When Condensed Matter Physics became King

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Condensed matter physics is huge. This surprises no one who has attended a March meeting of the American Physical Society (APS) or perused the society's member rolls. The Division of Condensed Matter Physics has been the society's largest for decades. But the prominence of condensed matter physics, at least by population, is recent. Before World War II, no such field existed. Only in the late 1940s would solid state physics—a precursor to condensed matter physics—emerge as a physical subdiscipline.

In his superb book *When Physics became King*, Iwan Rhys Morus describes how physics itself, practically nonexistent in 1800, grew into the preeminent science by 1900.[1] Even with the vantage offered from atop Isaac Newton's shoulders, no one in 1800 could foresee the vast changes in the status and fortunes of physics that the nineteenth century would witness. Similarly, in 1900, when physics was beginning to probe the secrets of the atom, the prominence that physics of complex matter would attain by the turn of the twenty-first century was scarcely conceivable. Morus describes physics as becoming "king" in the sense that it came to occupy a central role in Western culture. Physics marshalled cultural resources—institutional spaces, audiences, patrons, trust—to carve out a niche where it could become the science entrusted both to probe nature's secrets and to spawn new technologies.

Condensed matter physics inherited many of the cultural resources nineteenth-century physics had secured, so both the manner of its coronation and the nature of its sovereignty differed. It grew quickly into the largest subfield of physics, and it certainly became most closely linked to technology, but the reputation for uncovering nature's deepest secrets resided with high energy physics and cosmology. Nevertheless, condensed matter physics became king in another sense. Its rise reconfigured how the field of physics itself was defined and subcategorized. It reflected new ideas about what it meant to be a physicist and challenges to the cherished ideals upon which the American physics community had been founded.

Should physics be pure?

Henry Augustus Rowland became the foremost proselyte of the ideals that defined turn-of-the-century American physics—principally, the pure-science ideal. European physicists infatuated with stellar spectra eagerly snapped up Rowland's precision diffraction gratings (figure 1). He could count himself among the few Americans commanding the international physics community's attention. But the practically minded Thomas Edison remained the public face of American science and Rowland lamented that "much of the intellect of the country is still wasted in pursuit of so-called practical science which ministers to our physical needs but little thought and money is given to the grander portion of the subject which appeals to our intellect alone."[2] Rowland and thirty-five others founded the American Physical Society in 1899 to minister to the intellect.

Advocacy of a staunch pure-science ideal by the leading organization for American physics, however, scarcely slowed enthusiasm for physics in technical quarters. In 1916, amidst World War I, John J. Carty, president of the American Institute of Electrical Engineers, considered it "the high duty of our institute … to impress upon the manufacturers of the United States the wonderful possibilities of economies in their processes and improvements in their products which are opened up by the discoveries in science."[3] Nor were physicists unreceptive to these overtures. Through the interwar period, industrial laboratories employed an appreciable proportion of American physicists and generated an appreciable proportion of the papers published in American physics journals.[4]

