Materials science and engineering is a discipline that extends from understanding the microscopic structure and properties of materials to designing materials in engineering systems and evaluating their performance. Achievements in materials engineering underpin the revolutionary advances in technology that define the modern standard of living. Materials scientists and engineers understand how the properties of materials relate to their microscopic structure and composition and engineer the synthesis and microstructure of materials to advance their performance in conventional and innovative technical applications.

The Department of Materials Science and Engineering of the Case School of Engineering offers programs leading to the degrees of Bachelor of Science in Engineering, Master of Science, and Doctor of Philosophy. The technological challenges that materials engineers face demand knowledge across a broad spectrum of materials. The Department conducts academic and research activities with metals, ceramics, semiconductors, polymers, and composites. Timely research and education respond to the demands for new materials and improved materials performance in existing applications, often transcending the traditional materials categories.

While a discipline of engineering, the field brings basic science to bear on the technological challenges related to the performance of industrial products and their manufacture. Materials science draws on chemistry in its concern for bonding, synthesis, and composition of engineering materials and their chemical interactions with the environment. Physics provides a basis for understanding the atomistic and electronic structure of materials and how they determine mechanical, thermal, optical, magnetic, and electrical properties. Mathematics, computation, and data science provide quantitative physical theories and modeling of the atomistic and electronic structure and provide advances in methods for microstructural analysis, materials design, and manufacturing processes.

**Mission**

The Department of Materials Science and Engineering engages faculty, students, postdoctoral researchers, engineers, and staff in developing and understanding relationships between processing, structure, properties, and the performance of materials in engineering applications. The Department provides a research-intensive environment that encourages collaboration and underpins modern education of undergraduate and graduate students as well as professionals in the field. This environment provides a strong foundation for advancing the frontiers of materials research, developing important technical innovations, and preparing engineers and scientists for challenging leadership careers.

**Research Areas**

**Deformation and Fracture**

Stress–strain relations during elastic and anelastic deformation. Plastic deformation mechanisms controlled by dislocation activity, twinning, or transformation-induced shear mechanisms, as well as by creep and viscous flow mechanisms under uniaxial, biaxial, and triaxial stress states, in particular in plane-strain and/or plane-stress conditions. Relationships between structure (atomistic structure and microstructure) and mechanical behavior of crystalline and glassy materials, including metals, intermetallics, semiconductors, ceramics, and composites. State-of-the-art facilities are available for testing mechanical properties over a range of strain rates, test temperatures, stress states, and size scales under monotonic and cyclic loading and under stress—corrosion conditions.

**Materials Processing**

Phase-transformation- and thermo-mechanical processing of alloys, including solution-, precipitation-, recovery-and-recrystallization- and stress-relief heat-treatments, also for intentional generation of residual-stresses. Deformation processing of materials. Surface engineering, crystal growth, sputter-, vapor- and laser-ablation synthesis of films. Melting and casting of metal alloys into sand/ceramic molds, injection into metallic molds, and by rapid solidification to form crystalline or (metallic-) glass ribbons. Ceramic- and metal powder synthesis. Consolidation processing by cold-pressing and sintering, electric-field-assisted compaction, or hot-pressing. Composite materials by forming of layered materials, electroplated metals, diffusion-bonding, brazing, and welding. Electrochemical- and thermo-chemical conversion processing, e.g. oxide-film growth by anodizing or thermochemical conversion. Synthesis of micro-to-nano-porous metal/oxide structures, e.g. for battery and capacitor electrodes or for catalyst support.

**Environmental Effects**


**Surfaces and Interfaces**

Material surfaces in vacuum, ambient-, and chemical environments, grain- and phase boundaries, hetero-interfaces (interfaces between different metals, ceramics, carbon/graphite, polymers, and combinations thereof).

**Electronic, Magnetic, and Optical Materials**

Materials for energy conversion technologies, such as photovoltaics, organic and inorganic light-emitting diodes and displays, fuel cells, electrolytic capacitors, solid-state Li-ion batteries, and building-envelope materials. Processing, properties, and characterization of magnetic, ferroelectric, and piezoelectric materials.

**Microcharacterization of Materials**

Facilities for high-resolution imaging, spatially resolved chemical analysis and spectrometry, and diffractometry. Conventional, analytical, and high-resolution transmission electron microscopy, scanning electron microscopy, focused ion beam techniques, scanning probe microscopy, light-optical microscopy, optical and electron spectroscopies, surface analysis, and X-ray diffractometry.

**Materials Data Science**

Rapid qualification of alloys, data science applications in polymers and coatings. Distributed computing, informatics, statistical analytics, exploratory data analysis, statistical modeling, and prediction. Hadoop, cloud computing, and computationally intensive research are supported.
through the operation of a scalable high-performance computing (HPC) system.

**Faculty**

Frank Ernst, Dr. rer. nat. habil.
(University of Göttingen)

*Leonard Case Jr. Professor of Engineering*

Microstructure and microcharacterization, alloy surface engineering, defects in crystalline materials, interface- and stress-related phenomena.

William A. “Bud” Baeslack III, PhD
(Rensselaer Polytechnic Institute)

*Professor*

Welding, joining of materials, and titanium and aluminum metallurgy.

Jennifer W. Carter, PhD
(The Ohio State University)

*Assistant Professor*

Processing—structure—property relationships of crystalline and amorphous materials. Multi-scale material characterization methods for correlating local microstructural features with mechanical and environmental responses.

Mark R. DeGuire, PhD
(Massachusetts Institute of Technology)

*Associate Professor*


Roger H. French, PhD
(Massachusetts Institute of Technology)

*Kyocera Professor*

Optical properties and electronic structure of polymers, ceramics, optical and biomolecular materials. These determine the vdW interactions which drive wetting of interfaces and mesoscale assembly biomolecular and inorganic systems including CNTs, proteins and DNA. Energy research focused on lifetime and degradation science. Including developing CRADLE, a Hadoop/Hbase/Spark-based distributed computing environment, for data science and analytics of complex systems such as photovoltaics and outdoor exposed materials. This allows multi-factor real-world performance to be integrated with lab-based datasets to identify mechanisms and pathways activated over lifetime using statistical and machine learning.

Peter Lagerlof, PhD
(Case Western Reserve University)

*Associate Professor*

Mechanical properties of ceramics and metals. Low-temperature deformation twinning. Light-induced plasticity of semiconductors. Methodology of transmission electron microscopy and diffractometry.

John J. Lewandowski, PhD
(Carnegie Mellon University)

*Arthur P. Armitage Professor of Engineering*


David H. Matthiesen, PhD
(Massachusetts Institute of Technology)

*Associate Professor; Director, Wind Energy Research and Commercialization (WERC) Center*


James D. McGuffin-Cawley, PhD
(Case Western Reserve University)

*Arthur S. Holden Professor of Engineering*


Alp Sehirlioglu, PhD
(University of Illinois at Urbana Champaign)

*Assistant Professor*


Gerhard E. Welsch, PhD
(Carnegie Mellon University)

*Professor*


Matthew A. Willard, PhD
(Carnegie Mellon University)

*Associate Professor*


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**Research Faculty**

Laura S. Bruckman, PhD
(University of South Carolina)

*Assistant Professor*

Electronic materials, lifetime and degradation science, data science.

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**Secondary Faculty**

Clemens Burda, PhD

*Professor*

Chemistry

Sunniva Collins, PhD

*Associate Professor*

Mechanical Engineering

Liming Dai, PhD

*Kent Hale Smith Professor*

Macromolecular Science and Engineering
The curriculum leading to the Bachelor of Science in Engineering degree with a major in Materials Science and Engineering includes the “Engineering Core” – basic courses in mathematics, physics, chemistry, and engineering along with breadth electives – and the CWRU General Education requirements. To these are added courses in engineering materials, which also allow students to choose one of several areas of concentration within the major. A total of 129 credit hours (units) is required.

Throughout the undergraduate curriculum in Materials Science and Engineering, scientific fundamentals are integrated with coverage of current manufacturing, design, and applications of engineering materials.

The goal of the Department of Materials Science and Engineering is to prepare students for rewarding careers that provide creative, effective
solutions to societal needs, through coursework and associated activities that emphasize:

- The interrelationships among the processing, structure, properties, and performance of engineering materials
- The mutual reinforcement of education and professional development throughout one's career

The undergraduate experience in Materials Science and Engineering at Case Western Reserve is marked by a high degree of hands-on experience and many opportunities for professional development before graduation. Lab courses, senior projects, and plant tours ensure that every student sees the field first-hand in current research and industrial settings.

The Bachelor of Science in Engineering degree program with a major in Materials Science and Engineering is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

Program Educational Objectives

1. Graduates will take an active part in professional organizations.
2. Graduates will assume leadership positions in materials science related industries.
3. Graduates will be effectively involved in solving technical problems.
4. Graduates may successfully enter and complete graduate and professional degree programs.

Student Outcomes

As preparation for achieving the above educational objectives, the Bachelor of Science in Engineering degree program with a major in Materials Science and Engineering is designed so that students attain:

- An ability to apply knowledge of mathematics, science, and engineering
- An ability to design and conduct experiments, as well as to analyze and interpret data
- An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- An ability to function on multi-disciplinary teams
- An ability to identify, formulate, and solve engineering problems
- An understanding of professional and ethical responsibility
- An ability to communicate effectively
- The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- A recognition of the need for, and an ability to engage in life-long learning
- A knowledge of contemporary issues
- An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Bachelor of Science in Engineering

Required Courses for Major in Materials Science and Engineering

In addition to Engineering Core (http://bulletin.case.edu/undergraduatestudies/csedegree) and CWRU General Education (http://bulletin.case.edu/undergraduatestudies/degreeprograms) requirements, the major requires the following courses.

- EMSE 110 Transitioning Ideas to Reality I - Materials in Service of Industry and Society 1
- EMSE 120 Transitioning Ideas to Reality II - Manufacturing Laboratory 2
- EMSE 220 Materials Laboratory I 2
- EMSE 228 Mathematical and Computational Methods for Materials Science and Engineering 3
- EMSE 276 Materials Properties and Design 3
- EMSE 319 Processing and Manufacturing of Materials 3
- EMSE 320 Materials Laboratory II 1
- EMSE 327 Thermodynamic Stability and Rate Processes 3
- EMSE 328 Mesoscale Structural Control of Functional Materials 3
- EMSE 330 Materials Laboratory III 2
- EMSE 343 Processing of Electronic Materials 3
- EMSE 345 Engineered Materials for Biomedical Applications 3
- EMSE 349 Role of Materials in Energy and Sustainability 3
- EMSE 372 Structural Materials by Design 4
- EMSE 379 Design for Lifetime Performance 3
- EMSE 398 Senior Project in Materials I 1
- EMSE 399 Senior Project in Materials II 2

Related Required Courses

- EMAC 270 Introduction to Polymer Science and Engineering 3
- EMAC 276 Polymer Properties and Design 3

Total Units 60

Concentrations

The undergraduate program includes courses that expose students to greater depth in areas related to materials science and engineering. These concentration sequences are of two types:

- Students may select an area of concentration that is based on an application or subfield of engineering materials. Each concentration will be a coherent set of courses that, in conjunction with one or more of the courses already required for all EMSE majors plus a specified mathematics/natural science/statistics course, will provide significant depth in an area of materials specialization.
- Students also have the option of designing a concentration — Advanced Materials Science and Engineering — in consultation with their advisors and subject to approval by the department's Undergraduate Studies Committee.

