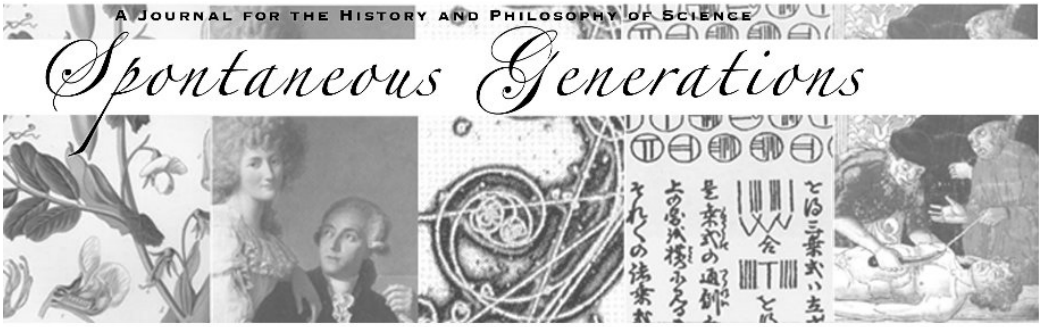

“Old” Technology in New Hands: Instruments as Mediators of Interdisciplinary Learning in Microfluidics

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"Old" Technology in New Hands

Instruments as Mediators of Interdisciplinary Learning in Microfluidics*

Dorothy Sutherland Olsen†

In his article on radical innovation, Shinn (2005) examined the role of scientific instruments in innovation. This paper continues to investigate this theme, but the main focus is on how scientists or engineers from one discipline may learn from another and produce new knowledge and new technology. The paper looks at the role that tools and instruments developed by one discipline, in one environment, can play in the development of knowledge in a new environment. The theoretical basis for this study is Vygotsky's (1978) concept of tool-mediated activity. The proposed conceptualisation views instruments as dynamic and suggests types of tool-mediated activities which may contribute to knowledge creation. The collaborative process of experimentation is examined and opportunities for knowledge creation are discussed in relation to the instruments used. Methods used are interviews and observations. The case study is a small multidisciplinary laboratory developing a new process for producing nanoreactors, with potential applications in pharmaceuticals and energy.

I. INTRODUCTION

The importance of tools and instruments in the development of new technologies and of scientific and technological knowledge has long been recognised (Galison 1997; Latour and Woolgar 1979; Mody and Lynch 2009). There are many historical examples describing how the development of instruments has gone hand-in-hand with the development of new fields (Lemaine et al. 1976). As well as playing an important role in innovation (von Hippel 1988), it has also been suggested that scientific instruments are a vehicle for communication of technological knowledge (Fujimura 1992) and promote a kind of lingua franca between different groups of scientists (Shinn 2005).

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The starting point for this paper is an assumption that tools and instruments moved from one domain into another provide an opportunity to develop the new domain and to create new knowledge. The intention here is to explore this as a learning process by examining the interplay between scientists and their instruments. The paper reviews some earlier studies, which look at the relationship between instruments and the development of knowledge. The concept of tool-mediated activity from cultural historical activity theory (CHAT) is introduced as a way of studying the activities of scientists in a dynamic research environment and examining how instruments mediate these activities. The intention is to gain a better understanding of how instruments may aid the sharing of knowledge between different people and how these instruments may also play a role in the creation of new knowledge and innovative ways of working. In the next section the way in which tools are used in experiments within the emerging field of microfluidics is examined through the lens of the cultural-historical perspective. The history and development of this emerging field is described, then examples from both the historical development and of current practice are analysed in an attempt to understand the role of instruments in knowledge-sharing and knowledge creation.

II. The role of instruments in the creation and sharing of knowledge

There have been many attempts within STS to understand how not only scientific theory, but also material artefacts, contribute to the creation of new knowledge and new ways of working. Some of these view the processes of knowledge creation in laboratories, where tools are seen as inscription devices (Latour and Woolgar 1979) or as part of the epistemic machinery necessary for the production of scientific knowledge (Knorr-Cetina 1999, 3) and as such, an integral part of ongoing practice in this environment. Another strand of research has concerned itself with the successful development of new technology and is based on studies carried out in industrial settings (Fleck 1997; Pickering 1995). Although the focus of these various writers is different, they all provide valuable contributions as to how we might understand the role that tools and instruments play in collaborative knowledge creation. Some of the important works are presented and discussed here and an attempt is made to conceptualise tools in a way that might help us to understand the role they play in knowledge development.

Instruments as carriers of encapsulated knowledge

By examining historical examples of technological development Baird (2004) draws our attention to the importance of practical experimental work in the development of technological knowledge. While acknowledging the importance of scientific theory, which can be codified in written form and then removed from its context and passed on to others, he attributes a high importance to technological knowledge or "thing knowledge" as he calls it. He recounts the story of Faraday sending instruments he had designed to colleagues, so that instead of reading a description, they would be able to see and test these instruments themselves. These colleagues were able to contribute to the rapid development of this technology. Baird also draws our attention to scientists and engineers working with theories which they knew were incomplete or did not apply to all the situations they were experiencing. Instead of trying to develop the right theory, they made the instruments they deemed necessary, and this actually helped them to develop the theory on the long term. He implies that instruments allow us to encapsulate knowledge, which is not fully understood, or cannot be made explicit. "The materials bear the knowledge independently of theory or in spite of bad theory." (Baird 2004, 170) When encapsulated, it can then be passed on to others who may be able to develop it, leading potentially to new tools and instruments or contributing to the development of theoretical knowledge.

