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Thermal expansion

By

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Thermal Expansion

Why does matter expand on heating ?

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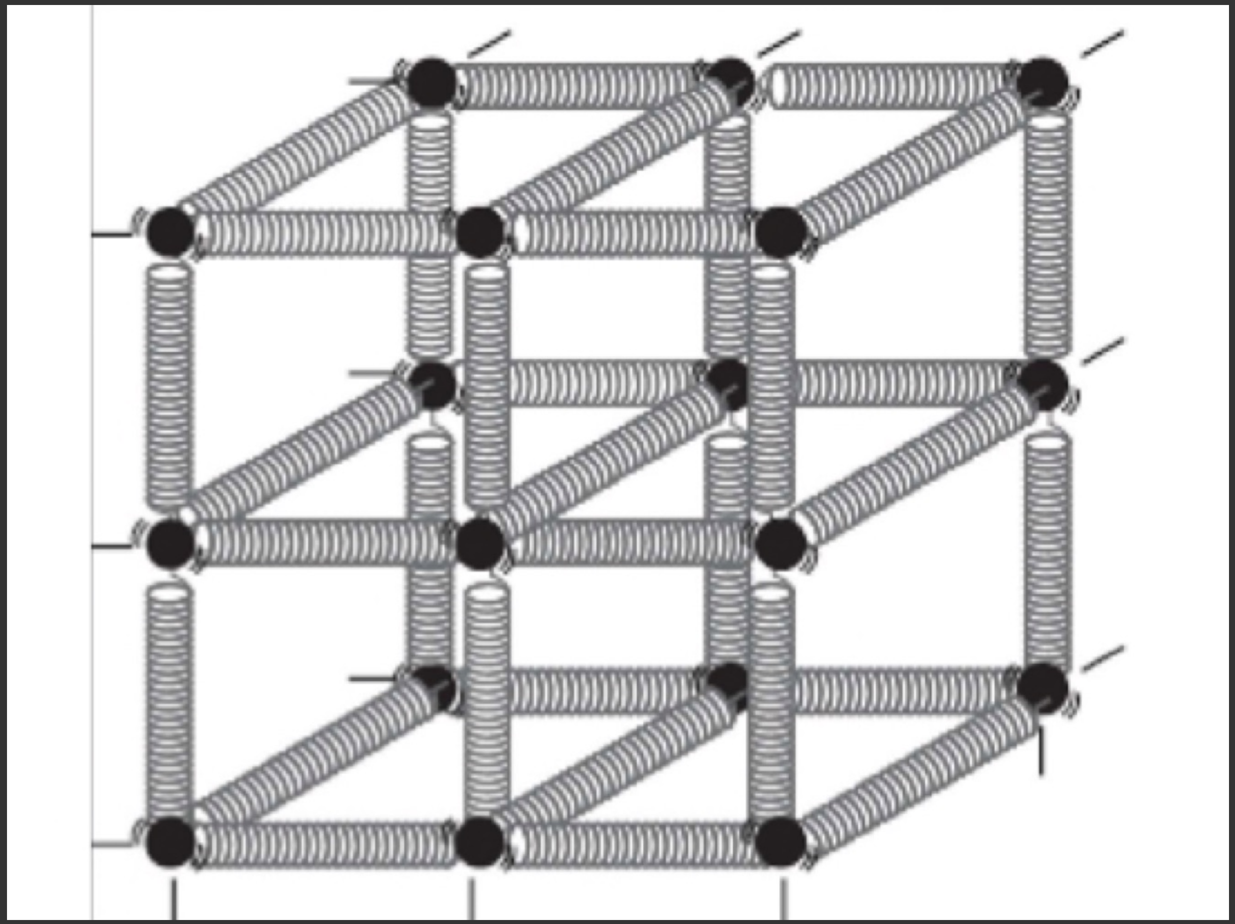

Fig. Spring ball model

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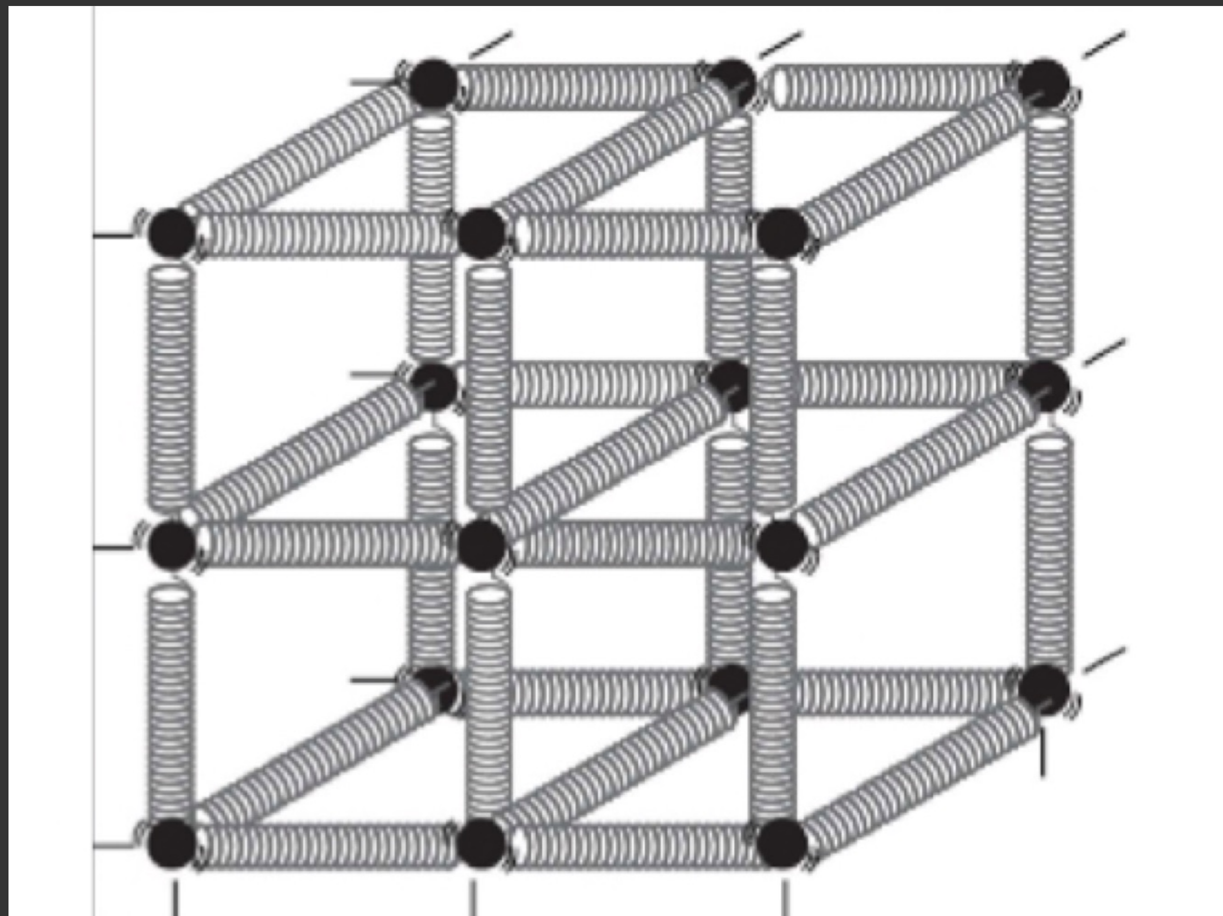
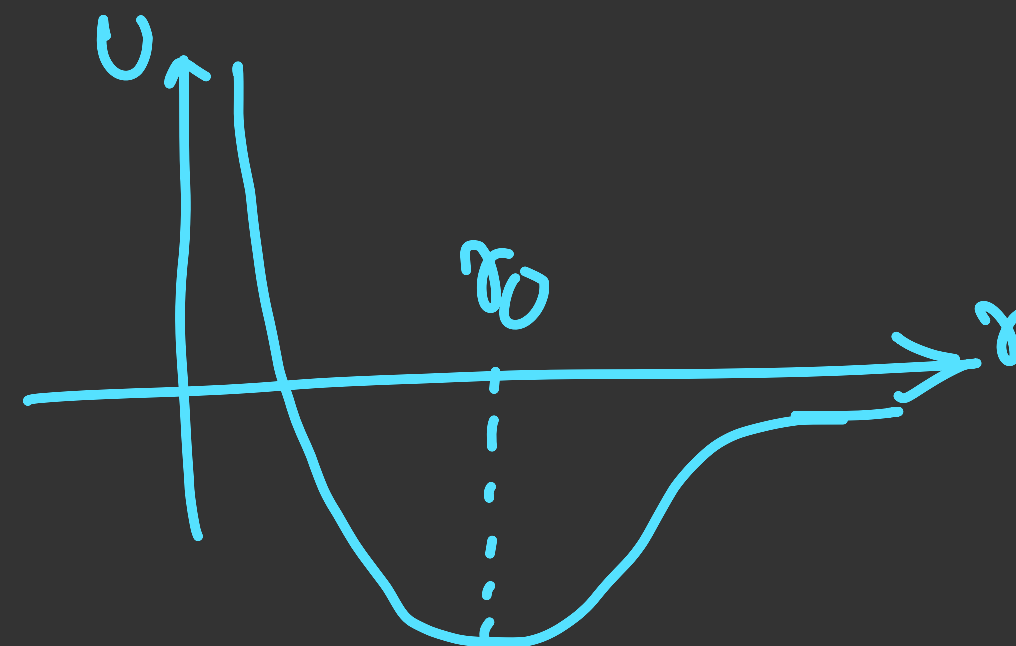


Fig. Spring ball model



$r < r_0$: Slope >> F >>

$r > r_0$: Slope F

$$F = -\frac{dU}{dr} = -(\text{slope})$$

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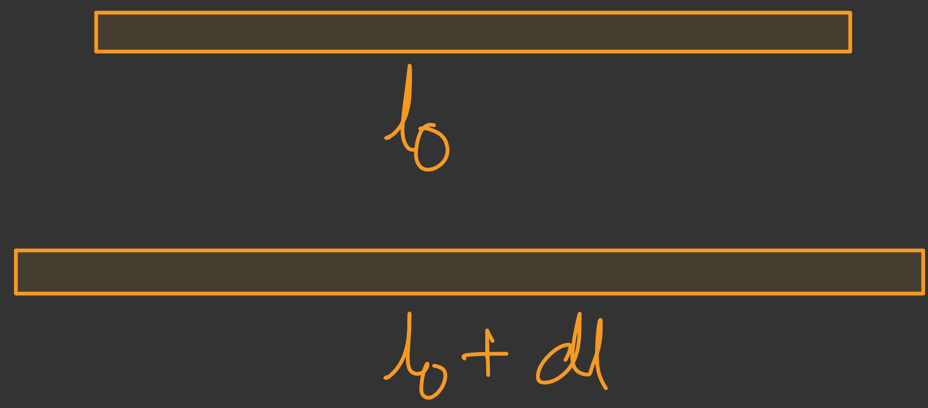
Linear Expansion



at temp θ

at temp $\theta + d\theta$

It has been seen:

$dl \propto l$

$dl \propto d\theta$

$\therefore \; dl \propto l \cdot d\theta$

$dl = \alpha \, l \cdot d\theta$

Alpha

where α is a proportionality constant and is called Coeff. of linear expansion.

Note: for small temperature differences, α is generally independent of temperature.

However, if temp diff. is very large, then α doesnot remain constant, and varies with temp.

** $$\boxed{dl = \alpha \cdot l \cdot d\theta}$$

$$\int dl = \int \alpha \cdot l \cdot d\theta$$

$$\int \frac{dl}{l} = \int \alpha \cdot d\theta$$

Special Cases:

$\Rightarrow$ If α is Constant

$$\int_{l_0}^{l} \frac{dl}{l} = \alpha \int_{\theta_0}^{\theta} d\theta$$

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$$\ln \frac{l}{l_0} = \alpha(\theta - \theta_0)$$

** $$\boxed{l = l_0 \, e^{\alpha(\theta - \theta_0)}}$$ $\rightarrow$ Assuming α is Constant

* $$\boxed{l = l_0 \, e^{\alpha \Delta \theta}}$$

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Another Special Case:

If $(\alpha \Delta \theta)$ is very small:

We know that:

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots$$

If x is very small, neglecting higher order terms:

$$\boxed{e^{x} \approx 1+x}$$

$\Rightarrow$ If $(\alpha \Delta\theta)$ is very small:

$$\boxed{e^{\alpha\Delta\theta} \approx 1+\alpha\Delta\theta}$$

$$l = l_0\, e^{\alpha\Delta\theta} \approx l_0\left[1+\alpha\Delta\theta\right]$$

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**

$$\boxed{l = l_0\left[1+\alpha\Delta\theta\right] = l_0\left[1+\alpha(\theta-\theta_0)\right]}$$

valid only if, α is constant
and $(\alpha\Delta\theta)$ is very small.

eg

$\alpha \rightarrow$ Constant

(given)

$\Delta\theta = ?$

Sol^n:

Wrong Approach:

$\Delta l = \alpha l \cdot \Delta\theta$

$2l - l = \alpha l \cdot \Delta\theta$

$l = \alpha l \cdot \Delta\theta$

$\Delta\theta = \dfrac{l}{\alpha \cdot l} = \dfrac{1}{\alpha}$ Ans.

Applicable only when $(\alpha \cdot \Delta\theta)$ is very small.

