Department of Materials Science and Engineering Courses

About Course Numbers:

Each Carnegie Mellon course number begins with a two-digit prefix that designates the department offering the course (i.e., 76-xxx courses are offered by the Department of English). Although each department maintains its own course numbering practices, typically, the first digit after the prefix indicates the class level: xx-1xx courses are freshmen-level, xx-2xx courses are sophomore level, etc. Depending on the department, xx-6xx courses may be either undergraduate senior-level or graduate-level, and xx-7xx courses and higher are graduate-level. Consult the Schedule of Classes *(*https://enr-apps.as.cmu.edu/open/SOC/SOCServlet/*) each semester for course offerings and for any necessary pre-requisites or co-requisites.*

27-052 Introduction to NanoScience and Technology
Summer: 9 units
This course is offered within Carnegie Mellon's Advanced Placement Early Admissions (APEA) program. The course is primarily intended to provide an introduction to nanoscience and technology to a wide audience of students at the advanced high school to incoming freshmen level. The course goals are twofold: (1) to provide students with a holistic view of the objectives, opportunities and challenges of the emerging field of nanotechnology and 2) to sensitize students at an early stage of their career to the relevance of the connections among the traditional disciplines as a vital element to the progress in interdisciplinary areas such as nanotechnology. The course will cover: Introduction and fundamental science; Preparation of nanostructures; Characterization of nanostructures; Application examples, Social and ethical aspects of nanotechnology. Admission according to APEA guidelines.

27-100 Engineering the Materials of the Future
Fall and Spring: 12 units
Materials form the foundation for all engineering applications. Advances in materials and their processing are driving all technologies, including the broad areas of nano-, bio-, energy, and electronic (information) technology. Performance requirements for future applications require that engineers continue to design both new structures and new processing methods in order to engineer materials having improved properties. Applications such as optical communication, tissue and bone replacement, fuel cells, and information storage, to name a few, exemplify areas where new materials are required to realize many of the envisioned future technologies. This course provides an introduction to how science and engineering can be exploited to design materials for many applications. The principles behind the design and exploitation of metals, ceramics, polymers, and composites are presented using examples from everyday life, as well as from existing, new, and future technologies. A series of laboratory experiments are used as a hands-on approach to illustrating modern practices used in the processing and characterization of materials and for understanding and improving materials' properties.

27-201 Structure of Materials
Fall: 9 units
This course covers the fundamentals of crystallography and diffraction. Topics covered include: the periodic table of the elements, bonding in different classes of materials, Bravais lattices, unit cells, directions and planes, crystal geometry computations, direct and reciprocal space, symmetry operations, point and space groups, nature of x-rays, scattering in periodic solids, Bragg's law, the structure factor, and the interpretation of experimental diffraction patterns. 24 crystal structure types of importance to various branches of materials science and engineering will be introduced. Amorphous materials, composites and polymers are also introduced. This course includes both lectures and laboratory exercises.
Prerequisite: 21-122 Min. grade C

27-202 Defects in Materials
Fall: 9 units
Defects have a fundamental influence on the properties of materials, including deformation, electrical, magnetic, optical, and chemical properties, as well as the rates of diffusion in solids. As such, by the controlling the population of intrinsic and extrinsic defects, one can tailor the properties of materials towards specific engineering applications. The objective of this course, which includes classroom and laboratory sessions, is to define approaches to quantifying the populations and properties of defects in crystals. The course will be divided into three sections: point defects, dislocations, and planar defects. The formation of point defects and their influence on diffusion, electrical, and magnetic properties will be considered. The properties and characteristics of dislocations and dislocation reactions will be presented, with a focus on the role of dislocations in deformation. The crystallography and energetics of planar defects and interfaces will also be described, with a focus on microstructural evolution at high temperatures. Time permitting, volume defects or other special topics are also discussed.
Prerequisites: 27-201 or 27-215 or 21-122 Min. grade C or 21-120 Min. grade C

27-210 Materials Engineering Essentials
Fall: 6 units
This course approaches professional skill holistically, having materials science and engineering students understand that being a professional includes having competencies and responsibilities that are personal, organizational and professional.
Prerequisites: 21-122 Min. grade C or 21-120 Min. grade C

27-211 Structure of Materials (Minor Option)
Fall: 6 units
This course is identical to 27-201, but without the 3-unit lab component.

27-212 Defects in Materials (Minor Option)
Spring: 6 units
THIS IS FOR THE MSE MINOR ONLY: Defects have a fundamental influence on the properties of materials, including deformation, electrical, magnetic, optical, and chemical properties, as well as the rates of diffusion in solids. As such, by the controlling the population of intrinsic and extrinsic defects, one can tailor the properties of materials towards specific engineering applications. The objective of this courseis to define approaches to quantifying the populations and properties of defects in crystals. The course will be divided into three sections: point defects, dislocations, and planar defects. The formation of point defects and their influence on diffusion, electrical, and magnetic properties will be considered. The properties and characteristics of dislocations and dislocation reactions will be presented, with a focus on the role of dislocations in deformation. The crystallography and energetics of planar defects and interfaces will also be described, with a focus on microstructural evolution at high temperatures. Time permitting, volume defects or other special topics are also discussed.

27-215 Thermodynamics of Materials
Fall: 12 units
The first half of the course will focus on the laws of thermodynamics and the inter-relations between heat, work and energy. The concept of an equilibrium state of a system will be introduced and conditions which must be satisfied for a system to be at equilibrium will be established and discussed and the concepts of activity and chemical potential introduced. The second half of the course will focus on chemical reactions, liquid and solid solutions, and relationships between the thermodynamics of solutions and binary phase diagrams.

