"WEAK" AND "STRONG" KNOWLEDGE IN SOLID STATE PHYSICS AND THE MATERIAL SCIENCES

ABSTRACTS

Weak and strong forms of knowledge in Materials Science & Engineering

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Like many other activities, scientific research is driven by core values. The epistemic values underlying the cognitive structure of each research field are often expressed through the disqualification of existing forms of knowledge. This talk is an attempt to describe the shifting epistemic valuations in materials research from the emergence of the research field in the 1960s to the emergence of nanotechnology in the early 2000s. Three successive (albeit overlapping) systems of cognitive valuation and devaluation can be distinguished in the discourse of materials scientists.

The first one corresponds to the emergence of a generic concept of materials implicit in the constitution of Materials Science & Engineering (MSE) as a discipline. This concept built on the basis of solid-state physics and the access to the microstructure of materials entailed an ascription of weakness to the rich empirical knowledge about the properties of materials, the chemical knowledge about metals in particular.

The second epistemic configuration is captured in the concept of materials by design, materials with never- seen-before properties designed for specific purposes. Materials scientists initially focused on structure-sensitive properties were encouraged to pay more attention to process. This shifting focus is particularly visible in the textbooks of Materials Science published in the late 1970s and 1980s which provided a visual representation of the conceptual basis of the discipline in the form of a tetrahedron of four parameters, structure, properties, performances and process. This re-valuation of practical aspects was accompanied by strong criticisms of the linear model of innovation and the valuation of systems approach.

A third epistemic configuration was initiated by nanotechnology which disqualified the top-down approach to the design of materials, with special disqualification of conventional chemical technologies. The champions of nanotechnology flaunted the promises of the bottom-up approach to design multifunctional, eco-friendly and adaptive materials. This new cognitive landscape is characterized by a focus on bio-inspiration and the valuation of sustainability.

(The talk will not be held at the conference but one week later, May 15)

Coming to the Surface: Molecular Beam Epitaxy and the Material Culture of Semiconductors

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Very long time periods of human history are named after the leading materials technology. Semi-conductors caused the most recent change from the Age of Iron to the Age of Silicon in the middle of the 20th century. Macroscopically, the impact on industry, science and society has been and still is revolutionary. This study deals with the less obvious consequences of the epochal break like changes in the scientific culture. The author argues that semiconductors caused a diversification of the classical interplay between theory, experiment and instrumentation in physics. Materials established themselves as a fourth, epistemically equivalent category. This substantially affected the roles of actors and artefacts. How did the interrelation between the three established categories and the fourth 'newcomer' develop during the transition process? Did 'natural allies' emerge among them?

These questions are addressed on the basis of the history of **Molecular Beam Epitaxy** (MBE). In-vented in 1968, MBE is not only the first experimental system to enable bottom-up growth of precise material structures atom layer by atom layer, but MBE also provides unique features in basic surface physics studies. In 1980, the instrument industry successfully launched MBE machines for large scale production of semiconductor lasers on the market. Today, MBE and its numerous modifications maintain a leading role in basic and applied research as well as for the production of solid state specialties.

Methodically, MBE is a form of **Physical Vapor Deposition**. Molecular beams are directed onto the surface of a heated substrate in Ultra High Vacuum (UHV). Arriving molecules or atoms are adsorbed, migrate, react and grow a new top layer. Epitaxy means that the growing layer inherits the crystal structure of the surface. The process derives from the convergence of separate instrumental systems in one modular device. Therefore, technical improvements of the individual components like vacuum pumps determined the pace of progress on the instrumental side.

The epistemic trigger for the engagement was the invention of so-called compound semiconductors in 1952. These man-made materials set off a train of creative thought in theoretical physics. Due to superior microwave- and optoelectronic properties that compensate natural restrictions of silicon, large interest was raised in the industry. Initial tests with unsophisticated samples had been promising, but the envisioned complex material structures required beyond state-of-the-art processes. In the 1960s, early epitaxial methods provided improved samples. However, low precision and reproducibility remained obstacles for the breakthrough.

MBE marks the beginning of a new era in physics and the trajectory is reflective of the transition period, in which materials took the 'driver's seat' of innovation.

