AML 883 Properties and selection of engineering materials

LECTURE 15. Thermal properties of materials

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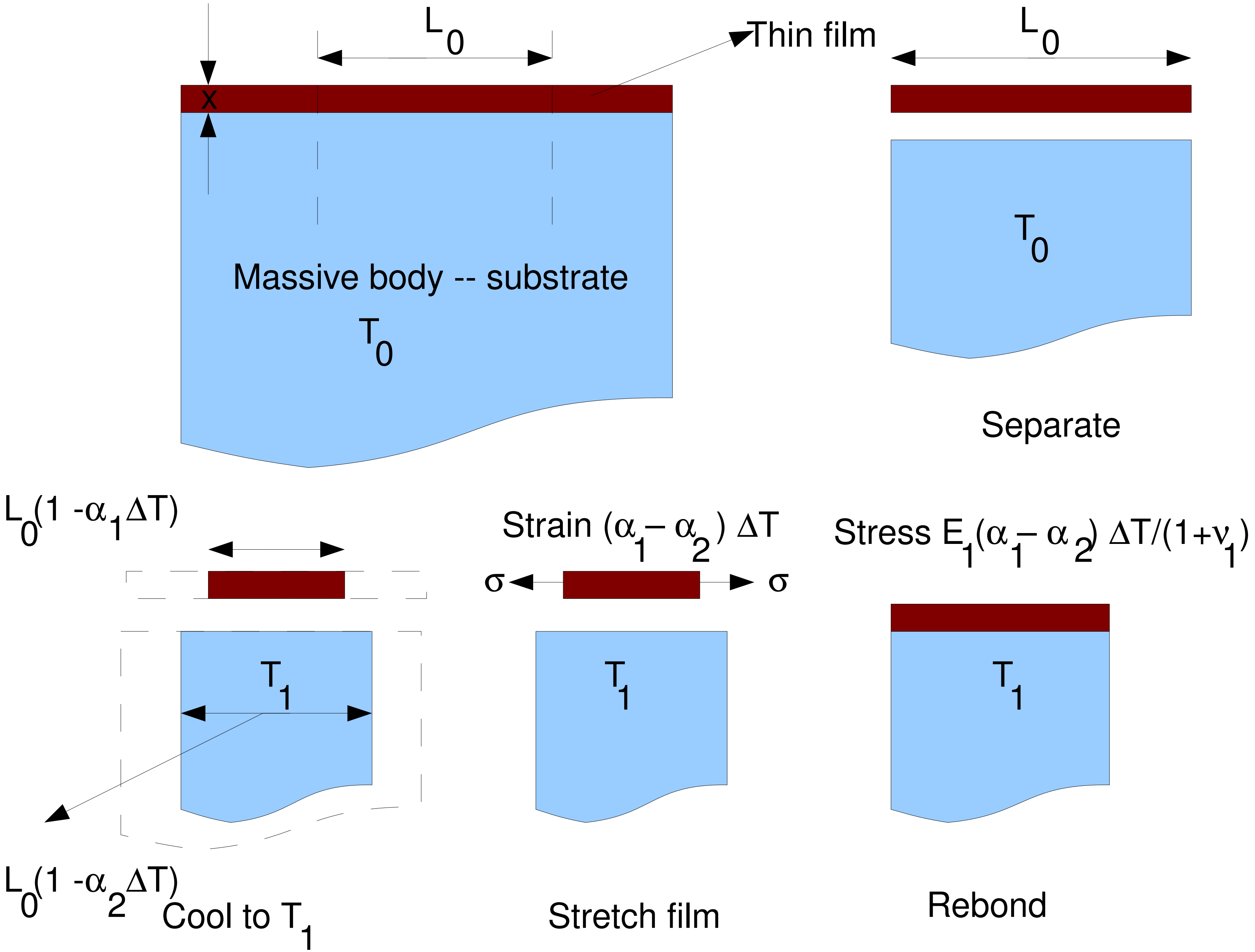
Thermal stress

- Thermal distortion is a common phenomenon: doors jam; bearings seize; overhead tranmission lines sag; railway tracks bend and buckle in exceptionally hot weather.
- Equipment design for making high-performance computer chips, for example: loss of accuracy due to changes in temperature makes it very difficult task
- Why thermal distortion?