This idea of knowledge encapsulated in tools is similar to Fleck's (1997, 383) and Buchiarelli's (2003, 69) ideas of knowledge embodied in tools or technological artefacts. Fleck recognises the link between innovation and instrumentalities, particularly the way in which instrumentalities make possible "the introduction of innovations from other technological sources" (Fleck 1997, 387). He describes instrumentalities as knowledge embodied, not only in the tools we use, but also our working knowledge of the tool or how we make it work in a local context. Fleck's perspective is based on participant studies of the implementation of new technology in industrial environments in the UK (particularly robotics and aeronautics). He examines what he calls the "learning process" occurring when new technologies are implemented. However what he describes is not simply a case of users learning to use a new technology, but users adjusting this technology to make it work in the local context. Fleck stresses the importance of this phase of technological development as a source of innovation and suggests that it should not be viewed as a separate phase from the design.

Tools "in use" or dynamic tools

Knorr-Cetina further develops this idea of tools being open to adjustment and change in her concept of epistemic objects (Knorr-Cetina 1997). This epistemic object may be a physical tool or a conceptual object. This concept allows the object to have a kind of dynamic state, whereby it is being used, but at the same time being changed; for example, software may be perfectly usable and support practical tasks, but at the same time may be under development. In the act of using tools the users expose gaps between the current functionality and their expectations of functionality.

Knorr-Cetina is not alone in emphasising the relationship between adapting tools and developing knowledge; Pickering (1995) refers to the process of knowledge creation as the "mangle of practice," a metaphor designed to invoke the continually changing interactions between humans and machines. Rather than examine how stability or equilibrium is achieved, Pickering examines what he calls the "temporal emergence" of practice. As he says, "In advance we have no idea what precise collection of parts will constitute a *working* machine" (Pickering 1995, 24, italics added); the working machine can only come into existence after a period of trial and error, which constitutes practice. His studies recount the continuous cycles of change, whereby technology is designed, used, changed, used, changed again, etc. He uses data gathered by others in ethnographic studies on, among other things, the introduction of N/C manufacturing (numerically controlled machine tools) in an industrial environment. The metaphor of tuning is used to describe this continuous process of adaptation. Of course the adaptation of tools is not seen as an isolated activity, but integrated in and influencing on-going work.

Tools as mediators of knowledge creation

Cultural-historical activity theory has its origins in the works of Vygotsky (1978) and has been further developed by Engeström (1999; 2001) in his studies of collaborative work. It has been also been used in studies of science and technology (Saari and Miettinen 2001; Matilla 2005). This perspective views knowledge creation as a collaborative activity directed at an object. The activity is typically mediated by tools, which can be conceptual tools (such as theories or models) or material artefacts.[1] In this paper I will use the concept of tool-mediated activity to explore the role of scientific instruments in knowledge creation. Learning or knowledge creation is seen as occurring when people interact with the outside world in some way, i.e. it is not merely a cognitive process inside the head. These

[1] For a comparison between CHAT and actor network theory see Miettinen (1999).

interactions can be with people or with tools. Tools are not seen merely as artefacts to support human actions, nor are they seen exclusively as constraints influencing human actions. It is the conscious attempt of the human actor to expand his or her abilities by interacting in some way with the tool, which is a central part of CHAT. These interactions are typically in the form of using the tool to achieve some aim and/or developing the tool to fulfil new aims or simply to function more efficiently. Thus the creative aspect of new or changed tools or existing tools being used in new ways is encompassed within this concept. The concept of tool-mediated learning has been used extensively and has proved useful in understanding the relationship between tools and changes in working processes and how "objectification of knowledge into artefacts" (Miettenen and Virkkunen 2006, 154) makes it possible to transmit knowledge to different groups of people in different places and at different times. Tools are also seen as playing an important role in the development of networks and the links between tools and the object of activity are central to this approach. In empirical work based on the cultural-historical perspective, learning is usually studied by observing the activities of actors involved in collaborative practice.

Conceptualisation of tools

While each of the perspectives mentioned here has a different focus, they can all contribute to our understanding of the role instruments play in knowledge creation. Both Baird and Fleck suggest that the kind of knowledge generated by tool use and stored in tools is different from traditional definitions of tacit, explicit, formal or propositional. It is what Baird calls "thing knowledge" and which can best be described in examples where the technology works, but we do not understand, or cannot explain exactly how or why it works. This knowledge is based on previous use, the trial and error of previous generations. The resulting tools or instruments can be viewed as complex artefacts within which knowledge and past experience has been embedded over time; "cultural artefacts" or artefacts developed in collaboration over time. These artefacts are not only important as tools to get the job done, but play an important role in the process of spreading knowledge. This view of tools suggests that if we wish to fully understand their role in knowledge creation we should also look, not only at how they are being used today, but also where they came from and what knowledge they may have carried with them. Types of tool-use should include situations where new users may use tools differently from the tool-makers original intention either deliberately or by mistake.

The fluidity of the state of instruments described by Knorr-Cetina and

Pickering presents a challenge to studying the role of instruments in knowledge creation. However, the close link between using instruments and adapting them as expressed by these perspectives is not new in studies of technological development and can be seen in studies by Fleck and particularly in the work of Eric von Hippel (1976; 1994) on the development of scientific instruments.

Both Fleck and von Hippel suggest that the continuing development of instruments should be regarded as an integral part of the usage rather than something separate, only occurring in certain situations. This close relationship between using instruments and changing instruments suggests that any study of instruments in use should endeavour to capture the adaptation of instruments in such a way that their contribution to knowledge creation can be analysed.

