A COMPARATIVE STUDY OF THE DEVELOPMENT OF TWO CHEMICAL TECHNOLOGIES: POLYPROPYLENE AND EPDM RUBBER

by

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ABSTRACT

This paper examines the dynamic characteristics of R&D communities and their role in technological development. Using a comparative study of two chemical technologies, polypropylene and epdm rubber technology, it empirically investigates the development of the two R&D communities using the literature and patents published by polypropylene and epdm researchers as a source of information. The data allow us to study the influence of the structural and behavioral characteristics of R&D communities on the rate of technical progress, since both technologies have experienced a rather differential path of progress. The two chemical technologies also enable us to see how the dynamics of R&D communities may change when the creations of the researchers become incorporated within a corporate environment such as the chemical industry. Our findings point to the emergence of a hybrid system, in which both managerial control and community autonomy cooperate in the choice of the directions technological development takes. Moreover, a comparison between polypropylene and epdm sheds further light on the influence particular community variables possibly have on the rate of technical progress.
Introduction

The existence of invisible colleges, embedded within broader scientific communities, has for long been a major interest of students of science (Hagström, 1965; Griffith and Mullins, 1972; Mullins, 1972; Ziman, 1984; Price, 1986). The notion "R&D community" developed in this paper seeks to extend the concept of an invisible college, to offer a more encompassing view, and in doing so, to explore its relevance to technological development.

An R&D community is defined as a group of individuals, composed of scientists and engineers, who are committed to solving a set of interrelated scientific and technological problems, who may be organizationally and geographically dispersed, and who communicate in some way with each other. The ultimate goal for some members of the community may be to create new knowledge, while for others it may be to apply existing knowledge in the creation of new products or processes. Furthermore, the community can include individuals employed in any type of organization, such as universities, private firms, new ventures, quasi-public corporations, and government research institutes wherever they may be located throughout the world.

Obviously, this concept of an R&D community extends beyond traditional disciplinary and industry boundaries. It is broader in nature than the discipline-based scientific communities and than the smaller subsets within those communities that are formed by the existence of the invisible college. Rather, the R&D community has an interdisciplinary character and can include researchers from a wide variety of academic specialties. Moreover, within the private sector, it includes firms irrespective of their standard industrial classification. The only requirement is their focus on some part of the relevant problem set. Thus, the community is defined by the nature of the problem set and not necessarily by the end product, as is normally the case with an industry definition.

The dynamics underlying R&D communities are explored through a comparative study of the
development of two chemical technologies: polypropylene technology and epdm rubber technology. It is believed that this approach broadens the scope of current thinking on technological development which tends to emphasize the instrumental role of the firm in bringing new technology to the market place. Much academic research on the subject of technological development has been directed at understanding the functioning of firms (and industrial research laboratories in particular), attempting to unravel the relationships between numerous organizational variables and success in developing new technologies (Allen, 1977; Roberts, 1984). There is no doubt that previous work along this line of inquiry has yielded important insights about the management of technological development. However, in focusing on the firm in isolation of the broader environment in which technological development occurs, this approach may have lost sight of some other critical dynamics in the emergence of new technologies.

In particular, we believe that technological development is not the exclusive domain of firms -- or for that matter, a collection of firms in a given industry -- but rather an activity which cuts across many types of public and private organizations. Furthermore, it is proposed that technological development may come about through the concerted efforts of a community of researchers which forms over time and that spans these diverse organizations. If this is indeed the case, then the progress of such communities may be better understood through a careful examination of how they function. This functioning is now further explored in the cases of polypropylene and epdm technologies.

The choice of these chemical technologies fulfills three general research interests. First of all, up till now, the role of R&D communities in technological development has been studied for a variety of electronics and computer technologies (e.g., Josephson junctions, gallium arsenide semiconductors, magnetic bubble memories, microgravity crystal growth, neural network technology, RISC technology, high-temperature superconductors). Polypropylene and epdm
rubber technology are the first chemical technologies on our research agenda. It is thus interesting to see what role R&D communities play in the field of chemicals. Second, polypropylene and epdm rubber technology have quite a different history. The development of polypropylene technology has been characterized by quite a number of breakthroughs since its onset in the early 1950's. These have had a tremendous influence on the efficiency and the cost of polypropylene manufacturing processes. Recent advances in catalyst systems and process technology enable reductions in plant investment of more than 50% compared to previous practice. Epdm rubber technology, on the other hand, has been characterized by most experts as a rather "stagnant technology". No real breakthroughs have been made since its inception, although incremental refinements have increased the performance of epdm rubber technology as well. Thus, a comparative study of both technologies enables us to focus on the similarities and differences between the two R&D communities associated with them. Third, both technologies are by now well internalized within an industrial environment. This adds an important dynamic dimension to the R&D community concept proposed above. It allows us to shed some light on the question of how R&D communities evolve as their mental creations become commercialized within an industrial setting.

Polypropylene and epdm rubber technology: an overview

The empirical data for this paper are provided by the journal and patent literature on two chemical technologies. The focus is on the development of manufacturing technologies for polypropylene and epdm rubber. As a consequence, no attention is paid to subsequent uses of the products which result from polypropylene or epdm rubber manufacturing processes. The production of polypropylene and epdm rubber rests on two fundamental, though intertwined, components: the catalyst system used to polymerize the monomers and the process technology in which this polymerization takes place. Both are intertwined in the sense that the type of catalyst system a manufacturer uses has tremendous implications on the number of process steps necessary
to reach the end product. On the other hand, a restricted number of process technologies (e.g. whether the polymerization reaction takes place in a gas phase or liquid phase) using slightly different catalyst systems are competing for licensees in an oligopolistic manufacturer market place. In order to investigate the role R&D communities have played in the development of both technologies, a brief historical account of polypropylene and epdm is necessary. Both technologies have their roots in scientific and technological developments which took place in the early 1950's and which eventually led to the formation of a new branch of organic chemistry and a Nobel Prize for its founders, Ziegler from the Max Planck Institit für Kohlforschung in Mülheim and Natta from the Politecnico di Milan, in 1963.

The early years of Ziegler-Natta chemistry

The origins of the polypropylene and epdm rubber technologies which are presently in use go back to the work of Ziegler and Natta in the 1950's:

"The discovery of stereoregular polymers was foreshadowed by certain events in polymer science and by aborted discoveries that, like minor tremors preceding a major earthquake, can be seen afterwards as signalling and triggering earth-shaking events. Karl Ziegler and Guilio Natta are justly famous for their epochal discoveries: Ziegler for his linear, crystalline polyethylene, Natta for his isotactic, crystalline polypropylene and other stereoregular polymers. Yet Ziegler was not the first to make a linear polyethylene, and stereoregular polymers were postulated, prepared and published prior to Natta's work. Linear, crystalline polyethylene was, in fact, made half a century before Ziegler by another German, named von Pechmann." (McMillan, 1979)

However, Ziegler and Natta were able to arise massive industrial interest for their discoveries. Natta's close links with Montecatini (later to become Montedison) and Ziegler's agreements and relationships with such companies as Hoechst and Hercules Powder Company (a result from the Du Pont break-up following an anti-trust litigation) are of tremendous importance for the structure of the R&D communities as we will observe them for both technologies. When von Pechmann announced his product at the time, it was regarded a mere laboratory curiosity and it did not receive any follow-up. Ziegler's low-temperature polymerization of ethylene by means of organo-metallic
catalysts and Natta's subsequent polymerization of propylene, however, generated research activity and plant construction all over the world.