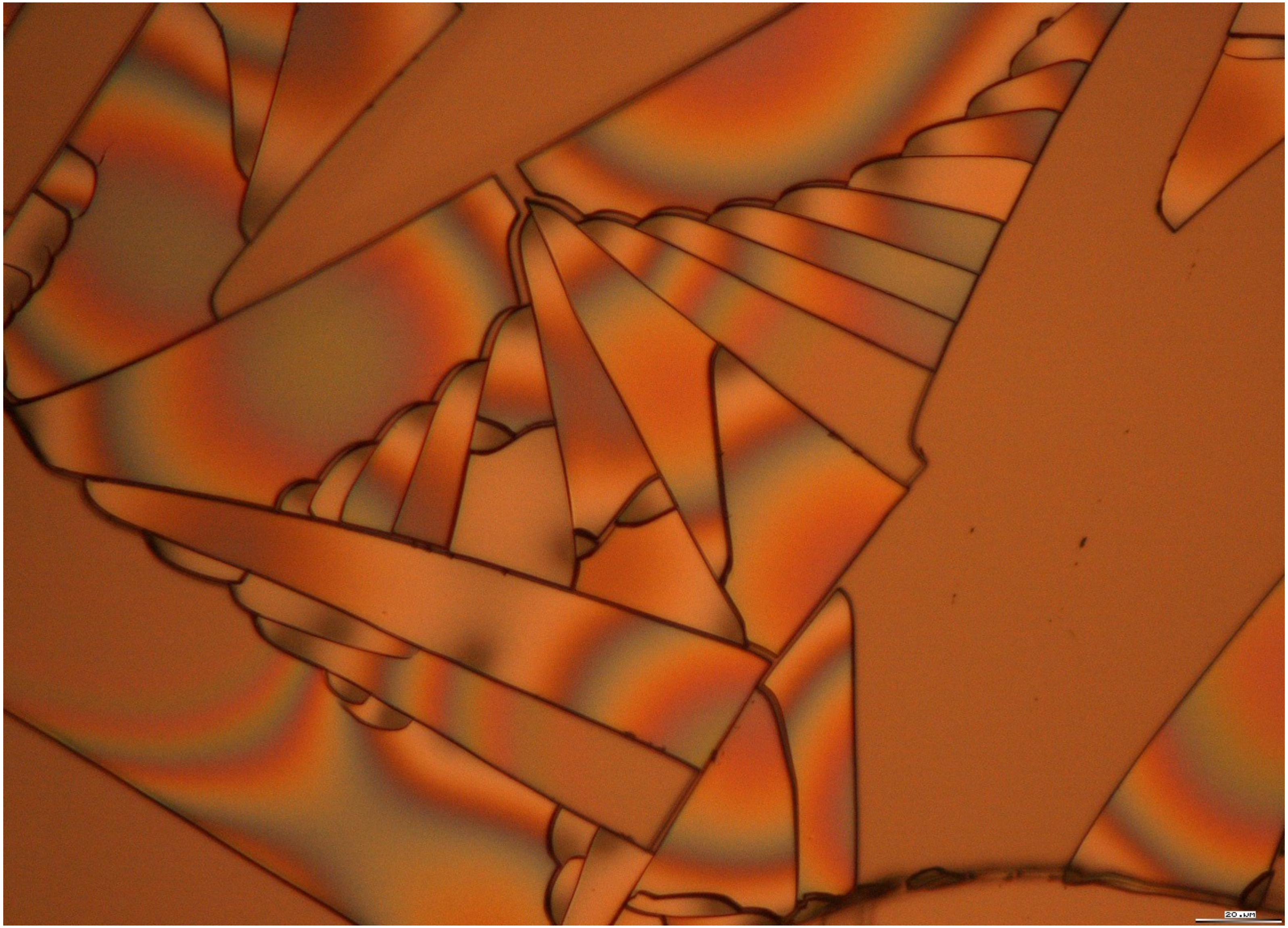
Differential thermal expansion

- Mismatch between the thermal expansion of two materials – if there be constraints, results in stresses
- Suppose, we give a thin layer coating to a component (to impart wear resistance, or resistance to corrosion, or oxidation)
- Deposition – typically at high T
- On cooling, the substrate and film shrink by different amounts – leading to stress
- How to calculate this residual stress?

