



New Resources for Introduction to Materials Class

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Abstract

Experience suggests that learning is better achieved by discovery for oneself than by passive listening. The aim of the CES EduPack Materials Science and Engineering (MS&E) Packageⁱ is to allow students to explore the relationships between Processing, Structure and Properties. It includes curated data for the elements of the Periodic table, for engineering, bio and functional materials, and for shaping, joining and finishing processes. There is an animated tool to aid understanding of phase diagrams. Finally, it also includes a resource that focuses explicitly on process-structure-property relationships, which consists of seven unique sets of records for the properties of the same material in different processed states. The motive here is to stimulate discovery and pose questions: why does this property change in that way when the material is processed? Why is this other property left unchanged? Worked examples show what you can do with the package, and a set of “micro-projects” (with specimen answers for the Instructor’s use) prompt students to explore for themselves. We have trialled the package, which is currently in Pre-release form, with a small number of students and are now looking for feedback, particularly on the Interactive Phase Diagram Tool and the Active Learning “Micro Projects”. The paper will outline the work done so far, illustrate its features and solicit feedback.

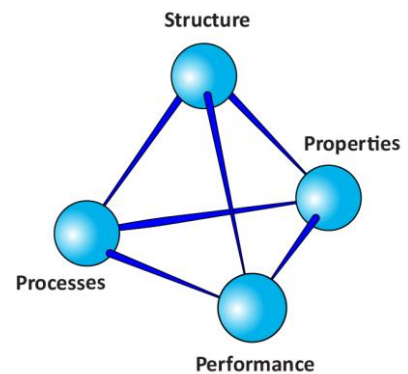


Figure 1. The Process-Structure-Properties-Performance tetrahedron

Introduction

The Introduction to Materials course is common to many different engineering disciplines. It is a tricky course to teach; the scope spans from the atomic to the macro scale (Figure 2), and the students have different starting knowledge and interests. Regardless of teaching approach, it generally does two things; provides an overview of the classes of materials and their properties, explains how those properties are affected by composition, structure and processing. There are well-regarded textbooks commonly used on this course to provide a structure for learning as well as act as a reference, both at the time of the class and later.

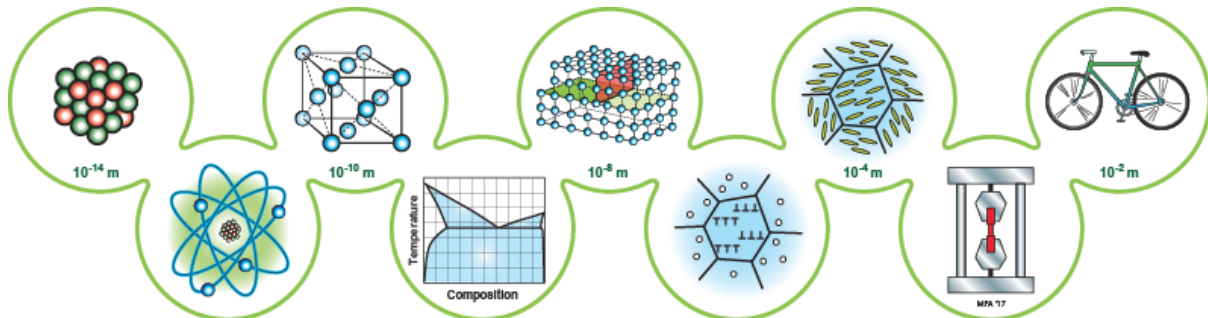


Figure 2. Length scales and the structures and properties associated with them. A bottom-up approach to teaching MS&E flows from left to right in this diagram; a top-down approach flows from right to left.

To support teaching on these courses the authors and colleagues have worked to create the CES EduPack Materials Science and Engineering (MS&E) Package as a set of resources that allows students to explore the relationships between Processing, Structure and Properties (Figure 1) and find out about the classes of materials and their properties in an engaging, interactive way. It includes curated data for the elements of the Periodic table, for engineering, bio and functional materials, and for shaping, joining and finishing processes. There is an animated tool to aid understanding of phase diagrams. Finally, it also includes a resource that focuses explicitly on process-structure-property relationships, which consists of seven unique sets of records for the properties of the same material in different processed states.

Accompanying the database and tools, are teaching and learning resources designed to support different teaching styles, from Multiple Choice Questions to Active Learning Micro Projects. The motive here is to stimulate discovery and pose questions: why does this property change in that way when the material is processed? Why is this other property left unchanged?

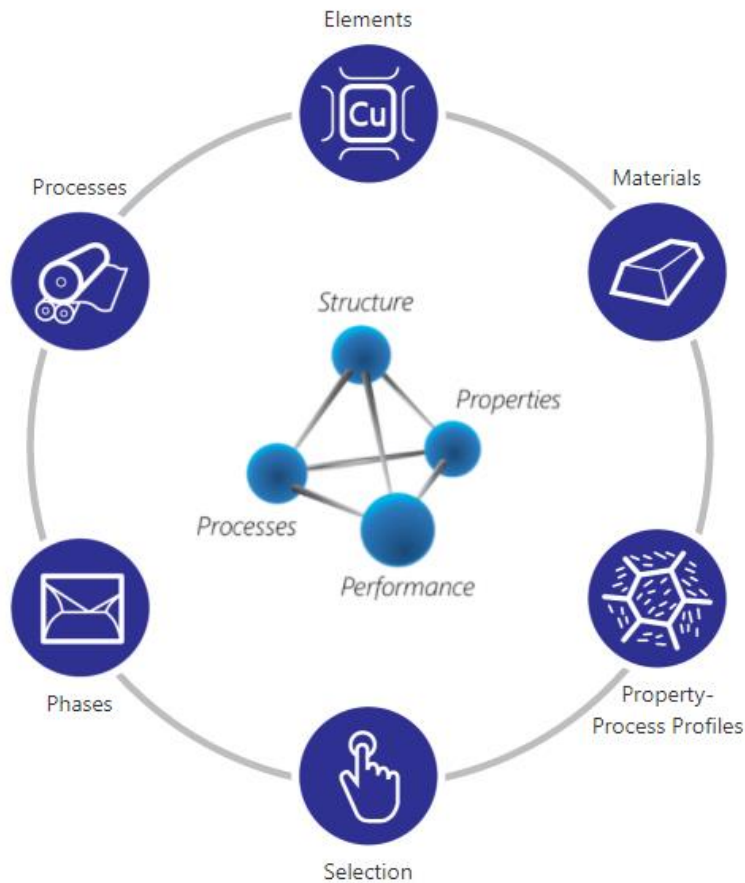
In this paper we hope to give an overview of what is available and then concentrate on two areas in particular, the interactive Phase Diagram Tool and the Micro Projects, with the hope that this will stimulate discussion and feedback and help us to improve these areas which are new to us.

