What's the difference between Materials Science and Condensed Matter Physics?

Chuliang Fu
(Dated: August 11, 2025)

I recently noticed that a rather old answer of mine on Zhihu (a Chinese social media like Quora) has been getting some attention, so I asked ChatGPT to help me tidy it up, reformulate, and post a revised version here on my WeChat blog. (For the record, all the polite, slightly wooden sentences are probably ChatGPT's doing; anything that feels awkward, I'm more than happy to blame on the bot—job done, scapegoat secured, haha.)

I won't say exactly which Zhihu answer it was, but here's a funny side note: I've been hitting up new restaurants on Saturdays with a few younger lab-mates, then heading to the library to study together. They came across that post on Zhihu and started discussing it, and I just didn't have the heart to tell them, "Uh, yeah... I actually wrote that."

Whenever we talk about a discipline, we usually point to its "core courses" as a kind of "characterization" or "representation". Math majors have the four Analyses (real, complex, Fourier, functional) plus layers of algebra and geometry. Physics students get the "four mechanics": classical mechanics, quantum mechanics, electrodynamics, and statistical mechanics in the common Chinese physics department. The chemistry department has inorganic chemistry, organic chemistry, analytical chemistry, and physical chemistry. These foundational fields, polished by generations of theorists and experimentalists, look elegant and complete. Applied or engineering disciplines, by contrast, rarely fit so neatly into a box; they straddle fundamental science and real-world practice and can easily lose their identity. Compared with condensed-matter physics, materials science (or "applied physical matter science," if you like) sometimes feels hard to pin down.

So what should we teach? Where should the emphasis lie? Should students dive deep into fundamentals or jump straight into hands-on work? If you do theory in a materials department, how do you distinguish yourself from physics? Too theoretical—why not just study physics? Too practical—why not go to a technical college and master a trade? How do we build a curriculum that genuinely prepares the next generation?

Let's walk through it.

Historically, materials science in the U.S. is young and eclectic: in the 1960s, ARPA (now DARPA) funded "Materials Science Laboratories" to bundle disparate research efforts under a new banner. At first glance, materials science may appear to be a product of funding structures and administrative organization. However, this does not mean the discipline lacks intrinsic coherence. While many people perceive it as fragmented, encompassing a wide array of subfields from structural to functional materials, and classified by material types such as polymers, metals, ceramics, and quantum materials, there have been ongoing efforts to establish a unified framework that can treat these diverse systems within a common conceptual foundation. To reconcile factions, the field adopted the "tetrahedron" of structure–property–performance–processing, later adding "characterization." Theory and computation minted ICME and the Materials Genome, and now, with AI everywhere, we've embraced machine learning at warp speed. On the other hand, as we may have noticed, older departments kept a strong metallurgy flavor; newer ones skew toward functional or quantum materials. A senior metallurgist might tease nanoscience for "re-selling old wine," overlooking that nanoscience pushes quantum confinement and size effects—very different goals sharing the same "push-to-the-limit" research style and focusing on the emerging singularities.

In nearly all top U.S. programs of materials science & engineering, four pillars frame the graduate curriculum: crystal structure, defects, materials thermodynamics, and materials kinetics. Structure and defects form an explicit "symmetry vs. symmetry-breaking" pair, while thermodynamics and kinetics separate equilibrium from time evolution—geometry and algebra, if you want an Atiyah-style analogy [1]. In practice, the second pair may be more mathematically sophisticated, but the first pair captures the essence of materials science: it's a defect-centered field. Elite schools layer on quantum mechanics, solid-state physics, mechanics for structural materials, and electives in characterization, synthesis, or computation. If you want to plunge into field-theoretic condensed matter within a materials department, paths do exist—whether that's wise is another debate.

Take some concrete cases. Northwestern's PhD core (thermo-crystal-Imperfection-phase transition-solid state-mechanics) is rock-solid. Stanford's mix (thermo, kinetics, defects/disorder, structural symmetry, quantum) aligns perfectly with the idea that "materials = structure + defects + time evolution." MIT, on the other hand, looks a bit disjointed—something I poked fun at in that Zhihu post.

