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"Old" Technology in New Hands: A case study of using tools to create knowledge in a bio-nanotechnology laboratory

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Abstract

This report is produced in the context of the Knowledge-Practice Laboratory (KP-Lab) project. This is the report from the case study "Interdisciplinary Knowledge Practices in nanotechnology". The case study is from a bio-nano laboratory, and took place in period M20-M31.

This report explores the role of tools and instruments in knowledge creation and production processes in a leading edge knowledge practice. We selected nanotechnology, which is a field of scientific practice in which different scientific disciplines' is involved and new knowledge is produced, for the sciences involved and for the society. The case study provides ideas and principles for design of KP-lab tools, and contributes to analytic benchmarking of tools, infrastructure and practices innovative potential in the cases where KP-lab technologies are experimented with.

The theoretical resources selected for understanding the knowledge practice in this leading edge field are tool-mediated activity Vygotsky (1978), knowledge encapsulated in tools (Baird, 2004), instrumentation (Pickering, 1995) and epistemic objects (Knorr-Cetina, 1999). These theoretical resources are used to examine the collaborative process of experimentation where tools 1) contribute to solve scientific problems and 2) are used to create and accumulate knowledge. Tools are viewed as dynamic and several types of tool-mediated activities that contribute to knowledge creation are explored.

Recent studies about development of nanosciences and nanotechnologies indicate that tools and instruments play an important role in the development of the knowledge bases in these emerging fields. Other studies of the development of scientific knowledge suggest that the importance of tools and instruments has gone largely unexplored due to a persistent differentiation between science and technology. We report from a case of a small multidisciplinary laboratory developing a new process for producing nanoreactors. Nanoreactors will make it possible to carry out high-speed controlled experiments on the molecular and sub-molecular scale in a cost-efficient way for potential applications in pharmaceuticals and energy development. To study the everyday practices of tool-mediated experimentation data was collected from interviews and observations in the laboratory.

The paper concludes by pointing to the opportunities for knowledge creation provided by various ways tools are used, and the implications for KP-Lab's studies of tool-mediated knowledge creation and transformation processes.

Keywords: tools, technology, instrumentation, knowledge creation, bio-nano, leading-edge field, work places

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1. Introduction

In KP-lab a main objective is to explore and understand in which ways tools are part of knowledge creation and trialogical learning. In the first review of the consortium's R&D activities, one of the critics raised was that studies of 'leading edge knowledge practices' were missing. The purpose of such studies in KP-lab is to provide insights to the design and analysis of tools and environment with a historical and recent perspective on knowledge creation and practice transformation. This means that these studies will bring ideas and principles for design of KP-lab tools and infrastructures. In addition these studies can serve as studies for analytic benchmarking of knowledge creation processes and transformations taking place in cases where KP-lab technologies are developed and experimented with.

The creation of new tools and the 'tuning' of tools for different groups of users' involves problems of adaptability to existing tools and platforms. One of the hot topics is of course the relationship between the accumulations of knowledge in the tools and how that relates to human judgement and evolving knowledge practices. This point us to a core issue in the field of technology enhanced learning; how can we automate human action and build up machine intelligence, and how is this related to knowledge creation and human learning. Such more general questions should be addressed in specific knowledge fields and contexts, and then compared and contrasted so we can understand the general and specific features of advancing knowledge practices in contemporary society.

The field most research communities, universities, policy makers and funding bodies see as representing the most innovative knowledge practices is the large sector of life sciences and in particular the emerging field nanosciences and nanotechnologies. A recent analysis of relationship between science and technology in this emerging field demonstrated the importance of instruments and tools to advance the field (Meyer, 2001). Based on these assumptions we selected the 'nano' field as a representative example of 'leading edge knowledge practice' to be included in our portfolio of case studies. Therefore, we will explore how tools and instruments play out in the development of scientific knowledge, and to gain a better understanding of the process of knowledge creation in the emerging nanosciences and nanotechnologies. Thus the question addressed in this paper is "How do tools contribute to knowledge creation in bio-nano?".

The paper deals with this question by exploring and analysing the way scientists' use instruments in their experiments in this case study within a sub-field of bio-nano. This paper is organized as follows: In section 2 we explore how the relationship between tools or instruments and knowledge creation is conceptualised, and outline the concept of tool-mediated activity, and then examine how others have tried to understand the role of tools in the creation of scientific and technological knowledge. Then, in section 3, we present the case study of nanoscience. In section 4 we discuss elaborate on their technology and development of microfluidics, one particular scientific field of bio-nano. In section 5 we use the resources to conceptualise tool use to examine knowledge creation in the dynamic environment within the emerging field of microfluidics. As part of the specification of the overall idea and framework of trialogical learning, the ways the tools are used in experiments in microfluidics will be examined through the lens of socio-cultural theory. The history and development is described, then examples from both their historical development and of current practice are analysed to illustrate the role of instruments or tools in processes of knowledge creation and sharing. We will conclude this report by summing up implications from this study for the KP-lab project.

2. Various perspectives on tools and instruments in science and technology

Historians, philosophers and sociologists of science and technology have all discussed tools and instruments in relation to knowledge creation. Some attempt to understand how, not only scientific theory, but also how material artefacts contribute to the creation of new knowledge. Others attempt to understand the processes of knowledge creation in laboratories, where tools are seen as inscription devices (Latour & 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 (Pickering, 1995). 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; von Hippel 1976, 1988). Some refer to tools and others to instruments and most of them operate with different definitions. Although the aims of these various writers is very different, they all provide valuable contributions to how we might understand the role which tools and instruments play in collaborative knowledge creation. Some of the main perspectives are presented and discussed here in an attempt to conceptualise tools in ways that help us understand their role in knowledge development.