Thermal stresses in thin films



Stress cracking of thin films



Optical micrograph of cracked silica film on silicon substrate – U Mich homepage

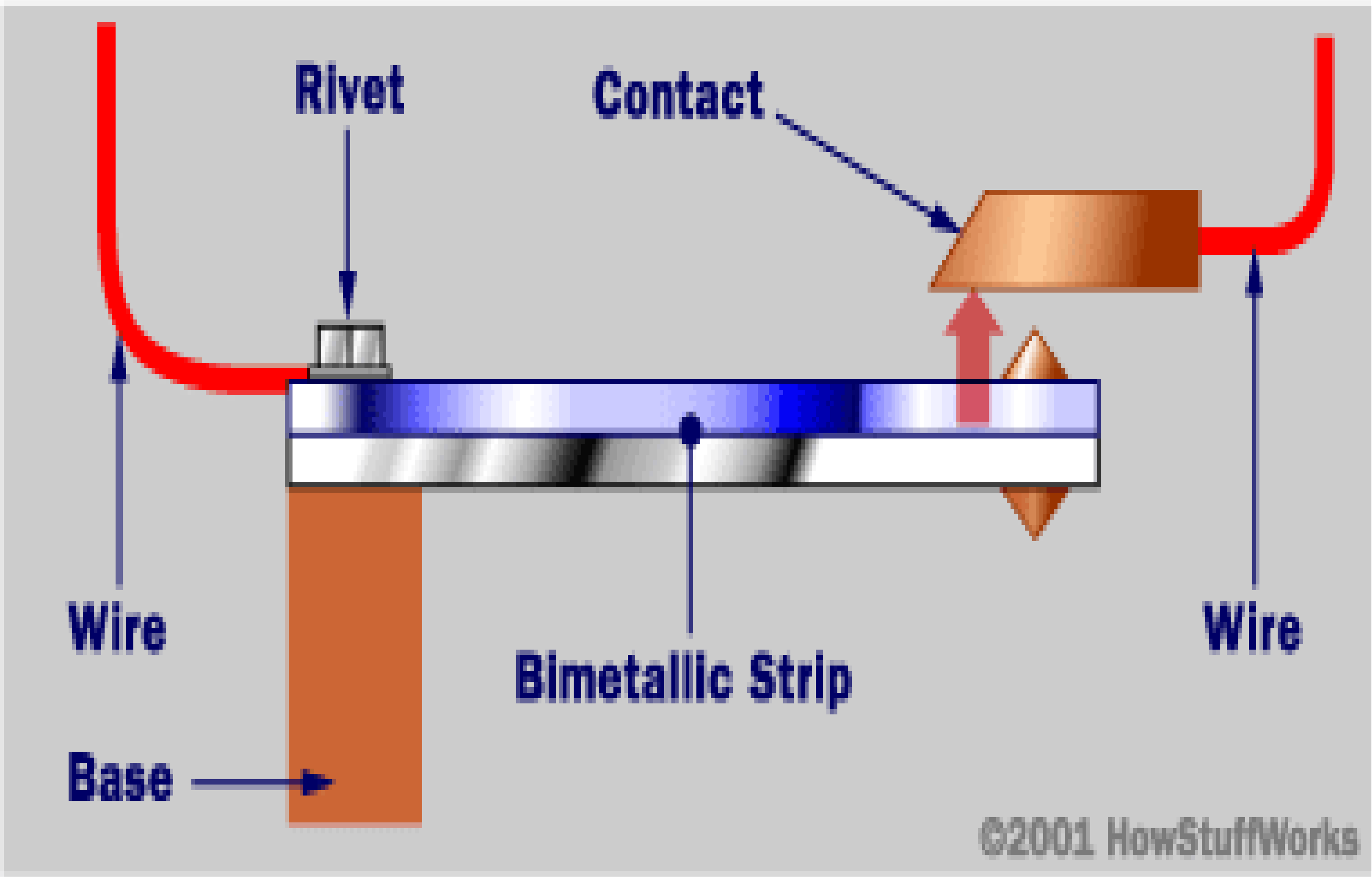
Stress cracking of thin films

- Stress can be large enough to crack the surface film
- Car windows on steel frame, say: mismatch could be a factor of four or five
- Put a compliant material in between – rubber, for isntance
- Not always possible – put a layer or layers so that the expansion coefficients change gradually – case study of thermal barrier coatings

