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# When CONDENSED-MATTER PHYSICS became king

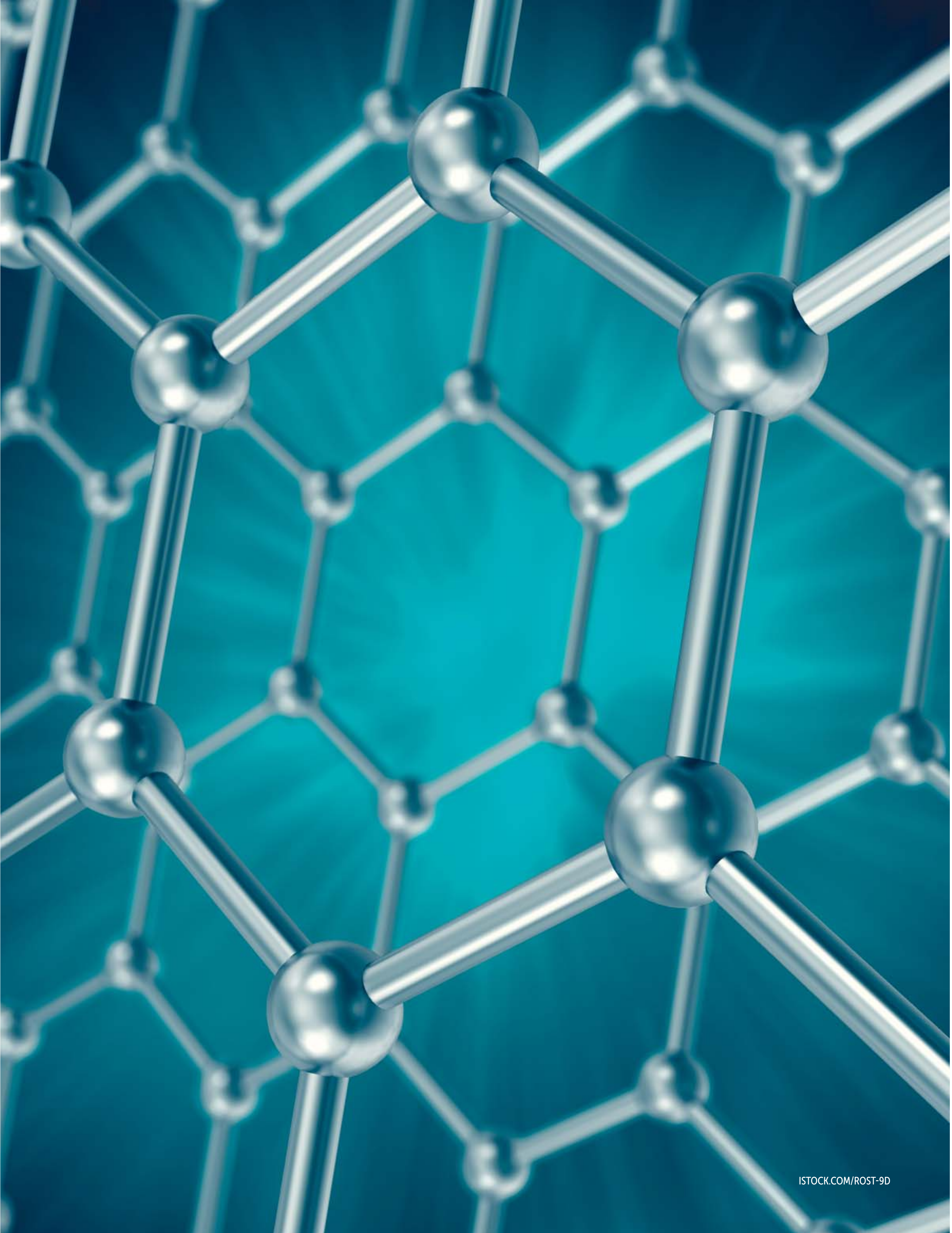
Joseph D. Martin

**The story of how solid-state physics emerged in the postwar period and was eventually rebranded as condensed-matter physics illuminates some major shifts in the late-20th-century physics community.**

Condensed-matter physics is huge. That statement will surprise no one who has attended a March meeting or perused the member rolls of the American Physical Society (APS). The division of condensed matter physics has been the society's largest for decades. But the prominence of condensed-matter physics is recent. Before World War II, no such field existed. It was not until the late 1940s that solid-state physics, its precursor, emerged as a physical subdiscipline.