The importance of instruments is not only a recent preoccupation of science and technology analysts. For example, when investigating high technology innovation, Derek de Solla-Price suggested that the importance of what he calls “instrumentality” has been paid scant attention in studies of the development of technological knowledge (de Solla-Price, 1984) He defines instrumentalities as “advances in instrumentation and experimental techniques” (ibid:3). The role of formal scientific theory has been given great attention, while the role of instruments has been largely neglected. He suggests that instruments may be what defines the grouping of scientists and goes as far as to suggest that developments in instruments in one area may lead to breakthroughs in other areas and may be responsible for some of the more revolutionary changes in technological trajectories (ibid:15). Studies of the history of science (e.g., Galison, 1997) also suggested that greater importance should be placed on the experiments and instrumentality when explaining the development of scientific knowledge, hence the activities of experimentation and practical use of instruments should be more thoroughly accounted for.

Instruments and tools are becoming increasingly important to create knowledge that produces changes in science. Pickering (1995) describes examples from physics as real-time dialectics in experimentations or activities of “tuning” and “transforming” of tools as important when creating and accumulating knowledge in the instruments and advancing the field. Baird (2004:89) describes changes in chemistry as a kind of instrumental revolution. Traditionally, chemists understood chemical components by applying compounds and noting the reactions, but since 1950 most chemists have instead used instruments to measure the physical properties of the components with much greater accuracy. Now instruments are being used, not only to measure, but also to change or manipulate matters. Baird suggests that this change has altered the way scientists regard instruments, he calls it “the introduction of the instrumental outlook” (ibid:108). Biology has also experienced changes related to the introduction of a string of new technologies. Paul Nightingale (2000) describes recent changes in this field, which has, at least in part, moved from being craft-based to being highly automated (biotechnology) with experiments being carried out by simulating biological mechanisms based on linkages to databases.

2.1. Tools as mediators of knowledge creation

Socio-cultural theories (Vygotsky, 1978; Wertsch, 1991) view tools as mediators of the processes of knowledge development. The concept of tool-mediated activity (Vygotsky, 1978) is used to study 1) how tools may aid the sharing of knowledge between different people and 2) how these tools may also play a role in the creation of new knowledge. Knowledge creation, learning or change, is seen as occurring when people interact with the outside world in some way, i.e. not merely a cognitive process inside the head. These interactions can be with other people or with tools. Tools are not merely seen as artefacts to support human actions, nor are they seen exclusively as influencing human actions. It is the conscious attempt of the human actor to expand their abilities by interacting in some way with the tool, which is a central part of socio-cultural theory. 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. These tools may be conceptual, for example, in the form of a written and described method; or these tools may be physical artefacts.

The concept of tool-mediated learning has been used extensively, notably in connection with Engeström's (2001) concept of expansive learning, and has proved useful in understanding the relationship between tools and changes in working processes. It also helps our understanding of how "objectification of knowledge into artefacts" (Miettenen & Virkkunen, 2006:154), whereby knowledge and experience becomes embodied in the artefacts, 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 their links to the object of activity, epistemic or otherwise, are central to this approach. In empirical work based on socio-cultural theories, learning is usually studied by observing the activities of actors involved in collaborative practice.

2.2 Tools to support human activities

Some of the more traditional views of tools and their use in science are summarised by philosopher Don Idhe (from Verbeek, 2005: 123 – 124). He explains how the tool mediates our perception of the world, by strengthening or extending our physical abilities, for example seeing nano-sized objects by looking at the digital image generated from the microscope. Idhe also talks of the skill needed to operate these instruments, it is only when we have mastered these skills that the instruments can become transparent. By transparent he means we are unaware of them until they stop working, like the dialling tone on a phone or using other parts of a knowledge infrastructure (ref. also, KP-Lab's D10.3 where knowledge infrastructures are further discussed). In the discussion, it is differentiated between the type of instrument like a pair of glasses, which simply enhances an ability we already have, and a thermometer, which also makes something which we could not see visible to us, but which requires the ability to interpret what we see before it becomes meaningful. This skill of interpretation is often embedded and will vary in different situations and contexts, e.g., to a doctor examining a child a reading of 40°C means danger, but to a biologist in a laboratory, the same reading might mean the point at which an organism thrives.

2.3. Tools 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. His examples support the idea of de Solla-Price that the development of technological knowledge is not dependent upon and, in fact, often precedes scientific theory. 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 the "thing knowledge" as he calls it. Baird (2004) 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), ideas of knowledge embodied in tools and instruments. Like de Solla-Price (1984), Fleck (1997) 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 innovations and suggests that it should not be viewed as a separate phase from the design.

2.4. Tools "in use" or dynamic tools

Fleck mentioned users adjusting their technology to make it work, this idea of tools being open for adjustment or change is something which Knorr-Cetina develops in her concept of epistemic objects (Knorr-Cetina, 1997). This epistemic object may be a physical tool, material artefact or a conceptual object. As a concept, *'epistemic object'* allows the object to have a kind of dynamic state, whereby it is being used, but at the same time being changed, e.g., software tools may be perfectly usable and support practical tasks, but at the same time may be under development. This could be interpreted as saying that gaps between current functionality and the expectations of the user become exposed in the act of using the tools.

Knorr-Cetina is not alone in emphasising the relationship between adapting tools and developing knowledge. Pickering also refers to the process of knowledge creation as the "mangle of practice", a metaphor designed to invoke the real-time dialectics or continually changing interactions between humans and machines (Pickering, 1995). 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 evolving practice. His studies recount the continuous cycles of change, whereby technology is designed, used, changed, used, changed etc., as tuning and transformation. 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 working practice and moulding and re-moulding strategic plans. In other words although tuning may look like an ever-present minor process, it can lead to more wide-ranging transformations and changes of direction for those using it.