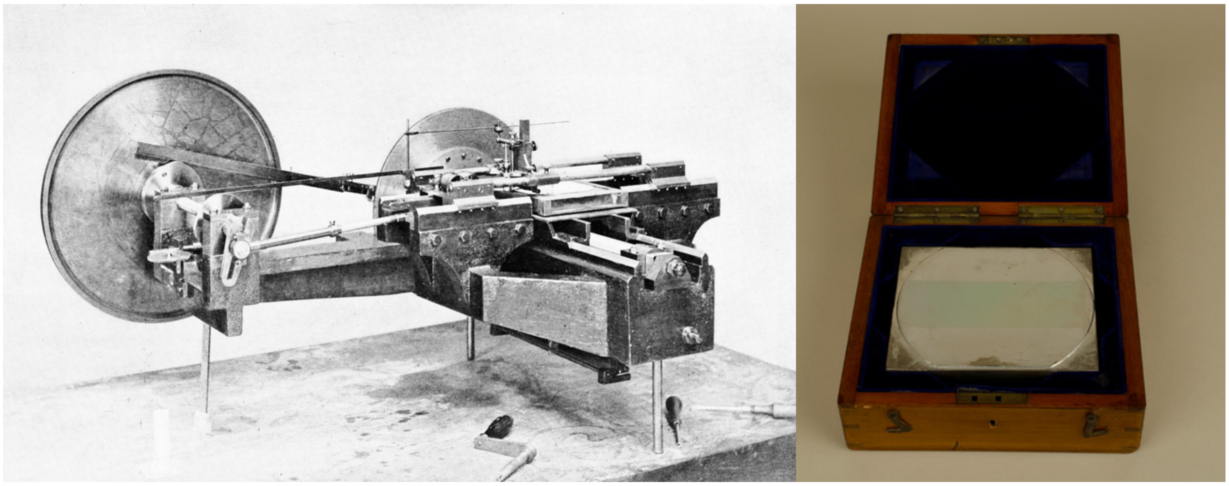

FIGURE 1. **(a)** Henry Rowland's ruling engine allowed him to make precision diffraction gratings that were in high demand worldwide. (Courtesy of Wikimedia Commons.) **(b)** A grating ruled with Rowland's engine. (Courtesy of the Whipple Museum for the History of Science.)

Many American physicists *never* regarded purity as a laudable goal. But although American industry was much enamored of physicists, many of whom reciprocated its affections, practical work remained stigmatized. A piece of doggerel that made the rounds at MIT's Radiation Laboratory in 1944 channels the attitude that prevailed through mid-century. The final verse disdained the comparative riches awaiting physicists who went corporate:

> Now all you bright young fellows with your eyes upon the stars,
> You graduate assistants who subsist on peanut bars
> If industry should woo you with two hundred bucks a week
> Refuse the job and say, without your tongue in your cheek,
>
> It ain't the money
> It's the principle of the thing
> It ain't the money
> There's things that money can't buy
> It ain't the money
> That makes the nucleus go round
> It's the philosophical ethical principle, we keep telling ourselves, of the thing.[5]

The conviction that academic and industrial cultures were irreconcilable reflected a broader transition: science, previously a calling for few, became a vocation for many. A new cadre of sociologists, including Robert Merton, who sought to understand the norms governing scientific practice, also observed the resulting cultural incompatibility.[6] The prevalence of the attitude that industrial work necessarily compromised dearly held ideals, combined with rapid growth in the number of physicists employed at industrial labor, created a rift that many physicists hoped could be bridged after World War II.

Redrawing the map of physics

The new field of solid state physics emerges from efforts to ease tensions between industrial and academic research. But before describing those efforts, it will be useful to discuss the assumptions about the nature of physics that stood in their way. In order for a field like solid state to make sense, physicists had to begin thinking about physics differently.

In 1939, Bernard (Bern) Porter, a Brown University graduate student, drew a map of physics (figure 2). The following year he joined the Manhattan Project, which he would quit, traumatized and disillusioned, following the bombing of Hiroshima. Instead, Porter followed his passion for art, through which he expressed his struggle with the complicity he felt in the use of nuclear weapons. But in 1939 he remained enamored of physics. He contributed little to postwar developments that shaped solid state and condensed matter physics, but his map aptly reflects prewar attitudes about how physics was organized—attitudes that solid state physics flouted.

FIGURE 2. Bern Porter's Map of Physics, 1939, illustrates a perspective in which physics is categorized in terms of natural phenomena. Reproduced with permission of Mark Melnicove, literary executor for Bern Porter, mmelnicove@gmail.com. From Bern Porter Collection, Colby College, Special Collections, Miller Library, Waterville, Maine

Porter's map illustrates the habits of mind that relegated applied and industrial research to the fringes, if not placing them outside physics entirely. Porter represented provinces of physics as geographical regions linked by a river of energy. The river, joined by a reservoir of radioactivity at its delta, flows into an ocean labeled "Research: The Future of Physics." Thus represented, physics is conceptually unified. Defined by phenomena that exist in the world, "physics" means the same thing at one point in history as it does at any other. Physics is out there. Physicists are those called to discover it. Technology, at best, is a distant outpost, unworthy of depiction in a map of the metropole. This view might seem natural, but it had professional consequences. It encouraged assumptions that made it difficult for industrial physicists to gain purchase in the American Physical Society, or to publish in the *Physical Review*.

