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MATERIAL INSPIRATION

Supporting Introductory Materials Science Teaching for All Majors: Callister-Based Courses and CES EduPack

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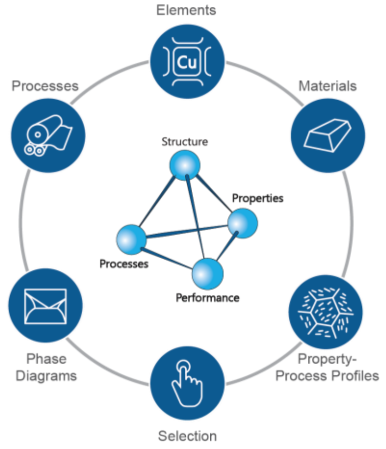
Abstract

Introductory materials science and engineering (MSE) courses are an integral part of the curricula for many engineering disciplines. It is often the case that students from multiple majors are enrolled in such a course; thus, meeting the needs of all students may prove to be a challenge to the instructor. Introductory materials textbooks (such as the ones written by William Callister) are used to connect fundamental principles of materials science and materials engineering to real-world applications. As a supplement to these textbooks, Granta has developed a new *MS&E Edition* of its CES EduPack software. This includes a new Phase Diagram Tool and Property-Process Profiles data, in addition to the familiar property-graphing capability for both elements and families of materials. Thus, the *MS&E Edition* provides students additional resources to explore complex materials topics.



Proper implementation of this *MS&E Edition* in an introductory materials science and engineering course can help build the students' confidence in understanding the basic principles of MSE and generate a greater interest in the science and engineering of materials. This paper describes the process of how these outcomes may be accomplished alongside textbooks written by Callister.

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Introductory Courses: Balance of Engagement and Information

For most materials majors as well as majors in other engineering disciplines, an introductory MSE course is their first exposure to the discipline of materials. Unfortunately, many nonmaterial students are reluctant to take an introductory materials course, often because they are unfamiliar with materials concepts and vocabulary and, also, don't appreciate the importance of developing an understanding of materials in terms of success in their future careers. For ongoing interest and retention, the quality of this course experience is crucial. It is important that students be firmly grounded in the fundamentals of materials science and materials engineering and be provided abundant opportunities to learn and understand at an appropriate level of comprehension. Learning activities should be interesting and relevant to their disciplines—in order to motivate students to study and become engaged with the concepts and principles that need to be mastered. How does an instructor accomplish these objectives?

Several introductory MSE textbooks are available that provide instruction and guidance to students focusing on vocabulary, property definitions and the basic principles of the materials discipline.[1] Typically, these textbooks start with the fundamental principles of *materials science*, and continue with some elements of *materials engineering* and the use of materials in engineering design. Perhaps the most widely used of these textbooks is the 9th edition of William Callister's *Materials Science and Engineering: An Introduction.* In essence, from both materials science and materials engineering perspectives, it explores the relationships among the processing, structure, properties (viz. mechanical, electrical, magnetic, optical), and performance of metals, ceramics, polymers, electronic, and composite materials. In this paper we detail how elements of this new *MS&E Edition* can be used to supplement and complement the introductory materials textbook (specifically Callister's 9th edition) to enhance the learning experience for students of all engineering disciplines.

CES EduPack MS&E Edition: Designed with materials scientists and engineers in mind

For many years, CES EduPack has been a resource for supporting materials and manufacturing process-related courses across many engineering, science, and design disciplines. It is used at over 1000 universities and colleges worldwide and has gradually evolved into an elegant education resource by incorporating improvements that were implemented in response to feedback from EduPack users.

The core of CES EduPack is a Materials and Processes database containing records for thousands of materials and hundreds of processes. Metals, polymers, ceramics and composites are joined by biological materials, functional materials, and fibers. Properties include standard mechanical, electrical, thermal and optical properties as well as environmental and durability data. These databases serve as a reliable data source for students to use in projects or homework. This data can be graphed, allowing a visual and interactive overview of and comparison across material classes. Each property is linked to a 'Science Note'—a technical document giving a brief explanation of the definition and origin of the property and references for where students can get further information in commonly used textbooks (e.g. Callister). EduPack gives students the tools to look up, visualize and compare data, select materials for an application, or asses the environmental impact of a design. Additional learning support is provided through Learn Online, where students can access teach-yourself exercises and tutorials. Educators can access over 300 teaching resources created to be used alongside EduPack

[1] ***"Materials: engineering, science, processing and design"*** 3rd edition by M.F. Ashby, H.R. Shercliff and D. Cebon, Butterworth Heinemann, Oxford, 2014; ***"Materials Selection in Mechanical Design",*** 5th edition by M.F. Ashby, Butterworth Heinemann, Oxford, 2016; "**Introduction to Materials Science for Engineers"** 8th edition by James F. Shackelford, Pearson, 2014

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via Granta's Education Hub. Examples of how CES EduPack can be used will be found throughout this paper to showcase the strength of the software in the classroom.