Even if I haven't exhausted every school's list, the consensus on those four core courses is becoming clear. Except for defects, the other three map almost one-to-one onto physics: thermodynamics → statistical mechanics; kinetics → diffusion/transport theory; crystal structure → the prelude to solid-state physics. What truly sets materials apart is their systematic focus on defects. Some departments even drop a dedicated defect course, perhaps wisely: defects are too rich to squeeze into a single semester. Physicists, famous for studying the "spherical cow in vacuum," cherish perfect systems; only occasionally, say, quantum Hall physics, do they confront edges and disorder. Materials scientists, rooted in metallurgy's four strengthening mechanisms, start with defects, impurities, and disorder by default. Criticisms of "random doping" or "one different doping, one different paper" merely reflect an era when defect understanding was still crude.

Of course, it may be somewhat unfair to claim that the physics community only concerns itself with idealized or perfect systems. In fact, one of the greatest physicists, Michael Berry, famously celebrated the beauty of singularities—a perspective that considers phenomena such as conical intersections and topological edge states, all of which can be broadly understood as manifestations of a broader "defects" concept in parameter space:

"An old-fashioned view of quantum mechanics is that it studies waves. A not-so-old-fashioned way to extract interesting physics from mathematics is to study singularities." —Michael Berry [2]

The difference is just perspective: physics frames defect as broken perfection; materials frames it as a tunable reality to explore. How many kinds of "defect" you can see determines how many kinds of materials science you can imagine. Even characterization methods betray the split: materials folks chase real-space defect images with electron microscopes; condensed-matter physicists chart dispersion in k-space via inelastic scattering.

That gap could be an opportunity, but often shrinks because curricula and practice don't line up. Some curricula suggest that the importance of defect-centered thinking has yet to be fully embraced. After all, if the focus remains solely on crystal structures, phase transitions, and thermodynamics, students might reasonably ask why they shouldn't pursue more advanced treatments of these topics in physics or mechanical engineering departments. This may suggest that, in many cases, curriculum design is still compromised more by faculty composition and historical legacy than by deliberate pedagogical strategy.

Dig deeper and you find that defects are the single lever prying materials science away from physics. Just as applied math must wrestle with messy reality, materials science must tackle local heterogeneity that shatters perfect symmetry—only then can we engineer. Machine learning gave applied math a systemic toolkit for complexity; materials science now faces the same turning point. We grasp symmetry and band theory, yet "materials by design" still feels hard because materials are inherently complex systems. Each crystal's defect landscape stamps a unique fingerprint, and that multiscale coupling seeps into both equilibrium thermodynamics and non-equilibrium dynamics. Without quantitative defect descriptors, perfect-lattice theory is scenery, not scaffolding for precise engineering.

Breakthroughs demand that we marshal every tool—mathematics, simulation, characterization, data science—into an integrated framework that captures the topology, energy spectra, and evolution of defect networks. Multiscale modeling, CVM-CALPHAD (well...), in-situ 4D STEM, ultrafast scattering—all render complexity computable, observable, learnable. Our depth of defect insight sets the bounds of controllable material properties and defines how far we can shrink the "materials space" into a searchable design–manufacture space.

Physics, by contrast, prizes universal laws and minimal models. To spotlight generality, it treats most defects as perturbations. Yet defect interactions themselves can spawn new universality, leaving ample terrain for crossover research. The divide isn't value but focus: abstract universality versus concrete complexity. Pure and applied math share a similar tension; the routes sometimes meet but start from different priorities.

Translate that back to teaching, and you see why "defect science" belongs at the curriculum's heart, as defects provide the essential design space to tune and control the materials. But only when these insights are clearly and systematically integrated into education can materials science evolve from merely describing messy reality to designing messy reality—a leap that is essential for any engineering discipline in the AI era. With tools like ChatGPT, the engineer's goal should edge closer to the artist's: create and design, not merely perform a craft. Pure craft is too easily reduced to a tool, and anything that is purely tool-like will soon be done better by machines. Realistically, you might still keep a job simply because you cost less than the machine, but that prospect is, to say the least, rather ironic.