A decade later, solid state physics had emerged as a new province. How might Porter might have represented it? Solid state physics drew from almost all of the regions of Porter's map. It was not a self-contained assembly of topics and methods that could appear as an island, continent, or other natural outcropping of the disciplinary landscape. It was, in that sense, a strange category.

Nor is this a retrospective assessment. In the mid-1940s, the proposal that resulted in the APS Division of Solid State Physics (DSSP) prompted the University of Iowa theorist Gregory Wannier to declare, "solid state physics sounds kind of funny." Two decades later when the second edition of the AIP handbook added a new chapter on solid state physics, its editor griped that "adding a chapter so named to the conventionally labeled group of mechanics, heat, acoustics, and so forth is … like trying to divide people into women, men, girls, boys, and zither players" (D. E. Gray, PHYSICS TODAY, July 1963, page 40).

These assessments seized on the oddness of an unusually broad field. The boundaries of solid state physics were unconventional. They cut across the physical phenomena that defined more familiar categories. Further, physicists did not tend to think in terms of subdisciplinary allegiance. A category with which physicists were invited to identify that did not revolve around shared techniques, concepts, or phenomena offended prevailing aesthetic and professional sensibilities. Nuclear and high energy physicists, for instance, continued to think of their work as simply *physics*. They shunned divisions of the APS for their activities until the late 1960s, judging such institutional apparatus necessary only for peripheral fields. But solid state would be the first of many ostensibly peripheral, artificial categories that would become central to postwar physics.

A new division, a new discipline

Solid state physics was strange by design. Industrial and applied physicists, feeling marginalized, had clamored persistently for greater representation in the institutions of American physics. When a 1931 amendment to the APS constitution permitted subject-based divisions, suggestions began to roll in for a division of industrial physics. The APS council balked. Industry, in the eyes of society leadership, was not a subject; a division devoted to it would only deepen academia–industry rift.

The needs of industrial physicists were nevertheless on the mind of the Polish émigré and General Electric (GE) physicist Roman Smoluchowski when he spearheaded a proposal for a division of metals physics. The preponderance of industrial research, he reasoned, concerned metals. They suffused his day-to-day responsibilities at GE, where he collaborated often with metallurgists. A division of metals physics would offer a home to industrial researchers, who often had to transition nimbly between topical specialties as they moved from project to project, while also representing academic physicists interested in topics like magnetism, electricity, and thermal conductivity.

FIGURE 3. Roman Smoluchowski, advocate for a metals division of the APS, works with alloy samples at General Electric. *Credit:* AIP Emilio Segrè Visual Archives, courtesy Roman Smoluchowski

As with proposals for an industrial division, the APS council demurred when presented with a proposal for a division of metals physics, which they judged too transparently industrial. The society secretary Karl Darrow suggested that the solid state of matter might offer a better basis for a successful division. Through this delicate sequence of contingencies, solid state physics became a recognized subdiscipline of physics when the DSSP was approved in 1947.

A precise distinction between solid state physics and condensed matter physics remains elusive, but, as it is taught today, solid state physics most centrally concerns quantum approaches to regular crystalline solids. Smoluchowski and his collaborators envisioned a significantly broader field. At a January 1945 symposium convened to discuss the proposal for a new division, the slate was strong with theoretically sophisticated talks. Wannier outlined new applications of statistical methods to cooperative phenomena (in which component parts can't be considered as acting independently). John Van Vleck surveyed ferromagnetism, the common form of magnetism seen in iron, beginning with phenomenological treatments of the early twentieth century before describing competing quantum mechanical approaches.

