of design knowledge the community required. This informal approach was not used on the disastrous prototypes produced by others. Instead, rigid contracts, separate design teams (often spread across a continent) and patent disputes were commonplace and complicated engineering and project failure the result.

The Harrier community continued to work in the same way until March 2011 in the UK, with the virtues of engineering simplicity, flat structures, an absence of 'not invented here' mentalities all remaining key features of their approach. This method of community practice continued, with many other companies brought in over time to work as part of the community even though they were ostensible competitors, something outsiders found hard to grasp.

IV

Implications for Research Management and Technology Development

We argue the content of knowledge that is being developed determines the way in which a research and development should be structured. The paper suggests communities of practice are one way to work in the creative but uncertain realm of project design and development. These self-assembling groups marshal original design skills, based on tacit knowledge and experience. The imposition of more formal approaches to project management is likely to inhibit the ability of teams to innovate. Even if formal structures are imposed, participants will form into communities of practice and find ways of working round these hierarchies.

The existence of these communities of practitioners resolves the central paradox of R&D management that innovations are discoveries that entail the growth of knowledge, so how do you formally manage something that has yet to be discovered (Metcalfe and De Liso, 1998)? It may be possible to roadmap desirable outcomes against a time line, but the reality of progress month by month cannot be anticipated. These communities are heuristic, problem solving devices that search out satisfactory solution guided by prior experience, technical analysis, hunch and trial and error, grabbing appropriate resources and people as they grope towards a solution. The clear management implication is tight control over the broad aims of projects and loose

handling of the creative personnel engaged in the day to day development. If the management group are part of the community themselves, they may feel more comfortable with simply giving broad sanction for resources within loose and flexible aims, as we have seen with the Harrier. But that may imply creative engineers need to be led by creative engineers, not general managers who cannot judge the technical significance of what is going on.

One great strength of communities of practice is they can stretch beyond the borders of one organisation. In our examples Ferranti Automation and ICI Alkali Division and Hawker airframes and Bristol engines worked together on a shared problem across organisational boundaries, despite not being formally associated in a 'project team'. In both cases these communities supported breakthrough innovation. They had informal ways of working, relying on shared appreciation of what each party knew. There was a strong reliance on trust and little regard for niceties of overlapping intellectual property.

But here is the paradox of these communities of practice. While they facilitate knowledge exchange within communities, they can erect strong barriers against the outside world. These communities can become exclusive and divisive. Their very strength as a set of sub-cultures within the firm may militate against cooperation with other parts of the firm, as we have seen within Ferranti and between erstwhile partners Bristol and Shorts. More to the point, strong communities of practice may preclude cooperation across business functions. Since successful innovation often involves combining close attention to customer needs, careful marketing and strong financial controls with technical excellence, the existence of strong technical communities within the firm may inhibit cooperation between different roles and prevent successful innovation.

The two examples considered here focus on novel, cutting edge, complex technology problem solving in organisations dependent upon the key skills of individuals who gain status and influence from creative solutions. This raises the issue of power within research organisations. It has been suggested that power has been divorced from technical mastery in modern organisations (Hardy and Clegg, 1996). It is clear from these examples technical influence and position in the organisational hierarchy are different. Ill-advised managers sometimes made life difficult for gifted engineers at Ferranti, but it is evident that problem solvers derived considerable status and fast promotion. But again there is an evident tension between generalist management attempting to keep control and practitioners coalescing around a pet project.

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Footnotes

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1. This is what Blackler (1995) calls "embrained knowledge" as opposed to routine "embedded" knowledge of the sort described by Weick and Roberts (1993) where individuals on an aircraft carrier flight deck respond with well-drilled routines to urgent and foreseeable crises. In practice, the distinction is not so hard and fast as design has it collective routines and military action often requires improvised and novel solutions.

2. There are numerous anecdotes about Camm. At a recent (November 2010) celebration of the fiftieth anniversary of the first flight of the Harrier prototype, the Hawker P.1127, this story was told by the designer of the aircraft Ralph Hooper: Sir Sydney with Roy Chaplin (deputy Chief Designer) talking to Sir James Martin (of ejector seat firm Martin Baker) and referring to the new P.1127 with Ralph Hooper present, "If it works we (SC and RC) done it; if it doesn't 'e done it" (indicating RSH). (Ralph later said, "It's the nearest Sir Sydney came to paying me a complement.")
Source: http://myweb.tiscali.co.uk/hawkerassociation/hanewsletters/hanewsletter029nvu/ralphhooper.html accessed 23 March 2011

3. Cancellation of Blue Envoy is said to have prompted the design of Bloodhound 2 in a London taxi outside Ferranti's head office by David Farrar, Taffy Higgenson and Don Rowley – almost an instant community of practice! See Adams (1976, p.55)

4. Thus offering a clear example of Wittgenstein's distinction between "saying" (equations of motion for the gyro) and "showing" (building the circuitry to control the gyro).

5. Derek Whitehead had not heard of the American SAGE air defence system developing along similar lines to those he proposed. If Norman Alder was aware of what was going on in the USA, he clearly did not approve! See Edwards (1996) and Redmond and Smith (2000).

Interviews
The experience at Ferranti is based on 25 interviews carried out over four years from early 2007, with former employees of Ferranti and ICI from board level to technician level, plus a number of repeat interviews with key participants.

The Harrier section is a result of many interviews with former design staff, ongoing research by Michael Pryce with current Harrier design staff and innumerable informal talks with members of the Harrier community, presentations of research findings to them and comments etc. Indeed, it may be that to understand such a community one needs to become 'part' of it!