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Theories of Invention and an Industrial Innovation

In this paper I will explore the relevance of four theories of invention in the context of a Finnish industrial innovation process. The theories are as follows: the traditional genius theory, the classical sociological theory of cultural maturation, the theory of attribution and the theory of chance and serendipity. I study their explanatory value by studying the emergence and development of a research-based innovation, enzyme-aided pulp bleaching. The idea of biotechnical pulp bleaching was formulated in a meeting at the Biotechnical Laboratory of the Technical Research Centre of Finland (VTT) in January 1984. The results of the experiments that confirmed the bleaching effect of enzymes were published in summer 1986. The respective method was implemented by the pulp and paper industry in the early 1990s. I will focus on four problems: 1) Is it possible to find an individual inventor in this process? 2) What was the significance of shared, global cultural resources and of the local knowledge and practices in the invention process? 3) How was the status of invention attributed to the experimental results? 4) What was the significance of chance and contingency in the process?

Genius Theory of Invention

Traditionally, invention has been explained as an individual or psychological phenomenon involving an exceptional talent or intuition of the inventor. Arthur Koestler's well known *Act of Creation* (1964) is an example of an analysis of rare individuals in science having a gift of creativity. This 'hero' or 'genius' account of scientific and technological development has been criticized since the 1980s by philosophers (Feyerabend, 1987), sociologists (Schaffer, 1990), and psychologists (Gruber, 1981; Oeche, 1990; Weisberg, 1993).

The social constructing genius stories has also been analyzed. It has been shown that scientists and inventors, their followers and disciplinary communities have been interested in constructing such accounts. These accounts have also been reproduced for nationalistic purposes and to catch the attention of a large public (Schaffer, 1986; Shermer, 1990; Sulloway, 1979).

Recent empirical research on scientific creativity has proposed 'systemic accounts' of creativity in which the sociocultural surroundings must be taken into consideration (Csikszentmihalyi, 1988; Harrington, 1990; Gruber, 1989b): Accordingly, creativity or inventiveness is social or collective in nature. Even the inventions by outstanding scientists or inventors have been analyzed in terms of "projects," issues of persistent interest and long periods of work rather than of mere ingenuity or exceptional talent (Amabile, 1983; Gruber, 1989a). Such a project takes place in collaboration with other persons within communities and networks of practitioners.

Multiple Discoveries and the Theory of Cultural Maturation

In the history and the sociology of science the phenomenon of multiple discovery has been an important issue of debate. The research on multiples was initiated in 1922 by Ogburn and Thomas with their paper "*Are inventions inevitable?*". In their paper they presented a list of 148 multiple independent discoveries and asked why a multiple discovery is so frequent in science. They emphasized two essential factors, i.e. cultural preparation and the development of scientific technique and instrumentation. Forty years later Merton (1961) thought that the study of multiple discoveries could be a 'strategic object' for science studies. The study of 'multiples' would reorient the study of scientific work from an individualistic and localist account to a 'decisive fact' in clarifying the advancement of science. Scientists live and work in a social and cultural environment larger than their local milieu and local interpersonal relations. Merton characterized the kind of account the study of multiples calls for (1973: 371):

> Such occurrences suggest that discoveries become virtually inevitable when prequisite kinds of knowledge and tools accumulate in man's cultural store and when attention of an appreciable number of investigations becomes focused on a problem by emerging social needs, by development internal to the science, or by both.

According to Merton joint problems, joint scientific theories and joint instruments are the essential ingredients of cultural maturation and at the same time preconditions of an invention. Moreover, in his essay on energy conversion serving as an example of simultaneous discovery, Kuhn (1977) has pointed to a similar explanation: the rapidly accumulating laboratory results of different conversion processes, the problems of efficiency in steam and electric engines and – to some extent – the theoretical ideas of natural philosophy. He has also analyzed how the pioneers of the conservation principle came to the formulation through different routes using different cultural resources.

The system-oriented historians of technology have developed one of the aspects of Merton's scheme of common or universal problem. Hughes and Constant have viewed the critical problems of the technical or sociotechnical systems as central in explaining technological change. Hughes has used the term *reverse salient* to refer to the weakest point in an expanding technological system. *Critical problems* are problems that retard economic or technical development and can be solved by invention (Hughes, 1971: 69). Constant has regarded *'functional failure'*, a system's inability to function in new and more demanding circumstances, as a major impetus to technical change. All functional failure based problems or anomalies are objective: a specific system really does not work well in a specific context (Constant, 1984: 648). Weingart regards the identification of the weakest point or critical problem as the core of invention (1984: 132): "One of the mechanisms of change, the essence of inventive activity, is the improvement of 'unsatisfactory patterns', the rectification of 'imbalances' or the identification of the 'weakest point'. This corresponds to the conception according to which the formulation of a problem or question in important inventions has been more essential than its solution. The latter is more a matter of work (see. e.g. Getzels 1987).

