



# Granta EduPack Exercises with solutions: Materials Science and Engineering

-To accompany Lecture Unit 6

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## Exercises with Worked Solutions

This collection of exercises and solutions has been put together to help you as an instructor choose or develop your own exercises for your students. You may simply want to browse through them for inspiration, or you may use them with your class. We are providing these in Word format, so that you may pick and choose the questions you find suitable for your course this year. We have also included variations on a theme so that you can set different questions for different classes.

Most of the questions come from or are inspired by the exercises in the following books by Professor Mike Ashby of the University of Cambridge Department of Engineering, co-founder of Granta Design.

- **Materials Selection for Mechanical Design (5<sup>th</sup> ed)** by Michael F. Ashby (ISBN: 978-0-08-100599-6)
- **Materials: Engineering, Science, Processing and Design (4<sup>th</sup> ed)** by Michael F. Ashby, Hugh Shercliff, and David Cebon (ISBN: 978-0-08-102376-1)
- **Materials and Design: The Art and Science of Material Selection in Product Design (3<sup>rd</sup> ed)** by Michael F. Ashby and Kara Johnson (ISBN: 978-0-08-098205-2)

Most of the questions require the use of Ansys Granta EduPack. Granta EduPack is a materials teaching resource used at 1,000+ Universities and Colleges worldwide. You can find out all about it at:

<https://www.ansys.com/products/materials/granta-edupack>

The topic areas of the available Exercises are<sup>1</sup>:

Title	Associated Lecture Unit
Materials: Classification and Properties	Lecture Units 1-2
The Elements	Lecture Unit 3
Materials Science and Engineering	Lecture Unit 6
Material Selection: Translation, Screening, Ranking	Lecture Unit 7
Manufacturing Processes: Classification and Cost	Lecture Unit 10
Eco Properties and Eco Design	Lecture Unit 11
The Eco Audit Tool	Lecture Unit 12
Energy: Power Systems Generation and Storage	Lecture Unit: <i>"Materials for low carbon power"</i>
Materials and Sustainable Development	Lecture Unit: <i>"What is a Sustainable development"</i>
Bioengineering	Lecture Unit: <i>"Materials for Bioengineering"</i>
Design Database for Products, Materials and Processes	Lecture Unit: <i>"The Design database for Products"</i>
Introductory Materials (basic excerpts)	<i>Compiled, Lecture Units 1, 2, 3, 7</i>

You can find the other units here: <http://www.ansys.com/education-resources>. If there are suggestions, or if you have questions, please contact the Ansys Education Team at [education@ansys.com](mailto:education@ansys.com). Reproduction and copyright information can be found on the last page. Please make sure to credit Professor Mike Ashby and Ansys if you use these questions.

<sup>1</sup> Exercise units follow the same numbering of the PowerPoint lectures for the same topic

## Contents

### Discovering the Science behind Material Properties with the Granta EduPack

Learning by discovery is more effective (and much more fun) than simply remembering what you're told. These Granta EduPack-based exercises are designed to guide discovery, provoke thinking and stimulate self-learning. There are relationships between material properties, some easily explained, others so complex that they are not yet fully understood. Exploring relationships between material properties brings a deeper understanding of the physics that underlies the properties themselves. And it brings a "feel" for material property-values, valuable to engineers and designers, giving them a sense of when material property-values should be questioned and an ability to estimate property-values when no direct measurements are available. The exercises are in 4 groups, each group centered on one of the top-level data-tables in the Granta EduPack Materials Science and Engineering (MS&E) database. The table below acts as an index.

Data-table	What to expect	Exercises	Page
<b>1. Elements</b>	Dependence of nuclear properties on nucleus structure Dependence of properties on atomic number Dependence of properties on cohesive energy Other relationships between bonding-sensitive properties	1 - 17	4-18
<b>2. Biological materials</b>	Properties of biomaterials Relationship between bio and man-made materials	18 - 24	19-22
<b>3. Functional materials</b>	Piezoelectric, pyroelectric and ferroelectric materials Properties of magnetic materials Properties of semiconducting materials	25 - 32	23-27
<b>4. Phase diagrams</b>	Introduction to binary phase diagrams and the lever rule	33-38	28-30
<b>5. Property-Process profiles</b>	Dependence of properties on processing and microstructure	39 - 47	31-37

The properties themselves fall into three broad groups: those most directly related to the atomic nucleus, those related to interatomic bonding and packing, and those relating to microstructure. None are entirely independent on others, so we refer to them as "nucleus-sensitive", "bonding-sensitive", "microstructure-sensitive" to suggest the dominant influence. The table below gives examples.

Nucleus-sensitive properties	Bonding-sensitive properties	Microstructure-sensitive properties
Nuclear stability Abundance of the elements Atomic number Neutron-capture cross section	Crystal structure Atomic radius Cohesive energy Melting point Latent heats of melting and fusion Modulus Specific heat Expansion coefficient Electronegativity Ionization energy Activation energy for diffusion Surface energy Saturation magnetization Ferroelectric properties	Yield and tensile strength Hardness Elongation Fracture toughness Thermal conductivity Electrical resistivity Coercive field Energy product

## 1. Discovery with the Elements Data-table

**Exercise 1: Getting to know the Elements data-table.** The Elements data-table contains records for all the elements of the Periodic table.

Legend:

- Nonmetals
- Alkali metals
- Alkaline Earth metals
- Transition elements
- Other metals
- Metalloids
- Halogens
- Noble gases
- Lanthanides
- Actinides

Find the record for Nickel.

- When was it discovered?
- What is its crystal structure?
- What is its abundance in the Earth's crust?
- Which two nations produce the most nickel per year?
- What is the carbon footprint associated with its production?
- What is its thermal conductivity?
- Is it magnetic?

**Answer.**

- (a) 1751
- (b) Face-centered cubic (FCC)
- (c) 59 – 90 ppm
- (d) Australia and Brazil
- (e) 14.6 – 16.2 kg/kg
- (f) 90.7 Watts/(m.°C) at 300 K
- (g) Yes, it is ferromagnetic

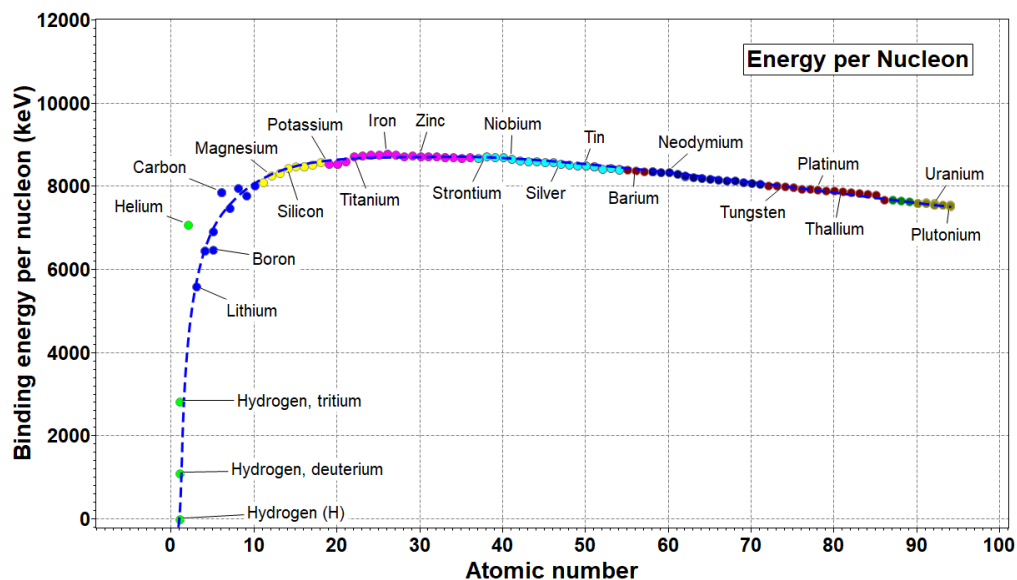
## Nucleon-sensitive properties

**Exercise 2: energy per nucleon.** The protons and neutrons (“nucleons”) that make up the core of a stable atom bind together. The bigger the binding energy per nucleon, the more stable is the atom. Make a chart of Binding energy per nucleon plotted against Atomic number. Use linear scales for both. Which element is the most stable? Approximately how much energy per nucleon is released if Uranium decays to the most stable element in a fission reaction? How much is released if Deuterium (H-2) transmutes to the most stable element in a fusion reaction? Select from *Elements: All Elements*

**Answer.** The most stable nucleus is that of Iron.

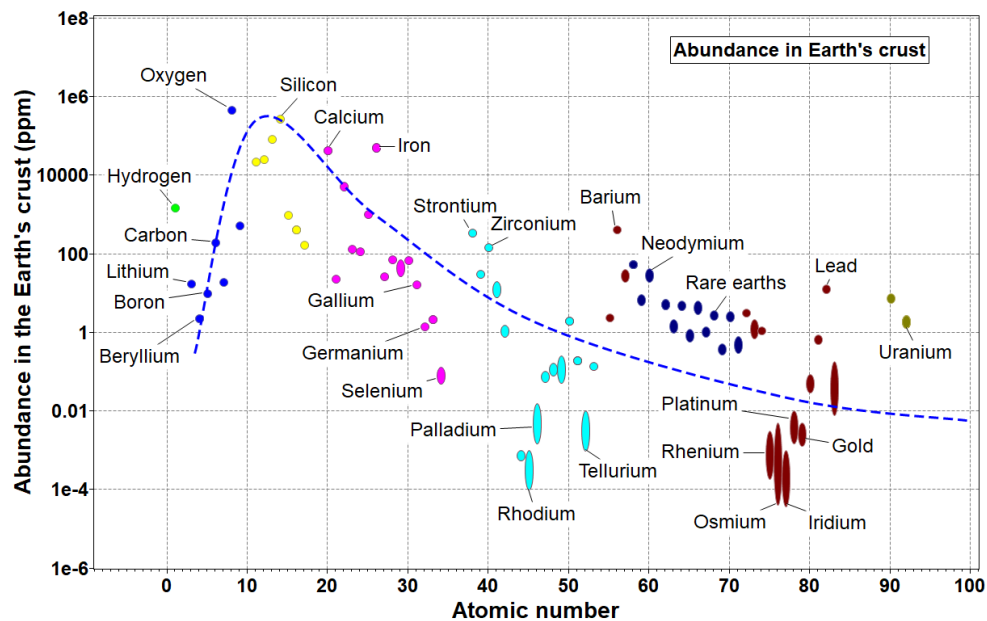
If Uranium decays to Iron, the energy release is approximately  $8790 - 7570 \text{ keV} = 1,220 \text{ keV} = 1.95 \times 10^{-13} \text{ J per nucleon}$ .

If Deuterium fuses to Iron, the energy release is approximately  $8790 - 1110 \text{ keV} = 7,680 \text{ keV} = 1.23 \times 10^{-12} \text{ J per nucleon}$ .



**Exercise 3: Abundance of the elements in the Earth's crust.** The Earth formed by the aggregation of the debris of supernovae explosions about 4.6 billion years ago. You might expect that the preponderance of elements in the earth would reflect the nuclear stability – the more stable the nucleus, the greater the occurrence of the element. Test this hypothesis by making a chart of Abundance in the Earth's crust (use Log scale) against Atomic number (use Linear scale). Is the hypothesis even approximately true? (Ignore the element Promethium)

**Answer.** The chart shows the abundance, which spans an enormous range (a factor of  $10^{10}$ ). The most abundant elements are those near iron (O, Si, Ca); the least abundant are those near the Platinum group (Au, Pt, Ir, Os). This is broadly consistent with the predicted link to nuclear stability.



### Bonding-sensitive properties

The tell-tail signature of a bonding-sensitive, microstructure-insensitive property is that its value oscillates in a periodic way across the rows of the periodic table. The next five exercises illustrate this, plotting chosen properties against Atomic number. The software automatically color-codes the rows to identify its members. The coding is shown in the adjacent table.

Color coding for rows of Periodic table	
●	Row 2
●	Row 3
●	Row 4
●	Row 5
●	Row 6
●	Row 7
●	Lanthanides
●	Actinides

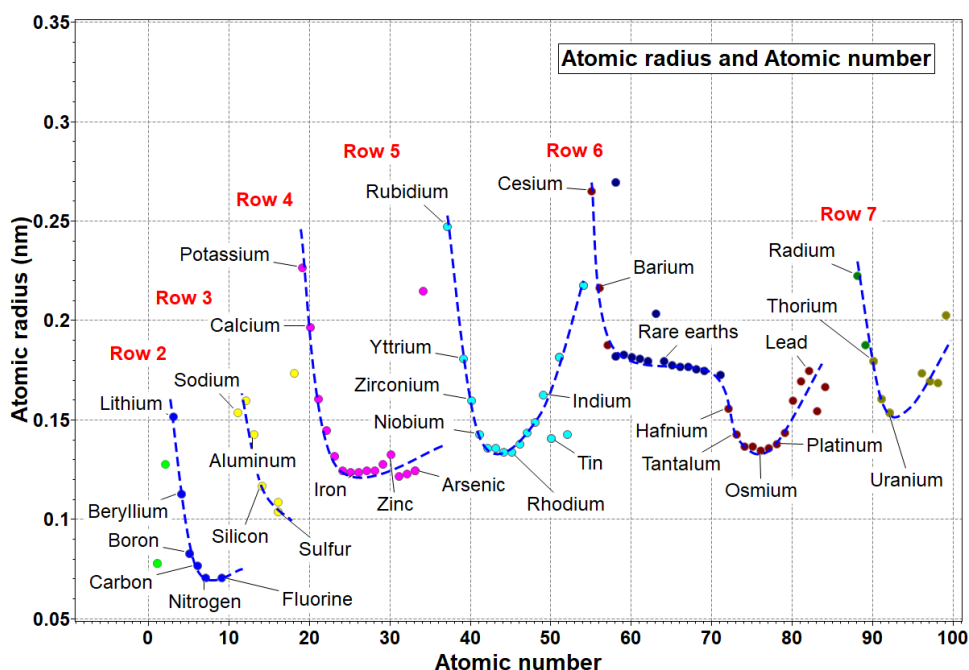
These are followed by a set of exercises that explore the relationships between properties – the dependence of Modulus on Cohesive energy, for example. They are particularly revealing about the ways in which bond strength and character affect properties. They also provide a tool for checking material property values and estimating values when none are available. The section ends with four more advanced questions: estimating Cohesive energies, Surface energies, Activation energies for lattice diffusion and visualizing the Hume-Rothery criteria for solid solution and its applications.

**Exercise 4: Atomic size across the rows of the Periodic table.** Make a chart with Atomic radius on the y-axis and Atomic number on the x-axis. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose 'Linear'. Use the "Curve" facility to sketch in the trends. What trends appear? How do you explain them?