What's in the package?

The package is a set of interrelated resources.

- An overview paper.
- PowerPoint sets to help present it to students.
- Exercises, multiple choice questions and micro projects that stimulate self-learning.
- Interactive tools to explore phase diagrams, and environmental audits
- The MS&E database itself. It needs a little explaining.

The MS&E database is a set of linked data-tables (Outer ring of Figure 3) that connect key information and concepts from the atomic to engineering scale, from processing to performance, and from science to application.



Science Notes

[Material Science notes »](#)
[Process Science notes »](#)
[Structure Science notes »](#)

Figure 3. The data-structure of the CES EduPack MS&E database. This schematic appears as the Home Page of the database. Clicking on any one of the six icons takes the user to that component of the database.

The **Elements data-table** provides fundamental data about the elements of the Periodic Table: nuclear, electronic, atomic and crystallographic data, and mechanical and thermal

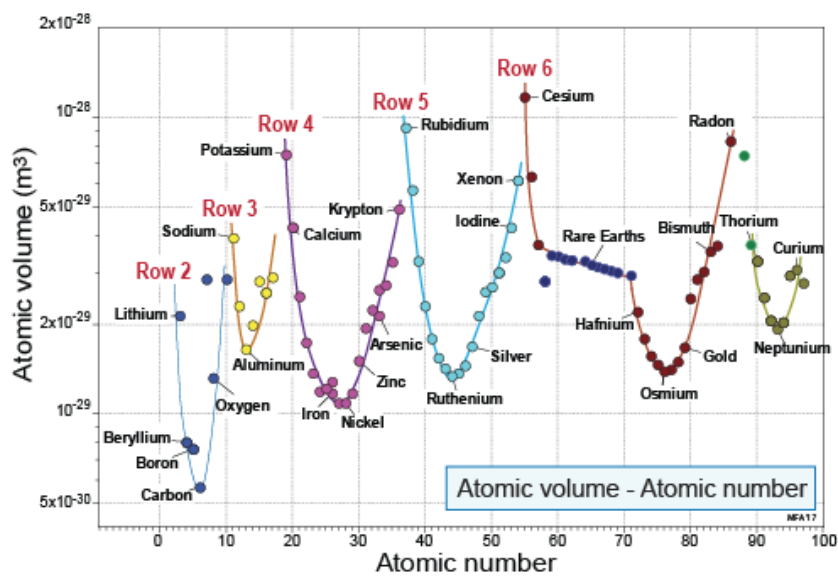


Figure 4. Variation of atomic volume across the rows of the Periodic Table. (Made with the Elements data-table.)

properties, environmental characteristics and global geo-economic and criticality standing. It is linked to the other data-tables giving direct access from their records to the relevant element-records.

The **Materials data-table** has around 220 of the most commonly used materials and their Mechanical, Thermal, Electrical, Optical, Eco and Durability properties. New editions to this database include:

- Records for **functional materials**, including magnetic, magneto-caloric, piezo/pyro/ferroelectric, semiconducting and thermoelectric materials. The functional properties are described in embedded Science Notes.

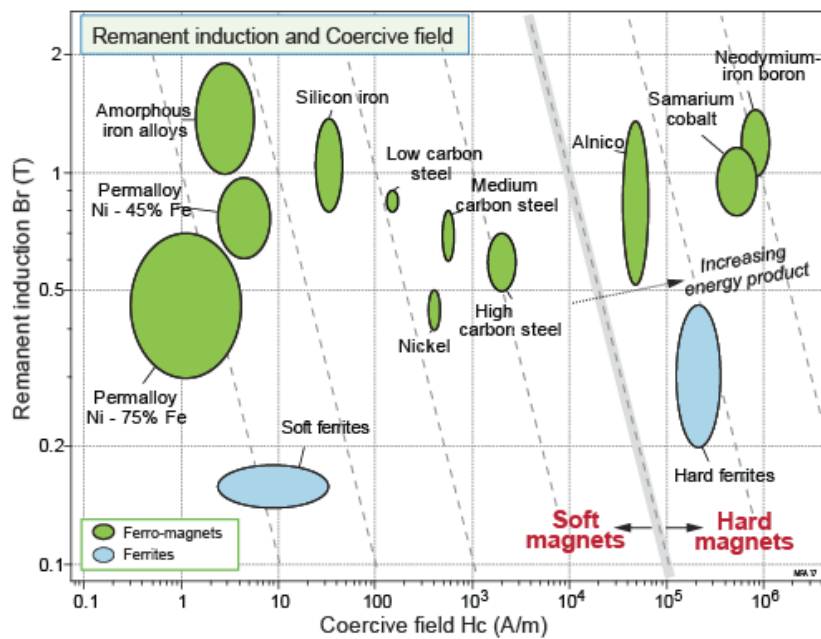


Figure 5. Remanent induction and coercive force for common magnetic materials. Soft magnetic materials lie on the left of the chart, hard magnetic materials on the right. (Made with the Functional materials subset of the MaterialUniverse data-table.)