Based on this understanding of materials science, there remains considerable room for improvement in current curricula. One notable issue is the incomplete implementation of this "double dual structure". For example, based on limited surveys, some institutions do not include a dedicated course on defects as a core class. In others, mechanical and electronic/optical/magnetic (EOM) properties are taught separately, without emphasizing their interrelation through defect structures. This gap may stem from the historical divide within the field: traditional materials science has emphasized metallurgy and mechanical properties, while newer directions focus more on quasiparticle structures and functional phenomena. As a result, "defects" are often treated mainly in terms of mechanical implications, and some departments may not consider a defect-focused course as essential for all students. Conversely, a few departments do recognize the need for students to understand both mechanical and functional properties of materials, but lack the structure to coherently connect them, placing an additional burden on students to integrate the concepts themselves. A well-designed, integrative defect course could bridge this gap. Such a course would address both the mechanical and functional consequences of defects, completing the double dual structure in a synergistic way. It would serve as a common foundation for students specializing in structural materials (e.g., metallurgy) and those focused on semiconductors or functional materials. One potential issue may arise for the polymer or biological materials community, but this may indicate the necessary to consider whether the ”defect tunability-crystal structure” duality also exists in the daily research within bio-materials community. While the defect course would emphasize tunability, complexity, and symmetry breaking in real materials, a complementary course on crystal structure would cover ideal lattice representations, symmetry principles, and basic characterization. On the other axis of the double dual structure, the duality between thermodynamics and kinetics is already better accepted, thanks in part to advances in computational thermodynamics and kinetic modeling. However, when defects are included, the integration of thermodynamics and kinetics remains underdeveloped in both research and teaching. A deeper extension of these concepts, especially in the context of complex and functional materials, would offer a unified perspective across subfields. In addition, the current wave of AI4Science is transforming all four domains of materials science and engineering. Generative models are accelerating the discovery of new crystal structures; defect engineering is benefiting from predictive machine learning; and multiscale modeling of thermodynamics and kinetics increasingly relies on data-driven potentials and force fields. This broader framework may offer a more practical and forward-looking picture than the traditional ”tetrahedron” model of MSE. However, it also imposes greater demands on the curriculum, particularly in undergraduate and early PhD training. To implement such a framework effectively, students will need a solid foundation in mathematics, physics, and computer science (including AI). As a result, different departments may need to develop tailored emphases and adapt their core curricula accordingly.