In his superb book *When Physics Became King*,[1] Iwan Rhys Morus describes how physics itself grew into the preeminent science by 1900. No one in 1800 could have foreseen the vast changes in the status and fortunes of physics that the 19th century would witness. Morus describes physics as becoming "king" in the sense that it came to occupy a central role in Western culture. Physicists marshaled cultural resources—institutional spaces, audiences, patrons, and trust—to create an environment in which their science would become the one most trusted both to probe nature's secrets and to spawn new technologies.

Similarly, in 1900, when physicists were just beginning to probe the secrets of the atom, the prominence that the physics of complex matter would hold by the turn of the 21st century was scarcely conceivable. Condensed-matter physics inherited many of the cultural resources 19th-century physics had secured, so the manner of its coronation and the nature of its sovereignty differed. High-energy physics and cosmology continued to be known for uncovering nature's deepest secrets. But the rise of condensed-matter physics reconfigured how the field of physics was defined and subcategorized. It reflected new ideas about who should be considered a physicist. And it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challenged the cherished ideals on which the US physics community—especially APS—had been founded.

## Should physics be pure?

Henry Rowland, the first president of APS, was the foremost promoter of the ideals that defined turn-of-the-century US physics. Above all, he advocated the pure-science ideal, which held physics separate from applied or "practical" science. Rowland could count himself among the few Americans commanding the international physics community's attention. European physicists infatuated with stellar spectra eagerly snapped up Rowland's precision diffraction gratings (see figure 1). But the practically minded inventor Thomas Edison remained the public face of US science, and Rowland lamented that "much of the intellect of the country is still wasted in the pursuit of so-called practical science which ministers to our physical needs and but little thought and money is given to the grander portion of the subject which appeals to our intellect alone."[2] Rowland and 35 others founded APS in 1899 to minister to the intellect.

APS's advocacy of a pure-science ideal, however, scarcely slowed enthusiasm for science in technical quarters. In 1916, in the middle of World War I, John 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 overtures from industry. Through the interwar period, industrial laboratories employed an appreciable proportion of US physicists and generated an appreciable proportion of the papers published in US physics journals.[4]

At that time, US industry was much enamored of physicists. Many reciprocated its affections, but other physicists stigmatized practical work. A song by physicist Arthur Roberts that made the rounds at MIT's Radiation Laboratory in 1944 manifests the attitude that prevailed in midcentury academic physics. 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 idea that academic and industrial cultures were incompatible reflected a broader transition: Science, previously a calling for few, had become a vocation for many, not all of whom sought traditional academic employment. Sociologists of science like Robert Merton, seeking to understand the norms governing scientific practice, also observed the cultural incompatibilities that resulted from science's expansion.[6] After World War II, the prevalence of the attitude that industrial work compromised dearly held ideals, combined with rapid growth in the number of physicists employed in industry, created a rift within physics that many physicists hoped could be bridged.

## Redrawing the map of physics

The field of solid-state physics emerged 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. For a field like solid state to make sense, physicists had to begin thinking about physics differently.

In 1940 physicist Bernard "Bern" Porter joined the Manhattan Project, which he would quit, traumatized and disillusioned, following the bombing of Hiroshima. He ultimately pursued his passion for art, through which he expressed his struggle with feelings of complicity in the use of nuclear weapons. But in 1939, when Porter was still enamored of physics, he drew a map of it (see figure 2). The map aptly reflects prewar attitudes about how physics was organized—attitudes that solid-state physics flouted.