27-216 Transport in Materials
Spring: 9 units
This course is designed to allow the student to become familiar with the fundamental principles of heat flow, fluid flow, mass transport and reaction kinetics. In addition, the student will develop the skills and methodologies necessary to apply these principles to problems related to materials manufacture and processing. Topics will include thermal conductivity, convection, heat transfer equations, an introduction to fluid phenomena viscosity, etc., Newtons and Stokes Laws, mass momentum balances in fluids, boundary layer theory, diffusion and absolute reaction rate theory. Where appropriate, examples will be taken from problems related to the design of components and the processing of materials.
Prerequisites: 27-210 and 27-215

27-217 Phase Relations and Diagrams
Spring: 12 units
Stability of structures. Hume-Rothery rules. Free energy-composition curves with applications to binary and ternary phase diagrams. Quantitative concepts of nucleation and growth with examples from solidification. Development of microstructures in various classes of phase diagram under near-equilibrium conditions. Atomic mechanisms of solid state diffusion and approach to equilibrium through diffusion.
Prerequisites: 27-201 and 27-215

27-227 Phase Relations and Diagrams (Minor Option)
Spring: 9 units
This course is identical to 27-217, but without the 3-unit lab component.

27-301 Microstructure and Properties I
Fall: 9 units
The objective of this course is to convey some of the essential concepts in materials science and engineering that relate properties (strength, toughness, formability, elasticity, magnetism, thermal expansion, for example) to the microstructure (crystal structure, dislocation structure, grain size, atoms in solids solution, precipitate characteristic, cellular materials). These relationships will be illustrated in terms of idealized materials and actual materials used in many applications. The course contains both lectures and laboratory exercises. The labs will include studies of recrystallization, the effect of microstructure on the properties of wood and the effect of microstructure on the mechanical behavior of a low ally steel, 4140.
Prerequisites: 27-217 and 27-216

27-305 Introduction to Materials Characterization
Spring: 6 units
The course introduces the modern methods of materials characterization, including characterization of microstructure and microchemistry of materials. A classroom component of the course will introduce the wide array of methods and applications of characterization techniques. Basic theory will be introduced where needed. Students will then be instructed in the use of several instruments such as AFM, SEM, and EDS, using a hands-on approach. All instruments are part of the existing lab facilities within MSE and CIT. The methods learned in this course will serve the student during several other higher level courses, such as the Senior level MSE Capstone Course (27-401).

27-357 Introduction to Materials Selection
Spring: 6 units
In this course we follow the design-led approach to evaluate possible materials. In this approach, we start with a property (or combination of properties) which are relevant to a particular design, and then consider what classes of materials and what specific materials meet the design criteria. The logical path is hence from application to material. We shall give attention to materials fundamentals (such as grains and bonding) where these are relevant and useful to understanding differences between different materials - such as why the elastic modulus of steel cannot be changed by heat treatment or alloying, whereas the strength can be changed a great deal.

27-367 Selection and Performance of Materials
Spring: 6 units
This course teaches the selection methodologies for materials and processes for satisfaction of a design goal. Topics such as performance under load, shape effects, material properties (intrinsic and as influenced by processing) are discussed and applied so as to determine the fitness of use of materials for applications. Expanded topics include economics, codes and standards, environmental and safety regulations, professional ethics and life cycle analysis where applicable. The course incorporates a project where virtual teams work to provide material selection for a specific application problem.
Prerequisites: 27-301 and 27-100

27-401 MSE Capstone Course I
Fall: 6 units
This is the first of 2 course that together fulfill the Capstone requirement. This capstone course introduces the student to the methodology used for projects and teams based research as practiced in the Materials Science and Engineering workplace. This is a project course that requires the knowledge relationship among processing, structure, and performance to address an important contemporary problem in materials science and engineering. Student taking this course will work in a team environment to complete a design project to resolve scientific and engineering issues relating to materials. Research topics will be selected from a list of material problems or research concepts generated from companies or academia - industry research partnerships. This course will establish the research goals, review applicable research methodologies, introduce project management skills and discuss ethical concepts as teams assemble and set their research directions. On the topic selected, the work product is a report that provides clear definition of the problem being addressed, sets out a methodology for the research, includes a literature review, and reports early experimentation results and provides recommendations for future work.
Prerequisites: 27-367 and (27-305 or 27-205) and 27-301

27-402 MSE Capstone Course II
Spring: 6 units
This is the spring extension of 27-401. Teams or team members that have the industry agreement and that wish to continue their research project may do so in this course. As with 27-401, all research is expected to be original, and proper scientific ethics, and methodologies are enforced for the research and reports. Team participation and communication is an important issue and the presentation and reports must be technical and professional in structure. The course requires full project management and accounting for the research being conducted. On the topic selected, the work product is a report that provides clear definition of the problem being addressed, a methodology for the research, literature review, experimentation and reporting of findings, conclusions based on findings, and recommendations for future work.
Prerequisite: 27-401

27-406 Sustainable Materials
Fall and Spring: 9 units
This course is intended to instill a sense of how materials properties and performance are conceived and brought to market specifically under sustainability constraints arising from the increasing demand of materials, Students will be introduced to the global nature of materials and will explore the global influences on the materials supply and value chains. The student will explore issues through the framework of the materials lifecycle including resource availability, manufacturing choices, and disposable options for materials in light of their use and selection for application. As a result, the student will be able to make more informed material selection or be able to use this information to identify critical research directions for future material development.