Polyethylene was already a commercial reality and an enormous success 20 years before Ziegler's discovery. It was, however, a different kind of polyethylene, not linear but "branched". ICI was the leading licensor for this high-pressure polyethylene process (Freeman, 1982) in which discovery both serendipity and ICT's close links with the Thermodynamics Laboratory at the University of Leiden played an important role (Reader, 1975). Ziegler's discovery of organo-metallic catalysts made the production of low-pressure polyethylene (and polypropylene) possible. His new process did not need the enormous amount of pressure of the ICI process. Ziegler's catalyst was a combination of titanium chloride and aluminum alkyl. But Ziegler was not the only researcher working in this research area. Du Pont missed the (bloody) battle for priority rights on organo-metallic catalysis only with a one month's difference in time. As a consequence, researchers at Du Pont got really frustrated because of company patent policies which had refrained them from publishing their discoveries:

"Du Pont's chemists had a right to feel disappointed if not somewhat bitter, because they had made the same discovery that earned someone else fame and fortune. The legal and commercial aspects of these inventions prevented the industrial scientists at Du Pont and in the other companies from publishing their results and receiving credit for their scientific achievements. Perhaps in this particular case, immediate publication by the Du Pont chemists might have given the company a better legal position because not all publicity would have gone to Ziegler and Natta, who shared a Nobel Prize in 1963. In any event, the Polychem scientists led by Gresham, Anderson, and Robinson had made outstanding contributions of Nobel Prize caliber, but the extremely competitive nature of polymer R&D prevented them or Du Pont from receiving widespread recognition or monetary rewards for this work." (Hounshell and Smith, 1988)

Ziegler and Natta's discovery created a new branch of chemistry and, although the initial production processes for stereoregular polyethylene and polypropylene caused more problems than originally anticipated, industry all over the world was simply excited about the new prospects that had opened up. The property rights of Natta's polypropylene went to Montecatini (which later
became Montedison), while Ziegler somehow attempted to divide the world among a number of licensees. Patent battles, however, have been numerous before polypropylene rights were given to (and later on, redrawn from) Montedison (McMillan, 1979; Hounshell and Smith, 1988). In the early years, two other companies were developing alternative processes for the polymerization of propylene. The Standard Oil Company of Indiana pursued the development of molybdenum catalysts, though it lacked the determination to push it through. Phillips Petroleum developed and commercialized a chromium-based polypropylene process. Although not as successful as the Montecatini developments, a number of plants were built using this process.

Ziegler-Natta chemistry opened up entirely new vistas for both polyethylene and polypropylene. However, synthetic rubber offered another outlet. The search for synthetic rubber has been going on for long (Whitby et al., 1954). In 1860, Greville Williams succeeded in isolating a substance, which he named isoprene, from the distillation products of rubber. In 1933-34, the German IG Farben was able to polymerize a new class of synthetic rubbers, the Buna's. Natta's finding that certain of his catalysts could be used to make random ethylene-propylene copolymers that were amorphous and rubbery led the way to another type of synthetic rubbers, the ethylene-propylene rubber class. Over 90% of the ethylene-propylene rubbers are of the epdm type which means that in addition of the basic ethylene-propylene copolymer, they contain fractions of a third monomer which usually is a diene.

Polypropylene technology, further developments

Polypropylene has been one of the success stories of the chemical industry. Except for a sharp recession after the second oil crisis in 1974 and a suffering from an overcapacity in the beginning of the 80's, polypropylene has known a dramatic growth in supply and demand. Polypropylene is a bulk chemical. Its applications are diverse, for example: battery cases, automobile parts, kitchen wares, washing machines and dishwashers, fibers and filaments, and films. Data for the US alone
show that domestic demand for polypropylene grew at an average annual rate of 11% between 1971 and 1981, and at a rate of 8% in the last 7 years (Chemical and Engineering News, August 1989). Of the three major consuming areas, growth has been fastest in Western Europe, followed by Japan and the United States. Year after year, new plants are announced to meet a growing demand.

Two basic groups of production processes can be discerned (Kirk-Othmar, 1983; Encyclopedia of Polymer Science and Engineering, 1988): those where polymerization occurs in the liquid phase and those with a gas-phase polymerization. When looking at a polypropylene plant, one finds that the polymerization part is only a fraction of the total investment. The downstream investments are over 50% of the total investment. They include: removal of catalyst residues, removal of atactic polymer, and extrusion in order to reduce the solid polymer to commercial pellet-form. These huge investments can be totally omitted if the catalyst has the proper characteristics. It is not astonishing then that catalyst improvements have aimed at eliminating those downstream processes.

This search has resulted in a number of catalyst "generations". Since the start of polypropylene catalysis in the early 1950's four significant breakthroughs in catalyst development can be discerned together with numerous incremental improvements in catalyst performance (Kirk-Othmar, 1983; Encyclopedia of Polymer Science and Engineering, 1988). The present superactive third-generation catalysts (the most recent breakthrough since the third-generation catalysts) have eliminated the purification, atactic removal, and pelletization steps from the manufacturing process (Encyclopedia of Polymer Science and Engineering, 1988).

Process developments have been going on ever since the initial discoveries by Ziegler and Natta. Today, essentially two process technologies are competing for market share among the 30 or so manufacturers of polypropylene throughout the world: the Spheripol process by Himont
(which was initially formed as a joint venture between the Italian Montedison and the American Hercules, although the latter has by now withdrawn from the venture; Chemical and Engineering News, October 12, 1987 & February, 1, 1988; Encyclopedia of Polymer Science and Engineering, 1988) and the Unipol process by Union Carbide which uses a catalyst developed by Shell (European Chemical News, December 16, 1985; Burdett, 1986; Encyclopedia of Polymer Science and Engineering, 1988). These are of course not the only players in an extremely competitive environment. However, their processes are with no doubt the most important ones today. Other important knowledge producers on polypropylene technology are the German firm BASF, and the Japanese firms Mitsui Petrochemical Industries, Mitsubishi Chemical Industries and Mitsubishi Petrochemical Industries. The present Himont success, for example, has been preceded by a joint catalyst development between Montedison and Mitsui Petrochemical (from 1975 onwards).

**Epdm rubber technology, further developments**

From a technological point of view, epdm technology has evolved less dramatically than polypropylene technology. No significant breakthroughs have occurred and in the past 15 years no radically new processes have been developed (Encyclopedia of Polymer Science and Engineering, 1988). In 1987, there were 13 producers of ethylene-propylene elastomers in the world, excluding Central Planned Economy countries. This added up to a total nameplate capacity of 1,347 million pounds per year. (this can be compared with the 1985 polypropylene demand of 17,380 million pounds). Thus, epdm is much smaller than polypropylene as far as volume production is concerned, but it is the rubber with the fastest growth rate, which equals 6% annually (Chemical and Engineering News, August 1989). Notwithstanding their being the fastest growing segment among the synthetic rubbers, ethylene-propylene rubbers are not the most important form of synthetic rubber. Styrene-butadiene (the old Buna-S) and polybutadiene rubbers hit far bigger volumes.
At the outset, researchers and industrialists thought epdm rubber would find ideal applications in tires. However, this did not work out as expected and has led to a vast number of rather fragmented applications nowadays, for example: automotive applications such as radiator hoses and window seals, wire and cable insulation, footwear, coated fabrics and sheeting, belting and rug underlays. Epdm rubber is formed through the copolymerization of ethylene and propylene together with a third monomer, usually a diene. The catalysis uses organo-metallic catalysts of the Ziegler-Natta type. The result of this process, however, is a random and amorphous polymer and not a stereoregular polymer as in the case of polypropylene. Two basic processes are used for making ethylene-propylene elastomers - solution and suspension. The solution process, which was the first one used to produce commercial material, is the most predominant. Recent developments aim at increasing catalyst performance. This is at least partly a consequence of the progress which has been made with Ziegler-Natta catalysts for the polymerization of propylene. Major epdm producers are: in the USA - Du Pont, Exxon, Goodrich and Uniroyal; in Europe - Bunawerke Hüls (a joint venture of Hüls, Hoechst and Bayer), DSM, International Synthetic Rubber and Montedison; in Asia - Japan EP Rubber (which was established as a joint venture between Japan Synthetic Rubber and Mitsubishi Petrochemical), Mitsui Petrochemical and Sumitomo Chemical.

