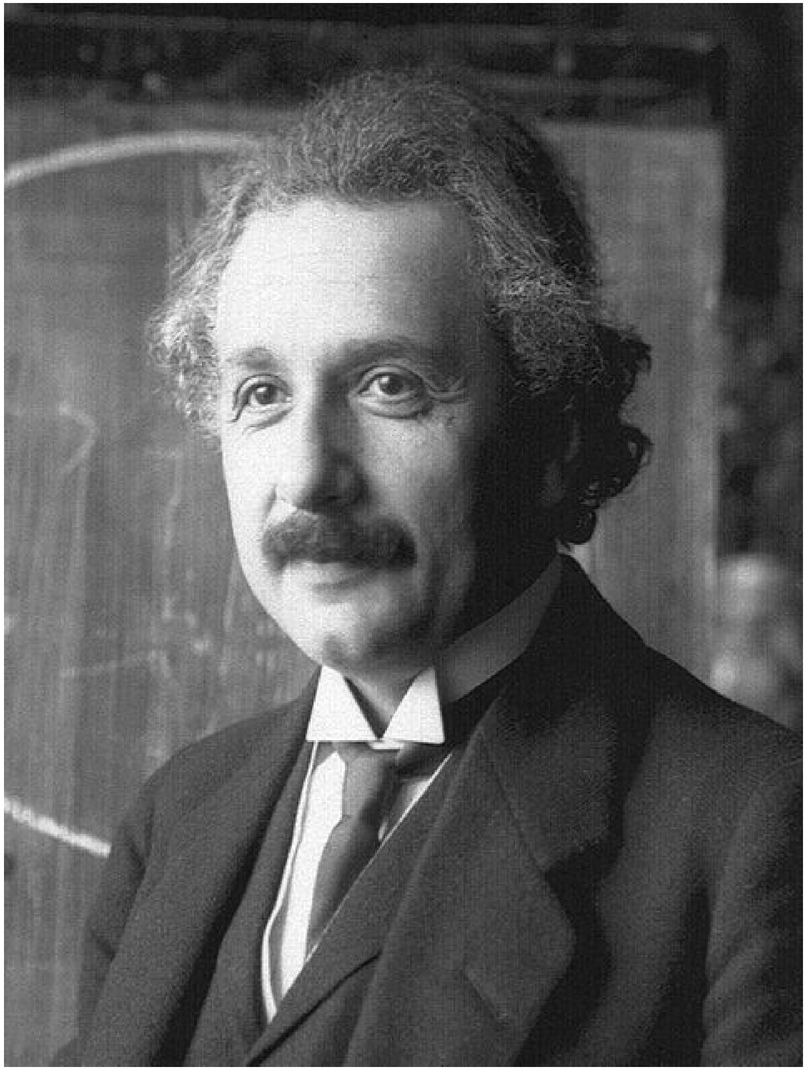
AML 883 Properties and selection of engineering materials