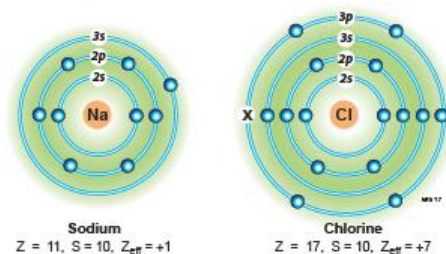
**Answer.** The atomic radius changes in a cyclic way across the rows of the Periodic table, starting from a maximum at the left-hand end. This is explained by *screening*, the degree to which the inner filled electron shells block the outer, valence, electrons from the positive charge of the nucleus. We define the effective nuclear charge,  $Z_{eff}$ , as

$$Z_{eff} = Z - S$$

Here  $S$  is the number of electrons in the inner filled shells, equal to the atomic number of the noble gas that is one period above the element in the Periodic table. As an example, the  $S$ -value for Chlorine is 10, the atomic number of Neon. The quantity  $Z$  is the total number of electrons, equal to the atomic number of the element itself, 17 for Chlorine. The 10 inner electrons ( $S$ ) of Chlorine screen out the positive charge of ten protons, leaving an effective nuclear charge  $Z_{eff}$  of  $(17 - 10) = +7$  that pulls the outer electrons closer to the nucleus, reducing the atomic radius.

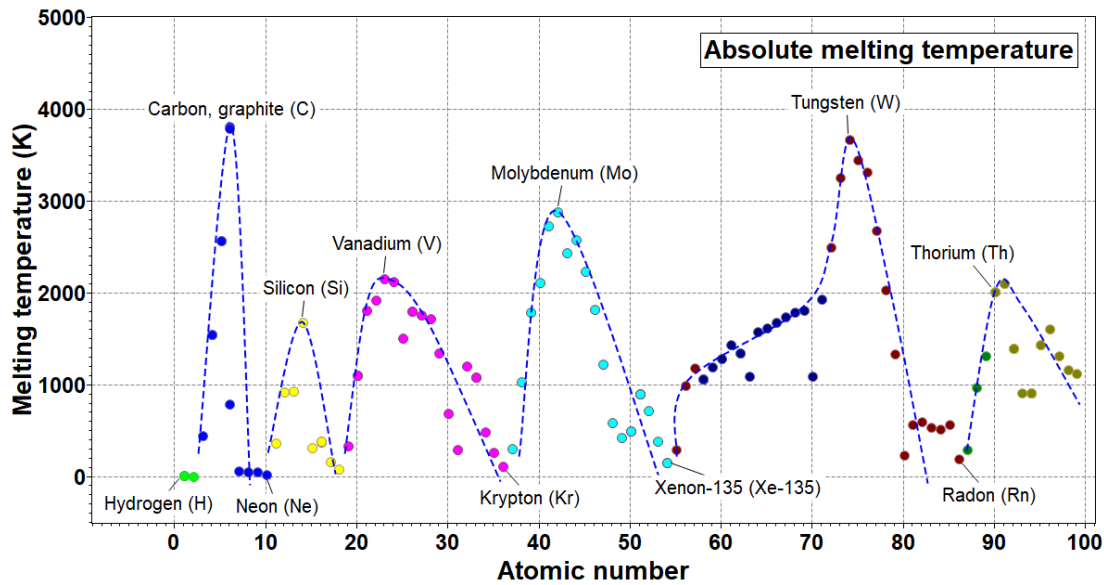


The effective nuclear charge increases, and the atomic volume decreases from left to right across a row in the Periodic table. Moving down a column of the periodic table, the number of filled electron shells increases. The effective nuclear charge remains the same but now the orbitals are farther from the nucleus, which exerts less pull on the outer electrons, increasing the atomic radii.



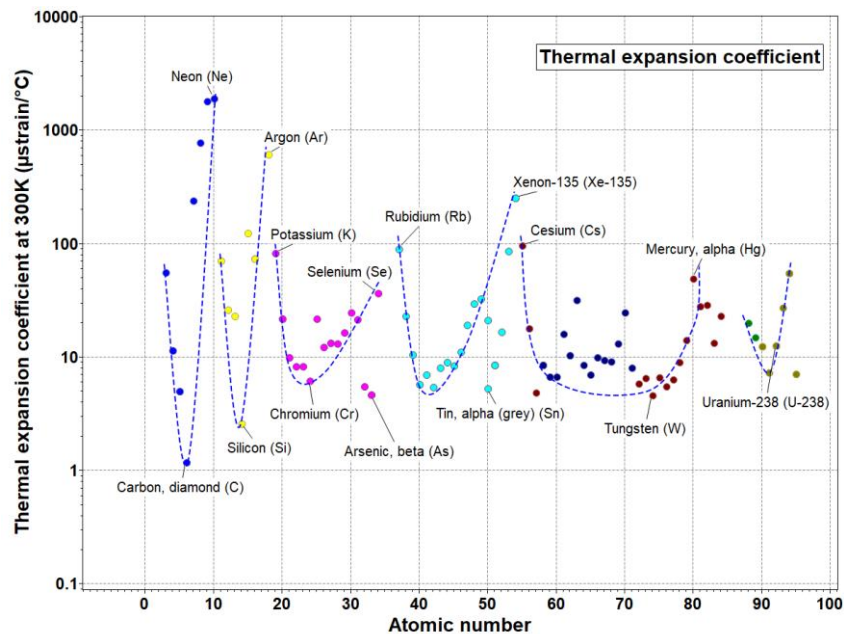
**Exercise 5: Melting point across the rows of the Periodic table.** Make a chart of the absolute Melting point for the elements across the Periodic table. To do so, set the temperature scale to Kelvin (Settings > Units > Use Absolute Units for Temperature) and plot Melting temperature on the y-axis against Atomic number. Use linear scales for both. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose 'Linear'. Use the "Curve" facility to sketch in the trends. Where are the peaks in the melting point? What does this suggest about the strength of atomic bonding?

**Answer.** The melting point peaks in the middle of each row of the Periodic table. It is least at the beginning and end of a row. This suggests that the strength of atomic bonds (the Cohesive energy) in the elements fluctuates in a similar way with atomic number (see Exercise 8).



**Exercise 6: Expansion coefficient across the rows of the Periodic table.** Make a chart of the Thermal expansion coefficient at 300K plotted against Atomic number. Use linear scales for the X-axis. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose 'Linear'. Use the "Curve" facility to sketch in the trends. What trends do you observe?

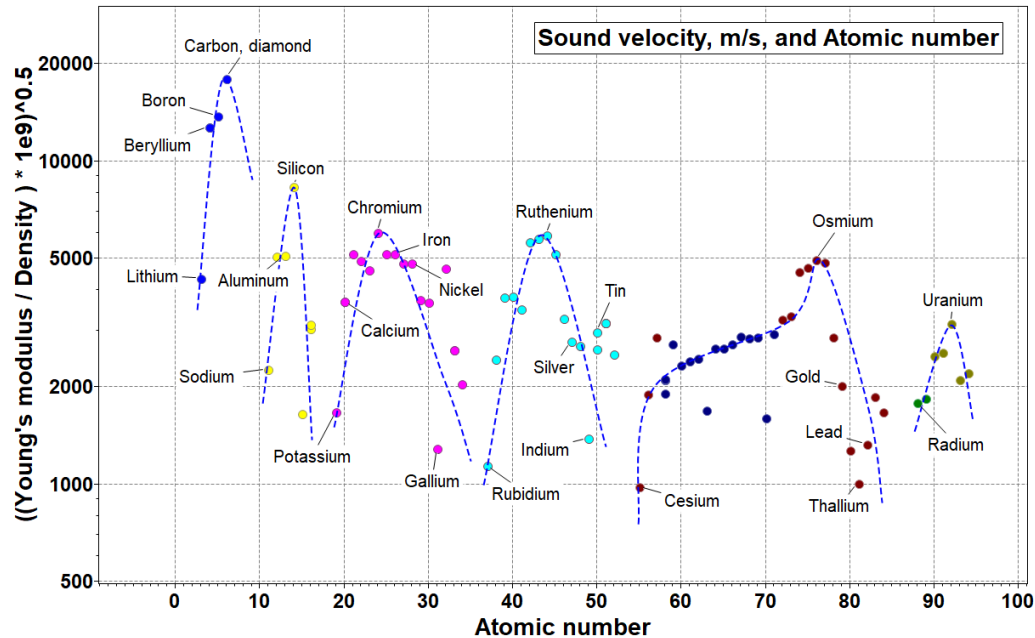
**Answer.** The Expansion coefficient is a minimum in the middle of each row of the Periodic table. It is greatest at the beginning and end of a row. This is because strength of atomic bonds (the Cohesive energy) in the elements is a maximum in the middle of each row of the Periodic table (see Exercise 8).





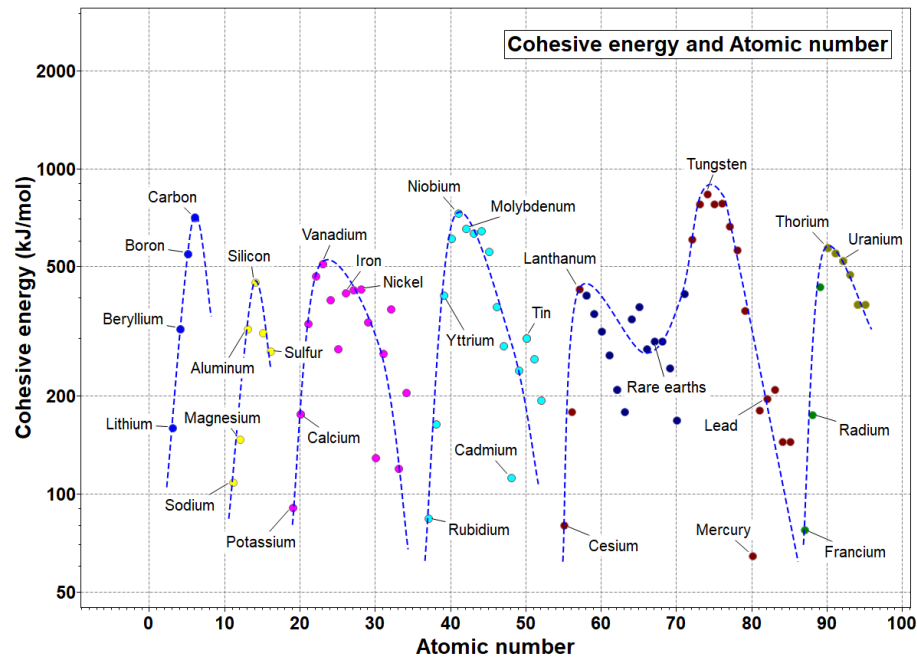
**Exercise 7: Sound velocity across the rows of the Periodic table.** Make a chart of the sound velocity  $(E/\rho)^{1/2}$  for the elements. To do so, construct the property-combination on the y-axis using the 'Advanced' facility in the axis-choice dialog box, and plot it against Atomic number. Multiply  $E$  by  $10^9$  to convert GPa to Pa, giving the sound velocity in m/s. Use a linear scale for Atomic number but retain the default log scale for sound velocity. In which element is the velocity greatest? In which is it least?

**Answer.** The values of sound velocity,  $(E/\rho)^{1/2}$ , range from 1000 m/s (Cesium) up to nearly 20000 m/s (Diamond). Most cluster around 3000m/s. The velocity peaks in the middle of each row of the Periodic table.



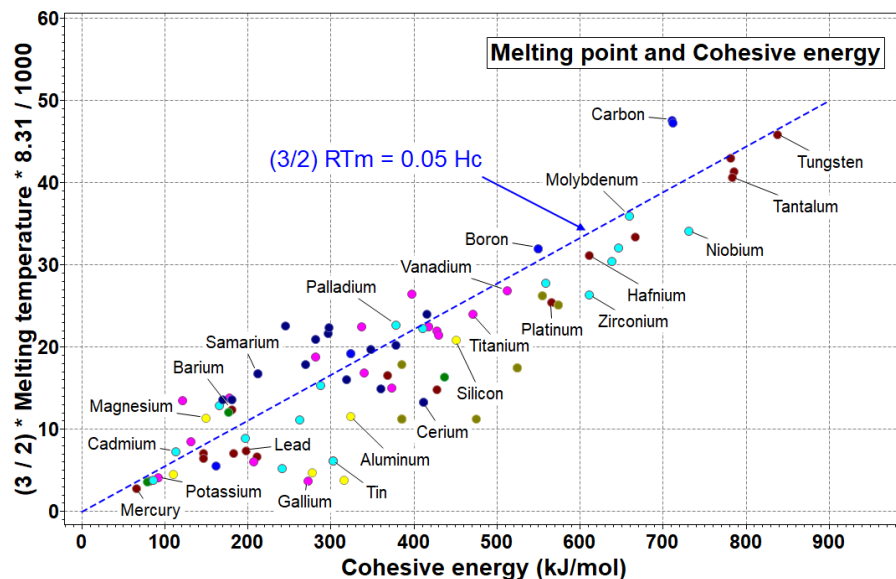
**Exercise 8: Cohesive energy across the rows of the Periodic table.** What is the “Cohesive energy”? (The Science Notes attached to each property in a datasheet will help here.) Make a chart of Cohesive energy plotted against Atomic number. Use linear scales for Atomic number but retain the log scale for Cohesive energy. Use the “Curve” facility to sketch in the trends. What trends do you observe?

**Answer.** The *cohesive energy* measures the strength of the bonds that bind atoms in a solid. It is defined as the energy per mol (a mol is  $6.022 \times 10^{23}$  atoms) required to separate the atoms of a solid completely, giving neutral atoms at infinity. Equally it is the energy released if the neutral, widely spaced atoms are brought together to form the solid. The chart shows that cohesive energy peaks in the middle of each row of the Periodic table. This is the reason that the Melting temperature (Exercise 5) and Young’s modulus have maxima and the Thermal expansion coefficient (Exercise 6) has a minimum in the middle of each row of the table.



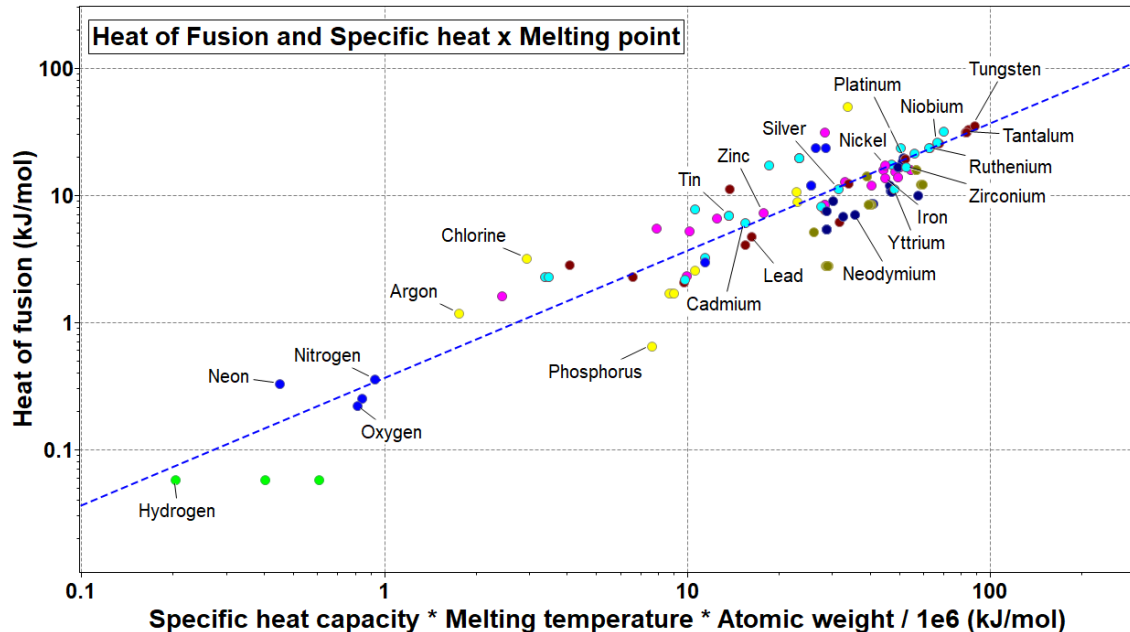
**Exercise 9: Melting point and Cohesive energy.** You might suspect that the melting point and the cohesive energy were at least roughly related. Make a chart to find out if this is so. To do this in a sensible way, plot the thermal energy at the melting point,  $(3/2) \bar{R} T_m$  against the Cohesive energy. To do this use the “Advanced” facility to multiply absolute melting point (K) [set the temperature scale to Kelvin (Settings > Units > Use Absolute Units for Temperature)] by the gas constant  $\bar{R}$  (8.31 J/mol.K), multiply by (3/2) and divide by 1000, to give the thermal energy in the same units (kJ/mol) as the cohesive energy. Use linear scales for both. What is the thermal energy at the melting point in units of cohesive energy?

