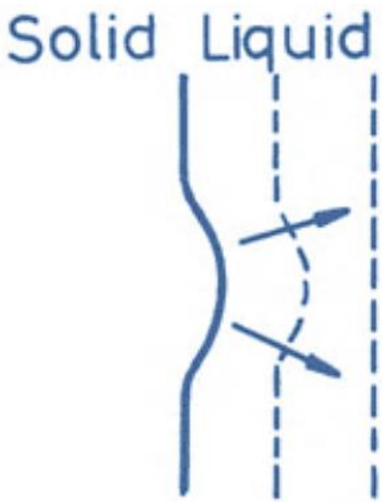
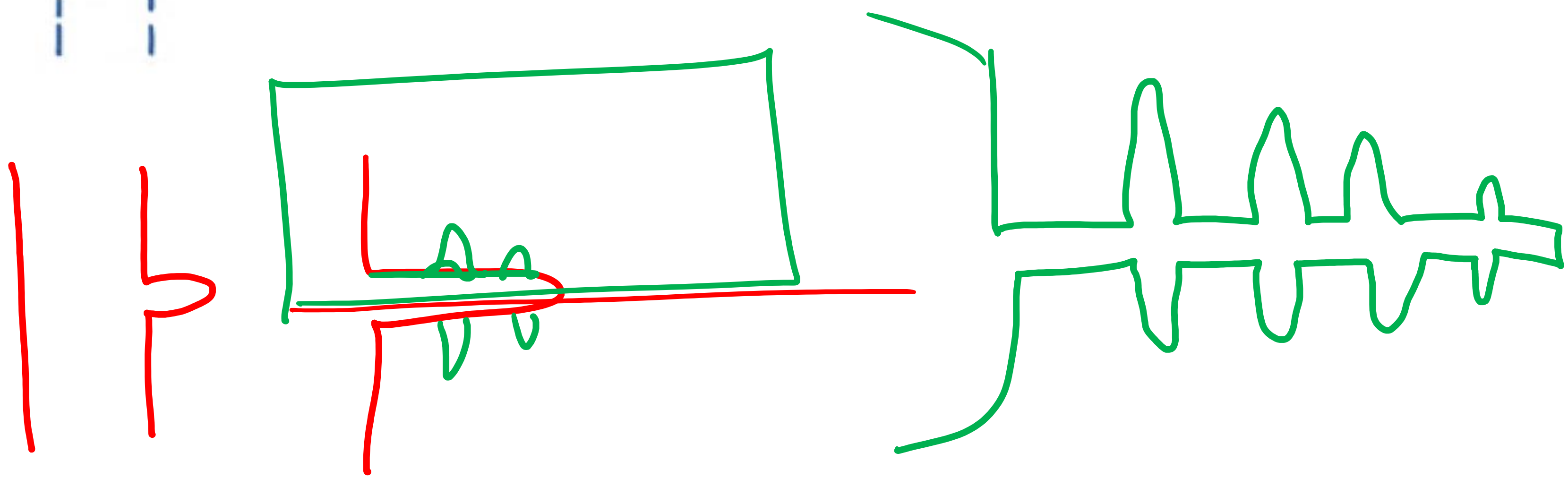
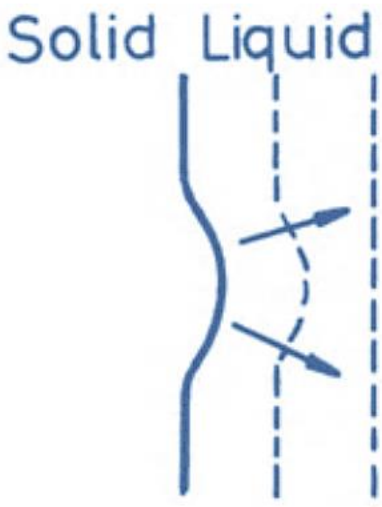
Solidification of pure material: - Gr.

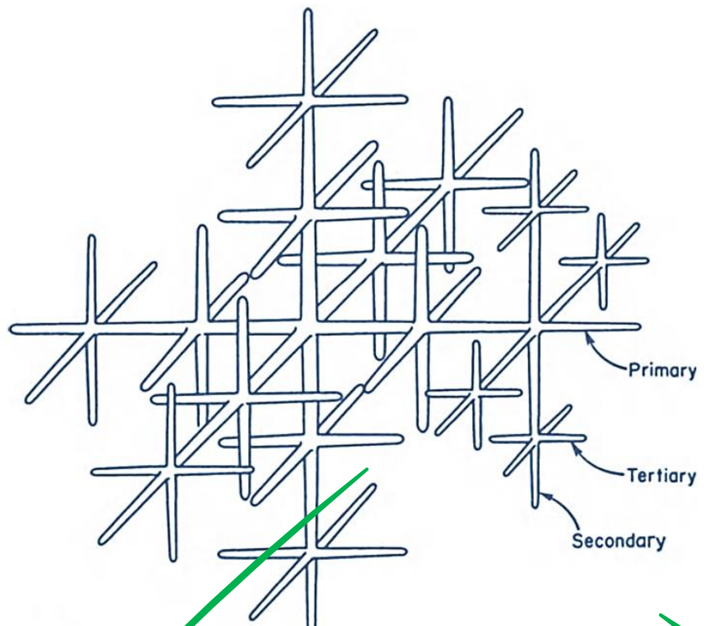


$$k_S \frac{\partial T_S}{\partial x} - k_l \frac{\partial T_l}{\partial x} = \rho L \frac{\partial x}{\partial t} = \rho L v$$



Solidification of pure material: - Gr.





$$k_S \frac{\partial T_S}{\partial x} - k_l \frac{\partial T_l}{\partial x} = \rho L \frac{\partial x}{\partial t} = \rho L v$$