- Records and data for **biological materials**, including molecular building blocks, natural fibers, tissues (both soft and mineralized), woods and wood-like materials

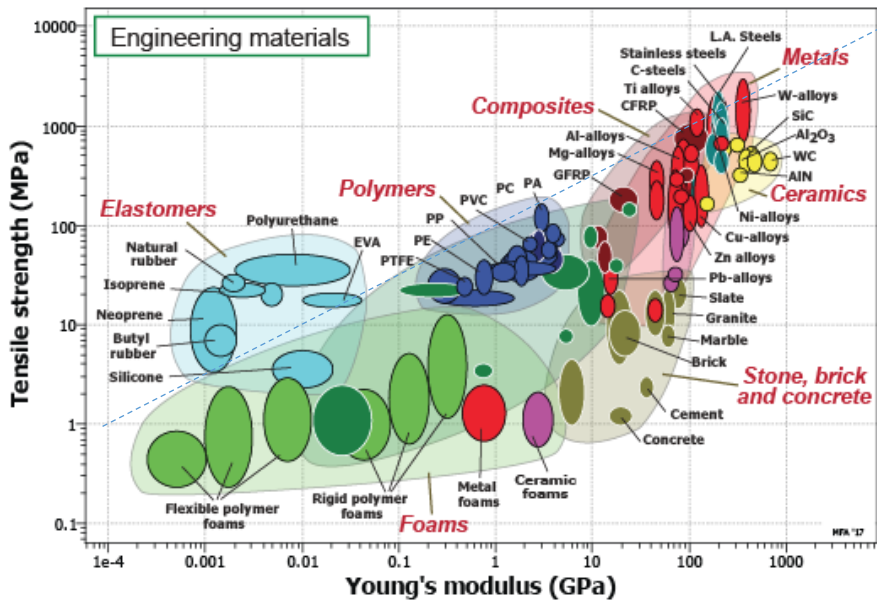


Figure 6. Strength σ_{ts} and modulus E of engineering materials, with a contour of maximum elastic energy storage, U_{max} .

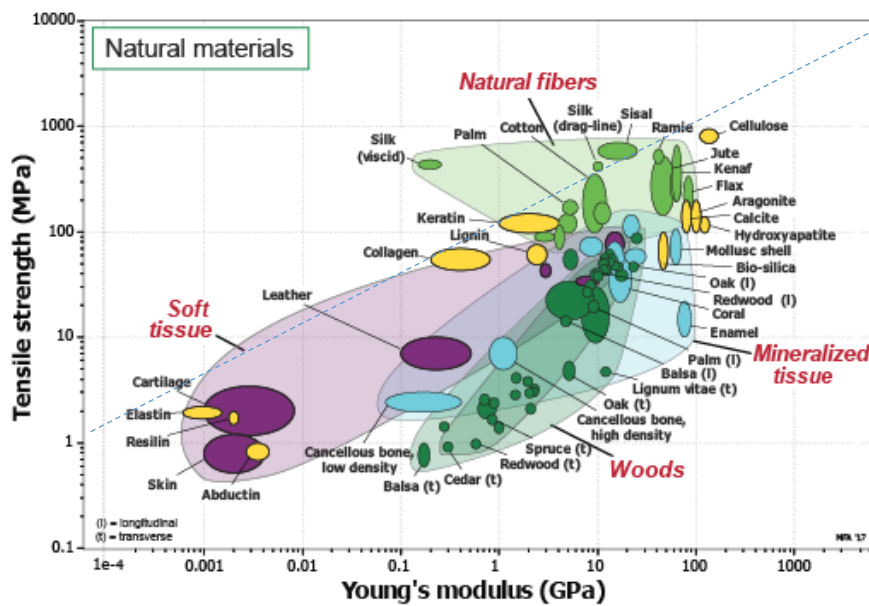


Figure 7. Strength σ_{ts} and modulus E of natural materials on the same axes Figure 20, with a contour of maximum elastic energy storage, U_{max} . (Made with the MaterialUniverse data-table.)

The **Process data-table** contains 109 shaping, joining and surface treatment processes with records that have information, schematics and images on the use of the process, what level of quality can be achieved, and its economics. A **cost model** allows the costs of alternative processes to be compared. **Links** between Materials and Processes allow selection of materials by their processing options and vice-versa.

The **Phase Diagram data-table** gives access to phase diagrams for 12 of the most widely use engineering alloys. It is further supported by an **interactive teaching tool** which works in four modes:

- the **glossary** mode explains the terminology of phase diagrams,
- the **phases** mode shows which phases are present in each phase field,
- the **cooling paths** mode explores the microstructural development during solidification through sketches, annotations and text
- the **Lever Rule** mode helps students visualise the weight fraction of two phases, while at the same time reviewing the Lever Rule calculation.

The tool uses three common phase diagrams to illustrate features of phase diagrams: Cu-Ni, Pb-Sn, and Fe-C. A “**Teach Yourself Phase Diagrams**” booklet encourages independent learning.

The **Process-Property Profiles data-table** illustrate control of properties by processing. It contains sets of records chosen to illustrate how processes such as alloying, heat treatment, mechanical working, sintering and foaming, change mechanical, thermal and electrical properties. Each set is accompanied by a folder-level record describing the underlying structural changes. Suggested micro-projects prompt students to explore significant property trajectories.

