AFTER THE BREAKTHROUGH

The emergence of high-temperature superconductivity as a research field

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Introduction: the emergence of a new research field

Discovered in 1911 at temperatures near absolute zero, superconductivity is the loss of resistance to electrical current some materials display when cooled below a "critical temperature". The phenomenon was confined to scientific laboratories until the late 1950s, when first technological applications became feasible. It also took nearly half a century before a theoretical explanation of the phenomena – the BCS[1] theory – was formulated. In the following two decades, numerous researchers contributed to the field, but no materials were found with critical temperatures higher than 23 Kelvin (–250° Celsius). By the mid-1980s, the scientific community had reached the consensus that superconductivity was a closed field, and that the dream of room-temperature superconductors should be abandoned.

But the year 1986 changed this situation dramatically. Two researchers at the International Business Machines (IBM) lab near Zurich, Switzerland, discovered a new class of materials among the ceramic oxides that display superconductivity at temperatures far higher than previously observed.

High-temperature superconductivity was born.

1.1 A surprising discovery and its consequences

Like a minor earthquake, the discovery of high-temperature superconductivity in late 1986 sent a shock wave through the research systems of the industrialized countries, exciting scientists, policy-makers, and the lay public alike. We followed the course of the discovery, intrigued to observe and analyze what the tremor revealed: which structures of the system of science and research

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[1] The theory was developed by Bardeen, Cooper & Schrieffer.

proved robust and resistant, and what gave way, crumbling under the unexpected shake-up?

But above all, we wanted to investigate what researchers, science policy-makers, industry, the media – and through them the general public – would make of the event. We were interested in the now-bared interconnections between the different parts of the "building" – the strategic research hinges and organizational structures that connect basic research, technological applications, and worldwide economic competitiveness – and especially how and why thousands of researchers all over the globe rushed to exploit the new opportunities, how and why national funding agencies decided to support them, and how the media told the continuing story in a collective and collusive effort to establish a new field of research.

Comparing the unexpected discovery of high-temperature superconductivity (HTS for short) to an earthquake raises the question of the magnitude of the convulsion. In any case, its repercussions are lasting, since they follow some of the major fault lines of the current science and research system. Moving from a seismic to an engineering metaphor, we can compare the breakthrough to a "transient" or "impulse" load. Engineers deliberately induce a well-controlled stress to test the strengths and weaknesses of a system or structure. We approached the science and research system as if the discovery of HTS were such a stress. We focused on the responses of the various components of this system – researchers and research institutions, policy-makers and governments, industry and the media – to see how they bore up under the test, how well- or ill-prepared they were for unexpected events of this kind, and what their responses showed about the underlying processes, strengths, and weaknesses of the system as a whole.

We witnessed the emergence of a new research field in an extremely short time. Yet the participants' intense efforts to establish the field were at odds with the cool, detached view of the prospects so strongly claimed in public rhetoric. For us, the point is not whether the new field's achievements thus far – in theoretical or in practical (i.e. technological or commercial) terms – fulfilled the initial hopes and expectations, not whether funding was adequate, and not whether the behavior of scientists and the media was disproportionate, a transgression of the conventional norms of science. We see the field of HTS as typical of the present mode of scientific research, an extended mode that combines separate scientific disciplines and research fields and in which even basic research must reach out into society and thus into unknown but anticipated contexts of potential technological applications. This mode of research presupposes the active and strategic participation of a widened set of social actors who work in more – and more various – sites of knowledge production and in novel patterns of alliances and cooperative or competitive behavior. Researchers intent on remaining active players in the game must now involve themselves much more directly in preparing, shaping, and managing the conditions that enable them to pursue the kind of research they desire. The discovery of HTS was unplanned, but it has proven a good test case for the ability and preparedness of individual researchers, local research groups, and national research systems to organize the prerequisites of research.

HTS was one of those bursts of scientific innovation, based on a discovery unanimously termed a breakthrough, that every working scientist, science administrator, or policy-maker secretly or openly yearns for. Yet when it occurred, it took everyone by surprise.

Indeed, few scientific discoveries in recent years have triggered such a wave of excitement and acceptance among thousands of researchers around the globe as did the discovery of HTS. With the exception of the ostensible discovery of cold fusion, none has comparably fired the layman's imagination. The common faith – as it must be termed – was that new technological goals could be realized, if not in the short term then in the medium and long term. Hope arose for an era of renewed economic growth and change in people's lives comparable to those resulting from the semiconductor revolution. Visions of technological utopias revived.