2.5. Conceptualisation of tools

In reviewing these different perspectives it is noticeable that the words tools, instruments and technology are used slightly differently, but all of them can contribute to our understanding of the role they play in knowledge creation. Some refer to instruments simply for measuring while tools have a more advanced function. The concept of instrumentalities used by de Solla-Price and Fleck includes simple measuring instruments, but also everything around them, which is necessary to make them work. Science/technology comparisons (e.g., Baird, 2004; Galison, 1987) refer to technology as most of the practical tools and devices related to experimentation. In the remainder of this paper the term *tool* will be used to denote both measuring instruments and more advanced tools and the term *technology* will be used when referring to a more complex grouping of tools, where some of the tools may be seen as components in a larger system.

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 knowledge. 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. They can be viewed as complex artefacts within which knowledge and past experience has been embedded and accumulated over time; "cultural artefacts" or artefacts developed in collaboration over time. These artefacts are not only important to get the job done, but play an important role in the process of spreading knowledge. This suggests that if we wish to fully understand their role in knowledge creation we should also look, not only at how tools 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 tools being used differently from the tool-makers original intention or tools being used wrongly by new users. The fluidity of the state of tools described by Knorr-Cetina and Pickering adds perspectives to studying the role of tools in knowledge creation. The close link between tool-use and tool adaptation suggests that the continuing development of tools should be regarded as an integral part of the usage rather than something separate, only occurring in certain situations. This close relationship between using tools and changing tools suggests that any study of tools in use should endeavour to capture the adaptation of tools in such a way that their contribution to knowledge creation can be analysed. By focusing on tools, all of these perspectives inevitably direct attention to knowledge creation as a learning process going on outside the head of the individual. All these perspectives appear to agree on the importance of the active use of these tools as the means of unlocking any "thing 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 the creation of new knowledge occurs.

In this study an analytical model is developed to make it easier to identify different instances of tool-mediated activity, which may contribute to knowledge creation. Conceptualizations of tools discussed earlier, e.g., Knorr-Cetina, Fleck and Pickering, are grouped together under the term dynamic, suggesting tools which are not stable or static and not fixed to one location. The concept of tool-use or activity are divided into several types of usage, either as adapting and re-building, or introduce a certain unpredictability by using the tool differently or wrongly from tool-makers' intention.

Tool	Activity
Dynamic (i.e., neither stable nor static)	Using
	Using differently or wrongly from tool-makers' original intention
	Adapting
	Rebuilding

Table 1 Expanded framework for studying tool-mediated activity

Tool-mediated activities include tools being used not simply as they are or as they were intended to be used, but also tools being used wrongly or differently and tools being adapted and re-built. Thus in this study tools are viewed as being dynamic; as tools being transported from one environment to another, or tools being adaptes, "tuned" or changed. The activities associated with this interpretation of tool-mediation are identified in this case and then examined to open up the unfolding processes of knowledge creation.

3. Case and methods

3.1 Case

This empirical case study looks at the activities of scientists in a particular phase of the development of their laboratory, and follows a team of scientists over a period of time to provide an extended snapshot into development in space and time to illustrate the technological trajectory of microfluidics (See Figure 1).

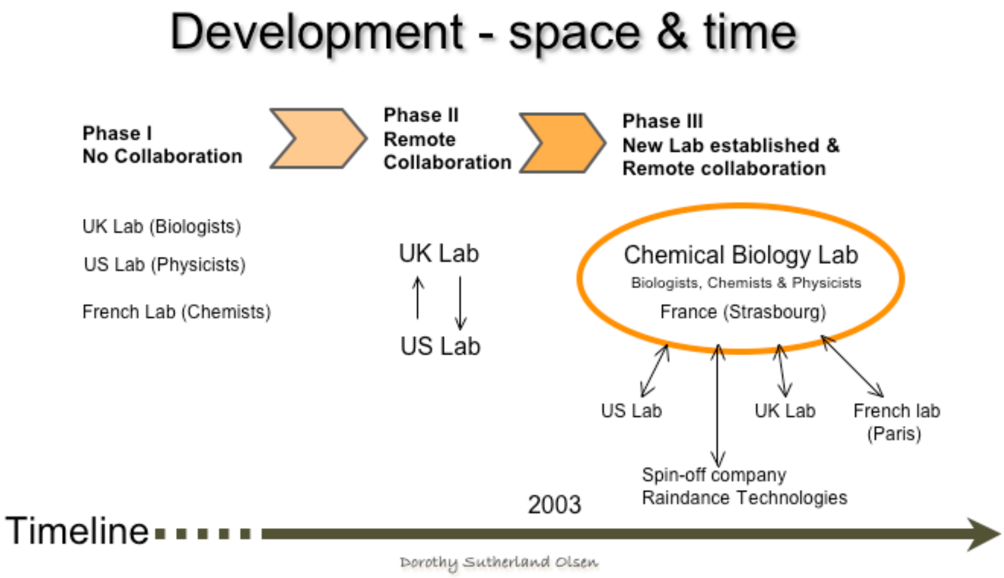


Figure 1 Microfluidics technology development, past and present

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 a group of physicists in the US. They in turn had taken tools and techniques developed in microelectronics and in chemistry. The current lab is a multidisciplinary lab consisting of physicists, biologists and chemists who have acquired this technology and are continuing to develop it in order to carry out their biological experiments. The team of biologists, physicists and chemists is working with a relatively new technology, microfluidics, to develop experiments in biology. To do this they create "nanoreactors" 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.

The scientists in the lab are trying to isolate enzymes or cells for use in a variety of future experiments and applications. They isolate these enzymes in nanoreactors, a droplets acting as isolated test environments where a reaction may occur. Some examples of application of these enzymes may be as catalysis in bio-fuel cells, preventing blood clots to prevent stroke or to neutralise chemical contamination. Traditionally this type of work would be carried out using time-consuming and expensive screening techniques. If this method works, the experiments would be much faster and more efficient because the sample sizes can be so small, allowing multiple tests iterations to improve the results.