Porter's map illustrates the view of physics that relegated applied and industrial research to its fringes. Porter represented provinces of physics as geographical regions linked by a river of energy. Joined by a reservoir of radioactivity at its delta, the river 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.

A decade later solid-state physics had emerged as a new province—but it is difficult to see how or where Porter might have included it on his map. Solid-state physics was not a self-contained assembly of topics and methods that could appear as an island, continent, or other natural feature of the disciplinary landscape. It drew from almost all of the regions of Porter's map. It was, in that sense, a strange category.

That strangeness is not a retrospective assessment. In the mid 1940s, the proposal that resulted in the APS division of solid state physics (DSSP) prompted University of Iowa theorist Gregory Wannier to declare, "Solid state physics sounds kind of funny." Two decades later, when the second edition of the American Institute of Physics 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" (see the article by Dwight Gray, Physics Today, July 1963, page 41).

Those 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 like acoustics and optics. Furthermore, physicists did not tend to think in terms of subdisciplinary allegiance. Nuclear and high-energy physicists, for instance, continued to think of their work as simply *physics*. Until the late 1960s they shunned APS divisions for their activ-

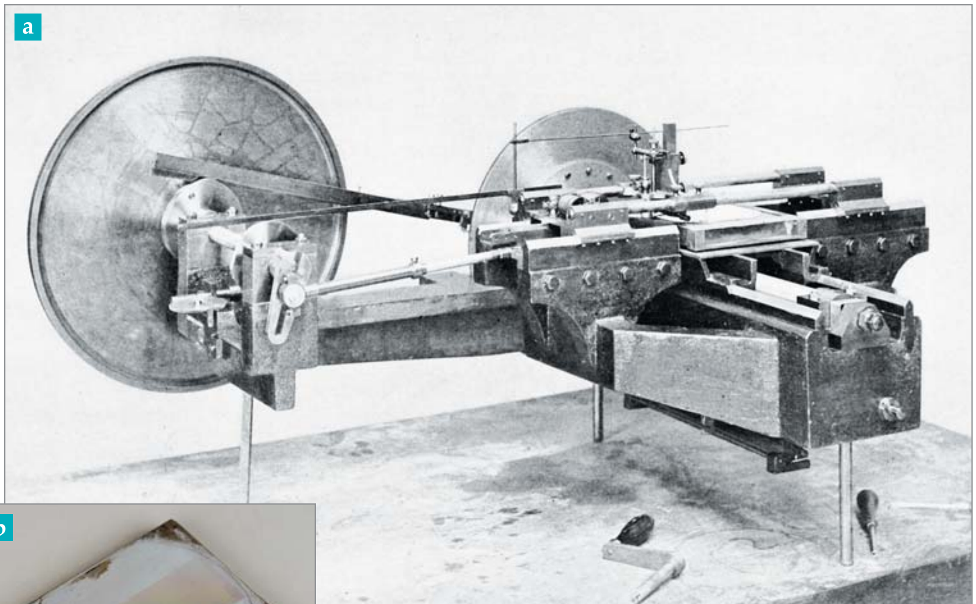

**FIGURE 1. HENRY ROWLAND** designed this ruling engine **(a)** to make precision diffraction gratings that were in high demand worldwide. (Image from *Popular Science Monthly*, May 1896, PD-US.) **(b)** This grating was ruled with one of Rowland's engines. (Image © the Whipple Museum, Cambridge, Wh.6610.)

ities, 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 US physics. When a 1931 amendment to the APS constitution permitted subject-based divisions, suggestions for a division of industrial physics began to roll in. The APS council balked. Industry, in the eyes of APS leadership, was not a subject; a division devoted to it would only deepen the academia–industry rift.