Rosenberg has provided a way of conceptualizing the relationship between the global and local aspects of technological problems. In his study of the development of the machine tool industry in the U.S.A., he has formulated a concept of *technological convergence*. The machine and metal using industry has certain basic processes that are common to the whole industry: turning, boring, drilling, grinding etc. Moreover (Rosenberg, 1963: 423):

> It is because these processes and problems became common to the production of a wide range of disparate commodities that industries which were apparently unrelated from the point of view of the nature and the uses of the final product became very closely related (technologically convergent) on a technological basis- for example, firearms, sewing machines, and bicycles.

The common nature of these problems indicates that once they are solved (by invention or development work) locally in one place, the solution can be diffused across the whole industry.

Attribution Theory

The representatives of the constructivist sociology of science have criticized the theory of cultural preparation for its universalistic and deterministic bias. Accordingly, two issues should be considered. The very quality of originality or inventiveness is attributed to a product by communities of specialists or users – in many cases after the construction actually has been established (Branningan, 1981; Schaffer, 1994). Discovery is a retrospective label attributed to a candidate event by research communities – a technique for marking technical practices which are prized by the community (Schaffer, 1986: 387). A classical example of a retrospective attribution is the "rediscovery" and reconstruction of the results of the experiments of Mendel by a group of geneticists in the first decade of the 1900s, thirty years after their publication (Brannigan, 1979). According to this view, the attribution or the social construction of the status of invention to any product is the central phenomenon in studying inventions.

The invention is also generated by a network of persons or communities of practitioners who in different ways contribute to the formulation and elaboration of the invention (Fleck, 1981). The constructivist studies of science stress that facts have evolved from unique local circumstances and practices. The problem of invention is how these locally created results and procedures can be transferred to society. There is an important difference between the theory of cultural preparation and the attribution theory of the constructivist sociology of science. The former has stressed the significance of shared cultural means and common preconditions for development in science and technology. In the latter theory the local nature of invention and the retrospective attribution of the status of invention become important. As the omission of shared knowledge has been seen as a weakness of the constructivist studies, focused on the local construction of facts and artifacts (Raiski, 1991), I will try to clarify the relationship between shared non-local and local resources by analyzing the case of biotechnical pulp bleaching.

Theory of Serendipity

Among the four theories of invention, the theory of serendipity has persisted especially in engineering literature and in the folklore tradition of chemistry (Haensel, 1994; Roth-Bernstein, 1994; Royston 1989). Royston (1989: xiii) has argued, that "most of the important discoveries in organic chemistry have been made by accident". These narratives of happy accidents have been connected to genius stories using the famous thought of Pasteur, according to which "chance favours only the prepared mind" (read genius mind). The protagonists of the model have concluded that science cannot be planned. Its development is basically contingent. But more room for free explanatory research is needed. This view raises a question: what is the significance of a plan and a hypothesis in the invention and innovation process? What is the impact of events and processes in the environment that cannot be anticipated?

The Emergence and Development of Enzyme-aided Pulp Bleaching

The discovery of enzymatic pulp bleaching was based on research on lignocellulose degrading enzymes at the Biotechnology Laboratory of the Technical Research Centre of Finland. Wood, cotton, straw and hay are lignocelluloses. The lignocellulose structure is composed of three fractions: cellulose (40–45 %), hemicellulose (30–35 %) and lignin (20–25 %). Cellulose and hemicellulose fibres are composed of chains of sugar molecules. The lignin molecule is a large, web-like molecule. Lignin ties the fibres together and makes the structure durable. In pulp making, lignin is degraded by cooking the wood chips in chemicals to separate the wood fibres. The research on cellulose degrading enzymes (or cellulases) begun in the Biotechnology Laboratory in 1974. The main application of cellulose research during the 1970s was the production of ethanol from wood using enzymes.

Formulating the Idea

The idea of the biotechnical pulp bleaching was formulated in a meeting at the VTT Biotechnology Laboratory on 19 January 1984. Five researchers participated in the meeting. In the minutes of the meeting, written by one of the researchers, the idea was called "*Enzymatic degradation of residual lignin and hemicellulose.*" In fact it was a double idea. In kraft pulping a small amount of lignin remains in the pulp causing its dark brown color. In the bleaching this residual lignin is removed from the pulp by using chlorine. The reactions between chlorine and residual lignin in bleaching produce toxic chlorine compounds that are released with effluent waters into the environment.