LECTURE 16. Origins of thermal properties and their manipulation

M P Gururajan
Email: guru.courses@gmail.com
Room No. MS 207/A-3
Phone: 1340

Heat capacity

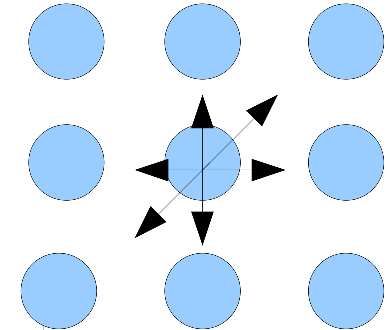


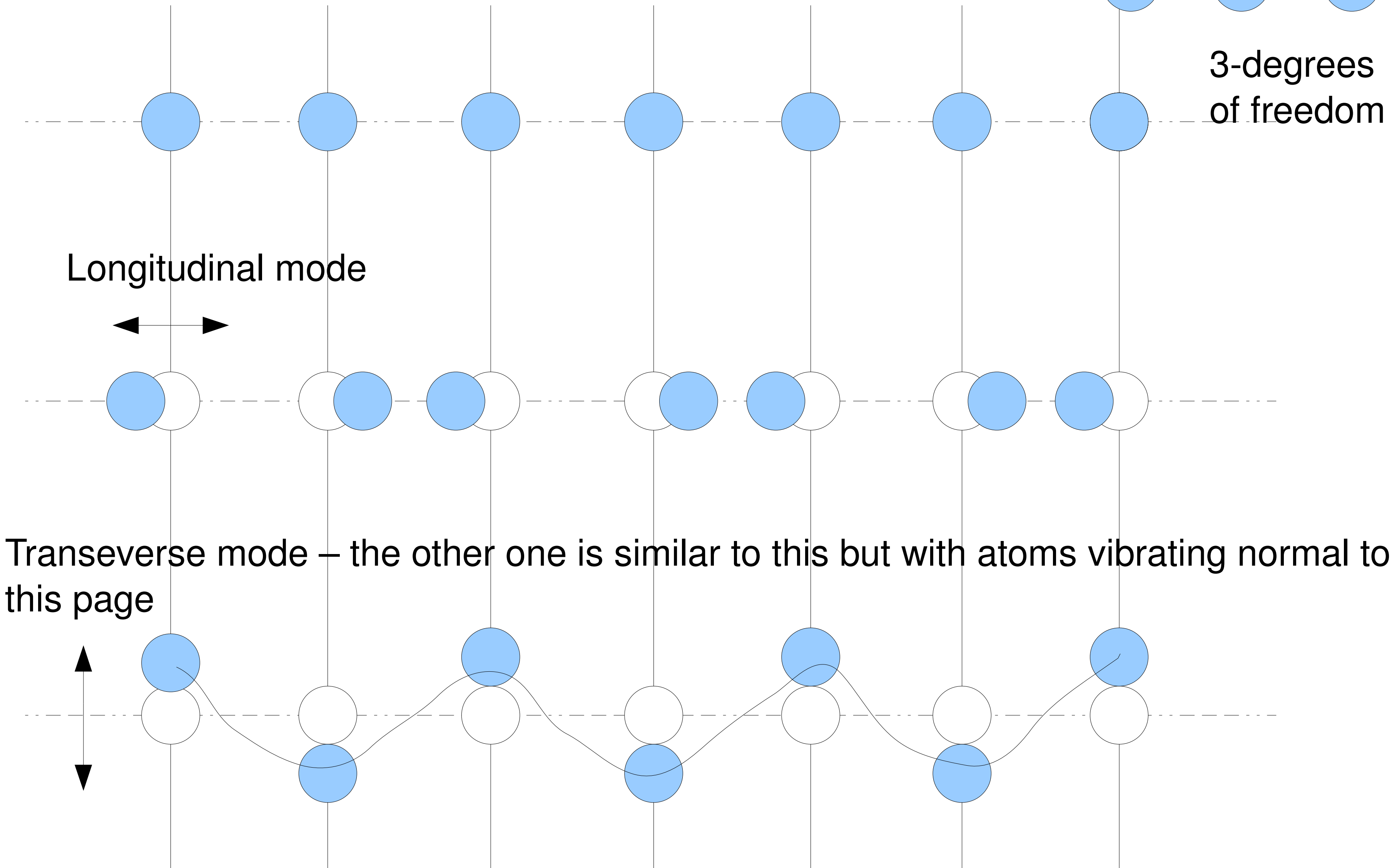
Einstein and Debye: Images – courtesy: Wiki