The *MS&E Edition* of CES EduPack was developed by consultation with some of the leading materials educators in the US, most of whom use Callister's book in their courses.[2] This edition introduces what is termed the *materials paradigm*, the essence of materials science and engineering—the link between processing, structure, properties, and performance of materials. Pictorially, the paradigm is represented using a tetrahedron shown in Figure 1. This connection is kept at the center of the *MS&E Edition* interface, encouraging students to explore the connections between these four topics and develop their *materials intuition*— the understanding a student builds of terminology, material properties and their typical values, and other connections associated with the paradigm. Developing this intuition early allows for students to engage in complex topics more quickly.

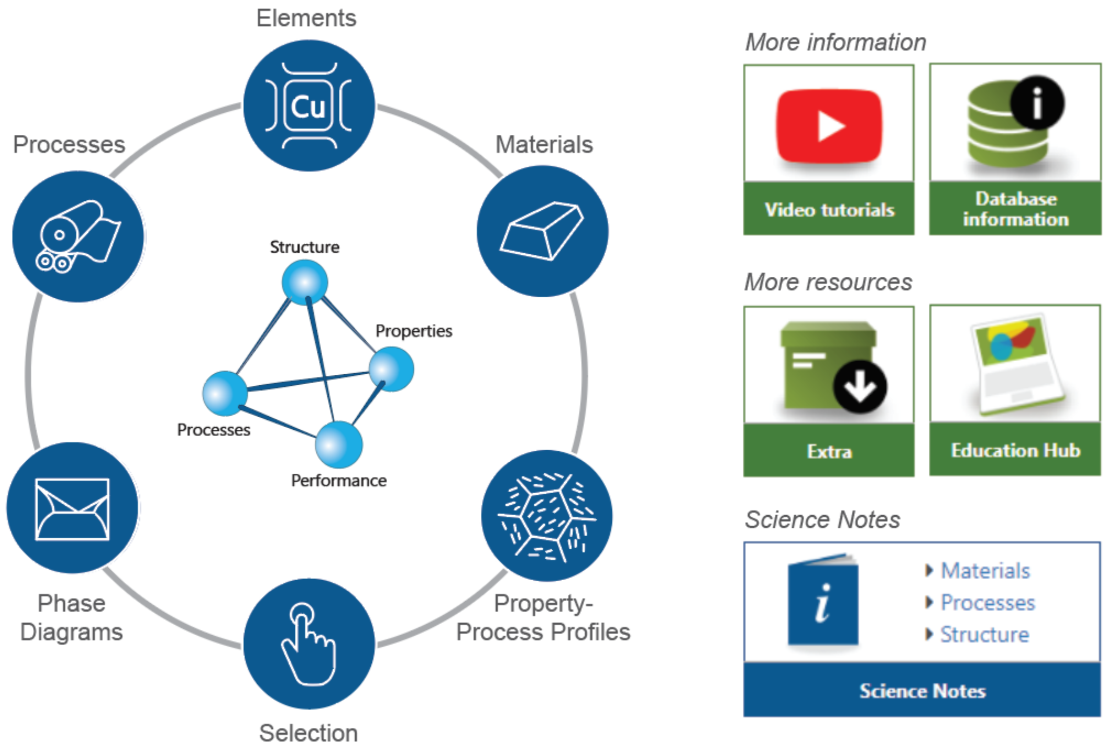

Figure 1. *MS&E Edition Interface. The materials paradigm is kept at the center of these six focus areas to reaffirm its importance. Links to the Science Notes (including the new MS&E structure notes), video tutorials, and the Education Hub are on the homepage for easy access.*

Surrounding this tetrahedron are six, what we have chosen to call, "focus areas": Elements, Materials, Property-Process Profiles, Selection, Phase Diagrams, and Processes. The two new topics specific to this Edition are on Phase Diagrams and Property-Process Profiles. The Phase Diagram topic delves into the complexities of learning to read phase diagrams and includes interactive tools to aid exploration. The Property-Process Profiles showcases sets of records that highlight the impacts of processing on properties. New Structure Science Notes on materials science specific areas, such as solid solution strengthening and phonon scattering, make the connection between the atomic and microstructure of the materials and their properties.

[2] Many thanks to Mary Vollaro, Bill Callister, Stephen Krause, John Nychka, Ron Kander, Matt Cavalli, Stéphane Gorsse, and Cindy Waters

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By using this Edition, we hope to support educators in the following learning objectives.

Students will be able to:

- Recognize that processing and composition change material properties
- Read a phase diagram and identify the phases present in typical systems
- Identify a broad range of materials and their properties
- Understand the definitions and origins of material properties
- Assess the environmental impacts of a product
- Demonstrate how to select a material or process for an application or product

The rest of this paper will be centered around the capabilities of the *MS&E Edition* and the connections between focus areas and Callister's textbook (9^{th} edition). The chapters highlighted were chosen because they appeared in the syllabi of multiple Callister-based introductory courses.

