ENGG103 – Materials in Design
Dr Ciara O'Driscoll

UNIVERSITY
OF WOLLONGONG
IN DUBAI

University of Wollongong in Dubai

ENGG103 – Materials in Design

Week 9: Lecture 9 – Thermal properties

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Consultation hours:

Tuesday 12:30 – 14:30

https://uow.webex.com/meet/ciara

Please email first for appointment.

Chapter 19:
Thermal Properties

ISSUES TO ADDRESS...

- How do materials respond to the application of heat?
- How do we define and measure...
  - -- heat capacity?
  - -- thermal expansion?
  - -- thermal conductivity?
- How do the thermal properties of ceramics, metals, and polymers differ?

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Lecture 10: Distance Learning Resources folder – 1. Specific Heat Capacity

Heat Capacity

The ability of a material to absorb heat

- Quantitatively: The energy required to produce a unit rise in temperature for one mole of a material.

heat capacity (J/mol-K)

$$C = \frac{dQ}{dT}$$

energy input (J/mol)

temperature change (K)

- Two ways to measure heat capacity:

  C_p : Heat capacity at constant pressure.
  C_v : Heat capacity at constant volume.

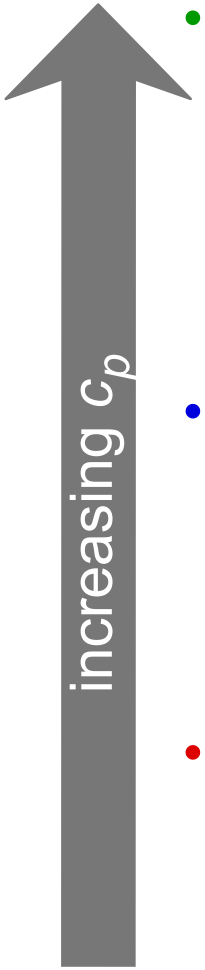
  C_p usually > C_v

Specific Heat capacity

$$C = \left(\frac{Q}{m * \Delta T}\right)$$

- Heat capacity has units of $\frac{\text{J}}{\text{mol} \cdot \text{K}} \left(\frac{\text{Btu}}{\text{lb} - \text{mol} \cdot {}^\circ\text{F}}\right)$

Specific Heat: Comparison



Material	c_p (J/kg-K) at room T
• Polymers	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
• Ceramics	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
• Metals	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

c_p (specific heat): (J/kg-K)

C_p (heat capacity): (J/mol-K)

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Properties – Specific heat

- **Metals** tend to have very low values. This means that they heat up quickly and cool down quickly; they also tend to expand significantly as they get

Substance	c/J kg^{-1} K^{-1}	Substance	c/J kg^{-1} K^{-1}
Aluminium	900	Ice	2100
Iron/steel	450	Wood	1700
Copper	390	Nylon	1700
Brass	380	Rubber	1700
Zinc	380	Marble	880
Silver	230	Concrete	850
Mercury	140	Granite	840
Tungsten	135	Sand	800
Platinum	130	Glass	670
Lead	130	Carbon	500
Hydrogen	14000	Ethanol	2400
Air	718	Paraffin	2100
Nitrogen	1040	Water	4186
Steam	2000	Sea water	3900

$$\boxed{\begin{array}{c} Specific\ Heat\ capacity \\ C = \left(\dfrac{Q}{m * \Delta T}\right) \end{array}} \qquad {}^{J}/_{kg.K}$$

$where$:

Q is Energy in Joules

ΔT is change in temperature in Kelvin

m is mass in kg

Temperature: Kelvin to Celsius conversion

$$\boxed{T(K) = T(°C) + 273.15}$$

Example: Specific Heat problem

Question: How much energy is needed to increase 10 kg of concrete from 22°C to 30°C?

$$\boxed{\begin{array}{c} \mathit{Specific\ Heat\ capacity} \\ C = \left(\dfrac{Q}{m * \Delta T}\right) \end{array}} \quad {}^{J}/_{kg.K}$$

$where$:

Q is Energy in Joules

ΔT is change in temperature in Kelvin

m is mass in kg

Substance	c/J kg^{-1} K^{-1}	Substance	c/J kg^{-1} K^{-1}
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Brass	380	Rubber	1700
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Silver	230	Concrete	850
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Platinum	130	Glass	670
Lead	130	Carbon	500
Hydrogen	14000	Ethanol	2400
Air	718	Paraffin	2100
Nitrogen	1040	Water	4186
Steam	2000	Sea water	3900