From Magnetic Cores to a Central Institute: The Institute for Magnetic Materials in Jena

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In my paper I will analyze the early history of the Institute for Magnetic Materials (Institut für magnetische Werkstoffe, IMW) in Jena. The Institute was founded in 1951 on the initiative of the physicist Fritz Kersten dating back to 1949. The Institute became a part of the German Academy of Science in 1954. Two years later the physicist Max Steenbeck, who became later one of the central figures of the science policy of the GDR, was nominated as the director of the institute. The IMW was reorganized and split up in three parts. The heads of the department of the IMW served periodically changing as directors of the institute. In the course of the reform of the academy at the late 1960s the institute became a part of a newly founded Central Institute for Solid State Physics and Material Science (Zentralinstitut für Festkörperphysik und Werkstofforschung) together with four other institutes in Dresden until 1981.

I will draw special attention to the research that was carried out from the late 1950s until the reform of the academy. During that period ferrite cores for random access computer memories became the predominant research area of the institute. Core memory uses tiny magnetic rings, through which wires are threaded to read and write information. The arrangement of wires and cores allowed magnetization in two different directions by an electric current through the core. This magnetization could then be read as a zero or as one. The core memories represent nonvolatile random-access memories. Later, also other magnetic technologies for random access memories were developed at the institute like a woven matrix of wires coated with magnetic materials. The knots of netting could then be addressed with different magnetization. Finally, all these magnetic technologies were followed up by technologies based on semiconductors. During the high time of the core memory a close collaboration with industry, especially the Keramische Werke Hermsdorf (KWH) was established. The KWH was one of the central companies of the GDR for the production of ceramics. In 1962 a laboratory for magnetic research was founded at the KWH as a basis for science driven industrial production of magnetic memories. The training of the laboratory staff (eleven physicists and chemists) was done at the IMW in the three years after the collaboration was initiated. The end of the magnetic laboratory came when all computer related research and development was transferred to the Dresden area at the end of the 1960s.

The analysis in my paper will be done within the theoretical framework of the DFG funded CRC 1095 "Discourses of weakness and resource regimes." Discourses of weakness are obvious in the competition of the socialist GDR and the capitalistic FRG. The whole reform of the GDR's academy can be interpreted in the context of Walter Ulbricht's policy ("Überholen ohne einzuholen") with the central aim of accelerating the transfer of scientific knowledge to the socialist market. Another aim was an ideological one, namely to incorporate the scientists stronger in the socialist production process. We can find these discourses of weakness also on a micro level, when the historical actors analyzed, which elements had to be developed faster, as the import costs from the Western hemisphere were too high. Finally, we find these discourses also in the Eastern hemisphere, e.g. in the relation to the Soviet Union or to the newly founded Central Institute in Dresden.

The Journal physica status solidi and the Formation of a Specific Market for Periodicals in Modern Solid State Physics

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In 1961 a new journal - physica status solidi - was launched by the East-Berlin physicists Karl Wolfgang Böer and his initiative reflected the shortages of the rapidly expanding research in solid state physics, in particular the lack of specific journals in the field and in the German speaking world as well. Solid-state physics had undergone a stormy upsurge since World War II and during the 1950s had established itself as an independent subdiscipline within physics. To this process of disciple institutionalisation belonged new specialized professional journals for solid state physics. By the mid-1950s the Physical Review had still not been divided into separate parts. That first happened more than a decade later, with Physical Review B, the largest part, being devoted exclusively to solids. In the meantime, in 1956 the Harvard physicist Harvey Brooks has founded the Journal of the Physics and Chemistry of Solids at Pergamon Press, expressing the feeling "that the coming of age of solid-state science should be recognized by the publication of a journal devoted exclusively to this field." Three years later, in 1959 the Russian Fizika Tverdo Tela was founded in Leningrad, but it was an exclusively Soviet Journal and its paper were mostly written in Russian. With the (East German) physica status solidi entered a journal the field, which played not only the role of a showcase for East Germany's (and other Eastern) physics research, but also became a forum of scienitific exchange between East and West. The new journal became very successfull and one of the leading journals in the field, surviving the political cataclysm and the hard Western rivalry of the time. Therefore its history is not only the story of scientific and publisher's success, but also a mirror of the Cold War in the field of scientific publishing and science in general.