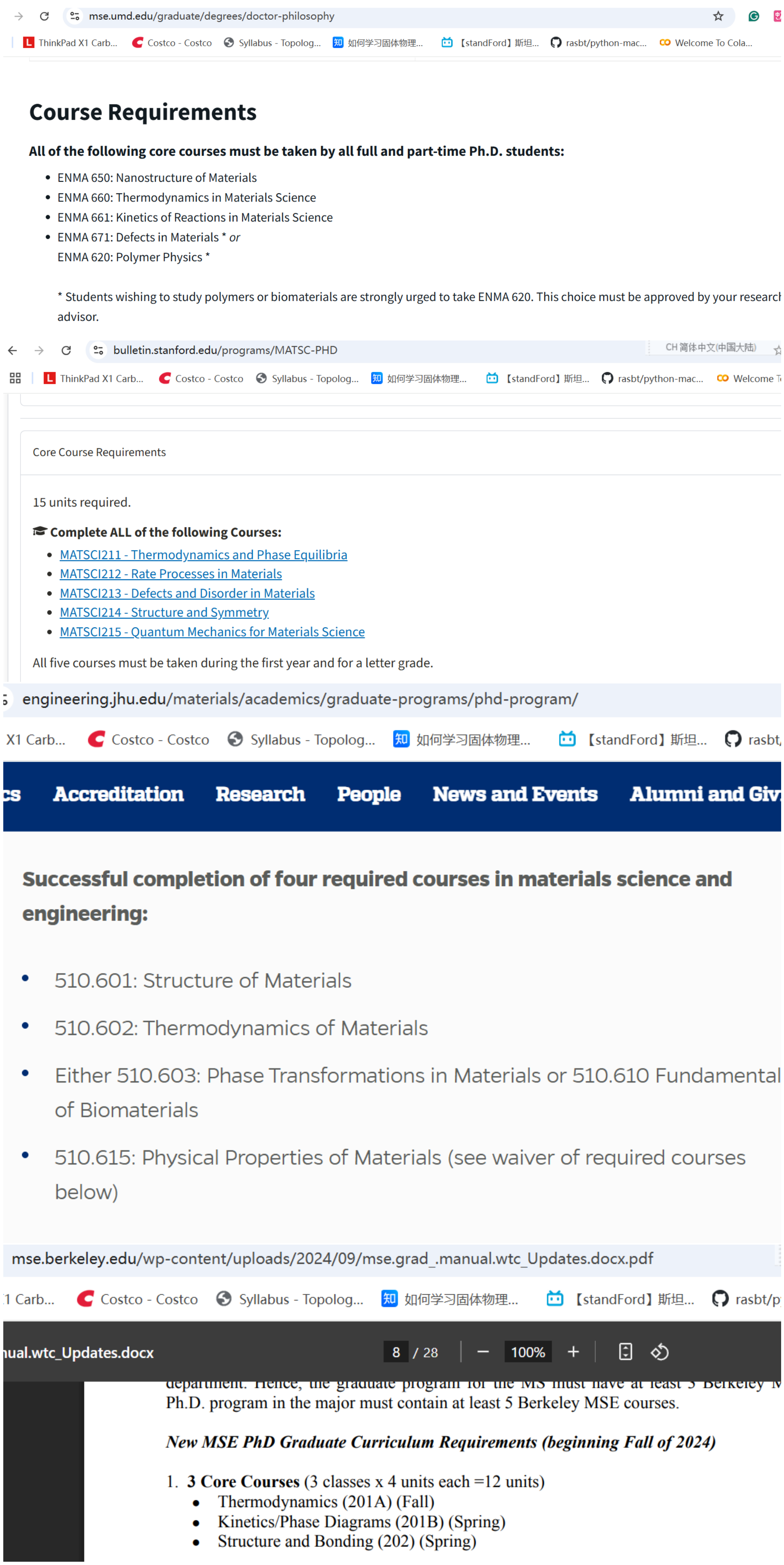
Finally, I want to emphasize that a solid grounding in physics and mathematics is essential, but equally important is recognizing how these foundations take shape differently in different disciplines. As Professor Gang Chen recently pointed out through the “Suh Paradigm”[3], researchers should avoid getting stuck in the vague space between basic and applied work: if your learning lacks direction, you’ll soon forget it; if your problems lack ”structure”, your thinking stays shallow. This article itself attempts to provide a discussion of the ”double dual-structure”. And now, a larger challenge is emerging: with tools like ChatGPT, DeepSeek, and other large models transforming how we access and use knowledge, how should our education systems adapt? This reflection, through the lens of materials science, is just one way to start thinking about how we might reimagine education in the age of AI.

[Curriculum screenshots for some institutes appear on the end pages.]

[1] M. Atiyah, Mathematics in the 20th century, Bulletin of the London Mathematical Society **34**, 1 (2002).

[2] M. Berry, Wave geometry: a plurality of singularities, Quantum Coherence , 92 (1991).

[3] G. Chen, Reflections on my research in heat and energy, ASME Journal of Heat and Mass Transfer **147** (2025).



mse.umd.edu/graduate/degrees/doctor-philosophy

Course Requirements

All of the following core courses must be taken by all full and part-time Ph.D. students:

- ENMA 650: Nanostructure of Materials
- ENMA 660: Thermodynamics in Materials Science
- ENMA 661: Kinetics of Reactions in Materials Science
- ENMA 671: Defects in Materials * *or*
  ENMA 620: Polymer Physics *

  * Students wishing to study polymers or biomaterials are strongly urged to take ENMA 620. This choice must be approved by your researcl advisor.

bulletin.stanford.edu/programs/MATSC-PHD

Core Course Requirements

15 units required.