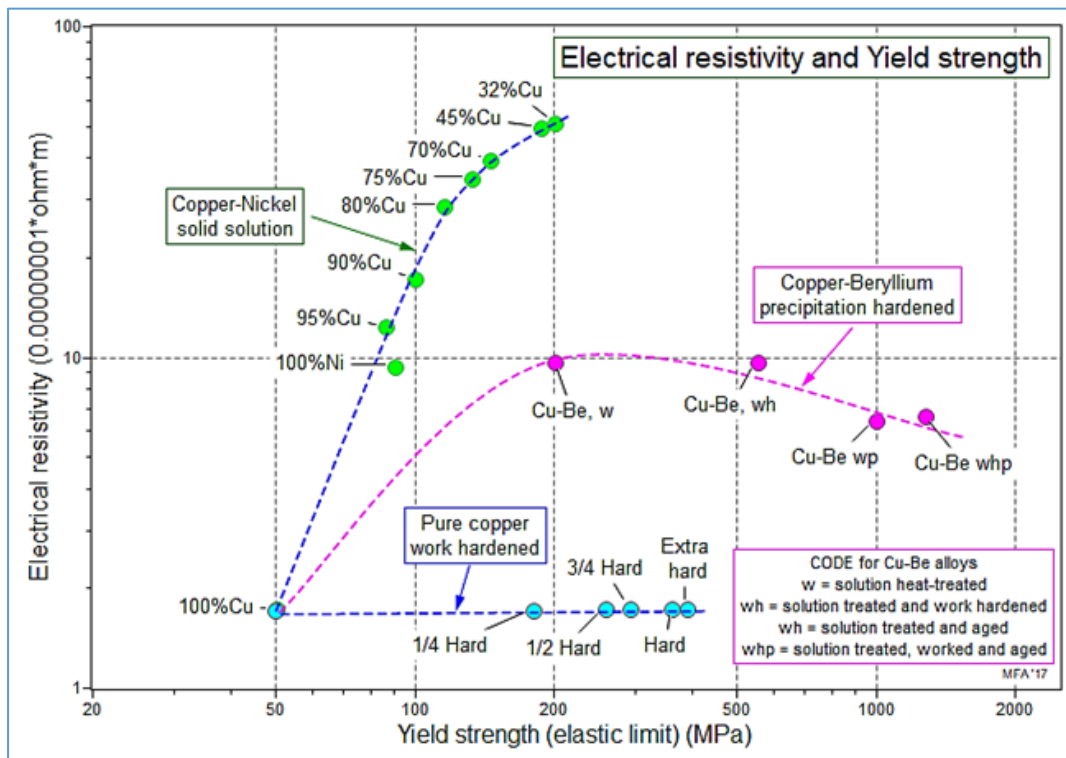


Figure 8. Plot illustrating how hardening mechanisms effect Electrical Resistivity and Yield Strength, created using the Process-Property Profiles datatable.

Comprehensive sets of **Science Notes** are accessed from the Home Page (Figure 3, top right). They give background to material properties, to processes attributes, and to the mechanism that underlie properties and the way processes change them.

The Phase Diagram Tool

The first area that we would specifically like feedback on in the Phase Diagram Tool. Phase Diagrams are essential for understanding materials, presenting rich information in a succinct and elegant way. However, for most engineering students, they can seem very dry and complex. The authors and collaborators wanted to create an interactive, visually pleasing tool, that would:

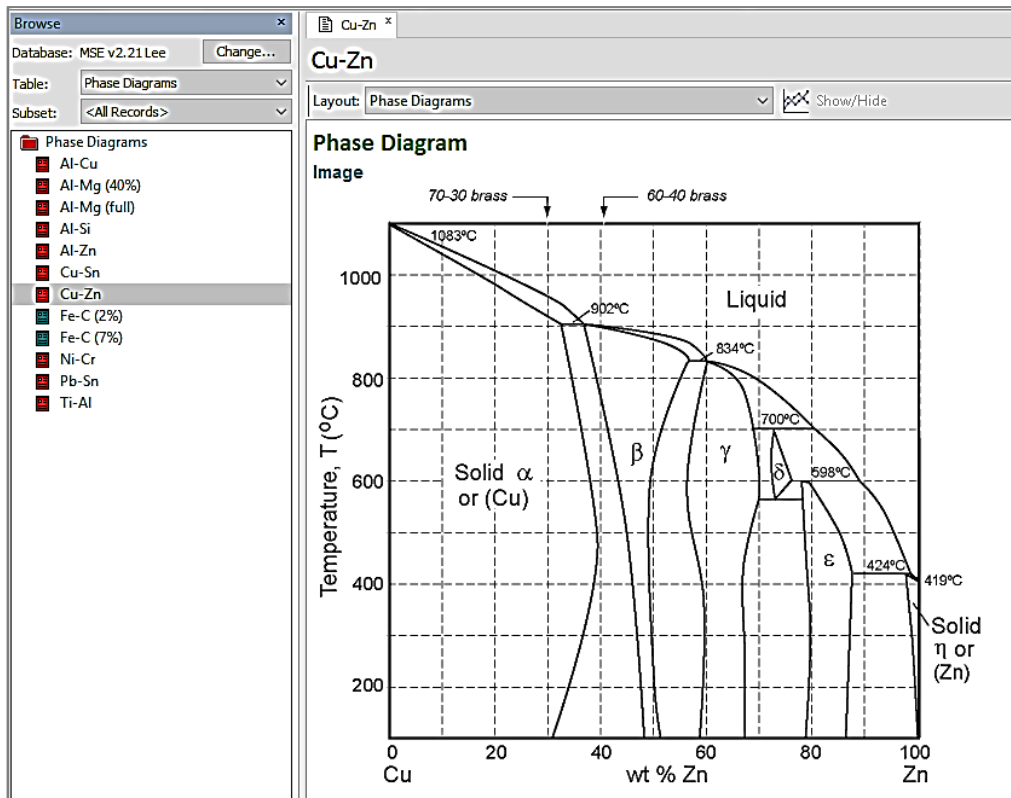


1. Help students understand what a phase is and some of the terminology used on phase diagrams.
2. Help students understand what phases are present on key phase systems.
3. Help students be able to use the Lever Rule.
4. Help students understand how microstructures develop on equilibrium cooling.

