Mildred Dresselhaus and Solid State Pedagogy at MIT

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When Mildred Spiewak Dresselhaus (figure 1) passed away in February 2017, she left behind an indelible legacy. The "Queen of Carbon," as she was known, pioneered the physical study of the sixth element well before the keen attention attracted by buckyballs and nanotubes. Her groundwork ensured that when Andre Geim and Konstantin Novoselov isolated and characterized graphene, they were a shoe-in for the Nobel Prize, which they took home in 2010. Dresselhaus also earned renown for her advocacy on behalf of women in science. She was the first woman to be honored with the title of Institute Professor at the Massachusetts Institute of Technology (MIT) and she pioneered leadership roles for women in many of the professional societies and organizations to which she belonged. Here, I focus on a less noted (though no less noteworthy) aspect of her legacy: her influence as a pedagogue.

The characteristic approach Dresselhaus brought to her teaching is evident in two sources. The first is a series of oral history interviews, which document her childhood, education, and career, and record some of her convictions about teaching. The second is set of notes from the 1972 iteration of Dresselhaus's solid state theory course at MIT. Taking these sources as a starting point presents two paths for exploration. The inward path probes Dresselhaus's personal development and the experiences that informed her teaching. The outward path explores how this one course fit within the pedagogical practices of physics in postwar America. The first reveals how early experiences shaped the convictions of a successful and much-lauded teacher. The second reveals some of the strategies committed teachers could employ to combat the dog-eat-dog environment that began to prevail as the population of physics students boomed in the post–World War II years. Together, they help us think about why we teach physics the way we do.

Figure 1. Mildred Dresselhaus stands by her portrait at American Institute of Physics. Credit: American Institute of Physics, Emilio Segrè Visual Archives

Student and Teacher

Dresselhaus began teaching university physics in 1967 when she transitioned to the Massachusetts Institute of Technology (MIT) electrical engineering department from the Lincoln Laboratory, a defense research installation loosely affiliated with the institute. But her teaching career had much deeper roots. Appreciating their influence on her later career requires understanding something of her origins.

The front page of the *New York Times* announced "1.7% Decline in Jobs Spurs Relief Groups to Rush Aid for Idle" on the day Mildred Spiewek was born in Brooklyn. It was November 11, 1930, just over a year after the Black Tuesday stock market crash. The Great Depression weighed heavily on the Polish–Jewish immigrant family in which Dresselhaus grew up.[1] From the time she was able, she contributed to the household finances by doing piecework assembly tasks at home and working in a zipper factory over the summer.

But what the Spiewek family lacked in private means the young Millie, as she was known, more than made up for with public resources. She was captivated by New York's museums. The American Museum of Natural History, the Metropolitan Museum of Art, and others allowed free admission and a keen teenager could scurry among them on the subway for a nickel a ride. Dresselhaus would later credit these museums with sparking her interest in science. It wasn't only the *free* museums that caught her attention. She also snuck into the Hayden Planetarium repeatedly, committing their shows and collections to memory. Once, she was caught: "I told them that I wasn't trying to do anything wrong as far as their collection was concerned; I didn't have any money, and I was interested in astronomy. And they just sent me packing; they didn't book me for charges. And then I went right back, after a couple of weeks, you know, a cooling-off period. I went right back to my old tricks of getting in."[2]

New York City's public resources again served Dresselhaus well when it came time to select a high school. The under-resourced grade school in the Bronx that she attended had little knowledge of how to funnel talented students into the city's magnet schools for high-achieving students, but her older brother (nuclear engineer Irving Spiewak), who attended the Bronx High School of Science, made her aware of the opportunity for girls with strong academic records to apply to the Hunter College High School. "I wrote away for information and got some old exams and looked at them," Dresselhaus recalled. "I didn't know what anything was. I couldn't even understand the language on these exams; it was like another world. But, New York has very good libraries.... I checked out books and got to work, and I figured out how to do all these problems. I took the exam, and I got into the school."[3]