We provide examples of how tools play a role in bringing scientists from different disciplines together, and of how their use of the same tool contributes to collaborative knowledge creation. It also shows how the use of tools, new or wrong use of the tools and development of the tool are difficult to separate as activities, but that it is these activities, which are contributing to knowledge creation.

3.2 Design and Methods

This study is designed as an exploratory case study to explore everyday practices of how scientists use tools in a leading edge research field – within bio-nano subfield of microfluidics. The primary methods used in gathering 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 published reports and articles. The intention was to study the practice, but also to gain a perspective of the activities and the community in their historical context, and was based at the lab for a three-month period and later 2 week follow-up. All together, 31 in-depth, formal interviews were carried out. In addition to this there were several follow-up conversations to clarify technical details and many informal interviews. Data was also gathered from observations of lab-meetings and the available documentation in the form of reports and articles. The continuous observations in the microfluidics room were carried out twice, first iteration as a 14 day period and second iteration as a 10 day period.

As part of the specification of the overall idea and framework of trialogical learning, a specific socio-cultural approach is taken in this case study. The concept of tool-mediation is the lens for analyses and interpretation of the empirical data to gain a better understanding of the role of instruments in knowledge creation. When taking a socio-cultural approach it is important to analyse on-going activities in light of their historical development. Therefore, in addition to studying the work in the laboratory a brief analysis of the historical development of the instruments, as cultural artefacts will be presented. The descriptions of the experiments are based on 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.

4. The Technology and its development

Nanosciences and nanotechnologies have been described as "new approaches to research and development (R&D) that aim to control the fundamental structure and behaviour of matter at the level of atoms and molecules open[ing] up the possibility of understanding new phenomena and producing new properties that can be utilised at the micro- and macro-scale. Applications of nanotechnology are emerging and will impact on the life of every citizen" (European Commission, 2004).

It is controversial to say that "nanotechnology" exists as one technology, although it is sometimes referred to as an emergent technology. No field of science or technology today is exclusively nano, since all of them work on the micro or macro scale as well as the nano scale. There are three main areas, which have been influenced by the potential of nanosciences and nanotechnologies (NST); microelectronics, material technology and biology. In biology nanosciences and –technologies has given rise to a particular sub-field called bio-nanotechnology or more commonly bio-nano. Several of these sub-fields overlap and may be converging, e.g., sensor technology commonly draws upon biology and material science, microfluidics draws upon microelectronics and biology. Scientists working in these fields rarely use the word nano, other than to refer to measurements, but public funding bodies in most countries have tried to group everything nano together, likewise the media and investors.

The table below is an attempt to show how the field of microfluidics is related to the common definitions of nanoscience and nanotechnologies.

Nanosciences and nanotechnologies (NST)		
Biology	Microelectronics	Material Technology
New subfields with unclear boundaries are emerging		
e.g. Bio-nano	e.g. Nano-electronics	e.g. Functional nanomaterials
e.g. Lab-on-a-chip, Molecular Motors, Microfluidics, Bio-medial Sensor Technology		

Table 2 Microfluidics Technology in relation to NST

The OECD defines bio-nano or bio-nanotechnology as “the interface between physics, biology, chemistry and the engineering sciences” (OECD, 2005). Examples of the fields typically included within bio-nano are lab-on-chip, microfluidics, molecular motors and bio-medical sensors. In all these fields technology developed elsewhere, usually within electronics, are incorporated into their methods and is being used to expand their knowledge and thereby their fields.

4.1 Microfluidics Technology

The lab has constructed 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. 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 can 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, and may for example involve extracting DNA or preparing enzymes.

Once the biological samples have been prepared, they are pumped into the tubes and into the flow of fluid emulsion. Electric current is applied in order to break up the flow into evenly sized droplets. Theories of electrowetting steer the application of electric current. If everything goes according to plan each droplet should contain one sample, e.g. an enzyme or a DNA-molecule depending on the experiment. 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. Almost all experiments in this laboratory are carried out using the digital microfluidics station, and it is central to the daily work carried out in this workplace. The digital microfluidics station (see figure 2 below) consists of polymer device or chip with capillary tubes and pumps (1), which is specially designed for each experiment. Produced as test environment on the polymer device is the nanoreactors (2), then placed under the microscopes (3), experiment is documented by the high-speed video camera (4), and kept in the storage devices (5 & 6). The different ways of viewing of the results have programmed by the scientists using standard Labview software (5).