27-410 Computational Techniques in Engineering
Spring: 12 units
This course develops the methods to formulate basic engineering problems in a way that makes them amenable to computational/numerical analysis. The course will consist of three main modules: basic programming skills, discretization of ordinary and partial differential equations, and numerical methods. These modules are followed by two modules taken from a larger list: Monte Carlo-based methods, molecular dynamics methods, image analysis methods, and so on. Students will learn how to work with numerical libraries and how to compile and execute scientific code written in Fortran-90 and C++. Students will be required to work on a course project in which aspects from at least two course modules must be integrated.
Prerequisites: 21-120 and 21-122 and (15-122 or 15-112 or 15-110) and 21-260 and 21-259

27-421 Processing Design
Fall: 6 units
In this course, the concepts of materials and process design are developed, integrating the relevant fundamental phenomena in a case study of a process design. The course includes basic science and engineering as well as economic and environmental considerations. The case study is on environmentally acceptable sustainable steelmaking. Other case studies in materials processing could be used.

27-432 Electronic and Thermal Properties of Metals, Semiconductors and Related Devices
Intermittent: 9 units
Fall odd years: This is Part I of a two-part course (Part II is 27-433) sequence concerned with the electrical, dielectric, magnetic and superconducting properties of materials. Students taking Part I will develop an in-depth understanding, based on the modern theories of solids, of the electrical, electronic and thermal properties of metals and semiconductors and the principles of operation of selected products and devices made from these materials. Overarching and interrelated topics will include elementary quantum and statistical mechanics, relationships between chemical bonds and energy bands in metals and semiconductors, the roles of phonons and electrons in the thermal conductivity of solids, diffusion and drift of electrons and holes, the important role of junctions in the establishment and control of electronic properties of selected metal- and semiconductor-based devices. Examples of commercial products will be introduced to demonstrate the application of the information presented in the text and reference books and class presentations. Additional topics will include microelectro-mechanical systems and nanoelectronics.

27-433 Dielectric, Magnetic, Superconducting Properties of Materials & Related Devices
Intermittent: 9 units
Fall even years: 9 units This is Part II of a two-part course sequence (Part I is 27-432) concerned with the electrical, dielectric, magnetic and superconducting properties of materials. Students taking Part II will develop an in-depth understanding, based on the modern theories of solids, of the dielectric, magnetic and superconducting properties of materials and the principles of operation of selected products and devices made from these materials. Topics will include relationships between chemical bonds and energy bands in dielectric and magnetic materials; polarization mechanisms in materials and their relationship to capacitance, piezoelectricity, ferroelectricity, and pyroelectricity; magnetization and its classification among materials; magnetic domains; soft and hard magnets; and the origin, theory and application of superconductivity. Examples of commercial products will be introduced to demonstrate the application of the information presented in the text and reference books and class presentations.

27-445 Structure, Properties and Performance Relationships in Magnetic Materials
Spring: 9 units
This course introduces the student to intrinsic properties of magnetic materials including magnetic dipole moments, magnetization, exchange coupling, magnetic anisotropy and magnetostriction. This is followed by discussion of extrinsic properties including magnetic hysteresis, frequency dependent magnetic response and magnetic losses. This will serve as the basis for discussing phase relations and structure/properties relationships in various transition metal magnetic materials classes including iron, cobalt and nickel elemental magnets, iron-silicon, iron-nickel, iron-cobalt and iron platinum. This will be followed by a discussion of rare earth permanent magnets, magnetic oxides, amorphous and nanocomposite magnets. Polymers used in Electromagnetic Interference (EMI) Absorbers applications will also be covered.

27-454 Supervised Reading
Spring
This course provides the opportunity for a detailed study of the literature on some subject under the guidance of a faculty member, usually but not necessarily in preparation for the Capstone Course, 27-401/402.

27-477 Introduction to Polymer Science and Engineering
Spring: 9 units
This survey-level course introduces the fundamental properties of polymer materials and the principles underlying the synthesis, engineering, manufacturing, and design with polymer materials. Fundamental concepts of molecular interactions and structure formation in molecular materials will be introduced and the effect of chemical composition on physical properties of polymers will be discussed. The basic principles of polymer chemistry will be introduced and discussed in the context of step- and chain-growth reactions. This is followed by an introduction to technologically relevant engineering properties of polymer materials with focus on mechanical properties, concepts of viscoelasticity and their application to polymer product engineering, a survey of relevant forming technologies as well as the effect of processing on material performance. Case studies will introduce students to the various stages of technical product development, i.e. problem analysis, material selection and processing plan. A final section will discuss polymer recycling and sustainable polymer technologies for a circular economy.
Prerequisite: 27-215

27-503 Additive Manufacturing and Materials
All Semesters: 9 units
This course will develop the understanding required for materials science and engineering for additive manufacturing. The emphasis will be on powder bed machines for printing metal parts, reflecting the research emphasis at CMU. The full scope of methods in use, however, will also be covered. The topics are intended to enable students to understand which materials are feasible for 3D printing. Accordingly, high power density welding methods such as electron beam and laser welding will be discussed, along with the characteristic defects. Since metal powders are a key input, powder-making methods will be discussed. Components once printed must satisfy various property requirements hence microstructure-property relationships will be discussed because the microstructures that emerge from the inherently high cooling rates differ strongly from conventional materials. Defect structures are important to performance and therefore inspection. Porosity is a particularly important feature of 3D printed metals and its occurrence depends strongly on the input materials and on the processing conditions. The impact of data science on this area offers many possibilities such as the automatic recognition of materials origin and history. Finally the context for the course will be discussed, i.e. the rapidly growing penetration of the technology and its anticipated impact on manufacturing.