In the meeting, two possible ways were formulated to remove the residual lignin using enzymes. First, it was decided to initiate studies on the use of lignin degrading enzymes (or ligninases). This idea was stimulated by a recent discovery, made by an American research group, of the extra cellular enzyme of a white fungus being able to degrade lignin. However, the VTT group had not studied the production and use of ligninases. Instead it had wide experience on hemicellulose degrading enzymes (or hemicellulases), especially of xylanases that degrade xylan, the main hemicellulose of hardwoods. According to the participants of the meeting, it was known that the residual lignin is somehow connected to the hemicellulose in the unbleached pulp. Consequently a second idea was presented. By selectively degrading hemicellulose, the residual lignin could more easily be extracted from the pulp. This secondary idea was later found to be successful and it formed the basis of the innovation.[1]

Who invented the idea? It is not relevant to pose such a question as the idea was developed and elaborated during the discussion. Nevertheless, two of the participants willingly accepted the honour, though in a conditional and modest way:

> We didn't know much about ligninases. If we decided to study them, it would take a long time(...) Instead a question was raised – I think it was me who asked it – where is lignin attached to the wood? The answer is that it is attached to the hemicellulose. I also suggested that we should degrade the hemicellulose to the extent that the lignin is released. We know how to degrade hemicellulose. We have the enzymes for that. This was the basic idea. The research started to evolve from this idea.
>
> It came to mind that the residual lignin is somehow attached to the hemicellulose.

> (...) This led to the idea that it might be worth while to use the hemicellulases of the Biotechnical Laboratory to split off a part of it and maybe the fragments of lignin would come off easier. (...) This was the idea which – as far as I can remember – I presented at the meeting. (...) If I made any contribution, it was the idea that the gentle removal of the hemicellulose might be a feasible solution.

The formulation of the idea of the enzymatic pulp bleaching provides an example of a distributed invention. This was the formulation that was worked out at the meeting. However, the accounts of the researchers suggest that the issue had already been discussed earlier. No single person can be considered the inventor. Both of the researchers claiming priority for the presentation of the idea made their own contributions. This argument becomes more valid, if the cultural and organizational conditions of the invention are considered.

The basic idea of using hemicellulose was a secondary issue in the meeting. The primary option was to start a study on the possibility of using ligninases. The hemicellulase solution was only later found to be an innovative idea – after a long process.[2]

Disciplinary Background of the Idea: Studies on Biotechnical Pulp Bleaching

The idea of biotechnical pulp bleaching was not new. In the 1970s several research groups had studied methods for degrading the residual lignin present in unbleached pulp. The groups of Kirk, at the Forest Product Laboratory of the US Department of Agriculture, and of Eriksson, at the Swedish Forest Products Research Laboratory had studied the effect of white-rot fungi on the degradation of kraft lignin since the beginning of the 1970s (Hiroi & Eriksson, 1976; Lundquist et al., 1977). Kirk had defined the problem of available bleaching methods very clearly (Kirk & Yang, 1979: 347):

> Wood pulp produced in the kraft ('sulfate') process generally contains 5 to 8 % by weight of residual, modified lignin, which gives the pulp a characteristic brown color. This residual 'kraft' lignin is removed commercially by bleaching with chlorine and chlorine dioxides. Chlorinated products derived from the craft lignin during these bleaching procedures have been recently shown to be mutagenic (Ander et. al., 1977) and they obviously represent a waste treatment problem, both because of their toxicity and their dark color, which resist classical biological methods. Alternative methods are needed for bleaching pulp.

Kirk's group cultivated the fungus *Phanecrochaete crhysosporium* on pulp. Compared with control treatments, 27 % less chlorine was needed in the bleaching experiments with this pulp and the brightness of the pulp, achieved was considerably higher (1979). These studies were well known and they evidently contributed to the formulation of the idea at the VTT Biotechnical Laboratory.

The Decisive Impulse: Discovery of Ligninases Outside the Cell

The micro-organisms cannot be directly used in the industrial bleaching processes. The revolutionary discovery of Kirk's group in 1983 was a lignin-degrading enzyme excreted outside cells (Tien & Kirk, 1983). The possibility of producing and using ligninases raised great expectations and hopes. Three of the participants of the meeting at the VTT, where the idea of enzymatic bleaching was formulated, recollect the influence of Kirk's discovery:

> Kirk's observations, combined with the work of Eriksson, created an new spirit and everybody started to dream of biotechnical pulp production. So did we in the same rush of enthusiasm.

> There was tremendous enthusiasm. We all thought that everything could be done with this, for instance removing the residual lignin from the fibre.

> In 1982 – 83, research results were published on the biological degradation of lignin. This raised general interest in what could be done with biotechnical methods. Everybody of course thought that the pulp industry is a new area to which we should go. This was evidently the background for the discussions we had.