Although tools may be the bearers of knowledge it is the very use of tools, or the activity of using tools, which often leads to the changes in the tools and at the same time it is in the interaction between people and tools that learning, or the creation of new knowledge, occurs. Therefore we should not view tools as things which are fixed in one place, static or stable, but as things which may continue to evolve and change and be made usable while they are being used. The cultural historical perspective assumes that tools or instruments are developed over time by a group of people to satisfy some practical need. They are referred to as cultural artefacts. The creation of these material artefacts can also be the object of an activity. If the creation of a working artefact is the object of collaborative activity then it will continue to evolve and change as required. I would like to emphasise this aspect of dynamic instruments in a research environment by viewing them as in the following way:

Tool	**Activity**
Static	Using as the tool-maker intended
Dynamic (i.e. Neither fixed nor static)	Using differently (from the tool-maker's original intention) Deliberately Adapting

Table 1. Conceptualisation of tools and instruments.

The activities associated with this interpretation of tool-mediation are identified in this case and are examined to gain an understanding of the process of knowledge creation. The terms tool and instrument have both been used in this brief review of previous studies. I interpret tool as the

more general term, which includes scientific instruments.[2]

The starting point for this paper was the idea that moving scientific instruments from one domain to another would provide an opportunity to develop new knowledge or innovative practice. After reviewing some of the different theoretical perspectives on the role of instruments I would like to refine the original question by suggesting that using or tinkering (Knorr-Cetina 1981) with instruments from another domain is one of the ways in which new knowledge or innovative practices develop. In the next section a case study will be introduced, thereafter the above conceptualisation (Table 1) will be used to select and analyse examples of instruments in use.

III. Case and methods

Case

The Laboratoire de Biologie Chimique studied in this paper is part of the Institut de Science et d'Ingénierie Supramoléculaires, established by a Nobel Laureate at the University of Strasbourg in France. The intention was that the institute should bring together scientists from different disciplines, mainly chemists, biologists and physicists to study supramolecular science and engineering from various perspectives. This particular laboratory was established by a small group of biologists who had previously worked together at the Laboratory of Molecular Biology at the University of Cambridge (UK). These biologists wanted to use new technology to improve and broaden the range of their experiments. To do this they invited physicists, electronic engineers and chemists to join them from the start. Deliberate efforts were taken to ensure that scientists from the different disciplines were in constant contact with each other, such as shared offices and lab space as well as lots of social events. During recruitment the lab director deliberately sought people who were positive to a multidisciplinary environment, as he said "not purists." For example he chose a biologist who built hi-fi systems in his spare time and often looked for a broader science-based educational background or varied work experience rather than the more traditional mono-disciplinary specialised background. All the participants were very conscious of the interdisciplinary nature of their work. The lab had also established formal collaboration with a group of physicists in the Experimental Soft Condensed Matter Group at Harvard in the US, chemists from the Department of Biological Chemistry, the Weizmann Institute of Science in Israel, and a less formal collaboration with some chemists at the Colloids

[2] For a more in-depth discussion of the differences see Verbeek (2005).

and Divided Materials Laboratory in ESPCI (École Supérieure de Physique et Chimie industrielles) in Paris and a US spin-off in Massachusetts called Raindance Technologies that is already marketing some of their jointly developed technology. At the time of the study the lab was very dynamic, with the lab director continually inviting people from both academic and industrial labs to bring in their own samples to test using microfluidics technology. The scientists working at the institute were also encouraged to invite others. This open attitude to visitors meant that the scientists were used to talking about their technology and appeared happy to allow a social scientist into the laboratory.

This case study looks at the activities of scientists in a particular phase of the development of their laboratory. The team is attempting to use a relatively new technology, microfluidics, to develop experiments in biology. To do this they create "nanoreactors"^{TM} which are droplets within which they can carry out experiments. This involves developing and modifying existing technology and developing and modifying the biological experiments to make best use of the new technology. In addition to studying the work in the laboratory a brief analysis of the historical development of the microfluidics technology, as a cultural artefact has also been carried out.

Methods

The methods used to gather empirical data were interviews and observations in the laboratory, supplemented by documentation in the form of lab books (written records kept by the scientists about their experimental work) and some of their scientific publications. The intention was to study the practice, but also to gain a perspective of the activities and the community in their historical context. The researcher was based at the lab for a three-month period in 2006 and a fourteen-day follow-up in 2007. Thirty-one in-depth interviews were carried out. In addition to this there were many conversations where technical details were clarified and many informal conversations. Data was also gathered from lab meetings and other available documentation in the form of reports and articles. The continuous observations in the microfluidics room were carried out during a fourteen-day period in 2006 and a ten-day period in 2007. Many of the examples recounted in this paper occurred over a period of time and were not observed in their entirety. The descriptions of these experiments are based on separate interviews with all the various actors involved. Some of the examples are also taken from the historical development of the microfluidics technology, which the current scientists have participated in and recounted in interviews.

In order to safeguard the identities of individual participants they have

been grouped into the categories of physicist, biologist or chemist. Thus no distinction is made between, for example, biochemists and chemists. A cultural-historical approach is taken in the analysis and interpretation of the empirical data and the concept of tool-mediation is used to gain a better understanding of the role of instruments in knowledge creation.