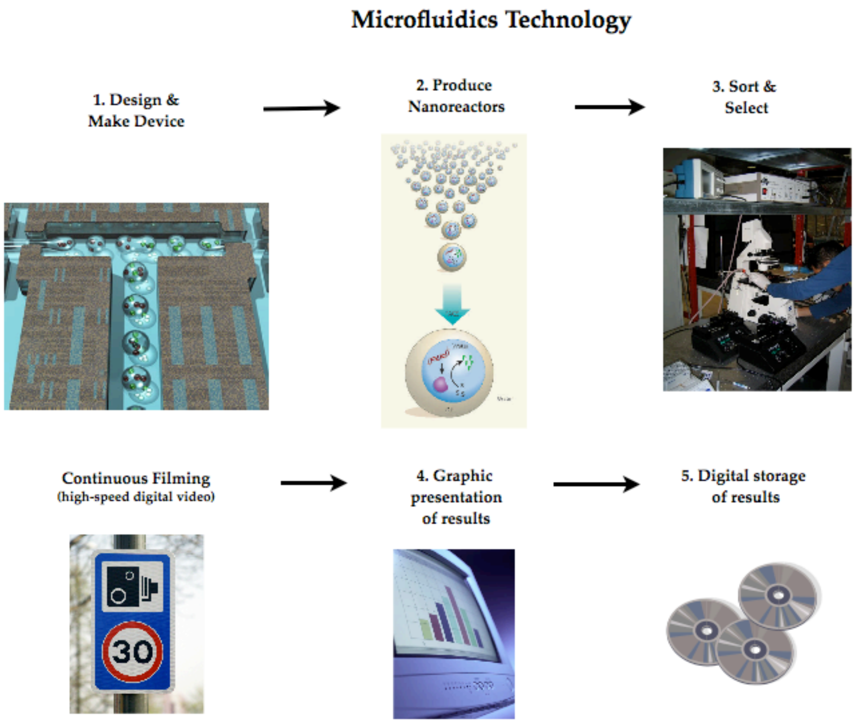


Figure 2 Overview of the stages in a typical experiment using microfluidics

As the droplets flow through the system they are filmed by the high-speed video camera (2000 frames pr. second) and the images produced can be viewed on the monitors. When satisfied with the results (i.e. the quality is sufficient and no more testing is deemed necessary) the scientists typically explore several different ways – views - of presenting the data. These views can be adjusted to highlight different things. The "views" (still pictures and video sequences) considered most appropriate for their publications are selected and stored digitally. This is then stored electronically and also copied into their lab books.

The success of experiments is dependent on the fine balance between the content of the emulsion fluid, the electrical 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 interdisciplinary practice of experimenting in this lab is described in more detail in Olsen (2007).

4.2 Knowledge encapsulated in a cultural artefact

If we try to see beyond the exterior of the microfluidics station and view it as a cultural artefact containing and accumulating knowledge which has been found successful in the past we can identify and trace back to several, different fields of knowledge. Table 3 gives an overview of breadth and depth of the past experience.

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

Table 3 Technologies from different fields of knowledge leading to microfluidics

The polymer 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 and is typically used for DNA-sequencing.

This list has doubtless omitted some of the many techniques or theoretical knowledge "encapsulated" in the digital microfluidics station gained by using the various parts of the modern microfluidics system as well as some of the better-known theory, which is now incorporated today's technology.

5. Findings – Knowledge creation and production using tools

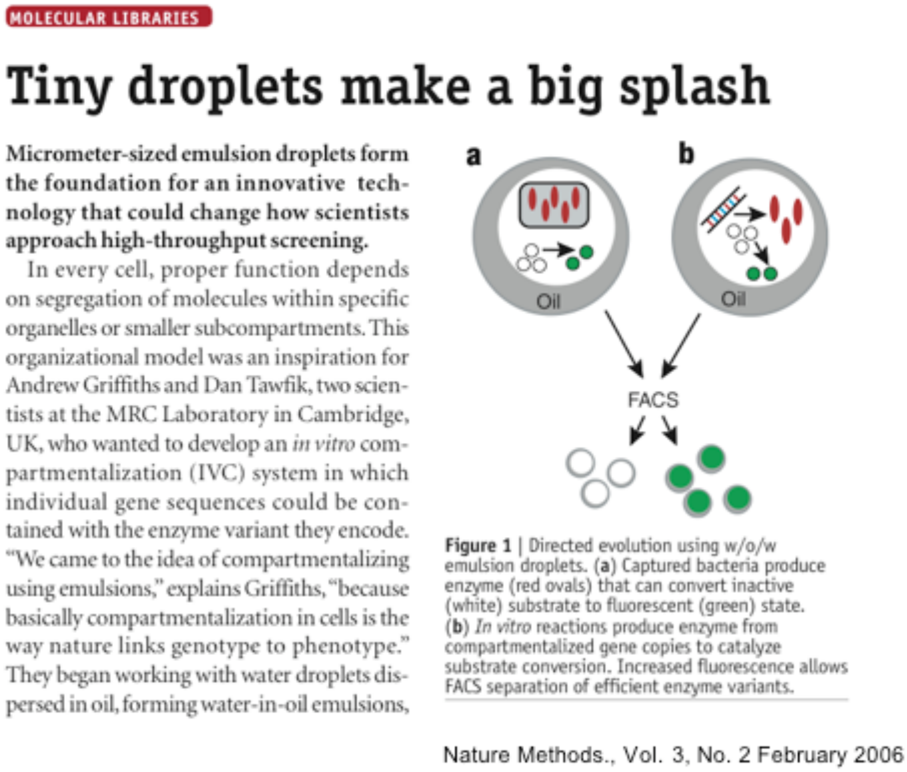
The findings are based on observations and data gathered from interviews in the lab and exhibits situations where the interactions between the scientists and their technology show learning or knowledge creation taking place. Separate incidents are exemplified and they are not presented in a way that shows all the stages in the work the scientists carry out.

The tools appear to mediate knowledge creation and production processes in several different ways. In each case the scientists who use the microfluidics technology learns to do something new or to do something differently while experimenting. The analytical framework viewing tools as dynamic (outlined in section 2.5 above) is used to group these examples by the type of tool-mediation occurring.

5.1. Using tools differently or wrongly

There are several instances of using tools differently or 'wrongly' compared to the way the tool-maker originally intended. The examples are found in the data gathered in the specific laboratory we had access to, but also in the events leading up to the creation of lab. Before the present lab was established, some the biologists in the team worked in a UK lab where they were trying to create droplets for their experiments. The droplets were produced by mixing oil and water, a water-in-oil- emulsion, not very precise they said "more like making mayonnaise". They produced 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 machine called a FACS for Fluorescent-Activated Cell Sorting, but designed to work with water droplets. Some of the scientists thought it might be an idea to try putting their emulsions through this machine to sort cells. In fact using water-oil emulsions 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. As a solution a colleague suggested a second emulsions – so each experiment would be in a water-oil-water emulsion. Since this proved sound they explored the FACS analysis further.



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Tiny droplets make a big splash

Micrometer-sized emulsion droplets form the foundation for an innovative technology that could change how scientists approach high-throughput screening.