These statements demonstrate the significance of the 'discovery' of Kirk's group. The results opened a new perspective for research on the degradation of lignocellulose: the possibility of degrading and modifying the most complex of the fractions of wood, lignin.[3] It was a promise, a hypothesis or a signal for a reorientation for the research groups in the field. The results were seen in this way, even though they later were found to be problematic. As lignin degradation is the key phenomenon in pulp and paper production, these results also directed the research toward the pulp and paper industry. Moreover, Kirk visited Finland and the Repligen biotechnology firm sold services based on Kirk's group's results. A Finnish construction company, Partek, having a holding in Repligen was active in organizing collaboration between Repligen and the Finnish forest industry.

The research on biotechnical pulp bleaching by the Swedish and the American groups, as well as the discovery of Kirk s group on ligninases, were necessary for the formulation of the idea of enzymatic pulp bleaching at the VTT. These studies were conducted before the VTT group started studying pulps. They can be well interpreted as the creation of the necessary cultural tools for the formulation of the idea of enzymatic pulp bleaching.

Local Factors Affecting the Idea Formation: Hemicellulase Research at the VTT Biotechnical Laboratory

The general idea of biological pulp bleaching was not new. What was new at the VTT Biotechnical Laboratory was the idea of using hemicellulases in bleaching. Hemicellulases had been produced and used at the Biotechnical Laboratory and they could be used easily and immediately in bleaching experiments, in contrast to the long-term perspective of studying and producing ligninases. The idea was closely connected with the research tradition of the laboratory. The production and use of hemicellulases were actively studied around the time of the meeting in several projects. An idea or a hypothesis of the attachment between hemicellulose and lignin in the pulp was also required to formulate the idea.

Research on hemicellulases was a direct outgrowth of research on the cellulose. One of the first objects of enzymatic degradation experiments in the 1970s, waste liquid from Savon Sellu (a Finnish pulp factory), contained a considerable amount of xylan, the most important hemicellulose of hardwoods. Another raw material, peat, also contains a large amount of hemicelluloses. Research on the production of hemicellulases began in 1976 at the VTT Biotechnical Laboratory. The organism used in the production of cellulases, *Trichoderma reesei*, was also found to be a good producer of hemicellulases (Linko et al. 1977).

In the beginning of the 1980s hemicellulases were studied in several projects. The use of hemicellulases was analyzed in a project on the pretreatment of cellulosic materials since 1982, jointly with the Biotechnical Laboratory and the Institute for Wood Chemistry of the Federal Research Centre for Forestry and Forest Products of the Federal Republic of Germany (Hamburg). As a result of this research, several types of hemicellulases were produced and used by 1984, and they could immediately be used in degradation experiments. The hemicellulase know-how was the decisive local resource contributing to the formulation of the idea for biotechnical pulp bleaching and to the rapid success of bleaching experiments with hemicellulases.

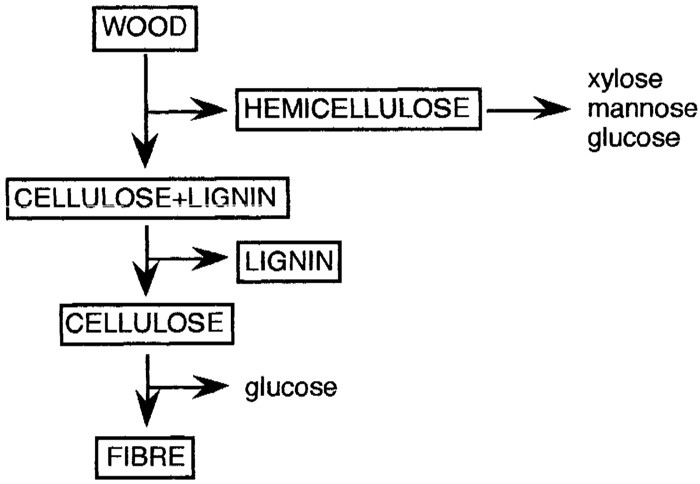

Figure 1. Outline of a new pulping process (Enari, 1985: 66).

Less Funding for Ethanol Research: New Applications Are Sought from the Forest Products Industry

As mentioned before, the main application of cellulose research at the Biotechnical Laboratory during the 1970s was the production of ethanol from wood using enzymes. After the oil crisis recession in 1983, funding for ethanol research was cut, and the laboratory had to find new applications for cellulose and hemicellulose degrading enzymes. The most significant of them was the use of enzymes in pulp bleaching. The formulation of the idea of pulp bleaching was preceded by an extensive discussion on the possibilities of utilizing biomasses and of connecting enzyme technology to the forest production industry.

The senior researchers of the laboratory emphasised that the forest industry does not use the other fractions of wood in the best way. In conventional pulping processes more than half of the raw material is dissolved into the waste liquid (called black liquor) and subsequently burned to produce energy. New uses that add more value should be found for these fractions. Professor Enari, from the VTT Biotechnology laboratory, outlined the new pulping process (Figure 1) arguing as follows (Enari, 1985: 66):

> Cellulose is of course so valuable as a fibre, that the macromolecules should not be hydrolyzed. Current pulping processes are inefficient in that they make use of only half of the raw material. They also cause pollution. The pulping process should therefore be developed to allow profitable use of all wood components.