The symposium also demonstrated commitment to applications, and included contributions from Richard Bozorth and Howell Williams of Bell Labs, who described their work as "understanding of the behavior of magnetic materials in apparatus developed as a part of the war effort."[7] Watertown Arsenal's Clarence Zener framed his treatment of the fracture stress of steel by noting that the "sinews of warfare, namely guns, projectiles, and armor, are made of steel."[8]

Solid state physics aimed to unite this menagerie of approaches and questions, at least professionally. Van Vleck's concern with a robust, quantum-mechanical account of ferromagnetism had little to do conceptually with Zener's interest in the phenomenology of steel. The shared basis of these questions in solid matter was a link much weaker than, say, the link between ferromagnetism and magnetic susceptibility in gases, another Van Vleck specialty.

Solid state's odd constitution reflected changing attitudes, especially with respect to applied and industrial physics. The notion remained widespread that "physics" referred to natural phenomena and "physicist" to someone who deduced the rules governing them. But suspicion of this view grew around mid-century. Stanford University's William Hansen, whose own applied work led to the development of the klystron (a microwave-amplifying vacuum tube), reacted to his colleague David Webster's suggestion that physics was defined by the pursuit of natural physical laws in 1943: "It would seem that your criterion sets the sights terribly high. How many physicists do you know who have discovered a law of nature?... It seems to me, this privilege is given only to a very few of us. Nevertheless the work of the rest is of value."[9]

The rest tended to agree. The unwieldy breadth of solid state physics illustrates how they responded. The solid state of matter was an expedient category *because* it was broad enough to encompass such a diversity of topics. Its scope assured that it would not discriminate against industrial or applied physicists, who could often not state their focus area narrowly, allowing the DSSP to span academic and industrial territories, as well as topical categories, that were otherwise dissociated.

The solid state boom

Two factors account for the rapid expansion of solid state physics in the early postwar era. First, it scratched a persistent itch. Applied physicists, long underserved by the flagship institutions of American physics, embraced new organizational efforts that advanced their interests. Second, because it was organized to address professional problems of the postwar era, rather than to unite a coherent set of concepts or practices, solid state could serve physicists from sundry topical specialties, as well as those with peripatetic interests. The new field boomed. At a time when government and industry were willing to spend liberally—indeed, almost haphazardly—on both abstract and technical research, it attracted a significant proportion of PhDs students, generated ample new positions in universities and industrial laboratories, spawned copious conferences and workshops, and subsumed vast swaths of conceptual terrain.

The transistor, invented in 1947 by Bell Laboratories physicists working with semiconductors, illustrates how the flexibility of "solids" (versus "metals") permitted solid state physics to lay claim to lively new research areas. The late 1940s also saw the birth of nuclear magnetic resonance (NMR) spectroscopy. But because the solid state of matter did not mark the conceptual boundary of many research programs, solid state physics often included research that had little solid about it. Van Vleck's work on the magnetic susceptibility of gases canonical. The first maser, assembled by Charles Townes and his research group, was based on ammonia gas. And the superfluidity of hydrogen, discovered by Pyotr Kapitsa in 1937, launched a fruitful research program that solid state physicists also called their own.

Some of these areas, such as semiconductor physics, were integral to solid state physics when it formed. Others, such as NMR and low-temperature physics, the field would claim in retrospect. Because solid state physics was an artificial category, it was a flexible one, with latitude to claim promising new research areas. So long as solid state physics succeeded in its institutional objectives by providing a space for physicists working on the properties of aggregate matter, who otherwise had few professional outlets, its practitioners were willing, for a time, to turn a blind eye to its categorical infelicities.

The field's catholic attitude to both the topics and the institutional settings of physics spurred rapid growth. In the early 1960s, the DSSP became—and has remained since—the largest division of the APS, regularly outstripping the Division of Particles and Fields, the next-largest every year since 1974, by ratios of between 1.5 and 2. By 1970, following a membership drive at APS meetings, the DSSP enrolled over 10% of the society's members. It would reach a maximum of just shy of 25% in 1989 before the APS imposed extra $5 in dues for each division joined and all divisions saw an abrupt decline in membership.