Strong correlations: Postwar physics and its unity

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An inner tension permeates the history of postwar physics: On the one hand, as the discipline grew bigger and new fields of research (and entire new subdisciplines) emerged, physicists' practices and terminologies diverged increasingly. On the other hand, despite talk of a Balkanization of physics, few physicists questioned the underlying intellectual unity of their discipline, rooted, first and foremost, in the foundational role attributed to quantum theory in most (yet not all) of these new fields. Sure, some were recognized as more "fundamental," others as more "applied," and the actors (physicists, funding institutions, politicians) drew manifold conclusions from this hierarchization of the discipline. But what particle physicists, high- and low-energy nuclear physicists, solid-state, and low-temperature physicists did was still: physics.

How then did physicists cope with the increased diversity of their discipline? One way, which lies at the center of my contribution, is by establishing strong, and often rather surprising, correlations between subdisciplines, often through (formal) analogies between models of otherwise rather disparate phenomena, which allowed them to transfer concepts and methods from one field to another. A—if not *the*—key playground for this activity, at least during the 1950s and 1960s, was many-body physics, a rather hybrid field centered not around a shared object of study, but around a shared set of methods and new heuristics for coming to grips with systems consisting of large numbers of interacting, often "strongly correlated" particles (such as electrons in superconductors, or nucleons in an atomic nucleus). I will present selected case studies and discuss how physicists mediated between the seemingly monolithic subdisciplines of physics. I will also reflect on lessons that can be drawn for debates about the unity of physics and about weak vs. strong knowledge in fields such as nuclear, solid state, and condensed matter physics.

The 'weakness' of rigorous theory and the need for 'weak' knowledge in technology

Shaul Katzir, Tel Aviv University

Scientific theory rarely provides full instructions for developing practical devices and methods. The efforts to use material sciences for technical ends suggest clear examples for these limitations. The limitations of these theories are characteristic of the relationship between knowledge on the one hand and technics on the other. By technics I mean devices and methods for their use, distinct from the knowledge about their working principles, which is the realm of technology and science. Facing with the inadequacy of scientific knowledge, developers either use more or less sophisticated trial and error methods, or embark on a technological research, i.e. research aimed at elucidating particular relationships deemed useful for solving the specific technical problem at hand. Often these studies examine specific conditions, kind of materials, etc. In other cases, they examine more general natural processes, contributing to the scientific research and directing it into topics of their interest. The knowledge of these topics, however, is often partial and less rigorous or secure than that regarding topics of disciplinary research. In other words, it is epistemically 'weak' knowledge. Although "weak" this knowledge often provided highly valuable insights into the technical world and sometimes also into nature.

In this talk I shall illustrate these claims with examples from my research on crystal frequency control and the quartz clock. Crystal frequency control technics originated in a scientific discovery – that piezoelectric crystals, like quartz, sharply change their electric behaviour in elastic resonance, whose frequency remain stable. Theoretical accounts for this behaviour, however, were developed only with the development of useful methods for harnessing the resonators. Elasticity provided firm basis for calculating the resonance mechanical frequency, but no similar theory predicted the electric behaviour. Moreover, in the mid 1920s when precision and stability became important for the technical use of the resonators, the theory provided only limited elucidation e.g. in providing means for reducing variations in the resonance frequency with temperature. To solve this vexing problem engineers combined general knowledge about these variations with experiments on particular cuts to reach stable cuts. At the same time, they worked on improving their knowledge regarding particular cuts of quartz. In a more general way, scientists studied variations of a few connected piezoelectric properties with temperature, building tentative theories for the variations in the frequency of resonance, hopping that they would help in designing resonators.

I will further examine the employment and limitations of theoretical tools taken from physics and engineering to cope with gaps in the knowledge about the dynamic of the resonators, which were used to understand and predict their behaviour. The development of electronics needed for implementing the resonators in devices like the quartz clock provides another example for a weak knowledge. In this case, the equations of the valves were rigorously deduced, but they were nonlinear and unsolvable analytically. This led to the use of 'rules of thumb' for their operation within technical systems, and to the development of numeric partial methods for their solutions.