**Answer.** The relationship between thermal energy at the melting point and cohesive energy is approximately linear. The thermal energy at the melting point is about 1/20 of the cohesive energy.



**Exercise 10: Latent heat of melting and energy to raise material to the melting point.** To melt a solid, it must first be raised from an ambient temperature to the melting point, absorbing an energy  $C_p T_m A_w$  kJ/mol. Here  $C_p$  is the specific heat (J/kg.K),  $T_m$  is the melting temperature (K) and  $A_w$  is the atomic weight (kg/mol). Once it reaches the melting point it absorbs a further Latent heat of fusion,  $L$  (kJ/mol) in the process of melting. Are the two related? What are their relative magnitudes? Make a chart of  $L$  plotted against  $C_p T_m A_w$  to find out. Be careful with the units – there is risk of losing a factor of 1000 if mol and kmol are confused, same with J and kJ.

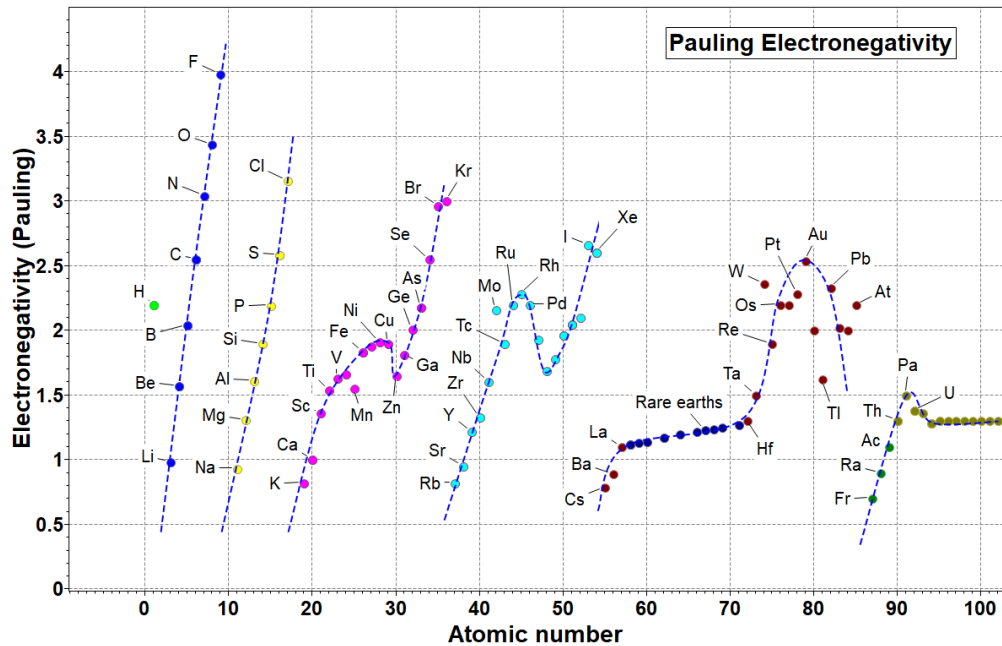
**Answer.** The chart plots the two properties, both in units of kJ/mol. The blue broken line has a slope of 1, meaning that are at least approximately proportional. The equation of the line is  $L = (1/3) C_p T_m A_w$  meaning that it takes three times more energy to heat an element to its melting point than to melt it once it gets there.



**Exercise 11: Electronegativity of the elements.** What is meant by “electronegativity”? (The Science Notes attached to each property in a CES datasheet will help here.) Make a chart of Electronegativity plotted against Atomic number. Use linear scales for both. Elements that differ in electronegativity by 1.7 or more on the standard Pauling scale will form ionic bonds. Use this criterion to identify elements that will form an ionic bond with Sodium (Na).

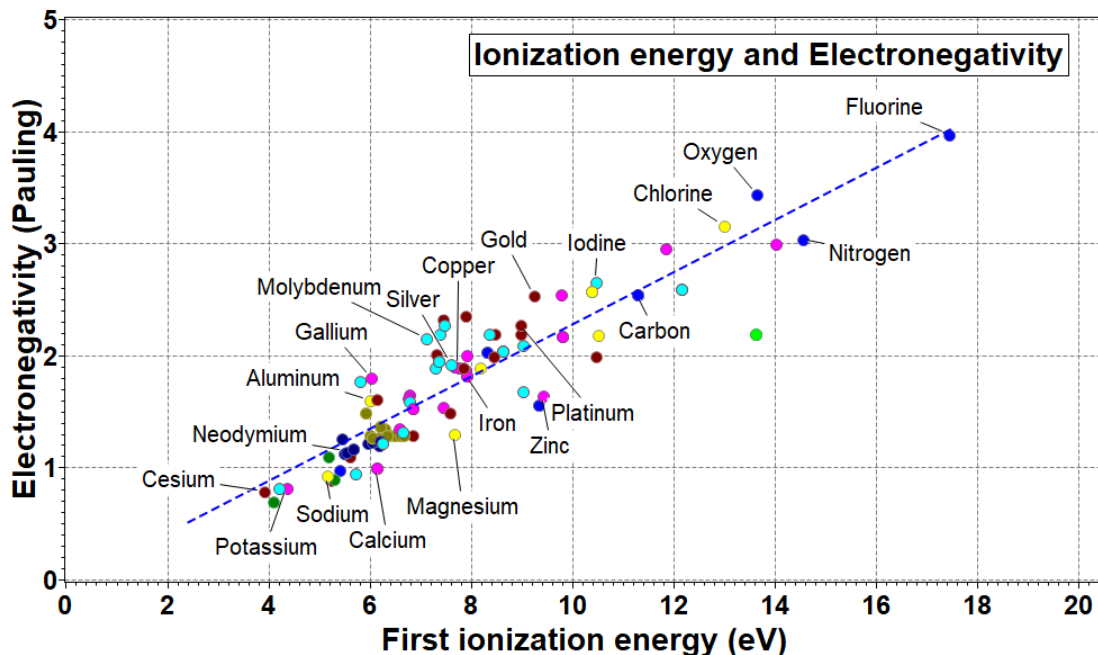
**Answer.** Electronegativity is a measure of the tendency of an atom to attract a bonding pair of electrons. It is measured on an arbitrary dimensionless scale proposed by Pauling. Fluorine (the most electronegative element) is assigned a value of 4.0. The values range down to cesium and francium with the value of 0.7. An atom with low electronegativity tends to lose electrons to become a positive ion; one with high electronegativity tends to gain electrons to become a negative ion.

The chart plots the electronegativity of the elements. The elements F, O, N, Cl, Br and I have electronegativities that are larger than that of sodium by more than 1.7. They are expected to form ionic bonds with sodium.

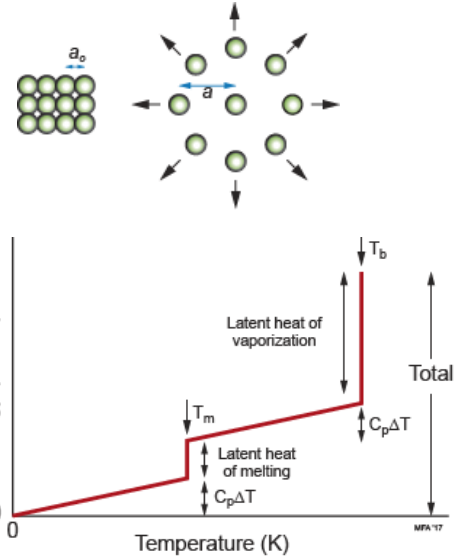


**Exercise 12: Electronegativity of the elements.** What is the First ionization energy of an atom? (The Science Notes will help here.) Is it related to the Pauling electronegativity? Make a chart with Electronegativity on one axis and First ionization energy on the other to find out. Use linear scales for both.

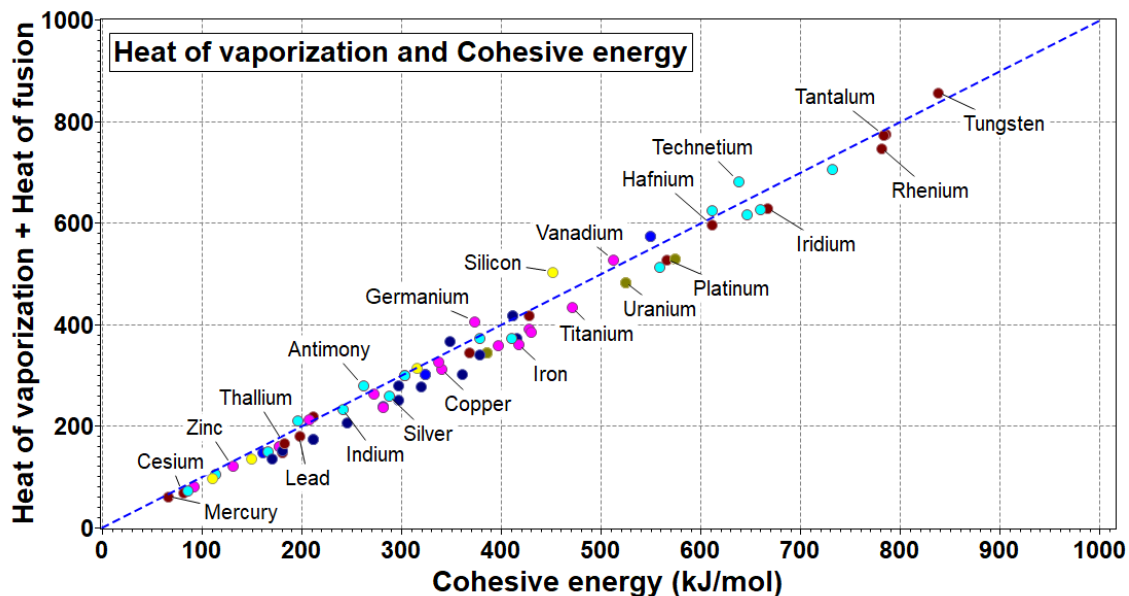
**Answer.** The first ionization energy is the energy needed to remove an electron completely from a neutral atom. It is least for the alkali metals and increases across a row of the Period table reaching a maximum for the noble gases. The ionization energy is a way to quantify chemical bonds in terms of energy, so it sounds a bit like the Pauling electronegativity of Example 11. The chart suggests that the two are almost proportional: the blue broken line has a linear slope and passes through the point (0,0).



**Exercise 13: Heat of vaporization and Cohesive energy.** The Cohesive energy  $H_c$  of a solid material is the energy required to separate its atom or ions into neutral atoms at infinity (upper part of the figure). Can it be estimated as the energy to vaporize a material? The lower part of the figure shows that this is the sum of the energy to heat it to the melting point,  $C_p T_m$  plus the latent heat of melting  $L_m$  plus the further energy to heat it to the boiling point  $C_p(T_b - T_m)$  plus the latent heat of vaporization,  $L_v$ . Here  $C_p$  is the specific heat,  $T_m$  and  $T_b$  are the melting and boiling points and  $L_m$  and  $L_v$  are the latent heats of melting and vaporization. In reality  $L_v$  is 15 to 30 times larger than the terms involving the specific heat so a first trial might be to plot Cohesive energy against the sum  $L_m + L_v$ . Create this chart and form a judgement about the validity of its use to estimate cohesive energies. Use linear scales for both.



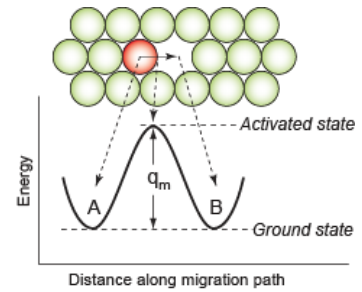
**Answer.** The chart is shown below. The broken blue line traces equality between the two axes. The correlation is a strong one. The estimate  $L_m + L_v$  slightly underestimates the Cohesive energy  $H_c$  probably for the reason mentioned in the question: the neglect of the terms involving  $C_p \Delta T$ . The estimate is useful for cross-checking data for  $L_m$ ,  $L_v$  and  $H_c$ , and as a way of estimating values for  $H_c$  when none are available.



**Exercise 14: Activation energy for lattice diffusion and Cohesive energy.**

Diffusion is the spontaneous intermixing of atoms over time. The unit diffusive step in a crystal is sketched here. Two things are needed for an atom to switch sites: enough thermal energy for the atom to break at least one of its bonds and an adjacent vacancy. The Maxwell-Boltzmann equation describes the probability  $p$  that a given atom has an energy greater than a value  $q$  Joules:

$$p = \exp\left(-\frac{q}{kT}\right)$$



A vacancy has an energy  $q_v$ , so the probability  $p_v$  that a given site be vacant is also given by this equation with  $q = q_v$ . To switch sites, the atom marked in red must break away from its original comfortable site at A, its *ground state*, and squeeze between neighbors, passing through an *activated state*, to drop into the vacant site at B where it is once again comfortable. There is an energy barrier,  $q_m$ , between the ground state and the activated state to overcome if the atom is to move. The probability  $p_m$  that a given atom has thermal energy this large or larger is our equation again with  $q = q_m$ . The overall probability of an atom changing sites is

$$p = p_v p_m = \exp\left(-\frac{q_v + q_m}{kT}\right) = \exp\left(-\frac{q_d}{kT}\right)$$

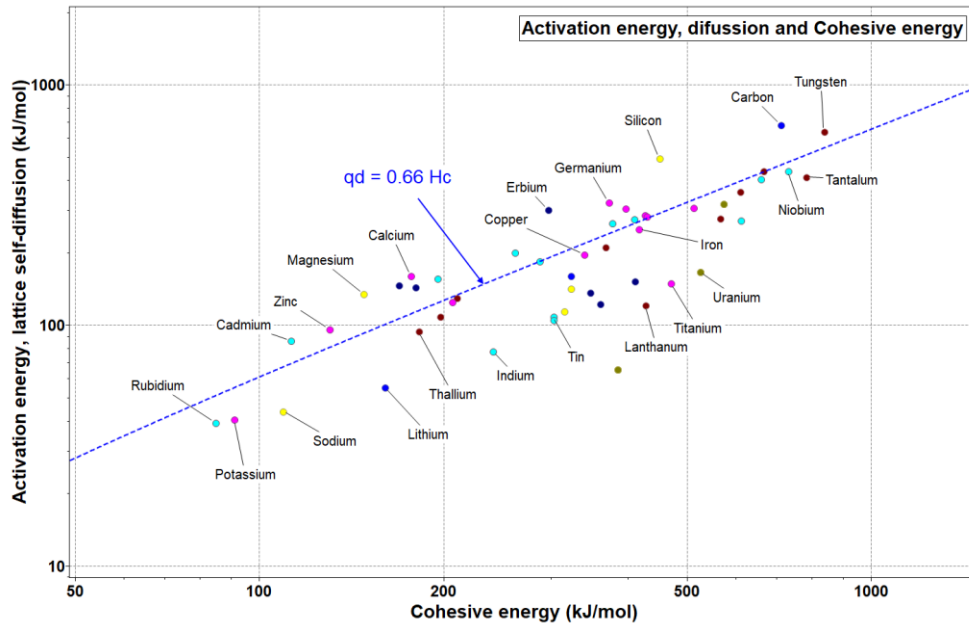
where  $q_d$  is called the *activation energy for self-diffusion*.