IV. The technology and its development

Brief history of this branch of Microfluidics Technology

One of the first references to the technology we now call microfluidics was in IBM's research laboratories, where engineers were striving to improve the accuracy and speed of inkjet printing (Bassous et al. 1977). They took advantage of recent developments in photolithography and silicon chip technology to control the flow of liquids by passing the liquid through specially designed silicon chips. In 1989 Manz et al. suggested that the future of this technology lay in fact in applications within life sciences and chemistry (Nguyen and Wereley 2002). Along with microsensors, micropumps, and microvalves, this technology continued to become more miniaturized and in 2005 was classified as one of the heterogeneous technologies under the term bio-nanotechnology by the OECD; technologies "at the interface between physics, biology, chemistry and engineering sciences" (OECD 2005). These technologies include lab-on-a-chip, molecular motors, biomedical sensor technologies, and microfluidics.[3]

While this study has attempted to follow a team of scientists and engineers over a period of time, it is still only an extended snapshot in the technological trajectory of microfluidics. Instruments were playing an important role in the development of knowledge on microfluidics and the development of the microfluidics community long before this study began. The technology used in this lab came from physicists in the Experimental Soft Condensed Matter Group at Harvard. They in turn had taken the techniques of soft lithography developed by the Whitesides Research

[3] References to nanoscience and nanotechnology normally draw a line between the micro scale as over 100 nm and nano as under 100nm. Recently the term bio-nano has been applied by the OECD (2005) to a heterogeneous group of technologies currently being developed and used in research and development within biology and medicine. Working at the nanoscale is a feature of all these fields, however none of them are exclusively nano. The case investigated in this paper is in microfluidics and the scientists are encountering problems of scalability, such as changing properties, both at the micro and the nano levels. Sometimes these challenges are encountered over 100nm, sometimes below. The examples in this case have been chosen to demonstrate tool-mediated learning rather than the specific challenges of scalability at the micro or nanoscale.

Group in the Department of Chemistry and Chemical Biology, also at Harvard. The current lab in Strasbourg is a multidisciplinary team who have taken on this technology and are continuing to develop it in order to carry out their biological experiments.

Knowledge encapsulated in a cultural artefact

If we view the microfluidics station as a cultural artefact, then we accept that it contains knowledge which was found to be successful in the past and we can identify various theories, like theories of electrowetting which steer the application of electric current. The different ways of viewing the results have been programmed by the scientists using standard Labview software. The device or chip is based on techniques of soft lithography and the speed at which the droplets move through the channels is determined by enzyme kinetic techniques and stopped-flow methods. The consistency of the droplet is determined by emulsion chemistry. Using digital pumps to bring in the liquid and the whole concept of using flowing liquid to carry out biological experiments is not new and has been developed and refined in recent years, typically for use in DNA sequencing. This brief list has doubtless omitted some of the many techniques or theoretical knowledge "encapsulated" in the digital microfluidics station; however, it gives an overview of huge breadth and depth of the past experience, gained by using the various parts of the modern microfluidics system as well as some of the better known theory, which is now incorporated in today's technology.

Technology	**Field of Origin**
Device	Microelectronics
Controlled droplet production	Fluid physics
Automatic pumps	Biotechnology
High speed digital video camera	Various fields including defence and aerospace
Software for analysis of data	Based on Labview software, configured in-house
Digital storage of results	Standard data storage solution

Table 2. Overview of the origins of microfluidics technology.

Almost all experiments in this laboratory are carried out using the microfluidics station. It is central to the daily work carried out in this

workplace. The success of experiments is dependent on the fine balance between the content of the emulsion fluid, the current applied, the angle of the channels on the device, the angle and strength of the laser and of course all this can be affected by, or may affect, the substance inside the droplet. Each biologist, biochemist or chemist carries out different experiments and they frequently require that this delicate balance be adjusted. The practice of experimenting in this lab is described in more detail in Olsen (2009).

Work in the current laboratory

In this case study the group of scientists are trying to isolate enzymes or cells for use in a variety of future experiments and applications. These enzymes are isolated in nanoreactors, or droplets acting as an isolated test environment, within which a reaction may occur. Some examples of what these enzymes may be used for are catalysis, bio-fuel cells, preventing blood clots in potential stroke patients or to neutralise chemical contamination. Traditionally this type of work would have been carried out using time-consuming and expensive screening techniques. However, the scientists in this case are using digital microfluidics technology, making it possible for them to select, rather than screen for, promising enzymes for further development. The advantages of this new technique are its speed and cost-efficiency.

The lab has what they call a "digital microfluidics station"; this could be described as a hybrid tool, or a combination of tools and instruments used to carry out experiments in the lab. This consists of a microscope; under the lens of the microscope is a polymer device or chip which is specially designed for each experiment. Connected to this chip are capillary tubes and pumps. Once the samples have been prepared at the lab bench, they are pumped into the tubes and into the flow of fluid emulsion. Electric current is applied in order to break the flow into evenly sized droplets. If everything goes according to plan each droplet should contain one sample, e.g. an enzyme or a DNA molecule. Some experiments require that two different droplets with different contents be merged. The droplets continue their path through a box containing carefully positioned lasers. These lasers will pick out the droplets where a reaction has occurred, typically by showing up fluorescent bacteria made visible by the reaction. In this way the scientists can select the samples where reactions occur. This gives them a faster and cheaper alternative to more traditional screening.