Heat Capacity

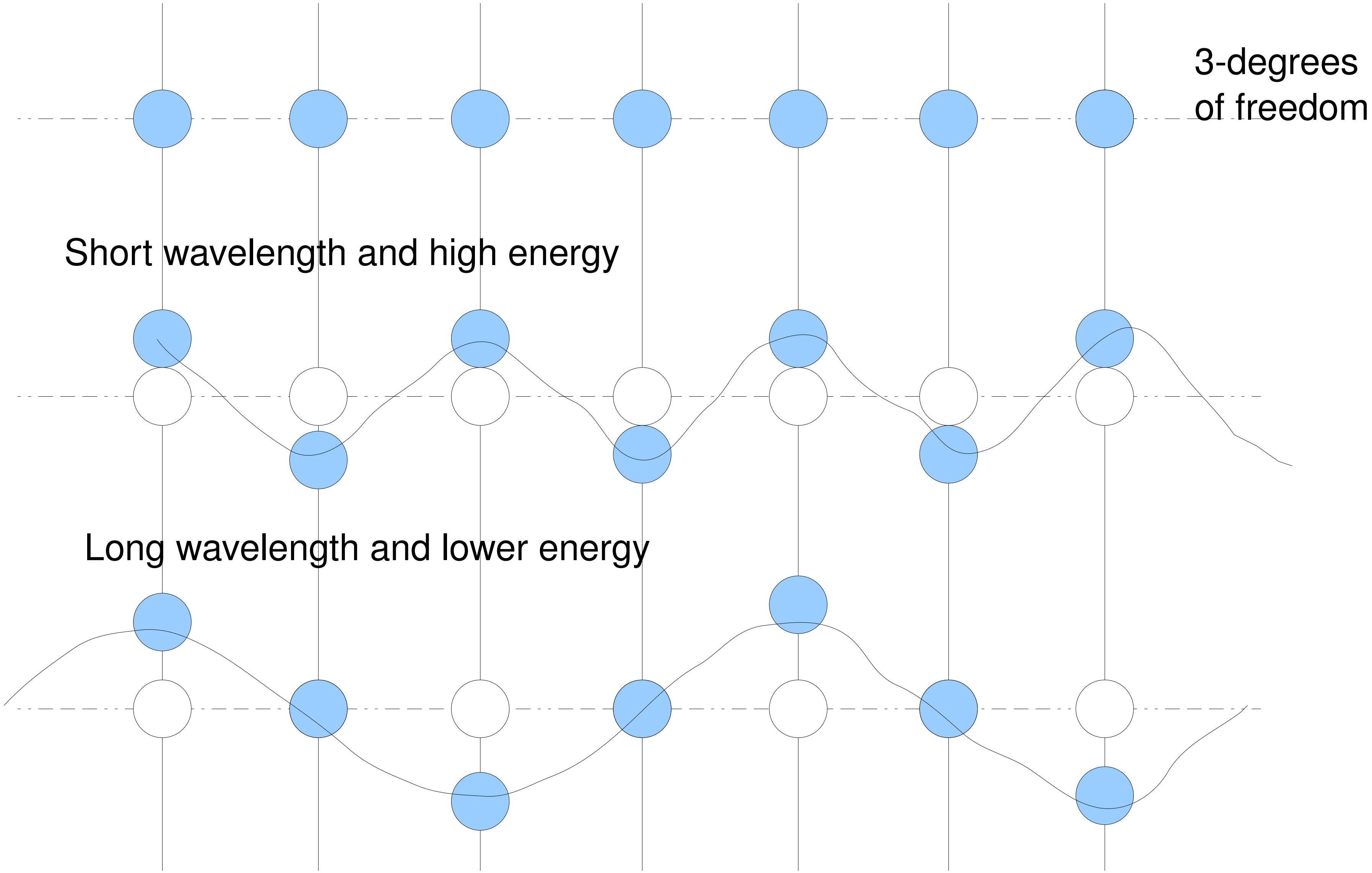
- Heat – atoms in motion
- Atoms in solid – vibrate about their mean position
- Increasing T, amplitude of vibration increases
- Atoms in solids – can't vibrate independently of each other – coupled to each other by bonds
- Vibrations – like standing elastic waves

Vibrational modes





Vibrational modes



Vibrational modes

- Along any row, there are two transverse modes and one longitudinal mode
- Some have short wavelengths – what is the shortest wavelength?
- Some have long wavelenths
- Energies are inversely proportional to wavelength

Vibrational modes

- Solid with N atoms – each atom has three modes
- Total – 3N modes
- Amplitudes of vibration – such that each mode has an energy kT where “k” is the Boltzmann constant and T is the absolute temperature