A model for technological development

Our previous research into the development of new technologies, e.g. the emergence of neural network technology, has convinced us that the nucleus of this process is to a large extent the work of a dedicated R&D community which creates a momentum for the further development of the new technology. This community is formed and nurtured not by administrative decree, but by the autonomous actions of individual researchers who become intrigued by an idea and are committed to solving the problems necessary to make that idea work. In a sense, it is a self-organizing process. Out of the chaos of the actions of hundreds, sometimes even thousands, of individual scientists and engineers an ultimate order may arise. This idea of self-organization has found
numerous applications in several branches of science, and even in the science of science (Prigogine and Stengers, 1984). It is our contention that the same principle can be applied to the emergence of a new technology. This self-organization implies at the same time a subtle form of collective action. Researchers all over the world are cooperating on the same problem set, but at the same time they are competing for a scarce amount of rewards that will accrue to those who arrive at new knowledge and its application first. But even though researchers compete for a limited pool of rewards, they may see themselves as members of a larger community from which they can draw on, and contribute to, in a variety of ways. Mutatis mutandis, the model of scientific evolution depicted by Hull characterizes technology as well:

"Science is a matter of competitive cooperation, and both characteristics are important. The most important sort of cooperation that occurs in science is the use of the results of other scientists' research. This use is the most important sort of credit that one scientist can give another. Scientists want their work to be acknowledged as original, but for that it must be acknowledged. Their views must be accepted. For such acceptance, they need the support of other scientists. One way to gain this support is to show that one's own work rests solidly on preceding research. The desire for credit (i.e. competition) and the need for support (i.e. cooperation) frequently come into conflict. One cannot gain support from a particular work unless one cites it, and this citation automatically confers worth on the work cited and detracts from one's own originality." (Hull, 1988) (italics added)

We propose that technological paradigms (Dosi, 1984) are selected and gain momentum as a result of a similar interaction between cooperation and competition. The locus of paradigm selection is the R&D community. Scientists and engineers seek credit through the development of technological knowledge and artefacts themselves and they give credit through the incorporation of technological knowledge and artefacts developed by other community members into their own work. To use Kuhn's terminology (1970), the members of the community attempt to create a shared "exemplar" as outcome of their selection process. The discovery of organo-metallic catalysts useful for low-temperature polymerization is a clear example of such a creation. The new class of catalysts has been the onset of a new branch of chemistry, Ziegler-Natta chemistry or
stereochemistry. It has spawned research activity all over the world aimed at a better understanding of those particular catalysts and, at the same time, it has aroused enormous industrial interest. However, even if the chemical world showed an immediate interest once Ziegler and Natta had made their discoveries, it took some time before researchers started to appreciate what they were doing. Ziegler's career offers a clear example of the dedication of an individual to a particular research cause and the initial lack of appreciation of that cause by other researchers in the chemicals field. A subtle mixture of competition, cooperation and controversy emerges.

When Ziegler first came to the Max Planck Institute for Coal Research he made it clear that "he would not accept any outside control in either choice or pursuit of research goals" (McMillan, 1979). Ziegler had never done anything with coal in his life at the moment the director's office was offered to him, and he was clear that he did not want to have anything to do with coal for the rest of his life either. The representatives of the Max Planck Institute gave him carte blanche to "play around" with his organo-metallic compounds. Ziegler took an active stance in patenting, publishing and promoting his research results internationally. However,

"As so often happens when one scientist is asked to evaluate another's work, Ziegler's hearers generally missed the main point because they could see the practical difficulties so clearly. At one leading US industrial laboratory, for example, the director solicited the opinions of those who had heard Ziegler's lecture, asking whether there was anything worth following up in what they had heard. The uniform response was that the process made such a mixture of products that there would be a serious problem of product separation and a low yield of any specific desired chain length. This disadvantage impressed most people much more than the intriguing linearity of the products. Even some of the eminent representatives of the German chemical industry did not escape the occupational hazard of the industrial scientist: looking upon his academic colleague as an intellectual dilettante whose ideas and work are of dubious practical import. Bayer, one of the big German chemical companies, never took a license from Ziegler, although they had an early opportunity. Part of the reason may have been the attitude exemplified by Bayer's research director, Dr. Otto Bayer. He was among a number of leading German chemists present at a dinner which Ziegler attended and at which he was asked about the importance of the new chemistry coming out of the Max Planck Institute. Ziegler, with characteristic dignified assurance, said he was sure that it would stand as an important contribution and would be known in the future as 'Mülheimer Chemie'. Bayer, polishing his reputation for sarcastic wit, remarked that this would be an unfortunate choice of a name for an internationally famous process. The problem would be that all Frenchmen would be sure to mispronounce it as
'Müll-eimer' (initial 'h' being silent in French). In German, Mülleimer means garbage can." (McMillan, 1979)

Similar disinterest in Ziegler's favorite research was demonstrated by the sponsors of the Max Planck Institute for Coal Research. Upon his request, they guaranteed him not only autonomy in directing research and freedom of publication, but also the rights to any useful inventions that fell outside the field of interest of the sponsoring coal companies. McMillan adds: "His sponsors would have had no cause to regret the first of these provisions had it not been for the last. They obviously could not foresee the rivers of money that would arise as a result of Ziegler's work and flow to him as a result of this contract." (McMillan, 1979).

Of course, not everyone showed the same lack of interest in Ziegler's research program. The parallel efforts pursued by Du Pont researchers are a proof of this interest. Also, the polymer pioneer and authority Herman Mark played the role of a "prophet" and "publicist" as he was disseminating Ziegler's research throughout the community of polymer researchers. The earlier years of Ziegler catalysts were then clearly marked by a subtle mixture of cooperation and competition, and even by some sparks of controversy. Hull (1988) considers this mixture of cooperation and competition which often goes along with overt or silent conflict, as necessary to scientific progress. The same argument undoubtedly holds for technological progress.

Our research interest in this paper, however, focuses on how the R&D communities in two particular instances of Ziegler-Natta chemistry, polypropylene and epdm rubber, have evolved since these epochal discoveries in the early fifties. As mentioned previously, the chemical industry was very excited and almost immediately internalized Ziegler-Natta chemistry. This industry was at that time, perhaps more than any other industry, heavily research oriented. And, of course, it still is today. Meyer-Thurow (1982), describing the evolution of the R&D activities of the German firm Bayer, speaks of the industrialization of invention. Hounshell and Smith (1988) demonstrate the
important role of corporate research at the Du Pont company, though at the same time they give numerous descriptions of the tensions which arise between the researcher's desire for autonomy on the one hand, and corporate goals and objectives on the other hand. The conflict is between a self-organizing technology development and a corporation-driven one. Scholars have argued that technology is local, contrary to science which is universal (Allen, 1977). However, indications exist that openness, even in technology development, may be beneficial:

"It is also unrealistic to see the transistor as the product of three men, or of one laboratory, or of Physics, or even of the forties. Rather its invention required the contributions of hundreds of scientists, working in many different places, in many different fields over many years." (Braun and Macdonald, 1978)

Similar considerations have been made for the chemical technology:

"A powerful impulse to the growth of the world market also came from the decision of the United States court in 1952 to compel ICI to license several other US chemical firms, in addition to Du Pont, the original licensees. Although bitterly contested at the time, on the grounds that the court had no jurisdiction over ICI, the decision may well have been a blessing in disguise even for ICI, in that it almost certainly led to a more rapid growth of new applications." (Freeman, 1982)

We agree that technological development is a complex process. In our model, however, we want to focus on the functioning of R&D communities in relation to technological progress. We assume that technology is, in essence, a body of knowledge. With this assumption we follow Arrow (1962), Layton (1974), and Constant (1980). Even though the ultimate goal may be to produce something, the currency of R&D communities is not so much actual things as it is the ideas, or theories, about how and why things work the way they do. Therefore, technological development can be understood as an intellectual process that evolves over time, whereby new knowledge is created and applied in order to construct a new product or process. The central actors in this process are the individual researchers who become dedicated to solving the problems, and it is they who set the process in motion with their efforts to create and apply knowledge. In the course of their work, those researchers perform three basic activities: (1) they produce information,
(2) they transform information into knowledge, or in other words, they solve problems. and (3) they communicate information and knowledge to each other. The central proposition of our model is then that the rate of progress in a technology's development is a function of how quickly problems are solved, which, in turn, depends on the amount of information produced, the number of diverse solutions attempted, and the extent to which information and knowledge is communicated among researchers. We expect that the more information available to a researcher, the more likely he is to arrive at a useful solution. Moreover, we anticipate that the more diversity in the types of solutions attempted, the more likely that critical solutions will be found. Lastly, we hypothesize that communication between researchers enhances the probability of finding useful solutions.

The amount of information and knowledge available to a researcher depends upon how much he can produce himself, or receive in the process of communicating with others. The communication of information and knowledge implies that a researcher can also gather information and knowledge produced by another researcher, and disseminate to others that which he produces or learns. For the most part information is communicated informally by means of interpersonal conversations, whereas knowledge is communicated in the form of documented claims, such as with the submission of papers to refereed journals or patent applications.

This process of communication of information among researchers is influenced by the existence of organizational boundaries between researchers and their (and their organization's) economic interests. Organizational boundaries are important for two reasons: first, they give rise to information asymmetries among researchers because they impede the flow of information and increase the cost of information gathering. As a result, organizational boundaries can slow the rate of production of knowledge within a community by reducing the amount of information available to each researcher. However, organizational boundaries can also enhance knowledge production to
the extent it increases the diversity of problem solutions pursued by the community as a whole, since researchers in different organizations are likely to have different information sets. This phenomenon is illustrated by the excerpts from the Braun and Macdonald (1978) and Freeman (1982) studies above. The communication impedance effect of organizational boundaries is overcome via researchers who act as technological gatekeepers -- that is, researchers who tend to communicate with others in different organizations (Allen, 1977).

Moreover, it is reasonable to assume that researchers are rational, in the economic sense that they are motivated by self-interest: that is, they are eager to solve problems because there are rewards for those who do. The researcher's objective is to maximize the amount of knowledge he produces and can lay claim to before other researchers, because these claims have potential value. A researcher need not produce all of the knowledge required to commercialize a technology, as long as his own knowledge claims are secured. Given this economically rational behavior on behalf of researchers, the communication of information across organizational boundaries likely occurs as a form of quid pro quo (von Hippel, 1988).

In summary, we argue that the speed at which a technology develops will depend on how rapidly a community forms and grows, and the structural and behavioral characteristics the community adopts as it matures. Some characteristics promote cooperation between researchers, while others foster competition. In combination, both elements are important contributors to the swift conduct of the problem-solving process: the competition that breeds with the growth and diffusion of the community, escalating the amount of information produced and increasing the diversity of solutions pursued; and the cooperation which flows from a community information grapevine, enabling researchers to exchange notes on the latest experiments and to pursue solutions without squandering their precious time on lost causes.
The general model proposed in the previous paragraphs is now further elaborated through a comparative study of the growth of the polypropylene and epdm rubber R&D communities. As we clearly described, those technologies have developed, since the 1950's, within a research-intensive, industrial context. The juxtaposition of the two technologies allows for a comparison of the structure and conduct within two R&D communities that have generated differential technological progress, although from a commercial point of view, the two can be considered successful.

**Methodology**

The data presented in this paper were obtained by studying the extensive body of scientific, technical and patent literature generated by the polypropylene and epdm researchers themselves in the course of their work. Since communication among its members is a defined characteristic of an R&D community, studying the documented, or formal, communication among researchers is a convenient means for gaining insight into the functioning of a community. This literature provides us with a richness of background information about the technology itself, and subsequently about the structure and behavior within an R&D community.

In order to systematize the study of the polypropylene and epdm communities, two electronic relational databases were analyzed. The polypropylene database contained 1383 abstracts of journal articles, conference proceedings and patents since 1955. The epdm database contained 613 comparable abstracts. As explained previously, our literature search was specifically oriented towards polypropylene and epdm rubber manufacturing technologies, and not towards specific applications of polypropylene or epdm rubber. The present analysis does not focus on the well-established bibliometric methods for analyzing citation frequency and co-citation clusters (for example, see Hjerpe, 1978; Narin, Noma and Perry, 1987). Instead, the retrieved abstracts are used in a different manner: namely for the detailed information contained within each document.
Indeed, each abstract provides a wealth of reliable, unobtrusive information about research activities within the community. The first advantage is its longitudinal character. By studying an R&D community over time, it becomes possible to show the dynamic patterns which emerge. The second advantage lays in the information obtained from the abstracts. Each abstract tells us who the researchers are and how their numbers vary from year-to-year. The abstracts also show what topics the researchers are working on and which organizations employ them. They also reveal the ties which develop over time among the different researchers and organizations by looking at the co-authorship of the papers or patents and by showing the mobility of researchers between different organizations. By examining this information during a three-decade time-span, one is able to visualize the structural changes in the R&D community, and also, to draw inferences about the behavior of the researchers dedicated to the particular technology. Comparing the patterns for the rapidly progressing technology (polypropylene) with those obtained for the more stagnant technology (epdm rubber) allows us to make certain propositions about the influence of structure and conduct within a community upon the rate of technological progress.

Notwithstanding its apparent reliability and unobtrusiveness, the journal and patent literature does have certain non-trivial limitations. First, there are some technical limitations which may be cumbersome, though they can be overcome. Patent databases have the unappealing characteristic that not all patents contain inventor names. This is mainly a problem with Japanese patents and with older patents. We were able to resolve this problem through the combination of several databases: Derwent, Dialog and Inpadoc. This, however, can be a cumbersome process.

Second, patents which have been applied for, though never got issued, do not appear in electronic databases. However, as we are only interested in detecting active members of R&D communities, we do not experience this to be a serious problem. What matters for us is our ability
to capture major trends in the structure and conduct of R&D communities. It is therefore not necessary to identify every possible participant.

A third, and often heard, objection to the use of the journal or patent literature states that the sheer quantity of articles or patents does not necessarily tell you which organizations are most active in a certain area (Lambert, 1989). However, as we count inventors and not numbers of articles or patents, this objection does not hold for the methodology claimed here.

A fourth, and somewhat similar problem may occur with respect to inventor and author names (Rappa, 1989). Although database services try to standardize author and inventor names, this is not always the case. Thus, the researcher himself has to make sure that names are standardized. This may be a tedious job, though given our use of the literature data, it is a vital one.