Phase transformations
in metals and alloys

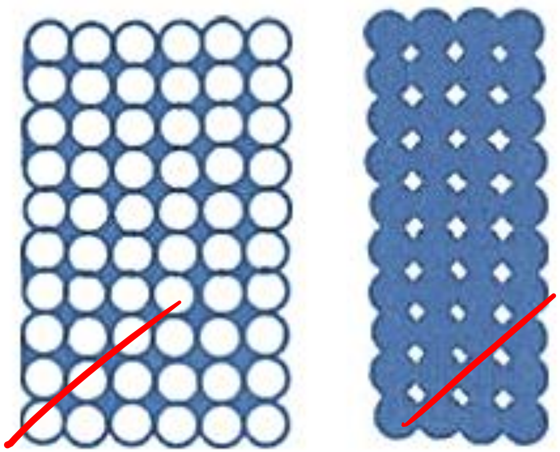
Binary Mixture

$X_A + X_B = 1$

Cu

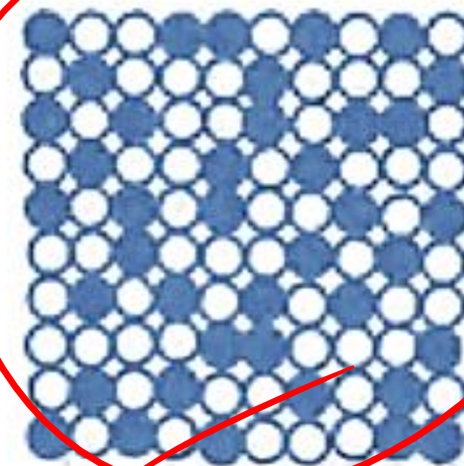
Before mixing

Al



MIX

After mixing



X_A mol A　　X_B mol B

F.E. $X_A G_A$　　F.E. $X_B G_B$

Total free energy =

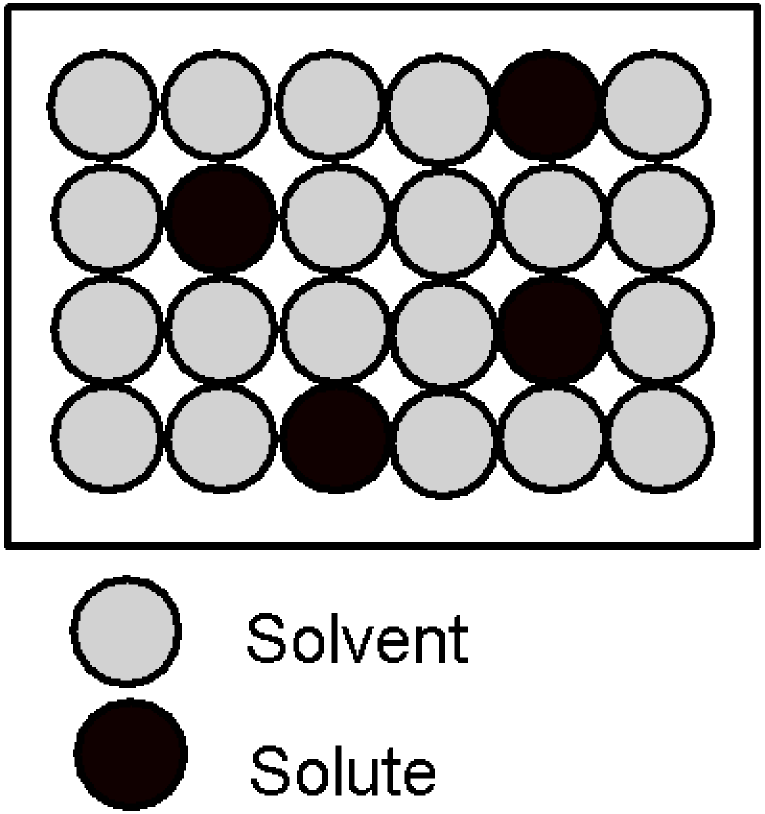
$$\boxed{G_1 = X_A G_A + X_B G_B}$$

1 mol solid solution

Total free energy =

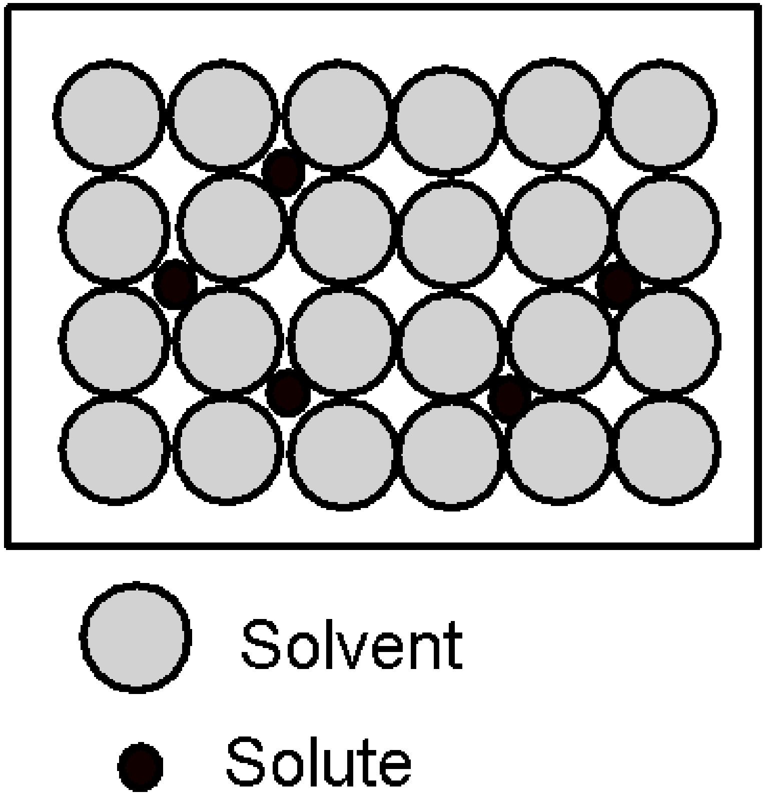
$$G_2 = G_1 + \Delta G_{mix}$$

Solid solution – Multi-component Metals



(a) Substiutional solid solution

Similar atomic size (same order)
+/- 15%
Eg: Brass, Cu-Ni



(b) Interstitial solid solution

Much smaller
(at least one order of magnitude lower)
Eg: Carbon in Iron (Steel)

Binary mixture

A

B

x_A mol

x_B mol

Before mixing

$x_A + x_B = 1$

$x_A G_A$

$x_B G_B$

J/mol

$G_1 = x_A G_A + x_B G_B$

Before mixing

Binary mixture

A + B

After mixing

$$G_2 = G_1 + \Delta G_{mix}$$

$$\boxed{\Delta G_{mix} = G_2 - G_1}$$

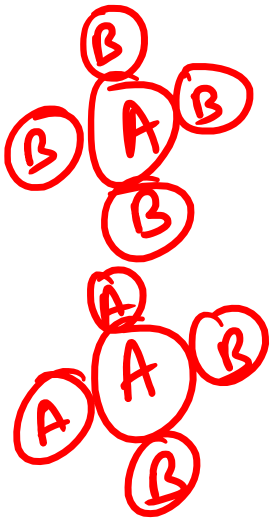
$$\boxed{\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}}$$

$$\Delta H_{mix} = H_2 - H_1$$

$$\Delta S_{mix} = S_2 - S_1$$

$=$

Binary mixture : IDeal Soln



$$\boxed{\Delta H_{mix}} = 0$$

$$\Delta G_{mix} = 0 - T\,\Delta S_{mix}$$

$$= -T\,\Delta S_{mix}$$

$$\boxed{S = k \ln w} \rightarrow$$ measure the randomness.