For a brief moment, scientists seemed on the verge of even more exciting discoveries. One of the leading researchers in this field recently told of a recurrent dream he had when he first began work on high-temperature superconductors. He saw himself:

> standing at the threshold of a vast, dark room, with the door open barely a crack, sending a narrow shaft of light onto the floor. I would try to open the door further to illuminate the whole room, but it would not move: I could only put my head inside and see what was directly lit, not what was hidden in the darkness. The feeling was one of longing, fear and expectation, for I desperately wanted to see what was inside, but I was afraid of what it might be and how I might respond. My subconscious was clearly grappling with what many were probably feeling at the time – that we were on the verge of a great moment – and that we would be part of, or at least direct observers of, a historic time in solid state physics and materials science
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> *(Cava, 1993: 297).*

But the private worlds of dreams and the shared hopes and expectations on which they were based were inevitably intertwined with the more sober public world, where funding for research must be obtained and where government policies, international rivalries, and economic competition prevail. Nine years after the discovery, the initial excitement has subsided and the work of those remaining in the field has long since assumed a more normal pace and pattern. National science and technology policies have been established to strengthen the national scientific base and thus put national industries in position to partake in any spurt of technological growth. Investment in basic research continues at a modest level. After an initial wait-and-see period, some of the larger industrial companies decided to pursue HTS research on a longer-term basis. Many small companies could not wait long enough to see their investments mature and had to withdraw.

Scientific journals still report the latest experimental results on the many remaining theoretical and empirical puzzles. New HTS compounds continue to be discovered, the most prominent recent example being the buckminsterfullerenes. While they differ fundamentally from the ceramic oxide HTS materials, they also show transition temperatures far higher than earlier limits. Their structure and composition is another surprising example of how atoms can fill space and of their resulting unexpected behavior. But no real advance has been made in understanding the physics underlying the superconductivity of such diverse substances as cuprates among the ceramics and the almost pure carbon of the fullerenes.

Although media excitement has subsided, hope is sustained by the knowledge that any technological innovation takes time. Cautiously optimistic reports on the production of technological devices still trickle in, such as Superconducting Quantum Interference Devices (SQUIDs), which incorporate HTS, and which are utilized in outer space and in medical diagnostics. But the general consensus is that it is still too early to say where HTS technologies will ultimately make their greatest contribution. Many feasibility studies predicted HTS would find a prime field in the microelectronics industry, but here economic competition is fierce, making it difficult for any new component to replace existing ones. The second realm of application commonly associated with HTS, the transmission of electric power, may hold surprises as well. Projections exist that the next growth phase of the electric system will be an order of magnitude larger than the one that has now reached saturation. Energy lost in transmission is a stable 10% – huge in absolute terms, but still judged too small to justify replacing existing transmission lines with HTS lines – however efficient they would be – in a continental or even intercontinental system. But superconductivity could revolutionarily reduce the size of machines, thus permitting the construction of units of larger capacity (Ausubel & Marchetti, 1993: 8–9).

HTS has lost its prominence in the media. After vociferously pushing the HTS story, especially in the United States, the media unsurprisingly moved on to newer issues, leaving the impression that the early hopes had been dashed and the future of the field looked less bright than expected. The many commercial HTS newsletters set up after the breakthrough are also gradually disappearing, except where they are mellowing into more conventional industry journals. The initial flurry of books on HTS, written largely by science journalists, has been followed by a second wave that places the discovery in a larger historical context (Vidali, 1992; Ott, 1992).

1.2 The extended laboratory and its constraints

The research field emerging in the nine years since HTS was discovered provides an example of the general trend of science and technology to move closer together. In this sense, HTS is an example of technoscience extending in whatever directions appear technologically promising. This brings us to the concept of the extended lab, a term used to characterize the vast and heterogeneous network linking each laboratory to its economic, political, administrative, technological, and scientific environment. Each network includes many partners who shape and define the content of research, the orientation of the programs, and the evaluation of results. Networks include not only individuals, but also resources, documentation, instruments, and funding. In this sense, a laboratory is not sharply separated from other production units in society. This is not surprising, since all competence and scientific knowledge has to find or construct its own space to circulate its products, if it is to sustain itself. Scientific research must continually create new products and generate demand for them (Callon, 1989: 13).