The needs of industrial physicists were nevertheless on the mind of Polish émigré and General Electric (GE) physicist Roman Smoluchowski (see figure 3) when he spearheaded a different proposal for a division of metals physics. Most industrial research, he reasoned, concerned metals—they suffused his day-to-day responsibilities at GE, where he often collaborated with metallurgists. A division of metals physics would offer a home to industrial researchers and also represent academic physicists interested in topics such as magnetism, electricity, and thermal conductivity.

But the APS council demurred when presented with Smoluchowski's proposal, which it judged as too transparently industrial. APS secretary Karl Darrow suggested that the solid state of matter—encompassing metals, other regular solids, and amorphous solids—might offer a better basis for a successful division. Smoluchowski, although initially concerned that a division of solid-state physics would have a more difficult time attracting interest from metallurgists, proved willing to compromise. Through that delicate sequence of contingencies, solid-state physics became a recognized subdiscipline of physics when the DSSP was approved in 1947.

As it is taught today, solid-state physics centers on quantum approaches to regular crystalline solids. Smoluchowski and his collaborators envisioned a significantly broader field, and they convened a January 1945 APS symposium to discuss the proposal for a new division and showcase both its experimental and theoretical scopes. The theorists on the program emphasized the links between the solid state and the latest developments in statistical and quantum physics. 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, beginning in the early 20th century with phenomenological treatments and later describing competing quantum mechanical approaches.

The symposium also demonstrated a commitment to applied research. Among the speakers were Richard Bozorth and Howell Williams of Bell Labs, who described their efforts to understand "the behavior of magnetic materials in apparatus developed as a part of the war effort."[7] Watertown Arsenal's Clarence Zener, presenting on the fracture stress of steel, noted that "the sinews of warfare, namely guns, projectiles, and armor, are made of steel."[8]

Van Vleck's interest in a robust, quantum-mechanical description of ferromagnetism had little to do conceptually with Zener's work on the phenomenology of steel. The link between those topics was much weaker than, say, the link between ferromagnetism and the magnetic susceptibility of gases, another Van Vleck specialty. The new DSSP aimed to unite a menagerie of approaches and questions, at least professionally.

Solid state's odd constitution reflected changing attitudes about physics, especially with respect to applied and industrial research. A widespread notion in the physics community held that "physics" referred to natural phenomena and "physicist" to someone who deduced the rules governing them—making applied or industrial researchers nonphysicists almost by definition. But suspicion of that view grew around midcentury. Stanford University's William Hansen, whose own

**ON THE WEB**

**PHYSICIST AND BLOGGER DOUGLAS NATELSON WEIGHS IN ON THE MODERN IMAGE OF CONDENSED-MATTER RESEARCH.**

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applied work led to the development of the klystron (a microwave-amplifying vacuum tube), reacted to his colleague David Webster's suggestion in 1943 that physics was defined by the pursuit of natural physical laws: "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 ensured that it would not discriminate against industrial or applied physicists, who often described their focus broadly. The new DSSP could span academic and industrial territories and topical categories that were otherwise dissociated.

## The solid-state boom

The new field flourished. In the early Cold War, government and industry were willing to spend liberally—indeed, almost haphazardly—on both abstract and technical research, and solid-state physics reaped the rewards of that largesse. It attracted a significant proportion of PhD 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 Labs physicists working with semiconductors, illustrates how the flexibility of the term "solids" (as opposed to