Binary mixture

$\ln(100000)!$

$=$

$5!$

$\ln N!$

$N \to \infty$

$= N \ln N$

$\Delta S_{mix} = k \ln \omega$

$\Delta S_{mix} = S_{th} \xrightarrow{} 0 + S_{conf.}$

$N_A = x_a N_a$

avogadro no.

$$\omega_{conf} = \frac{(N_A + N_B)!}{(N_A)!\,(N_B)!}$$

$N_B = x_B N_a$

Binary mixture

$$\Delta S_{mix} = k \ln \frac{(N_A + N_B)!}{N_A!\, N_B!}$$

$$N_A = x_A N_a$$

$$N_B = x_B N_a$$

$$= k \ln \frac{(x_A N_a + x_B N_a)!}{(x_a N_a)!\, (x_B N_a)!}$$

$$= k \left\{ \ln (x_a N_a + x_B N_a)! - \ln (x_a N_a)! - \ln (x_B N_a)! \right\}$$

$$\ln N! = N \ln N$$

$$x_a + x_B = 1$$

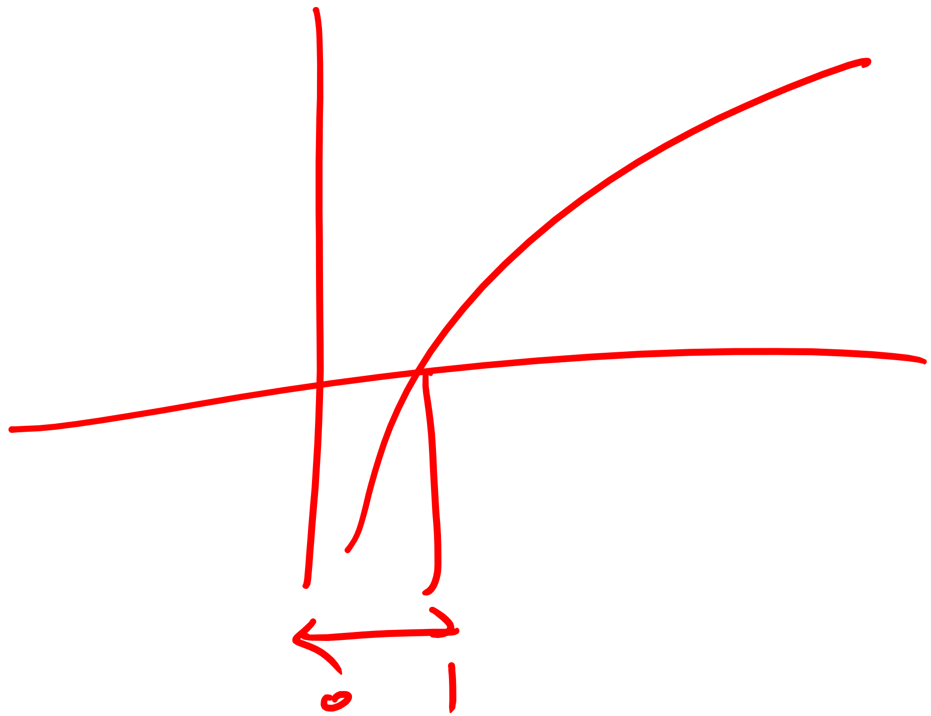
Binary mixture

$$\Delta S_{mix} = -\underbrace{N_a k}\{x_A \ln x_A + x_B \ln x_B\}$$

$$= -R\{x_A \ln x_A + x_B \ln x_B\}$$