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Sol^n:

$\alpha \rightarrow$ Constant (given)

$\Delta\theta = ?$

$$dl = \alpha\, l\, d\theta$$

$$\int \frac{dl}{l} = \int \alpha \cdot d\theta$$

$$\int_{l}^{2l} \frac{dl}{l} = \alpha \int_{\theta_0}^{\theta} d\theta$$

$$\ln 2 = \alpha\,(\theta - \theta_0)$$

$$\theta - \theta_0 = \frac{\ln 2}{\alpha}$$

$$\Delta\theta = \frac{\ln 2}{\alpha} \quad \text{Ans.}$$

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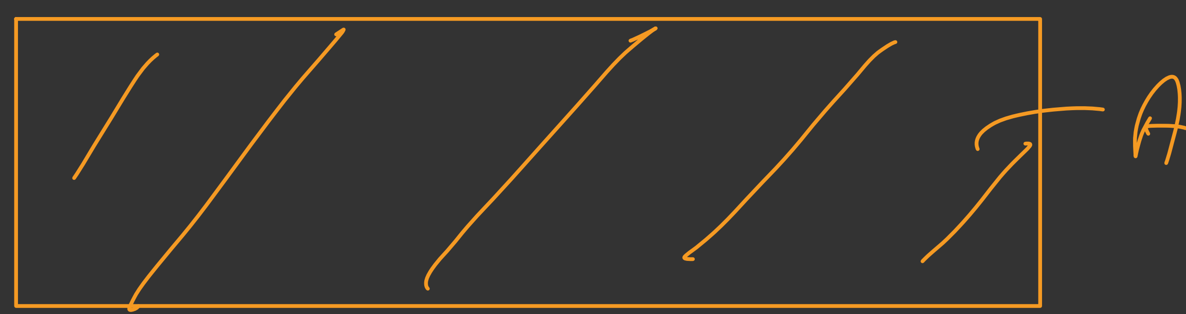
$$\alpha = \frac{dl}{l \cdot d\theta} = \frac{(dl/l)}{d\theta}$$

Change in length per unit length, per unit change in temp.

Areal expansion



at θ

at $\theta + d\theta$

$dA \propto A$

$dA \propto d\theta$

$dA \propto A \cdot d\theta$

$dA = \beta \cdot A \cdot d\theta$

$$* \boxed{\beta = \frac{dA}{A \cdot d\theta}}$$

Coeff. of Areal expansion.

Volume expansion

$\theta \rightarrow V$

$\theta + d\theta \Rightarrow V + dV$

$dV \propto V$

$\propto d\theta$

$dV \propto V \cdot d\theta$

$dV = \gamma \cdot V \cdot d\theta$

$\gamma = \frac{dV}{V \cdot d\theta}$ → Coeff. of volume expansion

$\alpha \rightarrow$ Coeff. of linear expansion. $\alpha = \frac{1}{l} \cdot \frac{dl}{d\theta}$ $\Rightarrow dl = \alpha\, l \cdot d\theta$

$\beta \rightarrow$ Coeff. of Areal expansion. $\beta = \frac{1}{A} \cdot \frac{dA}{d\theta}$ $\Rightarrow dA = \beta \cdot A \cdot d\theta$

$\gamma \rightarrow$ Coeff. of volume expansion. $\gamma = \frac{1}{V} \cdot \frac{dV}{d\theta}$ $\Rightarrow dV = \gamma \cdot V \cdot d\theta$

$\Rightarrow l - l_0 = \alpha\, l_0 \Delta\theta$ $\Rightarrow l = l_0 [1 + \alpha \Delta\theta]$

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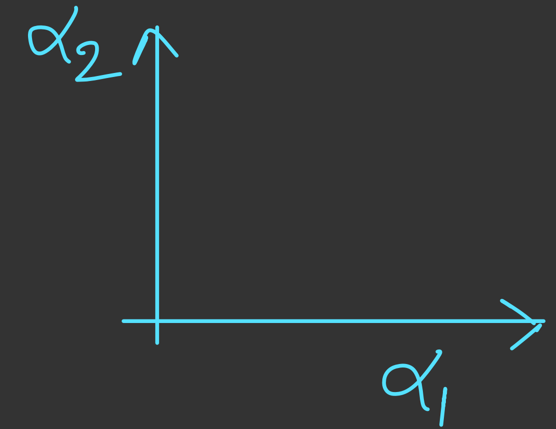
$\Rightarrow A - A_0 = \beta \cdot A_0 \Delta\theta$ $\Rightarrow A = A_0 [1 + \beta \Delta\theta]$

$\Rightarrow V - V_0 = \gamma \cdot V_0 \Delta\theta$ $\Rightarrow V = V_0 [1 + \gamma \Delta\theta]$

* Areal Expansion:



Anisotropic

$$\alpha_x \neq \alpha_y \neq \alpha_z$$

Isotropic

$$\alpha_x = \alpha_y = \alpha_z$$

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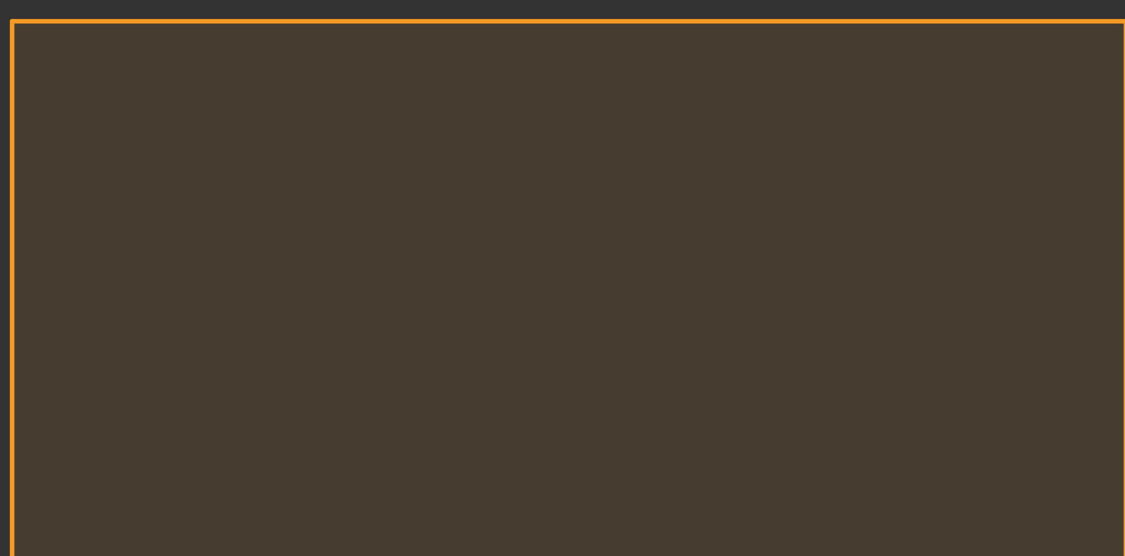
$$A_0 = l_1 \, l_2$$



$l_2 (1 + \alpha_2 \Delta\theta)$

$l_1 (1 + \alpha_1 \Delta\theta)$

$$A' = [l_1(1+\alpha_1 \Delta\theta)][l_2(1+\alpha_2\Delta\theta)]$$

$$A' = l_1 l_2 \,(1+\alpha_1\Delta\theta)(1+\alpha_2\Delta\theta)$$

$$A' = A_0\left[1+\alpha_1\Delta\theta+\alpha_2\Delta\theta+\underbrace{\alpha_1\alpha_2(\Delta\theta)^2}\right]$$

Neglected, If $\Delta\theta$ is very small

$$A' \approx A_0\left[1+(\alpha_1+\alpha_2)\Delta\theta\right]$$

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Comparing with $A' = A_0[1+\beta\,\Delta\theta]$

we get:

** $\boxed{\beta = \alpha_1+\alpha_2}$

* $\boxed{\beta = \alpha_x+\alpha_y}$

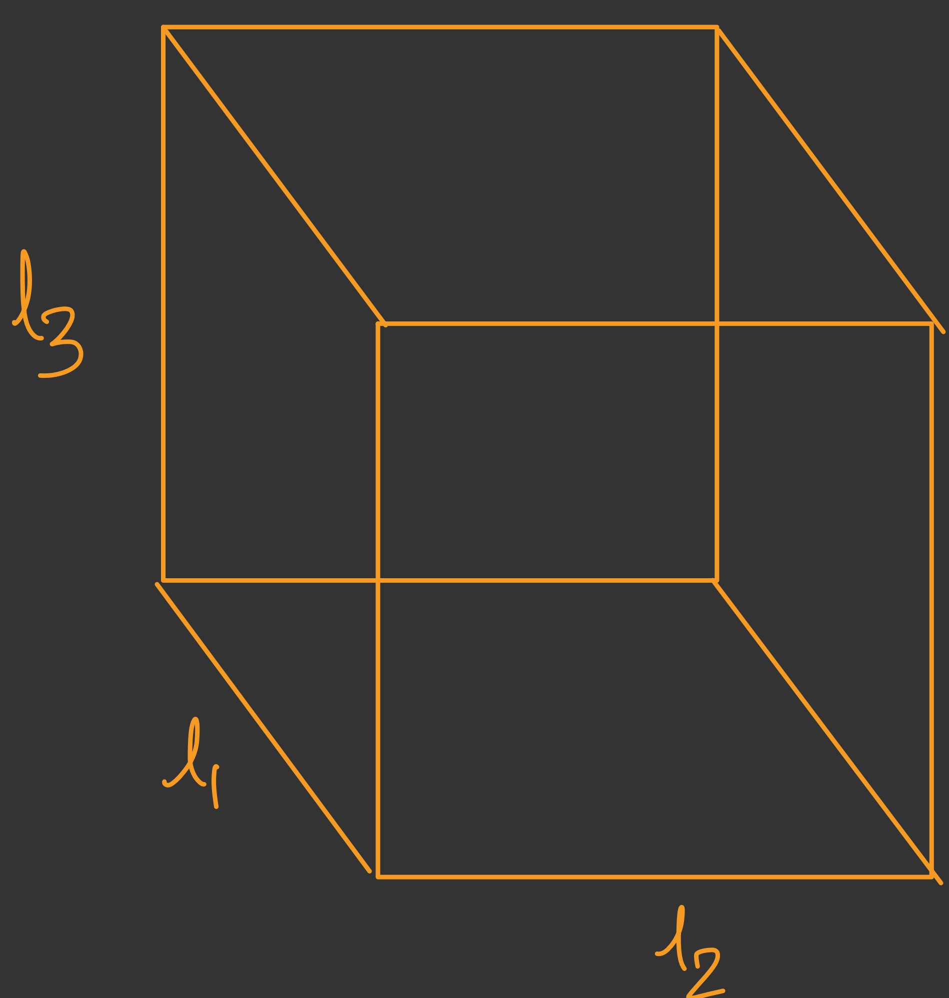
For Anisotropic materials.

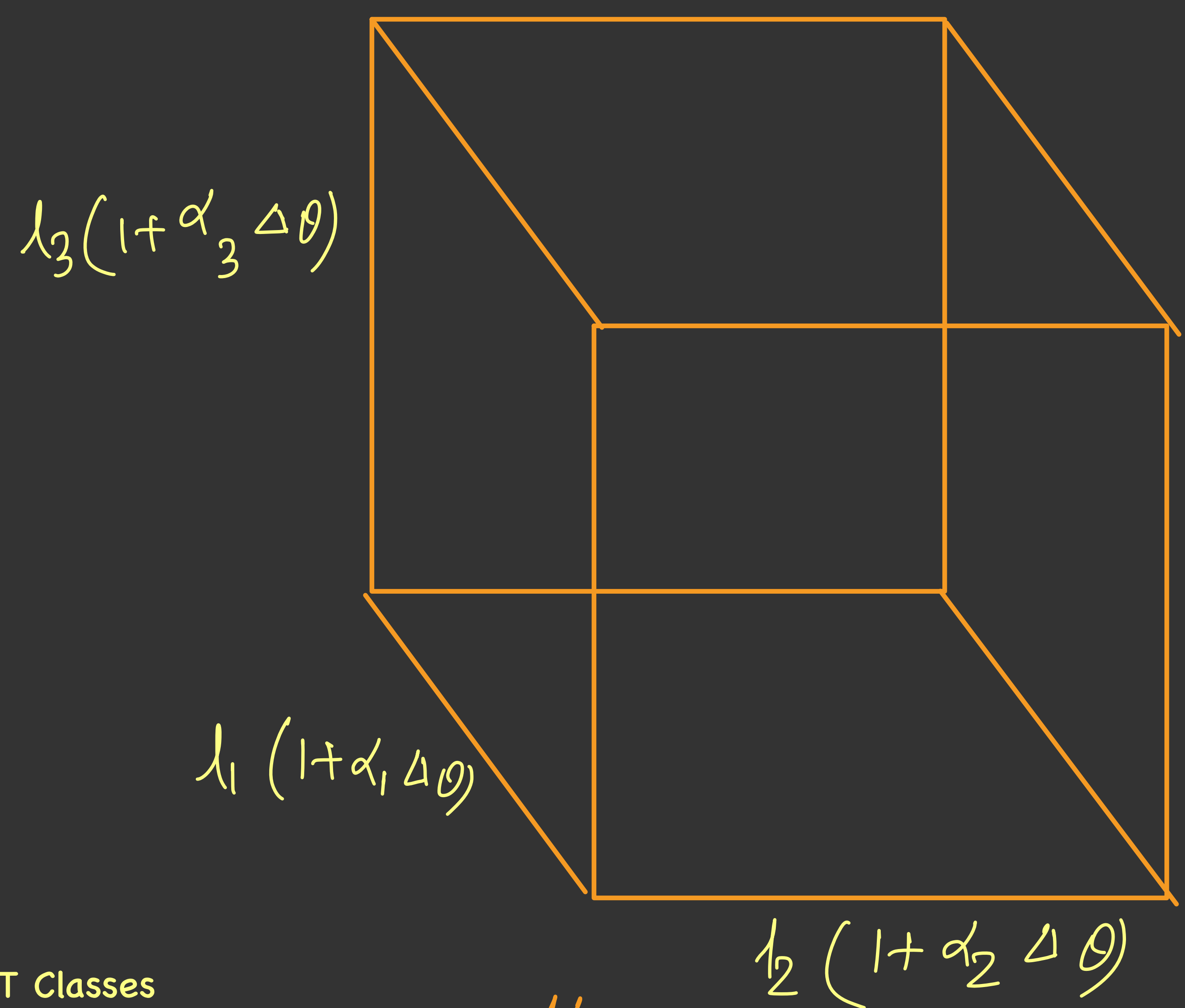
For Isotropic materials:

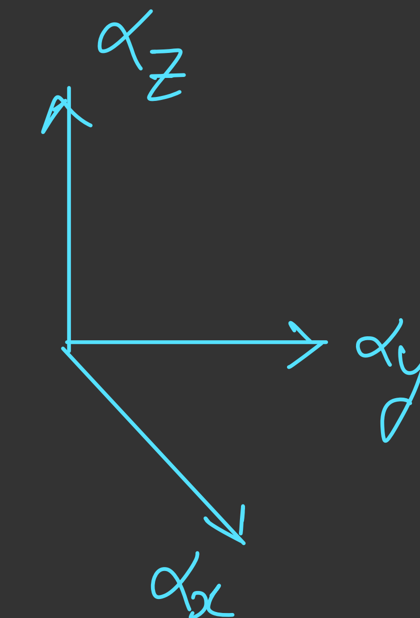
$$\alpha_1 = \alpha_2$$

$$\therefore \beta = 2\alpha$$

* Volume expansion:







$$V_0 = l_1 l_2 l_3$$

$$V' = l_1(1+\alpha_1\Delta\theta)\cdot l_2(1+\alpha_2\Delta\theta)\, l_3(1+\alpha_3\Delta\theta)$$

$$V' = l_1 l_2 l_3 (1+\alpha_1\Delta\theta)(1+\alpha_2\Delta\theta)(1+\alpha_3\Delta\theta)$$

$$V' = V_0\left[1 + \alpha_1 \Delta\theta + \alpha_2 \Delta\theta + \underbrace{\alpha_1\alpha_2(\Delta\theta)^2}_{\text{Neglecting}}\right](1 + \alpha_3 \Delta\theta)$$

$$V' = V_0\left[1 + \alpha_1 \Delta\theta + \alpha_2 \Delta\theta + \alpha_3 \Delta\theta + \alpha_1 \underbrace{\alpha_2(\Delta\theta)^2 + \alpha_3\alpha_1(\Delta\theta)^2 + \alpha_3\alpha_2(\Delta\theta)^2 + \alpha_3\alpha_1\alpha_2(\Delta\theta)^3}_{\text{Neglecting higher order terms}}\right]$$

$$V' = V_0\left[1 + (\alpha_1 + \alpha_2 + \alpha_3)\Delta\theta\right]$$

Comparing with $V' = V_0[1 + \gamma \Delta\theta]$

we get: **

$$\boxed{\gamma = \alpha_1 + \alpha_2 + \alpha_3}$$

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* $\boxed{\gamma = \alpha_x + \alpha_y + \alpha_z}$ $\Rightarrow$ Anisotropic materials.