David Kaiser has illuminated the boom and bust cycles that characterized the explosive growth of postwar American physics, emphasizing the incentives this growth exerted in graduate education.[10] Physics students, instead of being closely supervised, began to be trained in bulk. Close mentorship of graduate students gave way to techniques designed to confer the necessary facility with the mathematical formalism of quantum mechanics quickly and efficiently, favoring a focus on calculation over foundations.

Rapid quantitative growth, that is, led to a qualitative change in the way physics was taught, and therefore practiced. We can discern further qualitative changes by examining how different regions of physics grew during this postwar boom. The way in which solid state physics, scarcely a glimmer in the eye of a few industrial researchers in the mid-1940s, grew into the largest province of American physics speaks to the appetite for an outlet that embraced the links between the abstract and the technical, and that sanctioned industry as a viable and even desirable career path. Even as high energy physicists kept the pure science ideal alive by championing the role of fundamental knowledge in sustaining national prestige, the complexion of American physics was changing. It was beginning more and more to resemble a loosely aligned patchwork of specialties with varying degrees of commitment to the founding ideals of the APS. Physics as a whole was beginning to look much more like solid state physics.

<u>Solid state becomes condensed matter</u>

Solid state physics was engineered to address distinctive, mid-century professional challenges. It is therefore little surprise that, as time wore on and circumstances changed, the name began to seem old hat. Beginning in the 1960s, a subset of solid state physicists began to prefer calling their field "condensed matter physics."[11]

The new name took hold in Europe before spreading gradually to the United States. The journal *Physik der kondensierten Materie* (published simultaneously as *Physique de la matière condensée* and *Physics of Condensed Matter*), was founded in West Germany in 1962. The journal contrasted itself explicitly with solid state physics, explaining: "Inclusion of work in the physics of both solid and the liquid phase is intended to increase closer contact between both areas and especially to further research in the area of liquids."[12] The University of Cambridge made a similar leap in 1968, when its prominent solid state theory group rebranded itself "theory of condensed matter." Philip Anderson, a Bell Labs theorist who held a seasonal professorship at Cambridge, championed this change and his support helped popularize the term in the United States. In 1978, the Division of Solid State Physics became the Division of Condensed Matter Physics.

The new name offered self-identified condensed matter physicists distinct advantages. Crucially, it projected greater conceptual consistency. Even in the early days of solid state physics, the name was maligned because the field's topics and techniques were often equally relevant to liquids, molecules, plasmas, and other non-solids. So long as areas like semiconductor physics remained at the forefront, these inconsistencies were forgivable; but in the 1970s the frontiers shifted. Critical phenomena such as phase transitions, nonlinear dynamics of the type seen in fluid systems, liquid helium research, and other areas that had little or nothing to do with solids moved to the forefront. "Solid state physics" became too blatant a misnomer to ignore.

The name further highlighted the field's intellectual rigor. "Condensed matter," more so than "solid state," called to mind the notoriously difficult quantum many-body calculations. Challenging trends during the 1960s prompted solid state physicists to emphasize their intellectual contributions. High energy physics consumed more and more federal dollars as particle accelerators grew larger. As federal enthusiasm for blue-skies research waned in the Vietnam War era, funding for fundamental solid state research shrunk. Government and industrial funders began demanding clearly articulated, short-term technical payoffs. Some worried that the good questions were drying up alongside the easy money. The Cambridge solid state physicist Brian Pippard groused that "the disappearance of liquid helium, superconductivity, and magneto-resistance from the list of major unsolved problems has left this branch of research looking pretty sick from the point of view of any young innocent who thinks he's going to break new ground" (A. B. Pippard, PHYSICS TODAY, November 1961, pages 39–40).