$$x_A + x_B = 1$$

$$0 < x_A \text{ or } x_B < 1$$



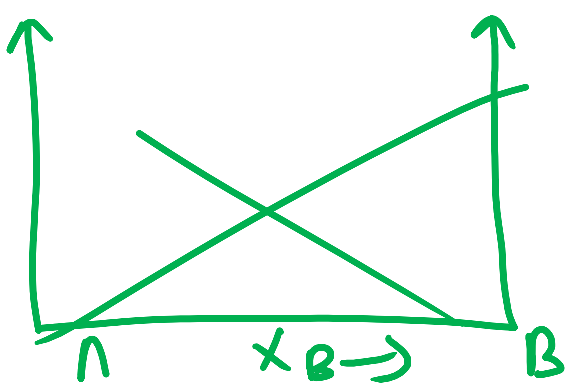
Binary mixture

$$\Delta G_{mix} = -T\Delta S_{mix}$$

$$= -R(-T)\{x_A \ln x_A + x_B \ln x_B\}$$

$$= RT\{x_A \ln x_A + x_B \ln x_B\}$$

$$\boxed{G_1 = x_A G_A + G_B x_B} \quad \boxed{G_2 = G_1 + \Delta G_{mix}}$$



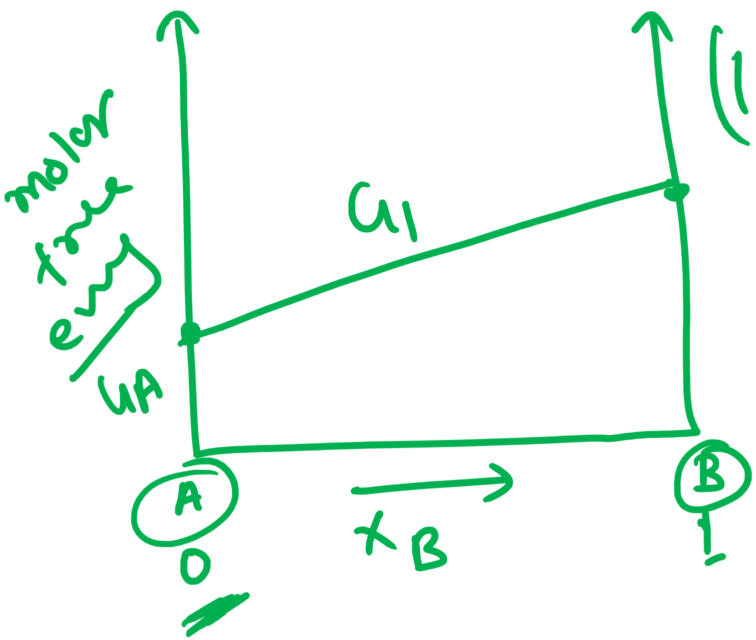
Binary mixture

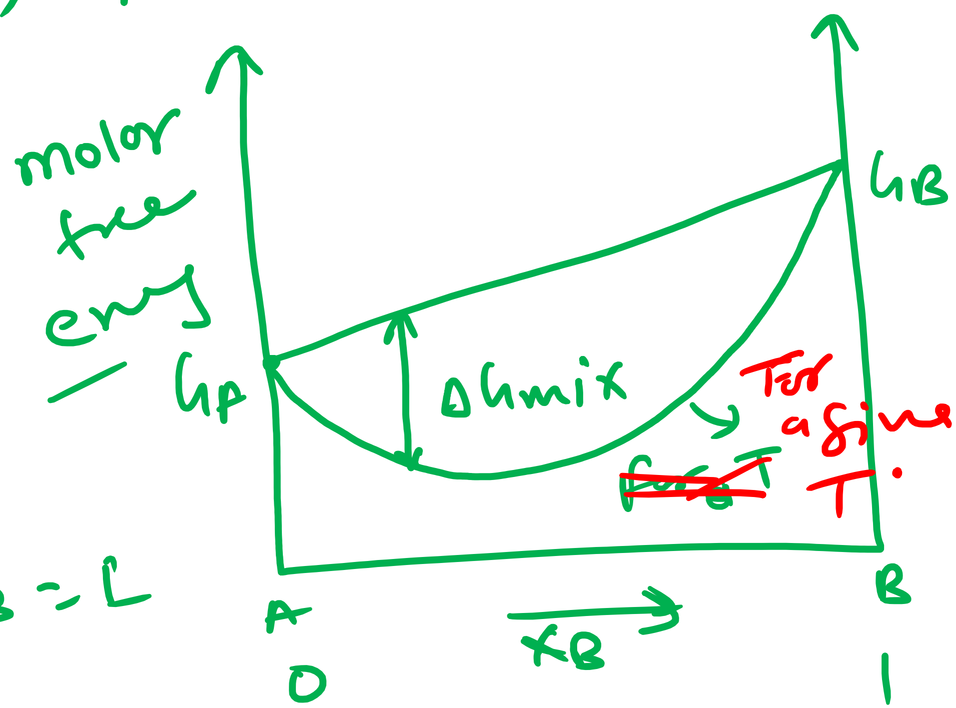
$$RT\{(1-x_B)\ln x_A + x_B \ln x_B\}$$

$$\Delta G_{mix} = RT\{x_A \ln x_A + x_B \ln x_B\} = -T\Delta S_{mix}$$

$$G_1 = x_A G_A + x_B G_B, \quad \boxed{G_2 = G_1 + \Delta G_{mix}}$$

$$(1-x_B)G_A + x_B G_B$$

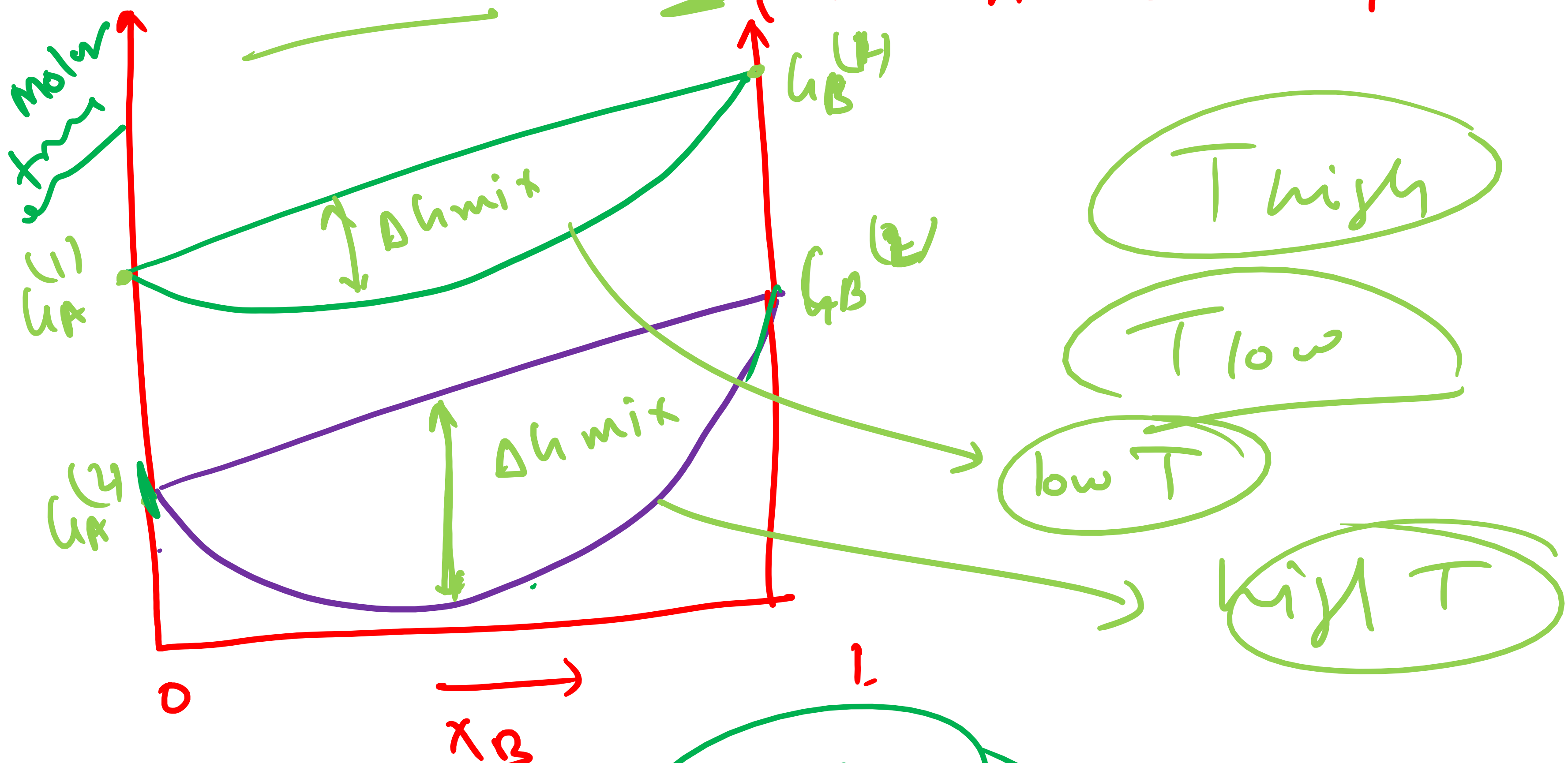




$$x_A + x_B = 1$$

Binary mixture

$$\Delta G_{mix} = RT\{x_A \ln x_A + x_B \ln x_B\}$$