27-505 Exploration of Everyday Materials
Spring: 9 units
This course is developed for upper level undergraduate and master level students outside of the College of Engineering that wish to learn about materials by experientially exploring a material and or an application of a material. Each year the course will select a material that through its' application, presents and opportunity or a concern in service. It will engage the students with studio-based exploration of the material and application, the selection criteria applicable, and engineering principles that influence the performance. It will explore a wide range of influential topics constraining material selection including societal concerns about materials and global sustainability.

27-514 Bio-nanotechnology: Principles and Applications
Spring: 9 units
"Have you ever wondered what is nanoscience and nanotechnology and their impact on our lives? In this class we will go through the key concepts related to synthesis (including growth methodologies and characterizations techniques) and chemical/physical properties of nanomaterials from zero-dimensional (0D) materials such as nanoparticles or quantum dots (QDs), one-dimensional materials such as nanowires and nanotubes to two-dimensional materials such as graphene. The students will then survey a range of biological applications of nanomaterials through problem-oriented discussions, with the goal of developing design strategies based on basic understanding of nanoscience. Examples include, but are not limited to, biomedical applications such as nanosensors for DNA and protein detection, nanodevices for bioelectrical interfaces, nanomaterials as building blocks in tissue engineering and drug delivery, and nanomaterials in cancer therapy."

27-515 Introduction to Computational Materials Science
Fall: 9 units
This course introduces students to the theory and practice of computational materials science from the electronic to the microstructural scale. Both the underlying physical models and their implementation as computational algorithms will be discussed. Topics will include: Density functional theory Molecular dynamics Monte Carlo methods Phase field models Cellular automata Data science Coursework will utilize both software packages and purpose-built computer codes. Students should be comfortable writing, compiling, and running simple computer programs in C, C++, Fortran, MatLab, Python, or comparable environment. THIS COURSE IS FOR MSE UNDERGRADUATE STUDENTS ONLY.

27-520 Tissue Engineering
Spring: 12 units
This course will train students in advanced cellular and tissue engineering methods that apply physical, mechanical and chemical manipulation of materials in order to direct cell and tissue function. Students will learn the techniques and equipment of bench research including cell culture, immunofluorescent imaging, soft lithography, variable stiffness substrates, application/measurement of forces and other methods. Students will integrate classroom lectures and lab skills by applying the scientific method to develop a unique project while working in a team environment, keeping a detailed lab notebook and meeting mandated milestones. Emphasis will be placed on developing the written and oral communication skills required of the professional scientist. The class will culminate with a poster presentation session based on class projects. Pre-requisite: Knowledge in cell biology and biomaterials, or permission of instructor

27-533 Principles of Growth and Processing of Semiconductors
Fall: 6 units
Development of a fundamental understanding of material principles governing the growth and processing of semiconductors. Techniques to grow and characterize bulk crystals and epitaxial layers are considered. The processing of semiconductors into devices and the defects introduced thereby are discussed. The roles of growth- and processing-induced defects in determining long term reliability of devices are examined.

27-537 Data Analytics and Machine Learning for Materials Science
Spring: 9 units
Materials Science and Engineering has traditionally been taught by emphasizing the development and application of technology. This course will present an alternative approach that combines data mining, data analytics, and material fundamentals (i.e. materials informatics). Students will be introduced to informatics techniques related to data mining and large database analysis. The topics will include: ¥ Principal Component Analysis (PCA) ¥ Canonical Correlation Analysis (CCA) ¥ Neural Networks ¥ Machine Learning ¥ Computer Vision There will be a project in which students will apply appropriate techniques to a data set of their choosing. Students should be comfortable writing, compiling, and running simple computer programs in MatLab, Python, R, or comparable environment.
Prerequisites: 36-220 or 19-250

27-542 Thin Film Technologies
Fall: 9 units
This course will provide you with an understanding of the general science and technology involved in the production of solid thin films, the characteristics of thin film growth processes, methods to characterize important properties of thin films, and some of their current applications, particularly with regard to alternative energy sources, energy-efficient technologies and biosensing technologies. The class will include hands-on experience with thin film production, characterization and device fabrication (and characterization).

27-555 Materials Project I
Fall
This course is designed to give experience in individualized research under the guidance of a faculty member. The topic is selected by mutual agreement, and will give the student a chance to study the literature, design experiments, interpret the results and present the conclusions orally and in writing.

27-556 Materials Project II
Spring
Second semester of Materials Project. This course is designed to give experience in individualized research under the guidance of a faculty member. The topic is selected by mutual agreement, and will give the student a chance to study the literature, design experiments, interpret the results and present the conclusions orally and in writing.

27-561 Kinetics of Metallurgical Reactions and Processes
Fall: 6 units
This class uses examples from the ironmaking and steelmaking to illustrate different rate-determining reaction steps. Reaction times in ironmaking and steelmaking process vary quite widely; the fundamental origins of the large differences in reaction time are analyzed, after a brief overview of the main reactions and process steps in ironmaking and steelmaking. Particular skills to be practiced and developed include derivation of the mathematical relationships which describe the rates of metallurgical processes which involve heat transfer, and mass transfer for solid-gas, liquid-gas and liquid-liquid reactions; quantifying the expected rates of such reactions; identification of rate-determining steps, based on calculated rates and observed reaction rates; predicting the effects of process parameters such as particle size, stirring, temperature and chemical compositions of phases on the overall rate; and critical evaluation of kinetic data and models in scientific papers on metallurgical reactions.