MS&E Edition Capabilities: Supporting Materials Education

Elements: Bonding and how it impacts structure and beyond

Atoms and atomic bonding are fundamental to how materials form and behave. The basics of these topics have often been introduced to students in earlier courses (i.e. chemistry), but the effect bonding can have on material properties is rarely taught. Callister ***Chapter 2: Atomic Structure and Interatomic Bonding*** and ***Chapter 3: The Structure of Crystalline Solids*** do an excellent job of reframing facts about bonding for MSE interest and introducing the idea of unit cells and Miller Indices—the fundamentals of crystallography. The combination of detailed fundamentals on bonding types and unit cells provided in Callister can be supported with the *MS&E Edition* through the Elements focus area. An interactive Periodic Table, with data records for all 118 elements, allows for exploration of elemental properties such as electronic structure, crystal structure (see inset of Figure 2), mechanical properties, ecological data, and much more. These values can be plotted within the Chart tool of the EduPack to show elemental trends, such as the relationship between atomic radius and lattice parameter for different unit cells shown in Figure 2. With this tool, students can investigate which properties are bonding dependent (such as melting temperature) with those that are more microstructural dependent (such as strength). To address the complex three-dimensional visualization needs of Miller Indices, the software's built-in Learn Online function contains a "Teach Yourself Crystallography" resource, complete with exercises and detailed diagrams.

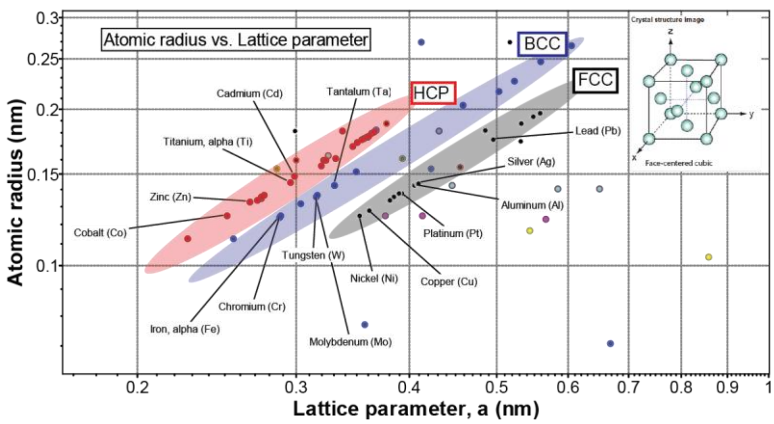

Figure 2. *Plot generated in the Elements Focus Topic Tab of Atomic Radius vs. Lattice parameter with unit cell groups highlighted. Inset shows Unit Cell from a single element datasheet.*

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Material Properties: What do they really mean?

Understanding the origins, definitions, and typical values of material properties is an important part of an introductory course. Words like tough, hard, and strong take on a new meaning in the context of materials. Learning how to communicate in this new language is critical to students' careers as engineers. By connecting to real materials and products that students are already familiar with, they can build up their *materials intuition*; but bridging this gap between theory and practical knowledge can be challenging in introductory courses. ***Chapter 6: Mechanical Properties of Metals*** as well as the mechanical properties sections of ***Chapter 12: Structure and Properties of Ceramics*** and ***Chapter 15: Characteristics, Applications, and Processing of Polymers*** give students the fundamental knowledge needed to understand mechanical properties and what is going on at an atomistic level. The *MS&E Edition* Materials focus area can support these chapters through:

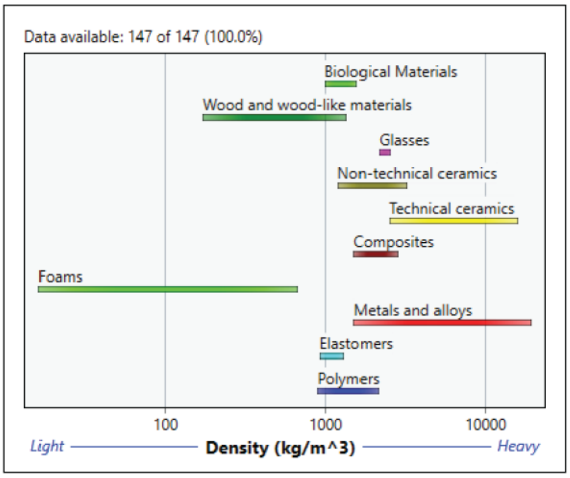

Figure 3. *Density range plot for various material family records. Found within the Limit Stage Tab.*

- Images of materials in typical uses
- Reliable, comparable materials data
- Embedded text with definitions of various properties
- Plots of typical property values for different material classes
- Descriptions of material classes
- Ability to display and interactively explore materials data

Figure 3 shows one example of this: a range plot of density values for various material families. Density and stiffness are properties that students have familiarity with; by plotting these tangible properties (using proper materials terminology and units) and correlating them to real-world objects, students can begin to create a picture of the materials universe (see Figure 4).