Bonds are broken when a vacancy forms. Bonds are also broken when an atom jumps from its starting site into an adjacent vacancy. One might, then, expect that the activation energy  $q_d$  was directly related to the Cohesive energy. If this turns out to be the case, the relationship becomes a valuable tool. Cohesive energies are known for almost all the elements and can be estimated when they are not known (see the previous exercise). Activation energies for diffusion have been measured in only a few. Make a chart of Activation energy for lattice self-diffusion against Cohesive energy to see if this is a winner.

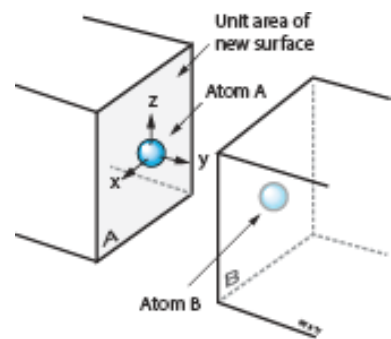
**Answer.** Here is the chart. The blue broken line is the equation

$$q_d = 0.66 H_c$$

It passes centrally through the data and follows their trend well. The scatter is considerable; 90% of the data are within a band  $\pm 40\%$ . The conclusion: the Activation energy for lattice self-diffusion is, to a good approximation, proportional to the cohesive energy. The equation derived from the correlation has an uncertainty of  $\pm 40\%$ .



**Exercise 15: Surface energy and Cohesive energy.** The figure shows a block of material that has been cut in half to create two new surfaces. Creating the surfaces breaks bonds such as the one that previously linked atom A and atom B in the figure. The surface energy  $\gamma$  (J/m<sup>2</sup>) is the sum of the energies of the broken bonds per square meter of new surface. Think of each atom as having 6 bonds, 1 each in the  $\pm x$ ,  $\pm y$  and  $\pm z$  directions; in the case of atom A the bond in the  $+y$  direction is broken in making surface A. The number of atoms per m<sup>2</sup> of surface is



$$n_A = \left( \frac{N_{AvO}}{M_V} \right)^{2/3}$$

where  $N_{AvO}$  is Avogadro's number ( $6 \times 10^{23}$  per mol) and  $M_V$  is the molar volume (m<sup>3</sup>/mol). The cohesive energy per ion is

$$E_C = \frac{H_C}{N_{AvO}}$$

where  $H_C$  is the Cohesive energy (kJ/mol).

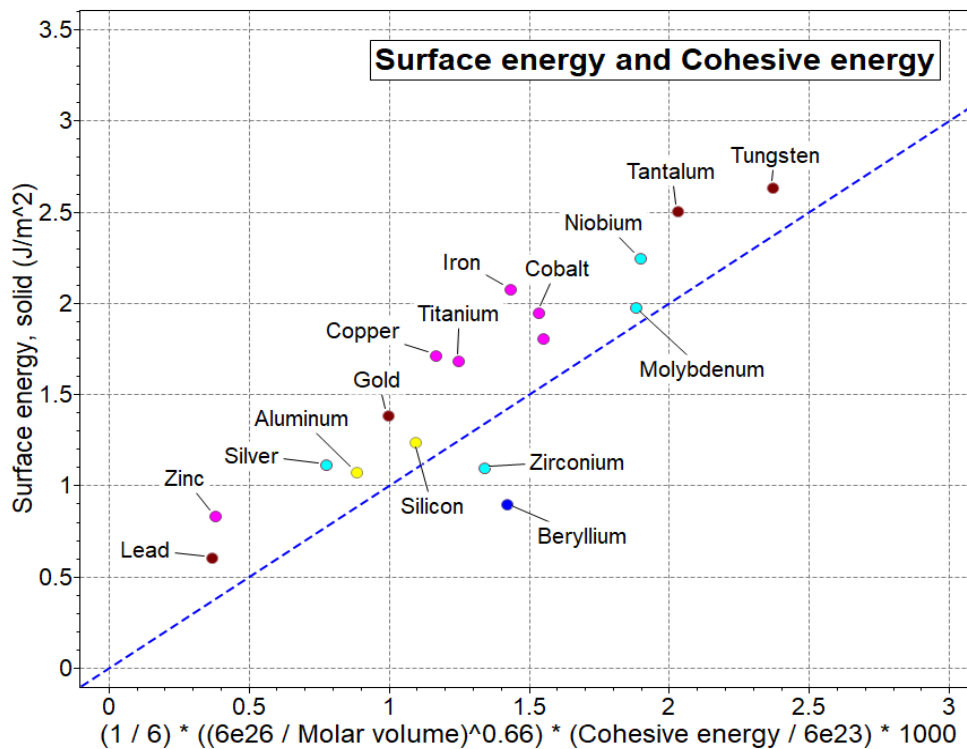
- Use this information to assemble an expression for the surface energy in terms of  $H_C$ ,  $M_V$  and  $N_A$  (values for these and for the surface energy  $\gamma$  are contained in the Elements data-table). Watch out for units!  $H_C$  is listed in kJ per mol,  $M_V$  in m<sup>3</sup> per kmol, and  $\gamma$  in J per m<sup>2</sup>.
- Make a chart with this expression as the x-axis and surface energy  $\gamma$  as the y-axis.
- Does the expression describe real surface energies well (allowing for the fact that they are difficult to measure, so not very precise)?
- Use the chart to estimate the surface energy of cadmium ( $H_C = 112$  kJ/mol,  $M_V = 0.013$  m<sup>3</sup>/kmol)

**Answer.** The predicted surface energy is

$$\gamma^* = \frac{1}{6} n_A E_c = \frac{1}{6} \left( \frac{N_{Avo}}{M_v} \right)^{2/3} \left( \frac{H_c}{N_{Avo}} \right)$$

It is plotted on the x-axis of this chart, on which the measured surface energy  $\gamma$  appears on the y-axis. The expression comes close to describing the measured surface energies, underestimating them a little (error at worst  $\pm 30\%$ ).

The calculated value of  $\gamma^*$  for cadmium is 0.50 J/m<sup>2</sup>, with a maximum error of 0.07 J/m<sup>2</sup>.



**Exercise 16: Solid solutions and High entropy alloys.** The Hume-Rothery rules set out criteria for the formation of extensive solid solutions:

- Atom size difference less than 15%
- Electronegativity difference less than 0.075
- The components have the same crystal structure
- The components have the same valence within  $\pm 1$

Make a chart of Electronegativity against Atomic radius. If you choose a log scale for the Atomic radius and a linear one for Electronegativity you can plot a selection box which meets the first two of these rules. If, in addition, you re-color-code the element-by crystal structure the chart allows the third criterion to be applied. To do this, add a

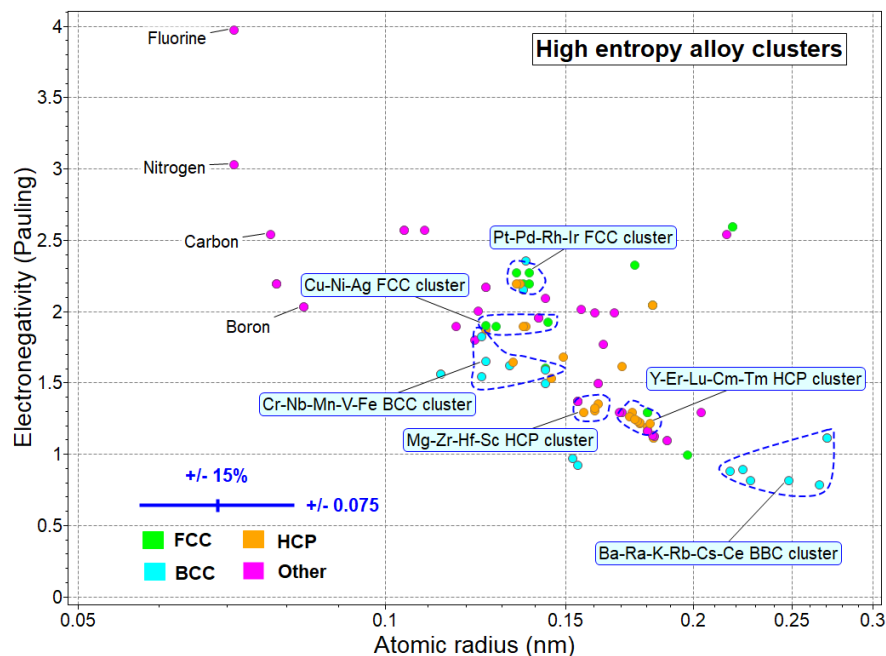


Limit stage, sequentially select; Crystal structure “Cubic: face centered”, “Hexagonal close packed” etc isolating materials of a single structure, high-light the list that appears in the Results window, right-click on high-lighted list and select new “Record color”; finally clear the Limit stage and proceed to the next structure. It is now easy to pick pairs of materials that will form extensive solid solutions. The final valence criterion can be applied if desired by adding another Limit stage.

High entropy alloys are solid solutions with four or more components each with concentrations above 5%. The cumulative entropy of mixing as the components mix reduces the free energy of the alloy, stabilizing the alloy and enhancing mechanical properties. The Hume-Rothery rules give guidance in selecting components to make such alloys. Use your chart to Identify some clusters of elements that might form high entropy alloys.

**Answer.** The chart is shown here. The elements have been recolored to identify crystal structure following the color code shown at the lower right. Bars in blue above them show the dimensions of a selection box that meets the first two criteria. Clusters of elements that meet the first three of Hume-Rothery’s rules are labeled.

Experience suggest that the Hume-Rothery rules are relaxed somewhat in multi-component systems. The rule that solvent and solute elements have the same crystal structure, for instance, does not seem to apply – a Fe-Ni-Cr-Co-Mn alloy, for example, forms a single fcc solid solution even though the components have four different structures. In a scoping exercise, the crystal-structure rule can be relaxed and the selection box widened a little to suggest a wider range of compatible components.



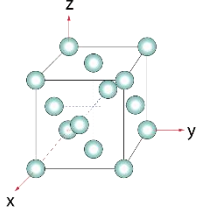
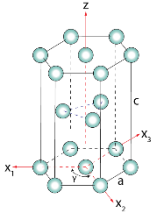
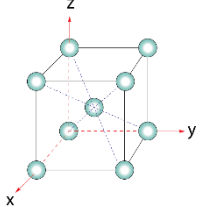
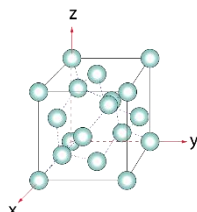
**Exercise 17: Make yourself a structure table.** There are many other things you can do with the Elements data-table. Here is one that will illustrate the method.

- Open the Elements data-table. Apply a limit stage. Select “Structure – Cubic, face-centered.” “Click Apply”.
- A list of all the elements in the Periodic table with the FCC structure appears in the “Results” window.
- Highlight the list and copy and paste into WORD as the first column of a 4-column table.

- Open any one of the selected records. Copy and paste into WORD. Copy and resize the crystal structure image. Paste it into the top of Column 1 of the table
- Clear the limit stage, and repeat the process for Hexagonal close packed, Cubic, body-centered and Cubic, diamond type, thereby filling the remaining 3 columns.

The result: a useful single-sheet look-up table for the elements with the most important crystal structures.

**Answer.** Here is a table made in the way described in the question

Face-centered cubic	Hexagonal close packed	Body-centered cubic	Diamond Cubic
			
Actinium (Ac) Aluminum (Al) Americium, beta (Am) Antimony, cubic (Sb) Argon (Ar) Calcium, alpha (Ca) Cerium, alpha (Ce) Cerium, gamma (Ce) Copper (Cu) Gamma iron (Fe) Gold (Au) Iridium (Ir) Krypton (Kr) Lead (Pb) Neon (Ne) Nickel (Ni) Palladium (Pd) Platinum (Pt) Radon (Rn) Rhodium (Rh) Silver (Ag) Strontium (Sr) Thorium (Th) Thorium-232 (Th-232) Thorium-233 (Th-233) Xenon (Xe) Xenon-135 (Xe-135) Ytterbium (Yb)	Americium alpha (Am) Antimony, hexagonal (Sb) Beryllium, alpha (Be) Cadmium (Cd) Cerium, beta (Ce) Cobalt (Co) Curium (Cm) Dysprosium (Dy) Erbium (Er) Gadolinium (Gd) Hafnium (Hf) Helium (He) Holmium (Ho) Lutetium (Lu) Magnesium (Mg) Osmium (Os) Rhenium (Re) Ruthenium (Ru) Scandium (Sc) Technetium (Tc) Terbium (Tb) Thallium (Tl) Thulium (Tm) Titanium, alpha (Ti) Yttrium (Y) Zinc (Zn) Zirconium (Zr)	Barium (Ba) Beryllium, beta (Be) Calcium, beta (Ca) Cerium, delta (Ce) Cesium (Cs) Chromium (Cr) Europium (Eu) Francium (Fr) Iron, alpha (Fe) Lithium (Li) Manganese (Mn) Molybdenum (Mo) Niobium (Nb) Potassium (K) Radium (Ra) Rubidium (Rb) Sodium (Na) Tantalum (Ta) Titanium, beta (Ti) Tungsten (W) Vanadium (V)	Carbon, diamond (C) Germanium (Ge) Silicon (Si) Tin, alpha (grey) (Sn)

## 2. Discovery with the Biological materials Data-table

The Biological materials data-table gives students access to data for Biological materials (like bone, horn, skin and woods, for example) and to the building blocks of which they are made (collagen, hydroxyapatite, elastin, cellulose and more) in the same format and units as those for the elements, engineering materials and functional materials contained in the database. Uniquely, this allows construction of charts that allow direct comparison of Biological materials with those of engineering, stimulating thinking about man-made substitutes for those of nature and of ways in which nature might inspire advances on the engineering side.