In every cell, proper function depends on segregation of molecules within specific organelles or smaller subcompartments. This organizational model was an inspiration for Andrew Griffiths and Dan Tawfik, two scientists at the MRC Laboratory in Cambridge, UK, who wanted to develop an *in vitro* compartmentalization (IVC) system in which individual gene sequences could be contained with the enzyme variant they encode. "We came to the idea of compartmentalizing using emulsions," explains Griffiths, "because basically compartmentalization in cells is the way nature links genotype to phenotype." They began working with water droplets dispersed in oil, forming water-in-oil emulsions,

Figure 1 | Directed evolution using w/o/w emulsion droplets. (**a**) Captured bacteria produce enzyme (red ovals) that can convert inactive (white) substrate to fluorescent (green) state. (**b**) *In vitro* reactions produce enzyme from compartmentalized gene copies to catalyze substrate conversion. Increased fluorescence allows FACS separation of efficient enzyme variants.

Nature Methods., Vol. 3, No. 2 February 2006

Figure 4 Excerpt from Nature Methods describing some of the early attempts to develop this technology

They tell their story of experimenting with different solutions, in Einstein (2006) (excerpt in figure 4 above), to find emulsions that would allow them to use the FACS machine for cell sorting, and advance the speed and accuracy of their directed evolution studies.

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 was established 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 chemistry lab nearby 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. This is what Pickering (1995) would have called a transformation, since prior to this event nobody knew how to control droplet production in this way and the consequences of this new knowledge have opened up a new scientific field.

Not all examples of technology being used wrongly have such revolutionary results as the previous ones. As told in an interview with Biologist H:

> *One biologist was unfortunate enough to have en 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. From the biology perspective, it was the wrong combination for this particular experiment. In spite of this, new knowledge on how to use microfluidics to make droplets coalesce was created. To the biologist this was not new knowledge, he was unable to do anything constructive with the observation, in fact he tore up his notes. The physicist, however, was able to recognise a phenomena from his formal training, saw the potential and gained an understanding of how he could re-create this situation in the future using the microfluidics technology.

5.2. Adapting Tools

These examples all occur during the practice of experimentation and demonstrate the type of problem-solving occurring during experimentation:

Two chemists had been testing yeast in droplets. They wanted to find 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 about a problem they are 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 kind of 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 become incorporated in the tool, thus knowledge created accumulates and is available to the others in the lab.

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 example is provided by the use of single cells in the droplets, as 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 is 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 loose 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 much smaller than the size of the droplet. This is not a problem with regard to isolating cells and producing a reaction, however, if they want to sort the cells, so that they can select the ones where a reaction has occurred, then they need to shine a laser beam at the droplets and select based on fluorescence. This is fine when the cell is large, however if the cell is much smaller than the droplet, then the polarised laser beam might just miss it. This has been proving a problem for several of the experiments. To further develop the tool, 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. Like 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 subjected 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 experiencing problems getting droplets to fuse properly, labelled synchronisation problem. The biologists invited some chemists to the lab to see if changing the substance the droplet is made of, can solve this problem. While the chemists were looking for a solution, one of the physicists (Physicist O) was 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 or tuning 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. So in sum it is an example of tool-mediated collective knowledge creation adapting the tools in the microfluidics station.

5.3. Re-building Tools

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 therefore wanted to move the microfluidics station, however moving everything was too difficult and there was high risk that moving things would disrupt the function of the microfluidics station. He decided to build his own microfluidics station. He copied the design of the existing station, got the physicists to advise him and did indeed manage to construct his own tool. Biologist I showed me round 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 microfluidics station], 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, opening up the black-box and exploring some of the knowledge accumulated in the microfluidics station.

[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 course 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 [Another lab on the campus] made it.

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 is has thousands 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 about how to construct a complete working microfluidics station has spread from the physicists to one of the biologists. He maintains that he does not understand everything and certainly not much of the theory encapsulated in the technology, but it all works very much to his satisfaction. Not only has he developed the skill of constructing the technology, 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.

6. Discussion and some conclusions

Analysis of everyday practice in the lab shows that the scientists appropriate microfluidics technology and use it for biological experiments. However they are regularly experiencing situations where problems occur and the technology needs to be modified, i.e., tuned, in order to carry out and complete their experiments. By solving these problems and making necessary changes they are developing a more robust technology, which can be used for a wider range of potential experiments. They are modifying existing knowledge or creating new knowledge and in so doing are advancing microfluidics technology. One of their approaches is by incorporating their new knowledge into the tools where it is accumulated 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 about the method used. However, much of this new knowledge may remain unarticulated as part of routines and habits in the lab and perhaps not very well understood.

The theoretical perspectives on knowledge encapsulated in tools (Baird, 2004) give some insight into how some of the expertise developed in the U.S. was shared with scientists in Europe and how technology developed by physicists could be used by biologists without all the users needing a full or comprehensive understanding of how or why the tools work the way they do. The theoretical perspectives suggesting more dynamic rather than static tools (Knorr-Cetina, 1999; Pickering, 1995), which are simultaneously used and changed gives some insight into the continuous tinkering observed in the case study. By linking together these different theoretical perspectives in a common conceptualisation of tools (Table 1 in section 2.5), the contribution of both previous and present use of tools in production processes and knowledge creation becomes more evident.