Boltzmann

Boltzmann and his grave with the entropy formula: images – courtesy: Wiki

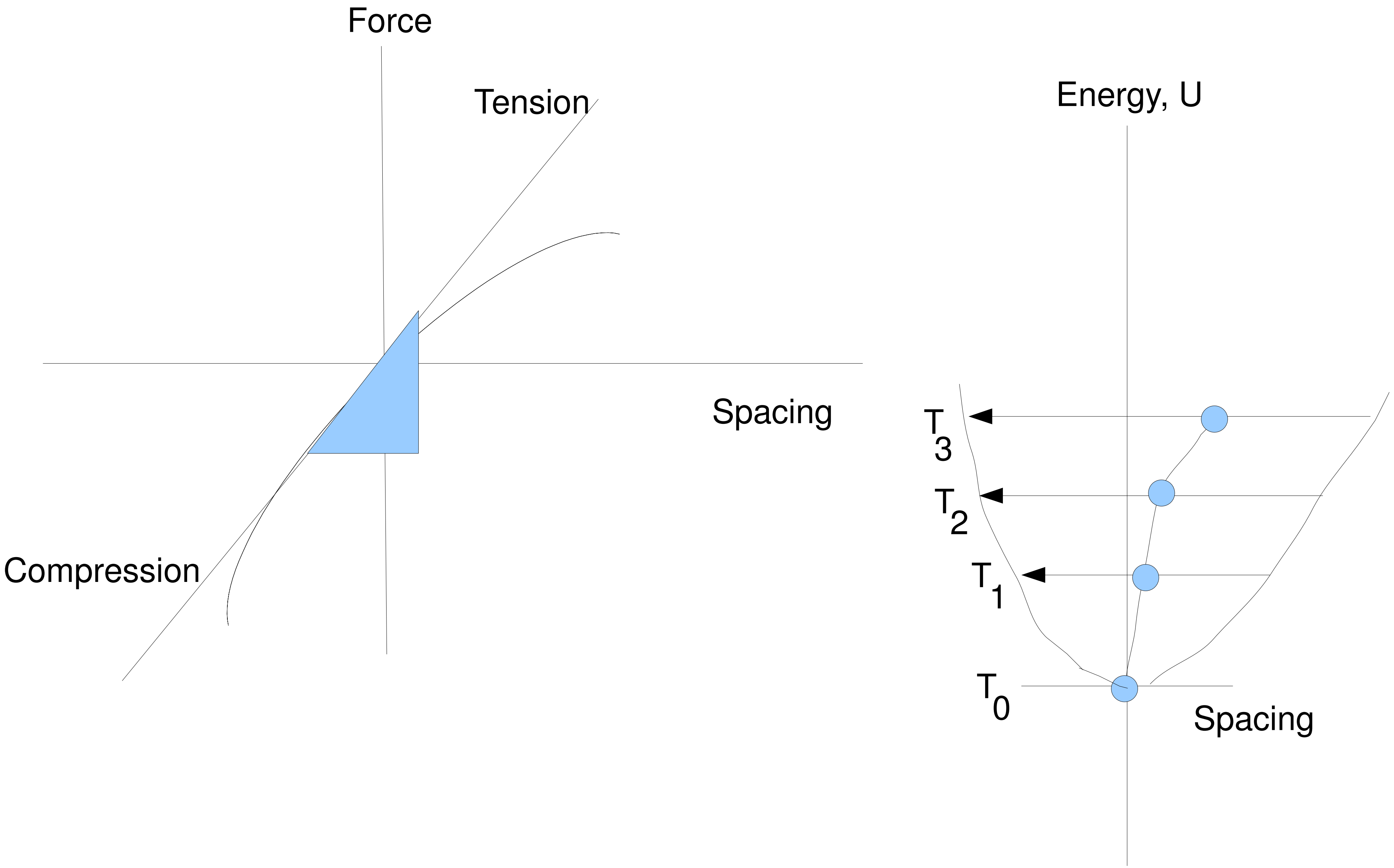
Heat capacity

- Assume that the volume occupied by an atom is Ω
- The number of atoms per unit volume is then $(1/\Omega)$
- Total thermal energy per unit volume is then $3kT/\Omega$
- Heat capacity per unit volume ρCp is the change in this energy per kelvin change in temperature: $\rho C_p = 3\mathrm{k}/\Omega$ J/cubic metre K