The concentrations are below. All concentrations equal 12 unit (four courses).
Biomaterials
EBME 201 Physiology-Biophysics I * 3
EBME 202 Physiology-Biophysics II * 3
Plus two of the following:
EBME/EMAC 303 Structure of Biological Materials 3
EBME 305 Materials for Prosthetics and Orthotics 3
EBME 306 Introduction to Biomedical Materials 3
EBME 316 Biomaterials for Drug Delivery 3
EBME 325 Introduction to Tissue Engineering 3
EBME 406/EMAC 471 Polymers in Medicine 3
EBME/EECS 480B The Human Body 3

Electronic Materials
PHYS 221 Introduction to Modern Physics * 3
Plus 3 (from either or both) of the following 2 categories:
1. Emphasis on Solid-State Physics
PHYS 315 Introduction to Solid State Physics 3
PHYS 326 Physical Optics 3
PHYS 327 Laser Physics 3
PHYS 331 Introduction to Quantum Mechanics I 3
2. Emphasis on Electronic Device Technology
CHEM 340 Solar Energy Conversion 3
ECHE 383 Chemical Engineering Applied to Microfabrication and Devices 3
EECS 309 Electromagnetic Fields I 3
EECS 321 Semiconductor Electronic Devices 4
EECS 322 Integrated Circuits and Electronic Devices 3
EMSE 427 Defects in Solids 3
EMSE 463 Magnetism and Magnetic Materials 3

Materials Data Science
STAT 312R Basic Statistics for Engineering and Science Using R Programming 3
DSCI 351M Exploratory Data Science 3
Plus 2 of the following, of which of 1 should be a DSCI course:
DSCI 352M Applied Data Science Research 3
DSCI 353M Data Science: Statistical Learning, Modeling and Prediction 3
MATH 307 Linear Algebra 3
MATH 304 Discrete Mathematics 3
EECS 321 Semiconductor Electronic Devices 4
EECS 322 Integrated Circuits and Electronic Devices 3

Polymers
CHEM 223 Introductory Organic Chemistry I * 3
or
CHEM 323 Organic Chemistry I * 3
Plus 3 of the following:
EMAC 351 Physical Chemistry for Engineering 3
EMAC 355 Polymer Analysis Laboratory 3
EMAC 372 Polymer Processing and Testing Laboratory 3
EMAC 375 Fundamentals of Non-Newtonian Fluid Mechanics and Polymer Rheology 3
EMAC 376 Polymer Engineering 3
EMAC 377 Polymer Processing 3
Completion of this concentration (including EMAC 270 and EMAC 276, as required for the major in Materials Science and Engineering) satisfies the requirements for a minor in Polymer Science and Engineering.
EMAC 270 Introduction to Polymer Science and Engineering 3

Structural Materials and Mechanical Behavior
STAT 312 Basic Statistics for Engineering and Science * 3
Plus three of the following:
ECHE 481 Corrosion Fundamentals 3
ECIV 310 Strength of Materials 3
EMAE 370 Design of Mechanical Elements 3
EMSE 417 Properties of Materials in Extreme Environments 3
EMSE 421 Fracture of Materials 3
EMSE 422 Failure Analysis 3
EMSE 427 Defects in Solids 3
EMAE 480 Fatigue of Materials 3

* Satisfies the Mathematics/Science/Statistics requirement of the Case School of Engineering.

Advanced Materials Science and Engineering
Students may satisfy the concentration requirement by taking 9 credit hours (units) of courses from engineering, math, statistics, or natural sciences departments (beyond those specifically required in the curriculum) at the 300 level or above, plus a course to satisfy the Mathematics/Natural Sciences/Statistics requirement in the Engineering Core. The courses are to be selected in consultation with the student’s advisor and will be subject to approval by the department’s Undergraduate Studies Committee. This option is appropriate for students who desire further study in topics relevant to materials science and engineering that are not represented in the specializations listed above.

Bachelor of Science in Engineering
Suggested Program of Study: Major in Materials Science and Engineering
The following is a suggested program of study. Current students should always consult their advisers and their individual graduation requirement plans as tracked in SIS (http://sis.case.edu).

First Year

<table>
<thead>
<tr>
<th>Course</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGES First year Seminar*</td>
<td>4</td>
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<tr>
<td>PHED 1xx Physical Education Activities*</td>
<td></td>
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</tbody>
</table>

Units

Fall | Spring
---|---
4 | |
Transitioning Ideas to Reality I - Materials in Service of Industry and Society (EMSE 110) 1
Calculus for Science and Engineering I (MATH 121)** 4
Principles of Chemistry for Engineers (CHEM 111)** 4
Elementary Computer Programming (ENGR 131)** or Introduction to Programming in Java (EECS 132) 3
SAGES University Seminar I 3
PHED 1xx Physical Education Activities*
Calculus for Science and Engineering II (MATH 122)** 4
Chemistry of Materials (ENGR 145)** 4
General Physics I - Mechanics (PHYS 121)** or Physics and Frontiers I - Mechanics (PHYS 123) 4
Transitioning Ideas to Reality II - Manufacturing Laboratory (EMSE 120)b 2
Year Total: 16 17

Second Year

<table>
<thead>
<tr>
<th>Units</th>
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<th>Spring</th>
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<tbody>
<tr>
<td>SAGES University Seminar 2*</td>
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<td></td>
</tr>
<tr>
<td>Calculus for Science and Engineering III (MATH 223)** or Calculus III (MATH 227)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>General Physics II - Electricity and Magnetism (PHYS 122)** or Physics and Frontiers II - Electricity and Magnetism (PHYS 124)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Materials Properties and Design (EMSE 276)</td>
<td>3</td>
<td></td>
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<tr>
<td>Introduction to Polymer Science and Engineering (EMAC 270)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Professional Communication for Engineers (ENGL 398)**</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Professional Communication for Engineers (ENGR 398)**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Breadth elective I**</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Elementary Differential Equations (MATH 224)** or Differential Equations (MATH 228)</td>
<td>3</td>
<td></td>
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<tr>
<td>Statics and Strength of Materials (ENGR 200)**</td>
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<td></td>
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<tr>
<td>Materials Laboratory I (EMSE 220)</td>
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<tr>
<td>Mathematical and Computational Methods for Materials Science and Engineering (EMSE 228)</td>
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<td>Year Total:</td>
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<td>17</td>
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Third Year

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<tr>
<th>Units</th>
<th>Fall</th>
<th>Spring</th>
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<tbody>
<tr>
<td>Thermodynamics, Fluid Dynamics, Heat and Mass Transfer (ENGR 225)**</td>
<td>4</td>
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<tr>
<td>Materials Laboratory II (EMSE 320)</td>
<td>1</td>
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<tr>
<td>Mesoscale Structural Control of Functional Materials (EMSE 328)</td>
<td>3</td>
<td></td>
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<tr>
<td>Structural Materials by Design (EMSE 372)</td>
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<tr>
<td>Concentration Ia</td>
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<tr>
<td>Breadth elective II**</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Introduction to Circuits and Instrumentation (ENGR 210)**</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Polymer Properties and Design (EMAC 276)</td>
<td>3</td>
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<tr>
<td>Thermodynamic Stability and Rate Processes (EMSE 327)</td>
<td>3</td>
<td></td>
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<tr>
<td>Materials Laboratory III (EMSE 330)</td>
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<td>Concentration IIa</td>
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Fourth Year

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<th>Units</th>
<th>Fall</th>
<th>Spring</th>
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<tbody>
<tr>
<td>Senior Project in Materials I (EMSE 398)c</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Breadth elective III**</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Processing of Electronic Materials (EMSE 343)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Engineered Materials for Biomedical Applications (EMSE 345)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Role of Materials in Energy and Sustainability (EMSE 349)</td>
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<tr>
<td>Concentration IIIa</td>
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</tr>
<tr>
<td>Senior Project in Materials II (EMSE 399)c</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Breadth elective IV**</td>
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<td></td>
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<tr>
<td>Processing and Manufacturing of Materials (EMSE 319)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Design for Lifetime Performance (EMSE 379)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Concentration IVa</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Year Total:</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>

Total Units in Sequence: 129

Hours required for graduation: 129

* University general education requirement
** Engineering general education requirement
a Actual courses and sequence will vary depending on the concentration chosen; see "Concentrations."
b This requirement may also be met by a minimum of two credit hours (units) selected from EMAE 160 Mechanical Manufacturing (3), EMSE 125 Freshman Research in Materials Science and Engineering or EMSE 325 Undergraduate Research in Materials Science and Engineering
c SAGES Capstone course

Cooperative Education (http://engineering.case.edu/coop)

Opportunities are available for students to alternate studies with work in industry or government as a co-op student, which involves paid full-time employment over seven months (one semester and one summer). Students may work in one or two co-ops, beginning in the third year of study. Co-ops provide students the opportunity to gain valuable hands-on experience in their field by completing a significant engineering project while receiving professional mentoring. During a co-op placement, students do not pay tuition, but maintain their full-time student status while earning a salary. Learn more at engineering.case.edu/coop. Alternatively or additionally, students may obtain employment as summer interns.

Five-Year Combined BS/MS Program

This program offers outstanding undergraduate students the opportunity to obtain an MS degree, with a thesis, in one additional year of study beyond the BS degree. (Normally, it takes two years beyond the BS to
earn an MS degree.) In this program, an undergraduate student can take up to 9 credit hours (units) that simultaneously satisfy undergraduate and graduate requirements. Students considering the combined BS/MS Program should use the Advanced Materials Science and Engineering concentration, and should select their concentration in consultation with their departmental academic advisor. Typically, students in this program start their research leading to the MS thesis in the fall semester of the senior year. The BS degree is awarded at the completion of the senior year.