Fifth, as far as patents are concerned, there are intercountry differences in the speed of issuing patents and in the time lag between the filing of the patent and its publication (although 18 months is a rather common delay period for most countries). The strategy we used to alleviate this problem consisted in taking the priority date as a time indicator, instead of the issue date. The priority date is thus considered indicative of the year in which the researchers identified on the patent were active in the field. Given publication and patent issue lags, our methodology also makes it impossible to obtain full information on what happened during the last two years. Once past 1986, the data do not tell us much. However, we assume that this is a common problem facing everyone who uses the patent literature as a source of data.

The notion of R&D community implies a blending of science and technology, of academic and industrial pursuits, and furthermore, suggests a situation where papers and patents are essentially two different mechanisms for staking intellectual claims. This unification of science and technology
is an increasing popular theme in scholarly literature (Latour, 1987). The existence of a body of literature in technology development is right at the heart of the concept of an R&D community. A community implies a degree openness, which finds an outlet in the documented literature. Our data on previous technologies show that researchers do indeed publish, regardless of whether they reside in an academic or in an industrial setting. Moreover, the same data show that the industrial laboratory is certainly not the only locus of technology development. Universities and government laboratories play prominent roles as well. Despite the argument of technology being local, industry scientists and engineers do indeed publish, whether their company encourages them to do so or not. This behavior has many advantages. Companies in rapidly moving fields often do research in order to stay up with them and to have the capability to exploit developments in a timely manner. Therefore they have to join in the relevant community, and this implies a sharing of knowledge (Nelson, 1989). The documented literature is one possible means to achieve this end. Moreover, publishing research results also enhances company reputation and visibility, and it may at the same time be a subtle form of advertising. This last aspect is very well visible in the chemicals under study. The major licensors (such as Montedison-Himont-Mitsui) tend to publish a lot. One of the reasons for this extensive amount publication (in refereed journals!) surely is to praise the versatility and quality of their technological prowess. If company researchers actively participate in the community, and perhaps receive some prestigious rewards such as Nobel Prizes, then their firm also benefits from the image thus created.

Although this publication behavior underpins our methodological approach to use the literature as a source of data to explore the characteristics of R&D communities, it also points to another limitation of the methodology. The formal communication, documented in journal and patent literature, may be just the top of the information-sharing iceberg. Formal communication is without doubt relatively limited compared to the amount of informal communication that likely occurs among researchers at conferences and via telephone and computer networks. Partly, as a
consequence, individuals participating in the community may not become visible in the documented literature. Furthermore, there may also be activity in developing the technology that is purposely hidden from public view by those who see it in their best interest to keep secret. It is our firm belief, however, that this last type of behavior is not necessarily confined to industry. We are convinced (although it is still a hypothesis at the moment) that academic scientists and engineers may also have personal incentives not to reveal all the information they possess.

Nevertheless, given these limitations, the literature can prove to be remarkably useful in obtaining an initial understanding of the structural and behavioral dynamics of R&D communities. The analysis presented here seeks to limit the obvious deficiencies of using the documented literature by minimizing the sensitivity to publication frequency, by not attempting to ascribe more or less importance to a particular publication or patent, and by analyzing the data historically. Thus, for example, we are not seeking to understand absolute magnitudes so much as the dynamic trends over time, and we are not seeking to uncover technical secrets so much as obtaining a basic understanding of the people involved, the nature of their work, who they worked with, where they worked, and when they worked. Taken together, the data obtained from the literature can provide a comprehensive picture of change over time within the communities under investigation.

The polypropylene and epdm communities, a case of differential technology development

Of the 1383 records in the polypropylene database, 555 (40%) are publication abstracts while 828 (60%) are patent abstracts. Of the 613 epdm records, 135 (22%) are publication abstracts while 478 (78%) originate from the patent literature. The fact that the majority of the retrieved abstracts belong to the body of patent literature may be an indication of the degree of internalization of both technologies within an industrial setting. At the very beginning of this paper, we outlined that the two chemical technologies might offer interesting insights into how R&D communities evolve once their mental creations become incorporated within the strategic
framework of a particular industry. In case of newly emerging technologies, such as neural network technology (Rappa and Debackere, 1989), the presence of patents within the body of documented literature is negligible or even non-existent. As the technology develops and becomes internalized within an industrial, competitive environment, the openness and communication through the journal literature may well shift in favor of communication through the patent literature.

Although this may point to an increase in "secrecy" considerations, we believe that it still remains an instrument of holding together the community. Patents are intellectual claims in the same sense as articles are intellectual claims. It is a means of sharing knowledge, though it may not have the same public good character as the journal literature (Sherer, 1980). Moreover, the presence of journal abstracts in our databases shows that (as well in industry as in academia), researchers keep publishing results in the open literature, and at the same time the use of patents is not confined to industry. Academic researchers take out patents as well at an increasing rate. Finally, we must not forget that we are dealing with chemical technologies. The abundant presence of patents may well be specific to the chemicals field (Sherer, 1980). Nelson reaches a similar conclusion:

"While I want to emphasize that patents play a much smaller role in enabling innovators to reap returns under modern capitalism, there are certain industries where patent protection is important, perhaps essential, for innovation incentive. Our questionnaire revealed two groups of industries of this sort. One consists of industries where chemical composition is a central aspect of design: pharmaceuticals, industrial organic chemicals, plastic materials, synthetic fibers, glass. The other consists of industries producing products that one might call devices: air and gas compressors, scientific instruments, power-driven hand-tools, etc. In both cases, the composition of the products is relatively easy to define and limit." (Nelson, 1989)

Thus, the important share of patents in our databases has at least two different reasons. First, patents may have become a more appropriate way of sharing knowledge, given the internalization of the technology within a corporate context. Second, chemicals in and of themselves may be more
conducive to the use of patents. Anyway, we can safely assume that patents are just one possible means of sharing knowledge. For our purposes, it certainly makes no difference whether we use patents or journal abstracts as a means to identify the respective R&D communities.

The differential growth of polypropylene and epdm communities

An analysis of both databases was conducted to determine the number of individual researchers worldwide, who were active each year in the research and development of the technology. If an individual is an author (or co-author) of a journal paper, conference presentation or patent on the subject of polypropylene or epdm technology in a given year, he is included as a member of the community; and he continues to be included as a member so long as he continues to be an author from year-to-year. In this way, membership in the community is not sensitive to the number of publications or patents by an author in a given year. The growth profile of both communities is shown in figure 1. The data cover the time span from 1956 till 1986. They thus cover the development of both technologies, once the basic paradigm (Ziegler-Natta organo-metallic catalysis) was firmly established. Moreover, as remarked previously, the lack of patent data due to publication lags make it impossible to stretch the analysis beyond 1986.

The growth profile of both communities is pretty much the same at the beginning, though the polypropylene community expanded a lot faster than the epdm community. The epdm community, after an initial increase, remained rather stagnant until the beginning of the 1980's. The polypropylene community manifests a continuous growth throughout its history. This is also the technology which has experienced the most significant breakthroughs.
However, contrary to what we have seen in newly emerging technologies such as neural networks (Rappa and Debackere, 1989), the growth is rather steady, with no real manifestation of a *bandwagon effect*. A closer examination of the polypropylene literature (Kirk-Othmar, 1983), for instance, reveals two important catalyst developments that have started in the 1960's: the use of electron donors and the use of a magnesium support for the titanium chloride catalyst. However, they became only included in the polypropylene manufacturing processes in the late 1970's, i.e. with the development of the third-generation catalysts and its subsequent superactive catalysts (Encyclopedia of Polymer Science and Engineering, 1988). We could find an article on electron donors as early as 1965, while a first development on the use of catalyst support systems could be detected in 1961 at Shell. At that time, none of the discoveries impressed the producers of
polypropylene. On average, a time lag of 10 years occurred before the initial catalyst developments were vigorously incorporated into industrial programs. However, each development, accompanied by a multitude of small incremental improvements, may have aroused interest in polypropylene catalyst research and may thus have caused other researchers to start working on the subject. The advent of the superactive third-generation catalysts in the second half of the 1970's has caused a similar increase in interest. Thus, certain developments in the state of technological knowledge may act as a trigger for researchers to enter the community. These considerations bring us to two central questions on our research agenda.