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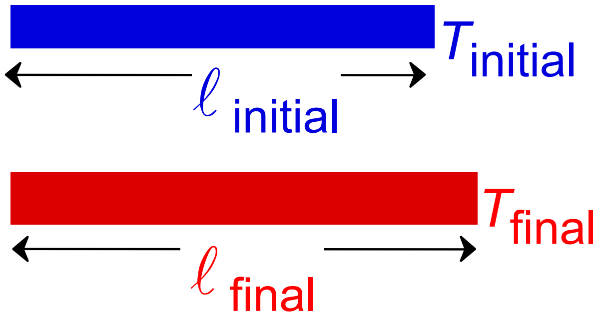
Lecture 10: Distance Learning Resources folder – 4. Thermal Expansion

Thermal Expansion

Materials change size when temperature is changed



$T_{\text{final}} > T_{\text{initial}}$

$$\frac{\Delta L}{L_0} = \alpha \Delta T$$

linear coefficient of
thermal expansion (1/K or 1/ºC)

Coefficient of Thermal Expansion: Comparison

Material	α_ℓ (10^{-6}/°C) at room T
• Polymers	
Polypropylene	145-180
Polyethylene	106-198
Polystyrene	90-150
Teflon	126-216
• Metals	
Aluminum	23.6
Steel	12
Tungsten	4.5
Gold	14.2
• Ceramics	
Magnesia (MgO)	13.5
Alumina (Al_2O_3)	7.6
Soda-lime glass	9
Silica (cryst. SiO_2)	0.4

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Expansion: Example

Ex: A copper wire 15 m long is cooled from 40 to -9ºC. How much change in length will it experience?

- Answer: For Cu $\alpha_\ell = 16.5 \text{ x } 10^{-6} \ (^\circ\text{C})^{-1}$

rearranging Equation 19.3b

$$\Delta\ell = \alpha_\ell \ell_0 \Delta T = [16.5 \text{ x } 10^{-6} (1/^\circ\text{C})](15 \text{ m})[40^\circ\text{C} - (-9^\circ\text{C})]$$

$$\Delta\ell = 0.012 \text{ m} = 12 \text{ mm}$$

Example: Thermal Expansion Coefficient

Question:
A bridge is made with segments of **concrete 50 m** long. If the linear expansion coefficient is **12×10^{-6} $(^0C)^{-1}$**, how much spacing (in m) is needed to allow for expansion during an extreme temperature change of **45°C?**

$\varepsilon = \alpha \Delta T$

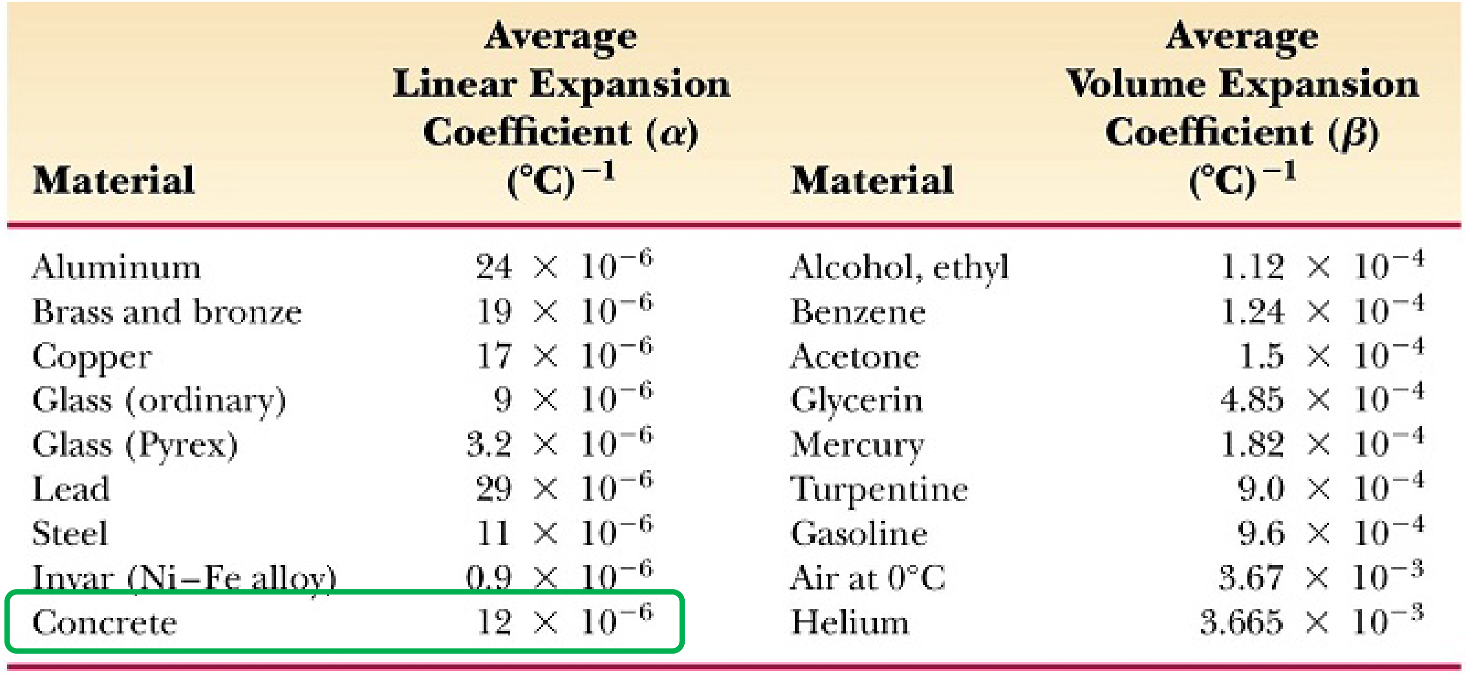
$$\frac{\Delta L}{L_0} = \alpha \Delta T$$