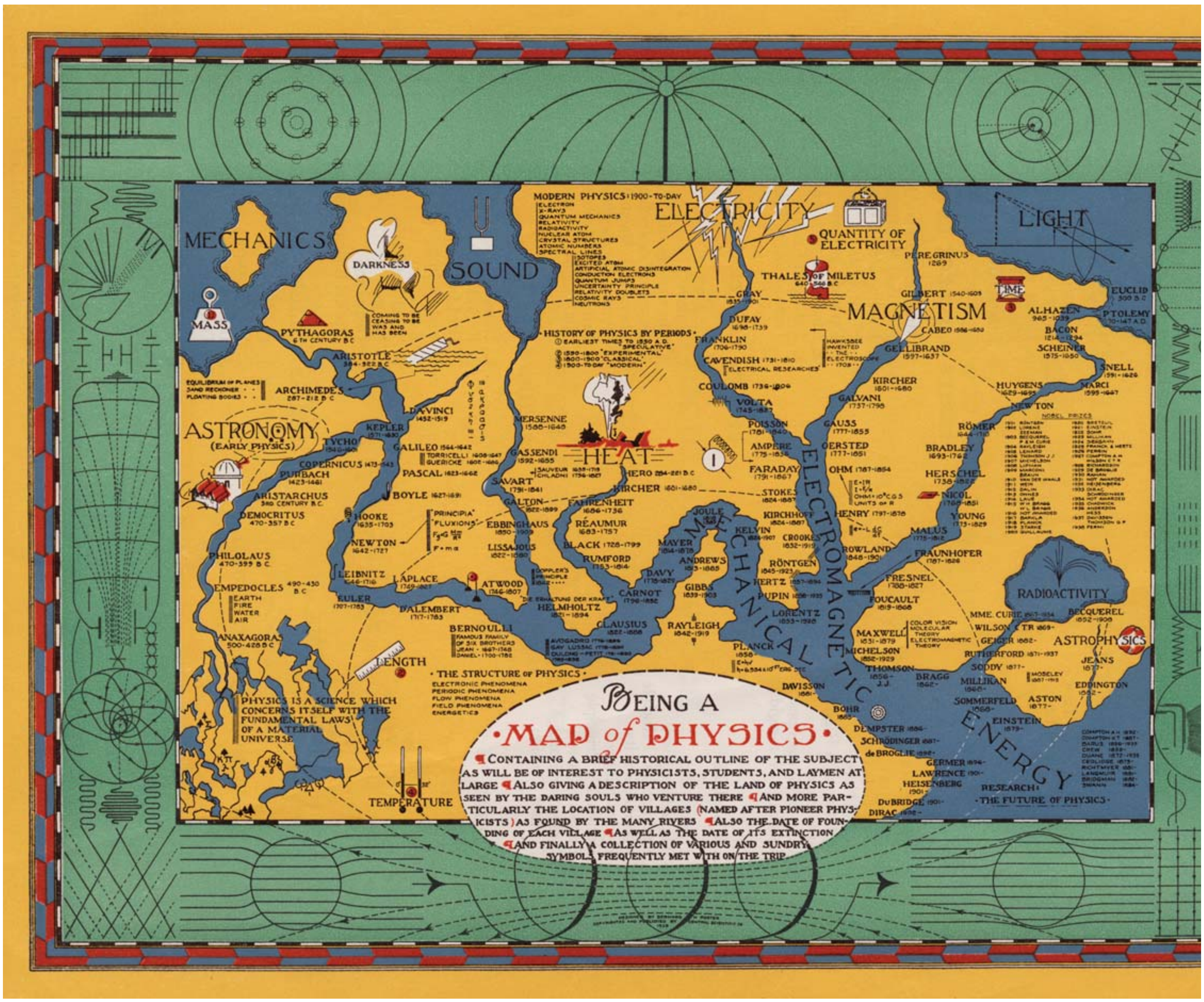
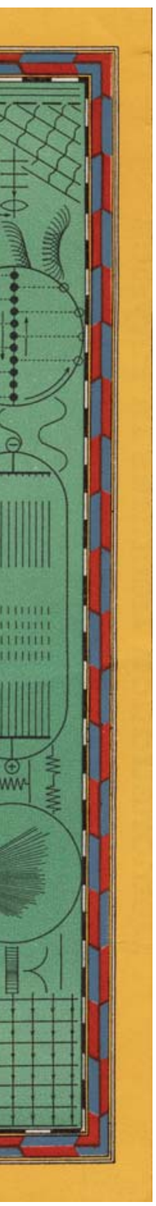



**FIGURE 2. BERNARD PORTER'S MAP OF PHYSICS, 1939,** illustrates a perspective in which physics is categorized in terms of natural phenomena. (Reproduced with permission of Mark Melnicove, literary executor for Bern Porter, mmelnicove@gmail.com. From the Bern Porter Collection, Special Collections, Miller Library, Colby College, Waterville, Maine.)