As the droplets flow through the system they are filmed by a high-speed video camera (2000 frames per second) and the digital images are stored in files on disc. The flow of droplets and the reactions occurring can be viewed on the monitors, either "as filmed" or in many different graphical

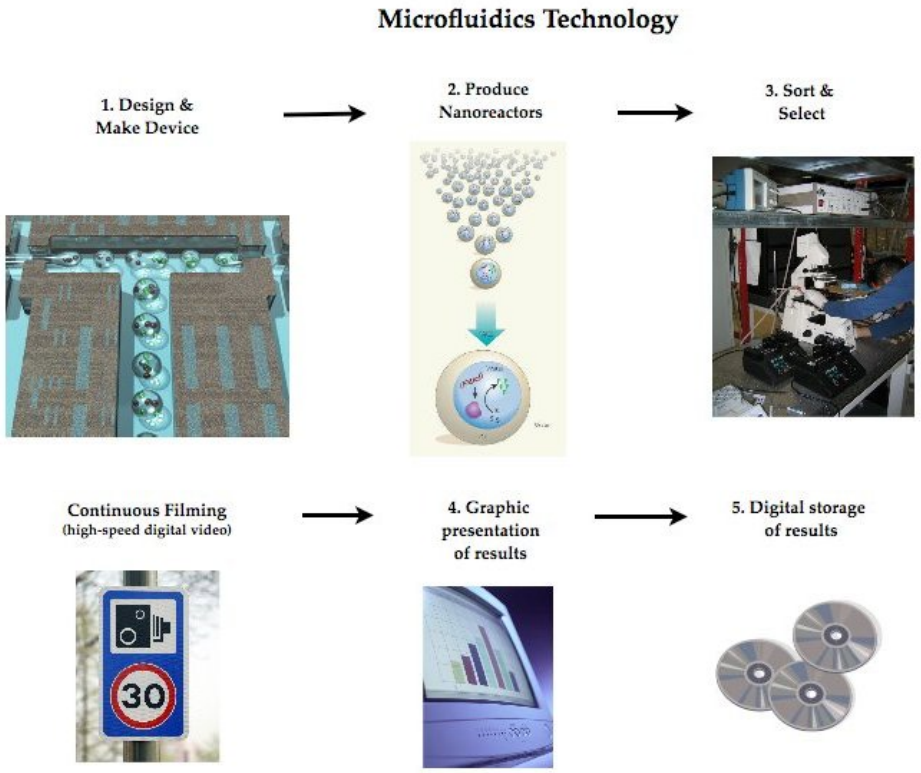

Figure 1. Overview of the stages in a typical experiment using microfluidics. Author's own figure containing pictures from the Strasbourg lab (www-isis.u-strasbg.fr) and Raindance (www.raindancetechnologies.com) webpages.

representations of the data, depending on which parameters are chosen to be highlighted. The scientists typically employ several different "views" (still pictures and video sequences) and those considered most appropriate for their publications are selected and stored digitally.[4]

[4] The following is a partial listing of instrument specifications: Cell sorter (Daco Cytomation, MoFlo); Inverted microscope (Zeiss, Axiovert 200); High speed camera (Phantom v4.2); Mask aligner (Suss, MJB-3); UV lamp (Dymax, 5000-PC avec cabine d'exposition et rideau électrique d'occultation); Spin coater (Laurell Technologies, WS-400B-6NPP-Lite Single Wafer Spin Processor); Oxygen plasma chamber (GaLa Instrumente, PlasmaPrep2); Fully equipped Digital Instruments - Dimension 3100 Scanning Force Microscopy and Scanning Tunneling Microscopy, running on a Nanoscope IV control unit. This instrument is equipped with the latest optional ("Nanoman"), combined with Dimensional Closed Loop SPM Microscope Head, which allows the manipulation of objects in the nanoscale using the SPM tip; A FEI Dual Beam 235: FIB-SEM-STEM with an ion beam (FIB, 5 nm) and electron beam (SEM, 1 nm) which allows state-of-the-art nanofabrication of samples (characterisation, deposition, milling, etc.); Keithley 6517 A Electrometer / High Res. Meter: (resolution 0.1 femtoAmp) interfaced with a PC; Spin coater with temperature controlled heating stage; Oven for

Current practice

As mentioned earlier it is the use of the tool that is important. The way this tool is used in the lab is part of the scientists' practice of experimentation. The scientists plan their experiments and typically confer with colleagues at this stage, particularly when deciding exactly how they might use the microfluidics station in their experiment. Once they have made their plans they will probably have to design and make a new device or chip. This will take a couple of weeks. They will also have to prepare all their samples. This preparation varies depending on what they are trying to achieve, but the samples are normally prepared at the lab-bench. It may for example involve extracting DNA or preparing enzymes. The samples are then pumped into the microfluidics station and monitored on the screen that relays the picture from the microscope. When satisfied with the results the scientists typically use the software to produce a graph showing the distribution of the samples in the droplets and normally choose some still pictures to illustrate their results. This is then stored electronically and copied into their lab books.

V. Learning by using instruments

The following examples all describe separate incidents and are not presented in a way that shows all the stages in the work the scientists carry out. These examples were chosen because they all exhibit situations where the interactions between the scientists and their technology suggest learning or knowledge creation taking place. The tools appear to mediate the learning process in several different ways. In each case the user of the technology learns to do something new or to do something differently while using the microfluidics technology. The analytical framework outlined in section II is used to group these examples by the type of tool-mediation occurring.

Using instruments differently

There are examples of using tools wrongly, or differently from the way the tool-maker originally intended, both in the data gathered in the Strasbourg lab and in the description of events leading up to the creation of lab.