The empirical data showed new users using the tools differently or wrongly (compared to the tool-makers1 intentions), adapting or rebuilding the tools. The U.S. physicists who developed the original technology may have considered their technology to be complete; after all at the time the technology was made available to biologists it could already produce perfectly controlled droplets. As soon as a new group of scientists began to use the technology, the tool entered into a new cycle of development. This is similar to the situations Fleck (1997) describes, as new technologies are adapted to work in new environments. The new group uses it in different ways or 'wrongly', and this sparks off a whole range of adaptations and modifications to the tool. If tools are viewed simply as static or stabilizing artefacts, then the U.S and European cycles of tool development would have to be viewed as separate phases or steps and the importance of the continuous flow of changes and the concurrent development of knowledge would not have been so evident. The ever-important continuity which, Pickering (1995) refers to as the ever-turning mangle, with its potentially far-reaching effects would be obscured to us if we viewed imported tools as always being complete and finished. Like von Hippels' producers and users, the requirements and the expectations of the new group of users (in this case, the biologists) are different from those of the designers and a stable tool becomes dynamic again (Hippel 1976, 1988). 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. It seems that new users create a gap of the type Knorr-Cetina writes about and in trying to fill this gap small and large changes may occur and new knowledge may be created.

We might expect that with repeated practice some of the knowledge would become embedded in their routines (Nelson & Winter, 1982). In this case the biologists are still in the process of mastering the technology and for them "routinization" of knowledge has not 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 new adjustments. This day has certainly not arrived, nor indeed has the technology become an invisible or transparent support to their work. The scientists regularly puzzle over which parameters, such as temperature or fluid concentrations, they might change in order to make their experiments work. This analysis shows us that tinkering (Knorr-Cetina, 1999) or tuning (Pickering, 1995) happens daily in this environment. By extending the analysis backwards in time we see that this is not just something occurring in the current lab, but has probably been going on all the time. The knowledge creation and production processes during this type of activity have been very different. One example is a path-breaking change leading the emergence of this branch of microfluidics from using microchips "wrongly" by putting fluids through them. The example of addition of motor and extending the range of enzymes that can be experimented on may not have radical effects, but illustrate incremental changes that expand the range of experiments that can be carried out using this technology. The exploration to make synchronisation of droplets easier, and a new nano particle was discovered, exemplifies the relationship between unplanned tuning and transformation (Pickering. 1995). Without paying attention to everyday tuning the relationship between this activity and some of the more important "transformations" might not be so evident.

We explored the way in which tools contribute to the creation of new knowledge in everyday practice. The findings from the case study make it possible to say that tools contribute to the process of knowledge creation by providing new opportunities for the scientists to experiment. They can interact with the tool in more than one way. We have illustrated these different, dynamic ways as using tools "differently or wrongly", "adapting the tools" or "rebuilding the tools" (see Table 1, section 2.5.). This highlight processes of instrumentation in collective knowledge creation

- when scientists bring a new tool into their laboratory, they also bring the opportunity to learn from others who have used the tool before them, however

this is also opportunities to use the tool wrongly or differently and in doing so, to potentially generate new knowledge.
- when a heterogeneous group of scientists uses a tool, it seems that they are continually creating gaps between their expectations and the practical use of the tool. In closing these gaps the scientists adapt the tools and create new knowledge.

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 everyday practices, or the tools "in use", it is possible to gain a better understanding of how tools mediate process of knowledge creation.

By using the concept of tool-mediated activity, we understand knowledge creation 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, we can also include the wrong use of technology or when the technology is being changed. These are all interactions with technology. The framework developed in Table 1 has proved useful in identifying different instances of tool-mediation and understanding the processes of knowledge creation. A refined version as presented below in Figure 5 grounded in the empirical data shows the different ways in which tools contribute to knowledge sharing and knowledge creation.

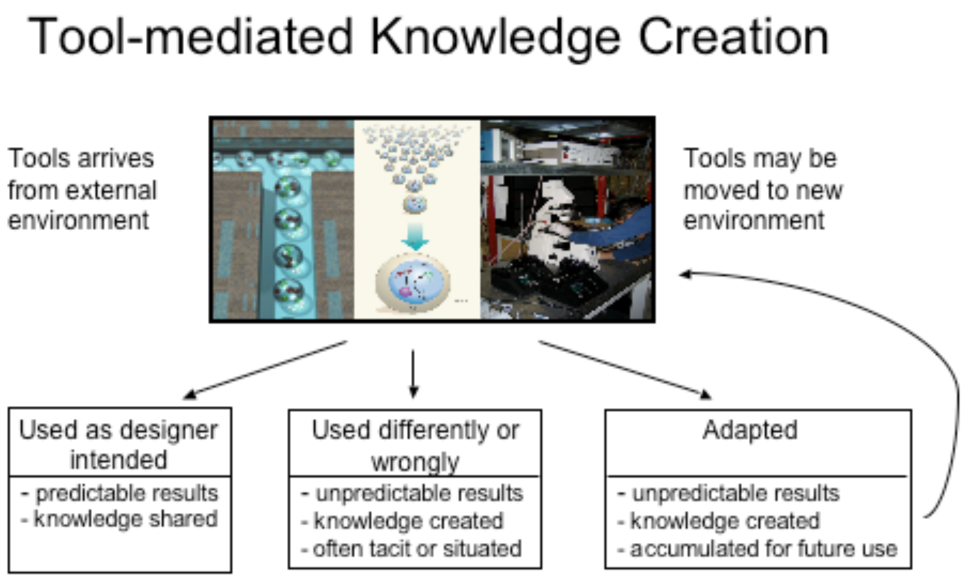

Figure 5 Tool-Mediated Knowledge Creation

The tool arrives from an external environment and the ways in which it is used can be grouped into three types:

1. Using the tool as the designer intended and producing the expected results. In this case knowledge would be shared between groups of scientists.
2. Using the tool differently or wrongly, either deliberately or accidentally, can produce new knowledge, which may become embedded in local practice.
3. Adapting or rebuilding the tool. New knowledge is created and made available to local users and accumulated in the tool for potential future users.

Apart from providing more elaborate understanding of how tools contribute to knowledge creation, this paper also raises some methodological issues. Many studies of technological development analyse the outcomes of the knowledge creation process for example in the form of publications or patents. Such studies are likely to miss the dynamics of the on-going practice and not be able to assess the role played by the technology in this process or to see how the scientists chose from available options when confronted with a problem. In this study of on-going practice and the historical development of this technology revealed the path the development of the particular microfluidics station and the microfluidics more broadly.