Application for admission to the five year BS/MS program is made after completion of five semesters of course work. Minimum requirements are a 3.2 grade point average and the recommendation of a faculty member of the department. Interested students should contact Professor Peter Lagerlöf. Review the Office of Undergraduate Studies BS/MS program requirements here (http://bulletin.case.edu/undergraduatestudies/gradprofessional/#accelerationtowardgraduatedegreestext)

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## Minor in Materials Science and Engineering

In addition to the Bachelor of Science in Engineering degree program with a major in Materials Science and Engineering, the department also offers a minor in Materials Science and Engineering. This sequence is intended primarily for a student majoring in science or engineering, but it is open to any student with a sound background in introductory calculus, chemistry, and physics. This program requires the completion of EMSE 276 Materials Properties and Design and a minimum of 12 additional credit hours (units) of EMSE courses, including no more than 3 credit hours (units) of EMSE 125 Freshman Research in Materials Science and Engineering and EMSE 325 Undergraduate Research in Materials Science and Engineering, and no more than 6 credit hours (units) of one- or two-unit courses. Interested students please contact Prof Mark De Guire (mark.deguire@case.edu) (510 White, 216.368.4221).

## Minor in Applied Data Science

This undergraduate Minor in Applied Data Science (ADS), based in the Case School of Engineering, is available as a minor to students across CWRU. The minor is directed to students studying in the domains of Engineering and Physical Sciences (including Energy and Manufacturing, Astronomy, Geology, Physics), Health (including Translational and Clinical), and Business (including Finance, Marketing, and Economics). Successful completion of the ADS minor requirements leads to a "Minor in Applied Data Science" for the graduating student. The ADS minor represents that the students have developed knowledge of the essential elements of Data Science and Analytics in the area of their major (their domain of expertise).

### Elements of the Minor

The minor is structured so that the students who qualify for the minor have a working understanding of the basic ADS tools and their application in their domain area. This includes:

- Data Management: datastores, sources, streams;
- Distributed Computing: local computer, distributed computing such as Hadoop or other cloud computing;
- Informatics, Ontology, Query: including search, data assembly, annotation; and
- Statistical Analytics: tools such as R statistics and high level scripting languages (such as Python).

The data types found in these domains are diverse. They include time series and spectral data for Energy and Astronomy, and sensor and production data and image and volumetric data for Manufacturing. In Health, Translational ADS includes Genomic, Proteomic and other Omics data, while Clinical ADS includes patient data, medical data, physiological time series, and mobile data. Business data types include stock and other financial market data for Finance, time series and cross section data for Economics, and operations and consumer behavior data for Marketing.

Students will develop comprehensive experience in the steps of data analysis:

- Define the Applied Data Science questions.
- Identify, locate, and/or generate the necessary data, including defining the ideal data set and variables of interest, determining and obtaining accessible data, and cleaning the data in preparation for analysis.
- Exploratory data analysis to start identifying the significant characteristics of the data and information it contains.
- Statistical modeling and prediction, including interpretation of results, challenging results, and developing insights and actions.
- Synthesizing the results in the context of the domain and the initial questions, and writing professional documents.
- The creation of reproducible research, including code, datasets, and documentation and reports that are transferable and verifiable.

## The ADS Minor Curriculum

The curriculum is based on five 3-unit courses, with one class chosen from each of Levels 1 through Level 5, which cover the spectrum of learning needed to achieve domain area expertise in data science and analytics. The courses are chosen to be both cross-cutting, i.e., intermixing students from across the university in the fundamental concepts such as scripting and statistics (Levels 1, 2, and 4), and domain-focused (Levels 3 and 5). For the Level 4 undergraduate research course, the research topic will be approved by the minor advisor, and will also be a 3-unit project. This will provide minor students both the domain focused learning they need, and a broadening perspective on applications, methods, and uses of ADS in other domains.

### Courses Counted Toward Minor Requirements

Established courses included in the Minor are found in Case School of Engineering (Materials Science, Electrical Engineering and Computer Science, Manufacturing), College of Art & Science (Mathematics, Astronomy, Philosophy), School of Medicine, School of Nursing, and Weatherhead School of Management (Marketing, Finance, Operations, and Economics).

The courses that meet the requirements for the Minor can also be taken by students to meet requirements in Major programs, and therefore serve a dual purpose in our academic offerings. However, each program, department and school may have its own criteria on whether a given course could be "double counted" towards major and minor requirements.

### Level 5

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAFI 361</td>
<td>Empirical Analysis in Finance</td>
<td>3</td>
</tr>
<tr>
<td>ECON 327</td>
<td>Advanced Econometrics</td>
<td>3</td>
</tr>
<tr>
<td>MKMR 308</td>
<td>Measuring Marketing Performance</td>
<td>3</td>
</tr>
<tr>
<td>MKMR 310</td>
<td>Marketing Analytics</td>
<td>3</td>
</tr>
<tr>
<td>SYBB 459</td>
<td>Bioinformatics for Systems Biology</td>
<td>3</td>
</tr>
</tbody>
</table>
The underlying PhD program combines acquiring a great breadth of knowledge and understanding with building in-depth knowledge and skills in a chosen cutting-edge field of active materials research. Doctoral students develop skills to realize their own, original, curiosity-driven scientific research. As they research a specific topic in depth, doctoral students experience an intellectual transformation that enables them to succeed universally in challenging professional tasks, positioning them for the most ambitious leadership careers in academia, national laboratories, industrial research, etc.

MS Degree Requirements
The (same) degree of MS (Master of Science) in Materials Science and Engineering is awarded through one of the following three programs.

"Research" (Thesis-Focused) Master’s Track
This plan is appropriate for full-time graduate students. It requires a total of 30 credit hours (units). The coursework component comprises successful completion of 7 courses (21 credit hours / units). 1 course can be 300-level, all others must be 400- or higher level. Up to 2 courses can be from an engineering or science curriculum outside the department. The minimum cumulative GPA is 3.0. Students with lower standing will be placed on academic probation. Up to 6 hours of course credit can be transferred from graduate level courses (grade B or better) taken at another university in excess of their BS degree requirements. The thesis component consists of individual research (EMSE 651 Thesis M.S.), totaling no fewer than 9 credit hours (units), and a final oral defense. The examining committee includes 3 faculty members of the department. Additional committee members may be added at the discretion of the student in consultation with their advisor. A PPOS (planned program of study) must be submitted by the end of the second semester, prepared by the student the advisor and submitted online to the School of Graduate Studies.

"Professional" (Project-Focused) Master’s Track
This program suites part-time graduate students, e.g. while employed elsewhere as materials engineers. The coursework component comprises successful completion of 9 courses (27 credit hours / units). 1 course can be 300-level, all others must be 400- or higher level. Up to 2 courses can be from an engineering or science curriculum outside the department. The minimum cumulative GPA is 3.0. Students with lower standing will be placed on academic probation. Up to 6 hours of course credit can be transferred from graduate level courses (grade B or better) taken at another university in excess of their BS degree requirements. The program involves a project, typically 3 credit hours / units (EMSE 649 Special Projects) and completed in a single semester, and a final comprehensive oral exam. The examining committee consists of three faculty members of the department. Additional committee members may be added at the discretion of the student in consultation with their advisor. An Academic Program must be submitted by the end of the second semester, prepared by the student the advisor and submitted online to the School of Graduate Studies.

"Accelerated" (Course-Focused) Master’s Track
Materials science and engineering is a discipline that extends from the basic science of materials micro-structure and properties to the design and evaluation of materials in engineering systems. Data science and analytics seeks to identify statistically significant relationships, model development, and predictive behavior of large data sets generated by e.g. manufacturing technologies. The Accelerated Master’s Track is a course-work-only program that extends classical education in materials science and engineering with data science and analytics. It can be completed in just one calendar year!
The suggested program of study includes 10 courses, taken over the fall-, spring-, and summer semester of one academic year.

- Fall Semester: EMSE 504 Thermodynamics of Solids, EMSE 503 Structure of Materials, EMSE 413 Fundamentals of Materials Engineering and Science, and EMSE 599 Critical Review of Materials Science and Engineering Colloquium for either 1 or 2 credit hours.
- Spring Semester: EMSE 505 Phase Transformations, Kinetics, and Microstructure, EMSE 414 Electrical, Magnetic, Optical, and Thermal Properties of Materials, one EMSE-400-level elective course, DSCI 453 Data Science: Statistical Learning, Modeling and Prediction, and EMSE 599 Critical Review of Materials Science and Engineering Colloquium for either 1 or 2 credit hours (units), adding up to a total of 3 credit hours (units) of EMSE 599 Critical Review of Materials Science and Engineering Colloquium.
- Summer Semester: DSCI 452 Applied Data Science Research and EMSE 515 Analytical Methods in Materials Science.

The 3 credit hours (units) of EMSE-599 can be replaced by an additional course of 3 credit hours (units), e.g. EMSE 468 Scientific Writing in Materials Science and Engineering.

**PhD Degree Requirements**

**Overview**
Candidates for a PhD degree in Materials Science and Engineering perform coursework and research that leads to a dissertation. The coursework must include the Materials Science and Engineering Core and fulfill a Breadth Requirement and a Basic Science Requirement. In addition, candidates must pass a General Exam and a Thesis Defense. The General Exam consists of two parts, taken in two subsequent semesters: (i) Comprehensive Exam ("PhD-Qualifying Exam"). (ii) Thesis Proposal Evaluation.

**Entering the Program**
Immediately upon entering the department, the PhD candidate generally will:

- Fill out and submit the first part of the Academic Program and the Supplementary Form.
- Register for 2 courses during the first semester and EMSE-499, "Materials Engineering Colloquium."
- Register for EMSE-701 Dissertation PhD (usually 3 credit hours / units) during the first semester. Note that registration for EMSE-701 is not permitted before the Academic Program form is turned in.

As specified in the University General Bulletin section of the School of Graduate Studies: "In order to meet the requirements for the doctorate, a student must pass satisfactorily a general examination (or a series of examinations covering different fields) specified and administered by the student’s department or supervising committee."

**PhD Program of Study -- Course and GPA Requirements**
The student's Academic Program is a list of the courses the student will take to fulfill the PhD requirements, will be discussed and updated as needed at the time of the Thesis Proposal Evaluation.

A PhD student must take a minimum of 18 credit hours (units) of EMSE 701 Dissertation Ph.D. and must continue registration each subsequent regular semester (Fall and Spring) until the dissertation is complete, unless granted a leave of absence.

The time limit for the PhD program is 5 years for full-time students, starting with the first semester of EMSE 701 Dissertation Ph.D. registration.

The minimum course requirement is 12 courses (36 credit hours / units) beyond the BS level, of which at least 6 courses (18 credit hours / units) must be taken at Case Western Reserve University. Of these 12 courses, 4 courses must satisfy the Breadth Requirement and 2 courses must satisfy the Basic Science Requirement for the department as outlined below.