We agree with Callon that the modern technoscience lab extends into the wider society, rendering the boundaries increasingly diffuse, and that networks can be conceptualized as abolishing these boundaries altogether. But, however fluidly, the extended lab is structured, and thus subject to constraints. The activities of doing research, organizing the research environment, and projecting technological advances – activities constantly in flux and dependent upon previous outcomes – combine to give different organizational forms to the extended lab and to determine the primary directions of its extension. The first explorations of a new field are conducted without knowing where the most promising results will be found, nor how they can be turned into a technological advantage, taking cost, reliability, and other performance criteria into account. Thus, search strategies include strong random components, and it is the task of research organizations and their management to optimize this process (Montroll & Shuler, 1979). The degree of preparedness to grasp new opportunities varies markedly between research groups, industries, and countries.

Research is conducted on an international scale, so the extended lab has a geographic dimension. Researchers scattered around the globe in university, government, or industry laboratories are linked to each other through their work on related problems. Attending conferences, reading each others' publications, and communicating, they stimulate each other to further exploration. They converge in their realm of inquiry, which they populate in different modes (Becher, 1989). Exciting new questions may arise near those already posed. Obstacles may lead to temporary or long-term abandonment of a topic. Thus, the extended lab and the free flow of exploration are constrained.

The social organization of research is also a powerful constraint. Although many similarities exist, researchers in a university group conduct inquiry differently than those in a government or industry lab Management in industry is more likely to set deadlines for programs with make-or-break evaluations of the progress made. Industry management houses researchers together and acquaints them with company goals, thus providing more specific directions, even in basic research, than university researchers must deal with. But university researchers must obtain funding from research councils, which also impose conditions.

The organizational form that arose to coordinate the inquiry opened by the discovery of HTS was the national research program. Its intent was – without inhibiting the free international flow of information – to strengthen cooperation between researchers within a country, especially between university and industry labs., to increase the likelihood that the new discovery would yield tangible technological results. We will describe in detail the obstacles encountered and how university researchers responded to such attempts at management. But the point is that the extended lab is indeed constrained and structured by boundaries: those of the national research programs.

Another constraint in the extended lab is often overlooked. Any new product or device has to fit into the existing technological system, infrastructure, or production process. Technological development is a sequence of replacements in which cost and other performance criteria are limiting factors throughout. It may take a long time before the exciting "bright spots" that appear in scientific inquiry mature into technological exploitation. The history of technology shows that every innovation must pass through selective filters and constraints; these are often unforeseeable and contingent upon interaction with economic, political, and social factors. Initial conditions often determine the trajectories of technological developments (Arthur, 1988; David, 1985). Technologies may also become "locked in", evolving along their initial pathways, while changing course seems too expensive, even if alternatives are found that would have been more advantageous if they had been implemented first.

Though technological systems may appear impervious, Thomas Hughes has pointed out that they do not become autonomous, even after prolonged growth and consolidation. They acquire momentum, have a mass of technical and organizational components, possess directions or goals, and display a rate of growth suggesting velocity, but they must be maintained by the interests of people and organizations committed to them. Their robustness is partly that of technical artifacts and partly that of interests and institutions (Hughes, 1983). A case in point is low-temperature superconductivity; it is still too early to tell how, in the extended lab, with its organizational structure, and search strategies for technological innovation, HTS will cope with the competition of this already existing technology.

At this point, we would like to underline our own methodological constraints. Following scientists around in an extended lab differs from the method of studying them in one localized lab at a given time, as has been the case in most laboratory studies published so far (Latour, 1987; Latour & Woolgar, 1986; Knorr-Cetina, 1984). The range and depth of observations is necessarily less complete. Observations are limited geographically and temporally; they can be neither continuous nor simultaneous. Observations of a social process are based on inferences. They are always obtrusive, altering their objects. In the social studies of science, we do not speak of measurements. Instead, we attempt to listen to the various stories told by the actors we include. We observe and interpret how they construct their accounts. We weave our actors' contexts and the influence of these contexts on the construction of their narratives into the stories as tightly as possible. We confront the accounts with each other. In the end, we too can only tell our own interpreting story.