$$\frac{\partial G}{\partial x}$$

Binary mixture

$$\mu = \frac{\partial G}{\partial x}$$

10 % A
90 % B

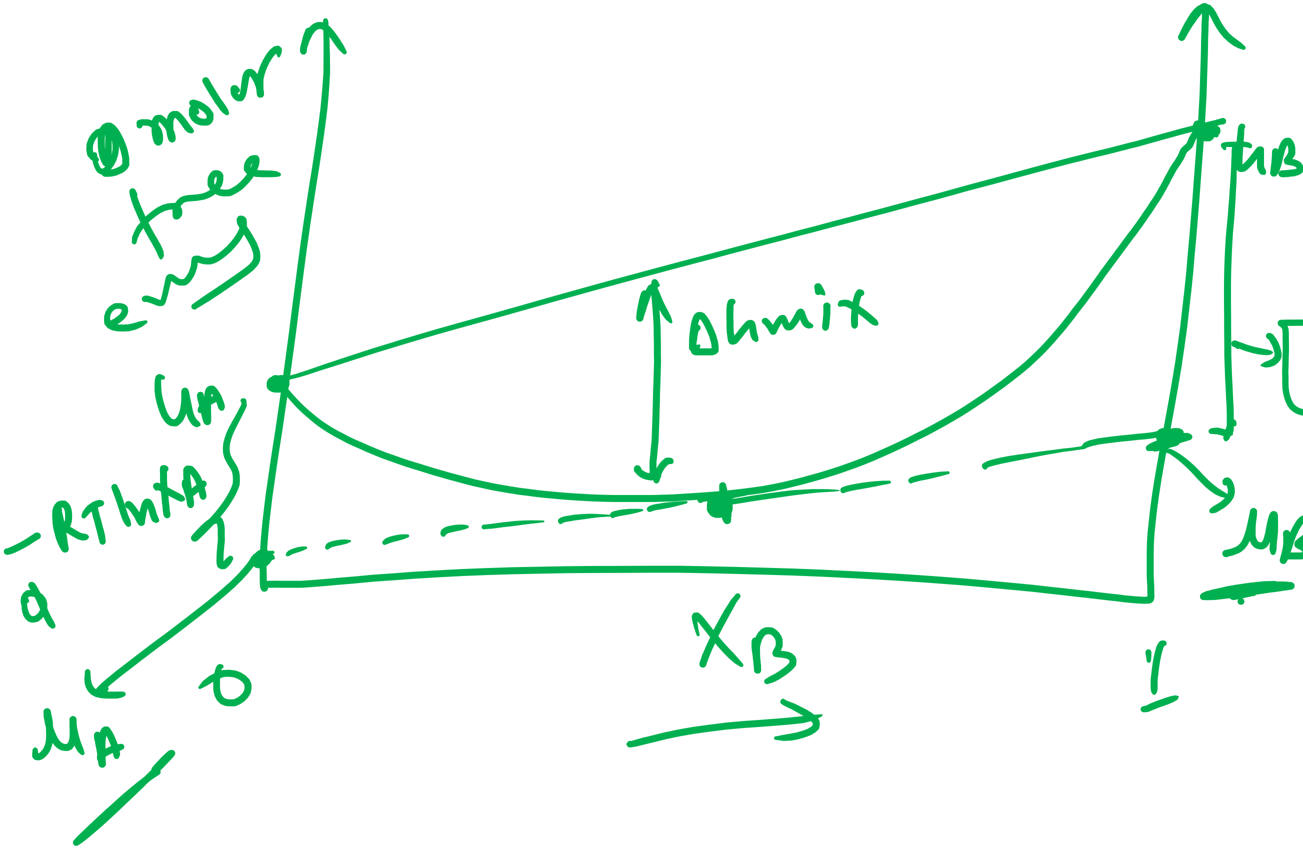
10.001 % A
89.999 % B

$$\boxed{G = \mu_A x_A + \mu_B x_B}$$

$$G_2 = G_2 + \Delta G_{mix} = x_A G_A + x_B G_B + RT\{x_A \ln x_A + x_B \ln x_B\}$$

$$\mu_A = G_A + RT \ln x_A \quad \Big| \quad \mu_B = G_B + RT \ln x_B$$

Binary mixture



$\mu_A = G_A + RT\ln X_A$

$\mu_B = G_B + RT\ln X_B$

$-RT\ln X_B$

$\frac{\partial G}{\partial x}$ = μ

Binary mixture : Regular soln

$$\Delta H_{mix} = \Omega X_A X_B$$

A–A

B–B

A–B

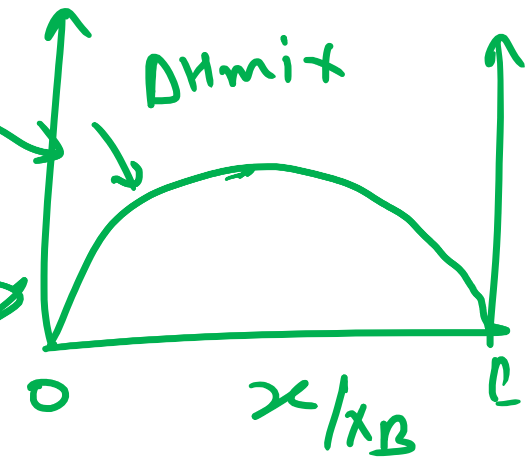
A B

$$\Omega = N_a \varepsilon z$$

$$\boxed{\varepsilon = \varepsilon_{AB} - \frac{\varepsilon_{AA} + \varepsilon_{BB}}{2}}$$