In the case of a student entering with a MS degree from another discipline, additional courses may be required at the discretion of the student’s academic advisor.

Graduation requires a GPA of at least 3.0. Students with a cumulative GPA below 3.0 will be placed on academic probation.

A required part of the PPOS for all PhD students is the Materials Science and Engineering Core. It consists of the following sequence of courses:

- EMSE 503 Structure of Materials
- EMSE 504 Thermodynamics of Solids
- EMSE 505 Phase Transformations, Kinetics, and Microstructure

Transfer credit for comparable graduate courses taken at another institution will be allowed on a case-by-case basis. Students may find it helpful to complete the Materials Science and Engineering Core sequence prior to taking the PhD comprehensive exam.

**Breadth Requirement**
The Breadth Requirement can be fulfilled by taking a total of 4 courses (12 credit hours / units) within the Case School of Engineering (including Materials Science and Engineering), selected in consultation with the student’s advisor.

**Basic-Science Requirement**
The Basic-Science Requirement consists of taking 2 corresponding courses (6 credit hours / units). These can be courses at the 400 or 500 level selected from the Physics-, Chemistry-, Biology-, Mathematics- and/or Statistics Department and/or certain engineering curricula approved by the Graduate Studies Committee of the Department of Materials Science and Engineering. Engineering courses used to meet this requirement must be approved prior to enrolling in the course. The deadline is the conclusion of add/drop in any given semester. Students making such a request are required to submit a petition to the Graduate Studies Committee that justifies the role of the stipulated course as basic (rather than applied) science. Such petitions are expected to be brief. Courses that are not approved as meeting the Basic-Science Requirement may still be applicable to the Breadth Requirement.

**Advanced Standing**
Students entering the PhD program with an MS degree are considered to be in advanced standing. For these students, the minimum course requirement is 6 courses (18 credit hours / units). The Breadth Requirement and the Basic-Science Requirement may require taking further courses.

**Exams**

**Comprehensive Exam**
The exam has multi-part questions that cover the following four areas:

- EMSE 503 Structure of Materials.
- EMSE 504 Thermodynamics of Solids.
Students who achieve a score of 70% or above on three of the completed questions and an overall average of 75% or above will pass outright. Students who do not achieve this on their first attempt of the written exam will have one more opportunity to take the Comprehensive Exam the next time the department offers it.

To register to take the Comprehensive Exam, students need a cumulative GPA of 3.0 or higher for courses taken at Case Western Reserve University. The exam will be offered once per year, typically in June. The time limits within which students must take the Comprehensive Exam are as follows:

- Full-time students entering with an MS degree: within one year.
- Full-time students entering with a BS degree: within two years of entering the Ph.D program.
- Part-time students: prior to accumulating 10 or more credit hours (units).

Dissertation Advisory Committee
In consultation with the advisor, the student needs to establish a Dissertation Advisory Committee. It must consist of at least three faculty members from the department and one non-departmental member.

Thesis Proposal Evaluation
The Thesis Proposal Evaluation must occur in the semester immediately following the successful completion of the Comprehensive Exam, unless a petition, supported by the research advisor, is approved by the Graduate Studies Committee of the Department of Materials Science and Engineering. The Thesis Proposal Evaluation tests the more specific knowledge of the PhD candidate concerning the science underlying the proposed research and the candidate's intellectual maturity. It is composed of a written and an oral evaluation, both dealing with the candidate's proposed research project and specialized courses taken in support of their research program. Both should include a literature search, analysis of a research problem, suggested research procedures, and major results and scientific advances to be expected. The written document must be submitted to the student's Dissertation Advisory Committee for examination at least one week prior to the oral evaluation. Both parts of the Thesis Proposal Evaluation will be graded Pass/Fail.

PhD Candidacy
Upon passing both the Comprehensive Exam and the Thesis Proposal Evaluation, a student will advance to PhD Candidacy.

Dissertation and Defense
Upon successful completion of all requirements, a PhD candidate must submit a written dissertation as evidence for their ability to conduct original scientific research. No later than 10 days before the defense, the candidate must provide a copy of the completed dissertation to each member of the Dissertation Advisory Committee. The defense consists of a (public) presentation and a (non-public) oral exam by the members of the student's Dissertation Advisory Committee.

Advanced Manufacturing and Mechanical Reliability Center (AMMRC)
The AMMRC (Advanced Manufacturing and Mechanical Reliability Center) permits the determination of mechanical behavior of materials over loading rates ranging from static to impact, with the capability of testing under a variety of stress states under either monotonic or cyclic conditions. A variety of furnaces and environmental chambers are available to enable testing at temperatures ranging from -196 °C to 1800 °C. The facility is operated under the direction of a faculty member and under the guidance of a full-time engineer. The facility contains one of the few laboratories in the world for high-pressure deformation and processing, enabling experimentation under a variety of stress states and temperatures. This state-of-the-art facility includes the following equipment:

- High-Pressure Deformation Apparatus These units enable tension or compression testing to be conducted under conditions of high hydrostatic pressure. Each apparatus consists of a pressure vessel and diagnostics for measurement of load and strain on deforming specimens, as well as instantaneous pressure in the vessel. Pressures up to 1.0 GPa loads up to 10 kN, and displacements of up to 25 mm are possible. The oil based apparatus is operated at
temperatures up to 300 °C room temperature while a gas (i.e. Ar) based apparatus is used at room temperature.

- **Hydrostatic-Extrusion Apparatus** Hydrostatic extrusion (e.g. pressure-to-air, pressure-to-pressure) can be conducted at temperatures up to 300 °C on manually operated equipment interfaced with a computer data acquisition package. Pressures up to 2.0 GPa are possible, with reduction ratios up to 6 to 1, while various diagnostics provide real time monitoring of extrusion pressure and ram displacement.

- **Advanced Forging-Simulation Rig** A multi-actuator MTS machine based on 1.5 MN, four post frame, enables sub-scale forging simulations over industrially relevant strain rates. A 490 kN forging actuator is powered by five nitrogen accumulators enabling loading rates up to 3.0 m/s on large specimens. A 980 kN indexing actuator provides precise deformation sequences for either single, or multiple, deformation sequences. Date acquisition at rates sufficient for analysis is available. Testing with heated dies is possible.

- **Advanced Metal-Forming Rig:** A four-post frame with separate control of punch actuator speed and blank hold down pressure enables determination of forming limit diagrams. Dynamic control of blank hold down pressure is possible, with maximum punch actuator speeds of 30.0 cm/s. A variety of die sets are available.

- **Servo-hydraulic Machines** Four MTS Model 810 computer-controlled machines with load capacities of 13 kN, 90 kN, 220 kN, and 220 kN, permit tension, compression, and fatigue studies to be conducted under load-, strain-, or stroke control. Fatigue crack growth may be monitored via a DC potential drop technique as well as via KRAK gages applied to the specimen surfaces. Fatigue studies may be conducted at frequencies up to 30 Hz. In addition, an Instron Model 1331 90 kN Servo-hydraulic machine are available for both quasi-state and cyclic testing.

- **Universal Testing Machines** Three INSTRON screw-driven machines, including two INSTRON Model 1125 units permit tension, compression, and torsion testing.

- **Electromechanical Testing Machine** A computer-controlled INSTRON Model 1361 can be operated under load-, strain-, or stroke control. Stroke rates as slow as 0.3 mm/s are possible.

- **Fatigue Testing Machines** Three Sonntag fatigue machines and two R. R. Moore rotating-bending fatigue machines are available for producing fatigue-life (S-N) data. The Sonntag machines may be operated at frequencies up to 60 Hz.

- **Creep Testing Machines** Three constant load frames with temperature capabilities up to 800 °C permit creep testing, while recently modified creep frames permit thermal cycling experiments as well as slow cyclic creep experiments.

- **Impact Testing Machines** Two Charpy impact machines with capacities ranging from 20 ft-lbs to 240 ft-lbs are available. Accessories include a Dynatup instrumentation package interfaced with an IBM PC, which enables recording of load vs. time traces on bend specimens as well as on tension specimens tested under impact conditions.

- **Instrumented Microhardness Tester** A Nikon Model QM High-Temperature Microhardness Tester permits indentation studies on specimens tested at temperatures ranging from -196 °C to 1600 °C under vacuum and inert gas atmospheres. This unit is complemented by a Zwick Model 3212 Microhardness Tester as well as a variety of Rockwell Hardness and Brinell Hardness Testing Machines.

### Microcharacterization: Swagelok Center for Surface Analysis of Materials

SCSAM, the Swagelok Center for Surface Analysis of Materials, is a multi-user facility providing cutting-edge major instrumentation for microcharacterization of materials. SCSAM’s instruments encompass a wide and complementary range of characterization techniques, which provide a comprehensive resource for high-resolution imaging, diffractometry, and spatially-resolved compositional analysis.

Current capabilities for SEM (scanning electron microscopy) include three scanning electron microscopes which are all equipped for FIB (focused ion beam) micromachining, XEDS (X-ray energy-dispersive spectrometry), and acquisition of EBSP (electron backscattering patterns). SCSAM operates a 300 kV high-resolution transmission electron microscope, equipped with field-emission gun and imaging energy filter. This instrument is capable of XEDS. SCSAM’s SPM (scanning probe microscopy) capabilities include a UHV (ultra-high vacuum) variable-temperature atomic-resolution system for STM (scanning tunneling microscopy), STS (scanning tunneling spectroscopy), and all modes of AFM (atomic-force microscopy). An AFM (atomic force microscope) is available, which can optionally be operated with an imaging nanoindenter scanhead or a stand-alone automated nanoindenter.

For XRD (X-ray diffractometry), SCSAM provides a 2D diffractometer capable of a variety of techniques.

SCSAM’s surface analysis suite of instruments includes an instrument for ToF-SIMS (time-of-flight secondary-ion mass spectrometry), a SAM (scanning Auger microprobe) for spatially resolved AES (Auger electron spectrometry), and an instrument for XPS (X-ray photoelectron spectrometry, also known as ESCA, electron spectrometry for chemical analysis), that accomplishes high spatial resolution by operating with a focused X-ray beam. A Keyence optical microscope is available providing the next-generation of optical microscopy with a large depth-of-field and advanced measurement capabilities for inspection and failure analysis.

SCSAM is administered by the CSE (Case School of Engineering) and is central to much of the research carried out by CSE’s seven departments. The facility is also extensively used by the CAS (College of Arts and Sciences) Departments of Physics, Chemistry, Biology, and Earth, Environmental, and Planetary Sciences, as well as many departments within the School of Medicine and the School of Dental Medicine. In addition to CWRU clients, many external institutions utilize SCSAM’s facilities, including the NASA Glenn Research Center, Cleveland Clinic, and numerous Ohio universities. Typically, more than 250 users utilize the facility per year.