A comparison to aerodynamics would help showing that laxity in the building of theories regarding the technics can have different forms. Unlike the theories regarding crystals and triodes, which used many approximations and estimations, in aerodynamics engineers made unrealistic assumptions. They can be seen as another form of epistemic weakness.

“More is Different,” or the “Transition from Quantity to Quality”

Alexei Kojevnikov, University of British Columbia

Soviet science planners did not recognize the concept of “pure science,” promoting instead the idea that every science worthy of this name should be practically relevant. Their Marxist approach was also consistently non-reductionist, rejecting, for example, eugenicists’ claims to explain social phenomena via biological laws. These general principles also affected the development of new branches within physics, such as physics of metals, condensed matter physics, radiophysics, many-body quantum theory, and non-linear mechanics. This paper will describe some of the pioneering Soviet works in these fields, their position within other subdisciplines of physics, and the new conceptual vocabulary and methods they introduced.

What is Moore's Law?

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Moore’s Law, a fundamental phenomenon in solid state electronics, is often understood as a self-fulfilling prophecy. This paper argues that it might be more accurate to view Moore’s Law as tool for technology development and research management and as an instrument of industrial governance. Moore’s Law emerged as a multipurpose tool in Silicon Valley in the first half of the 1960s. It was a technology of comprehension and persuasion; it was a marketing and promotion tool; it was a competitive device; and it was a contrivance used to allocate engineering resources and guide the development of new semiconductor technologies at the firm level. From the mid-1980s to the early 1990s, this multipurpose tool became the centerpiece of a new governance structure in the microelectronics industry: the technology roadmaps for semiconductors. In response to fierce competition from Japan, US corporations used Moore’s Law to guide, plan and coordinate the development of device, process, and design technologies across the whole industry. Thereby, they accelerated the miniaturization of microchips and the digitalization of many industrial sectors.

How Physics Became 'What Physicists Do': The Solid State Community and the Identity of American Physics

Joseph D. Martin, Cambridge University

Daniel J. Kevles, in the course of rejecting Paul Forman's claim that the military-industrial-academic complex distorted the course of American physics during the Cold War, wrote: "physics is what physicists do."[1] This slogan might strike the modern historian as an innocuous truism; historians are enculturated to aside preconceived ideas about what is essential to a historical practice. But for physicists themselves it has not always been so obvious. Physics, many of them maintained, consisted of certain regularities persisting in the natural world. Physicists' activities, from this perspective, qualify as physics only to the extent that they advance the goal of uncovering those regularities, and so the field could and should be organized according to natural classes of phenomena.

For solid state physics to emerge, and to become the largest segment of American physics, this orthodoxy would have to be challenged. The challenge came as World War II wound to a close and American physicists engaged in hurried and heated discussions about how to structure their community so as to best exploit the favor they had won on the power of their wartime labors. Central to this conversation was the question of what it meant to be a physicist. The traditional wing of the academic establishment continued to insist that the meaning and purpose of physics was strongly determined by the physical regularities of the natural world. The 1940s, however, had seen the rapid growth of industrial physics, representatives of which were receptive to a competing view. This perspective held that the institutional and professional landscape of physics might adapt and redefine itself to meet era-specific professional challenges—that is, that physics was what physicists did. This bloc of mostly industrial researchers advocated an intentional broadening of the definition of physics—and weakening of the ties between professional categorization and natural ones—to encompass more of its socially, economically, and technologically relevant applications. I argue that the emergence of the view that physics was but weakly and conventionally unified, a view that allowed a field as diverse and heterodox as solid state physics to emerge, was a watershed moment. It represented a real and permanent shift in what it meant to be a physicist in the United States and setting the stage for later developments, such as the rise of materials science.

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[1] Daniel J. Kevles, "Cold War and Hot Physics: Science, Security, and the American State, 1945–56," *Historical Studies in the Physical and Biological Sciences* 20, no. 2 (1990): 263.