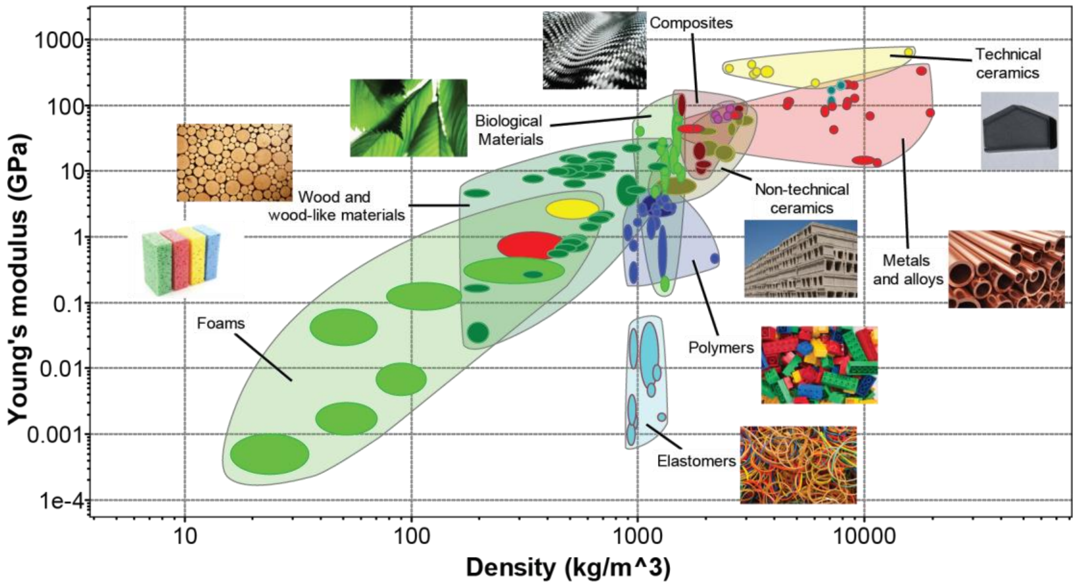

Figure 4. *Young's Modulus plotted against Density within the Materials focus topic of the MS&E Edition. Additional material reference photos were added for clarity.*

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Equations can also be visualized through plotting; see how the relationship between Shear Modulus (G), Elastic Modulus (E), and Poisson's ratio (v) in Equation 1 (Equation 6.9 from Callister) is made apparent in Figure 5.

$$E = 2G(1 + \upsilon) \tag{1}$$

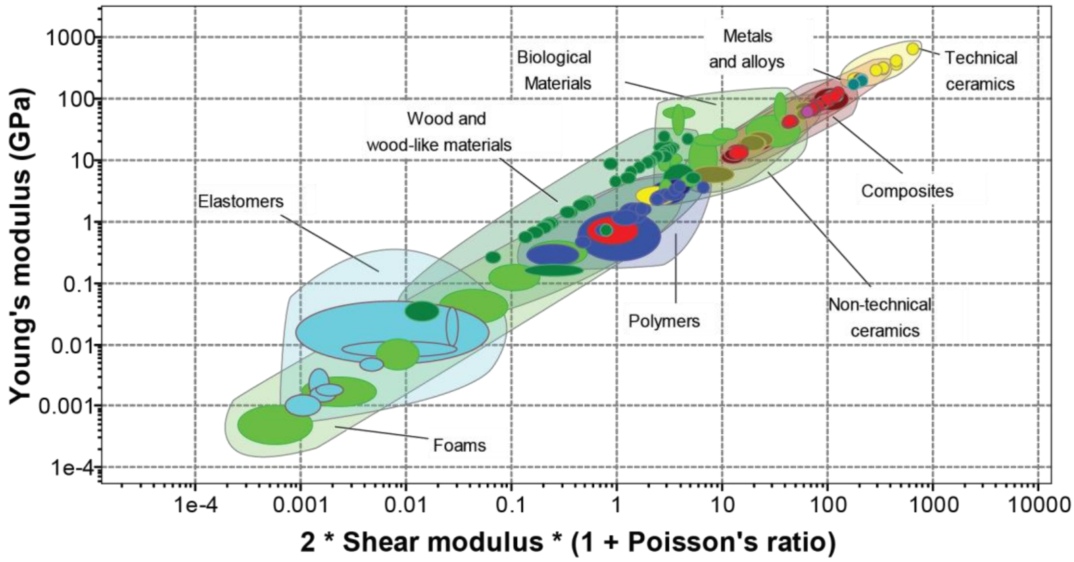
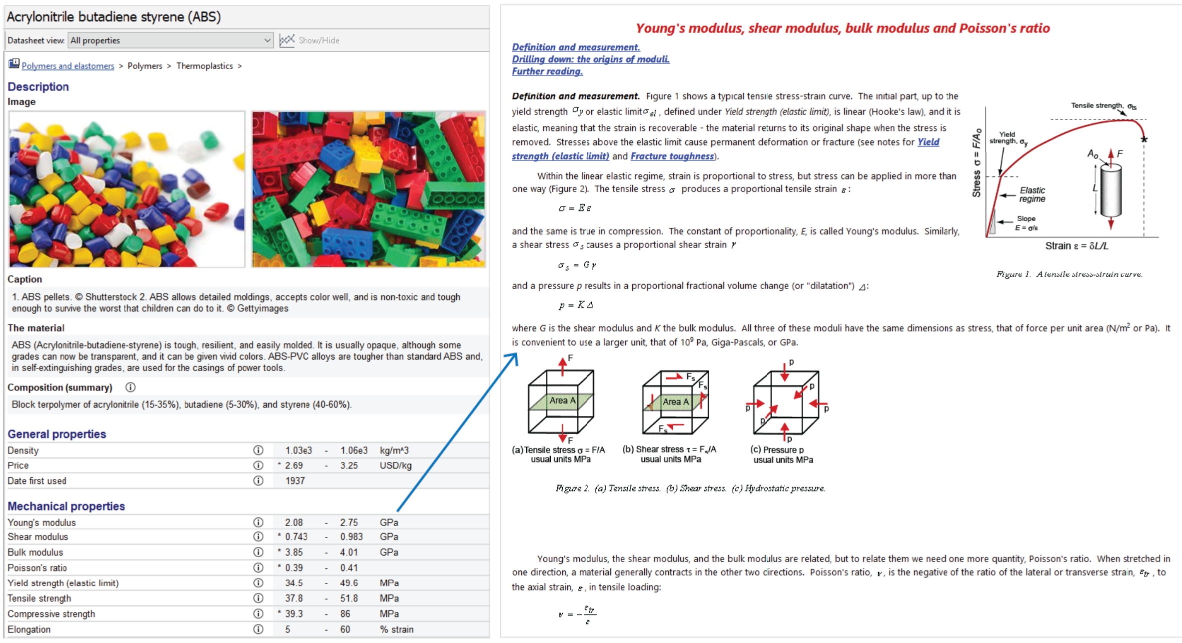