27-565 Nanostructured Materials
Intermittent: 9 units
This course is an introduction to nanostructured materials or nanomaterials. Nanomaterials are objects with sizes larger than the atomic or molecular length scales but smaller than microstructures with at least one dimension in the range of 1-100 nm. The physical and chemical properties of these materials are often distinctively different from bulk materials. For example, gold nanoparticles with diameters ~15 nm are red and ~40 nm gold nanoparticles are purple whereas bulk gold has a golden color. The course starts with a discussion of top-down and bottom-up fabrication methods for making nanostructures as well as how to image and characterize nanomaterials including scanning probe microscopies. Emerging nanomaterials such as fullerenes, graphene, carbon nanotubes, quantum dots and nanocomposites are also discussed. The course then focuses on applications of nanomaterials to microelectronics, particularly nanoscale devices and the emerging field of molecular-scale electronics. The miniaturization of integrated systems that sense mechanical or chemical changes and produce as electrical signal is presented. The principles and applications of the quantum confinement effects on optical properties are discussed, mainly as sensors. The last part of the course is a discussion of nanoscale mechanisms in biomimetic systems and how these phenomena are applied in new technologies including molecular motors.

27-570 Polymeric Biomaterials
Spring: 12 units
This course will cover aspects of polymeric biomaterials in medicine from molecular principles to device scale design and fabrication. Topics include the chemistry, characterization, and processing of synthetic polymeric materials; cell-biomaterials interactions including interfacial phenomena, tissue responses, and biodegradation mechanisms; aspects of polymeric micro-systems design and fabrication for applications in medical devices. Recent advances in these topics will also be discussed.

27-577 Advanced Polymer Science and Engineering
Fall: 9 units
This advanced-level course introduces the physical concepts necessary to understand the structure-processing-properties relationships of polymers in the solid state. Chain models fundamental to the description of polymers will be introduced. The structure of solid-state polymers will be discussed with focus on the amorphous, crystalline and liquid-crystalline state. The glass transition in amorphous polymers as well as the morphology and kinetics of crystal formation in semi-crystalline polymers will be discussed in detail. Mechanical properties of polymers will be discussed with emphasis of network elasticity and linear viscoelastic behavior. Models to describe nonlinear deformation will be introduced. Simplified and viscoelastic flow models as well as the solidification of polymers will be discussed and their relevance to polymer processing illustrated. Anisotropy development during processing and the application of symmetry concepts to deduce microstructure in processed parts will be discussed. A final section of the class will be dedicated to polymer blends. Basic concepts of lattice models will be introduced and applied to predict the phase behavior of polymer blends. Applications of polymer blends, including thermoplastic elastomers and rubber toughening will be discussed.
Prerequisite: 27-477

27-591 Mechanical Behavior of Materials
Intermittent: 9 units
Spring odd years: Fundamentals of stress and strain. Linear elastic behavior. Tensile testing and yield criteria. Relationships between stress and strain for the case of plastic deformation. Theoretical strength. Tensile tests of single crystals and the idea of a slip system. Shear stress versus shear strain curves for single crystals and the effects of crystal orientation, temperature, atoms in solid solution and precipitates on the shapes of such curves. Taylor's connection between tensile curves of single crystals and those of polycrystalline samples. Dislocations and plastic deformation. Strengthening mechanisms including solid-solution strengthening, strengthening by precipitates, work hardening and grain size effects on strength. Approaches to quantifying the fracture resistance of materials, including the Griffith approach, the energy release rate approach and the stress intensity factor approach. Crack tip behavior including stresses and strains at crack tips and the plastic zone. Fracture mechanisms including ductile fracture, cleavage fracture and intergranular fracture. The fracture of highly brittle materials. Time permitting fatigue and creep of materials will be discussed.

27-592 Solidification Processing
Intermittent: 9 units
Spring odd years: The goal of this course is to enable the student to solve practical solidification processing problems through the application of solidification theory. The objectives of this course are to: (1) Develop solidification theory so that the student can understand predict solidification structure; (2) Develop a strong understanding of the role of heat transfer in castings; (3) Develop an appreciation for the strengths and weaknesses of a variety of casting processes. The first half of the course will be theoretical, covering nucleation, growth, instability, solidification microstructure: cells, dendrites, eutectic and peritectic structures, solute redistribution, inclusion formation and separation, defects and heat transfer problems. The second part of the course will be process oriented and will include conventional and near net shape casting, investment casting, rapid solidification and spray casting where the emphasis will be on process design to avoid defects.

27-700 Energy Storage Materials and Systems
Fall and Spring: 12 units
Contemporary energy needs require energy storage and conversion for a range of mobile and stationary applications. This course will examine electrochemically functional materials, devices, and systems that are used to convert, store, and release electrical energy. The principles and mathematical models of electrochemical energy conversion and storage will be examined in depth; students will study thermodynamics and reaction kinetics pertaining to electrochemical reactions, phase transformations, transport, and processing relating to a wide range of related technologies. This course also will also cover the practical aspects associated with the application of batteries, fuel cells, supercapacitor technologies. Students are asked to conduct a class project that involves interacting with outside industry and culminates in a end-of-semester poster session.