This voracious appetite for free (or purloined) knowledge translated into the classroom, where Dresselhaus was a star student. She distinguished herself particularly at Hunter High, but even before she set foot on its Manhattan campus, her academic accomplishments had led to her first teaching job. When she was in the sixth grade, a teacher asked her to tutor a developmentally disabled first grader, a job she continued for two years, earning 50¢ a week. Although she founded it frustrating, it introduced her to teaching and she found she had an aptitude for it. In high school, tutoring became a money spinner. Her reputation grew so strong by the time she graduated from high school and enrolled in Hunter College that she could command the princely sum of $5 an hour (about $60–70 in 2018 dollars). Tutoring well-to-do students in everything from math and physics to English and Spanish covered her living expenses throughout her undergraduate years and allowed her to stash away funds that supported her graduate education as well.

The early knack Dresselhaus showed for math and the physical sciences blossomed during her university years. The late 1940s was an unusual time for Hunter. Although traditionally a women's college, it had opened its doors to the World War II veterans who flooded American universities following legislation that provided free tuition for returning service members (commonly known as the GI Bill). Dresselhaus found herself in math and physics classes alongside men who were, on the whole, much less well prepared than the Hunter women. "The boys in the science classes were toward the bottom of the class.... They always used to come to me for help," Dresselhaus recalled. "That might be somewhat significant in my story, because I *never* got the idea in college that science was a man's profession."[4]

If the particular circumstances of Hunter College in the postwar years provided the conditions that permitted Dresselhaus to envision herself as a scientist, an attentive professor gave her the push she needed to pursue a scientific career. In 1977 Rosalyn Yalow would win the Nobel Prize in Physiology or Medicine for work she did as a medical physicist employed by the Bronx VA Hospital. But from 1946 to 1950, she taught physics at her alma mater, Hunter College, where she became a mentor to Dresselhaus, encouraging her to apply for graduate fellowships and pursue a career in physics. By the time she graduated Hunter, winning a Fulbright Fellowship to continue her physics studies at the University of Cambridge, Dresselhaus was well on her way to one.

Two features of Dresselhaus's early education and teaching experiences are worth emphasizing. First, she cut her teeth as an instructor in one-on-one tutoring. Her experience engaging students in this way would stand out in a context dominated by the mass production, calculation-focused approaches that were adopted to cope with the influx of students into physics programs in the 1960s and 1970s. Second, even in the mid-1970s after her career was firmly established and she sat for an extended interview with Shirlee Sherkow, Dresselhaus remained acutely aware of the role public cultural and educational institutions had played in her own development and was reflective about the importance of a resource-rich environment for nurturing success. Both of these features would inform her pedagogical approach when she arrived at MIT.

Teaching Solid State Physics at MIT

Dresselhaus's Fulbright led to an MA at Radcliffe College and then studentship at the University of Chicago, where she completed a PhD with Enrico Fermi. Fresh out of graduate school, she landed a National Science Foundation postdoctoral fellowship at Cornell University. Millie had married a fellow Chicago physics student, Gene Dresselhaus, and the widespread anti-nepotism rules many universities employed at the time, which prevented husband-and-wife teams from holding paid employment in the same department, constrained their job search. Those constraints took them both to the Lincoln Laboratory, a defense research organization in Cambridge, MA, in 1960.

At Lincoln, Dresselhaus began her landmark work on the physics of carbon. The lab's association with MIT also afforded her the opportunity to begin co-supervising the occasional PhD student, paving the way for her 1967 move from Lincoln to the Institute. Amid the nationwide funding crunch of the mid-1960s, the research culture at Lincoln had deteriorated in Dresselhaus's eyes and a university job offered a welcome change. The appointment was originally a visiting professorship, the Abby Rockefeller Mauzé Chair, endowed by the Rockefeller foundation to support women faculty. But the teaching Dresselhaus conducted during her year in the Mauzé Chair, in particular her course on solid state theory, proved so essential that the electrical engineering department wrangled a permanent position for her after the one-year visiting post expired.