where:

$\frac{\Delta L}{L_0}$ is the fractional change in length

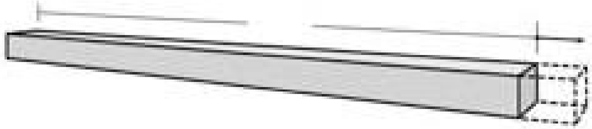
α is the coefficient of linear expansion

ΔT is the change in temperature



Material	Average Linear Expansion Coefficient (α) $(°C)^{-1}$	Material	Average Volume Expansion Coefficient (β) $(°C)^{-1}$
Aluminum	24×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Brass and bronze	19×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Acetone	1.5×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Lead	29×10^{-6}	Turpentine	9.0×10^{-4}
Steel	11×10^{-6}	Gasoline	9.6×10^{-4}
Invar (Ni–Fe alloy)	0.9×10^{-6}	Air at 0°C	3.67×10^{-3}
Concrete	12×10^{-6}	Helium	3.665×10^{-3}

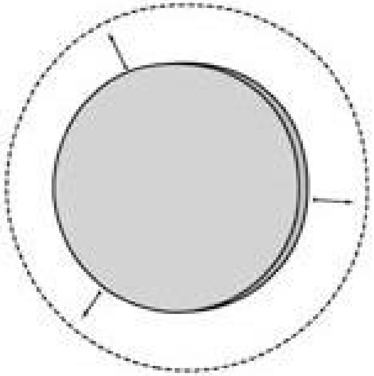
Thermal Expansion: Linear, area & volume



Linear

$$\Delta l = 1\,\alpha\, l_0\, \Delta T$$

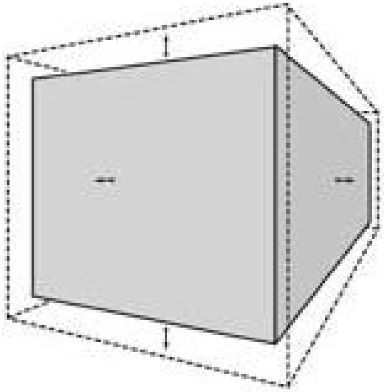
Δl = change in length
α = coefficient of linear expansion
l_0 = original length
ΔT = change in temperature



Area

$$\Delta A = 2\alpha\, A_0\, \Delta T$$

ΔA = change in area
α = coefficient of linear expansion
A_0 = original area
ΔT = change in temperature



Volume

$$\Delta V = \beta\, V_0\, \Delta T$$

$$\Delta V = 3\alpha\, V_0\, \Delta T$$

ΔA = change in volume
β = coefficient of volume expansion
V_0 = original area
ΔT = change in temperature
α = coefficient of linear expansion