Heat capacity

- Heat capacity per unit volume ρCp is the change in this energy per kelvin change in temperature: $\rho C_p = 3\mathrm{k}/\Omega$ J/cubic metre K
- Since atomic volumes do not vary much, ρCp is approximately a constant
- This is indeed the case: see Fig. 12.5 of the textbook

Thermal expansion



Thermal expansion

- Solids – expand on heating since the atoms are moving apart
- Force-spacing curve – not a straight line but curved
- Bonds are less stiff when atoms are pulled apart
- Atoms oscillate about a mean position which is farther and farther apart as the T increases
- Thermal expansion – non-linear effect; if bonds were linear, there would be no expansion

Thermal expansion

- Stiffer the spring – steeper the force-displacement curve – narrower the energy well of the atom – less scope for expansion
- Materials with a high modulus – low expansion coefficient $\alpha = 1.6\text{x}10^{-3}/E$
- Empirically, all solids expand by the same amount when heated from absolute zero to their melting point

$$\alpha \simeq 0.02/T_m$$

Thermal expansion

$$\alpha = 1.6\text{x}10^{-3} / E$$

$$\alpha \simeq 0.02 / T_m$$

$$E \simeq c\,T_m$$ “c” = a constant

Thermal conductivity

- Heat transmission in a solid – by thermal vibrations, by the movement of free electrons in a solid, and, if transparent, by radiation
- Transmission of thermal vibrations – involves propagation of elastic waves
- Heating a solid – heat energy enters as elastic wave packets – phonons
- Phonons – travel through the material with the speed of sound

Thermal conductivity

- Even though phonons travel with the velocity of speed, heat does not diffuse at the same speed. Why?
- Phonon scattering
- Mean free path of phonons – less than 0.01 μm
- Calculation of conductivity: net flux model – difference between the rate of entry and the rate of leaving of phonons per unit area (Derivation – left as an exercise)

Thermal conductivity

$$\lambda = (1/3)\rho C_p l_m c_0$$

Thermal conductivity

- Why does sound waves travel through the bar without scattering
- Waves are scattered by objectes of the same size or bigger
- Sound waves – wavelength is typically in metres
- Wavelengths of phonons – of the order of two atomic spacings

Pure metal conductivity

- Phonon contribution – very less in copper and aluminium, for example
- Free electrons in metals carry heat rapidly
- Same equation as earlier – however, the specific heat capacity, velocity of waves and the mean free path correspond to electrons
- Free electrons also conduct electricity – Wiedemann-Franz law

Manipulating thermal expansion

- Expansion – like modulus and melting point is little amenable to manipulation
- Exception – Invar
- Why?
- Already noticed the role of phase transitions and transformations – thermal buffer and super-elastic
- Invar – is another example!