A set of notes from the fall 1972 edition of this course provides crucial insight into how Dresselhaus introduced the theory of solids. The course adopted Charles Kittel's *Introduction to Solid State Physics*, by then in its third edition, as its principal textbook. This book had first appeared in 1955, when it responded to the strong applied inflection solid state physics had taken on after World War II. In that respect, it contrasted the previous standard, Frederick Seitz's *Modern Theory of Solids*. As John J. Hopfield recalls of his training at Cornell in the

1950s, Kittel's exposition "left you (as a theorist) with no idea of where to start to develop a deeper understanding of any of the topics covered."[5] This book would have been more accessible to engineers than the highly abstract style that dominated John Slater's physics department. Dresselhaus addressed the shortcomings Hopfield identified by supplementing Kittel's book with 302 pages of hand-written, photocopied notes.

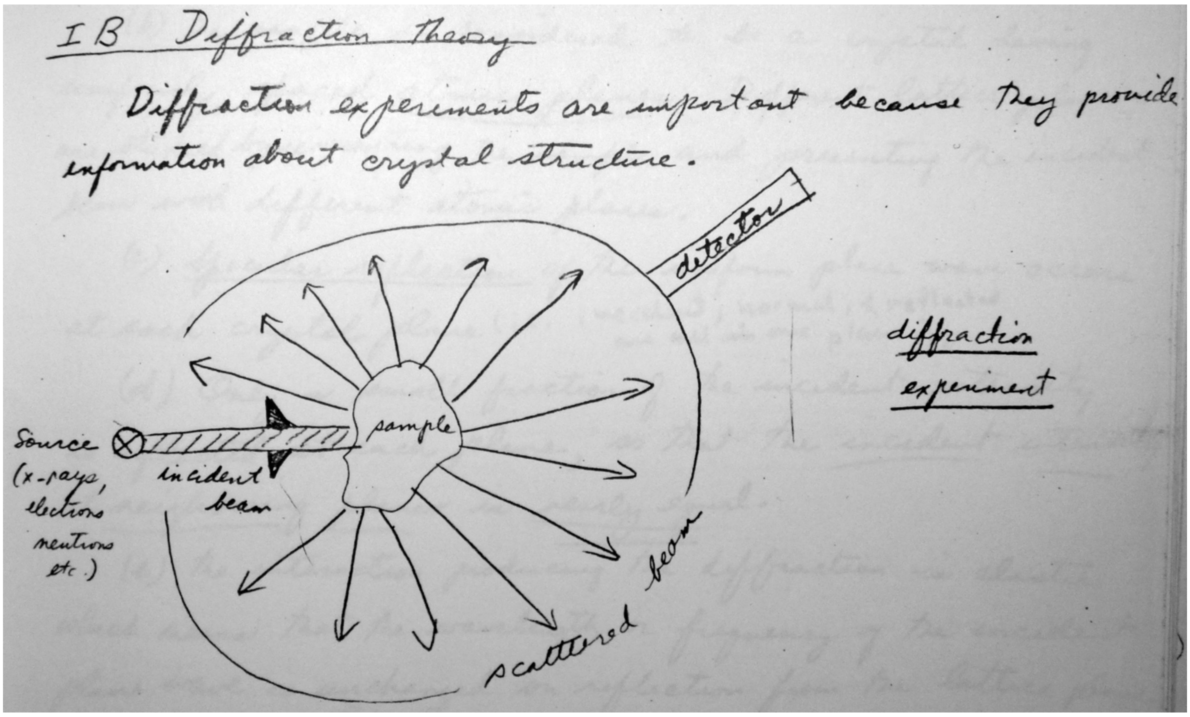

Figure 2. An excerpt from the course notes Mildred Dresselhaus prepared for her solid state theory course. Careful, qualitative explication and diagrams were a hallmark of her approach. *Credit:* Courtesy of Randal Richardson

The notes are so thorough, in fact, as to render any textbook secondary. They begin with a methodical presentation of crystal structure and lattice dynamics, before leading into a detailed presentation of the electronic states of solids, which the course dwelled upon because "for most of the practical applications of solids to our technological development, it is probably the electronic properties that are of the greatest interest."[6] Each section begins with a qualitative description of the phenomena under investigation, usually with some reference to the relevant experimental techniques (figure 2). Dresselhaus adopted the visual style found in *Principles of the Theory of Solids* by John Ziman, and reproduced many of its figures.[7] Relegated to the "Other Suggested References" section were Seitz's *Modern Theory of Solids*, Slater's *Quantum Theory of Molecules and Solids*, and other books that took a more abstract approach.