Mistaking the Sunset for the Dawn: Jack Kilby, Solar Energy, and the Weak National-Security State

Cyrus C. M. Mody, Maastricht University

Jack Kilby is widely remembered for co-inventing the integrated circuit in 1958, for which he shared the 2000 Nobel Prize in Physics. That invention, grounded in mid-century solid-state and materials science theory and practice, made possible Moore's Law and the modern ubiquitously networked world. It also made Kilby an enormously influential figure in the US high-tech and defense policy communities, and a beloved icon at the company where he invented the IC, Texas Instruments. Yet it is not widely known that Kilby left TI in 1970 to pursue a new career as an independent inventor. I show that early in this effort, Kilby focused on some of the same kinds of technologies – e.g., electronic teaching machines – which recent historiography has associated with the San Francisco anti-establishment counterculture (though Kilby's own politics were square and conservative).

After the 1973 OAPEC oil embargo, Kilby turned almost exclusively to development of a domestic solar energy system which he convinced Texas Instruments to bring to market. Kilby directly translated solid-state and materials know-how accrued from experience with integrated circuits to development of this new, silicon-based solar energy technology. Kilby and TI believed they could draw on the strengths of the Cold War national-security state which had supported commercialization of integrated circuits: generous military funding, close-knit networks of researchers, firms, and military grant officers, favorable intellectual property policies, etc. Kilby also believed he did not need to work with more countercultural advocates of solar power, such as the Earth Day organizer Denis Hayes (by then head of the government-funded Solar Energy Research Institute). Yet Kilby was wrong on at least two counts. First, his national-security "allies" favored nuclear power and saw solar energy as a threat. Second, in any case, the national-security state was by the late 1970s and early 1980s much weaker than it had been in the late 1950s and early 1960s – the state which was able to overcome market failures and finance development of integrated circuits in the earlier period was unable to overcome market failures and finance development of solar energy technologies in the face of the post-1980 election of Ronald Reagan and fall in the price of oil.

Extra-terrestrial substances and the organisation of mundane research in solid-state physics and materials science in the former GDR

Falk Mueller, Johann Wolfgang Goethe-University Frankfurt/Main

In 1970, the Soviet Lunar 16 mission – the unmanned answer to the US-American Apollo 11 and Apollo 12 missions – brought back to earth first samples of socialist moon-dust. A small sample of three micrograms was entrusted to the Institute for Solid State Physics and Electron Microscopy at the East German Academy of Science in Halle. Because various researchers had already analysed this rare substance it seemed unlikely that completely new insights were revealed. Hence, the institute's director, the physicist Heinz Bethge, decided to focus on methodological questions and demonstrate the institute's capacity to apply a broad field of research methodologies. Thus, a collective of several research groups of the institute, supported by foreign guest researchers, prepared a so called "method system" for investigating the sample, utilizing a variety of different instruments and methodologies. The results were dedicated "in honour of the 50th anniversary of the foundation of the Union of Soviet Socialist Republics" to the people of the Soviet Union.

In the paper, I want to use this episode as a starting point for a discussion of the challenges and opportunities the investigation of materials and solids – though mostly much more mundane than moon-dust – posed to the local, national, and international organisation of research. How was research organized in an institution that was constrained by the boundary conditions of a resource weak state as the GDR? How did national and international collaboration and competition shape the institute's performance? How did Bethge and his colleagues manage to counterbalance the disadvantages they experienced in comparison to many of their international colleagues?

The strength of tradition: Tungsten in Budapest

Gabor Pallo, Budapest University of Technology and Economics

In Budapest, the first institution worked under the name of 'solid state physics' started in 1970. Before this date, research groups, institute sections, and projects represented the new subdiscipline of solid state physics here and there, mostly under the name of research for solid bodies or something similar.

As it happened in many countries, there was a long prehistory of solid state physics. In the early 20th century, the first industrial research lab was set up in Hungary by a small factory (Electric Incandescent Lamp Ltd) that decided to produce electric lamps. Besides, locomotives, cars, telephone, movie, the owners hoped that electric lighting will also remarkably shape the material and cultural life in Budapest, a city loving modernity, and their investment will become a great success.

The firm was based on a Hungarian patent of using tungsten for the filament of the bulb. The manager, Lipot Aschner set up research lab for improving the lamp, including the filament. Since then tungsten have been a research subject in Budapest.