The problem of the raw material strengthened the reorientation of cellulose research toward the pulping process. The idea of the 1970s was to utilize the waste material from forest production. However, waste wood proved to be too resistant to enzyme attack (Miettinen 1986, 18–19). Consequently, the question arose of whether the enzymatic hydrolysis could somehow be used as a part of the pulping process, using the fractions of raw materials processed in it.

In 1983 the Ministry of Trade and Industry appointed a committee with the task of preparing a set of national technology programmes. Professor Enari from VTT finalized "The *use of wood as a raw material of the chemical industry.*" , the aim of the which was to promote a more efficient use of biomass by developing fractionation methods, and by the utilization of lignin and pentosan fractions. The user of the results was supposed to be the Finnish pulp and paper industry. In the words of the organizer (Enari 1985, 7): "Enzymes can play a key role in the development of a new sulfur- and chlorine-free pulping process which makes optimal utilization of all main wood components possible." This idea directly paved the way for the formulation of the idea of enzymatic pulp bleaching.

Knowledge on Biomass Fractionation from Batelle Institute is Transmitted to VTT

The recruitment of a new researcher with a strong background in forest production, fractionation and the use of biomasses contributed to the reorientation of the pulping processes. In the early 1980s, Johansson and his colleagues developed a fractionation method for biomass at the Batelle Institute in Geneva. The central idea of this approach is to use a solvent with which the lignin in the lignocellulosic material can be extracted leaving the cellulosic fraction undisturbed (Johansson et al., 1982: 9):

> The Batelle-Geneva fractionation process possesses the unique feature of allowing a separation of the three main components of biomass into separate fractions,which can be valorized independently without the need for the regeneration of chemicals. In contrast to other methods of biomass upgrading (..), in which both the lignous and fibrous structure of the original matter is totally or partially destroyed, the components are by this method recovered virtually in their original form (with the exception of the hydrolyzed hemicellulose fraction).

Johansson brought the idea of "biomass refining" and his knowledge of the pulp and paper production to the Chemical Laboratory of the Technical Research Centre of Finland. These ideas contributed to and concretized the idea of developing the total use of cellulosic materials and helped to connect it with the context of the pulp and paper production.

The Social Mechanism of Preparation

A year before the 1984 meeting on the enzymatic hydrolysis of pulp, a series of discussions concerning biomass refining were held by the laboratories of the VTT Division for Process Technology. All five laboratories conducted some uncoordinated research on biomass. The Chemical Laboratory explored solubilization of celluloses used in the production of viscose. The Fuel and Process Technology Laboratory studied alternative fuels and was initiating research on the utilization of waste liquid from the sulfate pulp process, black liquor. The Combustion and Thermal Laboratory analyzed peat and combustion processes. The declining funds for ethanol research also had an impact on the other laboratories studying alternative fuels and energy forms. An attempt was made to establish a synergistic programme on biomass that would interest all the laboratories.

> We tried to link these attempts to the Biomass program at VTT (...) We had some seminar-type discussions on how to link up the existing know-how and needs in some way without knowing exactly what to do. This is a very important market area – at least potentially – in Finland. An organization began to develop around biomass: discussions, idea generation, etc. We were quite open to new ideas.

During these discussions, different points of views and arguments were linked together and redefined and a four-year VTT research programme "Sustainable Technology" was initiated in 1984. One of the projects of the programme was on the utilization of pentoses (hemicelluloses). It was directed by Johansson together with a researcher from the VTT Biotechnical and Chemistry Laboratories. The issues essential in the idea of the enzymatic bleaching of cellulose – environmental impacts and utilization of waste materials (including hemicelluloses) using hemicellulases – were prominent in the discussions and activities of the VTT Division for Process Technology in 1983 – 1984. The meeting that formulated the idea of biotechnical pulp bleaching was a part of this search for new directions. The convener of the meeting was the organizer of the discussions. These background discussions further emphasized the distributed and social nature of the idea.

First Experiments and the Results

The bleaching project was organized into two project groups. One started research on ligninases. The lingninase group had to study the production of ligninases and characterize the enzymes to be used in the bleaching experiments. The hemicellulase project could begin degradation experiments immediately, with hemicellulase preparations already produced in the laboratory.

In the first experiments the pulp was of lower quality than that used in conventional bleaching. The enzyme preparation used also contained small amounts of enzymes that could degrade the cellulose fibres and make them weaker. In 1985, the researchers looked for new enzyme preparations with lower cellulase activity. In these experiments it turned out that the pulp treated by a hemicellulase preparation was more easily bleachable and the need for chlorine declined. A reduction of 25 % in the consumption of chlorine chemicals. was reported. The results were published in the Third International Conference on Biotechnology in the Pulp and Paper Industry in Stockholm, June 1986 (Viikari et al., 1986).