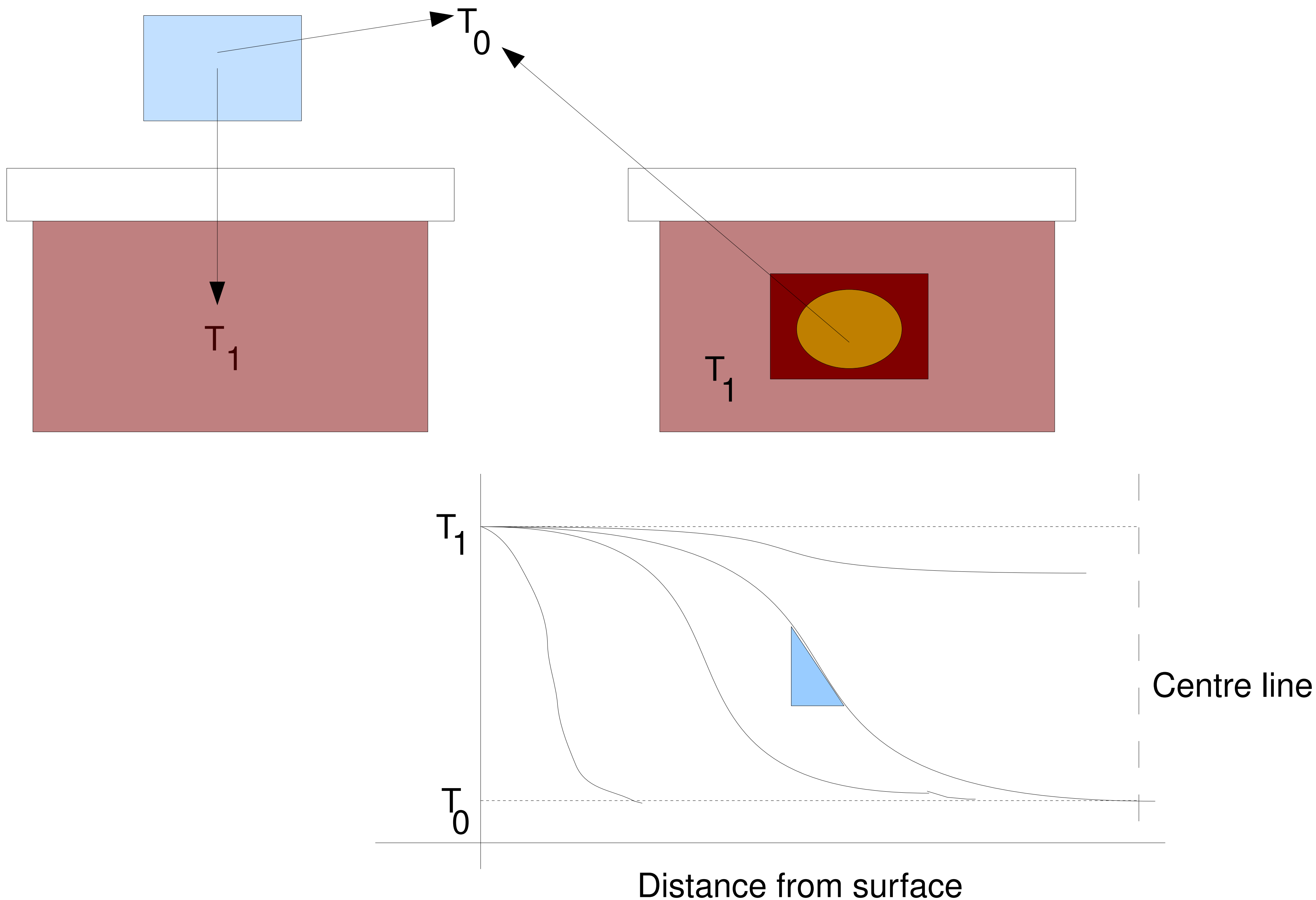
Thermal sensing and actuation

- Thermal expansion can be used to sense (measure temperature) and to actuate)open or close valves or electric circuits)
- Bi-material strips – strips of two materials with different expansion coefficients in specific geometry to accentuate the small thermal displacement so that temperatures can be accurately measured

Bimetallic sensor and actuator



Thermal gradients



Shock resistance

- Temperature gradient (even in a material with a single expansion coefficient) can lead to sresses – Glass toughening, for example
- Stresses could be as high to cause fracture in brittle materials
- Thermal shock resistance (in K or degree C) is the maximum sudden change of temperature to which such a material can be subjected without damage

Image courtesy: Biographical memoirs of FRS

- J D Eshelby
- Stresses due to transformational strains, dislocations, fracture, ...
- Well versed in Sanskrit, lover of old books
- Self-taught – no formal training
- A story about why he did not do experiments: Alex King – MRS Bulletin

Distortions due to thermal gradients

- While heat front diffuses in, temperature gradient gives rise to thermal stresses
- Material remains elastic -- after uniform heating has been achieved, the stresses fade away
- If the material partially yields, stresses never go away – surface yielded and centre hasn't
- Residual stress – a major problem
- Time – important variable – how long to cool?

Thermal diffusivity

- Time is determined by thermal diffusivity
- Bigger the conductivity, faster the diffusivity