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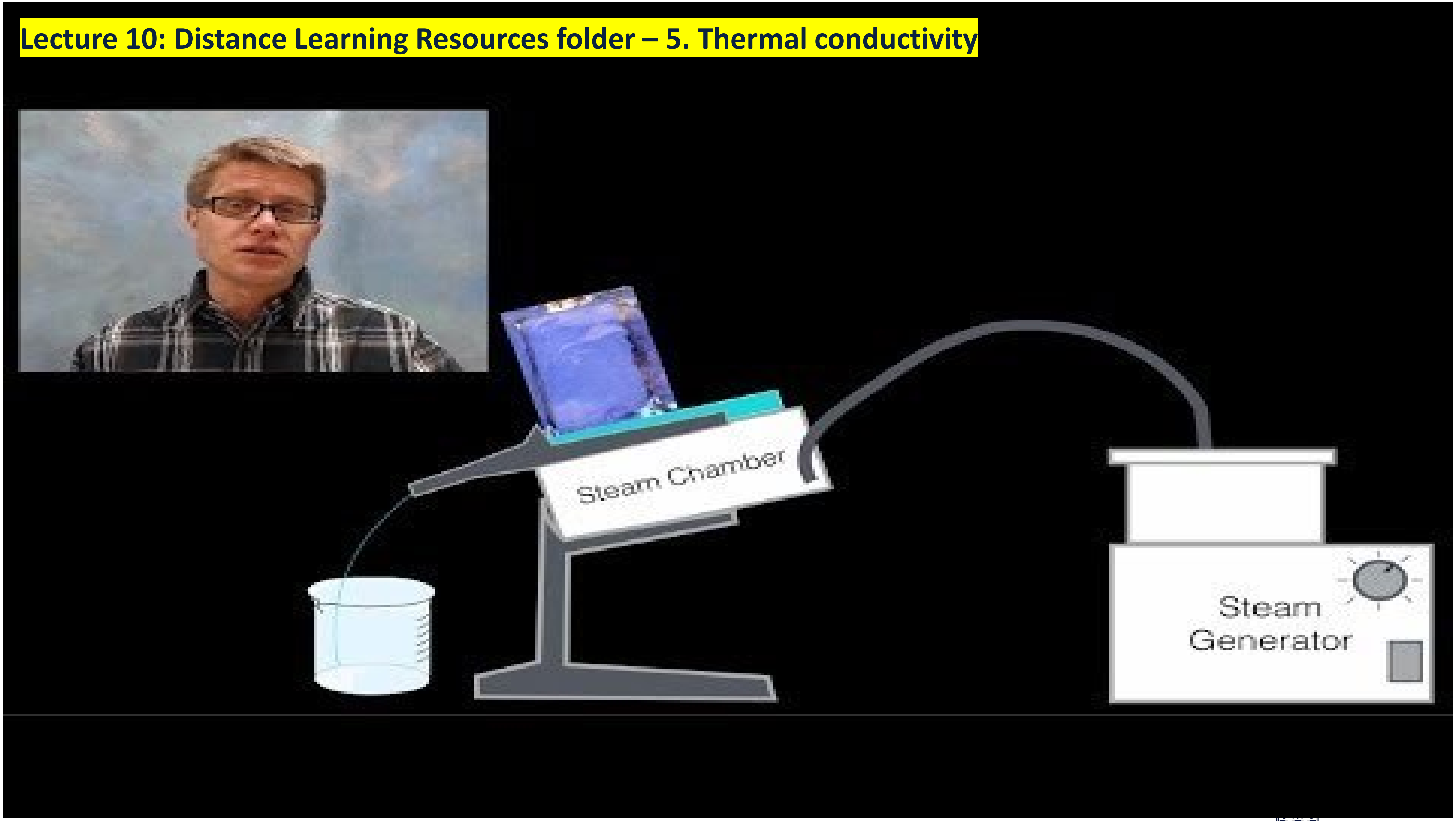


Lecture 10: Distance Learning Resources folder – 5. Thermal conductivity

Thermal Conductivity

The ability of a material to transport/conduct heat.

Fourier's Law

heat flux (J/m^2-s)

$$q = -k\frac{dT}{dx}$$

temperature gradient

thermal conductivity (J/m-K-s)

The negative sign shows that heat flux moves from higher temperature regions to lower temperature regions.

$T_2 > T_1$

- Atomic perspective: Atomic vibrations and free electrons in hotter regions transport energy to cooler regions.