We started with some of the ideas of Derek de Solla Price (1984) and others on the importance of instrumentalities in the development of scientific knowledge. This case supports the suggestions that tools and instruments draw scientists together and they build their communities around them. Through the history and the development of this branch of microfluidics technology the ever-changing technology used in the experiments has played a role in the composition of the team of scientists involved in experiments, developing their knowledge by using it and making the technology work. This exemplifies instrumentation where use of, experimentation with and creative modifications of tools accumulate knowledge, and play out in the "problem space" of conventions within collaborating disciplines, stabilized routines and multiple voices of what counts as knowledge. Therefore, the findings from the case demonstrate several ways in which instrumentalities are contributing to knowledge creation by transformation and tuning (Pickering, 1995), and transform tools and practices to move a leading edge research field like microfluidics forward.

6.1 Implications for KP-lab; tools and infrastructures in knowledge creation.

This case study from a leading edge research field – bio-nano technology and microfluidics – gives several important insights for the KP-lab project.

To start with, the case study demonstrates the trivial aspect that instruments and tools is an embedded part of the production of scientific results. What's' less trivial is their developments through iterations of experimentation and tuning the instruments in order to stabilize the scientific practice. Such finding breaks down the difference between routine work and innovation. One could argue that running the experiment is routine work, but as findings from this case points to, the process of stabilizing the instruments is part of the innovation and knowledge creation processes over a long period of time. We argue that this would be the case for the development of new tools and infrastructures in KP-lab as well. To intervene with and stabilize new tools takes a rather long period of time, but through longitudinally and iteratively designed in-depth studies we can explore potentials for innovation.

The second aspect is that the interdisciplinary nature of the nanoscience has strong resemblance to developing tools and environments for learning. In this case the everyday knowledge practice materializes in a hybrid (physical and virtual) shared space where knowledge and expertise of traditional disciplines are shared between participants and places. The object of improvement and innovation is shared by the participants, but individually they have only partial understanding of why and how the tools and instruments in the digital microfluidics station works. Hence the meanings generated from the experimentations differ given the background and knowledge people have. The three groups of scientist involved from chemistry, biology, and physics, draws out different scientific results based on the preparation to, carrying out and/or interpreting the results of the experiments. These interdisciplinary aspects provides for analytic benchmarking of how KP-Lab's tools contribute to knowledge creation and trialogical learning. This relates specifically to three intertwined aspects, the co-design processes of different tools, connections between the accumulating knowledge in the tools and the actual use in different contexts, and the generated meanings that the participants' draw from experimentations and tool use.

The third aspects we will highlight relates to deliberations of what you want to automate and what you choose to represent as non-automated processes in support if knowledge creation. In this case study the development of the microfluidics technology is *internal* to the production of scientific results, in the sense that it leads to iterative changes and transformation to advance the knowledge practice. The tools are part of the 'chain' that creates knowledge, but the tools must be integrated with the human reasoning about the knowledge produced to contribute to innovation. The question then for KP-lab becomes how tools and instruments are part of human learning; and in particular knowledge creation or trialogical learning. We think it is necessary to conceptualize tools as *internal resources* for learning building on accumulation of available knowledge, and as *external resources* that can contribute to and enhance the learning processes indirectly. To boost learning of specific knowledge domains designers can easily build technologies that make invisible some categories or parts of the body of knowledge and emphasize or make visible the knowledge categories students or workers need to learn. Cognitive tutors in mathematics provide an excellent example of technology that is internal resources to the learning activities in the sense that the premise is that the students work with knowledge that is given. On the other hand, the KP-lab project works under different assumptions and ideas since the creation of *new* knowledge for the participants is the key focus. If tools with built-in knowledge categories are external to the participants they are available, but can be ignored without a break down in the activities. If the resources are internal the participants must use them in order to perform the activities.

Therefore the relationship between tools as internal and external resources in production processes becomes critical, and how to design and provide the users the 'best' mix of resources that are internal and external is a key challenge for KP-Lab. In contrast to generic collaboration-oriented tools and instruments with the intention to structure social interaction, KP-lab's tools aim to go beyond this to scaffold collaboration as productive, collective knowledge creation processes. This means that resources to scaffold collaboration do not intent to automate human action per se, but provide resources for more advanced reasoning based on the type of problems that must be solved. To nuance this argument we claim that the semantic layer in the KP-lab platform provides a level of intermediate abstractions towards a common platform for creation of tools that accumulate results of previous activities and structure for further collaboration. This may be valuable for collaborative knowledge creation processes and it combines features of internal and external resources in tools for human learning. How the distinction of internal and external resources can be productive and utilized when designing tools for knowledge creation processes in educational and/or workplace settings needs to be specified further and complemented by other case examples.

The fourth aspect we will point out is the horizontal development dynamics and expansive learning in activities of co-configurations of tools and working processes as demonstrated in this case study. In the everyday practice we studied, the scientist contributes their knowledge and expertise, but have only partial knowledge of all the production chain leading to full use of microfluidics and bio-nano. Their knowledge-creation expands beyond accumulating existing knowledge and experiences available in their network. The emerging knowledge and experience accumulates in the tools and instruments, enabling the scientists to create, share and disseminate knowledge to different groups in different places and at different times. Their expansion take the form of incremental development – tuning - or co-configuration of tool and social practice when refining or improving efficiency of existing techniques or transformation when the tool are used and developed at the same time. This exemplifies that when putting “old” technologies to new uses, the tools are playing important roles in creating and sustaining networks that links the object of activity, in processes beyond accumulating experiences and existing knowledge in a network to historically new forms of knowledge creation.

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