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performing thermal annealing in controlled atmospheres; Inverted Nikon and Mitutoyo optical microscope, with liquid nitrogen cooled CCD 2D detector and spectrograph for optical measurements of nanoscopic objects; Autolab Galvanostat/Potentiostat for electrochemistry work; Spex Fluorolog spectrofluorimeter and Shimadzu UV-VIS spectrophotometer; A class 1000 clean room is available for the sample preparation; Emitech sputterer

Before the present lab was established some of the biologists in the team worked in a UK lab. They were trying to create droplets for their experiments by mixing oil and water; they described it as not very precise and "more like making mayonnaise." In other words they could produce beads of fluid or droplets, but they had very little control of the size and speed of droplet production. However, they wanted to a faster throughput and better cell sorting. A nearby lab had a FACS (fluorescent-activated cell sorting) machine designed to work with water. Some of the scientists thought of putting their emulsions through this machine to sort cells. They tell a story (Eisenstein 2006) of bribing the technician by buying him beer so that he would allow them to try out emulsions on the FACS machine. In fact this did not work and the FACS machine was full of emulsion for three weeks afterwards. Undeterred by this failure, the scientists claimed that they had gained better understanding of what was needed to produce their droplets and they started looking for other solutions.

In the current microfluidics station a central part of the equipment is the device or the chip which channels the flow of fluid before it passes under the microscope. Before the current lab existed a group of experimental physicists in the U.S. were trying to perfect the controlled production of identical droplets at high speed. The physicists had close contact with a nearby lab where techniques of soft lithography developed in the microelectronics industry were being pioneered, not to channel electrical current, but to channel liquid. The physicists began using these devices as they called them. By applying electricity to the steady flow of liquid, they were able to separate them into precise identical droplets. Prior to this, scientists had a limited ability to control droplet production and the consequences of this new knowledge have contributed to the opening up of a new scientific field.

Not all examples of technology being used wrongly have such revolutionary results as the previous one. Biologist H revealed the following in an interview:

> One biologist was unfortunate enough to have an experiment ruined when all the droplets coalesced into one large droplet. He had worked for several weeks on the preparations and was devastated. On the other hand, the physicist present was deliriously happy at what he called a major event. The fact that the droplets coalesced and the particular way they coalesced was something the physicist had not managed to achieve before on his own. The lab director was called in to share in this positive event. Everything was captured on video and published on their web page. (Olsen 2007, 21)

In the above example the biochemist was trying a new experiment, the combination of the fluid he was using, the device through which it was flowing, and the enzymes he had in the droplets did not work. It was the wrong combination for this particular experiment. In spite of all the mistakes, new knowledge on how to use microfluidics to make droplets coalesce was created.

Deliberately adapting instruments

These examples all occur during the practice of experimentation and are examples of the type of problem-solving occurring during experimentation.

Two chemists had been testing yeast in droplets. They wanted to find out which yeast enzymes were most efficient at producing ethanol. Their intension was to isolate the most efficient ones and develop them for use in bio-fuel cells. In the microfluidics room, while the experiment was in progress chemist Q told me about a problem they were experiencing:

> The experiment takes time, the yeast has to develop before it can produce ethanol, during this process carbon dioxide gets produced and this slows down the flow of droplets. So we added a motor, see here, to the pump to speed up the [flow of] droplets.

The added motor gave them a control, which was not possible before the chemists developed this solution. The chemist explained that they had also been trying out different fluids, but the pump was a quicker solution. Without some solution to speed up the flow of droplets it would not have been possible for them to continue with this experiment. The results of this learning process are available to the others in the lab because they have become incorporated into the tool.

As the biologists get more ambitious and more adventurous in their use of microfluidics, they have produced a wider range of potential experiments, most of which require minor adaptations to the technology. One such example is provided by the use of single cells in the droplets. This is told by physicist E.

> You have a droplet, before we just imagined [we would work with] whole droplets. Now we have a cell, it's just floating around [inside a droplet], it's much smaller, like 5 times smaller than the droplet. If you have a laser beam hitting, not the whole thing, but something in the middle part of the droplet, sometimes you hit the cell with the laser, sometimes you don't. As soon as you

> apply it [microfluidics technology] to biology, to cell research, you have to change the optics, but if you make the laser beam huge like a droplet, you lose signal, so we have develop the optics so that the beam is like a line. The laser becomes a line, so it doesn't matter where the cell is flowing in the droplet, because it will pass through the beam.

Several biologists are working with cells which are a much smaller than the size of the droplet. This is not a problem with regard to isolating cells and producing a reaction, but if they want to sort the cells in order to select the ones where a reaction has occurred, they need to shine a laser beam at the droplets and select based on fluorescence. This is fine when the cell is large, but since the cell is much smaller than the droplet, the polarised laser beam might just miss it. This has been a problem for several of the experiments. They were in the process of installing a new optical filter to make the laser beam shine in a line across the droplet, thereby making it impossible to miss any fluorescence in the droplet. As in the previous example, the functionality of the tool has been expanded to meet the requirements of its users and a new method has been developed for detecting fluorescence in smaller samples. Adaptations of this type are discussed with the biologists before implementation and are then subject to immediate critical testing by the biologists. The results of this learning process are encapsulated in the tool for future use.

A physicist noticed that several of the biologists were having problems getting droplets to fuse properly. The biologists had invited some chemists into the lab to see if changing the substance the droplet is made of could perhaps solve this problem. While the chemists were looking for a solution, one of the physicists (physicist O) was also trying to think of a solution. He told me how he did this:

> I was lying in bed one morning thinking about the synchronisation problem. I saw that people [biologists and chemists] had problems with synchronisation of droplets, then I had some ideas, so I did a new design, [i.e. designed and made a new device or chip]... tested it... it worked perfectly... Then I thought, since this works so nice, now I need to prove this. I had some videos and everything looked perfectly paired [i.e. the droplets had merged as intended]; I could see that it all looked perfect, but I needed some quantitative data. Then I put some stuff in the program... to measure the pairing over a long period. I took these measurements. ... I started to think about a model and that's when Physicist C helped me about how I could make a model of this whole system, with the frequency.