Thermal Conductivity: Comparison

increasing k

Material	k (W/m-K)	Energy Transfer Mechanism
• Metals		
Aluminum	247	atomic vibrations and motion of free electrons
Steel	52	
Tungsten	178	
Gold	315	
• Ceramics		
Magnesia (MgO)	38	atomic vibrations
Alumina (Al_2O_3)	39	
Soda-lime glass	1.7	
Silica (cryst. SiO_2)	1.4	
• Polymers		
Polypropylene	0.12	vibration/rotation of chain molecules
Polyethylene	0.46-0.50	
Polystyrene	0.13	
Teflon	0.25	

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Stresses

- Occur due to:
  - -- restrained thermal expansion/contraction
  - -- temperature gradients that lead to differential dimensional changes

$$\Delta l = \alpha \, l_0 \, \Delta T$$

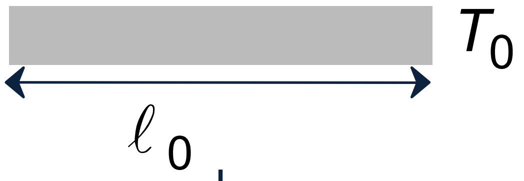
Thermal stress $= \sigma$

$$= E\alpha_{\ell}(T_0 - T_f) = E\alpha_{\ell}\Delta T$$

Example Problem

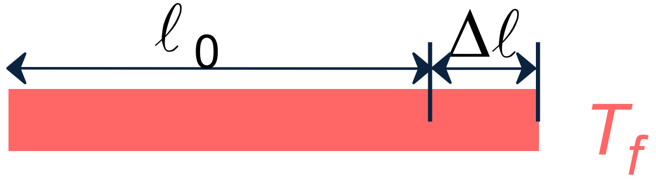
-- A brass rod is stress-free at room temperature (20ºC).
-- It is heated up, but prevented from lengthening.
-- At what temperature does the stress reach -172 MPa?

Solution:



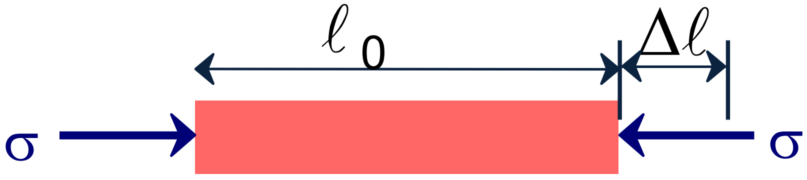
Original conditions

Step 1: Assume unconstrained thermal expansion



$$\frac{\Delta \ell}{\ell_{\text{room}}} = \varepsilon_{\text{thermal}} = \alpha_\ell (T_f - T_0)$$

Step 2: Compress specimen back to original length

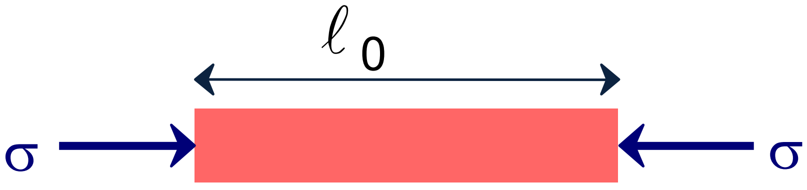


$$\varepsilon_{\text{compress}} = \frac{-\Delta\ell}{\ell_{\text{room}}} = -\varepsilon_{\text{thermal}}$$

note: $E = \frac{\sigma}{\varepsilon} \Rightarrow \sigma = E\varepsilon$

$\varepsilon_{thermal} = \alpha_l(\Delta T)$

Example Problem (cont.)



The thermal stress can be directly calculated as

$$\sigma = E(\varepsilon_{compress})$$

Noting that $\varepsilon_{compress} = -\varepsilon_{thermal}$ and substituting gives

$$\sigma = -E(\varepsilon_{thermal}) = -E\alpha_\ell(T_f - T_0) = E\alpha_\ell(T_0 - T_f)$$