SCSAM’s instruments are housed in a centralized area allowing users convenient access to state-of-the-art tools for their research.

### Transmission Electron Microscopy

**Tecnai F30 ST** SCSAM houses a transmission electron microscope Tecnai F30 ST (Philips). It provides conventional and advanced microscopy techniques required for state-of-the-art materials research.

The Tecnai F30 ST is a 300 kV field-emission gun energy-filtering high-resolution analytical scanning transmission electron microscope has a point resolution below 0.20 nm and an information resolution limit of 0.14 nm.

Conventional TEM techniques, such as bright-field and dark-field imaging, electron diffraction, or weak-beam dark-field imaging are used routinely to analyze line defects (dislocations) and planar defects (interfaces,
Modern XEDS systems are capable of detecting elements from boron to with great depth of field and the option of stereo-imaging. Compositional the surface topography of materials by combining nanometer resolution SEM (scanning electron microscopy) provides valuable information on Scanning Electron Microscopy

Gatan.

FIB systems described above, consist of two dimple-grinders, two SCSAM's specimen preparation facilities for TEM, in addition to the high-volume milling capabilities, an ESEM differential-pumping technologies, integrated onto a single platform, further include an enabled with this instrument, down to 7 nm. This is useful for high-resolution imaging and for Auger electron acquisition using low beam energy. The Elstar features other unique technologies, such as constant-power lenses for higher thermal stability and electrostatic scanning for higher deflection linearity and speed. Its through-the-lens detector, set for highest collection efficiency of SE (secondary electrons) and on-axis BSE (backscattered electrons), is complemented by FEI's advanced detection suite, which includes three novel detectors: (i) a multi-segment solid-state CBS retractable detector for backscattered electron imaging, able to detect low voltage BSE, (ii) a retractable multi-segment solid-state scanning transmission electron mode detector, able to simultaneously record BF, DF, and HAADF images, and (iii) a detector dedicated to FIB-SE and FIB-SI (secondary ion) imaging. Further, the Helios system is equipped with a state-of-the-art XEDS X-Max 80 mm2 SDD (silicon drift detector) system by Oxford with an energy resolution of 125 eV (full width at half maximum) at Mn Kα (5.899 keV). The large active area of the detector significantly provides a correspondingly large collection solid angle. This faster measurements, higher energy resolution, lower beam currents, and reduced risk of beam-induced specimen damage.

Light-Optical Microscopy

Keyence VHX This is an all-in-one microscope that incorporates observation, image capture, and measurement capabilities. A high resolution image is obtained with single-wavelength light and the HDR (High Dynamic Range) function that captures multiple images by varying the shutter speed, to produce a fine detail image. A wide area, high resolution image can be captured with just a button press on the console. Using the VHX XYZ-stage, images in a wide area can be stitched in short time without misalignment. This allows for a large field of view to be captured and observed at once. Images can be stitched up to 20000 (V) x 20000 (H) pixels.

Surface Science Instrumentation

PHI 680 Scanning Auger Microprobe This system consists of a field-emission scanning electron microscope with a Schottky emission cathode, a secondary electron detector, and an axial cylindrical mirror analyzer with a multi-channel detector to collect Auger electrons produced during electron imaging. Very small spot sizes can be realized with this instrument, down to 7 nm. This is useful for high-resolution imaging and for Auger electron acquisition using low beam currents. Inert gas sputtering (using a PHI 06-350 ion gun) is used to clean surface contamination from samples and to remove material from a small area on the surface for depth profiling. Several modes of operation are available to the user, including survey, line profile, and elemental mapping. Capable of multi-point analysis, the instrument in a gaseous chamber environment, a high-precision specimen goniometer with 50 mm travel along the xand y-axis, and automation serving unattended sectioning with full access to e-beam, i-beam, and patterning.

• Helios NanoLab™ 650 This instrument features recent advances in field-emission SEM and FIB technologies and their combined use. The instrument is designed to access a “new world” of extremely high-resolution 2D and 3D characterization, 3D nano-prototyping, and higher quality TEM sample preparation. The Helios’s capability of robust and precise FIB slicing, combined with a high-precision piezo stage (150 x 150 mm2), superb SEM performance, and advanced software allow unattended sample preparation or 3D characterization and analysis. The outstanding imaging capabilities of the Helios NanoLab begin with its Elstar™ FESEM. Thanks to its integrated monochromator (UC) and beam deceleration, it delivers sub-nanometer resolution across the whole 1-30 keV range of primary electron energy. The Elstar features other unique technologies, such as constant-power lenses for higher thermal stability and electrostatic scanning for higher deflection linearity and speed. Its through-the-lens detector, set for highest collection efficiency of SE (secondary electrons) and on-axis BSE (backscattered electrons), is complemented by FEI’s advanced detection suite, which includes three novel detectors: (i) a multi-segment solid-state CBS retractable detector for backscattered electron imaging, able to detect low voltage BSE, (ii) a retractable multi-segment solid-state scanning transmission electron mode detector, able to simultaneously record BF, DF, and HAADF images, and (iii) a detector dedicated to FIB-SE and FIB-SI (secondary ion) imaging. Further, the Helios system is equipped with a state-of-the-art XEDS X-Max 80 mm2 SDD (silicon drift detector) system by Oxford with an energy resolution of 125 eV (full width at half maximum) at Mn Kα (5.899 keV). The large active area of the detector significantly provides a correspondingly large collection solid angle. This faster measurements, higher energy resolution, lower beam currents, and reduced risk of beam-induced specimen damage.

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Scanning Electron Microscopy

SEM (scanning electron microscopy) provides valuable information on the surface topography of materials by combining nanometer resolution with great depth of field and the option of stereo-imaging. Compositional analysis is enabled by XEDS (X-ray energy-dispersive spectrometry). Modern XEDS systems are capable of detecting elements from boron to uranium. The laboratory houses the following instruments:

• xT Nova Nanolab 200 (FEI) This is a dual-beam system providing a scanning FIB (focused ion beam) and a scanning electron beam. The focused ion beam is used for preparing thin foils suitable for TEM directly out of the specimen surface. At the same time, enabled by the scanning electron beam, this instrument includes a complete and very-high-quality scanning electron microscope. This construction has the advantage that the specimen can be observed by (high-resolution) SEM while being milled by the ion beam. Moreover, the Nova includes an internal “lift-out.” system for transferring the thin film generated by ion-beam milling onto a special Cu support grid, which can then be loaded into the specimen holder of a TEM. For elemental and crystallographic analysis, the system is equipped with a state-of-the-art Oxford Aztec system with an xMax 50mm2 detector and a NORDLYS EBSP camera. EBSP mapping of phase and orientation relies on evaluating EBSP patterns of every scan point and can be run on bulk materials and in transmission mode on TEM samples.

• FEI Quanta 200 3D This is a versatile low-vacuum SEM/FIB for 2D and 3D material characterization and analysis. It features three imaging modes: high-vacuum, low-vacuum, and ESEM, and can accommodate a wide range of samples. The instrument is equipped with a field-emission Ga ion source and a thermal electron emitter. The enabling technologies, integrated onto a single platform, further include high-volume milling capabilities, an ESEM differential-pumping variable-pressure vacuum system (oil-free), gaseous secondary and backscattered electron detectors for imaging and analysis.
is a powerful tool for routine failure analysis and quality control of inorganic samples. An additional device permits in situ fracture of samples, at liquid nitrogen temperature if necessary.

- **PHI VersaProbe XPS Microprobe** Based on XPS (X-ray photoelectron spectrometry, also known as ESCA – electron spectrometry for chemical analysis), this is a multi-technique surface analysis instrument based on PHI's highly developed scanning X-ray microscope technology. The most important advantage of this instrument is that the VersaProbe can produce a focused, highly monochromatic X-ray beam that can be scanned over the specimen surface. In this instrument, a point source of X-rays is created by focusing an electron beam onto an Al anode. A monochromator, consisting of an ellipsoid-shaped crystal, collects X-rays from the point source and focuses them on the surface of the specimen. The focused X-ray beam can be scanned across the specimen surface by correspondingly scanning the electron beam across the surface of aluminum anode. A major advantage of this design is that most of the photoelectrons generated by the focused X-ray beam are actually collected by the electron energy analyzer, whereas in the conventional design, most of the photoelectrons are lost. With the VersaProbe, the spot size can be varied between less than 10 μm diameter (for highest spatial resolution) to 100 μm (for highest sensitivity).

- **PHI TRIFT V nanoTOF** This is a time-of-flight secondary-ion mass spectrometer. This instrument from PHI's surface analysis line of ToF-SIMS instruments utilizes a newly developed high-quality “TRIFT” analyzer. It is equipped with a Au-, a C60-, and an Ar-ion gun. An innovative new sample handling platform enables analysis of samples with complex geometries. In addition, the system has state-of-the-art charge compensation and ion-gun performance. ToF-SIMS (time-of-flight secondary-ion mass spectrometry) provides submicrometer 3D (!) elemental mapping. It can also be used to image the topography of solid surfaces. Different from D-SIMS (“dynamic” SIMS), ToF-SIMS enables analyzing the outermost one or two monolayers of a sample while basically preserving molecular integrity. While D-SIMS provides primarily elemental information, ToF-SIMS surface analysis yields chemical and molecular information. ToF-SIMS is ideal for both organic and inorganic materials and can be used to characterize both insulating and conductive materials. With detection limits in the ppm to ppb range, shallow depth profiling capabilities, and automated analysis, the nanoTOF can be used to study surface contamination, trace impurities, films, delamination failures etc. It is also a valuable tool to investigate surface modification chemistry and catalyst surface composition.

- **Veeco Dimension 3100** This is a multi-mode scanning probe microscope (SPM), equipped with a NanoScope IIIa controller and Quadrex signal processor for 16-bit resolution on all 3 axes. The tool works under atmospheric pressure at room temperature and can work in air and in liquids so that a full range of materials (metals, insulators, ceramics, polymers, and biological specimens) can be investigated with minimal sample preparation. It can accept samples with a diameter up to 20 cm, a height up to 1.5 cm, and a surface roughness up to 5.5 μm. The instrument is equipped with an in-line optical zoom microscope with color CCD camera, providing a magnification up to 800 times for precise placement of the SPM probe onto the sample. The Dimension 3100 can operate in numerous imaging modes. The primary operation modes are AFM (atomic force microscopy) in contact mode, tapping mode, and phase-imaging mode. Other data collection techniques include conductive-AFM to characterize local conductivity variations, magnetic force microscopy, which uses a ferromagnetic tip to probe magnetic fields, and force–distance measurements, which are performed to study attractive and repulsive forces on a tip as it approaches and retracts from the sample surface. Further, the Dimension 3100 SPM has been upgraded by a “TriboScope,” an attachment for nanomechanical testing, made by Hysitron. The TriboScope is a quantitative, depth-sensing nanoindentation and nanoscratch system that interfaces with the SPM. This attachment enables quantitative characterization of mechanical properties (hardness, scratch resistance, wear resistance) on the nanometer length scale and in situ AFM imaging of the surface topography before and after mechanical testing. The capability of in situ imaging allows the user to choose the exact area, with sub-nm precision, for each nanoindentation/nanoscratch investigation, and to fully characterize the local specimen surface.