The first crucial question, often raised by policy makers when looking at similar data, is one of causality: Does technological progress occur as a consequence of an increased manpower effort on behalf of the community who ultimately produces the advances, or is the increase in the number of researchers a consequence of technological advances which by and of themselves generate a brighter outlook for the technology under scrutiny? We believe the reality is a mixture of the two. Our data suggest that triggers are necessary to arise at least some interest. The discoveries by Ziegler and Natta were one such a trigger. The suggestion that electron donors or magnesium support might prove valuable can be considered another trigger. However, the most these triggers usually offer is a box of Pandora full of "problems still to be solved". At that moment, we believe an increase in manpower within the community really becomes a necessity and a determinant of the subsequent rate of technological progress. The issue is then reduced to the issue of whether the problems in Pandora's box can catch the imagination and elicit the interest of individual researchers. If it can, the future of the technology will look much brighter.

The contrast between polypropylene and epdm seems enlightening in this context. Polypropylene technology and catalysis have clearly been able to lure researchers into their lines of inquiry. Breakthroughs and incremental improvements have accumulated ever since. Epdm started with the same initial conditions. The take-off was similar, though at some point, challenges did not
seem appealing anymore and interest in the technology stagnated. This remained largely so throughout the 1960's and 1970's. "Stagnant technology" was the connotation subsequently reserved for epdm. However, recently, a cross-fertilization between both polypropylene and epdm communities seems to occur. The progress in polypropylene technology, mainly in the domain of catalysts, now provides an impetus to take up on epdm catalysts more vigorously research. The polypropylene developments have somehow created the belief that, since epdm uses an analogous type of organo-metallic catalysts, the example of polypropylene can be repeated in epdm. The coming years will show whether the increase in size of the epdm community will persist and will be able to fulfill the expectations. If not, we may expect once again a decline of the size of that community and a host of researchers switching to other (research) pastures.

The second important question revolves around the degree to which the evaluation of the content of Pandora's box and the subsequent decision on whether this content is interesting enough to enter the field of, for example catalyst research, is an autonomous decision of individual researchers or to what degree it is management driven. Our previous studies on newly emerging technologies hint in the direction of a quasi-complete autonomy on behalf of the individual researchers. In instances as neural network technology, the community then becomes the primary locus of technological progress (Rappa and Debackere, 1989). The direction the technology takes and the problems which are considered worthwhile are both heavily influenced by consensus and controversies that reign within the broader R&D community. Our data for the two chemical technologies suggest a slightly, though not completely, different pattern once the technology becomes internalized within an industrial environment such as the chemical industry. The internalization of both technologies within an industrial setting, and the fact that the initial development of significant catalyst improvements all occurred within industrial laboratories (such as Shell, Montedison, Mitsui) limit to a certain degree the freedom of individual researchers to enter the field. Since catalyst research is extremely expensive (new catalyst development requires
the availability of a pilot plant), the interests of the individual researchers are to some extent dependent upon the investment decisions of the large chemical corporations that form the primary locus for catalyst research.

However, even if the industrial world can control the entry rate of researchers into polypropylene research, a certain level of autonomy remains. First of all, our data show that we have been able to identify a group of researchers who share knowledge (through the documented literature) about their research efforts. In the methodological part of our paper, we discussed the importance of this knowledge sharing as a primary indicator of community existence. Second, even if large corporations are taking decisions on entering or quitting a certain line of catalyst research, they cannot do this without the input from individual researchers. Their opinion, however, will not be solely in terms of corporate objectives. They are researchers, having a stake at the community level themselves. Thus, part of their decision will almost certainly be based on what they perceive the wider community is judging a worthwhile research avenue. Third, when looking at the data in figures 2 and 3, we see that the industrial world only represents part of the community.

The other part consists of public sector organizations. This group is a mixture of university and government laboratories. Here corporate objectives are non-existent. The researchers at academic laboratories normally have great autonomy in deciding on the lines of research they want to pursue. We then see that polypropylene has been able to arouse a lot of interest within non-industrial settings. Certain triggers have been able to lure academic researchers into the field. This has, for instance, been the case with the emergence of superactive third-generation polypropylene catalysts in the late 1970's. This presence of academic researchers has led to subsequent developments in polypropylene catalyst research. A good example is Kaminsky's (University of Hamburg) present experimentation with aloxanes. The picture offered in figure 3 (epdm) is
remarkably different. Here, public sector interest has generally been low. The research community was able to improve on the technology, but compared to polypropylene these improvements resemble more a status-quo. Public sector researchers obviously did not use their autonomy to opt for this line of research.

![Figure 2: Sectoral distribution of polypropylene researcher community, 1961-1986](image)

To conclude, we can say that even in case of the technologies examined in this paper (and that are closely tied to corporate interests), we are able to identify a worldwide group of people who at least have the potential to influence the direction technological development takes. Moreover, there certainly exists a correletion between the progress of technological development and the growth of the community. This is exemplified by the comparison of polypropylene and epdm developments. It is, however, impossible and presumably wrong to suggest that there is a definite causality running in a particular direction. Rather, we suggest that triggers must exist, in
the form of developments which offer enough challenging problems for researchers to take the decision to enter a certain line of inquiry. The greater the number of researchers (and organizations) that can be attracted to a particular research agenda, the greater the likelihood that problems will be solved more quickly or that a consensus will be reached that the problems cannot be solved at the moment.

Figure 3: Sectoral distribution of epdm researcher community, 1961-1986

Cycles of enthusiasm and despair

The growth of the polypropylene research community is rather steady, progressing from its onset till the 1980's (figure 1). Since the community was able to sustain the momentum of technological progress, there existed no real reasons for researchers to get despairsed about the future prospects of the technology. Things look different, however, as far as epdm technology is
concerned. Obviously, researchers have not been able to create the momentum which was present in polypropylene technology. At the very beginning, the advent of Ziegler-Natta catalysts promised a bright future for epdm technology as well. However, when the first problems arised (such as epdm being not suited for tire applications), enthusiasm decreased. The stagnant technology has since then been sustained by a community of researchers whose size has gone through subsequent ups and downs. At present, the enthusiasm generated by a possible cross-fertilization between polypropylene and epdm catalysis seems to have spurred a new cycle of enthusiasm.

Figure 1 also illustrates the existence of core groups in both technologies. Specifically, the core group is defined to include researchers who were actively participating in the community in at least three years of a given five-year period. Notice that the core group is relatively small (on average, between 5 to 30 percent of the total community) and fairly stable in size over the entire period, as should be expected. They are the researchers who keep faith regardless of the obstacles that lie ahead, the true believers in the technology even when others move on to other research pastures or (within a corporate context) when their colleagues evolve towards a managerial career.