- However, larger the heat capacity per unit voume, more heat has to diffuse in out out of unit volume to change the temperature

$$a = \lambda / (\rho C_p)$$

Thermal diffusivity

- The characteristic distance “x” metres that heat diffuses in time “t” seconds is related by an (approximate) formula:

$$x^2 \simeq 2at$$

- Choosing materials: low expansion and high conductivity

Conduction with strength

- Heat exchanger – typically, one of the fluids is under pressure
- Heat conduction – efficient if the walls are thinner
- Strength of wall – better if it is thicker
- What is the material index?
- Derivation is left as an excercise
- Answer: $\lambda \sigma_y$
- Metals and some ceramics: metals because can be shaped into thin walls easily

Insulation

- Central heating and air-conditioning costs energy
- Good insulation can save you lots of money!
- For a given wall thickness, power consumption is minimized by choosing materials with the lowest possible conductivity
- Foams!
- Maximum service temperature: metals foams
- Still higher temperature: ceramic foams

Storage heaters

- Demand of electricity: high during the day than night
- Not economic for electricity companies to reduce output
- Charge less for off-peak electricity
- Storage heater – to expolit this – Use cheap eelctricity, heat a large block of material, and, later extract heat from it by blowing air over it!
- More technical roles also – simulation of re-entry vehicles and supersonic aircraft

Storage heaters

- What is the material index?
- Material (of lowest cost) with the largest heat capacity that can withstand the operating temperature!