Clicking on the Phase Diagram icon on the home page gives access to a set of interactive resources:

- A library of most-used phase diagrams
- A glossary tool that explains the meaning of terms that appear on phase diagrams
- A tool illustrating phase structure at the atomic level
- A tool tracking the evolution of microstructure down chosen cooling paths
- A tool illustrating the Lever Rule.

The CES EduPack MS&E package contains records for 12 common phase diagrams, typifying the most important features. Figure 8 is an example, here for the Cu-Zn system that includes common brasses. Each diagram is linked to the records for its constituents in the **Elements data-table** (here, Copper and Zinc) and to the records for prominent alloys that appear on it in the **Materials datatable** (here, Brass). The diagrams can be copied and used for educational purposes.



Description

Brasses, alloys of copper with 5-40% zinc, combine high formability with good corrosion resistance. The two most widely used compositions, 70%Cu-30%Zn and 60%Cu-40%Zn, are shown above the diagram. The major phases in brass are the fcc alpha phase and the bcc beta phase. Alpha brasses are malleable and easier to work, whereas beta brasses are harder and stronger.

Figure 8. CES EduPack Phase Diagram for the copper-zinc system.

Structure at the atomic level is illustrated by three interactive diagrams (Cu-Ni, Pb-Sn and Fe-C) with schematics that appear when the user clicks on a phase-field (Figure 9). The evolution of microstructure down selected cooling paths on the same three diagrams appears as the user drags the cursor down the path (Figure 10). An interactive Lever Rule tool calculates the composition of the liquid and solid phases on a cooling path of a schematic A-B phase diagram; boxes on the diagram list the composition and weight-fraction of each phase, updating as the point on the cooling path is changed (Figure 11).