The fluidity of researchers into and out of the community is shown in greater detail in figures 4 and 5. The databases were partitioned into three-year periods in order to examine the extent of participation from period to period. In each period, researchers were classified as new entrants (those not active in the previous period), sustainers (those also active in the previous period) and exits (those who were active in the last period but not in the present one). The degree of turnover from period to period is quite remarkable, with many researchers joining and others exiting each period.
Figure 4: The flow of polypropylene researchers into and out of the community
Figure 5: The flow of epdm researchers into and out of the community

The entry and exit patterns detected for both technologies are not remarkably different. Moreover, they are not really different when compared with the patterns found in newly emerging communities. In case of a newly emerging community (such as the neural network community), one could ascribe this remarkable fluidity to the freedom and autonomy of researchers to commit to a cause and to withdraw their commitment when that cause seems to lose its attractiveness. In case of the chemical technologies, we had expected a more stable pattern. One could, for instance, expect a greater commitment once research programs are carefully budgetted and managed by a professional corporate bureaucracy. This does not work out for our data. Several explanations are plausible, the first one being that even within a corporate bureaucracy researchers remain pretty autonomous as to what line of inquiry to settle on. Other explanations may be the short duration of industrial R&D projects and the subsequent assignment of researchers to slightly different research topics, and industrial career ladders which quickly divert researchers from benchwork to more
management-oriented work. However, fluidity seems to be a key characteristic of R&D communities. Researchers working on the development of a particular technology are seldomly highly committed to a particular topic. Rather, their background education offers them a range of areas amongst which they can switch without much apparent danger of being unable to catch on. Only a few become so committed to a particular cause that they flourish or perish together with that cause.

*Diffusion and participation in the grapevine*

As described in the introductory section, R&D communities can extend beyond industrial boundaries, such that technological development is not wholly the domain of firms. As shown in figures 2 and 3, R&D communities can consist of researchers employed by a variety of organizations, cutting across industrial and public sectors. The fact that both polypropylene and epdm technologies are commercial technologies, with huge investments at stake, does not prevent universities from participating in the community. Despite the fact that technology, once it enters the realm of commercial development, is believed to be local and confined to corporate boundaries, it becomes unified with science in the context of the R&D community.

Both communities are also international in scope (figures 6 and 7). The geographic distribution of researchers around the world, as obtained from our database analyses, also shows shifts in the centers of gravity of the development of a technology. In the last decade, Japan has certainly become a dominant force, both in polypropylene research and in epdm research. Europe also plays a dominant role in polypropylene, though its role in epdm research is subject to considerable variation. The longitudinal display of geographic distributions of R&D communities may further offer a valuable tool for policy makers when they try to assess and to monitor technological development within a geographic area.

Another important characteristic of R&D communities is believed to be their diffusion across
organizations, whether they be of a private or public character. This diffusion across organizations is yet another determinant of the ultimate rate of technical progress achieved.

Figure 6: Geographic distribution of the polypropylene researcher community, 1956-1986
To illustrate this point, assume the extreme conditions. In the first case, as the research community grows, all researchers are employed by the same organization. Thus, all researchers are exposed to the same information set, but the diversity of solutions attempted is limited by the researcher's mutual influence. In the second case, as the community grows, each researcher is employed in a separate organization. Thus, each researcher is working from a different, limited set of information and attempting independent solutions, such that the diversity of attempted solutions is maximized. Simply stated, in one situation, each researcher in the community has a wealth of information but a limited number of approaches in solving the problems being confronted; in the other situation, although the community can generate the same amount of information, the amount available to any particular researcher is small and the variety of approaches taken is great. We hypothesize that this second situation is more conducive to technical progress than the first one. The
differential progress of polypropylene technology and epdm technology seems to corroborate our views.

![Figure 8: Public sector concentration of polypropylene and epdm communities, 1961-1986](image)

One way of viewing the extent of the community's diffusion is with a concentration ratio, similar to that used by economists, which measures the percentage of researchers employed in a set number of organizations with the largest research groups. The polypropylene community quite consistently diffused both among public and private sector organizations. At present, less than 50% of all polypropylene researchers are employed by either the five largest public or the five largest private organizations. This enhances the number of attempted solutions to problems-yet-to-be-solved. The epdm community shows a less consistent diffusion pattern, although by now, the industrial sector concentration ratio is also falling below 50%. During the time periods considered in our study, the number of organizations involved in polypropylene research increased from less
than 5 during the first years of the technology to about 50 in 1986. Till 1966, industrial organizations clearly formed the majority of the polypropylene research establishments. Since then things changed with about half of the research organizations belonging to either sector. The situation for epdm is rather different. The total number of organizations involved in epdm research increased from less than 5 in the early years to about 25 in 1986. Here, industrial organizations constantly made up the vast majority of the epdm research establishments. On the average, the number of public sector research institutions identified from year-to-year in our epdm database varies between 3 and 5. As explained in a previous paragraph, epdm research was unable to elicit the same amount of interest among public sector researchers, contrary to its polypropylene counterpart.

Figure 9: Industry concentration of polypropylene and epdm communities, 1956-1986
This last remark also enables us to speculate on the influence of government sponsoring for technological development. It is not obvious from the data we gathered that polypropylene research has benefited from any kind of government program to sponsor its development. Notwithstanding this, academic researchers developed a genuine interest in the development and examination of polypropylene catalysts. On the other hand, the development of synthetic rubber has been an issue of national security in a few countries at least (e.g., the USA and Germany; Whitby et al., 1954; McMillan, 1979). Notwithstanding massive government interest in the search for improved synthetic rubbers in the first decades after World War II, mostly in the USA, only a limited number of public sector organizations have participated in the development of epdm rubber (which, we must remember, is of course only one type of synthetic rubber on the market place). Although the contexts are totally different, this remark would point in the direction of what we found in our neural network research, namely that public funding is neither a necessary nor a sufficient condition for researchers to start work in a certain area of technology. Similar findings have been reported for the influence of public funding on certain branches of science (Cohn, 1986).

It is, furthermore, a common characteristic of both technologies that the industrial organizations that show up in the community are all very large, long-established chemical firms. We certainly lack the presence of new-ventures and new technology-based firms which was so obvious in neural network technology.

A central premise of our R&D community definition is the existence of a communication network which holds the community together. One formal means of communication, which will be discussed at greater length below, is through the published literature. However, this is a very rudimentary communication mechanism with severe limitations given the constant flow of new, complex information abounding from laboratories. Instead, another mechanism is needed: the grapevine.
The grapevine is an informal, but remarkably efficient network of researchers who facilitate the flow of information among different laboratories. Chances are that researchers are well acquainted with each other, perhaps having previously worked or studied together, or having become friends at a conference. Moreover, the core researchers discussed above are likely central nodes in the grapevine. In case of both chemical technologies, we were able to visualize the grapevines which came into existence over the 3 decades under study. The networks, as illustrated in figures 10 to 15, were analyzed by examining the databases for instances where researchers in two different organizations were co-authors, or where a particular researcher (permanently or temporarily) changed his laboratory affiliation over the thirty-year period. The obvious assumption here is that researchers who collaborate with each other on a paper are also likely to talk with one another even though they are not (or no longer) working in the same laboratory. In any case, this is possibly one of the most stringent criteria one can use to define a link between two organizations, such that the true grapevine is likely to be more elaborate.

The network for epdm is at first sight much less elaborate than the one for polypropylene. However, when one compares the ratios of the number of organizations that are interconnected for each technology, the picture changes (table 1).

<table>
<thead>
<tr>
<th>period</th>
<th>polypropylene</th>
<th>epdm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955-69</td>
<td>13% (11.5%)</td>
<td>11.4% (5.9%)</td>
</tr>
<tr>
<td>1955-79</td>
<td>18.3% (18.1%)</td>
<td>29.3% (17.4%)</td>
</tr>
<tr>
<td>1955-88</td>
<td>20.4% (20.1%)</td>
<td>29.1% (18.5%)</td>
</tr>
</tbody>
</table>

Table 1: Percentage of organizations interconnected in the grapevine for both polypropylene and epdm communities (percentages between brackets are the ratios inclusive central planned economies). Each ratio gives the number of interconnected organizations to the total number of different organizations identified for the time period under study.
These results seem paradoxical, though we must not forget that as the number of organizations involved in a certain research area increases, the chances of two of them becoming interconnected rapidly diminish. Moreover, the simple statement that two organizations are interconnected does not yet magnify the number of links between them. This is done in the network diagrams. Several comments need to be made when interpreting the graphs.