Breakthroughs in areas like critical phenomena offered a way to defy such despondency while staking claim to some of the intellectual prestige that high energy physics enjoyed amply. When Anderson published his landmark article "More Is Different" in 1972, arguing that new scales of complexity promised a cornucopia of new fundamental and intellectually stimulating questions, applied physics did not need solid state physics to defend its importance. Applications were instead too central to the field for the likes of some.[13] Condensed matter physics was more than a simple rebranding. It represented a priority shift driven by changes in both the intellectual and professional circumstances of American physics.

FIGURE 4. John Trever's cartoon "The Supercompliant Superprovider" depicts the disconnect between high energy physicists' expectations and federal priorities. *Credit*: Copyright 1993, John Trever, Albuquerque Journal. Reprinted by permission

Condensed matter physicists would test these priorities in a high-stakes context during the debates that swirled around the Superconducting Super Collider (SSC). In what high energy physicists perceived as an unprecedented act of betrayal, many prominent condensed matter physicists, including Nobel laurates Anderson and Nicolaas Bloembergen, opposed the SSC—not only in private, but also before the very policymakers who controlled the project's fate. This was a conflict of ideals. For high energy physicists, the route to fundamental knowledge was a one-way reductionist road leading to smaller and smaller length scales. Condensed matter physicists, who perceived fundamental knowledge at many scales, argued that the funding regime the SSC represented hamstrung their field. As Anderson described their frustrations to Congress in 1990, condensed matter physics was "caught between the Scylla of the glamorous big science projects ... and the Charybdis of the programmed research ... where you are asked to do very specific pieces of research aimed at some very short-term goal."[14]

By the late 1980s and early 1990s, when the SSC's merits were being hotly debated in Congress, condensed matter physicists were emboldened to mobilize against it. Their gripes were time-worn. Solid state and condensed matter physicists had long shielded their intellectual worth against charges that they were engaged in "*Schmutzphysik*" or "squalid state physics." And the concern that big accelerator facilities were vacuuming up funds that might otherwise be dispersed more equitably had been voiced repeatedly since the mid-1960s. The significant numerical superiority solid state and condensed matter physics had enjoyed for decades, combined with the resurgence of its intellectual program, meant that by the early 1990s its leaders were prepared to argue not only that they deserved a place at the core of the discipline, but that their aims better represented the aims of physics as a whole than did the parochial interest of high energy physicists.

Conclusions

The story of how condensed matter physics became a central endeavor of American physics is a story of categories and why they matter. In the early twentieth century, physicists might have mapped their discipline straightforwardly like Bern Porter did—tracing the categories they perceived in the natural world—but this too was freighted with ideology. It bore on the type of activity physics was supposed to be. It drew a certain line between who was a physicist and who wasn't, who could claim to be leading the field from the metropole and who was toiling in its outposts. The way scientists build walls around their work, in short, shapes how that work is conducted and how it is valued.

Applied physicists, whose work had been relegated to the periphery by early twentieth-century notions of physics, had learned this lesson well by the end of World War II. Solid state physics was a category crafted because it proved useful for navigating gnarly midcentury professional politics. Condensed matter physics similarly redirected the field at a time when many sensed that "solid state" had grown long in the tooth and was holding portions of the field back. Both were efforts to redraw the map of physics so as to bring the outposts—applied physics in the first case, many-body theory in the second—closer to the metropole. But doing so was not so simple as drawing borders around a new territory on an existing map and calling it "solid state physics" or "condensed matter physics." It required changing the way those borders were drawn in the first place. The result was the subdisciplinary structure by which physicist now classify their labor.

A common sentiment, articulated most sharply by the historian Daniel Kevles, is that "physics is what physicists do."[15] It targets historians' deepest insecurities. *Of course*, we might respond, we don't think disciplines exist without the people who compose them. *Of course* we're critical of human-built categories. The rise of condensed matter physics, however, suggests a modification to the Kevles dictum: physics is what physicists *decide* it is. Solid state physics, and condensed matter physics after it, won prominence in large part because physicists recognized the power of categories and embraced their agency to craft them according to their needs.

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Biographies

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