> I thought I was at the point of publishing it and I went to the lab director. He said... well you still need an application for this. So [I thought] maybe use this reaction, which I did a year ago and it didn't work with a conventional microfluidics device, there was no chance of making these particles with a normal system. It destroyed all the devices. Then I created the droplets [using the new device] and made a video, that's what the lab director suggested for the publication. The droplets... fuse and the contents merge and it looks like they are solid contents, but it is lots of tiny particles. It is iron oxide and the smallest size anyone has created is 10–20 nanometeres and mine are about 3–5 nm. We could not do this before. Now we always get the same results and we have full control of the experiment. We are trying to analyse the particles to find out a bit more about them. Maybe we can patent both method and the particle. These particles are very interesting because they are used in the hard-drives on discs. There are potentially many applications for this particle, we could attach antibodies to this then we could steer it by magnetism. I really am happy, but I didn't plan this. I thought that this big clump [which I saw in the microscope] was a mistake.

Any applications of this discovery are a long way off, but this serves as an interesting example of new knowledge creation mediated by technology. At first glance this example may seem reminiscent of the traditional ideas of the lone scientist, but the motivation for all this work came from the problems experienced by his colleagues, the biologists when using the technology. The solution was found, not just by using the technology, but by adapting it. The work of the physicist produced a solution to the biologist's problem, a new method for fusing droplets and in proving the new method a new type of nano-particle was also produced. The results have been published (Frenz et al. 2008).

Re-building instruments

One of the biologists wanted to carry out some tests on dangerous bacteria and decided that it was safest to use a different room. He wanted to move the microfluidics station into another room, but moving everything was too difficult and there was high risk that moving things would disrupt the function of the MF-station. He decided to build his own MF-station. He copied the design of the existing station, got the physicists to advise him and did indeed manage to construct his own. Biologist I showed me around his lab and told me how he built his own microfluidics station:

> I think the main difference is a lack of fear about what is possible and how to do it. I am not scared anymore, now I try completely new things. Building it was quite fun, it was interesting; it made me appreciate what was really happening inside it, the idea behind it. Before it was just a black box.
>
> *Interviewer - do you mean the physics theory?*
>
> ...I mean I don't understand very much of the physics, When I started I didn't know that much about the microfluidics, but now I know approximately what will happen inside the chip if you have a certain layout. You know when you try things and you see that they work, then you want to change the design.

We could regard this as a simple example of learning by doing, of knowledge being spread from the physicists to the biologists, but it is more than that. The biologist is making improvements to the tool.

> [There is] a thing for holding the device under the microscope, it also lets you move the device, to examine it under the microscope... I didn't like the system, because it was difficult to move it. There were very coarse controls to manipulate the device, we needed finer controls... On the scale we are working on we needed more precision, so I designed a new system for manipulating the device. They made it [another lab on the campus].

The biologist also made some changes to the software used to steer the microfluidics station and to produce the results on the screen.

> The software physicist O developed is very good, but it has thousands of controls. It's too complicated to use for everyday experiments. I wanted something that was much simpler and focused on our experiment. It's based on the cell-sorter downstairs. It was a challenge to write the programs, but it takes much less time to produce the results we need in our experiments.

The knowledge of how to construct a microfluidics station is no longer the exclusive domain of the physicists. In this example the knowledge has spread from the physicists to one of the biologists. He maintains that he does not understand everything, including much of the theory encapsulated in the technology, but it all works very much to his satisfaction. Not only has he developed the ability to construct the apparatus, but he has also started to make his own improvements. In this case the experiences of one type of user have now been incorporated in a new version of the tool.

VI. Discussion and some conclusions

Analysis of everyday practice in the lab shows that the scientists are mastering the microfluidics technology and using it to carry out biological experiments. However they are regularly experiencing situations where new problems occur and the technology needs to be modified in order to carry out their experiments. By resolving these problems and making the necessary changes they are developing a more robust technology that can be used for a wider range of potential experiments. By resolving these problems they are also adding to the knowledge pool of microfluidics. One of the ways they are doing this is by incorporating their new knowledge into the tools for themselves and others to use in the future. Some of this new knowledge will also be presented in their scientific publications, particularly where they explain their methods. Much of this new knowledge may however remain tacit and perhaps not very well understood.

The theoretical perspectives on knowledge encapsulated in tools give some insight into how technology developed by physicists could be used by biologists without all the users needing a full understanding of how or why the tools work the way they do. As well as crossing the boundary between two different disciplines, it has also crossed geographical boundaries and some expertise developed in the U.S. was shared with scientists in Europe.

The conceptualisation of tools as dynamic rather than static artefacts gives some insight into the importance of continuous tinkering observed in the case study. The empirical data showed new users making mistakes when using the technology or trying to make it do things it was never designed for as they adapted or even rebuilt the technology. The U.S. physicists may have considered their technology to be complete; after all they could produce perfectly controlled droplets on request. As soon as a new group of people begin to use the technology, suddenly it is no longer complete. The new group uses it wrongly, or in different ways and this sparks off a whole range of adaptations and modifications to the tool. The requirements and the expectations of the new group of users are different from those of the designers and a stable tool becomes dynamic again. The tool is still being used by the original physicists in the U.S., but a whole new area has opened up and as the months pass there are more additions and variations on the original design. At the same time as the biologists are learning how to use this new technology; they are putting their mark upon it.