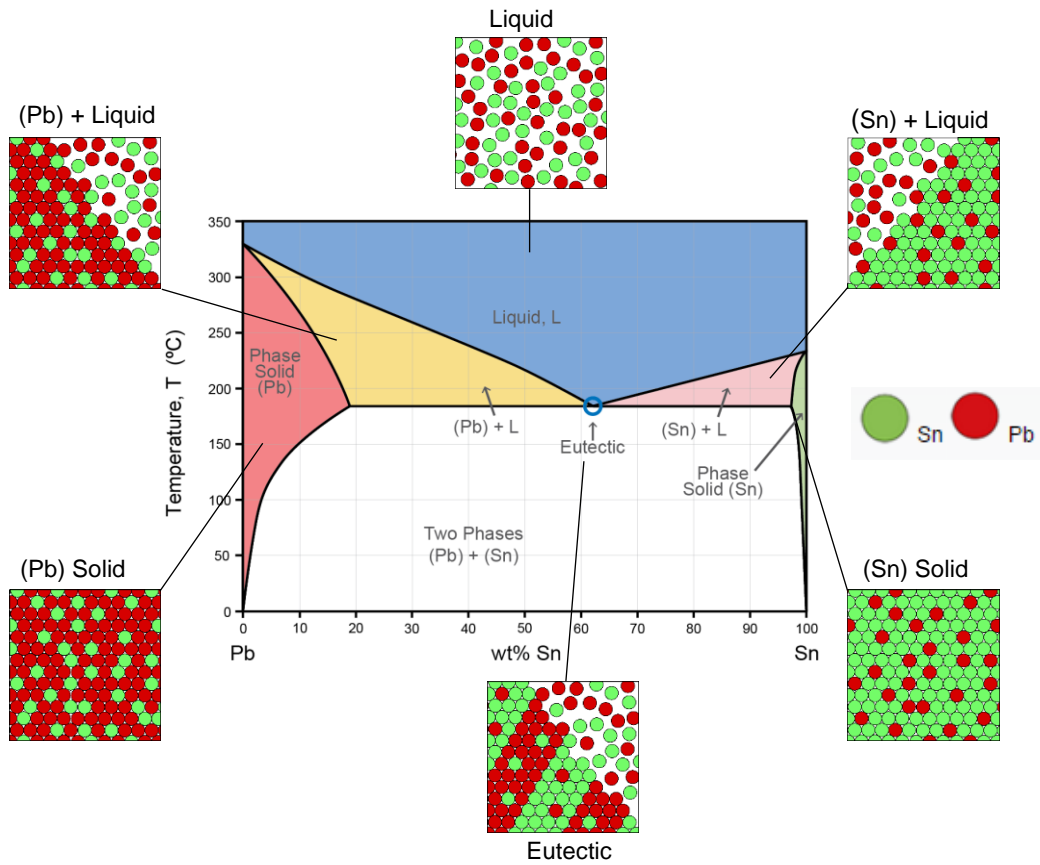


Figure 9. Interactive tool suggesting structure at atomic level

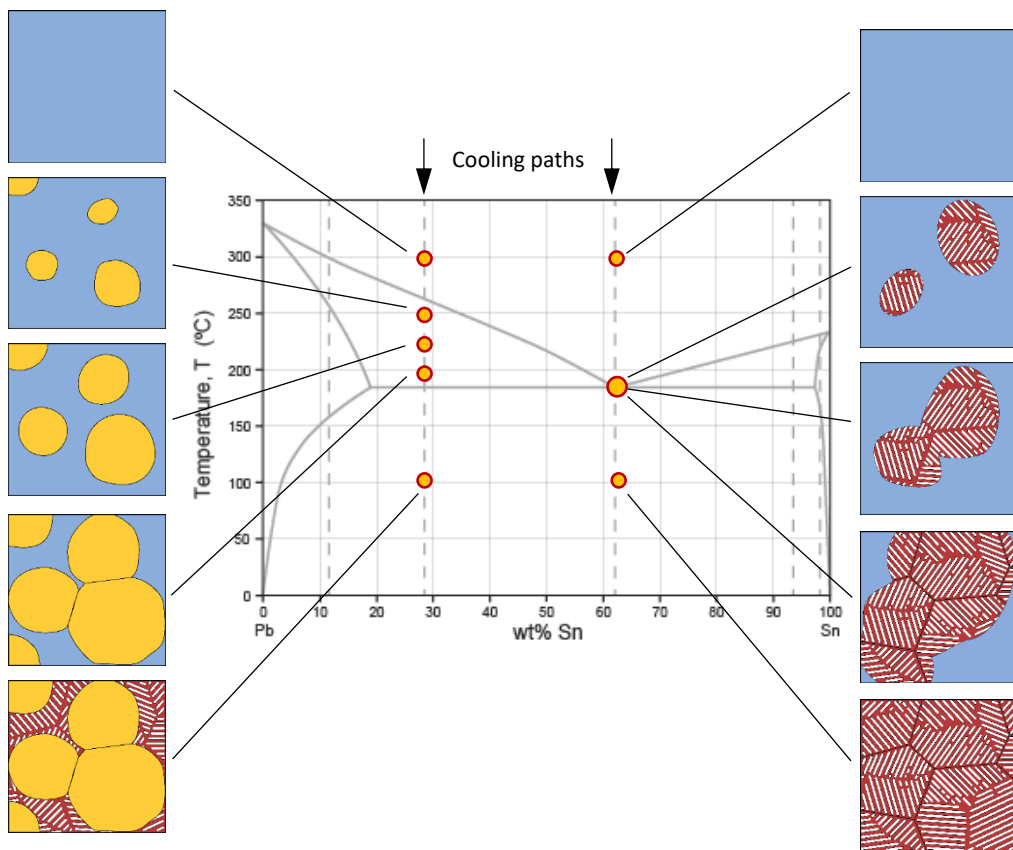


Figure 10. Interactive tool suggesting microstructure evolution on a series of cooling paths

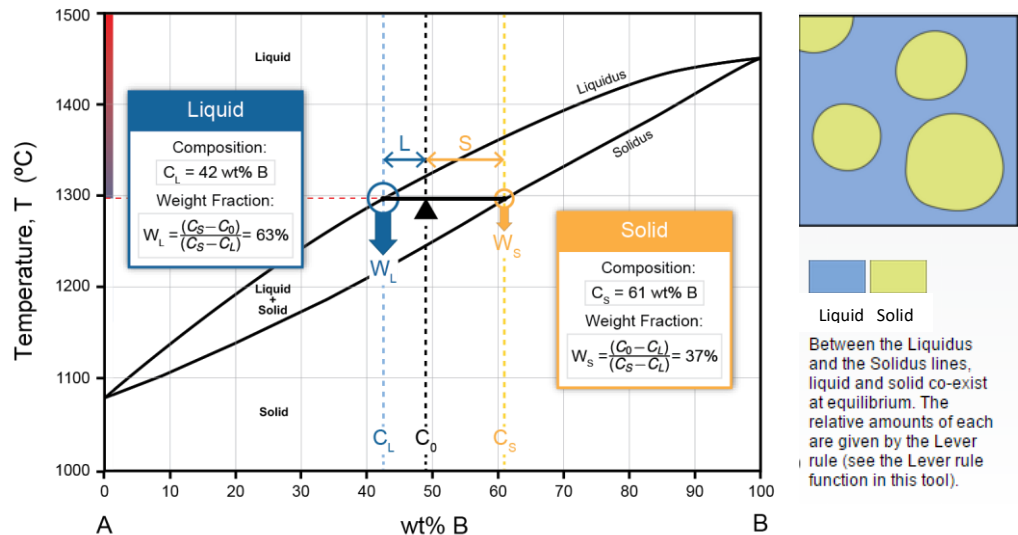
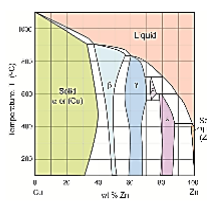


Figure 11. Interactive tool illustrating the Lever rule

Teach Yourself Phase Diagrams. Learning how to read and interpret phase diagrams is best achieved through practice. The CES EduPack includes a comprehensive Teach Yourself unit on Phase Diagrams and Phase Transformations¹. This can be reached from within the CES EduPack software via the **Learn** button on the main toolbar.

The unit has eight parts (Figure 30). The first four progress from an introduction to the terminology (“Component”, “Phase”, “Liquidus” etc.) to simple diagrams (Cu-Ni, Pb-Sn), the Lever rule, intermediate phases (Al-Cu) and the Iron-Carbon and other more complex systems. The remaining four introduce ideas of phase transformations: nucleation and growth in the liquid and solid state, the eutectic and eutectoid reactions, deviations from equilibrium and TTT diagrams. Each part ends with exercises with worked solutions. The unit can be copied and distributed for educational purposes.