27-703 Additive Manufacturing and Materials
All Semesters: 12 units
This course will develop the understanding required for materials science and engineering for additive manufacturing. The emphasis will be on powder bed machines for printing metal parts, reflecting the research emphasis at CMU. The full scope of methods in use, however, will also be covered. The topics are intended to enable students to understand which materials are feasible for 3D printing. Accordingly, high power density welding methods such as electron beam and laser welding will be discussed, along with the characteristic defects. Since metal powders are a key input, powder-making methods will be discussed. Components once printed must satisfy various property requirements hence microstructure-property relationships will be discussed because the microstructures that emerge from the inherently high cooling rates differ strongly from conventional materials. Defect structures are important to performance and therefore inspection. Porosity is a particularly important feature of 3D printed metals and its occurrence depends strongly on the input materials and on the processing conditions. The impact of data science on this area offers many possibilities such as the automatic recognition of materials origin and history. Finally the context for the course will be discussed, i.e. the rapidly growing penetration of the technology and its anticipated impact on manufacturing.

27-704 Principles of Surface Engineering and Industrial Coatings
Fall and Spring: 6 units
Many modern technologies rely on the use of innovative, multi-functional coatings to ensure competitive advantage in the fast-changing global markets. Building such coatings requires advanced planning of the entire coating-substrate system, and of the manufacturing steps. This course will discuss the design principles of multi-functional coatings, present advanced coating architectures and review the relevant manufacturing steps. The course will be illustrated with design principles of functional coatings in three major industries: aerospace, automotive, and machining. We will identify the relevant key challenges, and follow the thinking process of the industry leaders addressing the challenge. Then, we will examine the developed coating solutions: multi-functional tribological coatings on cutting tools; thermal barrier coatings on nickel alloy turbine blades for aircraft and power generation; diamond like coatings and wear protective coatings for automotive diesel engines; and corrosion protection in the aerospace and in the automotive industries. The course will conclude with a discussion of new trends in surface engineering and in the design of multi-functional coatings, including self-healing, self-cleaning, and other smart coatings.

27-706 Hard and Superhard Materials
Fall and Spring: 6 units
This course will focus on the fundamental principles of hard and superhard materials. We will first discuss the origin of hardness across materials, and then describe important examples of materials prized for their intrinsic or extrinsic hardness. We will focus on the preparation, microstructure, and properties of materials such as diamond, cubic boron nitride and compound carbides. Then, we will emphasize the design of novel nano-structured and nano-composite materials and coatings, which are at the frontier of material science. Finally, the course will present examples of the architecture and processing methods used to generate hard materials and coatings in manufacturing automotive and aerospace industries.

27-709 Engineering Biomaterials
Fall: 12 units
This course will cover structure-processing-property relationships in biomaterials for use in medicine. This course will focus on a variety of materials including natural biopolymers, synthetic polymers, and soft materials with additional treatment of metals and ceramics. Topics include considerations in molecular design of biomaterials, understanding cellular aspects of tissue-biomaterials interactions, and the application of bulk and surface properties in the design of medical devices. This course will discuss practical applications of these materials in drug delivery, tissue engineering, biosensors, and other biomedical technologies.

27-715 Applied Magnetism and Magnetic Materials
Spring: 12 units
In this course we address the physics of magnetism of solids with emphasis on magnetic material properties and phenomena which are useful in various applications. The content of this course includes the origins of magnetism at the atomic level and the origins of magnetic ordering (ferro-, ferri-, and antiferromagnetism), magnetic anisotropy, magnetic domains, domain wall, spin dynamics, and transport at the crystalline level. The principles of magnetic crystal symmetry are utilized to explore the various domains in ferromagnetic crystals, and tensors are used in the description of such magnetic properties as magnetocrystalline anisotropy, susceptibility and magnetostriction. To a limited extent, the applications of magnetism are discussed in order to motivate the understanding of the physical properties and phenomena.

27-719 Computational Thermodynamics
Spring: 6 units
Computational thermodynamics is a powerful tool of a Materials Engineer. We will examine how thermodynamic simulation software outputs an equilibrium calculation from a list of input conditions. This requires a description of Gibbs energy minimization calculations, Gibbs energy models, and the construction of these models from thermodynamic data. At the end of the class students should be able to use thermodynamic simulation software to solve engineering problems while recognizing its limitations. This class is for graduate students interested in these computational tools.

27-720 Tissue Engineering
Spring: 12 units
This course will train students in advanced cellular and tissue engineering methods that apply physical, mechanical and chemical manipulation of materials in order to direct cell and tissue function. Students will learn the techniques and equipment of bench research including cell culture, immunofluorescent imaging, soft lithography, variable stiffness substrates, application/measurement of forces and other methods. Students will integrate classroom lectures and lab skills by applying the scientific method to develop a unique project while working in a team environment, keeping a detailed lab notebook and meeting mandated milestones. Emphasis will be placed on developing the written and oral communication skills required of the professional scientist. The class will culminate with a poster presentation session based on class projects. Pre-requisite: Knowledge in cell biology and biomaterials, or permission of instructor

27-721 Processing Design
Fall: 6 units
In this course, the concepts of materials and process design are developed, integrating the relevant fundamental phenomena in a case study of a process design. The course includes basic science and engineering as well as economic and environmental considerations. The case study is on environmentally acceptable sustainable steelmaking. Other case studies in materials processing could be used.

27-729 Solid State Devices for Energy Conversion
Intermittent: 6 units
Intensive research efforts have yielded promising new materials approaches to 'alternative' energy conversion technologies, such as solar cells or photovoltaics; thermoelectric materials, which convert waste heat to electricity; metal/semiconductor superlattices for thermionic energy conversion; and fuel cells. At the same time, notable advances have been made in devices that substantially enhance our energy efficiency: e.g., chemical sensors and light-emitting diodes for solid-state lighting. In all of these devices, interfaces between dissimilar materials often govern and/or limit the behavior. In addition to the basic structures and operating principles, this course will cover practical materials interface issues, such as electrical transport, thermal stability, contact resistance, and bandgap engineering, that significantly affect the performance of a variety of energy conversion and energy-saving devices.