These experimental results subsequently led to a new bleaching method. In 1986, however, it was just one experimental result for the researchers. The reduction of 25 % in chlorine use was not particularly impressive in terms of the aim of the project, that was "the elimination or significant reduction of chlorine chemicals used for the bleaching of unbleached pulps." This particular result was not discussed in the conclusion of the paper. It was said that promising results were obtained both with hemicellulases and ligninases acting directly on lignin. "However, the application of ligninases offers the greatest potential for future development", the paper concluded.

The Latent Period: The Users and Paper and Pulp Researchers Regard the Results as Insignificant

The representatives of the pulp and paper industry, and most of the wood chemists, were skeptical toward the project on enzymatic bleaching. Chlorine was an efficient and cheap bleaching agent. Why degrade hemicellulose if lignin was to be removed from the pulp? The laboratory did not patent the results published in the summer of 1986 because the representatives of the pulp and paper industry viewed them as insignificant.

The Finnish pulp and paper producers had a negative attitude toward the continuation of the project as a part of the national technology program in 1986. The project was reformulated and the aim of developing biotechnical pulping was dropped. The firms had no interest in developing further enzymatic bleaching with public funds. The group in the Biotechnology Laboratory received funding for a project, "The uses of hemicellulases in pulp industry", being basic research on hemicellulases.

As regards enzymatic pulp bleaching there was no active collaboration in the years 1984–1989 between the researchers and the users. VTT Biotechnical Laboratory continued the studies with the Finnish Pulp and Paper Research Institute. An active collaboration with the users for developing and implementing the new method was not started until 1990.

Unexpected Social Processes Interfere: Dioxin and Chlorine Debate as Midwives of Innovation

Why did pulp and paper producers not become interested in experimenting with enzymes until 1989–1990? The background lies in environmental issues. In 1987 a discussion arose of dioxins, the highly toxic chlorine compounds that became known as "super poisons", after an accident in a chemical plant in Seveso, Italy in 1973. A research group in the U.S.A. discovered that paper products bleached with chlorine also include small amounts of dioxins. The results of these studies were published in the *New York Times* in September 1987 and in several other newspapers and journals during the following months. At the conference on dioxins in Toronto in 1989, the results were presented on the migration of dioxin from paper packages to foodstuffs. This meant the redefinition of the chlorine problem. It was transformed from a waste disposal problem of pulp plants into a problem of paper products.

In Germany, the environmental authorities launched their own studies on the issue and prepared to set strict limits on the dioxin content of paper products. A Finnish pulp and paper producer, Enso Gutzeit, was the biggest liquid board producer in Europe, and the Federal Republic of Germany was the most important export area for these products. A crisis group was formed in Enso to rescue the German markets and to eliminate chlorine compounds from the products. A professor of microbiology from the University of Helsinki consulted with Enso Gutzeit at that time. As a member of the crisis group, she had contacts with the Ministry of the Environment of the FRG and with research groups responsible for dioxin studies, among them the Peterkoff Institute. One of the measures taken by Enso Gutzeit to solve the crisis was plant-scale bleaching experiments with hemicellulases in its Uimaharju Plant, in March 1989. They were accomplished together with a Finnish enzyme producer Cultor. This network was independent of the collaboration network of the national research programme. The experiments were successful. Metsä Serla, another Finnish pulp and paper producer, immediately followed by making a research contract with the VTT BIO. In 1990–1992 enzymes were tested at most Finnish pulp mills.

The emergence of the markets of ECF (Elementary Chlorine Free) and TCF (Totally Chlorine Free) pulps were decisive factors contributing to the implementation of enzyme-aided bleaching. The printing and publishing companies in Europe began to request chlorine-free paper because readers began to prefer chlorine-free products. For example, *Der Spiegel* decided to switch to chlorine-free paper in December 1992. This change of orientation was partly a result of the campaigns of environmental groups, among them Greenpeace with its campaign against chlorine use.

Finnish pulp and paper companies regarded the dioxin problem as a quasi-problem, generated by overwhelmingly sensitive methods of analysis. They strongly campaigned for their viewpoint. Toxicologists instead calculated that the risk of excessive dioxin concentration in the human body was real. The users resolved the controversy by demanding chlorine-free products.

Enzyme-aided Pulp Bleaching Gains the Status of Invention

The status of invention was publicly attributed to the enzymatic bleaching in Finland when the method received an award from the Ministry of the Environment for being the most significant environmental invention in 1990. Since then, the method has been extensively used as an example of inventive activity at the Technical Research Centre of Finland. In 1996, a Finnish Fund granted an international award (Walter Ahlström Award) to the researcher at the Biotechnical Laboratory who had been in charge of the bleaching studies in 1985–1986. Concomitantly, the social construction of the invention was accomplished in six or seven years.