Rearranging and solving for T_f gives

$\sigma = E\alpha_l(T_o - T_f)$

$\frac{\sigma}{E\alpha_l} = T_o - T_f$

$T_f = T_o - \frac{\sigma}{E\alpha_l}$

20ºC

-172 MPa (since in compression)

$$T_f = T_0 - \frac{\sigma}{E\alpha_\ell}$$

Answer: 106ºC

100 GPa

20×10^{-6}/ºC

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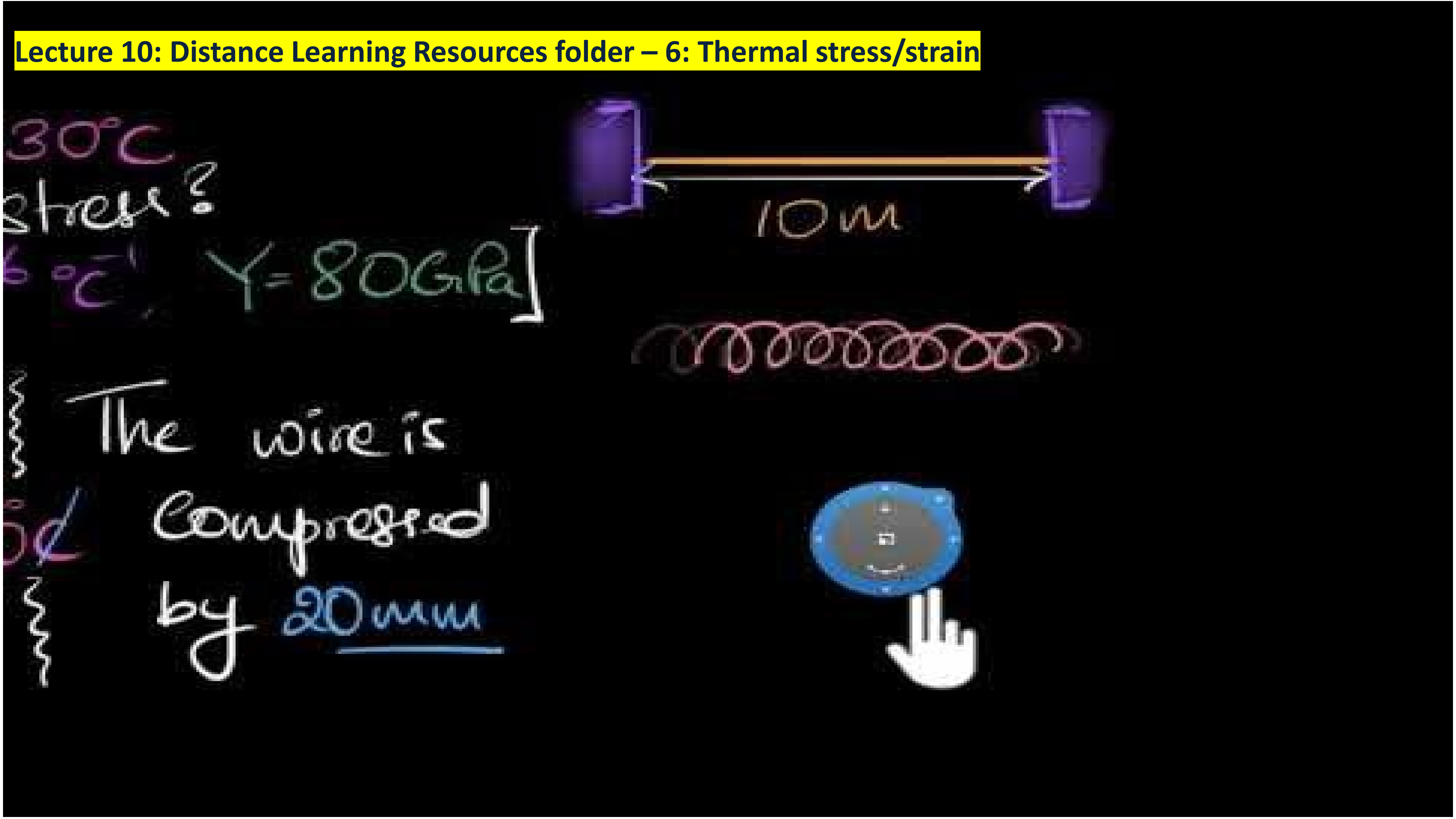


Lecture 10: Distance Learning Resources folder – 6: Thermal stress/strain

Summary

The thermal properties of materials include:

- **Heat capacity**:
  -- energy required to increase a mole of material by a unit *T*
  -- energy is stored as atomic vibrations
- **Coefficient of thermal expansion**:
  -- the size of a material changes with a change in temperature
  -- polymers have the largest values
- **Thermal conductivity**:
  -- the ability of a material to transport heat
  -- metals have the largest values