Figure 5. *Plot of Equation (1) from Callister's Book. Created using the Advanced axis function of CES EduPack*

The material records and connected Science Notes (see Figure 6) support the aforementioned chapters as well as ***Property Specific Chapters (i.e. Ch. 18, 19, 20)*** and ***Material Family Specific Chapters (i.e. Ch. 11, 12, 15, 16)***.



Acrylonitrile butadiene styrene (ABS)

Datasheet view: All properties Show/Hide

Polymers and elastomers > Polymers > Thermoplastics >

Description

Image

Caption

1. ABS pellets. © Shutterstock 2. ABS allows detailed moldings, accepts color well, and is non-toxic and tough enough to survive the worst that children can do to it. © Gettyimages

The material

ABS (Acrylonitrile-butadiene-styrene) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Composition (summary)

Block terpolymer of acrylonitrile (15-35%), butadiene (5-30%), and styrene (40-60%).

General properties

Density	1.03e3	-	1.06e3	kg/m^3
Price	* 2.69	-	3.25	USD/kg
Date first used	1937			

Mechanical properties

Young's modulus	2.08	-	2.75	GPa
Shear modulus	* 0.743	-	0.983	GPa
Bulk modulus	* 3.85	-	4.01	GPa
Poisson's ratio	* 0.39	-	0.41	
Yield strength (elastic limit)	34.5	-	49.6	MPa
Tensile strength	37.8	-	51.8	MPa
Compressive strength	* 39.3	-	86	MPa
Elongation	5	-	60	% strain

Young's modulus, shear modulus, bulk modulus and Poisson's ratio

Definition and measurement.
Drilling down: the origins of moduli.
Further reading.

Definition and measurement. Figure 1 shows a typical tensile stress-strain curve. The initial part, up to the yield strength σ_y or elastic limit σ_{el}, defined under *Yield strength (elastic limit)*, is linear (Hooke's law), and it is elastic, meaning that the strain is recoverable - the material returns to its original shape when the stress is removed. Stresses above the elastic limit cause permanent deformation or fracture (see notes for ***Yield strength (elastic limit)*** and ***Fracture toughness***).

Within the linear elastic regime, strain is proportional to stress, but stress can be applied in more than one way (Figure 2). The tensile stress σ produces a proportional tensile strain ε:

$$\sigma = E\varepsilon$$

and the same is true in compression. The constant of proportionality, E, is called Young's modulus. Similarly, a shear stress σ_s causes a proportional shear strain γ

$$\sigma_s = G\gamma$$

and a pressure p results in a proportional fractional volume change (or "dilatation") Δ:

$$p = K\Delta$$

where G is the shear modulus and K the bulk modulus. All three of these moduli have the same dimensions as stress, that of force per unit area (N/m^2 or Pa). It is convenient to use a larger unit, that of 10^9 Pa, Giga-Pascals, or GPa.

Figure 1. A tensile stress-strain curve.

Figure 2. (a) Tensile stress. (b) Shear stress. (c) Hydrostatic pressure.