For isotropic materials:

** $\boxed{\gamma = 3\alpha}$

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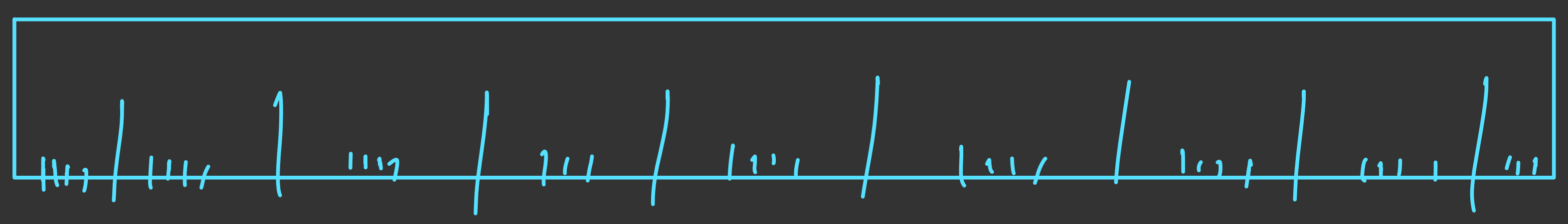
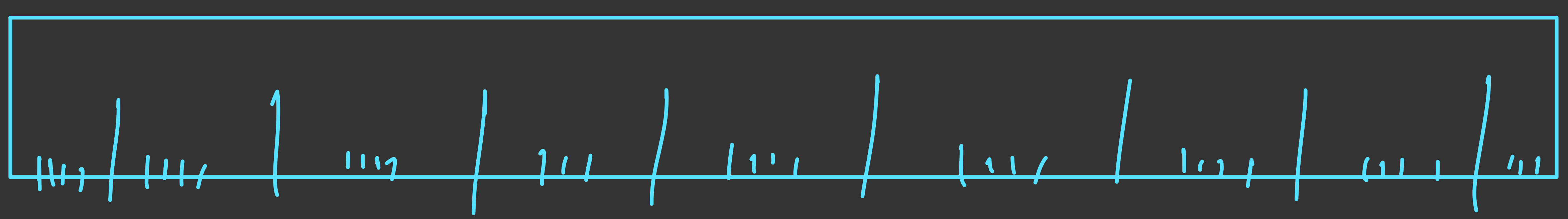
Ex. A brass scale correctly calibrated at 15°C is employed to measure a length at a temperature of 35°C. If the scale gives a reading of 75cm, find the true length. (Linear expansively of brass = 2.0×10^{-5}C°)$^{-1}$)

expansivity



← Shimla   15°C



Ex. A brass scale correctly calibrated at 15°C is employed to measure a length at a temperature of 35°C. If the scale gives a reading of 75cm, find the true length. (Linear expansively of brass = $2.0 \times 10^{-5} C°)^{-1}$)

expansivity

Ex. A brass scale correctly calibrated at 15°C is employed to measure a length at a temperature of 35°C. If the scale gives a reading of 75cm, find the true length. (Linear expansively of brass = $2.0 \times 10^{-5}C°)^{-1}$)

[Sol. Let the distance between two fixed divisions on the scale at 15°C be L_1 and that at 35°C be L_2.

Clearly, $(L_2 - L_1) = \alpha L_1 (35 - 15)$

or $L_2 = L_1 (1 + 20 \times 2.0 \times 10^{-5})$

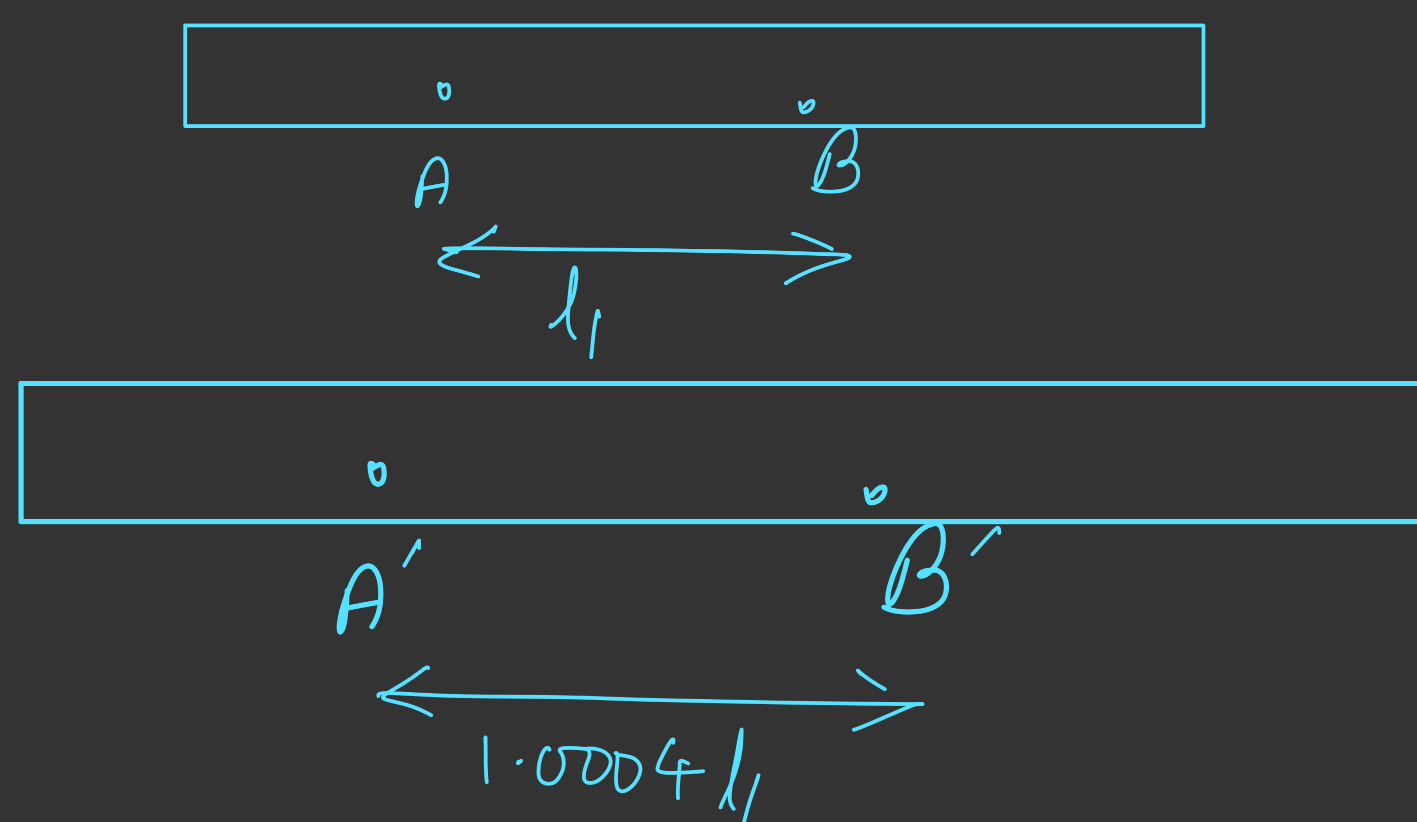
$L_2 = L_1 (1.0004)$

i.e., at 35°C, an actual length of L_2 will be read as L_1 (note), due to the increased separation of the divisions of the scale. In other words, the observed length will be less than the actual length.

Given: $L_1 = 75$ cm

$\therefore$ $L_2 = 75 (1.0004)$ cm

$= 75.03$ cm]



$l_1 = 75$ cm

1.0004×75 cm

Seconds Pendulam

$T = 2\ sec$

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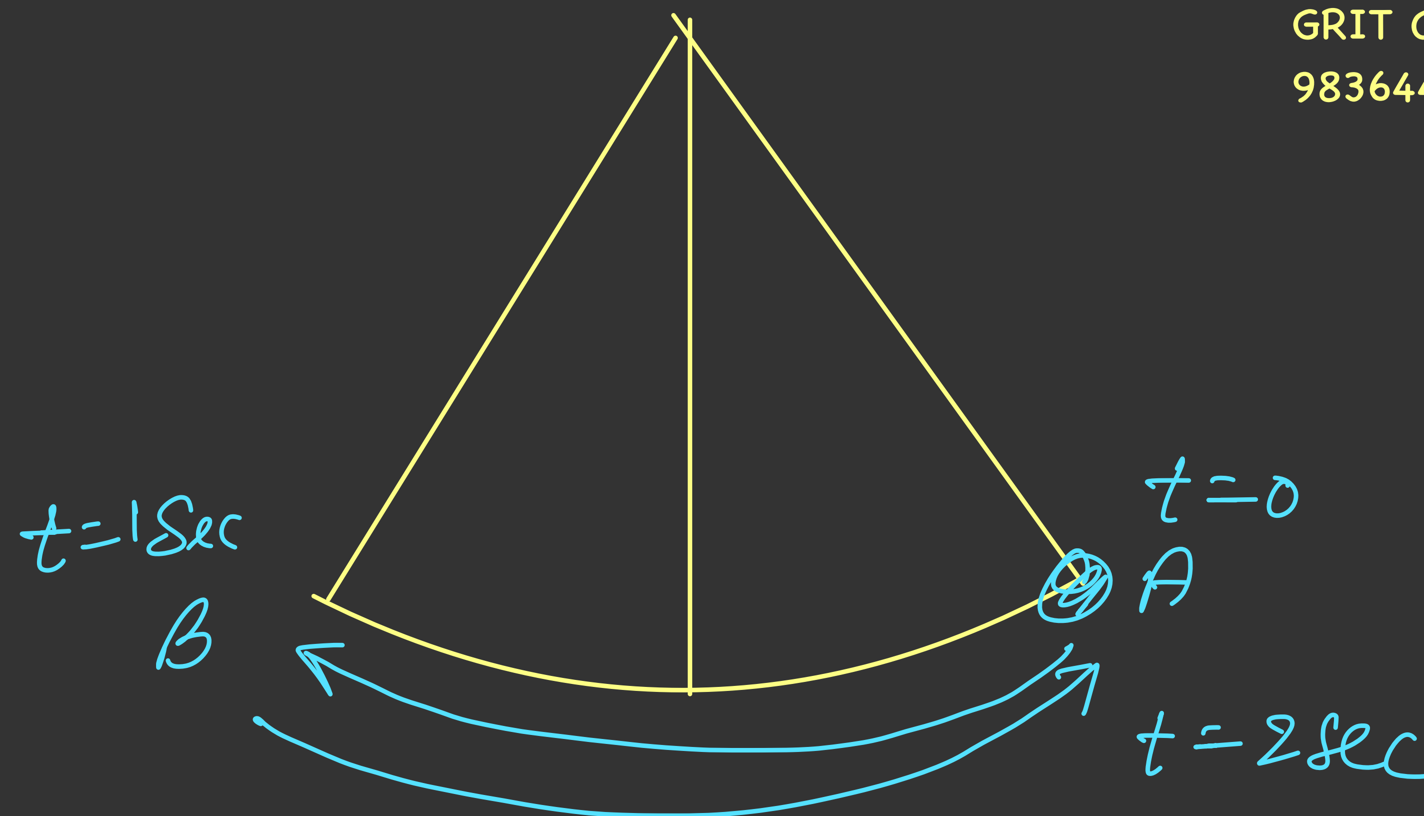
$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$2 = 2\pi\sqrt{\frac{l}{g}}$$

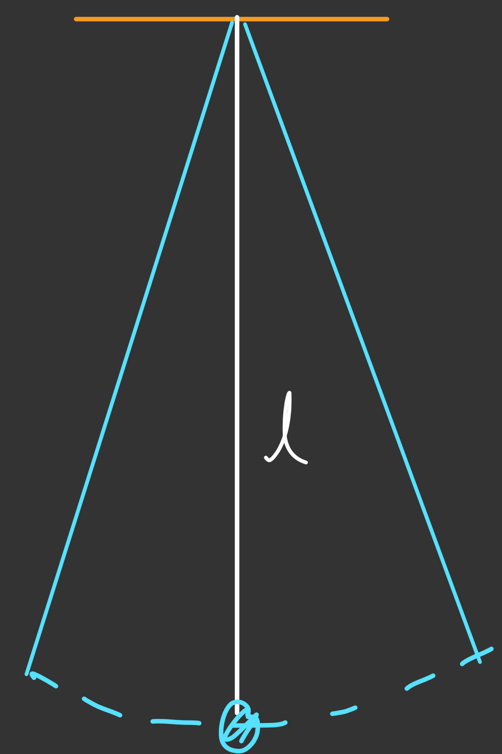


$l \uparrow \quad T' \uparrow$

$T = 5\ sec$

$5\ l_m$

* Pendulam clock :



$$T = 2\pi\sqrt{\frac{l}{g}}$$

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$$T' = 2\pi\sqrt{\frac{l'}{g}}$$

$$T' = 2\pi\sqrt{\frac{l_0(1+\alpha\Delta\theta)}{g}}$$

If temp $\uparrow$, $\Delta\theta = +ve$, $T' > T$

Slow down

If temp $\downarrow$, $\Delta\theta = -ve$, $T' < T$

will be fast

$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$\ln T = \ln 2\pi + \frac{1}{2}\ln l - \frac{1}{2}\ln g$$

$$\frac{dT}{T} = 0 + \frac{1}{2}\frac{dl}{l} - \frac{dg}{g}$$

$$\frac{\Delta T}{T} = \frac{1}{2}\left(\frac{\Delta l}{l}\right) + \frac{1}{2}\left(\frac{\Delta g}{g}\right)$$

Assuming no variation in g:

$$\frac{dT}{T} = \frac{1}{2}\ \frac{dl}{l}$$

Since, $dl = \alpha l\, d\theta$

$$\frac{dl}{l} = \alpha \cdot d\theta$$

**

$$\boxed{\frac{dT}{T} = \frac{1}{2}\alpha\, d\theta}$$

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Ex. Estimate the time lost or gained by a pendulum clock at the end of a week when the atmospheric temperature rises to 40°C. The clock is known to give correct time at 15°C and the pendulum is of steel. (Linear expansively of steel is $12 \times 10^{-6} / °C$).