Binary mixture

$$\Delta H_{mix} = \Omega X_A X_B$$



$\Omega > 0$

$\Omega < 0$

$\Omega (x_A x_B)$

$\Omega x_B (1 - x_B)$

$\Omega (x - x^2)$

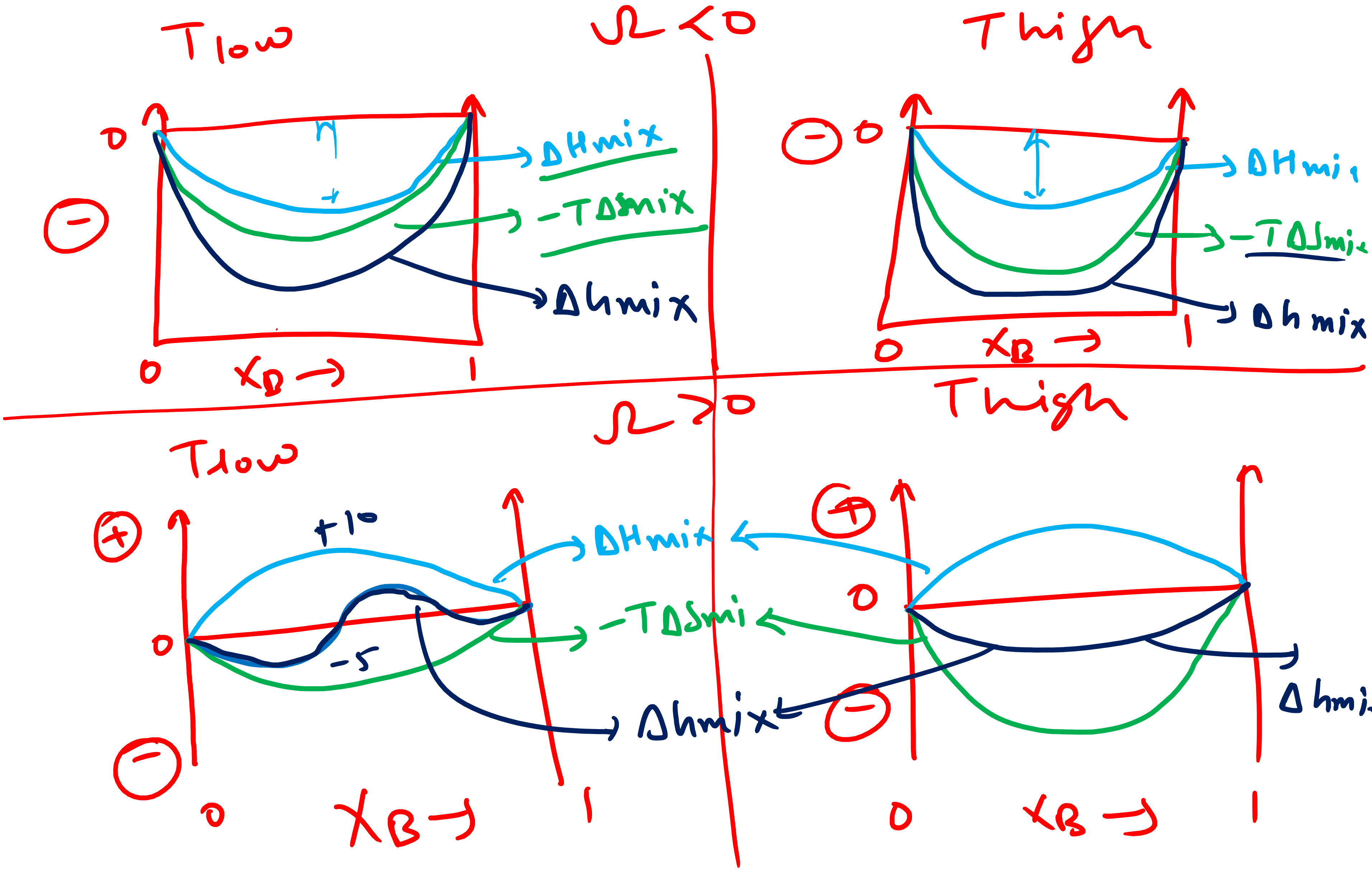
$$\varepsilon_{AB} = \frac{\varepsilon_{AA} + \varepsilon_{BB}}{2}$$

$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}$$

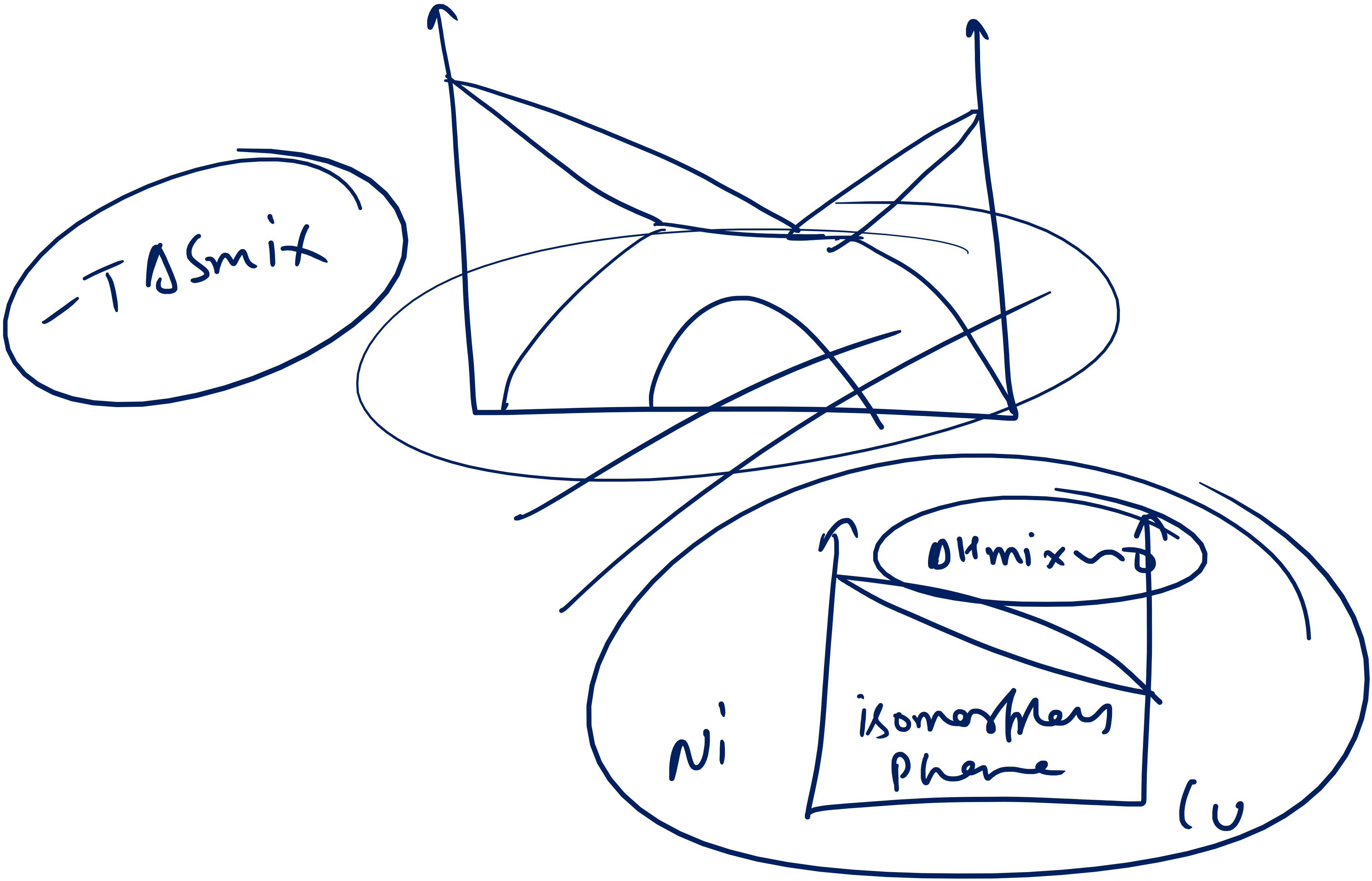
$$= \Omega x_A x_B + TR\{x_A \ln x_A + x_B \ln x_B\}$$