27-731 Texture, Microstructure & Anisotropy
Intermittent: 6 units
The purpose of Texture, Microstructure and amp; Anisotropy is to acquaint the student with a selected set of characterization tools relevant to the quantification of microstructure (including crystallographic orientation, i.e. texture) and anisotropic properties. The motivation for the course is problem solving in the areas of property measurement (e.g. grain boundary energy), prediction of microstructural evolution (e.g. in grain growth and recrystallization), and prediction of properties based on measured microstructure (e.g. anisotropy of work hardening and ductility). In this 6 unit mini version of the course, the specific objectives are to develop skills and understanding in the following areas: (1) The mathematical basis for crystallographic orientation distributions (aka ODFs), with explanations of the many representations of rotations/orientations; (2) Crystallographic preferred orientation (texture) and its representation by pole figures, inverse pole figures and orientation distributions, with a particular emphasis on the effects of symmetry in representations; (3) Methods of measuring texture such as X-ray (diffraction) Pole Figures and Electron Back Scatter Diffraction (EBSD) with reference to orientation mapping; (4) The effect of texture on elastic and plastic anisotropy in polycrystals; the uniform stress model (Sachs), the Taylor-Bishop and amp; Hill model, the Eshelby analysis; Emphasis is placed on the use and understanding of quantitative tools for texture data acquisition and amp; analysis (e.g. orientation distribution determination from pole figure data, and automated electron back-scatter diffraction/EBSD/OIM), the effect of crystal and sample symmetry on distributions and their representation, and the prediction of anisotropy (e.g. calculation of yield surfaces for plastic deformation). Since the datasets are often large, such as from EBSD scans, computer programs are essential.

27-734 Methods of Computational Materials Science
Fall: 12 units
This course introduces students to the theory and practice of computational materials science from the electronic to the microstructural scale. Both the underlying physical models and their implementation as computational algorithms will be discussed. Topics will include: Density functional theory Molecular dynamics Monte Carlo methods Phase field models Cellular automata Data science Examples and homework problems will be taken from all areas of materials science. Coursework will utilize both software packages and purpose-built computer codes. Students should be comfortable writing, compiling, and running simple computer programs in MatLab, Python, or comparable environment.

27-737 Data Analytics and Machine Learning for Materials Science
Intermittent: 12 units
Materials Science and Engineering has traditionally been taught by emphasizing the development and application of technology. This course will present an alternative approach that combines data mining, data analytics, and material fundamentals (i.e. materials informatics). Students will be introduced to informatics techniques related to data mining and large database analysis. The topics will include:Principal Component Analysis (PCA)Canonical Correlation Analysis (CCA)Neural NetworksMachine LearningComputer VisionThere will be twoprojectsin which students will apply appropriate techniques to data setsof their choosing; in the second (graduate level) project, students will be asked to build, train, and execute a multi-layer neural net to automatically recognize shapes that are relevant to material microstructures. One quarter of the lectures in this course will focus on the custom creation of convolutional neural networks. Students should be comfortable writing, compiling, and running simple computer programs in MatLab, Python, R, or comparable environment.

27-741 Practical Methods in Transmission Electron Microscopy
Fall and Spring
This course is designed to provide instrument training on transmission electron microscopes in the Materials Characterization Facility (MCF). Emphasis will be placed on acquiring the basic skills needed to successfully operate this type of microscope; this will be achieved by a combination of lectures and hands-on lab sessions. Lectures will provide the necessary background to understand electron scattering techniques, including electron diffraction, bright field and dark field imaging, phase contrast microscopy, and energy dispersive x-ray spectroscopy. Lab sessions will inform the student on standard operating procedures for the techniques discussed in the lecture portion of the course. At the end of the course, the student is expected to demonstrate the ability to independently use the transmission electron microscope for basic operations; successful demonstration of such skills will lead to certification for day-use of transmission electron microscopes in the MCF.

27-752 Fundamentals of Semiconductors and Nanostructures
Spring: 12 units
This course is designed to provide students with a foundation of the physics required to understand nanometer-scale structures and to expose them to different aspects of on-going research in nanoscience and nanotechnology. Illustrative examples will be drawn from the area of semiconductor nanostructures, including their applications in novel and next-generation electronic, photonic, and sensing devices. The course begins with a review of basic concepts in quantum physics (wave-particle duality, Schr and #246;dinger's equation, particle-in-a-box, approximation methods in quantum mechanics, etc.) and then continues with a discussion of bulk three-dimensional solids (band structure, density of states, the single-electron effective-mass approximation). Size effects due to nanometer-scale spatial localization are then discussed within a quantum-confinement model in one-, two-, and three- dimensions for electrons. An analogous discussion for photons is also presented. The basic electronic, optical, and mechanical properties of the low-dimensional nanostructures are then discussed. A select number of applications in electronics, photonics, biology, chemistry, and bio-engineering will be discussed to illustrate the range of utility of nanostructures. Upon completion of the course, students will have an appreciation and an understanding of some of the fundamental concepts in nanoscience and nanotechnology. The course is suitable for first-year graduate students in engineering and science (but advanced undergraduates with appropriate backgrounds may also take it with permission from the instructor). Pre-requisites include 09-511, 09-701, 09-702, 18-311, 27-770, 33-225, 33-234 or familiarity with the material or basic concepts covered in these courses.