**Teach Yourself:
Phase Diagrams and Phase
Transformations**



Hugh Shercliff and Mike Ashby
5th Edition, March 2009, Cambridge

Contents

- PART 1: Key terminology
- PART 2: Simple phase diagrams, and how to read them
- PART 3: The iron-carbon diagram
- PART 4: Interpreting more complex phase diagrams
- PART 5: Phase transformations and microstructural evolution
- PART 6: Equilibrium solidification

¹ https://teachingresources.grantadesign.com/Data_Booklets/BOKPHAEN09 Also available in *Materials: Engineering, Science, Processing and Design*, 3rd edition, Butterworth-Heinemann, Oxford, UK. ISBN-13: 978-0-08-097773-7, North American Edition: ISBN-13: 978-1-85617-743-6, Ashby, M. Shercliff, H. and Cebon, D. (2014)

PART 7: Equilibrium solid-state phase changes

PART 8: Non-equilibrium solid-state phase changes

Figure 12. The contents of the Teach Yourself Phase Diagram unit

Micro Projects

Encouraging students to actively learn through supporting activities has been highlighted as an important teaching technique for decades. A good summary of its benefits and pitfalls can be found here for exampleⁱⁱ. It is for this reason that the authors have sought to produce a set of teaching resources that can support and encourage educators wanting to introduce an element of Active Learning in the Introduction to Materials class.

The Micro-projects created are designed to be short investigations of an aspect of Materials Science and Engineering that can be completed in less than an hour – therefore in class. Each poses a set of questions that can be answered using the CES EduPack Material Science and Engineering (MS&E) database. All start at a level that is readily accessible, using the SEARCH function to find records, creating charts using the CHART/SELECT function, and extracting relevant data from a Record and its linked SCIENCE NOTES. Guidance notes in blue help with any difficult step.

Each Micro-project has an attached *Discussion Point* – a challenge to go further. The Discussion Point poses a question linked to or arising from the micro-project. Responding to the Discussion point requires independent thought and research, takes longer, but is rewarding if followed. It is an add-on for more advanced study.

Each Micro-project and its Discussion point has a fully worked *Specimen Response*, available to the instructor.

Topics have been picked to be of interest to first year students and cover a wide range of topics. The authors have worked with recent graduates to test an initial set of Micro Projects, refine them and build up the following current set of 14.

The Micro-projects

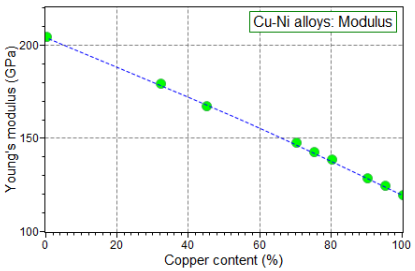
1. Zirconia, a ceramic that thinks it's a metal
2. Are biopolymers really greener than oil-based plastics?
3. Nichrome – the glowing heart of dryers and toasters
4. Is spider silk really stronger than steel?
5. What's special about egg shell?
6. Materials for acoustics guitars
7. Shields for Viking invaders
8. Are Additive Manufactured materials any good? (1) Polymers
9. Are Additive Manufactured materials any good? (2) Metals
10. Why don't things stick to Teflon?
11. Exploring solid-solutions using Process-Property Profiles
12. Which elements form extensive solid-solutions with copper?
13. Designing high-entropy alloys

14. Harvesting waste energy without regulatory risk

The following is one full example, with worked solution.

MS&E Micro-project 11 **What do Processes do to Properties?** **Level: Easy**

The Process-Property Profile (PPP) data-table in the MS&E database allows charting of the effect of processing on properties. This project uses the PPP facility to explore solid-solutions.

- Open the PPP data-table from the home page and isolate Copper-Nickel alloys for exploration. (Chart/Select – Select from: Custom Define your own subset – Deselect all then open 1. Alloying and work hardening: copper alloys – select Copper-Nickel alloys)
- Make a chart with Young’s modulus on the y-axis and Copper content on the x-axis. Use linear scales for both. Set the axis range for Copper content (%) to run from 0 to 100. (To choose linear scales and set axis ranges first make the chart then double click on the axis name on the chart to bring up Axis settings. Click on “Linear” and use “Set” to adjust range.)

Copper content (%)	Young's modulus (GPa)
0	200
30	180
45	170
70	150
75	145
80	140
85	135
90	130
95	125
100	120
- Add a title using the Text label function (T) and draw a curve through the data using the Curve function (C) above the chart. Your modulus chart should now look like this.
- Now step through the mechanical, thermal and electrical properties in the same way, copying and pasting the charts into WORD to allow comparison. Follow the order
 1. Yield strength,
 2. Fracture toughness
 3. Thermal conductivity
 4. Thermal expansion
 5. Heat capacity
 6. Electrical resistivity
- Some properties (like Youngs modulus) vary with composition in an almost linear way. Which behave like this?
- Some, by contrast, show a much stronger dependence, with a maximum or minimum in the middle of the composition range – which are these?

Discussion point: The underlying mechanisms.

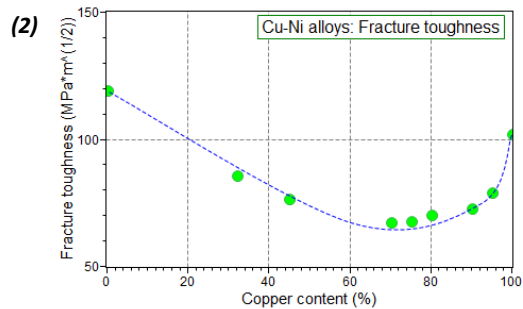
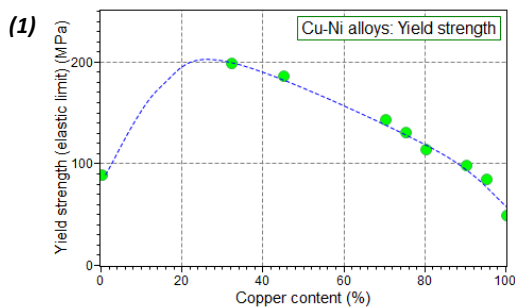
Why does the Yield strength vary with solute concentration in the way shown in Chart 1? Got to the Home page, locate Science Notes, open Structure Science notes and open “Solid-solution strengthening” to find out.