**Exercise 18: Getting to know the Biological materials data-table (1).** What is egg shell? What is the fracture toughness of egg shell? To find out, Browse or use the Search facility to find the record for egg shell.

**Answer.** **Egg shell** is calcite, calcium carbonate. It is porous to allow air to reach the developing bird. Egg shell is composed of four layers. From inside out, these are the cone, the palisade, the vertical crystal layer and the cuticle. The crystal layer is a thin layer just beneath the cuticle, a protein. The main structural layer is the palisade, made of calcium carbonate.

**The fracture toughness of egg shell** =  $0.3 - 0.35 \text{ MPa}\cdot\text{m}^{1/2}$  (or avg:  $0.324 \text{ MPa}\cdot\text{m}^{1/2}$ )

This is a very low fracture toughness, necessary to allow the chick to break out of the egg.

**Exercise 19: Getting to know the Biological materials data-table (2).** What is Ramie? What is the Tensile strength of Ramie fiber? How does this compare with Low carbon steel? Use the Search facility to find the record for Ramie.

**Answer.** **Ramie** (*Boehmeria nivea*) is a flowering plant in the nettle family. Ramie is one of the oldest fiber crops, used for at least six thousand years, for cordage and fabric production. Like jute, hemp, flax (linen) and ramie, ramie is a bast fiber plant, one in which the fibers are extracted from the stem or bast. It is one of the strongest natural fibers.

**Tensile strength of Ramie** =  $500 - 820 \text{ MPa}$  (or avg:  $640 \text{ MPa}$ )

**Tensile strength of Low carbon steel** =  $379 - 532 \text{ MPa}$  (or avg:  $449 \text{ MPa}$ )

Ramie is stronger than low carbon steel and much (a factor 5) lighter.

**Exercise 20: Getting to know the Biological materials data-table (3).** What is Resilin? What is the definition of the Mechanical loss coefficient? (The Science Note for Mechanical loss coefficient will help here.) What is the mechanical loss coefficient of Resilin? How does it compare with that for Collagen?

**Answer.** **Resilin** is an elastomeric protein found in the cuticle of insects (arthropods) such as fleas and locusts. It is resilin that allows fleas to jump, locusts to sing and dragon-flies to hover. It has unique resilience with an elastic “efficiency” of 97% and fatigue lifetime of hundreds of millions of cycles.

**The mechanical loss-coefficient (*tan delta*) or damping coefficient** (a dimensionless quantity), measures the degree to which a material dissipates vibrational energy

**Mechanical loss coefficient of Resilin** =  $0.03 - 0.04$  (or avg  $0.0346$ )

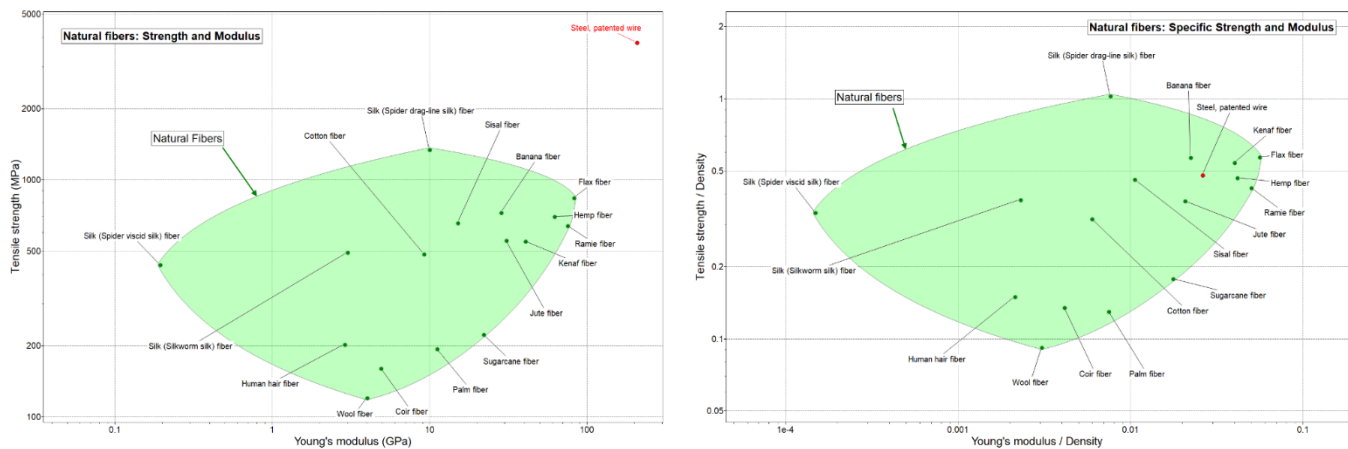
**Mechanical loss coefficient of Collagen** =  $0.03 - 0.3$  (or avg  $0.0949$ )

Mechanical loss in resilin is, on average, much lower than that of collagen, meaning that it can be stretched and relaxed much more quickly without heating up.

**Exercise 21: Natural and man-made fibers.** It is sometimes claimed that spider drag-line silk is stronger than steel. Patented steel wire (“piano” wire) has a tensile strength  $\sigma_{ts}$  of 3800 MPa, a modulus  $E$  of 207 GPa and a density  $\rho$  of 7900 kg/m<sup>3</sup>. Make a chart with Tensile strength on the y-axis and Young’s modulus on the x-axis. Limit the materials to Natural fibers (“Custom – Define your own subset – Biological materials - Natural fibers”). Piano wire can be found under man-made fibers or can be added: right click on the chart and select “Add Record”. Enter its values for tensile strength and modulus – it will appear on the chart. Is spider drag-line silk really stronger than steel?

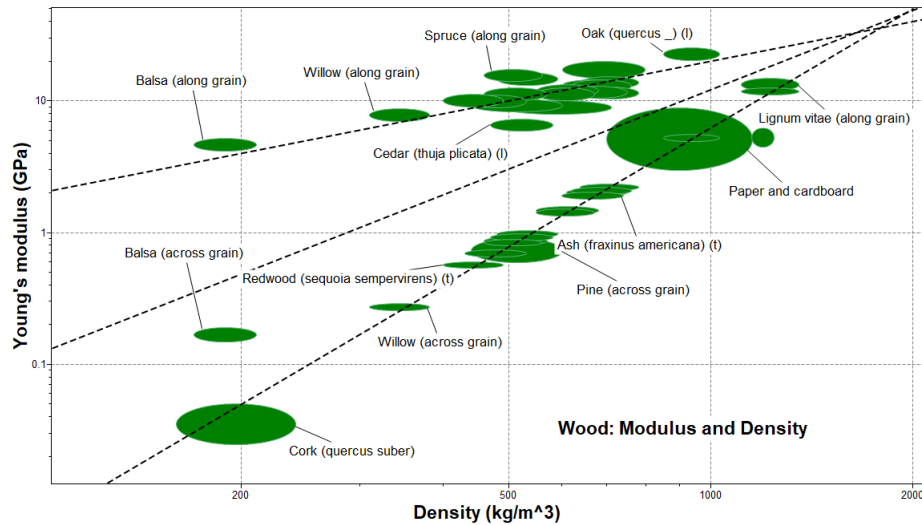
Perhaps the claimants mean “stronger per unit weight” ( $\sigma_{ts}/\rho$ ) rather than just “stronger” (just  $\sigma_{ts}$ )? Make a new chart with  $\sigma_{ts}/\rho$  on the y-axis and  $E/\rho$  on the x-axis using the “Advanced” facility on the axis-selection window to find out.

**Answer.** The first chart gives a nice overview of the strength of natural fibers. Even the least strong ones – Wool and Coir (coconut husk) at 160 - 190 MPa – are strong enough to be useful. Patented steel wire, however, is much stronger than any of them. When instead they are compared per unit weight the picture changes: spider drag line silk wins by more than a factor of 2.



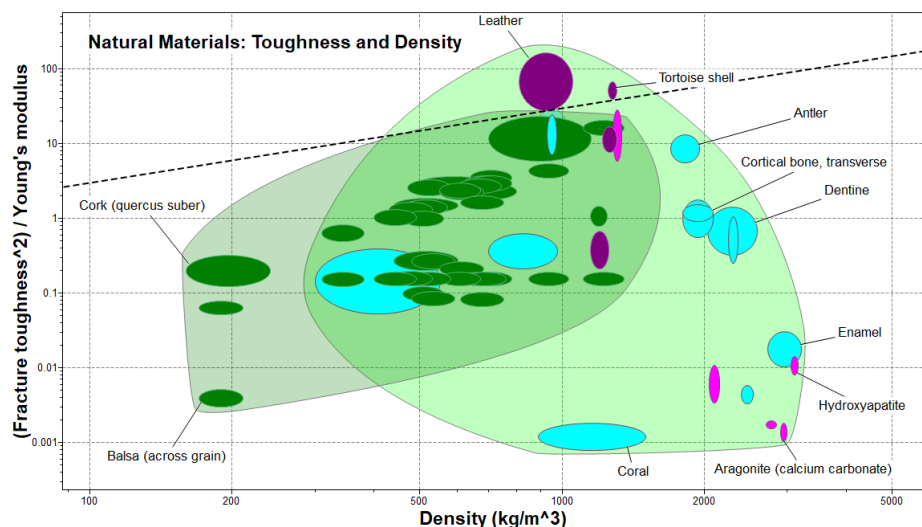
**Exercise 22: Modulus and density of woods.** How does the Young’s modulus  $E$  for hard and soft woods depend on density  $\rho$ ? Make a chart for the relevant materials with  $E$  on one axis and  $\rho$  on the other. Does the transverse (t) modulus – the one across the grain – depend on density in a different way from the longitudinal (l) modulus parallel to the grain? Fit a power law to each by plotting trial “display” lines onto the chart with slopes of 1 (a linear dependence), 2 (quadratic dependence) and 3 (cubic dependence) to see which best matches the data.

**Answer.** The data for the longitudinal modulus suggest a linear dependence on density. Those for the transverse modulus are well described by a cubic dependence. The remarkable lack of scatter suggests that all woods are made of the same basic material; the primary reason for their different moduli is that they differ in density but not in composition.



**Exercise 23: Materials for shields.** Imagine yourself to be a 12<sup>th</sup> century Viking seeking light, tough materials to make shields to protect yourself while you pillage and plunder. “Tough” means high  $G_{1c} = K_{1c}^2 / E$ , where  $K_{1c}$  is the fracture toughness and  $E$  is Young’s modulus. “Light” means low density,  $\rho$ . Use the “Advanced” facility to make a chart of biological materials with  $G_{1c}$  on the y-axis and  $\rho$  on the x-axis. Apply a selection line with a slope of 1 describing light, tough materials ( $G_{1c} / \rho$ ) and use it to find the best natural materials for shields. Then do a quick web-search to find out if these materials were ever, in the past, used in this way. Use a custom subset of Molecular Building Blocks, Tissues (Mineralized and Soft), and Wood.

**Answer.** Leather and Tortoise shell both have high values of  $G_{1c} / \rho$ . Both have been used to make shields in the past.

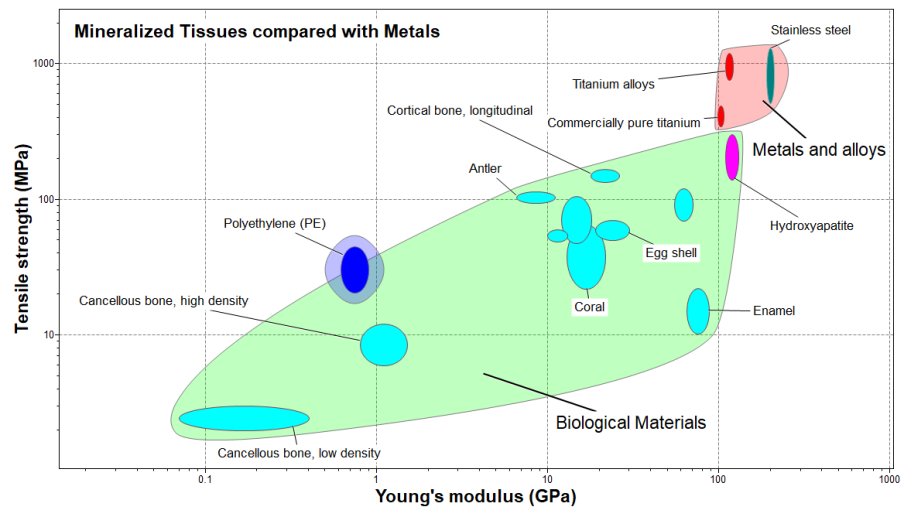


**Exercise 24: Bone implant materials.** Badly broken bones are repaired with bio-compatible implants. Stainless steel and Titanium (or one of its alloys) are standard choices. Ideally the implant material should match bone in modulus, strength and density. Do these materials meet or come close to this ideal? Create a subset containing

Mineralized tissue, Stainless steel, Titanium and Titanium alloys (“Custom: Define your own subset”). Make a chart with Tensile strength on the y-axis and Young’s modulus on the x-axis. Use it to form a judgement about the suitability of the three metals for implants in cortical bone.

Bone (simplifying a little) is a composite of Hydroxyapatite and Collagen. It has been suggested that a composite of Hydroxyapatite in polyethylene might make a good bone substitute. Add Hydroxyapatite and Polyethylene to your subset (simply edit the subset). Does it look as if a composite of the two has promise as a substitute bone material?

**Answer.** There is a large mismatch of strength and modulus between cortical bone and the three metals, which are chosen largely because they are biocompatible. The longitudinal strength and modulus of cortical bone lies directly between those of Hydroxyapatite and Polyethylene. Hydroxyapatite, we know is biocompatible (it’s in real bone). Polyethylene is already used for parts of hip and knee replacements. A combination of the two should not present compatibility problems.



### 3. Discovery with the Functional Materials Data-table

Although there is no standard definition of a functional material, it generally means materials with "interesting" properties that do more than just support loads, conduct heat and electricity. The group includes magnetic materials with piezoelectric, pyroelectric and ferroelectric behavior, and semiconducting materials including thermoelectrics.

**Exercise 25: Getting to know the Functional Materials data-table (1).** What is Terfenol-D? What functional properties does it exhibit? What does "giant magnetostriction" mean? Use the Search function to find the record for Terfenol-D and the science notes attached to Functional Properties to find out.

**Answer.** *Terfenol-D* is an alloy of terbium, dysprosium and iron. It is the material with the highest known magnetostriction at room temperature; it changes size when subjected to a magnetic field. It was initially developed for sonar detectors, but is now used in actuators, magnetomechanical sensors and transducers for acoustics or ultrasound.

**Functional Properties** of Terfenol-D: Ferromagnetic. Giant magnetostriction

**Magnetostriction** is shape change caused by a magnetic field. As a magnetic field is applied to a ferromagnetic material, magnetic domain walls move, rotating the domains to align with the field. This leads to a strain in the material. Alignment is complete at the saturation induction,  $B_s$ , requiring an applied coercive field,  $H_c$ . The material is described as having positive magnetostriction if its length increases with increasing magnetic field and negative magnetostriction if it does the opposite.