Moving around with researchers, science administrators, heads of research councils, and research directors of industrial labs in the extended HTS research lab thus provided the empirical basis for our account of the emergence of the new research field in the European countries we selected. The direct contact, interviews, and observation were necessarily limited in space and time. To follow the unfolding of the wider global context, we also utilized other sources: analyzing the scientific literature and of the general press; personally participating in international conferences; scrutinizing feasibility studies and other reports made to guide policy-making; and speaking with as many actors as possible. The overriding interest of our analysis remained the question: What does the case of HTS reveal about the present state of the science system?

1.3 Our study

Our analysis is based on more than 70 interviews carried out in 1988–89 with university researchers, science administrators in ministries, and representatives of various funding bodies and industry. Our interest focused on the gestation period following the discovery of HTS. Who joined the field, what were their motives, how did their different scientific backgrounds and skills shape the new research area, who pushed to set up national research programs and who were their allies, and what places became centers for HTS research? We were also interested in the speed with which and the extent to which national science policies adapted to a situation defined as exceptional.

In Austria, we interviewed the leaders of the research teams involved in the national coordinated HTS effort (*Stimulationsprogramm*), the leader of an independent team working at the *Atominstitut*, and representatives of the two industrial enterprises interested in the field, Elin Union AG and Metallwerk Plansee AG. We attended some of the national network meetings and two organized by the funding agency: an early one to enhance university–industry cooperation and a later one to evaluate the first two years of the national HTS program. We rounded out the information with discussions with representatives of the program's funding agency (the Austrian Science Foundation, FWF), who also gave us access to their written records.

In Switzerland, we visited the major groups involved in the national HTS program (SUPRA2), the national funding agency (Swiss National Science Foundation, SNF), and two industrial enterprises, the multinational company Asea Brown Boveri (ABB) and Spectrospin, a small company specialized in conventional superconductors. Regrettably, due to the "mainly confidential nature" of the subject matter, International Business Machines (IBM) did not grant us extensive interviews, which would have been invaluable in studying the influence exerted by a multinational research organization.

The German case was more complex, because we had to make choices on several levels: the regional distribution of the groups; the different forms of funding chosen; the variety of organizational structures; and the balance between basic and applied research institutions. Of the 15 associations of university groups set up in early 1988, we chose Tübingen, Cologne, Aachen, and Göttingen[2]; we also visited the Max Planck Institute in Stuttgart and the two "big science" laboratories in Karlsruhe and Julich. We took a closer look at the responses of two industrial companies, Hoechst and Siemens, and interviewed representatives of the Federal Ministry and the program managing

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[2] In making our decision, we were advised by the coordinator of the program management agency, Magda Gronau.

agency. To a degree, these choices were arbitrary. The strength of a research group in the very early phase did not automatically mean it would continue in the future, nor did latecomers necessarily play a subordinate role. But our main interest was in the formation process of the new research field.

The interviews in Austria, Switzerland, and Germany were carried out in 1988–89, when HTS research was at a relatively early stage. From a micro-level perspective, we observed the hopes triggered by the emergence of a new field and how funding agencies and industry responded. During a brief first phase, funding was relatively open. In the early 1990s, most countries entered a second phase, in which funding became more selective and focused. At this stage, we were invited to extend our analysis to the Netherlands, giving us a second empirical glimpse of a later stage in the development of HTS research and in the making of national research programs. The number of actors shaping the Dutch national research policy was small enough to allow the emergence of a coherent picture of the sequence of events and of the factors contributing to the outcome.

The interviews were semi-structured and almost always conducted within the respective person's institutional context. With a few exceptions, our interview partners were the team leaders or senior researchers; this undoubtedly biases the sample. We also asked them to fill out a questionnaire, but it revealed little. We were thus provided with a comparative overview of the scientists' actions, their motivations, and the difficulties various groups involved in HTS faced in the three countries. To test some of the impressions we gained from the interviews and to round out the picture, we visited some university labs for a longer period of time. We hoped for a better understanding of specific characteristics of the national science systems: their historical evolution, personnel structures, funding mechanisms, and other local contingencies.