Young's modulus, the shear modulus, and the bulk modulus are related, but to relate them we need one more quantity, Poisson's ratio. When stretched in one direction, a material generally contracts in the other two directions. Poisson's ratio, ν, is the negative of the ratio of the lateral or transverse strain, ε_{tr}, to the axial strain, ε, in tensile loading:

$$\nu = -\frac{\varepsilon_{tr}}{\varepsilon}$$

Figure 6. *Example Materials Data Sheet (Left) and Example Science Note (Right)*
Each record is linked (highlighted by arrow)

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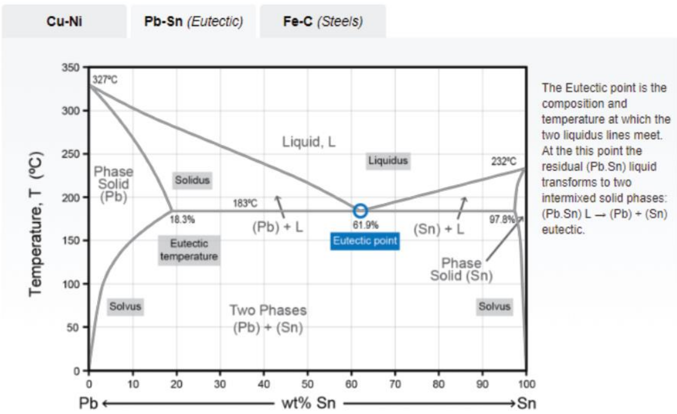
Phase Diagrams: One of the most complex introductory topics

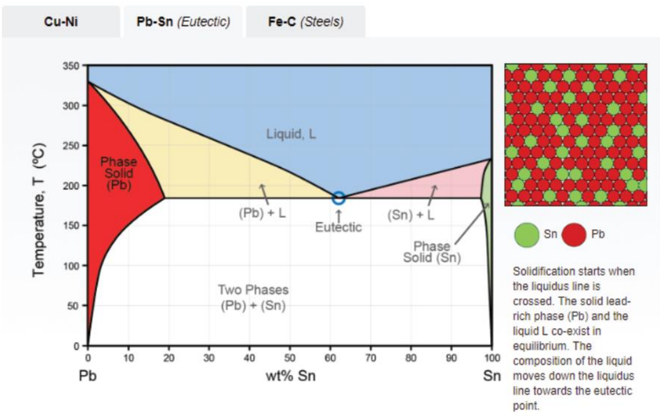
Phase diagrams are a fundamental part of MSE. They allow for understanding of phase formation at specific compositions and temperatures in (roughly) equilibrium conditions and serve as an introduction to microstructures, cooling rates, and the impact these have on the final material properties. Learning to read these diagrams is an integral part of introductory courses and is one of the most challenging topics covered. ***Chapter 9: Phase Diagrams*** in Callister gives a detailed overview of both isomorphous and eutectic phase diagrams, as well as an introduction into the important iron-carbon phase diagram. Our MS&E Edition compliments this with five interactive tools to explore topics such as: (i) terminology, (ii) phase formation, (iii) the Lever Rule, (iv) microstructural evolution during cooling, and (v) the variation within binary phase diagrams. Schematics of the tools and their key points can be found in the Figures 7-11 below. The Lever Rule tool (Fig. 9) is particularly relevant for introductory courses, helping clarify this confusing topic by presenting the equation, a schematic of the phases present, and the tie line simultaneously. All these resources are further supported via the learn online “Teach Yourself Phase Diagrams” link found within the software.



Key points:

- Interactive terminology exploration
- Can connect definitions across three phase diagrams.
  - » Build recognition of liquidus, solidus, and solvus lines.
  - » Build understanding of various reaction equations.

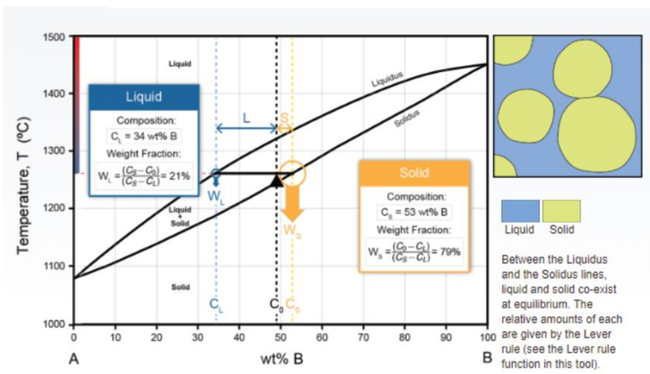
Figure 7. *Phase Diagram Glossary Interface and Key Points*



Key points:

- Interactive phase identification exploration.
- Atom arrangement during solidification shown.
  - » Shows solubility limits and the effect on phase composition across three phase diagrams.

Figure 8. *Phases Tool Interface and Key Points*



Key points:

- Three different demonstrations of the Lever Rule for each point.

1. Equations with corresponding labels on the diagram.
2. Microstructural schematic of phase fraction.
3. Graphical drawing of tie line and important points on the line.