Dresselhaus's own recollection of the role this course came to play at MIT is worth quoting at length:

> We had a following of the electrical engineering students and the physics students. In more recent times [mid-1970s], we've made the courses all a joint course between physics and electrical engineering.... When I first came to the Institute in the Electrical Engineering Department, there was a lot of applied work. What needed help was the teaching of basic solid state courses because these courses weren't being done in the Physics Department. That was an area of the Physics Department that was not much emphasized at the time. So there were inadequate courses available in the physics of solids. I helped in setting up courses in those areas.[8]

Solid state in the MIT physics department was the province of John Clarke Slater's solid state and molecular theory group. Focused on using the newest computing technologies to attempt increasingly exact *ab initio* calculations of wavefunctions for solids and molecules, this group advanced a brand of solid state theory too abstract for most physics and engineering undergraduates. In Dresselhaus's more pointed phrasing, "Slater's group taught Slater physics. He wasn't interested in the engineering students, and he wasn't interested in teaching them what they needed to know to solve their problems. So that was my job."[9] And the recently formed National Magnet Laboratory, although it conducted a great deal of in-house graduate research supervision, offered little in the way of core coursework.[10] Despite being an international center for solid state physics research, MIT had a dearth of solid state courses on the books that catered to the practical needs of its physics and engineering students.

Adherents to the abstract approach to solid state physics, which Slater championed in the physics department, had maintained an uneasy relationship with the applied arm of the field since it was established as a distinct area of physics in the late 1940s.[11] Dresselhaus's move to MIT unfolded amid that context. Solid state physics was struggling with its identity as a subdiscipline of physics; it had been founded to create greater representation for applied and industrial physicists, but many of its practitioners continued to fight for recognition as a fundamental area of physics, and so shied away from emphasizing the field's practical dimensions. That impulse created a lacuna at MIT, and Dresselhaus's willingness to present the latest in solid state theory in a way that emphasized its utility for practically minded physicists and engineers addressed the considerable appetite for such a course among MIT students.

Building Infrastructure

Dresselhaus's efforts to improve the educational environment at MIT did not stop at the classroom door. Remaining conscious of the power of an encouraging environment, she set about changing the institute in ways that created ambient resources talented people could exploit. Informed by both her own experiences as a learner and her family life, these efforts reflected a model of physics education that few other physicists were pursuing at the time.

Many of these focused on the needs of women at MIT, who were a steep minority among the students and the faculty alike. "The few women students that we had were having a really hard time. The dropout rate was very large. They were in classes and they were harassed by the guys and the professors," Dresselhaus recalled. Her response was to develop communal resources:

> All the undergraduates could come to my seminar, and we had a mentoring seminar helping them how to cope with being the only girl in the class and how to deal with harassment. They were getting advice from the other ones, how they coped with given situations. We discussed strategies. Many people, they remember this and they come to me and say how helpful that was in getting through their undergraduate work here. So team action…. We tried to address what to do and what not to do. And it was also education for the faculty. I had another seminar—I had a seminar for the students; I had a seminar for the faculty because we started hiring women faculty because we had only 4% women students, so we had essentially no women faculty. When they started coming, they also had trouble with the system and making progress, so I started a seminar.[12]

The seminar, which she co-led with her colleague, the aerospace engineer Sheila Widnall, also provided an orientation to engineering, covering skills, particularly manual skills, that many instructors assumed boys picked up as a matter of course as children.[13] This component of the seminar also became popular with MIT men, who increasingly arrived at the institute without such stereotypical backgrounds. Anecdotal evidence suggests that these interventions made a difference; veterans of the seminar reported to Dresselhaus that they were instrumental in keeping them at MIT at junctures when they were considering leaving.