The research lab became a most important center for research and an asylum for scientists who were persecuted by the frequently changing political regimes, including Nazism and Communism. For Jews the institute provided almost unique job opportunities. Its norms, values and research practice meant something like an island in the dark cultural and political atmosphere in the interwar period. People, like Edward Teller, Michael Polanyi and other famous scientists were connected to each other through the institute.

An inspiring multidisciplinary collaboration between engineers, and mostly physicists and chemists characterized the research as it was typical to the investigations of solid bodies in this period. Their most important result was the creation of the krypton bulb that brought great success for the factory in the international market. Meanwhile, the profile of the factory also changed: it produced vacuum tubes, later semiconductors and other things.

At the beginning of the communist period the institute was closed. The research however continued in various new institutes. The researchers, who survived the war and stayed in Budapest, went on cooperating with each other, and saved the mentality of the old institute under the circumstances of the cold war. Moreover, they could establish a new research institute and did not give up working on tungsten as a subject representing continuity through the fundamentally changing scientific, political, economic, cultural and philosophical cultures. It was still cold war but détente open new space to science.

Gradually, the various approaches gained common coherent theoretical basis, new instruments and methods were introduced, and the researchers achieved to set up a new institute but this was not an industrial institute anymore, rather an academic institute. Their field also changed from industrial research to academic research, and the strategy of their investigations was adapted to the new requirements. However, tungsten as central subject is still with them.

Cold War Materials Science: US Interdisciplinary Laboratories

Brit Shields, University of Pennsylvania

In the context of the space race, the United States' Advanced Research Projects Agency (ARPA) recognized a "materials bottleneck" and set out to strengthen the nation's research and production capabilities in this area through a program of Interdisciplinary

Laboratories (IDL) on university campuses. At the University of Pennsylvania, for example, the IDL was housed in a new and specifically constructed building for the research of materials science. With government, university and private industry funding, Penn's Laboratory for the Research on the Structure of Matter opened in 1965 and emerged as a physical manifestation of US Cold War science. Intended to bring physicists, chemists, metallurgists and engineers together through a system of shared facilities, laboratories, and office space, the IDL was meant to strengthen the research in materials science as well as expand the number of graduates trained in these related fields. In this paper, I will discuss the ideology behind the IDL program and how it was put into practice on US university campuses.

The MPG and its shift from traditional Materials Science to Solid State and Surface Science

Thomas Steinhauser, Max Planck Institute for the History of Science Berlin

In the first half of the 20th century the German Kaiser Wilhelm Society for the Advancement of Science (KWG) supported a group of institutes for Materials Science aiming at industrial applications of metals, alloys, and silicates. Throughout the Nazi period this orientation towards technical applications intensified with a focus on war related research. After World War II the Max Planck Society (MPG), successor of the KWG in the Federal Republic of Germany, changed its orientation. From then on, the officers of the Society described its major goal as fundamental research without strong interdependencies with state and industry.

Hence the former Kaiser Wilhelm Institutes in the field of Materials Science became Max Planck Institutes. But despite the official orientation towards fundamental scientific research they were strong enough to keep their tradition regarding research objects, methods, and researchers for the time being. During the 1960ies the MPG began to establish a new research program in modern Solid State and Surface Science, a field regarded as a weak spot of the West German research portfolio, particularly in relation to the USA. A new generation of Max Planck solid-state scientists pushed the field with a broader range of research objects like semi- or superconductors, ceramics and other compounds or microstructures. In addition, they extended the spectrum of methods for the synthesis and the analytics of materials.

The first hallmark event of this agenda was the foundation of the Max Planck Institute for Solid State Research in Stuttgart in 1969. Subsequently, other new Max Planck Institutes for Solid State and Surface Science were established, in particular during the 1990ies in the New Länder to support the allegedly weak research infrastructure. Furthermore, a re-orientation of some already existing Max Planck Institutes towards the new research field took place. At the end of the century Solid State and Surface Science had become one of the strongest research clusters of the MPG considerably outreaching the limits of this research organization. The talk will analyze the social, methodological, institutional, and political contexts, which weakened a traditional research field of the KWG/MPG in Materials Science and strengthened a new one.