Solⁿ

$$\Delta\theta = 40^\circ - 15^\circ = 25^\circ C$$

$$\alpha = 12 \times 10^{-6}$$

$$\frac{\Delta T}{T} = \frac{1}{2}\alpha(\Delta\theta)$$

$$\frac{\Delta T}{7 \times 24 \times 3600 \text{ sec}} = \frac{1}{2}(12 \times 10^{-6})(40-15)$$

$$\Delta T =$$

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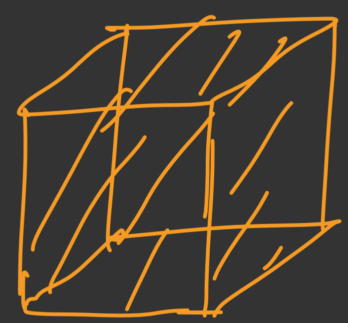
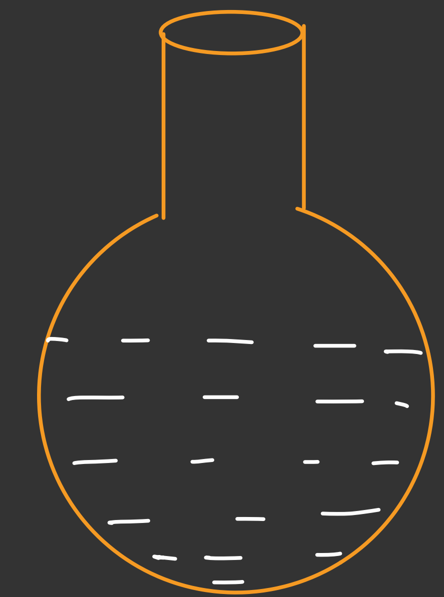
* Variation of Density with Temperature:





$$m = \rho_0 V_0 = \rho^* \left[V_0 (1 + \gamma \Delta\theta) \right]$$

**

$$\boxed{\rho^* = \frac{\rho_0}{1 + \gamma(\Delta\theta)}}$$

Special Case:

If $\gamma\Delta\theta$ is very less:

*

$$\boxed{\rho^* \approx \rho_0 (1 - \gamma\Delta\theta)}$$

$$\frac{1}{1+x} = (1+x)^{-1}$$

Formula:

$$(1+x)^n = 1 + nx + {}^nC_2\, x^2 + {}^nC_3\, x^3 + \dots$$

If x is very small, then, higher order terms can be neglected.

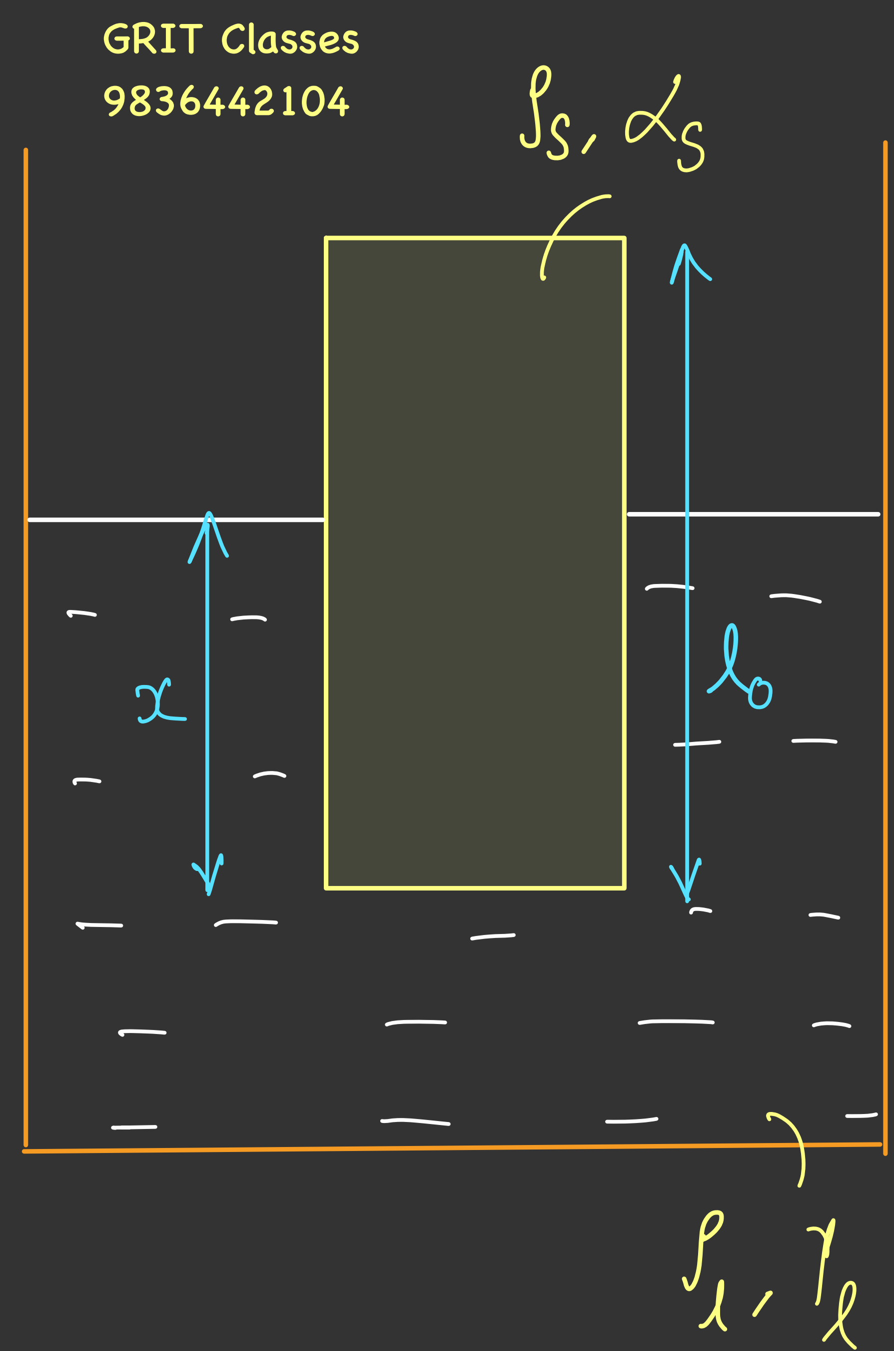
**

$$\boxed{(1+x)^n \approx 1 + nx}$$

$$\frac{1}{1+\gamma\Delta\theta} = (1+\gamma\Delta\theta)^{-1} \approx 1-\gamma\Delta\theta$$

(if $\gamma\Delta\theta$ is very small).

eg

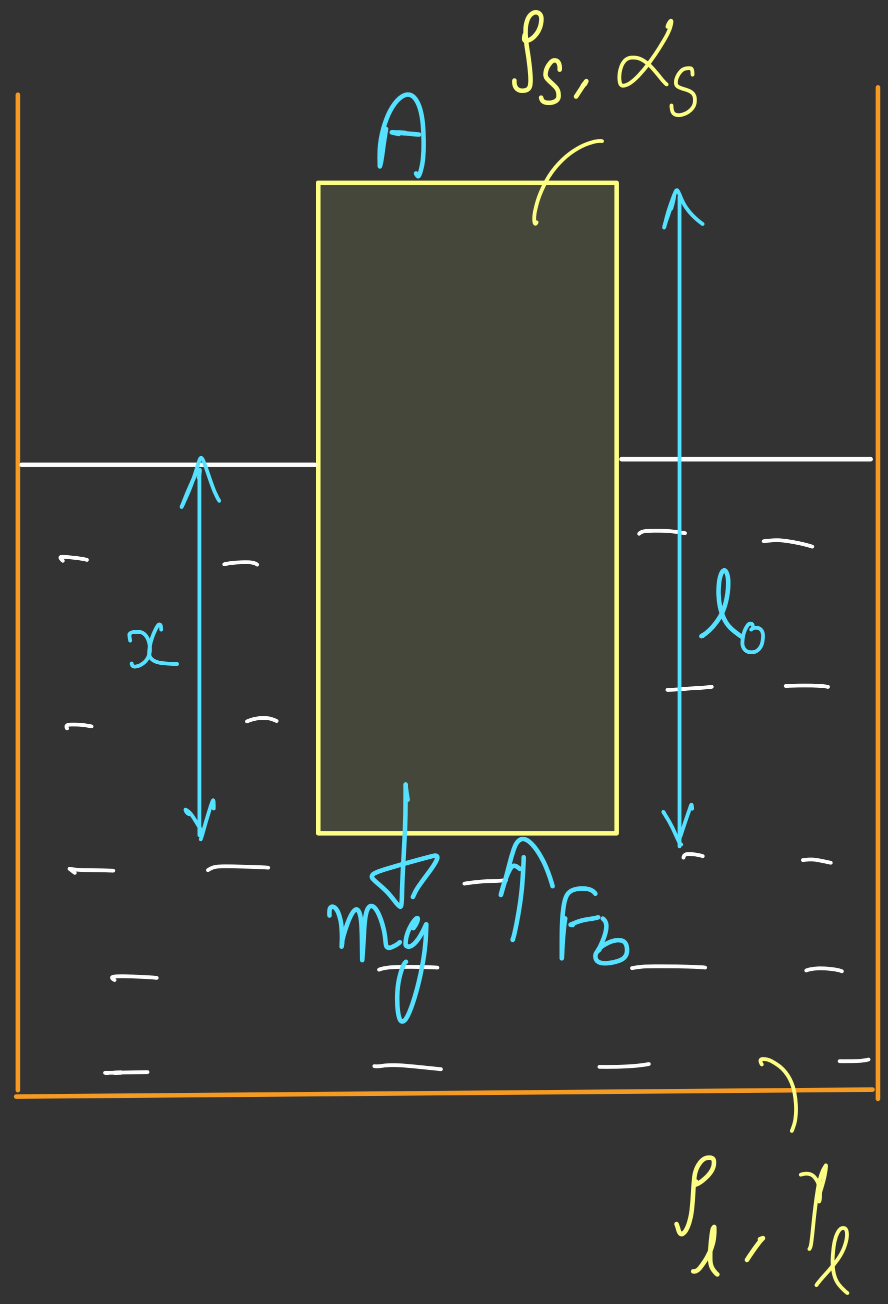


Find relation between γ_l and α_s so that length of cylinder inside liquid remains same.

(x remains same).

(Temp. of both cylinder & liquid is increased by $\Delta\theta$) ($\Delta\theta$ is small)

(Neglect the effects of vessel)



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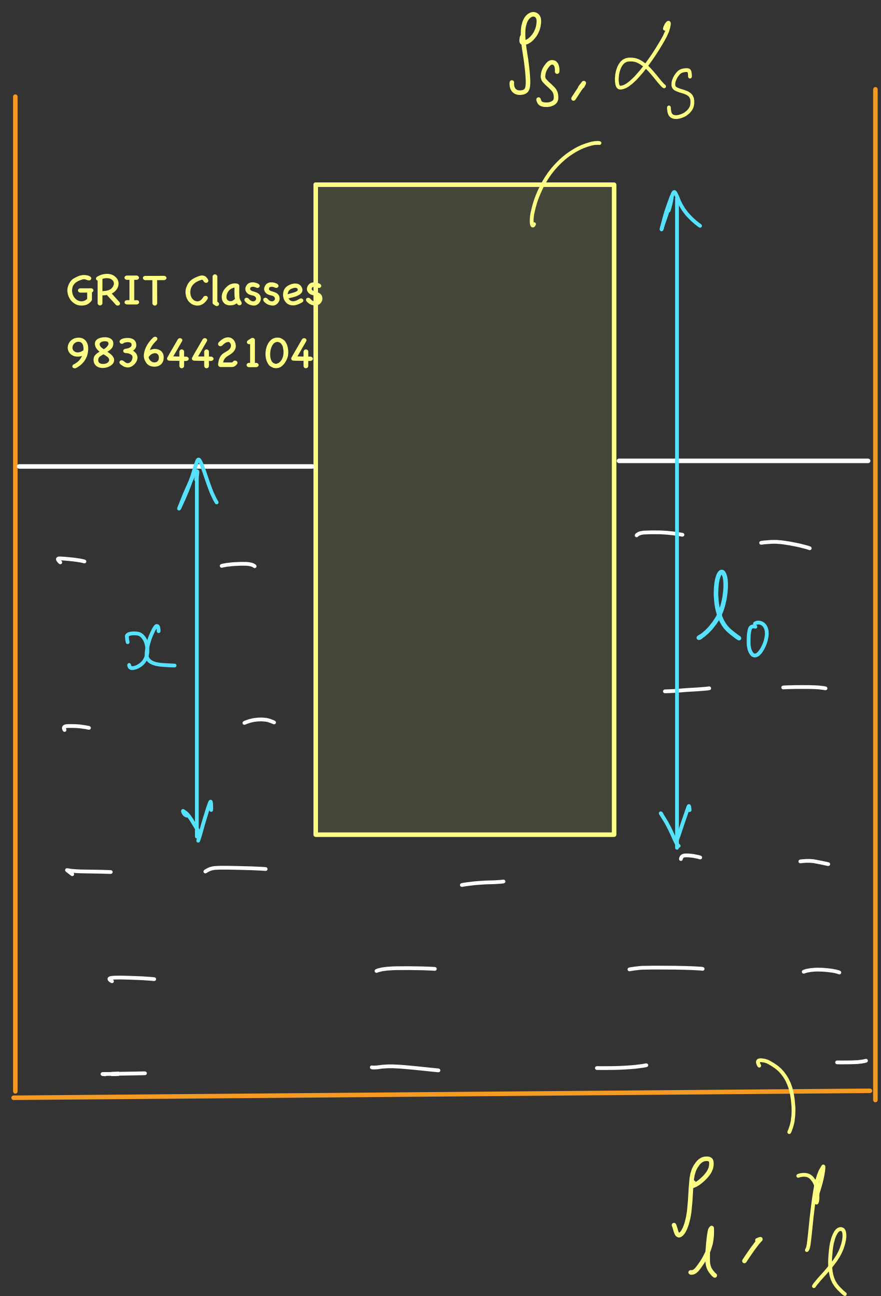
Equilib:

$$mg = F_b$$

$$\rho_s (\cancel{A} l) \cancel{g} = \rho_l (\cancel{A} x) \cancel{g}$$

$$\frac{x}{l} = \frac{\rho_s}{\rho_l}$$



Sol^n: We know that:

$$\boxed{\frac{x}{l_0} = \frac{\rho_{s0}}{\rho_{l0}}} \quad \text{—(1)}$$

$$\frac{x}{l^*} = \frac{\rho_s^*}{\rho_l^*}$$

$$\frac{x}{l_0\left[1+\alpha_s \Delta\theta\right]} = \frac{\left(\dfrac{\rho_{s0}}{1+\gamma_s \Delta\theta}\right)}{\left(\dfrac{\rho_{l0}}{1+\gamma_l \Delta\theta}\right)}$$

Note: $\gamma_s = 3\alpha_s$

$$\frac{\cancel{x}}{\cancel{l_0}\,(1+\alpha_s \Delta\theta)} = \frac{\cancel{\rho_{s0}}}{1+3\alpha_s \Delta\theta} \times \frac{1+\gamma_l \Delta\theta}{\cancel{\rho_{l0}}}$$

$$(1+\alpha_s\,\Delta\theta)\,(1+\gamma_l\,\Delta\theta) = 1+3\alpha_s\,\Delta\theta$$

$$\Rightarrow \cancel{1}+\alpha_s\cancel{\Delta\theta}+\gamma_l\cancel{\Delta\theta}+\underbrace{\alpha_s\,\gamma_l(\Delta\theta)^2}_{\text{Neglected if } \Delta\theta \text{ is small}} = \cancel{1}+3\alpha_s\cancel{\Delta\theta}$$

$$\alpha_s+\gamma_l = 3\alpha_s$$

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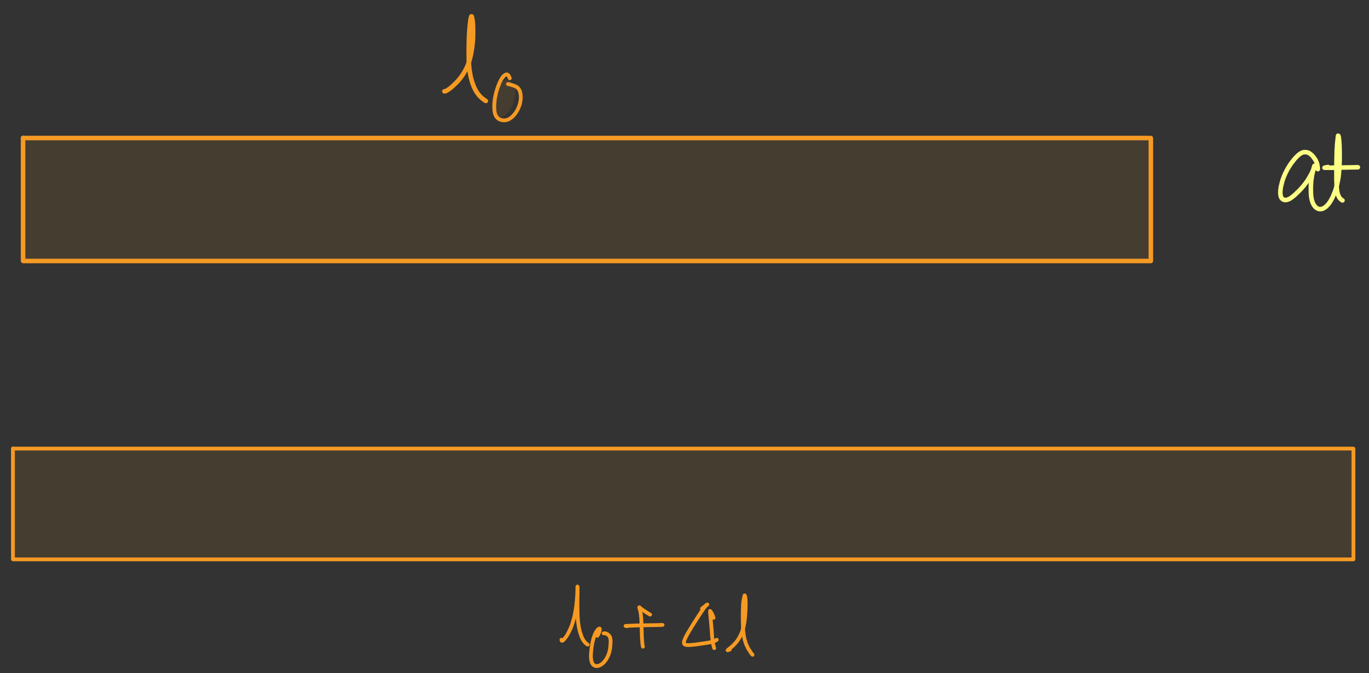
$$\boxed{\gamma_l = 2\alpha_s}$$ Ans.

Thermal Strain:



at θ

at $\theta + \Delta\theta$

Find Strain developed in the rod.

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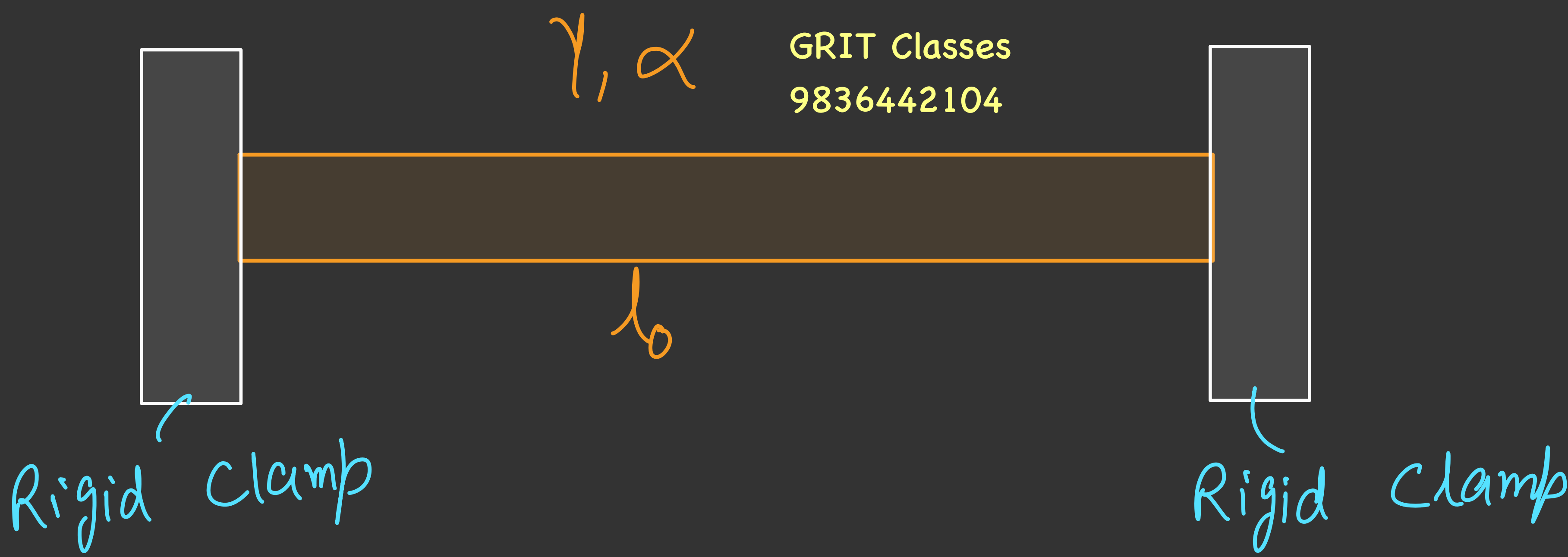
Solⁿ: no internal restoring force develops.

$\therefore$ Strain $= 0$

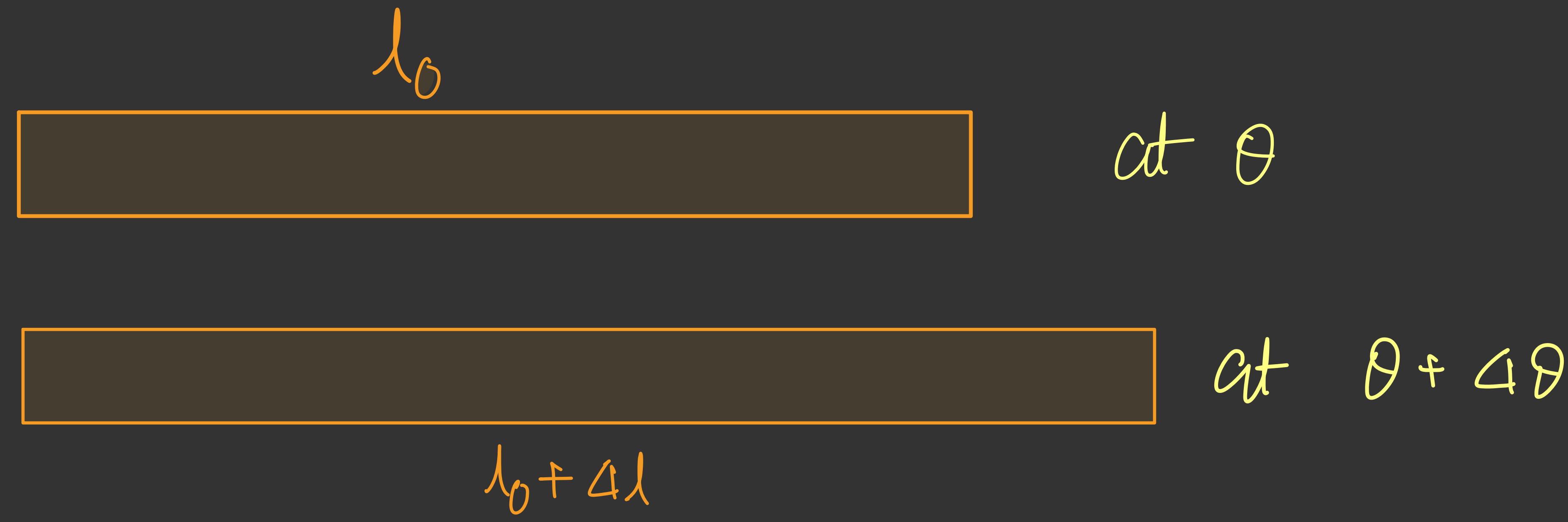
A change in shape/size i.e., dimensions need not necessarily imply a strain. For example, if a body is heated to expand, its volume change, as it acquires a new size, due to expansion. However, the strain remains zero. Unless and until, internal elastic forces operate, to bring the body to the original state, no strain exists. When a body is heated, the total energy of molecule increase, owing to an increase in the kinetic energy of the molecules. This results in a shift (increment) of the "equilibrium distance" of molecules and the body acquires a new shape and size, in the expanded form, whereby the molecules are in "zero force" state. Hence, there is no strain.

* Thermal Stress



$\Delta\theta \uparrow$

Force developed = ?