The Relevance of Theories and Invention in Explaining the Emergence and Development of Enzyme-aided Pulp Bleaching

How can the emergence and development of enzymatic pulp bleaching be explained by using the four models of inventions? To begin, it cannot be analyzed or explained at all using the genius theory. Enzymatic pulp bleaching was a collective, distributed invention. Several persons contributed to the formulation of the idea of enzymatic bleaching at the VTT. Three research groups participated in its further elaboration during the experimental work (see Miettinen, 1996: 37–40). I presume that a careful empirical analysis would often uncover this kind of social and shared nature of the early phases of the innovation process.

Theory of cultural maturation: Global or local?

The theory of cultural maturation suggests that there is a shared, critical problem behind an invention as well as shared knowledge and methods used in inventing a way of solving this problem. The critical problem that called for the invention was the toxic chlorine compounds that were produced by the use of chlorine gas in the bleaching of kraft pulp. Environmental research and analysis gradually created a chlorine problem shared by the research community, environmental authorities and pulp and paper producers, at least in Europe and North America. It was first a problem of waste water, which was primarily solved in Finland by constructing and developing biological treatment plants. The research results published in 1987 on the small amounts of dioxin in paper product were the turning point in the development of the problem. This suggested that dioxin migrates from the food containers to the food and afterwards to the human body (Ryan et al., 1988). The problem was raised in the public environmental discussion, and markets for environmentally friendly non-chlorine pulps emerged in central Europe, firstly in Germany. Accordingly, the chlorine problem turned out to be a full-fledged economic problem for the Finnish pulp and paper producers, resulting rapidly in the abandonment of chlorine in pulp bleaching.

To what extent was the chlorine problem shared or global? It was global in the sense that since the analysis methods were established, the chlorine compounds surely were found equally in the products of plants using pulp bleached by chlorine gas in Europe, Canada or South America. However, for several reasons reservations must be made. First, the problem has a different meaning to the pulp producer, depending on the end product. What is fatal for liquid packaging boards, food boards and filter papers can be insignificant for wallpaper or boxboard. Secondly, different markets have different demands for chlorine-free pulps. Environmentally-sensitive European consumers often prefer non-chlorine paper products. In England, the issue has not received such wide publicity. In economically and politically labile Russia, the issue has hardly been raised at all. Hence, while the chlorine problem has been known since the 1970s, it was constantly redefined by the development of research results and methods of analysis. The nature of the products and the markets determined whether or not it was a problem for the producer.

The study of enzymatic pulp bleaching had begun in Sweden and in North America before the VTT group was interested in pulps. For the formulation of the idea at the VTT, shared cultural resources were used such as knowledge produced by Kirk's group (the U.S.A), Eriksson's groups (Sweden) and the group lead by Johansson at Batelle Institute (Switzerland). These resources were transmitted to the VTT group by the scientific journals, by the participation in conferences and by the movement of scholars from one institute to another.

The novel part the Finnish group's idea of the was, instead of ligininase, to use another type and less evident enzyme, hemicellulase, in bleaching. This idea arose directly from the preceding research activity of the laboratory; the hemicellulases had already been produced and they were immediately available for the experiments. The local collaboration with the Finnish Paper and Pulp Research Institute enabled a rapid progress in the bleaching experiments. These conditions of discovery were local. The idea of enzymatic bleaching was worked out, utilizing global cultural resources; and its particular content was based on local conditions and knowledge.

Enzyme-aided pulp bleaching was no inevitable outcome of the chlorine problem and of the advances in enzyme research. The problem was immediately resolved by many pulp producers by replacing chlorine with chlorine dioxide, a less harmful chlorine chemical. Oxygen bleaching is an alternative bleaching system used in many new plants. The method of the next decade will probably be closed circulation, which presupposes the elimination of chlorine. Enzymes were an alternative for many existing mills because they can be added to the old bleaching equipment without significant investments (Viikari et al., 1994: 346).

The emergence of the enzyme-aided pulp bleaching suggests that the model of cultural maturation has a rational kernel: the significance of a shared problem and shared knowledge for the formulation of the idea. However, there is no support for determinism or for abstract universalism in the Mertonian meaning of cultural preparation. The chlorine problem was reconstructed by several actors: by pulp and paper researchers, by toxicologists, by environmental authorities, by Greenpeace and other environmental movements, by pulp and paper producers, and by consumers. However, even this complex and geographically dispersed network can be regarded and analyzed as a flat, "local at all points" (Latour, 1993: 117), i.e. composed of interaction and of concrete situated activities.

Attribution theory : Attribution by whom and why?