Figure 9. *Lever Rule Tool Interface and Key Points*

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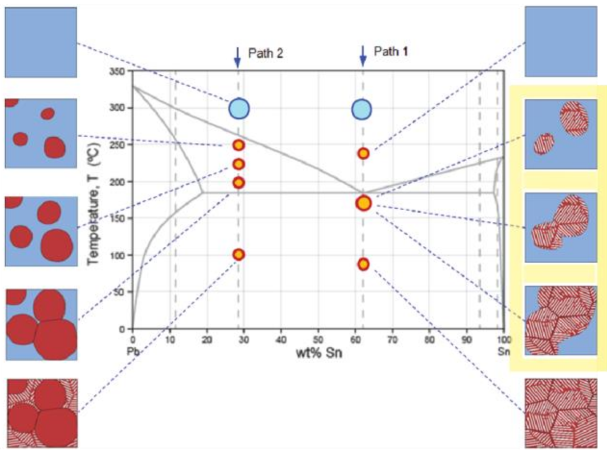
• Multiple temperature points highlighted to build understanding of phase fraction changes during solidification.
• Simple example of isomorphous phase diagram to build basic understanding.
  » Link to more advanced examples within the textbook, classroom, and homework.



Key points:
- Interactive tool to understand microstructural evolution at various points of solidification.
- Relative amounts of each phase are shown at every step.
  - » microstructural evolution shown at reaction points via gif (breakdown highlighted here)

Figure 10. *Cooling Paths Tool Interface Schematic and Key Points. Two Cooling paths and all relevant microstructures are shown for demonstration*

Key points:
- 14 additional phase diagrams to investigate
- Includes relevant compositions and temperatures for all reactions
  - » Allows for advanced investigation of more complex phase diagrams
- Able to copy and paste into homework assignments

Figure 11. *Phase Diagram Datatable Interface and Key Points*

By providing additional interactive tools, the CES EduPack hopes to support students and educators with this often frustrating, yet ultimately crucial aspect of an introductory course.

Property-Process Profiles: Connecting processing to structure to properties

As stated previously, the connections within the *materials paradigm* are the essence of materials science and engineering. Understanding how processing alters a material's structure (thereby changing its properties) is crucial for all engineers who use materials in their designs. ***Chapters 10 & 11: Phase Transformations: Development of Microstructure and Alteration of Mechanical Properties & Applications and Processing of Metal Alloys.***

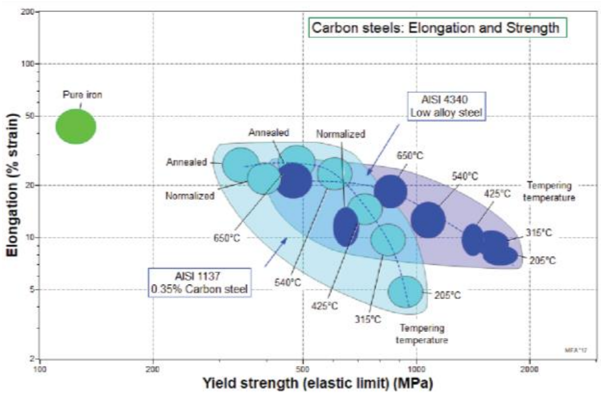


Figure 12. *Plot Illustrating how hardening mechanisms effect Yield Strength of Carbon Steels. Created using the Property-Process Profile Focus Area*

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go into this topic in detail and the Property-Process Profiles focus area of the *MS&E Edition* (Fig. 1) is specifically designed to illustrate how both composition and processing of materials changes their structure at the microstructural level (e.g. precipitate hardening) and macro level (e.g. foaming), and how that ultimately affects their properties. Seven different examples can be found in this section: (i) alloying and working of copper alloys, (ii) heat treatment of carbon steels, (iii) alloying and heat treatment of stainless steels, (iv) alloying and heat treatment of aluminum alloys, (v) filling and reinforcement of thermoplastic polymers, (vi) powder processing of sintered ceramics, and (vii) foaming of polymers, metals, and ceramics. Each set is accompanied by a folder-level record describing the materials contained and suggesting charts that students can create to explore how these structural changes affect different properties (see Figure 12). Embedded science notes help the students make the connection between structural changes and properties, as seen in Figure 13.

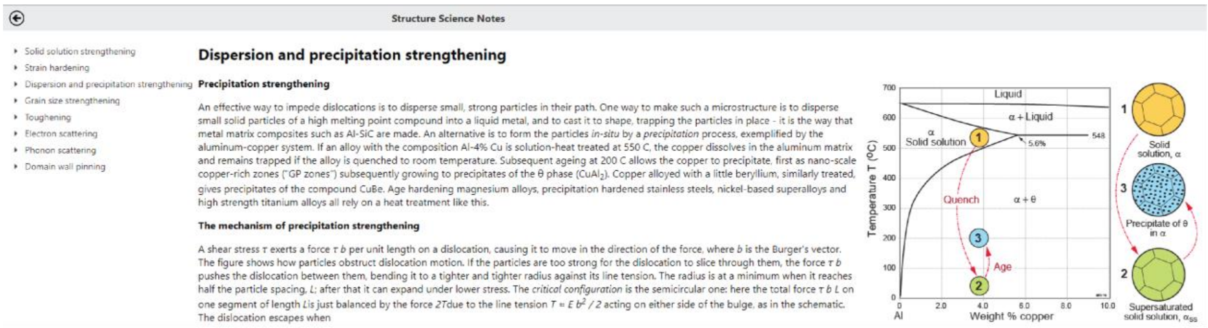

Figure 13. *Example of Structure Science Note on Dispersion and Precipitation Strengthening. Found from the main MS&E Interface (Fig. 1)*

Processes: The intersection of materials and properties

For many non-MSE students, the topic of processing can provide a more tangible real-world connection within the field of materials. The ***Application and Processing-Specific Chapters (i.e. 11, 13, 15)*** of Callister provide details of key processing techniques for different material classes. The Processes focus area of the MS&E Edition can support these chapters with over 100 processing technique records. These records are linked to the records in the Materials focus area, allowing for an understanding of which processing techniques are relevant for which material classes. They also include design guidelines that help students to see how final designs are a result of the combination of materials and processing.