"metals") permitted solid-state physics to lay claim to lively new research areas. The late 1940s also saw the birth of NMR spectroscopy, another technique that would become central to solid-state research.

Two factors account for the rapid expansion of solid-state physics in the early postwar era. One, it scratched a persistent itch. Applied physicists, long underserved by the flagship institutions of US physics, embraced new organizational efforts that advanced their interests. Two, because the field 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 many different topical specialties and those with diverse interests.



But because few research programs explicitly focused on the solid state of matter, solid-state physics often included research that had little solid about it. Van Vleck's classic work on the magnetic susceptibility of gases became part of the solid-state canon. The first maser, assembled by Charles Townes and his research group, was based on ammonia gas. And the superfluidity of helium, discovered by Peter Kapitza in 1937, launched a fruitful research program that solid-state physicists also called their own.

Some of those areas, such as semiconductor physics, were integral to solid-state physics when it formed. Others, such as NMR and low-temperature physics, the field claimed in retrospect. Because solid-state physics was an artificial category, it was a flexible one, with latitude to encompass promising new research areas. So long as solid-state physics provided a space for physicists who were working on the properties of aggregate matter, its practitioners were willing to turn a blind eye to any categorical oddities.

By the early 1960s, the DSSP had become—and has remained since—the largest division of APS. By 1970, following a membership drive at APS meetings, the DSSP enrolled more than 10% of the society's members. It would reach a maximum of just shy of 25% in 1989. Membership in the DSSP has regularly outstripped the division of particles and fields, the next largest every year since 1974, by factors of between 1.5 and 2.

David Kaiser has described the boom-and-bust cycles that characterized the explosive growth of postwar American physics as a whole, emphasizing the changes that growth exerted on graduate education.[10] Physics students, instead of being closely supervised, began to be trained en masse. Close mentorship of graduate students gave way to large lecture courses designed to quickly confer the necessary facility with the mathematical formalism of quantum mechanics, with a focus on calculation over foundations. Rapid quantitative growth, that is, led to a qualitative change in how physics was taught and, therefore, practiced.

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 US physics also speaks to a substantive transformation in US postwar physics. The new field embraced links between the abstract and the technical and 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 US physics was changing. It was beginning to resemble a loosely aligned patchwork of specialties with varying degrees of commitment to APS's founding ideals. Physics as a whole was starting to look much more like solid-state physics.

## Solid state becomes condensed matter

Solid-state physics was engineered to address a set of distinctive midcentury professional challenges. It is hardly surprising, therefore, 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" because of practitioners' increasing interest in nonsolid states of matter and the quantum many-body problem.[11]

**FIGURE 3. ROMAN SMOLUCHOWSKI,** an advocate for a metals division of the American Physical Society, works with alloy samples at General Electric. (AIP Emilio Segrè Visual Archives, courtesy of Roman Smoluchowski.)

The new name took hold in Europe before spreading to the US. The journal *Physik der kondensierten Materie*, published simultaneously in French as *Physique de la matière condensée* and in English as *Physics of Condensed Matter*, was founded in West Germany in 1962. The journal's editors contrasted their new publication's subject 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 its interests as "theory of condensed matter." Philip Anderson, a Bell Labs theorist who held a seasonal professorship at Cambridge, championed that change, and his support helped popularize the term in the US. In 1978, APS's division of solid state


**FIGURE 4. JOHN TREVER'S CARTOON "THE SUPERCOMPLIANT SUPERPROVIDER"** depicts the disconnect between high-energy physicists' expectations and federal priorities. (© 1993, John Trever, *Albuquerque Journal*. Reprinted by permission.)