**Exercise 26: Getting to know the Functional Materials data-table (2).** What is TAGS? What is its composition? What are its Functional Properties? What is the value of its Seebeck coefficient? How is the Seebeck coefficient defined? Use the Search function to find the record for TAGS and the science notes attached to the field for Seebeck coefficient to find out.

**Answer.** **TAGS** (an alloy of germanium, tellurium, silver and antimony), is a semiconductor with strong thermoelectric properties, particularly at elevated temperatures. It has a higher thermoelectric figure of merit than lead telluride across a similar operating range, so is of interest for satellite power units. Composition:  $(\text{GeTe})_x(\text{AgSbTe}_2)_{1-x}$ ;  $x \sim 0.85$ .

**Functional Properties** of TAGS: Semiconductor. Thermoelectric.

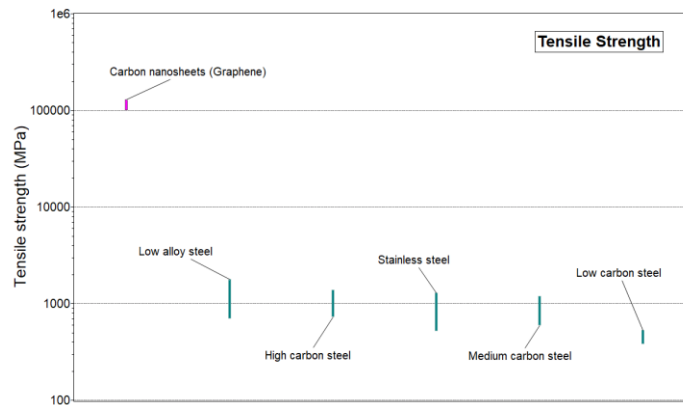
**Seebeck coefficient** for TAGS =  $123 \mu\text{V}/^\circ\text{C}$

**Definition of Seebeck coefficient:** The Seebeck coefficient  $S$  (also known as the thermopower) is a measure of the change in voltage  $\Delta V$  induced across a thermoelectric material by a thermal gradient  $\Delta T$ . For small temperature changes, the Seebeck coefficient is given by  $s = -\frac{\Delta T}{\Delta V}$ . A positive Seebeck coefficient indicates that the charge carriers involved are positive (holes); a negative Seebeck coefficient means that electrons are carrying charge.

**Exercise 27: Fullerenes.** Using Granta EduPack Materials Science and Engineering database, search for the term 'fullerene'. What is a fullerene? What are examples of fullerenes? What is graphene? How does its tensile strength compare with that of steels? To find out, make a bar-chart of Tensile strength. Use the "Custom -

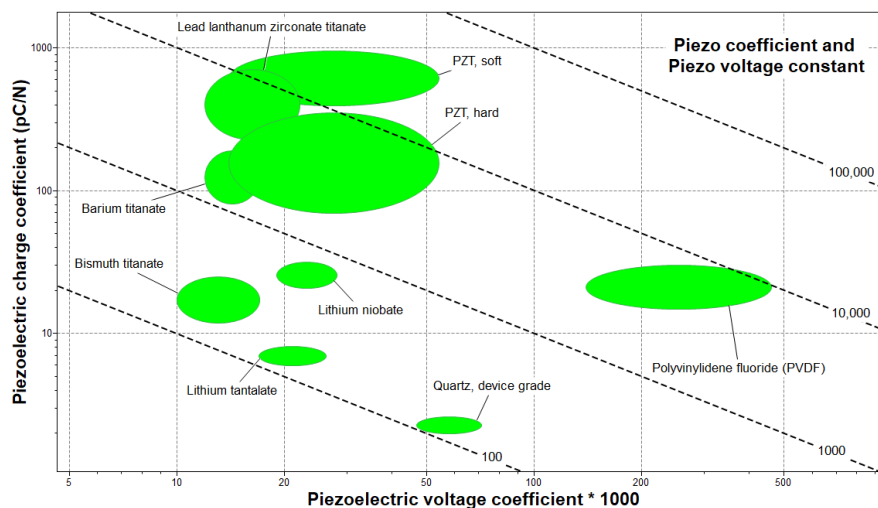
Define your own subset” option in the “Chart/Select” Window to narrow the choice to Graphene and the five steels that are in the database.

**Answer.** A fullerene is any allotrope of carbon that consists of a single sheet of hexagonal sp<sup>2</sup> hybridized carbon atoms. Examples include Buckminsterfullerene, graphene and carbon nanotubes. Graphene is a monolayer of carbon in a hexagonal lattice one atom (0.345 nm) thick. Graphene is almost 100 times stronger than the strongest steels. The problem in using this strength is that of incorporating that atom-thick platelets into a bulk material.



**Exercise 28: Piezoelectric materials.** Efficient piezoelectric power generation is characterized by the merit index  $d_{33} \cdot g_{33}$ , the product of the Piezo electric charge coefficient  $d_{33}$  and voltage coefficient  $g_{33}$ . Use the Granta EduPack Materials Science and Engineering database to make a chart with  $d_{33}$  on the y-axis and  $g_{33}$  on the x-axis. Plot contours of the product  $d_{33} \cdot g_{33}$  (they are parallel lines with a slope of -1 on log scales). Use them choose the materials with the highest value of this index, bearing in mind that the use of lead is now restricted by the European Restriction of Hazardous Substances Directive (RoHS) Directive.

**Answer.** Soft PZT (lead zirconium titanate) and PZLT (lead lanthanum zirconium titanate) have the highest value of the index, but both contain lead. The best choices that are not restricted are Barium titanate and the polymer PVDF

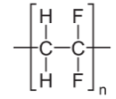




**Exercise 29: Piezoelectric polymers.** Polyvinylidene fluoride (PVDF) is unusual because it is a ferroelectric polymer. Its structure is sketched on the right.

(a) What makes it ferroelectric?

(b) Using either EduPack or the internet, find out what it is used for and why.



**Answer.** (a) The difference in electronegativity between Fluorine and Hydrogen is large. The  $-\text{CH}_2\text{-CF}_2$ - units carry an electrostatic dipole. It is this that creates the ferro-electric characteristics

(b) PVDF is used for tactile sensor arrays (exerting pressure on a PVDF panel generates a voltage), kinetic energy harvesters and lightweight transducers. PVDF is a polymer and much more flexible, less hard and easier to process than its ceramic piezoelectric counterparts.

**Exercise 30: Pyroelectric materials.** Pyroelectric materials are used in thermal detectors and thermal imaging. Incident IR radiation heats up the substance creating a voltage which can trigger a circuit. The merit index for voltage response is:

$$F_v = \frac{\gamma}{\epsilon_r C_p}$$

where  $\gamma$  is pyroelectric coefficient,  $\epsilon_r$  is dielectric constant, and  $C_p$  is heat capacity. Make a chart with  $\gamma$  on the y-axis and  $\epsilon_r C_p$  on the x-axis and add contours (lines of slope 1 on log scales) describing the index.

(a) Which material has the highest value of the index?

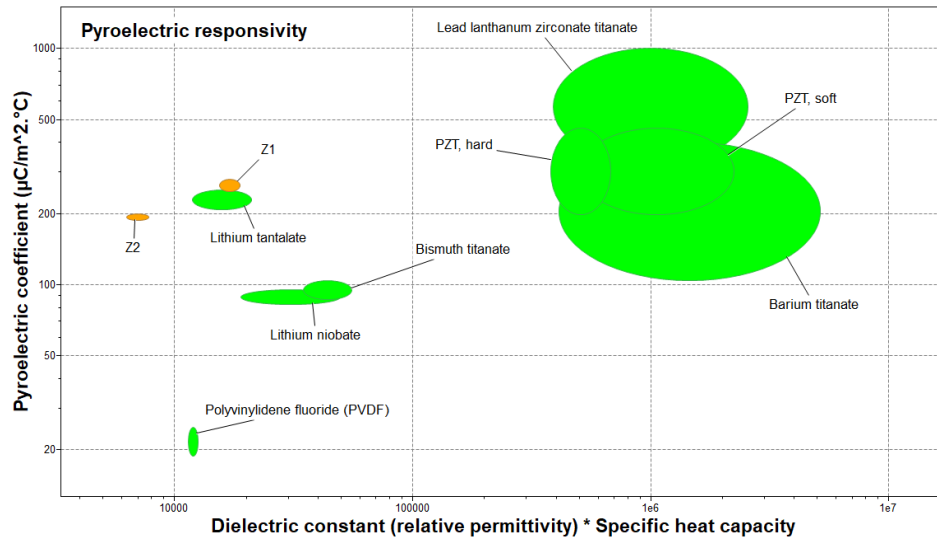
(b) Two new pyroelectric materials have been developed recently; they are known as Z1 and Z2. Their properties are listed in the table. Add these temporarily to your database by right-clicking with the cursor on your chart and selecting "Add record". Enter the data for Z1 and Z2, which will then appear on your chart. Are they better than the best of the older materials?

Property	Material Z1	Material Z2
Pyroelectric coefficient/ $\mu\text{Cm}^{-2}\text{K}^{-1}$	250-280	190-200
Dielectric constant	50-60	40-45
Specific Heat Capacity/ $\text{JKg}^{-1}\text{K}^{-1}$	300-320	150-180
Density/ $\text{kgm}^{-3}$	7900	4800

**Answer.**

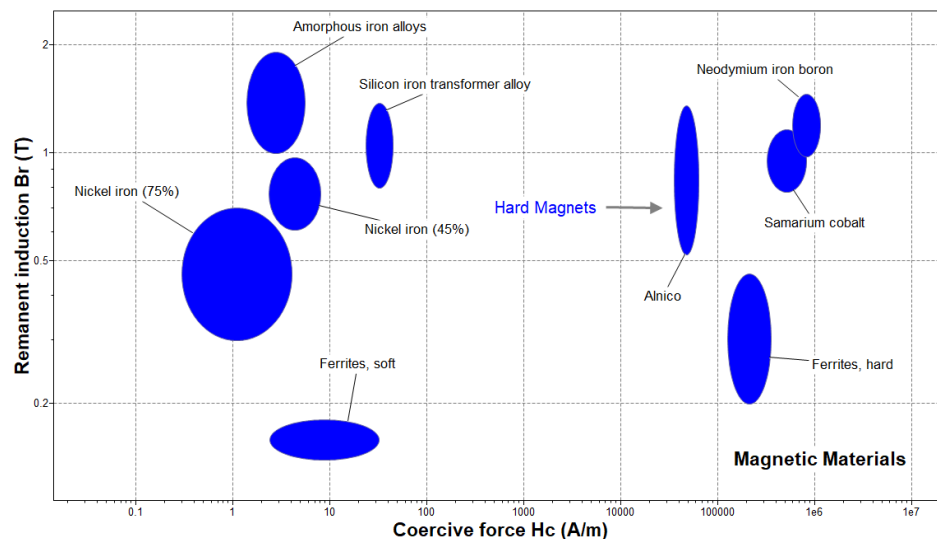
(a) The material with the largest merit index is Lithium tantalate.

(b) The performance of new material Z1 is approximately the same as that of Lithium tantalite. Material Z2 performs better, largely because its heat capacity is only half that of Z1.



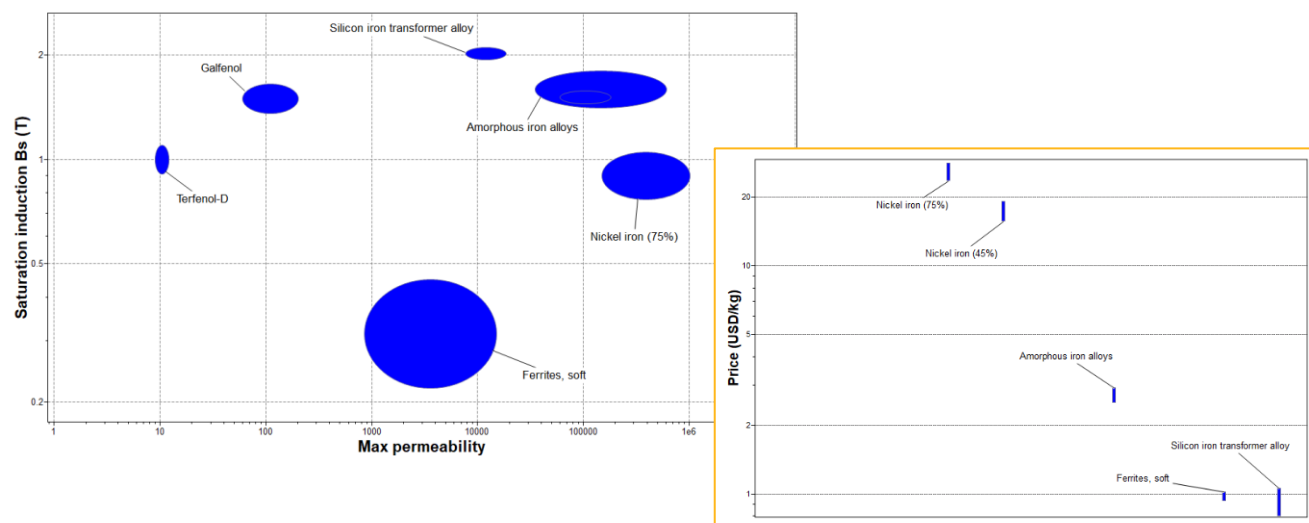
**Exercise 31: Hard magnetic materials.** Hard (permanent) magnets are the key functional materials in efficient DC motors, turbines, and many electronic devices. They require materials with a high remanent induction (determining the strength of the magnetic field) and a high coercive force (determining the resistance to demagnetization). Make a chart with the first of these on the y-axis and the second on the x-axis. Use it to identify the group of alloys that make the best hard magnets.

**Answer.** The material (actually a family of materials) based on Neodymium, iron and boron have exceptionally high values of both remanent induction and coercive force. They are widely used in the motors of electric vehicles, wind turbines and electronic devices.



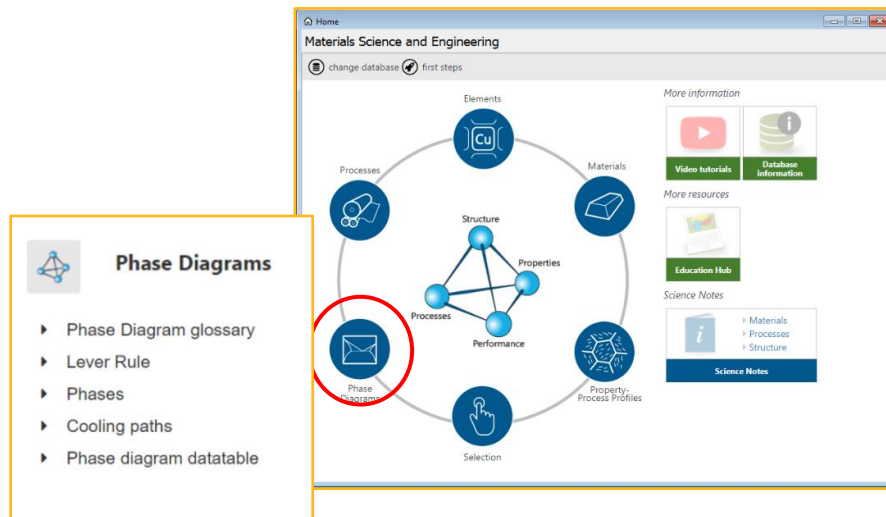
**Exercise 32: Soft magnetic materials.** Efficient transformers and AC electric motors rely on soft magnets with high saturation induction and high maximum permeability. Make a chart with Saturation induction on the y-axis and Max permeability on the x-axis. Use it to identify the best materials for transformer cores.