We might expect that with repeated practice some of the knowledge would become tacit or routine (Nelson and Winter 1982). In this case the biologists are still in the process of mastering the technology and "routinization" of knowledge may not yet have occurred. The scientists

all talk of "optimising" the technology as if one day it will be perfect and there will be no need to make adjustments. This day has certainly not arrived, nor indeed has the technology become transparent and the scientists regularly puzzle over which parameters, such as temperature or fluid concentrations, they might change in order to make their experiments work.

The multidisciplinary culture of this research team may play an important role in the way they use the instruments. They have access to expertise in more than one discipline and judging by their collaborations they also have access to wider networks of expertise. Firstly, this contact they have with different disciplinary environments continuously exposes them to new instruments of potential interest. Secondly, they have access to expertise to help resolve practical problems, and thirdly, the different disciplines take on the role of users of instruments designed or developed by colleagues. For example, in the situation described in this paper, the biologists and chemists were functioning in the role of users of new instruments and each new group of users generates new requirements. As the lab director keeps inviting new scientists to bring their samples and try them on the microfluidics station this heterogeneous group seems to continually create gaps between their expectations and the practical use of the tool. Examples of this type were observed in the lab and also recounted in the history of the technology.

This paper has questioned the way in which tools contribute to the creation of new knowledge and innovative ways of working. The results of the case study suggest that learning has occurred in different ways: by using a new tool from a different domain and by tinkering with the tools. The latter has been divided into the types of changes being made, in terms of deliberate changes or the more haphazard changes implemented to solve specific problems or simply mistakes. This view of tool-mediation in interdisciplinary knowledge creation is summarised in Figure 2.

By conceptualising tools as the bearers of encapsulated knowledge and as being in a state where they can both be used and developed at the same time, it becomes possible for us to understand the role which tools may play in the development of knowledge. By examining the practices, or the tools "in use," it is possible to gain a better understanding of how the tools mediate the process of knowledge creation. By using the concept of tool-mediated activity, we understand learning as happening when actors interact with tools. We need not confine ourselves to interactions occurring when the technology is used in the way it was meant to be used. All ways of using tools produce interactions with tools. The analytical framework developed here has proved useful for studying knowledge creation in an environment where tools and experimentation are so central

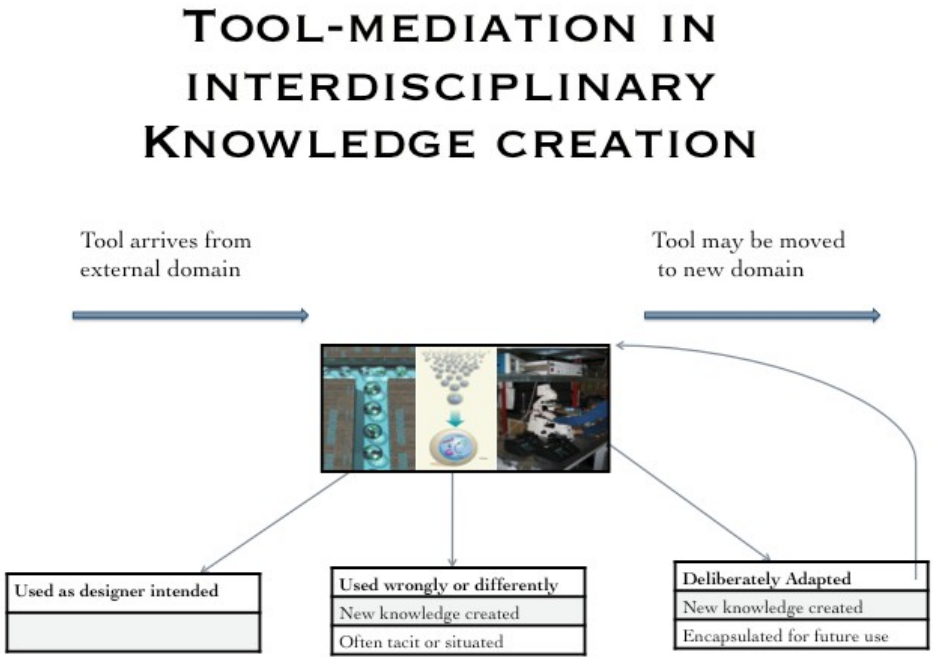

Figure 2. Tool-Mediation in Interdisciplinary Knowledge Creation. Author's own figure containing pictures from the Strasbourg lab (www-isis.u-strasbg.fr) and Raindance (www.raindancetechnologies.com) webpages.

to the everyday work. The main limitation of a study of this type is of course its localised context, which makes it difficult to generalise the findings. However, the multidisciplinary nature of this research group is not unique, particularly within emerging technologies at the boundaries between different disciplines.

This analysis has shown us that tinkering with technology is something which is happening daily in this environment and by extending the analysis backwards in time we can infer that it has probably been going on all the time. The consequences of this type of activity have been very different, one example being a path-breaking change leading to the emergence of this branch of microfluidics (using microchips "wrongly" by putting fluids through them), which might fall into the category of a radical innovation, in relation to Shinn's examples (Shinn 2005). The other changes are more incremental in their nature, expanding the range of experiments, which can be carried out using this technology (like the addition of motor and thus extending the range of enzymes which can be experimented on in this way). In spite of the limited examples of radical change, the transversality of the instruments is evident in the knowledge creation process described here.

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