Complete ALL of the following Courses:

- MATSCI211 - Thermodynamics and Phase Equilibria
- MATSCI212 - Rate Processes in Materials
- MATSCI213 - Defects and Disorder in Materials
- MATSCI214 - Structure and Symmetry
- MATSCI215 - Quantum Mechanics for Materials Science

All five courses must be taken during the first year and for a letter grade.

engineering.jhu.edu/materials/academics/graduate-programs/phd-program/

cs Accreditation Research People News and Events Alumni and Giv

Successful completion of four required courses in materials science and engineering:

- 510.601: Structure of Materials
- 510.602: Thermodynamics of Materials
- Either 510.603: Phase Transformations in Materials or 510.610 Fundamental of Biomaterials
- 510.615: Physical Properties of Materials (see waiver of required courses below)

mse.berkeley.edu/wp-content/uploads/2024/09/mse.grad_.manual.wtc_Updates.docx.pdf

ual.wtc_Updates.docx 8 / 28 100%

department. Hence, the graduate program for the MS must have at least 3 Berkeley M Ph.D. program in the major must contain at least 5 Berkeley MSE courses.

New MSE PhD Graduate Curriculum Requirements (beginning Fall of 2024)

1. **3 Core Courses** (3 classes x 4 units each =12 units)
   - Thermodynamics (201A) (Fall)
   - Kinetics/Phase Diagrams (201B) (Spring)
   - Structure and Bonding (202) (Spring)

FIG. 1. MSE Core course in UMD, Stanford, JHU, UCB

MATERIALS DEPARTMENT
http://www.materials.ucsb.edu
College of Engineering
University of California, Santa Barbara

Student Name: ______________________________ Perm: ____________________

DOCTOR OF PHILOSOPHY – MATERIALS – 2016-17

In addition to departmental requirements, candidates for graduate degrees must fulfill University requirements described in the "Graduate Education" section of the UCSB General Catalog.

Students admitted with a Bachelor's degree are required to complete a minimum of **72** units of academic work structured in the following manner: **42** units of 200-level courses (excluding seminars and independent study), **15** units of seminars and/or independent studies, and **15** units of dissertation research. Up to 8 units of upper division undergraduate courses may be taken for credit toward the 200 level course requirements with prior approval of the student's advisor. Students entering with a M.S. degree may petition to waive certain unit requirements for the Ph.D. (up to 15 units of 200-level courses and a possible six units of seminars) deemed to have been fulfilled by Master's studies elsewhere. Petitions should be directed to the Academic Affairs Committee.

In preparation for more advanced and specialized courses within their area of specialization, students are strongly encouraged to complete this core course sequence during their first year of study. A minimum grade of B in each of these courses is required prior to taking the Qualifying Examination (Advancement to Candidacy).

Time-to-Degree: 3 years to advance to candidacy, 5 years to complete the Ph.D.

CORE COURSE REQUIREMENTS (12 units total counted towards units of 200 level courses)			
COURSE #	COURSE NAME	UNITS	GRADE
MATRL 200A	Thermodynamic Foundation of Materials	4.0	
MATRL 200B	Electronic & Atomic Structure of Materials (Prerequisite: Matrl 200A)	4.0	
MATRL 200C	Structure Evolution (Prerequisite: Matrl 200A)	4.0	

EMSE 503. Structure of Materials. 3 Units.

The structure of materials and physical properties are explored in terms of atomic bonding and the resulting crystallography. The course will cover basic crystal chemistry, basic crystallography (crystal symmetries, point groups, translation symmetries, space lattices, and crystal classes), basic characterization techniques and basic physical properties related to a materials structure.

EMSE 504. Thermodynamics of Solids. 3 Units.

Review of the first, second, and third laws of thermodynamics and their consequences. Stability criteria, simultaneous chemical reactions, binary and multi-component solutions, phase diagrams, surfaces, adsorption phenomena.

EMSE 505. Phase Transformations, Kinetics, and Microstructure. 3 Units.

Phase diagrams are used in materials science and engineering to understand the interrelationships of composition, microstructure, and processing conditions. The microstructure and phases constitution of metallic and nonmetallic systems alike are determined by the thermodynamic driving forces and reaction pathways. In this course, solution thermodynamics, the energetics of surfaces and interfaces, and both diffusional and diffusionless phase transformations are reviewed. The development of the laws of diffusion and its application for both melts and solids are covered. Phase equilibria and microstructure in multicomponent systems will also be discussed.