**Answer.** Silicon iron transformer alloy has the highest Saturation induction, but its Maximum permeability is 10 to 100 times less good than the Nickel iron alloys, known as Permalloys. Why, then, is it the almost universal choice for large transformers? The answer is economic: the silicon iron transformer alloy is cheaper, by a large margin, than any of the others. A bar-chart of Price/kg will illustrate this.



#### 4. Phase diagram exercises and solutions

The new Phase diagram tool is located in the MS&E database under “Phase Diagrams” as shown below. Through visual examples, students learn about the phase diagram terminology, the lever rule, different cooling paths and the microstructure and atomic structure of phases. Some common binary phase diagrams with a short description can be found in the phase diagram datatable.



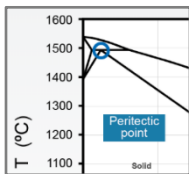
**Exercise 33.** In the **Phase diagram glossary**, there are three binary diagrams to explore. Explain the terms Liquidus and Solidus. Which important phase points only appear in the Fe-C diagram and what do they mean?

**Answer.** The Liquidus line shows the temperature at which solidification starts upon cooling. It is the upper boundary between a liquid region and the associated (Solid + Liquid) region.

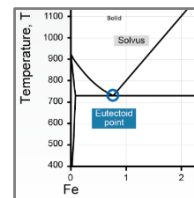
The Solidus line shows the temperature at which solidification ends upon cooling. It is the lower boundary between a (Solid + Liquid) region and the associated solid region.

Two important phase points only appear on the Fe-C diagram: a peritectic and a eutectoid point.

A eutectoid point is the lower limit of a single-phase solid field formed by two falling phase boundaries intersecting in a ‘V’. At the eutectoid point, a eutectoid reaction takes place upon cooling. A single-phase solid transforms into two different solid phases at constant temperature: Solid  $\gamma \rightarrow$  Solid  $\alpha$  + Solid  $\beta$



A peritectic point is the upper limit of a single-phase solid field formed by two ascending phase boundaries intersecting in an inverted ‘V’. At the peritectic point, a peritectic reaction takes place upon cooling. A liquid and a solid transform into a single-phase solid at constant temperature: Solid  $\delta$  + Liquid  $L \rightarrow$  Solid  $\gamma$



To summarize:

- *eutec-* means a normal ‘V’ meeting a horizontal line, whereas *peritec-* means an inverted ‘V’ meeting a horizontal line.
- *-tic* means a liquid phase is involved, whereas *-toid* means all phases are solid.

**Exercise 34.** Read and understand the text that comes up when you click on **Lever rule** for the first time. Move on to the Lever rule diagram. There are two important concepts: weight fraction and composition. What's the difference between the two?

**Answer.** *Weight fraction* describes the percentage in terms of weight of a certain phase present. Because of mass conservation the sum of all weight fractions must be one. If we only have two phases (solid and liquid) we have:

$$W_S + W_L = 1$$

*Composition* is the percentage with respect to the weight of the component present (on the X-axis of binary phase diagrams). The mass of one of the components in one phase plus the mass of the same component in the other phase must be equal to the mass of that component in the total alloy. Expressed mathematically:

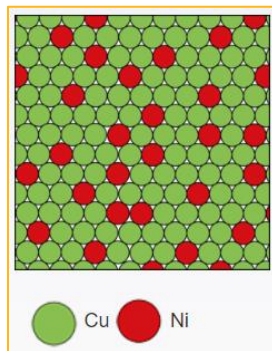
$$W_S C_S + W_L C_L = C_0$$

Combining these two equations and solving for the solid and liquid weight fraction, we obtain the lever rule:

$$W_S = \frac{C_L - C_0}{C_L - C_S} \text{ and } W_L = \frac{C_0 - C_S}{C_L - C_S}$$

**Exercise 35.** By looking at the Cu-Ni phase diagram in **Phases** how are the copper and nickel atoms arranged in the solid phase. What does the term solid solution mean?

**Answer.** This means that the atoms randomly substitute for each other within the crystal structure. The solubility depends on the similarity between the crystal structures of the components and their atomic radii among other things.



**Exercise 36.** In **Cooling paths**, looking at the eutectic phase diagram (Pb-Sn phase diagram), which of the five cooling paths contains the eutectic transformation? This transformation is isothermal, what does that mean?

**Answer.** Path 3 contains the eutectic transformation. Isothermal means that the transformation takes place at one single temperature. It is enough to cool the alloy to the eutectic temperature for the structure to completely transform from liquid to eutectic.

**Exercise 37.** Which of the three diagrams in *Cooling paths* contains a eutectoid point? When you cool eutectoid carbon steel (0.8wt%) what's the final solid microstructure called? Is this, strictly speaking, a phase?

**Answer.** Only the Steels (Fe-C) diagram contains a eutectoid point. The final solid microstructure of a eutectoid alloy is called Pearlite and it is not a phase. It's a mixture of two phases: ferrite and cementite.

**Exercise 38.** In the *Phase diagram datatable*, which one is not a binary metal alloy diagram? What's special about the components in this diagram?

**Answer.** The only phase diagram that doesn't represent a binary metal alloy is the  $\text{SiO}_2\text{-Al}_2\text{O}_3$  diagram. The components are ceramics and therefore compounds rather than pure elements.

## 5. Discovery with the Property-Process Profiles Data-table

Most mechanical properties and transport properties depend, to a greater or lesser degree, on microstructure. This means they can be manipulated by thermos-mechanical treatment. The Property-Process Profiles data-table contains a selected set of records for illustrating how properties change when materials are processed by alloying, working and heat treatment. The sets are:

1. Alloying and working: copper alloys
2. Heat treatment: carbon and low alloy
3. Alloying and heat treatment: stainless steels
4. Alloying and heat treatment: aluminum alloys
5. Filling and reinforcement: thermoplastic polymers
6. Powder processing: sintered ceramics
7. Foaming: polymers, metals, ceramics

**Exercise 39: Getting to know the Property-Process Profiles data-table.** Open the Alloying and working: copper alloys folder-level record. Double click on the name to reveal a summary of what the folder contains, what you can do with it and suggestions for projects.

The folder contains 3 sub-folders. Open Copper-Nickel alloys. The records in it illustrate, for 9 different composition of Cu-Ni, the way solid-solution hardening affects all the properties (not just the strength) of these alloys

Find the Thermal conductivity of 4 compositions: 32% Cu, 45% Cu 70% Cu and Pure Copper (the balance is nickel, of course). Which has the lowest Thermal conductivity?

**Answer.** The thermal conductivities are:

32% Cu: 22.8 (or 20-26) W/(m.K)

45% Cu: 20.2 (or 17.7-23) W/(m.K)

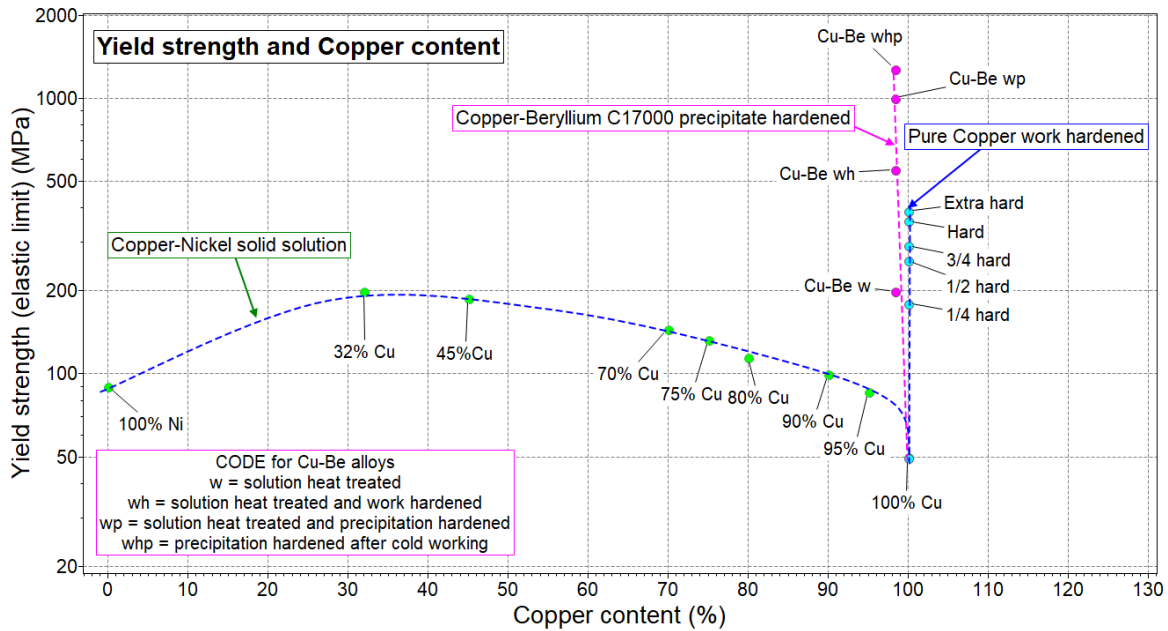
70% Cu : 22.4 (or 20-25) W/(m.K)

100% Cu: 381 (or 350-415) W/(m.K)

There is a minimum at 45% Cu. The solid solution has a dramatic impact on Thermal conduction of copper, reducing it from 381 to 20.2 W/(m.K).

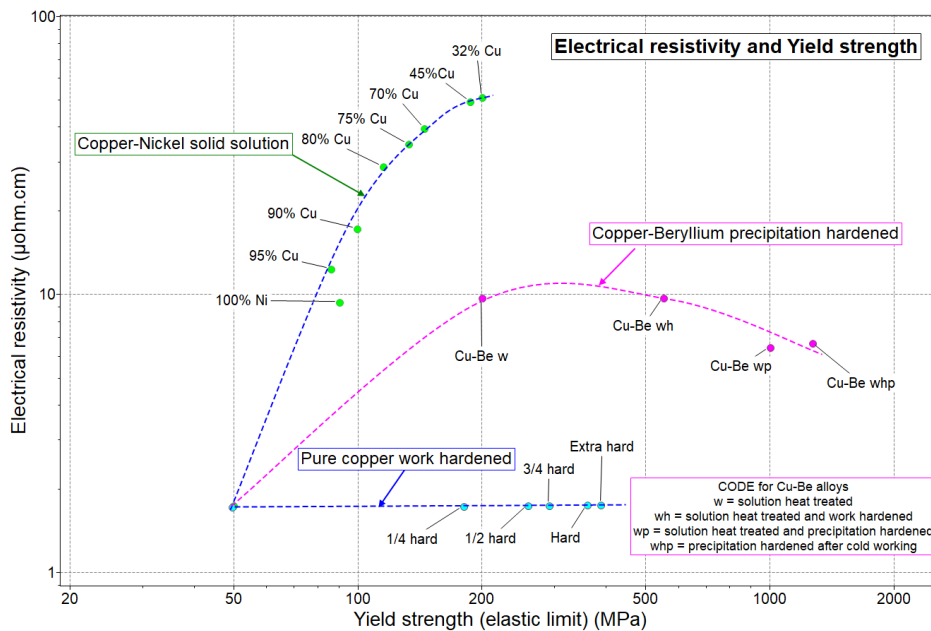
**Exercise 40: Copper alloys: strengthening mechanisms.** Copper can be strengthened by work hardening, solution hardening and precipitation hardening. Explore these using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table. To do so make a chart of Yield strength plotted against Copper content (chose a linear, not log, scale for the copper content). What are the characteristics of each strengthening mechanism? At what copper content is the strength contribution from solution hardening in Cu-Ni alloys a maximum?

**Answer.** Solution hardening in Cu-Ni alloys peaks at 200 MPa at about 30% copper / 70% nickel. It is less effective than work hardening (peak 370 MPa) or precipitation hardening (peak over 1000 MPa).



**Exercise 41: Copper alloys: trade-off between Conductivity and Strength.** Many applications require high electrical conductivity and strength. How much conductivity is lost when copper, an excellent conductor, is strengthened by work hardening, solution hardening and precipitation hardening? Find out by using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table to make a chart of Electrical resistivity against Yield strength.

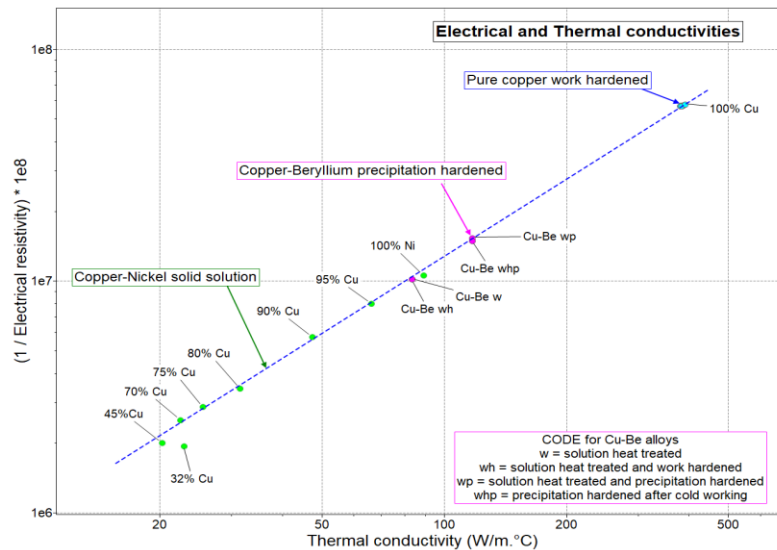
**Answer.** The chart shows the drastic increase in electrical resistivity caused by solid solution strengthening. Work hardening, by contrast, increases strength with no increase in electrical resistivity. Precipitation hardening gives the best compromise: the greatest increase in strength with only modest increase in resistivity.