Invar story – Ni-Fe alloys

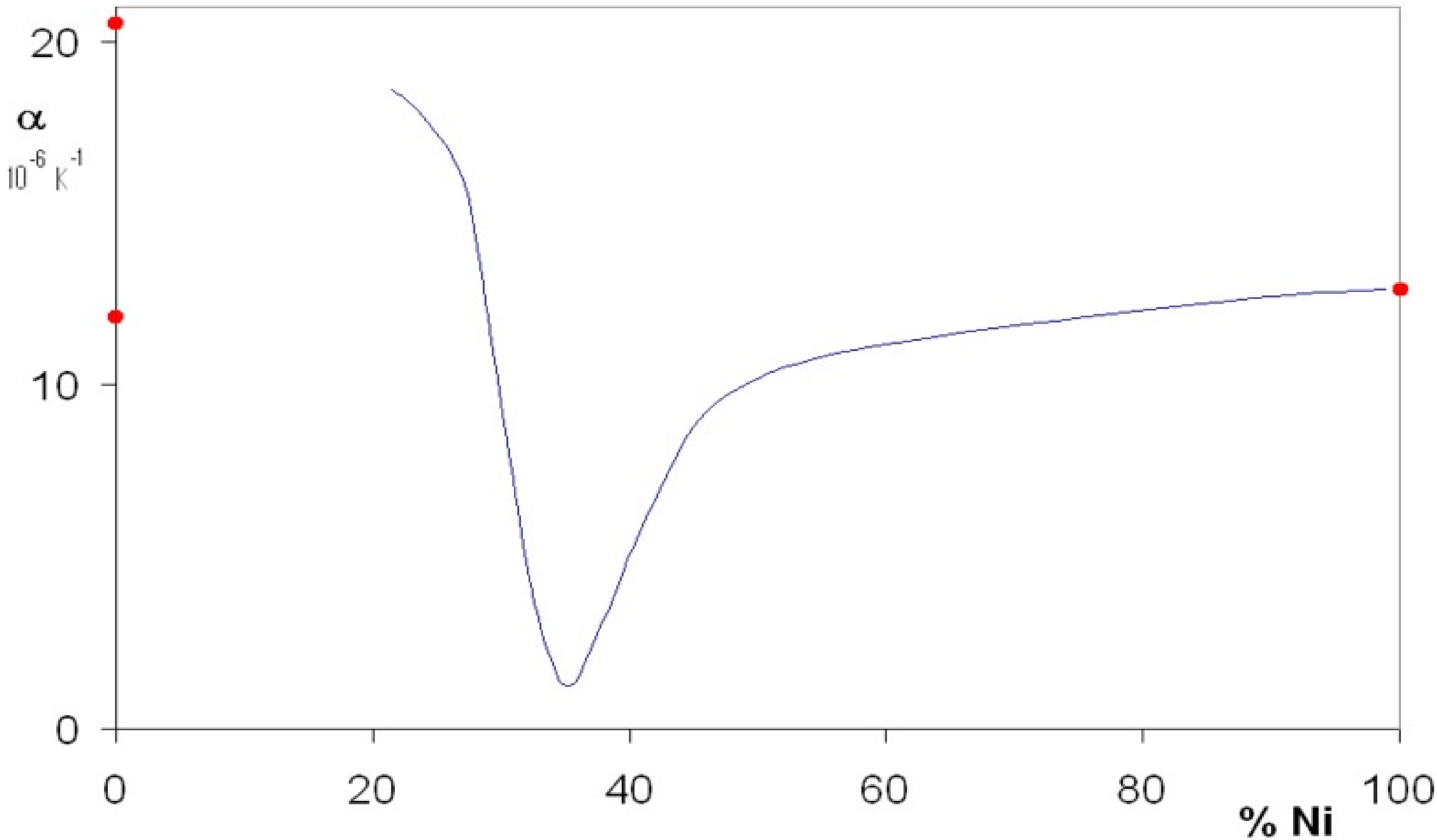


Image courtesy: wiki

Invar story

Charles-Edouard Guillaume

Image courtesy: wiki

Invar story

Charles-Edouard Guillaume, ... in 1896 discovered an iron-nickel alloy which had effectively zero coefficient of thermal expansion near room temperature, and eventually ... tracked this down to a loss of ferromagnetism near room temperature, which entails a 'magnestostrictive' contraction that just compensates the normal thermal expansion.

Invar story

This led to a remarkable programme of development in what came to be known as 'precision metallurgy' and products, 'Invar' and 'Elinvar' which are still manufactured on a large scale today ... Guillaume won the Nobel Prize for Physics in 1920, the only such prize ever to be awarded for a metallurgical achievement.

-- R W Cahn, *The coming of materials science*

Thermal conductivity and heat capacity

- Thermal conductivity:

$$\lambda = (1/3)\rho C_p l_m c_0$$

Almost a constant

Only manipulatable: alloys and glasses have low thermal conductivity – by virtue of their having scattering centres – large number of them

$$c_0 \simeq \sqrt{E/\rho}$$

Note: density can be manipulated – foamy materials take advantage of low conductivity air trapped in

Strengthening mechanisms

- Solid solution and precipitation hardening – reduce conductivity
- Work hardening – strengthens significantly without changing the conductivity much. Why?