Binary mixture

$\Delta h_{mix} = \Delta H_{mix} - T\Delta S_{mix} = \Omega x_A x_B + RT\{x_A \ln x_A + x_B \ln x_B\}$



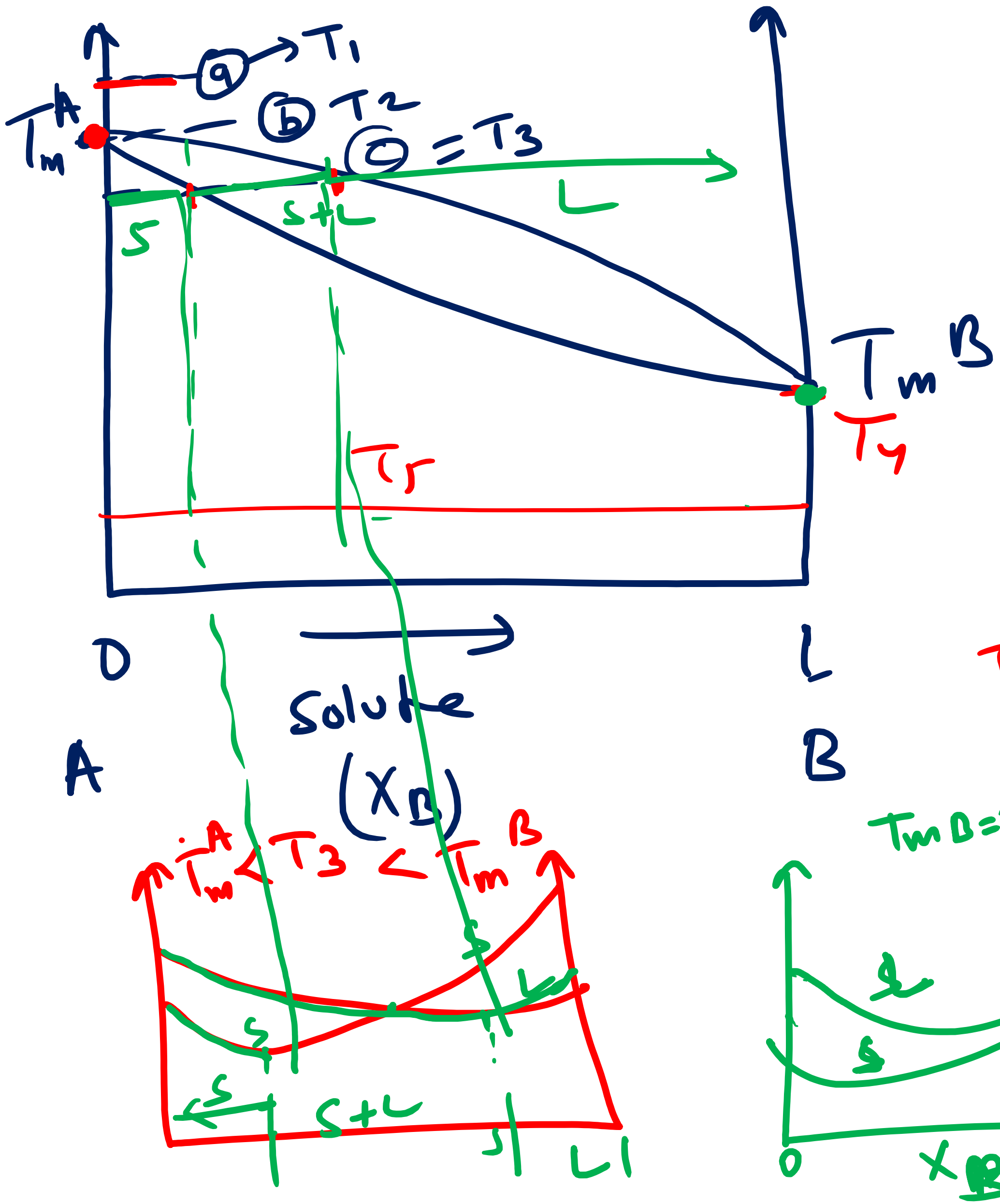
Binary mixture