Materials Selection

At the heart of the CES EduPack is the ability to interact with materials and processing data by applying criteria to screen out or rank candidates for an application. This can be done numerically or graphically and at a variety of levels. The Selection focus area of the *MS&E Edition* guides introductory users through materials selection, an integral skill for many engineering disciplines and ABET outcomes (see following section). Figure 14 from the software showcases three ways materials can be selected within the software. Choosing between options in a systematic way is a skill that is very widely applicable.

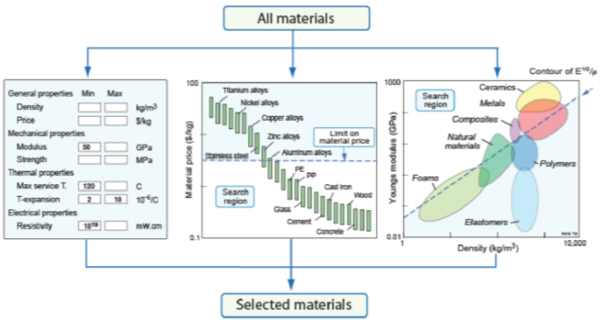

Figure 14. *Schematic of Selection Capabilities within the Selection Focus Topic. From Left to Right: Limit tool, Bar Chart with constraint box, and Bubble chart with constraint line.*

ABET Objective Support

Most engineering programs in the US today are accredited by ABET. CES EduPack can help support teachers in meeting the ABET requirements shown below in Figure 15. Additional information, including example performance indicators, can be found elsewhere.

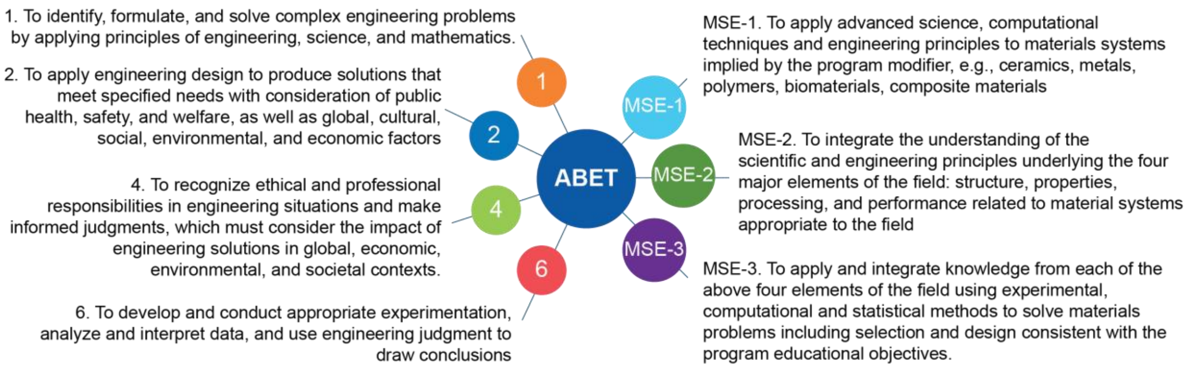

Figure 15. *ABET General and MSE-Program Specific Outcomes*

Conclusion

The purpose of this paper was to highlight how the *MS&E edition* of CES EduPack can be used in conjunction with Callister to provide a highly engaging first foray into materials for both MSE and non-MSE students alike. The graphical methods used within this software allow for the complex topics found within Callister to be displayed in alternative interactive ways, encouraging students to explore and build their *materials intuition* from the very beginning. The quality databases add real world context to abstract topics such as bonding/structure/property dependence. This can be especially critical for non-MSE students to understand the importance of materials and how it will impact their careers in a positive light. The new *MS&E edition* highlighted here has been designed to support educators teaching materials with emphasis on challenging topics such as phase diagrams with new, more interactive tools while keeping the *materials paradigm* at the core. Materials science and engineering is a complex yet important field for many disciplines, and with resources such as Callister and CES EduPack, future engineers can be more confident in their materials intuition.

Acknowledgements

The authors would like to thank Dr. William Callister for reviewing our paper and making suggestions for improvement. We would also like to acknowledge that most of the contents of the paper is the work of the whole team at Granta Design, including Professor Mike Ashby.

Granta's Education Hub aims to support teaching of materials-related courses in Engineering, Science and Design.

The resources come in various formats and are aimed at different levels of student.

The hub also contains other resources contributed by faculty at the ~1000 universities and colleges worldwide using Granta's CES EduPack, and includes both resources that require the use of CES EduPack and those that don't.

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