27-754 Mechanical Behavior of Engineering Materials
Intermittent: 12 units
Engineers employ all classes of materials (metals, polymers, ceramics and hybrids) in load-bearing applications. To reduce material cost, save energy and maximize performance, engineering materials are frequently designed to be used near their load-bearing limits. An understanding of underlying deformation mechanisms complements a design rule approach in that unexpected failures can be far better anticipated and hence minimized. This course will survey the major deformation mechanisms in the main materials classes. Topics will include structure, elasticity, continuum failure models, fracture mechanics, and plastic deformation mechanisms of polymers, fiber-reinforced, composites, ceramics and metals. Proper design practice and real-life failures will be discussed.

27-761 Kinetics of Metallurgical Reactions and Processes
Fall: 6 units
This class uses examples from the ironmaking and steelmaking to illustrate different rate-determining reaction steps. Reaction times in ironmaking and steelmaking process vary quite widely; the fundamental origins of the large differences in reaction time are analyzed, after a brief overview of the main reactions and process steps in ironmaking and steelmaking. Particular skills to be practiced and developed include derivation of the mathematical relationships which describe the rates of metallurgical processes which involve heat transfer, and mass transfer for solid-gas, liquid-gas and liquid-liquid reactions; quantifying the expected rates of such reactions; identification of rate-determining steps, based on calculated rates and observed reaction rates; predicting the effects of process parameters such as particle size, stirring, temperature and chemical compositions of phases on the overall rate; and critical evaluation of kinetic data and models in scientific papers on metallurgical reactions.

27-766 Defects and Diffusion in Materials
Fall: 12 units
Defects in materials, and the transport of matter through these defects by diffusion, strongly influence a material's physical properties and microstructural evolution. For example, the strength of materials, the electrical and optical properties of materials, and the rates at which microstructures coarsen, recrystallize, and oxidize all depend on the population of intrinsic and extrinsic defects and the transport of matter through these defects. The objective of this course is to define methods of quantifying the population and properties of defects in materials and the transport of matter through these defects. The course addresses both crystalline, semicrystalline, and amorphous materials and begins with the fundamentals of diffusion in amorphous materials. After describing point defect formation and equilibrium defect populations in elements and compounds, diffusion through these defects will be described. Point defect diffusion will be illustrated using examples such as the Kirkendall effect and diffusive creep. The properties and characteristics of dislocations, their motion, and the role of dislocations in deformation will also be discussed. Short circuit diffusion and the role of diffusion in dislocation creep will be described as examples of transport involving dislocations. Finally, the energetics of planar defects, grain boundaries, and interfaces will be discussed. Diffusive transport along interfaces will be described, using examples including transport in two phase systems, sintering, and coarsening.

27-791 Mechanical Behavior of Materials
Spring: 12 units
The intent of the course is to introduce various measures indicative of the performance of materials in applications. Properties often used in selecting materials will be introduced, and connections between these properties and microstructure will be developed. Mechanical properties are emphasized in this course. 4 hrs. lec.

27-792 Solidification Processing
Spring: 12 units
The goal of this course is to enable the student to solve practical solidification processing problems through the application of solidification theory. The objectives of this course are to: (1) Develop solidification theory so that the student can understand predict solidification structure; (2) Develop a strong understanding of the role of heat transfer in castings; (3) Develop an appreciation for the strengths and weaknesses of a variety of casting processes. The first half of the course will be theoretical, covering nucleation, growth, instability, solidification microstructure: cells, dendrites, eutectic and peritectic structures, solute redistribution, inclusion formation and separation, defects and heat transfer problems. The second part of the course will be process oriented and will include conventional and near net shape casting, investment casting, rapid solidification and spray casting where the emphasis will be on process design to avoid defects.

27-796 Structure and Characterization of Materials
Fall: 12 units
The objective of this course is for the student to be able to understand important crystal structures of both inorganic and organic materials in terms of their building blocks (atom positions, Bravais lattices, structural units, symmetry groups, stacking and packing configurations) and also to understand how modern experimental materials characterization techniques (including x-ray, electron, and neutron diffraction and spectroscopic techniques) are used to obtain structural and chemical information.

27-798 Thermodynamics of Materials
Fall: 12 units
This course offers a practical introduction to the principles of statistical thermodynamics that links the microscopic atomic details of materials to their macroscopic behavior, and applies these principles to multicomponent material equilibria. The laws and concepts of classical thermodynamics and probability are briefly reviewed, and then applied to introduce the atomic statistical definitions for temperature, entropy, and thermodynamic equilibrium. Statistical methods for enumerating the microscopic configurations of fluids, magnets, solid crystals, and polymers will be covered and applied to evaluate thermodynamic free energies subject to varying macroscopic constraints. These will be used to relate equilibrium properties and phase behavior to the engineerable molecular details of materials. Applications will include equilibrium phase diagrams (binary and ternary), predominance diagrams, chemical reactions, thermodynamics of surfaces, and electrochemistry.

27-990 SPECIAL TOPICS: Teaching Materials Science & Engineering
Spring: 3 units
This course is designed to prepare graduate students for their future role as educators in Materials Science and amp; Engineering. Teaching is a critical facet of higher education whether as a course assistant, instructor, or student mentor. Although excellent teaching can have a significant positive impact on students at all levels, formal training at the University level is relatively uncommon. Contrary to popular belief, teaching is not simply a skill you are born with, but rather one that requires significant practice and continuous refinement. The primary goal of this course is to provide pedagogical strategies necessary to be an effective teacher with a focus on fundamental topics in materials science and amp; engineering.