The development of enzyme-aided pulp bleaching fully confirms the significance of social attribution in the invention process. In 1986, the potential users did not regard the experimental results on enzymatic bleaching as significant or usable. Concomitantly, the VTT research group did not regard these results as promising enough to patent them. The environmental concern of consumers and the formation of chlorine-free markets forced the pulp producers to redefine the significance of enzymes in bleaching. After the enzyme-aided bleaching was implemented, it gained the status of an environmental innovation. Accordingly, the experimental results published in June 1986, reporting the impact of hemicellulases, were re-evaluated and regarded as an invention. Without the dioxine and chlorine debate, these results would have remained one among the many results reported in a congress, without any visibility outside the community of cellulose and enzyme researchers.

The attribution theory, however, leaves the problem of the emergence and the sources of an idea and invention without proper attention. To solve this problem, the analysis of the preceding, common cultural resources that has been used locally by inventors, is relevant. The concept of attribution or retrospective labeling also needs further elaboration. Who gives this new interpretation and why? Attribution can be analyzed as a process of giving a new meaning to a result or to a fact by some actors as a result of objective changes in their activity and environment. The pulp and paper producers gave a new meaning to the enzyme use because of the radically-changed environment and market situation. They protected their markets and tried to enlarge them by introducing enzymes in bleaching. They also introduced enzymes to create an image of environmentally- friendly and "green" products, which was important in changing European markets. The attribution of invention and innovation was not given to enzyme-aided pulp bleaching by any unified disciplinary community. It was given both by environmental authorities and organizations tied to the Finnish pulp and paper industry. A strong national interest unified this heterogeneous alliance in its attribution.

Theory of serendipity: Planned or contingent process?

There was no lucky accident in the formulation of the idea and early experimentation. The vision of the biotechnical bleaching emerged and was developed in the form of two ideas, the use of lignin degrading enzymes – inspired by the discovery of Kirk's group – and the complementary alternative of using hemicellulases. Both of these were hypotheses for a new possibility. Professor Enari from the VTT characterizes the hemicellulase alternative as follows:

> When we had that meeting, no experiments had been conducted. It was a hypothesis on the basis of which we started to work (...) We didn't know how it happened. But it worked. It does not matter whether a hypothesis is right or wrong. What is important is that it leads to experiments that solve the problem.

The use of ligninases in pulp bleaching proved to be a difficult problem scientifically and technically and the idea could not be developed into a workable method. The idea of using hemicellulases was elaborated by the experiments, and the results turned into an invention in the beginning of the 1990s. Most of the events and factors that decisively influenced the emergence of the invention were not and could not have been anticipated: the oil crisis recession, the results of Kirk's group in 1983, the development of research on dioxin in paper products in 1987–1989, the changes in the attitudes of paper consumers and the general public, and the formation of chlorine-free markets. There was a strong element of contingency in the process. The effects of several unanticipated development processes and events were timed and accumulated in a way that made the invention possible.

Neither was the invention a result of luck or change. The know-how and persistence of cellulase and hemicellulase research made the formulation of the idea possible. The idea of sulfur- and chlorine-free pulping (See Figure 1) played an orienting model in the process. Contingency, vision and persistence were intertwined. It was the persistence of the research programme on celluloses and hemicelluloses that made possible the formulation of the idea for enzyme-aided pulp bleaching, even though the status of invention was attributed to it only later and due to a series of unanticipated events in the environment.

NOTES

[1] Afterwards it is impossible to know what the participants knew about the bonds of lignin and hemicellulases. When the project started, the relevant literature was naturally reviewed. This later learning has no doubt influenced the way in which the interviewees remember what was discussed and proposed. In the first project plan (16.4.1984) the relation was formulated as follows: "With the aid of an enzyme that specifically degrades xylan, the bonds between residual lignin and hemicellulose can be weakened and the need for bleaching chemicals can be diminished".

[2] The primacy of lignin option is expressed in the documents in many ways. The minutes of the second meeting concerning the pulp bleaching (6.2.1984) were entitled: "The biological degradation of lignin". In the first articles on the research project (Viikari & al., 1986), the significance of lignin research was greatly emphasized. The ligninase project was financed by 6 millions FIM for the years 1984–1987, whereas the bleaching project (with hemicelluloses) by 3 millions FIM. Later on it turned out that the enzymatic degradation of lignin was a very difficult problem and short-term applications were unlike. The ligninase research at the VTT BIO came to an end in 1992.

[3] The basic phase in pulp production is cooking in which the lignin is dissolved to separate the cellulose and hemicellulose fibers at high temperature (170 grades) and pressure (12 bars) with 'hard' chemicals (NaOH, Na_2S). Consequently, the discovery of the lignin-degrading enzyme opened the revolutionary vision of a biological, environmentally sound and low-energy pulp production method.

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