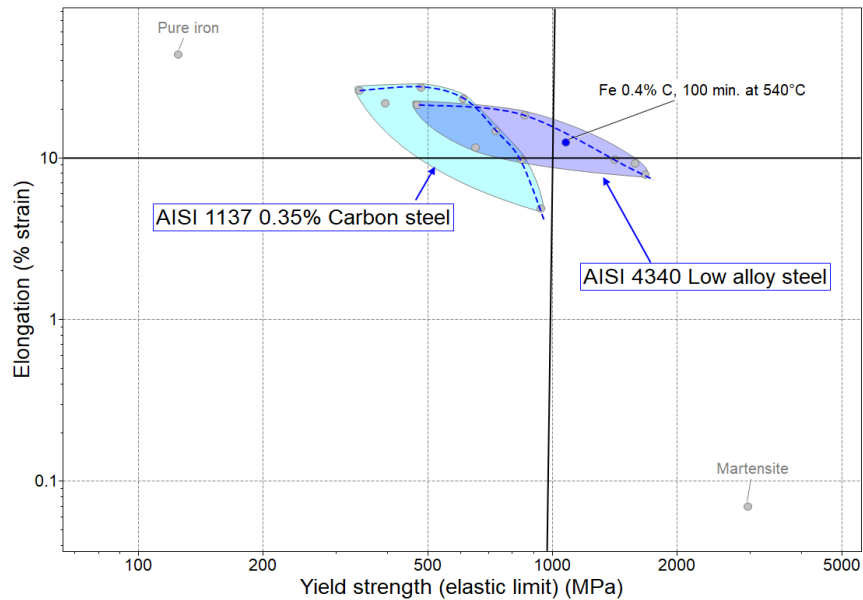
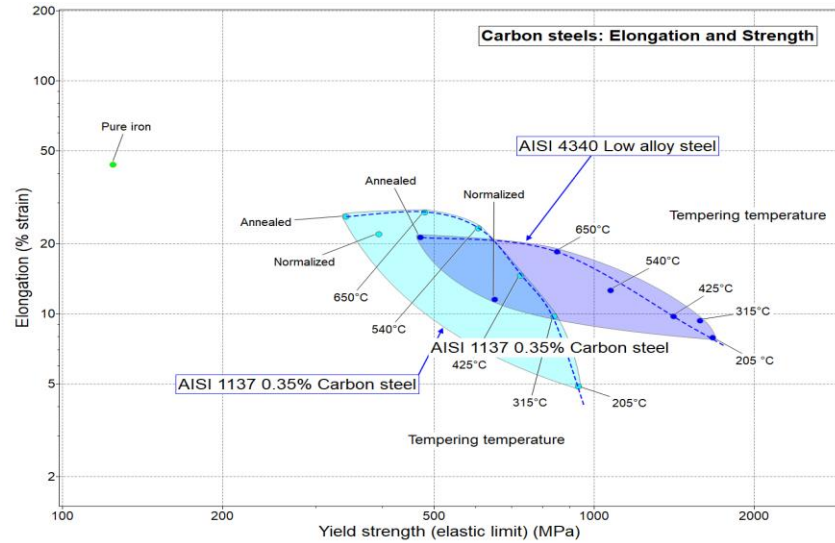
**Exercise 42: Relationship between Thermal and Electrical conductivity.** Electrical conductivity is easy to measure; thermal conductivity is much more difficult. If there were a reliable relationship between them the difficult measurement would not be necessary. Make a chart with Thermal conductivity on the x-axis and Electrical conductivity on the y-axis using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table. Make electrical conductivity in S/m by using the “Advanced” function to take the reciprocal of Electrical resistivity in micro-ohm.cm and multiplying it by  $10^8$ . A new copper alloy has an electrical conductivity of  $3 \times 10^7$  S/m. Use the chart to estimate its thermal conductivity?

**Answer.** Electrical and thermal conductivities are, to a good approximation, proportional (it is known as the Wiedemann-Franz law). An electrical conductivity of  $3 \times 10^7$  S/m corresponds to a thermal conductivity of more than 200 W/m.K.



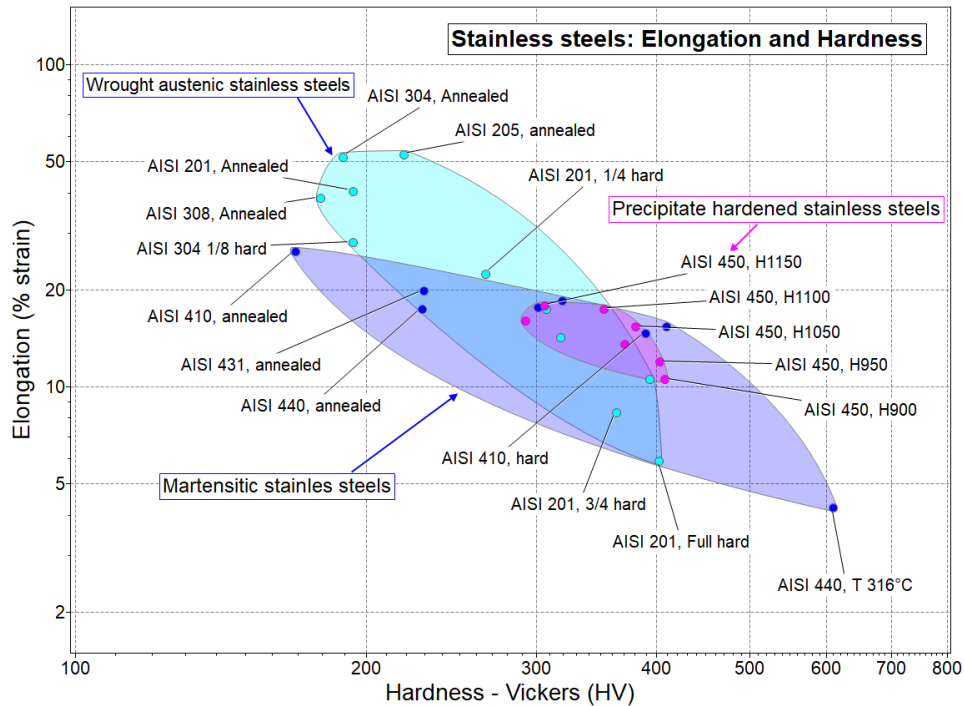
**Exercise 43: Tempering steel.** The properties of carbon and low alloy steels are manipulated by heating to the austenitizing temperature, quenching and tempering. The “Heat treatment of carbon steels” module of the Property-Process Profile data-table has data for the way in which all the properties of two steels change with tempering temperature (standard tempering time 30 minutes). Explore the trade-off between yield strength and elongation (ductility) for the two steels by making a chart with elongation on the y-axis and yield strength on the x-axis. A steel is sought with a strength above 1000 MPa and at least 10% ductility. Use the chart to select a composition and heat-treatment.

**Answer.** AISI steel quenched and tempered at 540°C provides the desired properties.



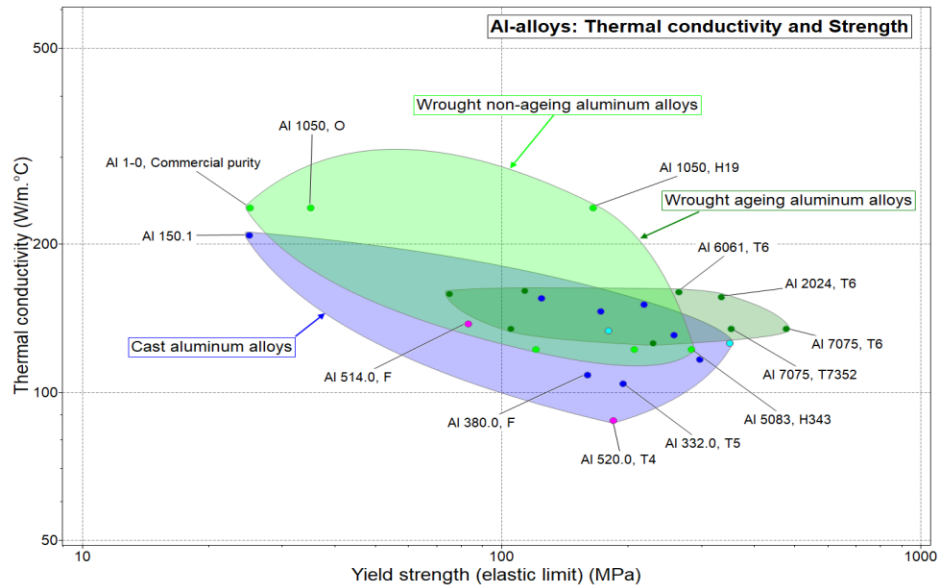
**Exercise 44: Stainless steels: Elongation and Hardness.** Explore the relationship between the elongation (important for metal forming) and the hardness (important as a cause of tool wear) for stainless steels. Use a plot of elongation against hardness using the “Alloying and heat treatment: stainless steels” module of the Property-Process Profiles data-table to select the five stainless steels look most attractive for making a deep-drawn shape from sheet. Which class do they belong to (Austenitic, martensitic, precipitation hardened)?

**Answer.** The five stainless steels with the greatest elongation and the lowest hardness are the austenitic AISI 304, AISI 205, AISI 308, AISI 201 and the martensitic AISI 410 (although its elongation is only half that of the others).



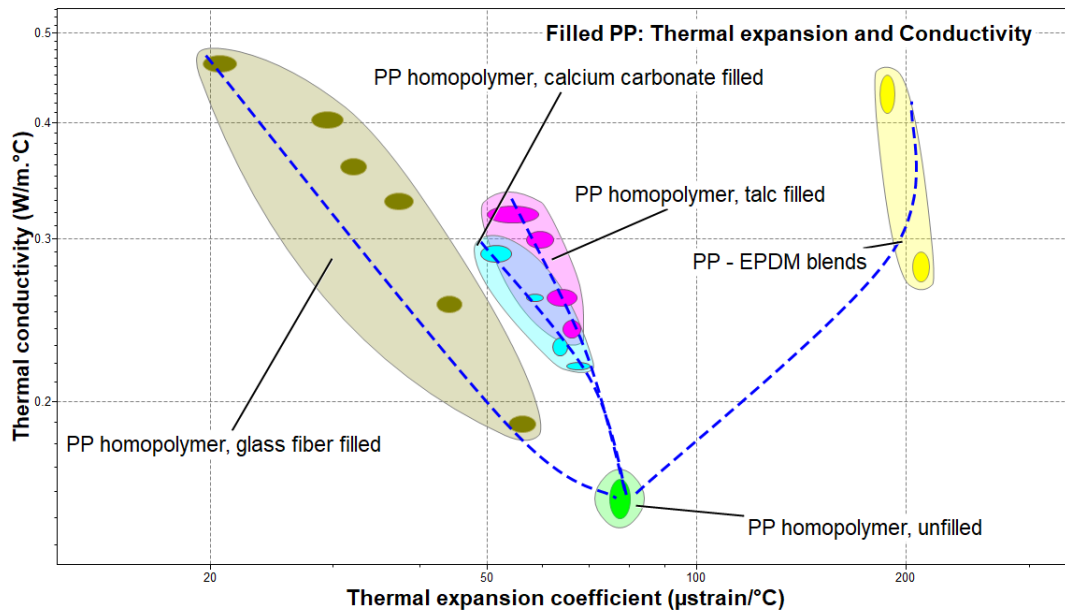
**Exercise 45: Aluminum alloys: Thermal conductivity and Strength.** Like copper alloys, aluminum alloys can be strengthened by work hardening, solution hardening and precipitation hardening. As always, there are trade-offs. Increasing strength tends to reduce elongation, toughness and thermal and electrical conductivities. An aluminum alloy is sought for the heat-exchanger of a domestic air-conditioning unit. Good thermal conductivity is essential, but since the unit is pressurized, a strength of at least 100 MPa is specified. Use the “Alloy and heat treatment: aluminum alloys” module of the Property-Process Profile data-table to make a chart with Thermal conductivity on the y-axis and Yield strength on the x-axis and use it to select a candidate for the job.

**Answer.** The chart shows the trends for wrought and cast aluminum alloys distinguishing between those that age-harden and those that don't. One alloy meets the requirements Al 1050 H19 – almost pure aluminum, heavily work-hardened.



**Exercise 46: Filled polypropylene: Thermal conductivity and Expansion.** Fillers such as talc, calcium carbonate and glass are added to polymers to increase stiffness and strength. But what do fillers do to the thermal properties of polymers? Use the “Filling and reinforcing: thermoplastic polymers” module of the Property-Process Profile data-table to make a chart with Thermal conductivity on the y-axis and Thermal expansion coefficient on the x-axis. Use linear scales for both. What trends are observable?

**Answer.** Three fillers (glass fiber, talc, and calcium carbonate) reduce thermal expansion and increase thermal conductivity while EPDM blends increase both thermal conductivity and thermal expansion. Glass fibers have the greatest effect, reducing expansion by up to factor of 4 and increasing conductivity by a similar factor.

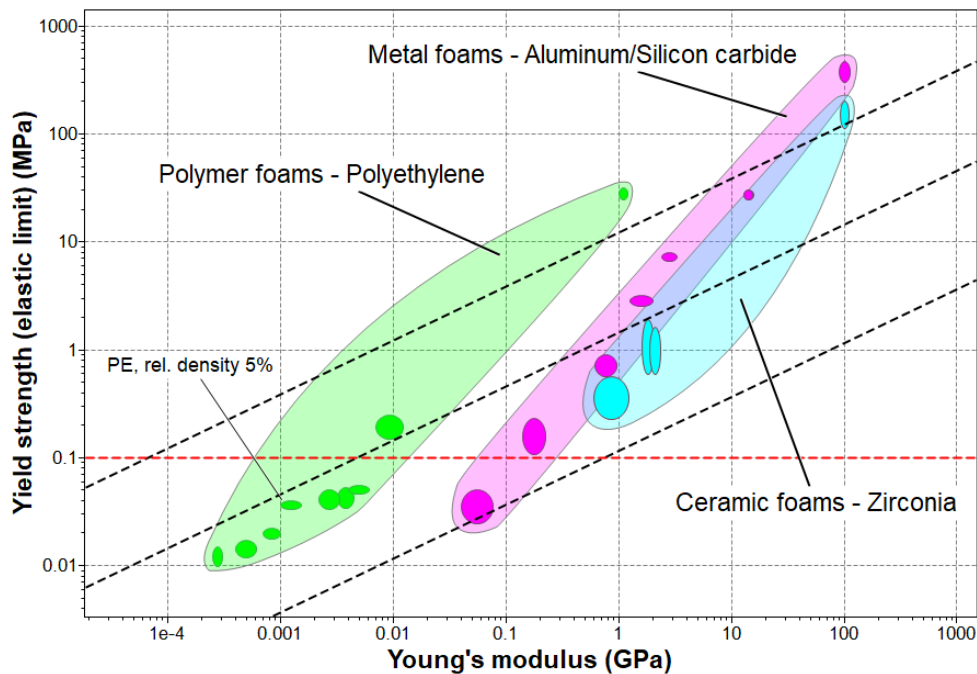


**Exercise 47: Foams: energy absorption.** Foams crush when compressed, absorbing energy. Two properties are important in choosing protective foams for energy absorption: the energy  $U$  absorbed per unit volume

$$U = \frac{1}{2} \frac{\sigma_y^2}{E} \text{ J/m}^3,$$

where  $E$  is Young's modulus, and the stress  $\sigma_y$  at which the crushing takes place because this determines the forces exerted on object that is being protected. Use the "Foaming: polymers, metals, ceramics" module of the Property-Process Profiles data-table to select a foam with a crushing strength below 0.1 MPa and the largest possible energy absorption. To do so make a chart with Young's modulus  $E$  on the x-axis and the Yield strength  $\sigma_y$  on the y-axis. Plot parallel lines (contours) of energy absorption  $U$  onto the chart (they are a family of parallel lines with a slope of 0.5 on a log-log scale). Then select a foam that best meets the design criterion.

**Answer.** The chart is shown below. Contours of  $U$  have been added using the "Index and display lines" tool. The required upper limit on crushing stress is marked. The foam that lies below this limit and has the greatest value of  $U$  is the Polyethylene foam with a relative density of 5%. It is able to absorb almost 1 kJ/m<sup>3</sup>.



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