FIG. 2. MSE Core course in UCSB, CWRU

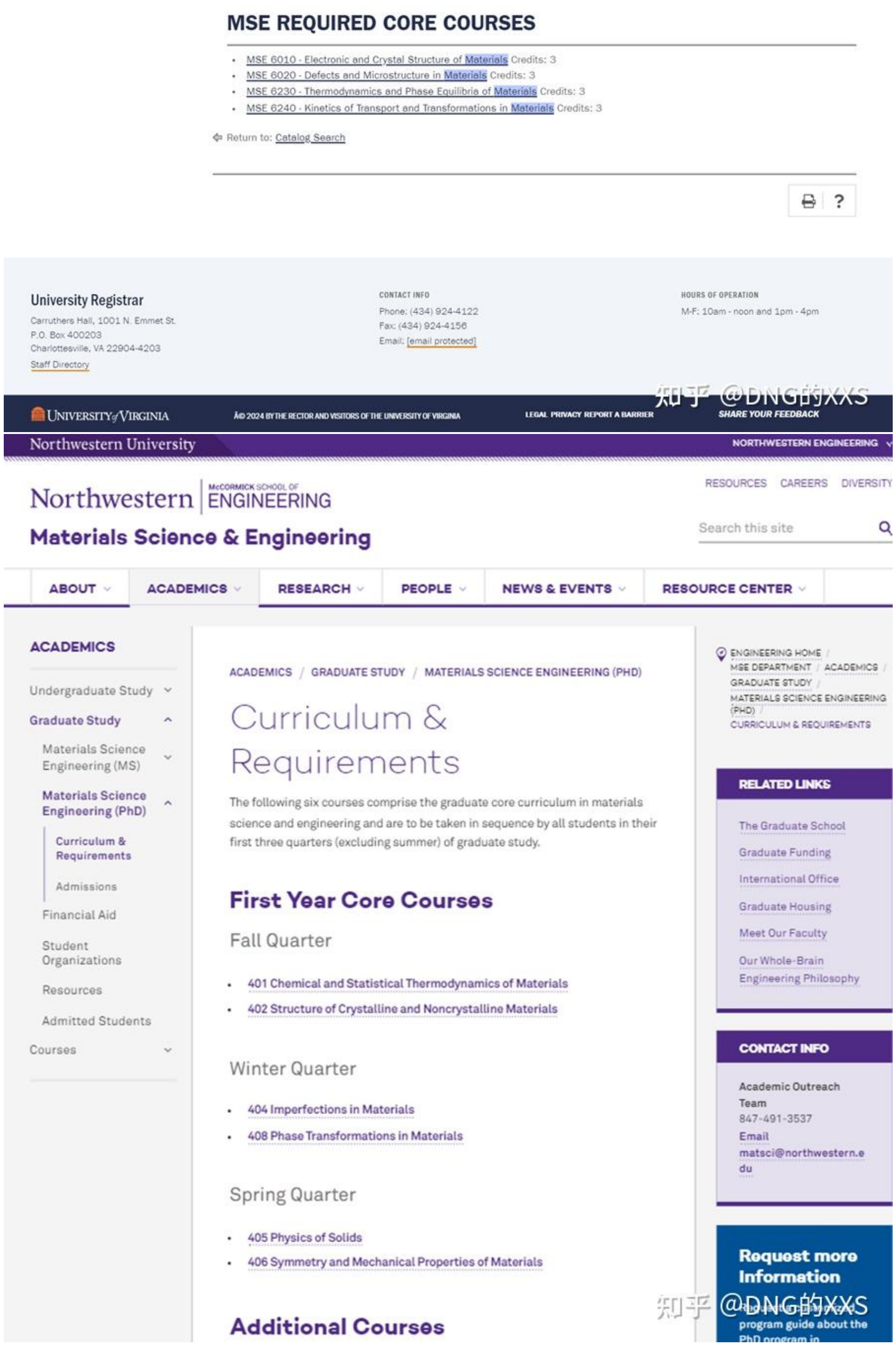
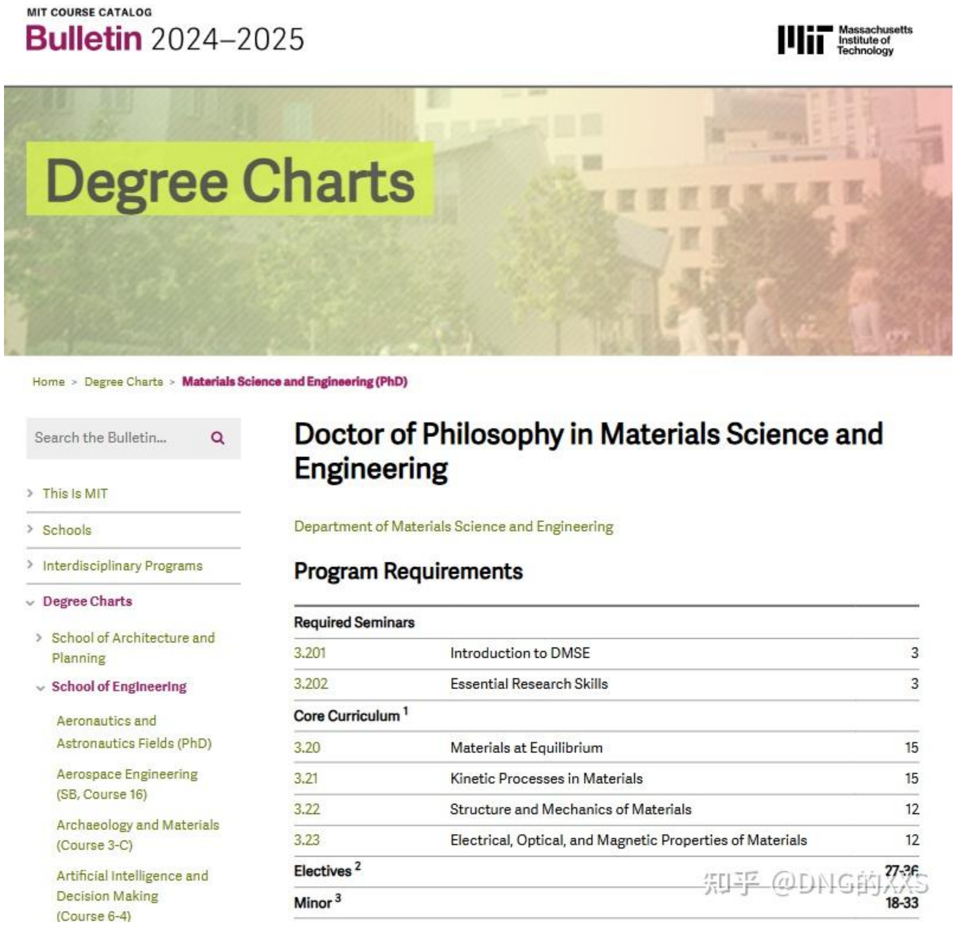


FIG. 3. MSE Core course in UVA, NWU



MIT COURSE CATALOG

Bulletin 2024–2025

Massachusetts Institute of Technology

Degree Charts

Home > Degree Charts > **Materials Science and Engineering (PhD)**

Search the Bulletin...

- This Is MIT
- Schools
- Interdisciplinary Programs
- Degree Charts
  - School of Architecture and Planning
  - School of Engineering
    - Aeronautics and Astronautics Fields (PhD)
    - Aerospace Engineering (SB, Course 16)
    - Archaeology and Materials (Course 3-C)
    - Artificial Intelligence and Decision Making (Course 6-4)

Doctor of Philosophy in Materials Science and Engineering

Department of Materials Science and Engineering

Program Requirements

Required Seminars		
3.201	Introduction to DMSE	3
3.202	Essential Research Skills	3
Core Curriculum [1]		
3.20	Materials at Equilibrium	15
3.21	Kinetic Processes in Materials	15
3.22	Structure and Mechanics of Materials	12
3.23	Electrical, Optical, and Magnetic Properties of Materials	12
Electives [2]		**27-36**
Minor [3]		**18-33**

FIG. 4. MSE Core course in MIT