- **RKH 7500 UHV VT** This system includes a variable-temperature ultra-high vacuum scanning probe microscope, made by RHK Technologies. This instrument is part of a complete UHV (ultra-high vacuum) system, which includes a separately pumped specimen preparation chamber and a load-lock chamber in addition to the actual SPM (scanning probe microscopy) chamber. The base pressure of the system is specified to 2.10–12 Pa. In the preparation chamber, an electron gun combined with a hemispherical electron energy analyzer is attached to enable chemical analysis of the specimen surface via AES (Auger electron spectroscopy). A specimen manipulator installed on the vertical axis of the chamber allows precise positioning of the specimen in front of the electron energy analyzer. The manipulator can be connected to a cryostat via a differentially-pumped rotary stage, permitting cooling the specimen down to 25 K. By resistive or electron-beam heating, it will also be possible to heat the specimen up to temperatures of 1500 K. To be able to clean the specimen surface, the system includes an Ar sputter gun. Evaporators installed at ports in the lower half of the chamber enable the deposition of metals onto the specimen surface. A gas dosing system facilitates gas adsorption experiments without backfilling the entire chamber or opening the main chamber to change gases. A mass spectrometer constantly detects and analyzes residual gas in the chamber. Finally, the preparation chamber includes a port large enough for a retractable reverse view LEED (low-energy electron diffraction) system for studying the surface structure of the specimen. Using a magnetic transfer arm, the specimen can be moved from the preparation chamber into the actual SPM chamber. This chamber houses a cantilever atomic force microscope combined with a scanning tunneling microscope, suitable to image the surface structure of conducting as well as non-conducting materials. Both instruments are capable of atomic-resolution imaging. The scanning tunneling microscope also permits probing the local work function and the local density of states in the specimen surface by STS (scanning tunneling spectrometry). All modes of SPM will work over a very broad range of specimen temperatures: 25 to 750 K. The SPM chamber accepts thermal evaporators, a sputter gun and a gas dosing system that can perform their functions while the sample is actively being studied by any of the available scanning probe techniques.

- **Agilent Nano Indenter G200** This is a very accurate, flexible, user-friendly instrument for nanomechanical testing. Electromagnetic actuation allows unparalleled dynamic range in force and displacement and measurement of deformation over six orders of magnitude (from nanometers to millimeters). Potential applications include a wide scope of materials, e.g. metals, ceramics, semiconductors (heterolayers, MEMS), coatings and DLC films, composite materials, fibers, polymers, and biomaterials.
X-Ray Diffractometry Laboratory

- **Bruker Discover D8** This X-ray diffractometer has a monochromated X-ray source (normally used with a Co-Kα X-ray tube), configured in point-focus mode. X-ray collimators are available for spot sizes from 200 µm to 800 µm, with 500 µm typical. The instrument includes a four-circle Huber goniometer equipped with an xyz stage and a laser video system to allow precision alignment of samples. Enabled by the small spot size of the incident X-ray beam and the precision alignment, small samples sizes can be evaluated and the instrument achieves much higher spatial resolution than conventional X-ray diffractometers. The 2D solid-state detector (VÁNTEC-500) allows a wide range of XRD techniques to be executed in short time. The detector has high sensitivity and is useful for detecting trace phases that might be missed by a conventional diffractometer. In addition, the detector allows rapid measurements of both stress and texture in a wide variety of materials. Software includes Diffrac.EVA for phase identification with the ICDD database and Diffrac.LEPTOS for stress measurement.

Electronic Properties Laboratories

Crystal Growth and Analysis Laboratory

The Crystal Growth and Analysis Laboratory is equipped for research studies and characterization of bulk semiconductor and photonic materials. The growth facilities include a high pressure Czochralski system, low pressure Czochralski system, and a Vertical Bridgman system with magnetic field stabilization. The characterization facilities include capabilities for sample preparation, a Hall effect system, and an Infra-red microscope.

Magnetometry Laboratory

The Magnetometry Laboratory has facilities used to investigate the magnetic properties of materials. This laboratory has the following instruments:

- **Lake Shore Cryotronics Model 7410 Vibrating Sample Magnetometer** This instrument serves for measurement of hysteresis loops (at constant temperature) and thermomagnetic measurements (at constant magnetic field). The maximum applied field at room temperature (without furnace in place) is 3.1 T. For high temperature measurements, the maximum applied field is 2.5 T over the temperature range from room temperature to 1000 °C.

- **Home-Built Magnetostriction Measurement System** This system has been designed and built to measure the change of magnetic materials under applied magnetic fields. Better than 1 ppm sensitivity is possible by this strain gage technique. An applied field of ≈0.2 T is used to saturate samples.

Fuel Cell Testing Laboratory

Facilities (located in the AW Smith Building) for testing of solid-oxide fuel cells include:

- **Furnaces** Dedicated furnaces and ovens for preparing cells for testing.
- **Test Stands for 4" Cells** 2 test stands for 4" cells and small stacks (Fuel Cell Technologies). Test temperatures to 1000°C. Professional turnkey LabView interface for system control and data acquisition.
- **Test Stands for 1" Cells** 2 test stands for 1" cells. Test temperatures to 1000°C. LabView interface for complete system control and data acquisition. Omega mass-flow controllers, Keithley and Amrel electronics. AutoLab Electrochemical Analyzer for I–V, galvanostatic, or amperometric testing and AC impedance spectroscopy.

All test stands are contained in dedicated enclosures rated for use with hydrogen, hydrogen sulfide, and carbon monoxide with ventilation system, leak detection, tank pressure monitors, alarm system.

**SDLE Research Center**

The SDLE Research Center was established in 2011 with funding from Ohio Third Frontier, and is dedicated to advancing the field of lifetime and degradation science. The research center activities focus on durability and degradation of environmentally exposed, long lived materials and technologies such as photovoltaics (PV), energy efficient lighting, and building envelope applications. The Center develops real-time and accelerated protocols for exposure to solar radiation and related environmental stressors to enable the evaluation of the environmental durability and lifetime of materials, components, and products. Data scientists identify statistically significant relationships using a data analytics platform (Energy-CRADLE) developed in the center. Researchers perform post-exposure optical and thermo-mechanical measurements to develop quantitative mechanistic models of degradation processes. The SDLE Research Center’s capabilities and equipment include:

- **Outdoor Solar Exposures** SunFarm with 14 dual-axis solar trackers with multi-sun concentrators, and power degradation monitoring.
- **Solar Simulators** For 1-1000X solar exposures.
- **Test Chambers** Multi-factor environmental test chambers with temperature, humidity, freeze/thaw, and cycling.
- **Evaluation Tools** A full suite of optical, interfacial, thermo-mechanical and electrical evaluation tools for materials, components, and systems.

**Courses**

**EMSE 110. Transitioning Ideas to Reality I - Materials in Service of Industry and Society. 1 Unit.**

In order for ideas to impact the lives of individuals and society they must be moved from "blue sky" to that which is manufacturable. Therein lies true creativity - design under constraint. Greater Cleveland is fortunate to have a diverse set of industries that serve medical, aerospace, electric, and advanced-materials technologies. This course involves trips to an array of work sites of leading companies to witness first-hand the processes and products, and to interact directly with practitioners. Occasional in-class speakers with demonstrations will be used when it is not logistically reasonable to visit off-site.

**EMSE 120. Transitioning Ideas to Reality II - Manufacturing Laboratory. 2 Units.**

This course complements EMSE 110. In that class students witness a diverse array of processing on-site in industry. In this class students work in teams and as individuals within processing laboratories working with an array of "real materials" to explore the potential of casting, machining, and deformation processes to produce real parts and/or components. An introduction to CAD as a means of communication is provided. The bulk of the term is spent in labs doing hands-on work. Planned work is carried out to demonstrate techniques and potential. Students have the opportunity to work independently or in teams to produce articles as varied as jewelry, electronics, transportation vehicles, or novel components or devices of the students’ choosing.
EMSE 125. Freshman Research in Materials Science and Engineering. 1 Unit.
Freshman students conduct independent research in the area of material science and engineering, working closely with graduate student(s) and/or postdoctoral fellow(s), and supervised by an EMSE faculty member. An average of 5-6 hr/wk in the laboratory, periodic updates, and an end of semester report is required. Prereq: Limited to freshman, with permission of instructor.

EMSE 220. Materials Laboratory I. 2 Units.

EMSE 228. Mathematical and Computational Methods for Materials Science and Engineering. 3 Units.
The course combines fundamental topics of material science and engineering with underlying mathematical methods and coding for computation. Focusing on the mathematics of vectors and using Mathematica as computational framework, the course teaches how to solve problems drawn from crystallography, diffraction, imaging of materials, and image processing. Students will develop a fundamental understanding of the basis for solving these problems including understanding the constituent equations, solution methods, and analysis and presentation of results. Prereq: (ENGR 131 or EEC 132) and ENGR 145.

EMSE 276. Materials Properties and Design. 3 Units.
Relation of crystal structure, microstructure, and chemical composition to the properties of materials. The role materials processing has in controlling structure so as to obtain desired properties, using examples from metals, semiconductors, ceramics, and composites. Design content includes exercises in materials selection, and in design of materials to meet specified performance requirements. Prereq: MATH 121 and ENGR 145. Prereq or Coreq: PHYS 122 or PHYS 124.

EMSE 308. Welding Metallurgy. 3 Units.
Introduction to arc welding and metallurgy of welding. The course provides a broad overview of different industrial applications requiring welding, the variables controlling critical property requirements of the weld and a survey of the different types of arc welding processes. The course details the fundamental concepts that govern the different aspects of arc welding including the welding arc, weld pool solidification, precipitate formation and solid state phase transformations. Offered as EMSE 308 and EMSE 408. Coreq: EMSE 327.