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 nonsolids. So long as areas like semiconductor physics remained at the forefront, those inconsistencies were forgivable, but in the 1970s the frontiers shifted. Critical phenomena such as phase transitions, nonlinear dynamics of fluid systems, and liquid-helium research that had little or nothing to do with solids took center stage. Solid-state physics became too blatant a misnomer to ignore.

The name also highlighted the field's intellectual rigor. "Condensed matter" called to mind the notoriously difficult quantum many-body calculations more than "solid state," and trends during the 1960s prompted solid-state physicists to emphasize their intellectual contributions. As federal enthusiasm for basic research waned in the Vietnam War era, funding for fundamental solid-state research shrank, even as high-energy physics consumed more federal dollars for larger particle accelerators. Government and industrial funders began demanding clearly articulated, short-term technical payoffs.

Some practitioners worried that the good research questions were drying up alongside the easy money. Cambridge solid-state physicist Brian Pippard groused that "the disappearance of liquid helium, superconductivity, and magnetoresistance 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" (see Pippard's article, PHYSICS TODAY, November 1961, page 39).

Breakthroughs in areas like critical phenomena offered a way for solid-state physicists to defy such despondency. They also helped the field stake a claim to some of the intellectual prestige that high-energy physics enjoyed. In 1972 Anderson published a landmark essay in *Science* entitled "More Is Different," in which he argued that each new scale of complexity that scientists engaged with promised a cornucopia of new fundamental and intellectually stimulating questions.[13] As condensed-matter physicists tackled more complex physical phenomena, they could therefore expect to open up new intellectual frontiers. Adopting the name 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 US physics.

Condensed-matter physicists would test those priorities during the debates that swirled around the Superconducting Super Collider (SSC) in the early 1990s (see figure 4). In what high-energy physicists perceived as an unprecedented act of betrayal, many prominent condensed-matter physicists, including Nobel laureates Anderson and Nicolaas Bloembergen, opposed the SSC—not only in private but also before the policymakers who controlled the project's fate.

It was a conflict of ideals. For high-energy physicists, the route to fundamental knowledge was a one-way road leading to smaller and smaller length scales. Condensed-matter physicists, who perceived fundamental knowledge at many scales, argued that the funding regime that supported projects like the SSC hamstrung other fields in physics, including and especially their own. As Anderson told Congress in 1989, condensed-matter physics was "caught between the Scylla of the glamorous big science projects . . . and the Charybdis of programmed research . . . where you are asked to do very specific pieces of research aimed at some very short-term goal."[14]

Gripes like Anderson's were timeworn. Solid-state and condensed-matter physicists had long defended 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. But the significant numerical superiority solid-state and condensed-matter physics had enjoyed for decades, combined with the resurgence of its intellectual program, emboldened the field's leaders. By the late 1980s, condensed-matter physicists 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.

## The power of categories

The story of how condensed-matter physics became a central endeavor of US physics is a story of categories and why they matter. In the early 20th century, physicists might have mapped their discipline like Bern Porter did—by tracing the categories they perceived in the natural world. But that method was freighted with ideology. It made a statement about the type of activity physics was supposed to be. It drew a 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 draw borders around their work shapes how that work is conducted and how it is valued.

Applied physicists, whose work had been relegated to the periphery by early 20th-century notions of physics, had learned that lesson well by the end of World War II. Solid-state physics was a category crafted to help industrial physicists navigate 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 to bring the outposts—applied physics in the first case, many-body theory in the second—closer to the metropole. But the process was not so simple as drawing borders around a new territory, appending it to an existing map, and calling it solid-state physics or condensed-matter physics. Creating those fields required changing the way those borders were drawn in the first place.

A common sentiment, articulated most sharply by historian Daniel Kevles, is that "physics is what physicists do."[15] 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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