In contrast to the prolonged, in-depth study of a single lab, as usually found in the social studies of science, we faced a sample of university institutes, research labs, and industrial enterprises with a broad geographical distribution, great historical complexity, and wide organizational diversity. A long-term, comparative, micro-level observation of scientific activity was clearly unfeasible for us. Forced to modesty, in the end we chose to visit at least one German, one Swiss, and one Austrian university lab. For one week in each lab, we recorded our impressions of working conditions, the everyday problems researchers face, the way routine research was conducted, the communication mechanisms within and beyond the laboratory, and the influence of all these factors on the research done. Such relatively short visits amounted to snapshots of the researchers present that particular week and of the parts of the experimental program we were shown. Thus our description does not pretend to be the full picture, and even the balance among the research topics may have been distorted by how our discussion partners presented their worksite to us. But we did gather a wealth of valuable information and data.

In Austria, we chose to visit the Technical University of Graz, home of the largest association of research groups taking part in the country's coordinated study of HTS. It was one of the first groups to apply for joint local project funding. We knew from their publications that they were also active on the international level. In Switzerland, we visited the University of Geneva, which has a long, internationally highly-reputed tradition in the field of superconductivity and where four professors and their teams were working on a joint project on HTS. In Germany, again, the choice was more complex, due to the large number and organizational variety of institutions involved. In the end, we chose the University of Cologne, where a special research program (*Sonderforschungsbereich*) on HTS had been set up, thus promising an interesting additional organizational feature not found in other German labs.

We made our visits between November 1989 and January 1990. HTS had entered a phase of consolidation, and permanent, more focused programs had begun to replace the first ad hoc initiatives.

To gain a more global perspective, we participated in three international conferences, in 1988 in Mauterndorf and Interlaken and in Stanford in 1989. Further, we followed developments in the United States, United Kingdom, and partly Japan on the basis of gray literature and accounts written by other scientists.

1.4 Scope and outline of this book

Students of social studies of science and technology may now want to look back to ask what the excitement was all about and what is still being done, assessing general and specific features of the development of HTS. This book seeks to retrace the achievements of the first phase of intellectual excitement, intense scientific work, media overselling, and the funding agencies' cautious but sometimes misguided policy-making.

Our interest is not in judging whether initial expectations were too high, whether investment in research was justified, whether expenditures should have been greater or less, or what the many technology assessment and feasibility studies should have considered. Rather, we remain intrigued by the degree to which the discovery of HTS gripped the scientific and lay imagination. This excitement was transformed into more tangible and long-lasting results: the emergence of a new research field and its organizational framework in national research programs. Were the features of this development unique to HTS, or were they indicative of processes typical for the current research system? An answer to this question must embrace several perspectives.

First, there is the historical perspective. Although HTS is a novel phenomena, it has a fascinating specific prehistory. In the past, superconductivity has attracted some of the best minds in physics, and the new aspect of HTS continues to excite a large number of talented theorists, experimentalists, and engineers from a wide variety of fields. The manifestation of superconductivity in artificially structured materials made it one of the most challenging research subjects in materials science, which attempts to make or discover new materials, determine their physical properties, grasp the reasons for their behavior, and finally to find applications for them. We investigate which specific materials science research modes have been embodied in HTS research. Then we place HTS in the context of the development of applications in the field of low-temperature superconductivity, which preceded it. Next, we address the event that shook the physics community and beyond: the actual discovery of HTS by Müller and Bednorz at the IBM laboratory in Zurich. We maintain that the discovery was unlikely, and investigate the features of the research system that allowed it to occur nevertheless. We then trace the frenetic, euphoric phase that followed the breakthrough. Eventually, research patterns returned to normal; by then the foundations of a new research field had emerged.

The second perspective is that of the main actors and the knowledge they brought to the field: the scientists who were drawn to the new discovery and decided to work in the new field. We investigate the reconfiguration of persons from varying institutional and disciplinary backgrounds and their motivation to join the swelling numbers of those who produced some 18 000 publications within a mere four years of the HTS discovery. We examine the relationship between the newcomers and researchers who had worked in the "old" field of conventional superconductivity, or LTS, and the role that the construction of scientific expertise played in the making of the new research field. The exciting prospects presented an opportunity and the necessity to actively shape the research environment: scientists had to exert effort devising strategies to obtain funding. In the process, they had to forge various kinds of alliances; they had to make promises and set up structures that made these promises credible. They had to mobilize resources of various kinds not associated with the conventional image of scientists' behavior. In shaping the research environment and setting up national programs, they displayed how the cognitive and social aspects of scientific activity interact inseparably in communication, competition, and