This strategy was adapted to the peculiar circumstances women at MIT encountered in the 1970s, but it was also reflective of Dresselhaus's general approach to creating an educational environment. According to her own description of her approach, she consciously imported strategies from her family life into her work life. Watching how her daughter coped as the lone girl among three brothers informed her implementation of support structures for MIT's women undergraduates. And a similar approach governed how she managed her research group. She instituted a practice that would now be considered routine: regular group meetings. Evidently uncommon at MIT at that time, such meetings were not a habit she had picked up in Chicago, where Fermi's laissez faire style left students with a great deal of independence.

Instead, Dresselhaus recalled, "I learned this from my children, how I do family. I have four children, and they learn a lot from each other.... So I said, 'Well, students should be the same way.' If we meet once a week and talk about some interesting thing we were doing for them to report, the other guys will learn about it and it will help them sometime in their career. It was a good idea. Everybody's doing it now, but at that time nobody was doing it."[14] Later in her career, Dresselhaus would apply this ethos to building other supporting structures for students, and especially for women in science. She helped found the Rising Stars initiative at MIT, a workshop founded in 2012 that brings together women graduate students and postdocs interested in academic careers to share their experience and access mentoring opportunities from established faculty.

Such a familial approach to physics pedagogy was novel. Quantum physics in the 1960s and 1970s, which most physics students would have to grapple with, was dominated by the "shut up and calculate" ethos. Thinking about foundations and broad conceptual issues was discouraged at the expense of mastering the demanding formalism of quantum mechanics.[15] Cambridge, MA, was the epicenter of this approach. At Harvard University, Julian Schwinger taught using his homebrew quantum formalism, lecturing by covering the board with equations, sometimes writing with both hands at once. Baffled Harvard students would travel down Massachusetts Avenue to audit Victor Weisskopf's quantum course, a more accessible, but no less formalism-focused offering.[16]

As David Kaiser shows, this laser focus on the mathematics of quantum mechanics at the expense of its foundations derived from the population pressures physics was experiencing. The same incentives that had populated Dresselhaus's Hunter College science courses with male students—in particular the GI Bill and the skyrocketing cachet of a physics degree—packed classrooms with physics students, at both the undergraduate and graduate levels. University teachers responded by retreating from one-on-one mentorship, teaching larger classes, and focusing on drilling students in mathematical techniques, which could be taught through lectures to hundreds of students and assessed straightforwardly with written examinations. The result was physics pedagogy red in tooth and claw. Students would have to develop the requisite mathematical competency quickly, and largely without direct oversight, or risk washing out.

The ethos Dresselhaus brought to MIT offers a stark contrast and demonstrates that the turn to narrowly calculational approaches and a sink-or-swim mentality, although reflective of the circumstances, were far from determined by them. Dresselhaus leveraged the abundance of eager physics students by using groups to encourage productive interaction effects among them. She embraced a visual and conceptual approach to solid state theory that made the link between foundations and applications evident. And to combat the psychological challenges the sink-or-swim culture exerted on student, especially women, she recognized the value of sharing tacit expertise and the salutary effects of community for a learning environment.

Conclusions

Dresselhaus was active in research, teaching, and professional organization up to the end of her life, and so the full extent of her legacy will come into clearer focus in time. But it is already evident that her story has much to tell us about the history of science, and that it contains timely lessons for its present. Many of these lessons come from examining Dresselhaus's career as a teacher. Physics curricula often feature an early "weed-out" course, designed to scare away students who lack the adequate mathematical preparation, or who can't acquire it quickly enough. Brutality is sometimes held up as a cultural ideal.[17] This practice, a legacy of those oversubscribed courses of the Cold War era, has little to recommend it in an era when physics is struggling to keep up with the much larger enrolments in biology programs. But even in the heyday of the shut-up-and-calculate ethos, Dresselhaus developed a way to teach physics that was supportive and inclusive while still being demanding and rigorous. The students who took Dresselhaus's solid state theory course at MIT remember it as a model of clarity, and her prolificacy as a graduate advisor—supervising over sixty PhDs and working with countless visiting students—speak to the fruitfulness of her educational philosophy.