First of all, the database methodology clearly enables us to visualize a communication network among research organizations in both technologies. This corroborates our idea of a community, though as we discussed previously, the degree of autonomy of the individual researchers in forming the network may be not as large as in case of a newly emerging technology.

This brings us to our second comment. Although the network is drawn at the level of interactions among individual researchers, the actual reasons for the links to come into existence are not always based on independent researcher decisions. At the very start of this paper, we mentioned that polypropylene and epdm offered an interesting research site for two reasons: both technologies had experienced different rates of development, but at the same time, they have been internalized within a corporate environment since their very beginning. No doubt, this internalization should have its influence on the community which evolves. The polypropylene network, for instance, corroborates this hypothesis. A number of important links can indeed be attributed to managerial decisions. The links which have emerged between Montedison and Mitsui are the outcome of a decision to avoid patent litigation, since both companies could stake claims of being the first to develop a magnesium support for catalyst systems. In order to avoid court battles, a joint development was pursued. The links evolving around Montedison in Italy stem from the early involvement of Natta with that company. The link with the USSR can be attributed to the fact that Montedison is the largest foreign polypropylene exporter to that country. Thus, although a
network emerges, it seems to be a hybrid combination of researcher actions and managerial actions.

A third remark concerns the absence of certain large companies in the network. Part of this absence stems from the fact that certain companies, like Union Carbide, only recently became important knowledge producers for polypropylene technology. The time lags inherently linked with patent publication prevent us from detecting linkages which may have evolved around those companies in the last two years. Moreover, a number of important knowledge producers do not appear in the network. Our best guess from a study of the documented history of polypropylene research is that a number of big players are particularly secretive, not actively sharing in the community. At the same time, interviews with industry experts suggest that the organizations that at present share most with the community, are those who are most eager to license their proprietary technological know-how.

Fourth, as already outlined, our grapevine is based on the most stringent criterium one can possibly choose to define a communication network. In this sense, it underestimates the level of communication among researchers. Informal communication among gatekeepers, which has been well established in research on technology management (Taylor, 1975; Allen, 1977; Taylor, 1986), is not always obvious from networks as ours. However, it is obvious that the central communicators in our network have a high probability of being gatekeepers for their organizations.

Fifth, if we come back to our comparative study, it is obvious that, despite the previous criticism, the polypropylene network has become the most elaborated of the two. When we first formulated our model of technological development, we pointed to the important role of communication grapevines in providing the cement that holds the community together. The importance of the grapevine lies in its underlying principle of knowledge sharing. The more
openness, the more sharing exists, the higher the likelihood of technological progress: "Finally, there are industry wide efficiency gains to be had by sharing technology. Everyone would be better off if everyone shared." (Nelson, 1989). Of course, we know that one cannot generalize from a comparative study of two technologies, but the difference in knowledge sharing among researchers in both communities at least points in the direction of our hypothesis that information exchange has an influence on the rate of technological progress.
Conclusion

In this paper, we have elaborated on a model for technological development that takes into consideration the broader social environment in which a technology tends to develop. This social environment consists of the R&D community dedicated to the technology. A focus on R&D communities enabled us to highlight some aspects of researcher behavior which may actually be conducive to technological progress, though they are often overlooked when one studies technology development at the level of the individual organization.

The comparison of polypropylene and epdm technology offered a possibility to speculate on characteristics of an R&D community which can stimulate technological progress. Such hypotheses are plausible since, if we assume technology is largely an issue of generating knowledge, the manpower available in the community, the interconnections among researchers of the community and the distribution of researcher efforts across many different institutional settings all affect the rate of knowledge creation, and subsequently, the rate of problem solving. The main benefactor in this process is the technology itself, which sees its rate of progress enhanced. Also, the study of two technologies, which have now been well-internalized within a corporate environment for a few decades, enabled us to unravel some of the dynamic characteristics of R&D communities. The data suggest that, even if a technology becomes incorporated within an industrial environment, R&D communities still have a role to play. The most important change affecting the community certainly is the emergence of corporate (commercial) needs with their accompanying emphasis on less openness. But throughout the process, openness is never completely silenced. Grapevines continue to exist, though they may be subject to a higher degree of managerial involvement and control. The influence of certain community characteristics (such as its size, distribution, and information exchange) on the rate of technological progress also seems to be preserved. To conclude, the researchers have to reconcile some of their autonomy within the
community with an increase in managerial control from their respective organizations. In summary, Kidder's remark at the end of his book "The Soul of a New Machine" gives us a view, although perhaps too extreme, of what happens when business interests take over the community's creations:

"The day after the formal announcement, Data General's famous sales force had been introduced to the computer in New York and elsewhere. At the end of the presentation for the sales personnel in New York, the regional sales manager got up and gave his troops a pep talk. 'What motivates people?' he asked. He answered his own question, saying, 'Ego and the money to buy things that they and their families want.' It was a different game now. Clearly the machine no longer belonged to its makers." (Kidder, 1981).
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Meyer-Thurow, G. (1982) "The Industrialization of Invention: A Case Study from the German Chemical Industry," *ISIS* 73, 286: 363-381


Figure 10. Interorganizational grapevine in EPDM community from 1955-1969 (formed through researcher mobility (plain lines) and co-authorships or collaborations (dashed lines). Arrows point to the direction of mobility or to the collaborator’s home organization, each arrow represents one physical person except when the number of persons is mentioned between brackets. Plain lines without arrows indicate a linkage where it was impossible to determine whether it consisted of researcher mobility or collaborations. Alphabetic characters besides arrows indicate specific individuals who moved between more than two organizations.)
Figure 11. Interorganizational grapevine in EPEC community from 1955-1979 (formed through researcher mobility (plain lines) and co-authorships or collaborations (dashed lines). Arrows point to the direction of mobility or to the collaborator’s home organization. Each arrow represents one physical person except when the number of persons to be mentioned is between brackets. Plain lines without arrows indicate a linkage where it was impossible to determine whether it consisted of researcher mobility or collaborations. Alphabetic characters besides arrows indicate specific individuals who moved between more than two organizations.)
Interorganizational glue view in EGEM community from 1955-1988

(formed through researcher mobility (plain lines) and co-authorships or collaborations (dashed lines), arrows point to the direction of mobility or to the collaborator's home organization, each arrow represents one physical person except when the number of persons is mentioned between brackets. Plain lines without arrows indicate a linkage where it was impossible to determine whether it consisted of researcher mobility or collaborations. Alphabetical characters besides arrows indicate specific individuals who moved between more than two organizations.)
Figure 1. Interorganizational grapevine in polypropylene community from 1955-1967. Arrows point to the direction of mobility or to the collaborator's home organization, each arrow represents one physical person except when the number of persons is mentioned between brackets. Plain lines without arrows indicate a linkage where it was impossible to determine whether it consisted of researcher mobility or collaborations. Alphanumeric characters besides arrows indicate specific individuals who moved between more than two organizations.
Figure 12: Inter-organizational gene flow in polypropylene community from 1955-1975
(formed through researcher mobility (plain lines) and co-authorships or collaborations (dashed lines), arrows point to the direction of mobility or to the collaborator’s home organization, each arrow represents one physical person except when the number of persons is specified between brackets. Plain lines without arrows indicate a borderline where it was impossible to determine whether it consisted of research mobility or collaboration. Alphabetic characters besides arrows indicate specific individuals who moved between more than two organizations.)