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$$\text{Strain} = \frac{\Delta l}{(l_0 + \Delta l)} = \frac{\alpha\, l_0\, \Delta\theta}{l_0 + \alpha\, l_0\, \Delta\theta} \approx \frac{\alpha\, l_0\, \Delta\theta}{l_0} = \alpha \cdot \Delta\theta$$

Note:

$l_0 >> \alpha\, l_0\, \Delta\theta$

** $\boxed{\text{Strain} = \alpha \cdot \Delta\theta}$

$$Y = \frac{\text{Stress } \sigma}{\text{Strain } \epsilon}$$

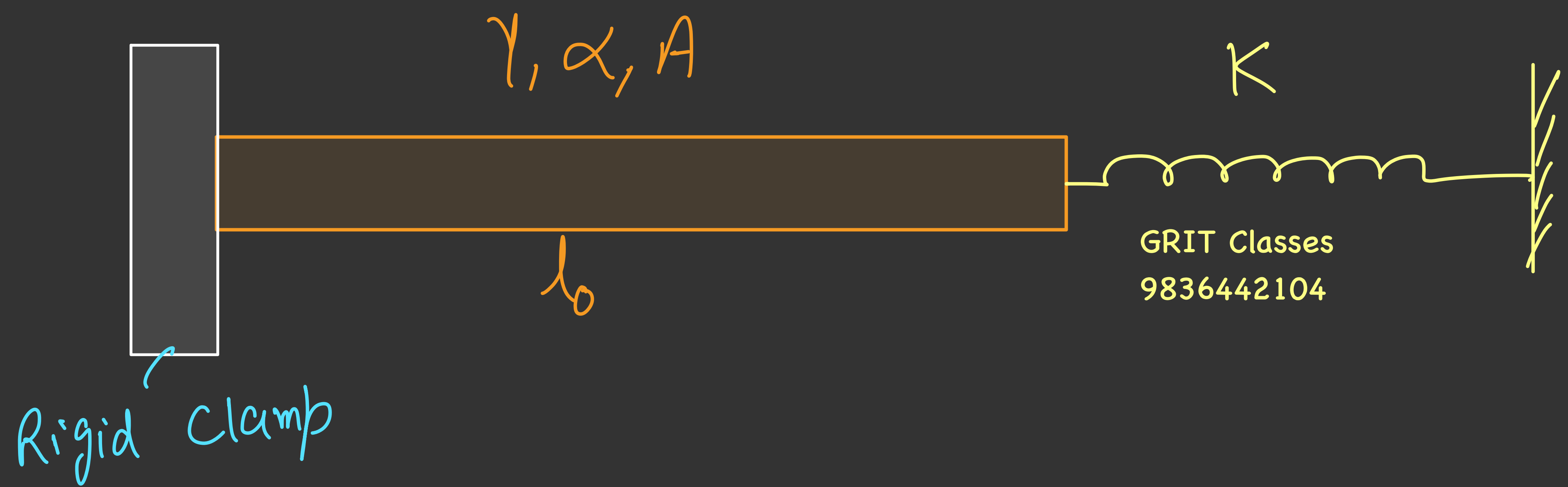
$$Y = \frac{\sigma}{\alpha \cdot \Delta\theta}$$

$\sigma = \alpha \cdot Y\, \Delta\theta$

$F = \sigma A = \alpha\, A\, Y\, \Delta\theta$

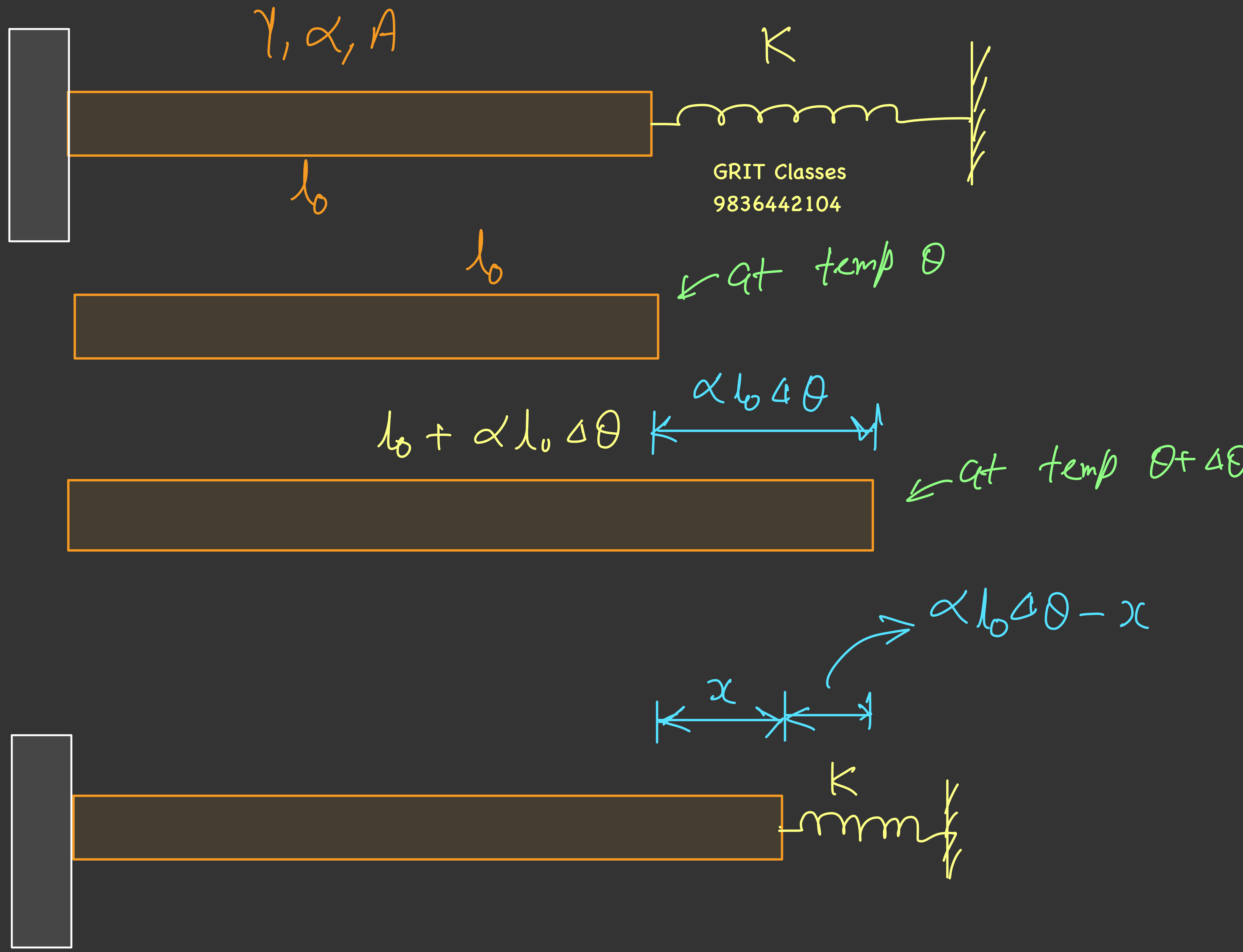
Ans.

eg



$\Delta\theta \uparrow$

$U_{spring} = ?$


γ, α, A
K
l_0
l_0
at temp θ
$\alpha l_0 \Delta\theta$
$l_0 + \alpha l_0 \Delta\theta$
at temp θ+Δθ
$\alpha l_0 \Delta\theta - x$
x
K

Strain, $\epsilon = \dfrac{\alpha l_0 \Delta\theta - x}{l_0 + \alpha l_0 \Delta\theta} \approx \dfrac{\alpha l_0 \Delta\theta - x}{l_0}$

$\because Y = \dfrac{\sigma}{\epsilon}$ $\quad\therefore \sigma = Y \cdot \left(\dfrac{\alpha l_0 \Delta\theta - x}{l_0}\right)$

$F = \sigma A = \dfrac{YA}{l_0}\left(\alpha l_0 \Delta\theta - x\right)$

At equilib: $F = \sigma A = Kx$

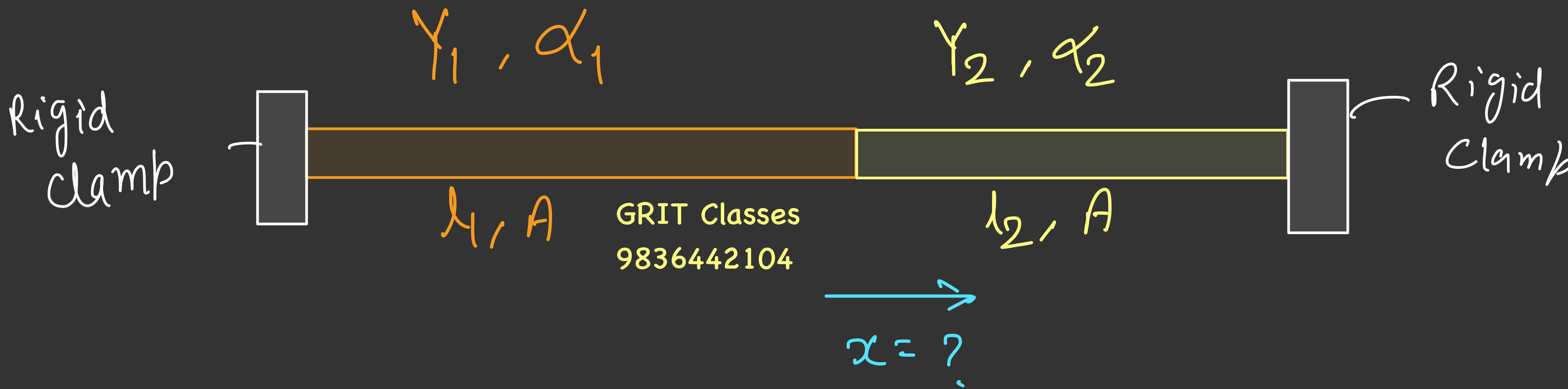
$\therefore \dfrac{YA}{l_0}\left(\alpha l_0 \Delta\theta - x\right) = Kx$

$\therefore \dfrac{YA\alpha \cdot \Delta\theta}{K + \dfrac{YA}{l_0}} = x$ Ans.

$U = \dfrac{1}{2} K x^2$

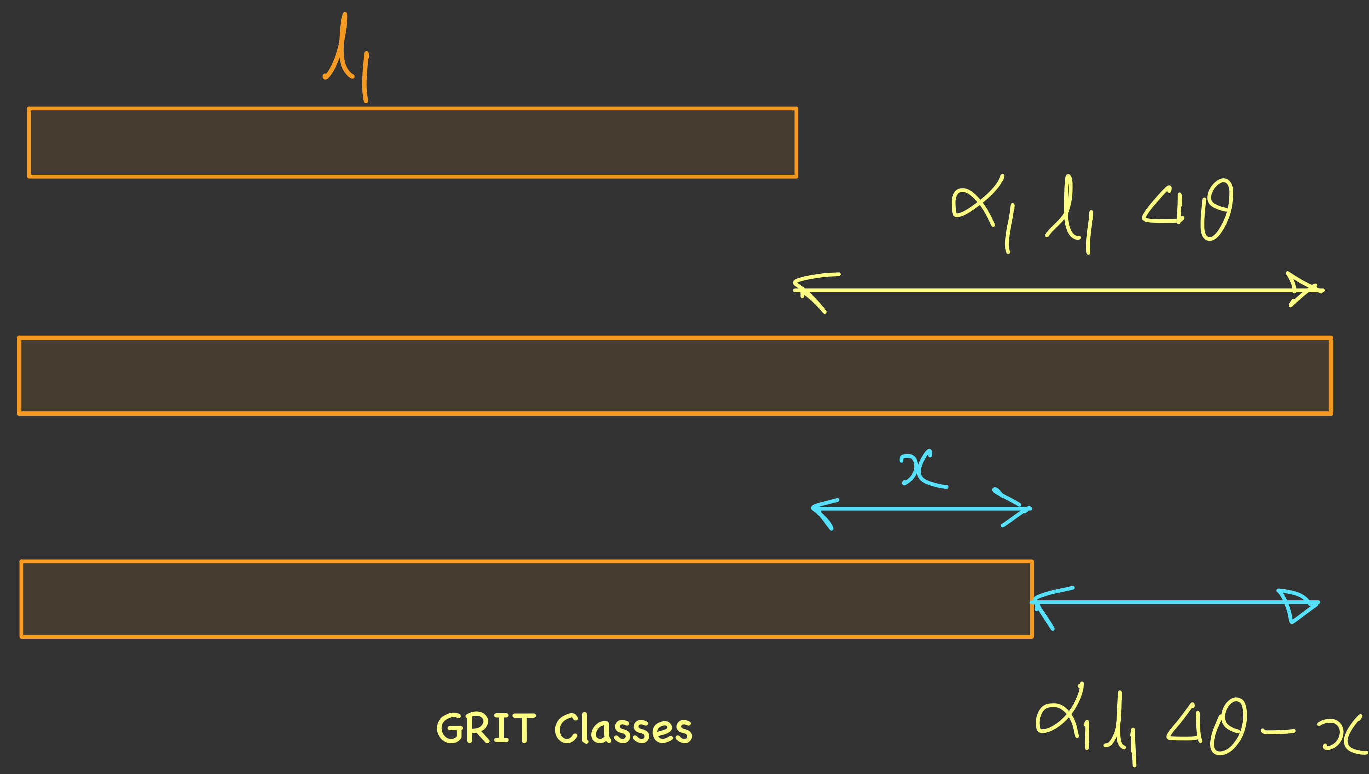
eg

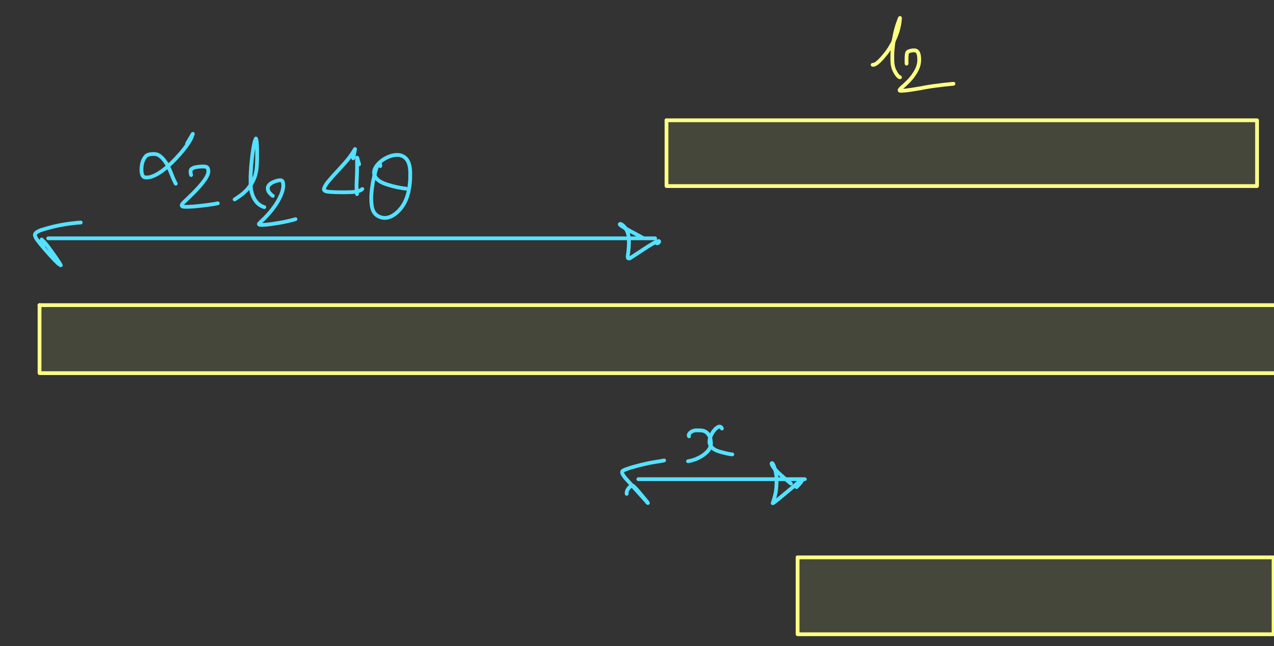
Shift of junction:



If temp of the whole assembly is increased by $\Delta\theta$, find shift in junction.