EMSE 319. Processing and Manufacturing of Materials. 3 Units.
Introduction to processing technologies by which materials are manufactured into engineering components. Discussion of how processing methods are dependent on desired composition, structure, microstructure, and defects, and how processing affects material performance. Emphasis will be placed on processes and treatments to achieve or improve chemical, mechanical, physical performance and/or aesthetics, including: casting, welding, forging, cold-forming, powder processing of metals and ceramics, and polymer and composite processing. Coverage of statistics and computational tools relevant to materials manufacturing. Prereq: EMSE 276.

EMSE 320. Materials Laboratory II. 1 Unit.
Measurement of thermophysical properties of materials emphasizing thermal and electrical properties of materials. Laboratory teams are selected for all experiments. Statistical analysis of experimental results also emphasized. Recommended preparation or corequisite: EMSE 276.

EMSE 325. Undergraduate Research in Materials Science and Engineering. 1 - 3 Units.
Undergraduate laboratory research in materials science and engineering. Students will undertake an independent research project alongside graduate student(s) and/or postdoctoral fellow(s), and will be supervised by an EMSE faculty member. Written and oral reports will be given on a regular basis, and an end of semester report is required. The course can be repeated up to four (4) times for a total of six (6) credit hours. Prereq: Sophomore or Junior standing and consent of instructor.

EMSE 327. Thermodynamic Stability and Rate Processes. 3 Units.
An introduction to thermodynamics of materials as applied to metals, ceramics, polymers and optical/radiant heat transfer for photovoltaics. The laws of thermodynamics are introduced and the general approaches used in the thermodynamic method are presented. Systems studied span phase stability and oxidation in metals and oxides; nitride ceramics and semiconductors; polymerization, crystallization and block copolymer domain formation; and the thermodynamics of systems such as for solar power collection and conversion. Recommended preparation: EMSE 228 and ENGR 225 or equivalent. Prereq: EMSE 276 or EMSE 201.

EMSE 328. Mesoscale Structural Control of Functional Materials. 3 Units.
The course focuses on mesoscale structure of materials and their interrelated effects on properties, mostly in electrical in nature. The mesoscale science covers the structures varying from electronic- to micro-structure. In each scale, fundamental science will be complimented by examples of applications and how the structure is exploited both to modify and enable function. The student will develop an understanding of how the structure across multiple scales are interrelated and how to tailor them for desired outcomes. Offered as: EMSE 328 and EMSE 428. Prereq: (MATH 223 or MATH 227) and (EMSE 276 or EMSE 201).

EMSE 330. Materials Laboratory III. 2 Units.

EMSE 335. Strategic Metals and Materials for the 21st Century. 3 Units.
This course seeks to create an understanding of the role of mineral-based materials in the modern economy focusing on how such knowledge can and should be used in making strategic choices in an engineering context. The history of the role of materials in emerging technologies from a historical perspective will be briefly explored. The current literature will be used to demonstrate the connectedness of materials availability and the development and sustainability of engineering advances with examples of applications exploiting structural, electronic, optical, magnetic, and energy conversion properties. Processing will be comprehensively reviewed from source through refinement through processing including property development through application of an illustrative set of engineering materials representing commodities, less common metals, and minor metals. The concept of strategic recycling, including design for recycling and waste stream management will be considered. Offered as EMSE 335 and EMSE 435. Prereq: Senior standing or graduate student.
EMSE 343. Processing of Electronic Materials. 3 Units.
The class will focus on the processing of materials for electronic applications. Necessary background into the fundamentals and applications will be given at the beginning to provide the basis for choices made during processing. MOSFET will be used as the target application. However, the processing steps covered are related to many other semiconductor based applications. The class will include both planar and bulk processing. Offered as: EMSE 343 and EMSE 443. Prereq: (PHYS 122 or PHYS 124) and EMSE 276.

EMSE 345. Engineered Materials for Biomedical Applications. 3 Units.
A survey of synthetic biomaterials from the perspective of materials science and engineering, focusing on how processing/synthesis, structure, and properties determine materials performance under the engineering demands imposed by physiological environments. Comparisons and contrasts between engineered metals, ceramics, and polymers, versus the biological materials they are called on to replace; consequences for materials and device design. Biomedical materials in applications such as orthopedic implants, dental restorations, wound healing, ophthalmic materials, and biomedical microelectromechanical systems (bioMEMS). Additive manufacturing of biomedical materials. Prereq: ENGR 200 and ENGR 145.

EMSE 349. Role of Materials in Energy and Sustainability. 3 Units.
This course has two parts: engineered materials as consumers of resources (raw materials, energy); and as key contributors to energy efficiency and sustainable energy technologies. Topics covered include: Energy usage in the U.S. and the world. Availability of raw materials, including strategic materials; factors affecting global reserves and annual world production. Resource demand of materials production, fabrication, and recycling. Design strategies, and how the inclusion of environmental impacts in design criteria can affect design outcomes and material selection. Roles of engineered materials in energy technologies: photovoltaics, solar thermal, fuel cells, wind, batteries, capacitors. Materials in energy-efficient lighting. Energy return on energy invested. Semester projects will allow students to explore related topics (e.g. geothermal; biomass; energy-efficient manufacturing and transportation). Offered as EMSE 349 and EMSE 449. Prereq: (ENGR 225 or EMAE 251 or EMAC 351) and ENGR 145 and (PHYS 122 or PHYS 124) or Requisites Not Met permission.

EMSE 365. Surface Engineering of Materials. 3 Units.
Introduction to surface engineering of materials, understood as a treatment that allows the surface to perform functions different from those performed by the bulk. This may include engineering the mechanical, chemical, electrical, magnetic, or optical properties of the surface and near-surface regions for specific applications. For a variety of technologically important classes of materials, the course reviews general concepts of surface engineering, the underlying physical and materials science principles, technical implementations, and typical applications. Recommended for graduate students and advanced undergraduate students. Offered as EMSE 365 and EMSE 465. Prereq: (EMSE 276 and ENGR 225) or Requisites Not Met permission.

EMSE 368. Scientific Writing in Materials Science and Engineering. 3 Units.
For writing a thesis (or a publication) in the field of materials science and engineering, students need a diverse set of skills in addition to mastering the scientific content. Generally, scientific writing requires proficiency in document organization, professional presentation of numerical and graphical data, literature retrieval and management, text processing, version control, graphical illustration, mathematical typesetting, the English language, elements of style, etc. Scientific writing in materials science and engineering, specifically, requires additional knowledge about e.g. conventions of numerical precision, error limits, mathematical typesetting, proper use of units, proper digital processing of micrographs, etc. Having to acquire these essential skills at the beginning of thesis (or publication) writing may compromise the outcome by distracting from the most important task of composing the best possible scientific content. This course properly prepares students for scientific writing with a comprehensive spectrum of knowledge, skills, and tools enabling them to fully focus on the scientific content of their thesis or publication when the time has come to start writing. Similar to artistic drawing, where the ability to “see” is as (or more!) important as skills of the hand, the ability of proper scientific writing is intimately linked to the ability of critically reviewing scientific texts. Therefore, students will practice both authoring and critical reviewing of material science texts. To sharpen students’ skills of reviewing, examples of good and less good scientific writing will be taken from published literature of materials science and engineering and analyzed in the context of knowledge acquired in the course. At the end of the course, students will have set up skills and a highly functional work environment to start writing their role thesis or article with full focus on the scientific content. While the course mainly targets students of materials science and engineering, students of other disciplines of science and engineering may also benefit from the course material. Offered as EMSE 368 and EMSE 468.

EMSE 372. Structural Materials by Design. 4 Units.

EMSE 379. Design for Lifetime Performance. 3 Units.
EMSE 396. Special Project or Thesis. 1 - 18 Units.
Special research projects or undergraduate thesis in selected material areas.

EMSE 398. Senior Project in Materials I. 1 Unit.
Independent Research project. Projects selected from those suggested by faculty; usually entail original research. The EMSE 398 and 399 sequence form an approved SAGES capstone. Counts as SAGES Senior Capstone.

EMSE 399. Senior Project in Materials II. 2 Units.
Independent Research project. Projects selected from those suggested by faculty; usually entail original research. Requirements include periodic reporting of progress, plus a final oral presentation and written report. Counts as SAGES Senior Capstone. Prereq: EMSE 398.

EMSE 400T. Graduate Teaching I. 0 Unit.
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exams/quizzes, homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

EMSE 408. Welding Metallurgy. 3 Units.
Introduction to arc welding and metallurgy of welding. The course provides a broad overview of different industrial applications requiring welding, the variables controlling critical property requirements of the weld and a survey of the different types of arc welding processes. The course details the fundamental concepts that govern the different aspects of arc welding including the welding arc, weld pool solidification, precipitate formation and solid state phase transformations. Offered as EMSE 308 and EMSE 408.

EMSE 409. Deformation Processing. 3 Units.
Flow stress as a function of material and processing parameters; yielding criteria; stress states in elastic-plastic deformation; forming methods: forging, rolling, extrusion, drawing, stretch forming, composite forming.

EMSE 413. Fundamentals of Materials Engineering and Science. 3 Units.
Provides a background in materials for graduate students with undergraduate majors in other branches of engineering and science: reviews basic bonding relations, structure, and defects in crystals. Lattice dynamics; thermodynamic relations in multi-component systems; microstructural control in metals and ceramics; mechanical and chemical properties of materials as affected by structure; control of properties by techniques involving structure property relations; basic electrical, magnetic and optical properties.

EMSE 414. Electrical, Magnetic, Optical, and Thermal Properties of Materials. 3 Units.
Reviews quantum mechanics as applied to materials, energy bands, and density of states; Electrical properties of metals, semiconductors, insulators, and superconductors; Optical properties of materials, including: metallic luster, color, and optoelectronics; Magnetic properties of materials, including: Types of magnetic behavior, theory, and applications; Thermal properties of materials, including: heat capacity, thermal expansion, and thermal conductivity. Prereq: Graduate Standing in Materials Science and Engineering or Requisites Not Met permission.

EMSE 417. Properties of Materials in Extreme Environments. 3 Units.
Fundamentals of degradation pathways of materials under extreme conditions; thermodynamic stability of microstructures, deformation mechanisms, and failure mechanisms. Extreme conditions that will typically be addressed include: elevated temperatures, high-strain rates (ballistic), environmental effects, nuclear radiation, and small scales. Examples will be drawn from recent events as appropriate.

EMSE 421. Fracture of Materials. 3 Units.

EMSE 422. Failure Analysis. 3 Units.
Methods and procedures for determining the basic causes of failures in structures and components. Recognition of fractures and excessive deformations in terms of their nature and origin. Development and full characterization of fractures. Review of essential mechanical behavior concepts and fracture mechanics concepts applied to failure analyses in inorganic, organic, and composite systems. Legal, ethical, and professional aspects of failures from service. Prereq: EMSE 372 or EMAE 372 or Requisites Not Met permission.