Why does the Electrical resistivity vary with solute concentration in the way shown in Chart 6? Open the Structure Science note “Electron scattering” to find out.
(Text and images can be copied from these Science notes by highlighting, copying and pasting into WORD.)

MS&E Micro-project 11
What do Processes do to Properties?
Specimen response

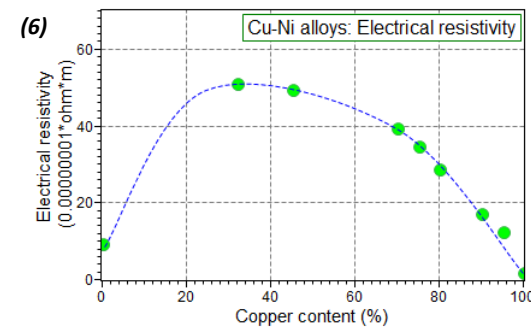
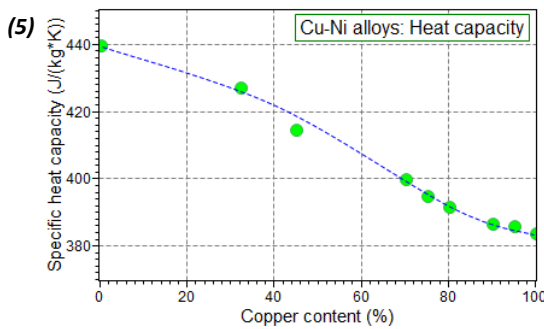
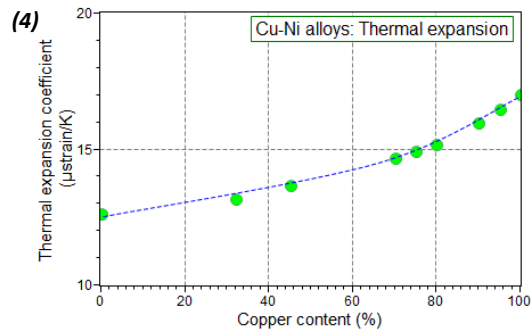
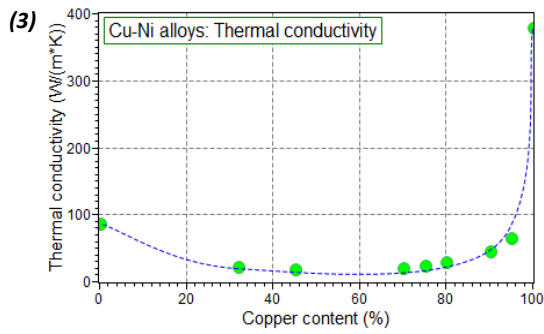
Mechanical properties

The Modulus, as we saw in the statement of the micro-project, varies almost linearly with composition. By contrast, Yield strength, Fracture toughness show a strongly non-linear behavior with a peak or trough towards the middle of the composition range.



Thermal and Electrical properties

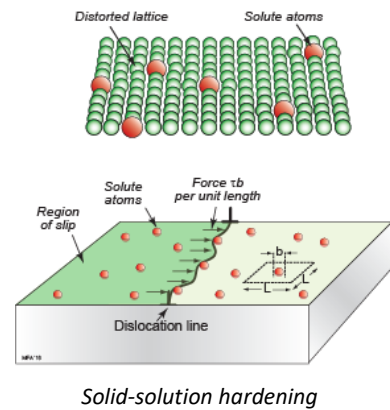
Thermal expansion coefficient and Heat capacity vary almost linearly with composition. Thermal conductivity and Electrical resistivity vary in a strongly non-linear way.



Discussion point: The underlying mechanisms.

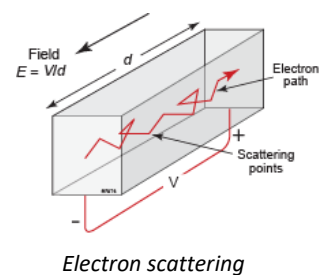
Why does the Yield strength vary with solute concentration in the way shown in Chart (1)? The Structure Science note gives the following insight.

Solute atoms differ in size from those of the host, roughening the planes on which dislocations move, and thus obstructing their motion. The number of such obstacles increases with solute concentration, c , leading to a parabolic ($c^{1/2}$) dependence of yield strength on concentration. This dependence is evident in Chart 1, which shows a roughly parabolic rise starting from 0% Ni or from 0% Cu.



Why does the Electrical resistivity vary with solute concentration in the way shown in Chart (6)? The Structure Science note for Electron Scattering gives the following insight.

Electrical conduction in a metal is by the movement of “free” electrons in response to the field V/d caused by the potential difference V . Impurity or solute atoms act as scattering centers, limiting the mean free path of the electrons, which is why alloys always have a higher resistivity than pure metals.



Feedback – What Next?

The database and teaching resources have been given to selected educators around the world to use in their teaching and provide feedback. It is hoped that this paper and the associated presentation will also provoke useful discussion and feedback. Particularly around how best to support active learning, whether the resources supplied are at the right level and what further developments do the ASEE Materials community see as useful.

Summary

The new Materials Science and Engineering Package, designed to support the teaching of Introduction to Materials courses, was presented in brief and two areas, the Interactive Phase Diagram Tool and the Micro Projects were presented in more detail. It is hoped that these resources will enliven teaching of the introductory course, support better student understanding and promote Materials as a great subject to study. Lastly, feedback is requested, now that these resources can be used on real courses.

ⁱ CES EduPack, Granta Design, Cambridge, UK (www.teachingresources.grantadesign.com/MSE)

ⁱⁱ Bonwell, C., and J. Eison, "Active Learning: Creating Excitement in the Classroom," ASHE-ERIC Higher Education Report No. 1, 1991 (<http://www.ntlf.com/html/lib/bib/91-9dig.htm>).