Thermal Properties

Specific Heat

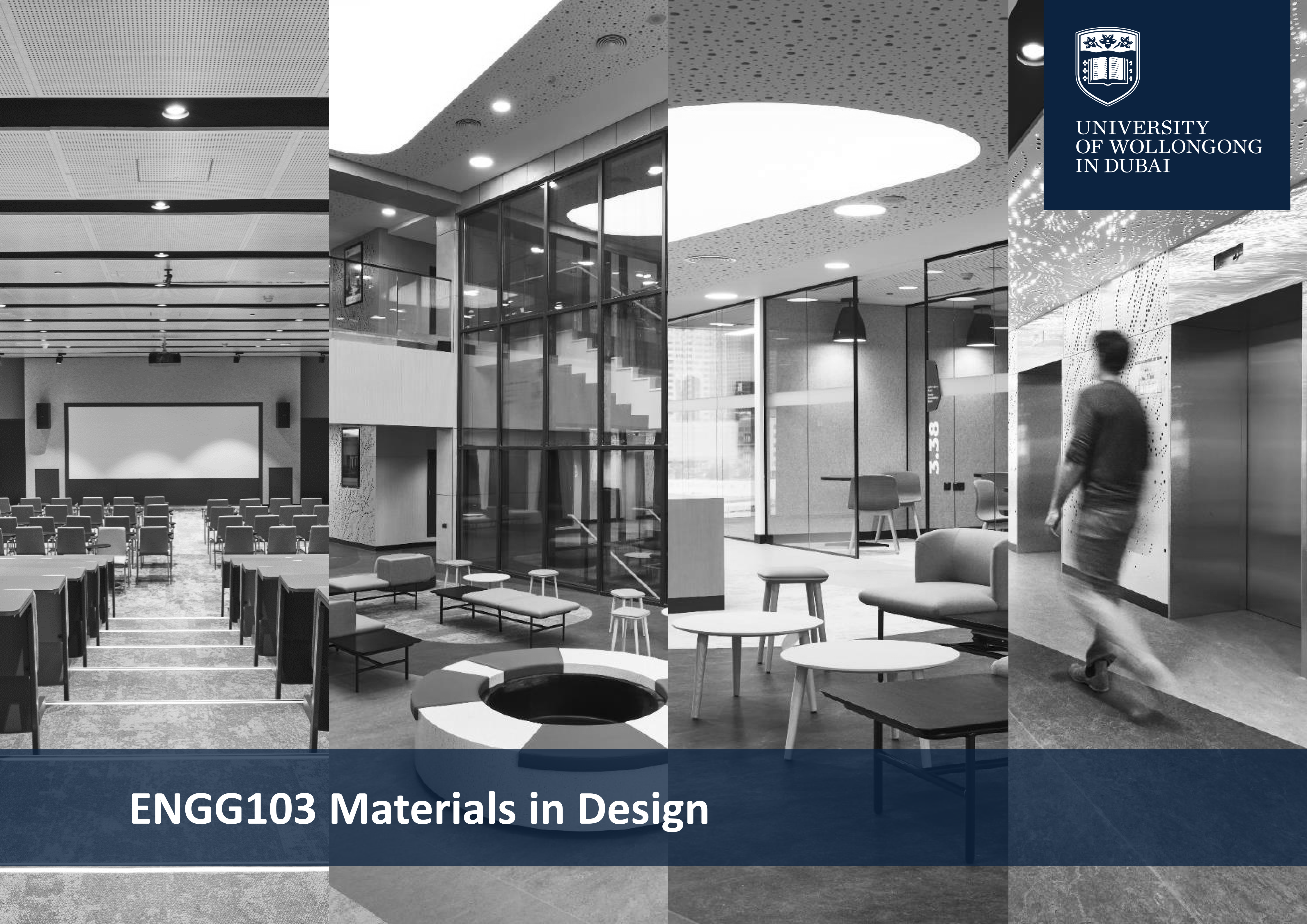
- Measurement used in thermodynamics and calorimetry that states the amount of heat energy necessary to increase the temperature of a given mass of a particular substance by some amount.

Thermal conductivity

- Measures the heat **conducting capability** of a material
- The rate at which a substance transfers heat

Thermal Expansion Coefficient

- Defined as the relative change in length or volume of a material for a unit change in temperature.
- Allowance often has to be made for the expansion of metal parts in structures and machinery is relative increase in length per unite temperature rise



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