Change of phase as thermal buffer

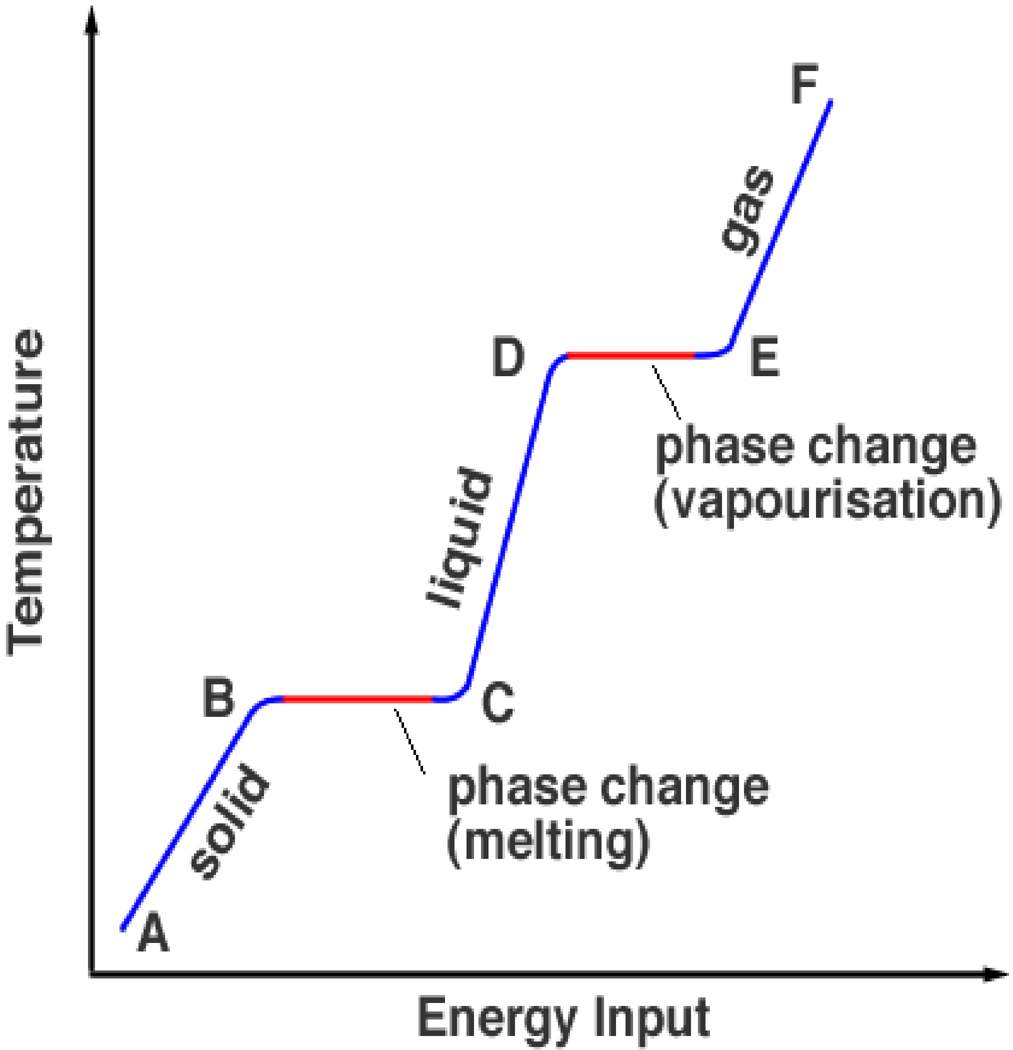


Image courtesy: Splung.com

- Keep something at fixed temperature without external power
- Use the fact that the latent heat of fusion or melting either absorbs or gives heat at constant temperature

Shape memory!

- Super-elastic materials
- Shape-memory materials – Distort the material; it changes phase; below critical temperature, retains the shape with enormous ditortion; above critical temperature, structure reverts back to original structure and hence original shape!
- What if room temperature is above the critical temperature?

Super-elasticity

- Say, you sit on an eyeglass frame, by mistake
- As soon as you get up, it goes back to original shape!
- Super-elastic – since strained to 100% or more, springs back to original shape!

Thermal properties

- Themal expansion
- Thermal conductivity
- Thermal diffusivity
- Specific heat capacity
- Along with density, yield strength, ... can be made use of in materials property charts to choose materials for applications – many of which, we spoke about

Whither?

- What are the origins of thermal properties?
- How do we manipulate them?