Dresselhaus's story also prompts us to look to solid state and condensed matter physics in order to enrich our understanding of twentieth-century science. The story of quantum pedagogy is now well explored, as is the way it translated into the postwar teaching of high energy physics.[18] The manner in which Dresselhaus arrived at MIT, the distinct issues that informed the landscape of solid state pedagogy, and the ways she navigated them, all suggest that engaging not only with how physicists learned the foundations, but also with how they absorbed the connections between foundations and applications, can open new ways of thinking about the history of how physics was taught and learned.[19]

Finally, at a moment when cultural institutions, especially in the United States, are threatened, Dresselhaus's childhood is a reminder of the importance of public resources for nurturing talent. The young Dresselhaus was a gifted, self-motivated child of humble means, and it would be tempting to suggest that she pulled herself up by her bootstraps. Indeed, she showed uncommon gumption. But she deployed it by clambering up the sturdy rungs of public infrastructure, including New York City's public libraries, public museums, public schools, and the public transit system linking them. "I know there must be hundreds of thousands of people out there," she reflected in 1976, who "could have done the same thing, if circumstances were a little different for them."[20]

Acknowledgments

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[1] Despite the anachronism associated with referring to the subject of this article as "Dresselhaus" at times before she married and changed her name, I refer to her that way throughout, except when referencing her birth name specifically, for the sake of consistency and to avoid placing any undue emphasis on her marriage as a discontinuity in her identity or career.

[2] M. S. Dresselhaus, interview with S. Sherkow, 7 and 15 June, 11 and 19 August, 13, 20, 22, 24, and 30 September, and 15 October 1976. MIT Archives and Special Collections, Cambridge, MA, 18.

[3] Dresselhaus, interview with Sherkow, 26.

[4] Dresselhaus, interview with Sherkow, 32–33.

[5] J. J. Hopfield, Annu. Rev. Condens. Matter Phys. **5**, 1–13 (2014), p. 3.

[6] M. S. Dresselhaus, 3.42J Theory of Solids, Course Notes of Randall M. Richardson, Fall 1972, in author's possession, to be conferred to the MIT Archives and Special Collections.

[7] J. M. Ziman, Principles of the Theory of Solids (Cambridge: Cambridge University Press, 1964)

[8] Dresselhaus, interview with Sherkow, 192–193.

[9] M. S. Dresselhaus, interview with J. D. Martin, 24 June 2013. Niels Bohr Library and Archives, College Park, MD.

[10] For more on the National Magnet Laboratory, see J. D. Martin, Hist. Stud. Nat. Sci. **45**(5), 703–757 (2015).

[11] For further discussion of this tension, see J. D. Martin, Solid State Insurrection: How the Science of Substance Made American Physics Matter (Pittsburgh: University of Pittsburgh Press, 2018).

[12] Dresselhaus, interview with Martin.

[13] Amy Sue Bix, in Jill M. Bystydzienski and Sharon R. Bird (eds.), Removing Barriers: Women in Academic Science, Technology, Engineering, and Mathematics (Bloomington: Indiana University Press, 2006), 55.

[14] Dresselhaus, interview with Martin.

[15] D. Kaiser, How the Hippies Saved Physics (New York: Norton, 2011).

[16] J-F. Gauvin, Phys. Persp. **20**(1), 8–42 (2018).

[17] See J. S. Rigden, History of Physics Newsletter **13**(6), 3 (Spring 2018), https://www.aps.org/units/fhp/newsletters/spring2018/upload/spring18-rev.pdf.

[18] See, e.g., M. Badino and J. Navarro (eds.), Research and Pedagogy: A History of Quantum Physics through its Textbooks (Berlin: Edition Open Access, 2013) and D Kaiser, Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics (Chicago: University of Chicago Press, 2005).

[19] See also C. Joas and M. Eckert, Annu. Rev. Condens. Matter Phys. **8**, 31–39 (2017).

[20] Dresselhaus, interview with Sherkow, 38.