EMSE 427. Defects in Solids. 3 Units.
Defects in solids control many properties of interest to the materials scientist or engineer. This course focuses on point, line, and interfacial defects in crystals and their interactions, including calculations of defect energies and interaction forces. Crystallographic defects presented include point defects (e.g., vacancies, interstitials, substitutional and interstitial impurities), line defects (e.g., dislocations), and planar defects (e.g., grain boundaries). The consequence of point defects on diffusion as well as on optical and electronic properties is discussed. Dislocation motion and dislocation dissociation are treated, and the influence of dislocation dynamics on yield phenomena, work hardening, and other mechanical properties are discussed. The role of grain boundaries and inter-phase boundaries in determining the physical properties of the material are presented. Experimental techniques for characterizing defects are integrated throughout the course. Recommended preparation: MATH 223 (or equivalent) and EMSE 276 (or equivalent).

EMSE 428. Mesoscale Structural Control of Functional Materials. 3 Units.
The course focuses on mesoscale structure of materials and their interrelated effects on properties, mostly in electrical in nature. The mesoscale science covers the structures varying from electronic- to micro-structure. In each scale, fundamental science will be complimented by examples of applications and how the structure is exploited both to modify and enable function. The student will develop an understanding of how the structure across multiple scales are interrelated and how to tailor them for desired outcomes. Offered as: EMSE 328 and EMSE 428.

EMSE 430. Additive Manufacturing of Metals, Polymers, and Ceramics. 3 Units.
Additive manufacturing, though rooted in well-established unit operations, has emerged as a distinctive approach to the production of components and assemblies. This course will cover the conceptual approach, its history, the current state of the art, and analysis of projections of it future role. The respective advances in digital description of parts and digital control of processes will be described as machine design and construction. The emphasis, however, will be on the processing-structure-property relationships. Polymers, metals, and ceramics will be treated separately and contrasted. The course will make extensive use of current literature. Prereq: EMSE 276 or Requisites Not Met permission.
EMSE 435. Strategic Metals and Materials for the 21st Century. 3 Units.
This course seeks to create an understanding of the role of mineral-based materials in the modern economy focusing on how such knowledge can and should be used in making strategic choices in an engineering context. The history of the role of materials in emerging technologies from a historical perspective will be briefly explored. The current literature will be used to demonstrate the connectedness of materials availability and the development and sustainability of engineering advances with examples of applications exploiting structural, electronic, optical, magnetic, and energy conversion properties. Processing will be comprehensively reviewed from source through refinement through processing including property development through application of an illustrative set of engineering materials representing commodities, less common metals, and minor metals. The concept of strategic recycling, including design for recycling and waste stream management will be considered. Offered as EMSE 335 and EMSE 435. Prereq: Senior standing or graduate student.

EMSE 443. Processing of Electronic Materials. 3 Units.
The class will focus on the processing of materials for electronic applications. Necessary background into the fundamentals and applications will be given at the beginning to provide the basis for choices made during processing. MOSFET will be used as the target application. However, the processing steps covered are related to many other semiconductor based applications. The class will include both planar and bulk processing. Offered as: EMSE 343 and EMSE 443. Prereq: (PHYS 122 or PHYS 124) and EMSE 276.

EMSE 449. Role of Materials in Energy and Sustainability. 3 Units.
This course has two parts: engineered materials as consumers of resources (raw materials, energy); and as key contributors to energy efficiency and sustainable energy technologies. Topics covered include: Energy usage in the U.S. and the world. Availability of raw materials, including strategic materials; factors affecting global reserves and annual world production. Resource demand of materials production, fabrication, and recycling. Design strategies, and how the inclusion of environmental impacts in design criteria can affect design outcomes and material selection. Roles of engineered materials in energy technologies: photovoltaics, solar thermal, fuel cells, wind, batteries, capacitors. Materials in energy-efficient lighting. Energy return on energy invested. Semester projects will allow students to explore related topics (e.g. geothermal, biomass; energy-efficient manufacturing and transportation). Offered as EMSE 349 and EMSE 449. Prereq: ENGR 225 and (ENGR 145 or EMSE 146) and (PHYS 122 or PHYS 124) or requisites not met permission.

EMSE 463. Magnetism and Magnetic Materials. 3 Units.
This course covers the fundamentals of magnetism and application of modern magnetic materials especially for energy and data storage technologies. The course will focus on intrinsic and extrinsic magnetic properties, processing of magnetic materials to achieve important magnetic performance metrics, and the state-of-the-art magnetic materials used today. The topics related to intrinsic properties, include: magnetic dipole moments, magnetization, exchange coupling, magnetic anisotropy and magnetostriction. Topics related to extrinsic properties, include: magnetic hysteresis, frequency dependent magnetic response and magnetic losses. Technologically important permanent magnets (including rare earth containing alloys and magnetic oxides), soft magnets (including electrical steels, amorphous, ferrites, and nanocrystalline alloys), and thin film materials (including iron platinum) will be discussed in the context of their technological interest. Throughout the course, experimental techniques and data analysis will be discussed. The course is suitable for most graduate students and advanced undergraduates in engineering and science.

EMSE 465. Surface Engineering of Materials. 3 Units.
Introduction to surface engineering of materials, understood as a treatment that allows the surface to perform functions different from those performed by the bulk. This may include engineering the mechanical, chemical, electrical, magnetic, or optical properties of the surface and near-surface regions for specific applications. For a variety of technologically important classes of materials, the course reviews general concepts of surface engineering, the underlying physical and materials science principles, technical implementations, and typical applications. Recommended for graduate students and advanced undergraduate students. Offered as EMSE 365 and EMSE 465.

EMSE 468. Scientific Writing in Materials Science and Engineering. 3 Units.
For writing a thesis (or a publication) in the field of materials science and engineering, students need a diverse set of skills in addition to mastering the scientific content. Generally, scientific writing requires proficiency in document organization, professional presentation of numerical and graphical data, literature retrieval and management, text processing, version control, graphical illustration, mathematical typesetting, the English language, elements of style, etc. Scientific writing in materials science and engineering, specifically, requires additional knowledge about e.g. conventions of numerical precision, error limits, mathematical typesetting, proper use of units, proper digital processing of micrographs, etc. Having to acquire these essential skills at the beginning of thesis (or publication) writing may compromise the outcome by distracting from the most important task of composing the best possible scientific content. This course properly prepares students for scientific writing with a comprehensive spectrum of knowledge, skills, and tools enabling them to fully focus on the scientific content of their thesis or publication when the time has come to start writing. Similar to artistic drawing, where the ability to “see” is as (or more) important as skills of the hand, the ability of proper scientific writing is intimately linked to the ability of critically reviewing scientific texts. Therefore, students will practice both authoring and critical reviewing of material science texts. To sharpen students’ skills of reviewing, examples of good and less good scientific writing will be taken from published literature of materials science and engineering and analyzed in the context of knowledge acquired in the course. At the end of the course, students will have set up skills and a highly functional work environment to start writing their role thesis or article with full focus on the scientific content. While the course mainly targets students of materials science and engineering, students of other disciplines of science and engineering may also benefit from the course material. Offered as EMSE 368 and EMSE 468.
EMSE 499. Materials Science and Engineering Colloquium. 0 Unit.
Invited speakers deliver lectures on topics of active research in materials science. Speakers include researchers at universities, government laboratories, and industry. Course is offered only for 0 credits. Attendance is required.

EMSE 500T. Graduate Teaching II. 0 Unit.
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exams/quizzes/homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

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.

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 constitutions of metallic and nonmetallic systems are determined by the thermodynamic driving forces and reaction pathways. In this course, solution thermodynamics, the energetics of surfaces and interfaces, and both diffusion and diffusionless phase transformations are reviewed. The development of the laws of diffusion and its application for both melts and solids is covered. Phase equilibria and microstructure in multicomponent systems will also be discussed.

EMSE 509. Conventional Transmission Electron Microscopy. 3 Units.
Introduction to transmission electron microscopy-theoretical background and practical work. Lectures and laboratory experiments cover the technical construction and operation of transmission electron microscopes, specimen preparation, electron diffraction by crystals, electron diffraction techniques of TEM, conventional TEM imaging, and scanning TEM. Examples from various fields of materials research illustrate the application and significance of these techniques. Recommended preparation: Consent of instructor.

EMSE 515. Analytical Methods in Materials Science. 3 Units.
Microcharacterization techniques of materials science and engineering: SPM (scanning probe microscopy), SEM (scanning electron microscopy), FIB (focused ion beam) techniques, SIMS (secondary ion mass spectrometry), EPMA (electron probe microanalysis), XPS (X-ray photoelectron spectrometry), and AES (Auger electron spectrometry), ESCA (electron spectrometry for chemical analysis). The course includes theory, application examples, and laboratory demonstrations.

EMSE 599. Critical Review of Materials Science and Engineering Colloquium. 1 - 2 Units.
Invited speakers deliver lectures on topics of active research in materials science. Speakers include researchers at universities, government laboratories, and industry. Each course offering is for 1 or 2 credits but the course can be taken multiple times totaling up to a maximum of six credits. Attendance is required. Graded coursework is in the form of a term paper per credit. The topic for the term paper(s) should be chosen from seminar topics. The term paper will be graded by the advisor of the graduate student.

EMSE 600T. Graduate Teaching III. 0 Unit.
To provide teaching experience for all Ph.D.-bound graduate students. This will include preparing exams/quizzes/homework, leading recitation sessions, tutoring, providing laboratory assistance, and developing teaching aids that include both web-based and classroom materials. Graduate students will meet with supervising faculty member throughout the semester. Grading is pass/fail. Students must receive three passing grades and up to two assignments may be taken concurrently. Recommended preparation: Ph.D. student in Materials Science and Engineering.

EMSE 601. Independent Study. 1 - 18 Units.

EMSE 649. Special Projects. 1 - 18 Units.

EMSE 651. Thesis M.S.. 1 - 18 Units.
Required for Master's degree. A research problem in metallurgy, ceramics, electronic materials, biomaterials or archeological and art historical materials, culminating in the writing of a thesis.

EMSE 695. Project M.S.. 1 - 9 Units.
Research course taken by Plan B M.S. students. Prereq: Enrolled in the EMSE Plan B M.S. Program.

EMSE 701. Dissertation Ph.D.. 1 - 9 Units.
Required for Ph.D. degree. A research problem in metallurgy, ceramics, electronic materials, biomaterials or archeological and art historical materials, culminating in the writing of a thesis. Prereq: Predoctoral research consent or advanced to Ph.D. candidacy milestone.