Solⁿ:





Strain, $\epsilon_1 = \dfrac{\alpha_1 l_1 \Delta\theta - x}{l_1 + \alpha_1 l_1 \Delta\theta} \approx \dfrac{\alpha_1 l_1 \Delta\theta - x}{l_1}$

Stress, $\sigma_1 = Y_1 \epsilon_1 = \dfrac{Y_1}{l_1}\left[\alpha_1 l_1 \Delta\theta - x\right]$

$F_1 = \sigma_1 A = \dfrac{Y_1 A}{l_1}\left[\alpha_1 l_1 \Delta\theta - x\right]$

Strain, $\epsilon_2 = \dfrac{\alpha_2 l_2 \Delta\theta + x}{l_2 + \alpha_2 l_2 \Delta\theta} \approx \dfrac{\alpha_2 l_2 \Delta\theta + x}{l_2}$

Stress, $\sigma_2 = Y_2 \cdot \epsilon_2 = \dfrac{Y_2}{l_2}\left[\alpha_2 l_2 \Delta\theta + x\right]$

$F_2 = \sigma_2 A = \dfrac{Y_2 A}{l_2}\left[\alpha_2 l_2 \Delta\theta + x\right]$

Now, $F_1 = F_2$

$$\therefore \frac{Y_1 \cancel{A}}{l_1}\left[\alpha_1 l_1 \Delta\theta - x\right] = \frac{Y_2 \cancel{A}}{l_2}\left[\alpha_2 l_2 \Delta\theta + x\right]$$

$$Y_1 \alpha_1 \Delta\theta - \frac{Y_1}{l_1} x = Y_2 \alpha_2 \Delta\theta + \frac{Y_2}{l_2} x$$

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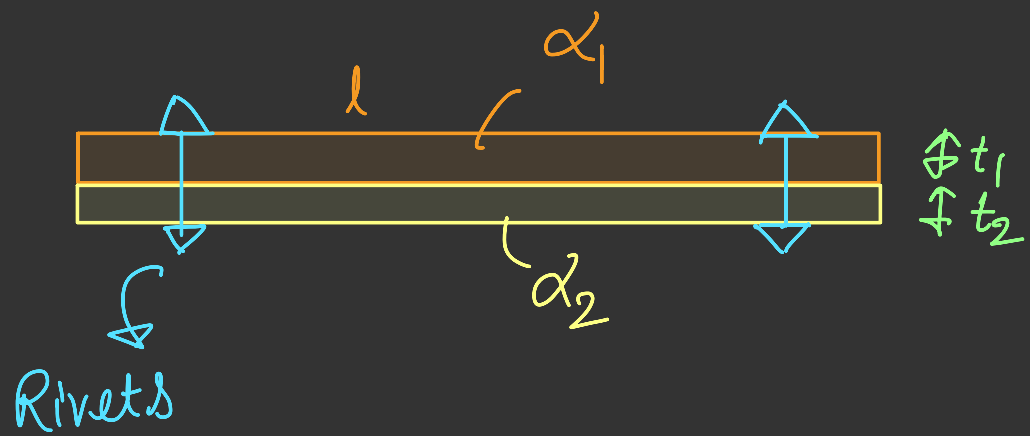
$$\therefore \boxed{x = \frac{Y_1 \alpha_1 \Delta\theta - Y_2 \alpha_2 \Delta\theta}{\frac{Y_1}{l_1} + \frac{Y_2}{l_2}}}$$

Ans.

Bi-metallic Strip :

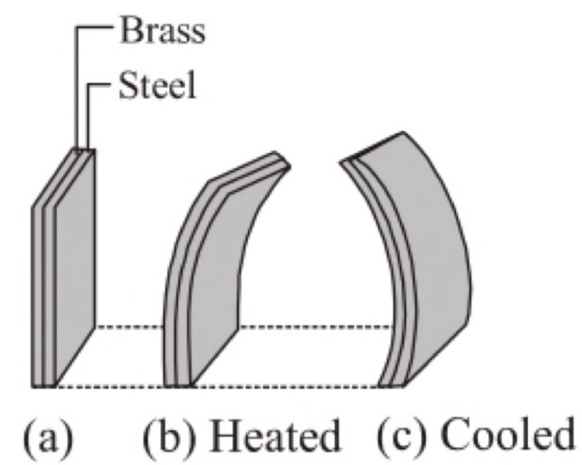


$\alpha_1 > \alpha_2$

$\Delta\theta \uparrow$

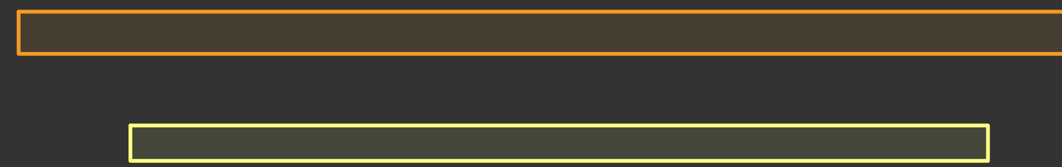
The Bimetallic Strip

A bimetallic strip is made from two thin strips of metal that have different coefficients of linear expansion, as figure shows.

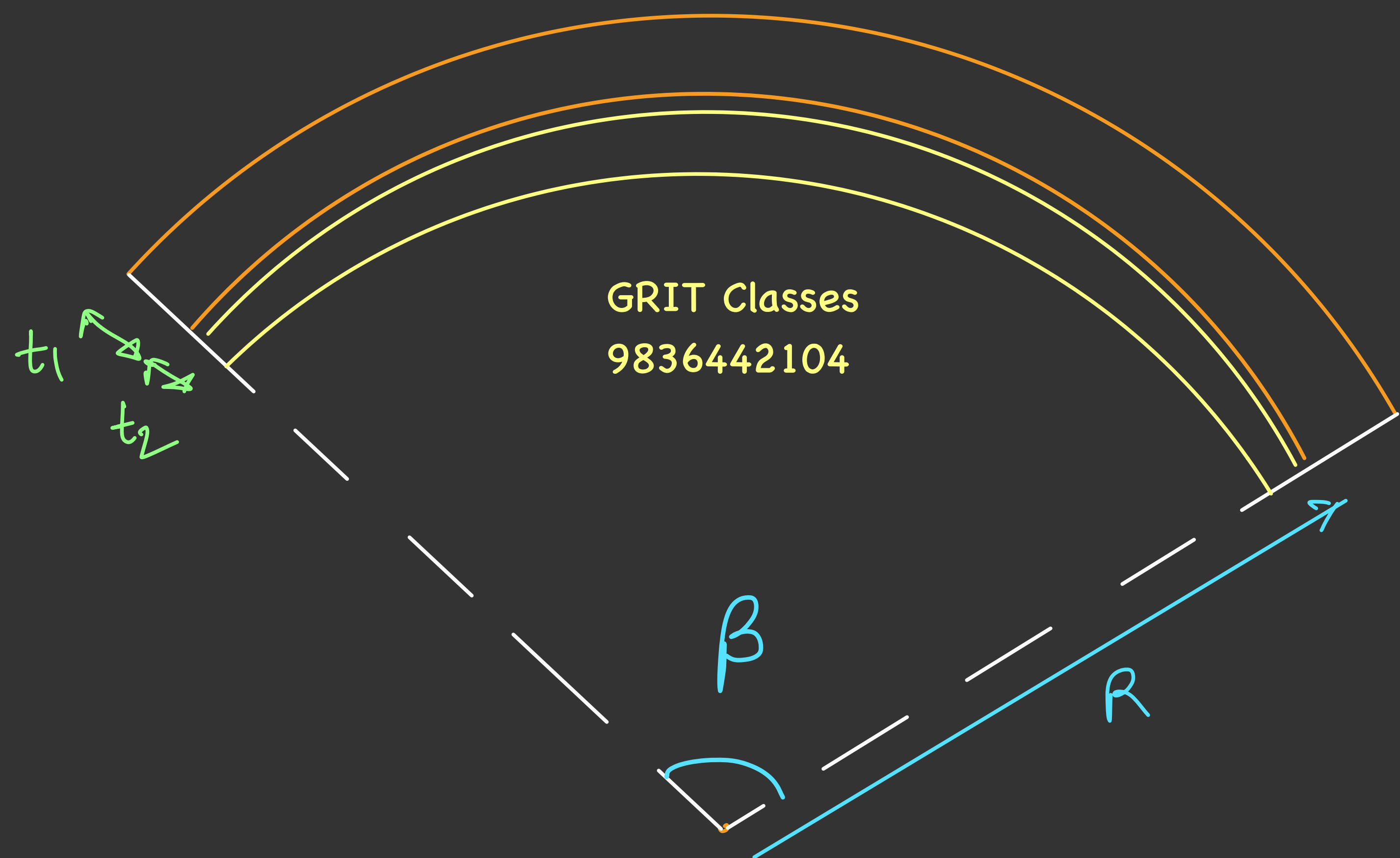


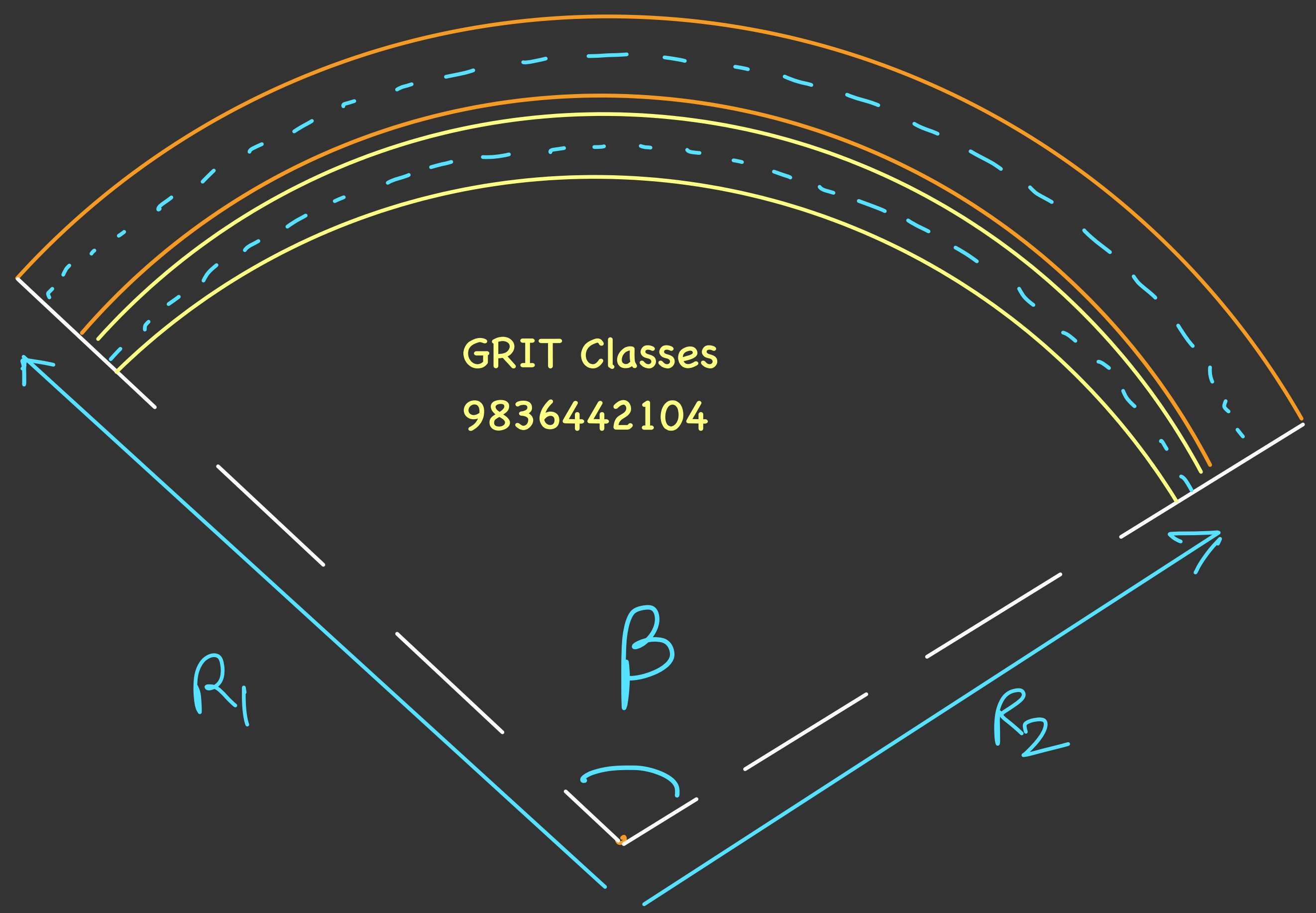
(a) A bimetallic strip and how it behaves when (b) heated and (c) cooled

$$l_1 = l(1+\alpha_1 \Delta\theta)$$



$$l_2 = l(1+\alpha_2 \Delta\theta)$$





$$l_1 = R_1 \beta \quad ; \quad l_2 = R_2 \beta$$

where, $R_1 = R + \frac{t_1}{2}$

$$R_2 = R - \frac{t_2}{2}$$

$$\therefore \beta = \frac{l_1}{R_1} = \frac{l_2}{R_2}$$

$$\Rightarrow \beta = \frac{\cancel{l}\left[1 + \alpha_1 \Delta\theta\right]}{R + \frac{t_1}{2}} = \frac{\cancel{l}\left[1 + \alpha_2 \Delta\theta\right]}{R - \frac{t_2}{2}}$$

$$\Rightarrow \quad \frac{1+\alpha_1 \Delta\theta}{1+\alpha_2 \Delta\theta} = \frac{R+\frac{t_1}{2}}{\frac{R-t_2}{2}}$$

Find $\underline{R}$

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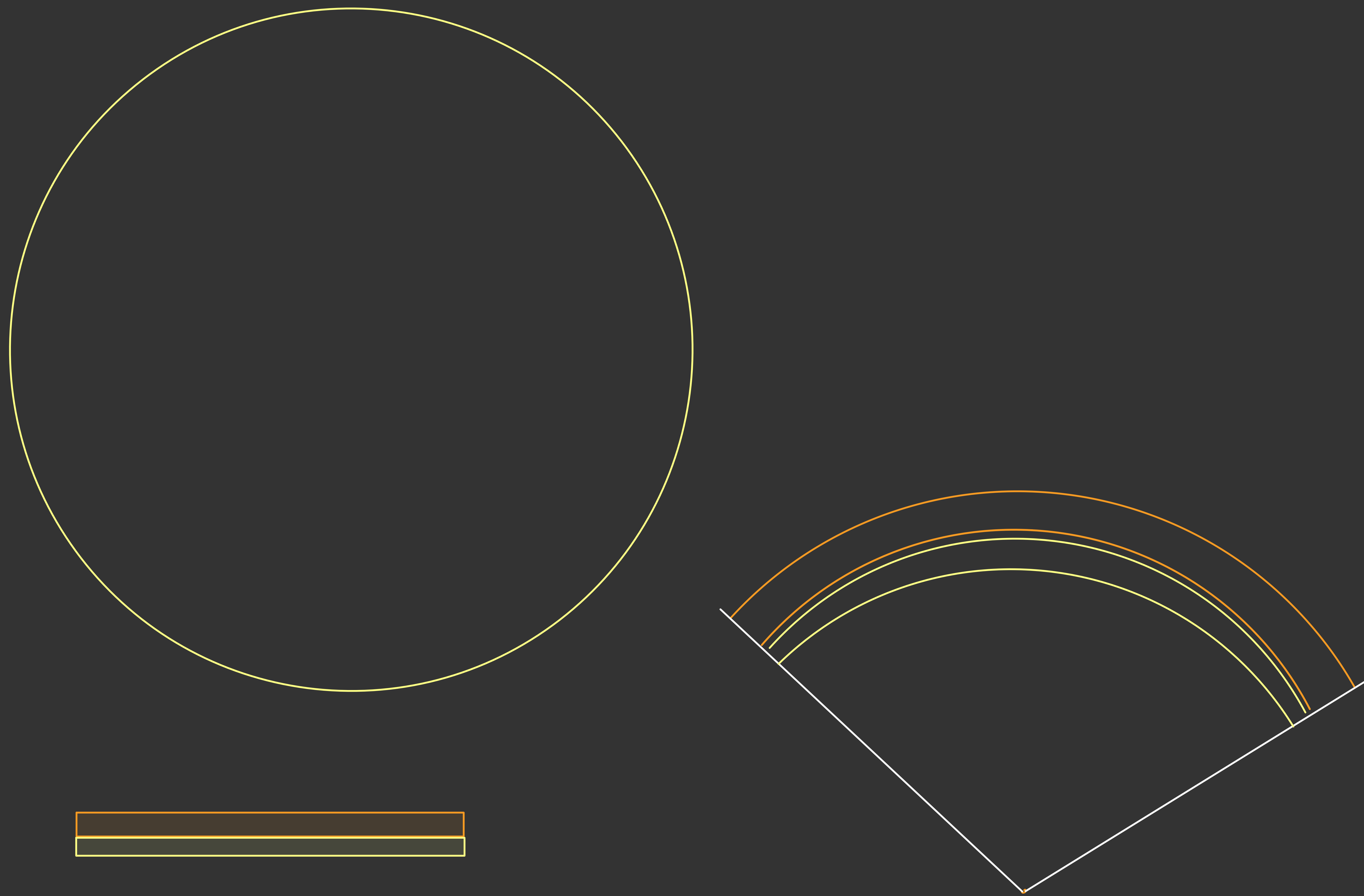
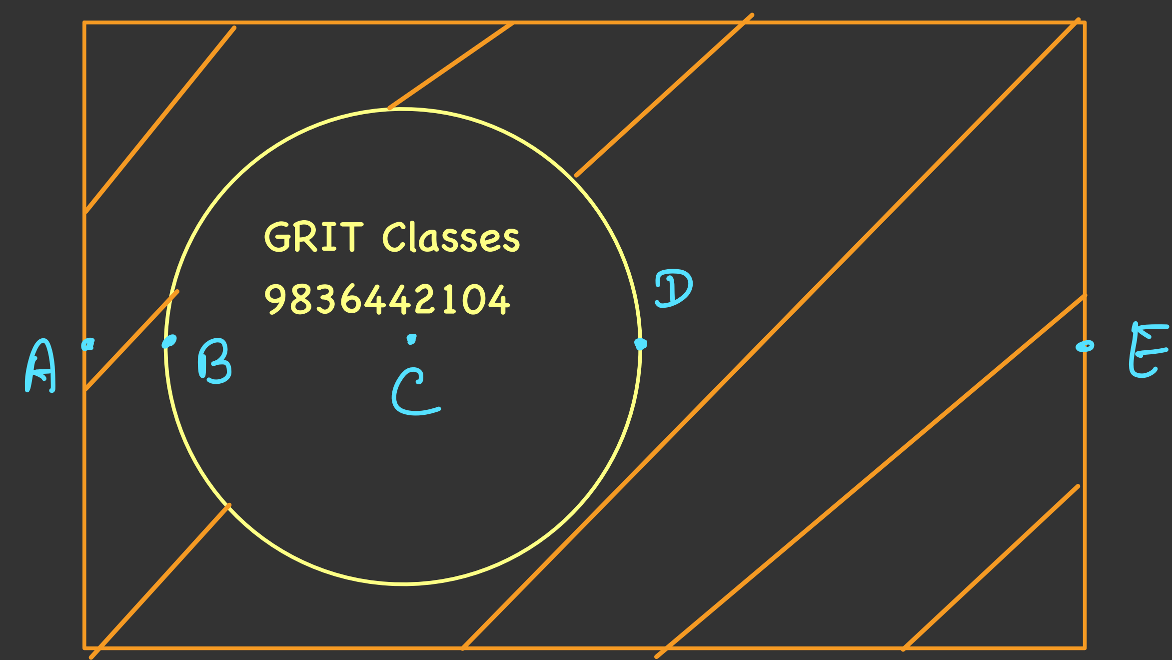


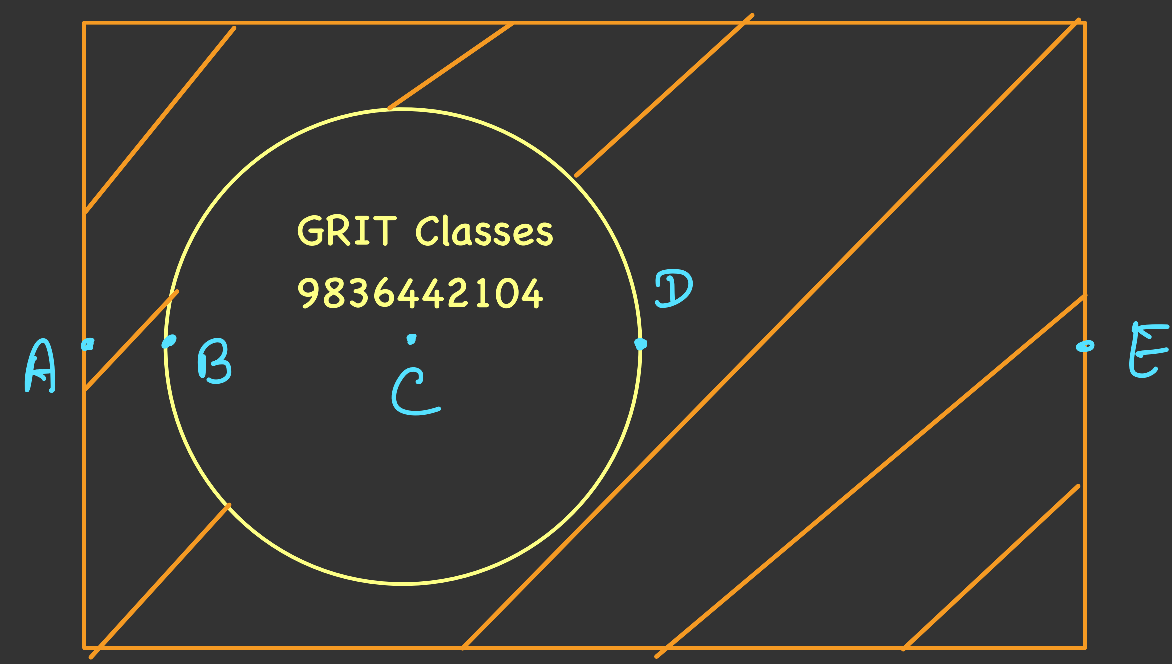
eg



If $\angle\theta \uparrow$

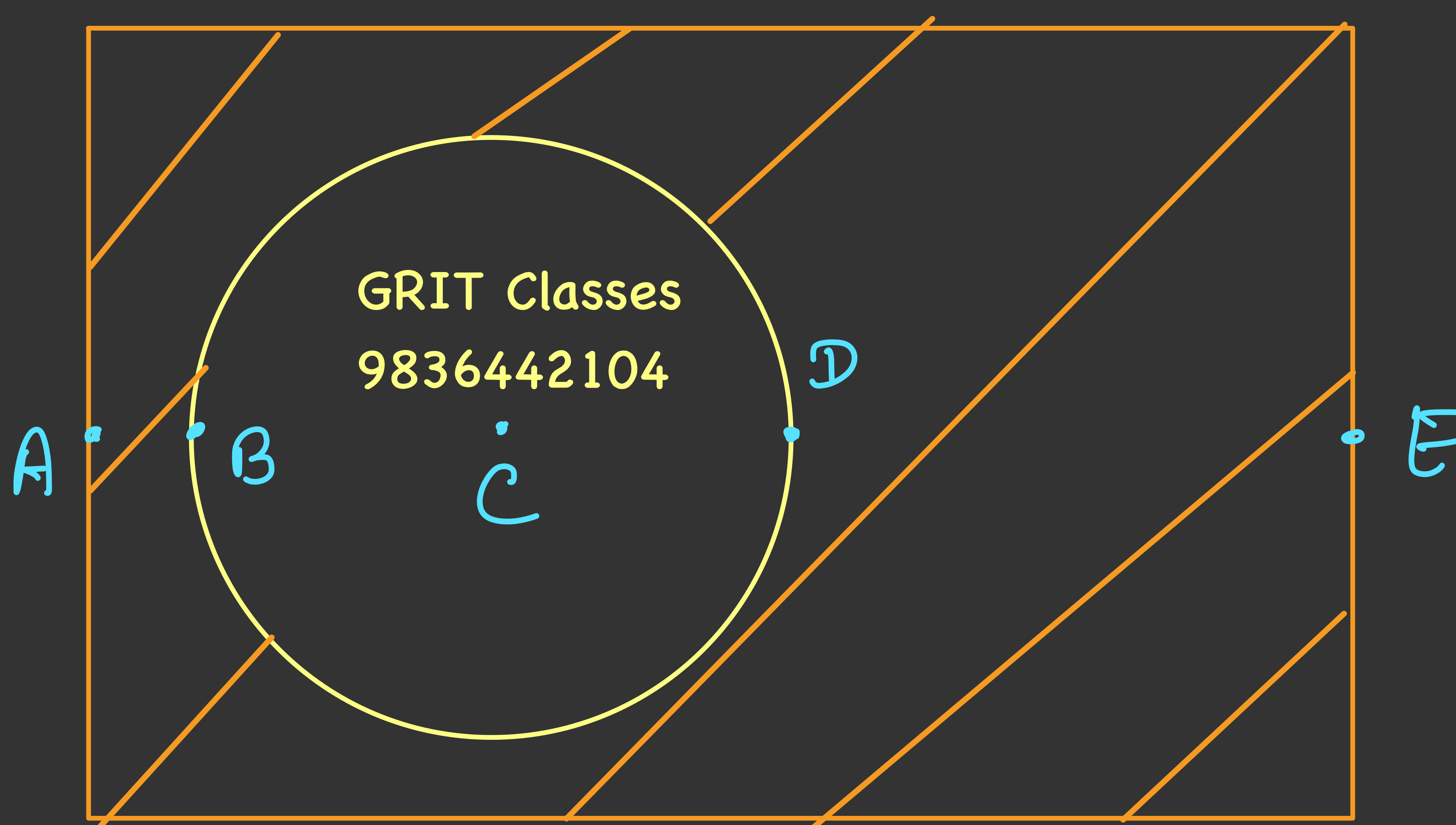
Whether these lengths increase or decrease ?

1) AB
2) BC
3) BD
4) DE



If $\Delta\theta \uparrow$ Zoom in

If $\Delta\theta \downarrow$ Zoom out



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TESTIMONIALS

UTSAV AGARWAL

ADV 2023- AIR 1187 - ROLL NO 235062143
IIT KHARAGPUR- ELECTRONICS AND ELECTRICAL COMMUNICATION

Hi. I am Utsav Agarwal. I am a second year undergraduate student of the department of Electronics and Electrical Communication Engineering at IIT Kharagpur. My significant academic achievements are as follows (all are general category ranks):
KVPY SA: AIR 464
JEE Advanced: AIR 1187
JEE Mains: 99.66 percentile
WBJEE: AIR 48
I scored 91 out of 120 in Physics in JEE Advanced 2023. Before Class 10 Boards (in 2021), I had no idea of JEE preparation. Amit Sharma Sir, who was my only physics teacher during these 2 years of JEE preparation has a major contribution in it.
Although I was an above average student and a class topper in my school, I used to secure very less marks (almost lowest) in my initial days of preparation. None of the tests in my two years of preparation predicted under 10000 rank.

The way Amit Sharma Sir taught me Physics not only made my concepts crystal clear but also made me fall in love with the subject. Unlike other teachers he focuses more on concept and learning rather than just rigorous problem solving without knowing the concept. He made us "feel" every concept that he taught. His knowledge and way of teaching Physics is just exemplary which helps me even now.
His teachings is not only limited to academia but also how to tackle the problems which we generally face during JEE preparation. He is such a teacher who will give you a constant dose of motivation in the most soothing way possible.Its because of him and his advice to focus on learning and not giving up that made me capable enough to secure such a rank. I dedicate my JEE rank and also my future academic achievements to him.
According to me he is the best Physics teacher you can find in Kolkata. He is no more a part of Fiitjee and runs his own classes with the name Grit Classes in Salt Lake.

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Scores

JEE (Advanced) 2023 Roll Number	235062143
Candidate Name	UTSAV AGARWAL
Chemistry Paper 1	39
Chemistry Paper 2	26
Chemistry Total	65
Physics Paper 1	45
Physics Paper 2	46
Physics Total	91
Mathematics Paper 1	21
Mathematics Paper 2	35
Mathematics Total	56
Total	212
Positive	226

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Rank

CRL Rank	1187