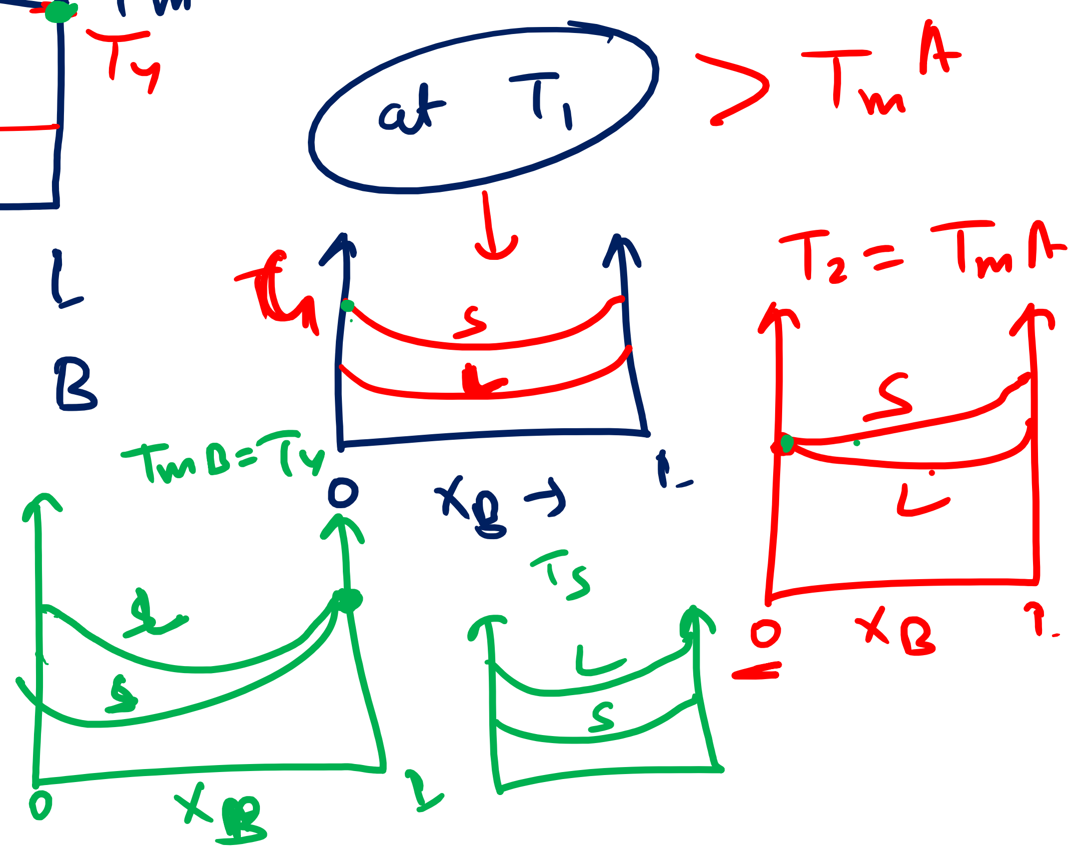


Binary mixture

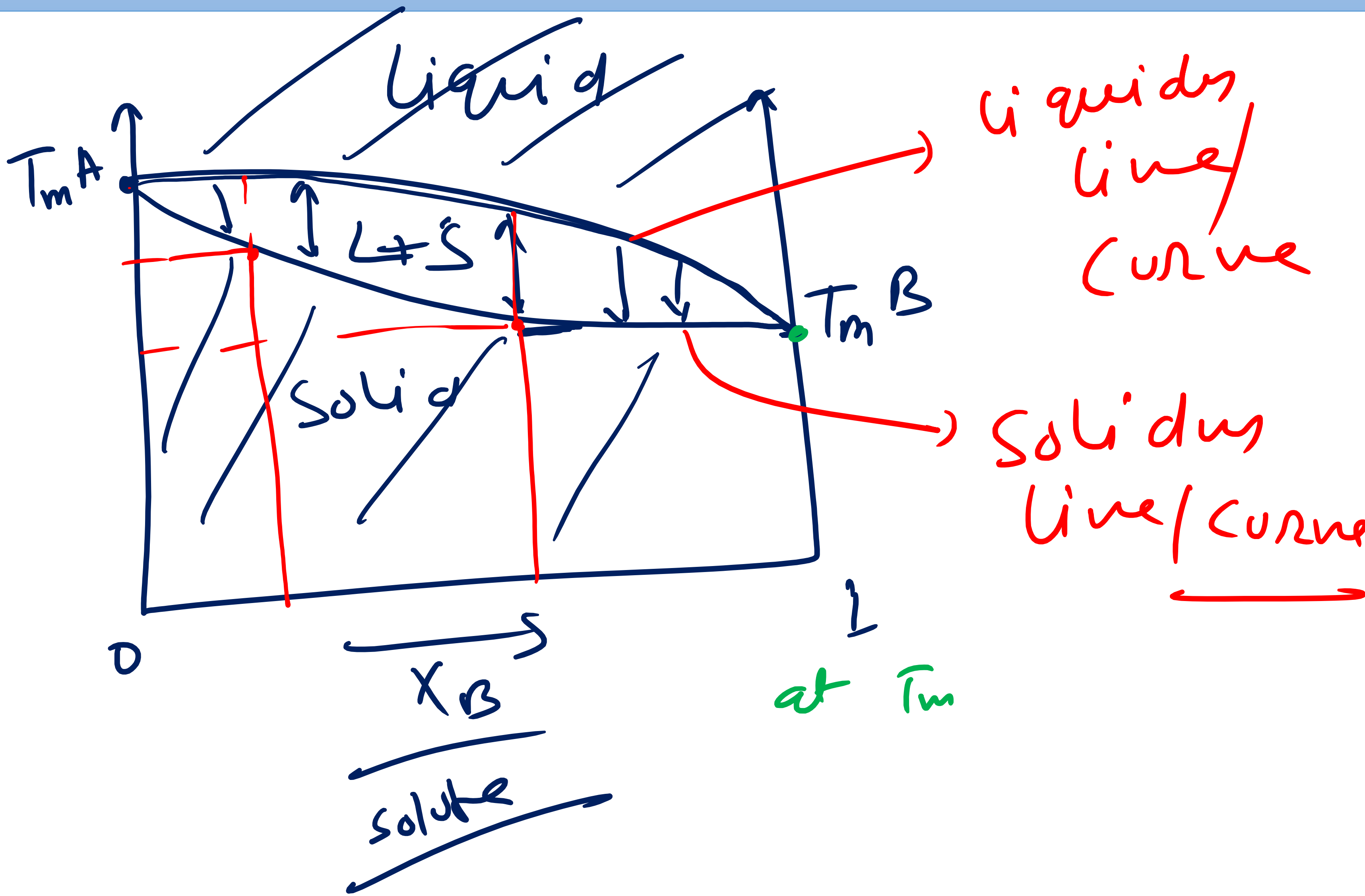
T_m^A = melting point of A

T_m^B = " " of B

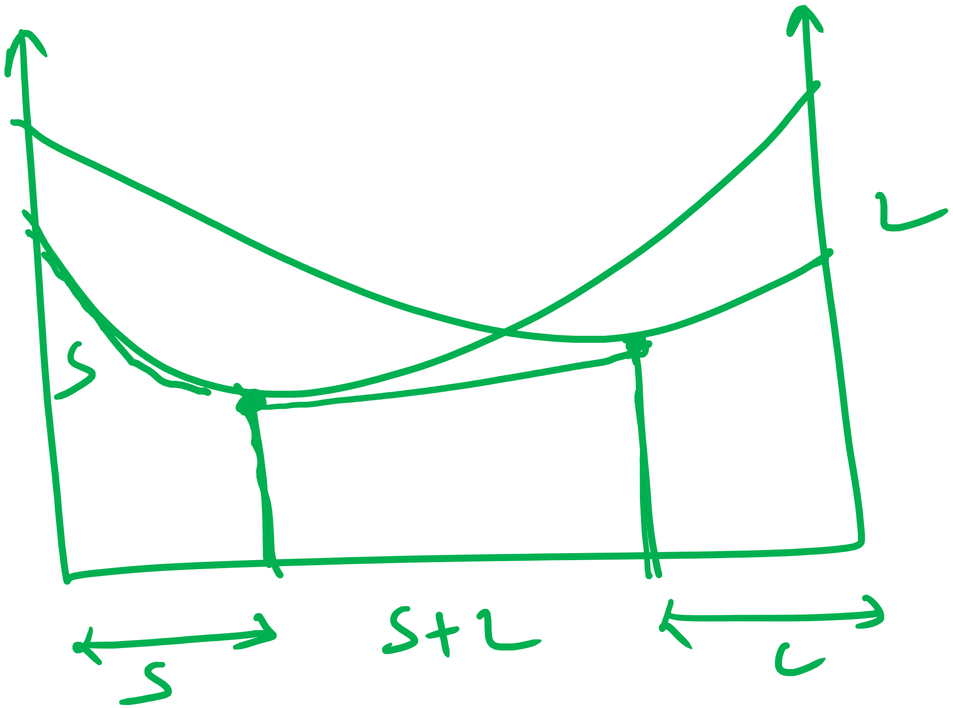




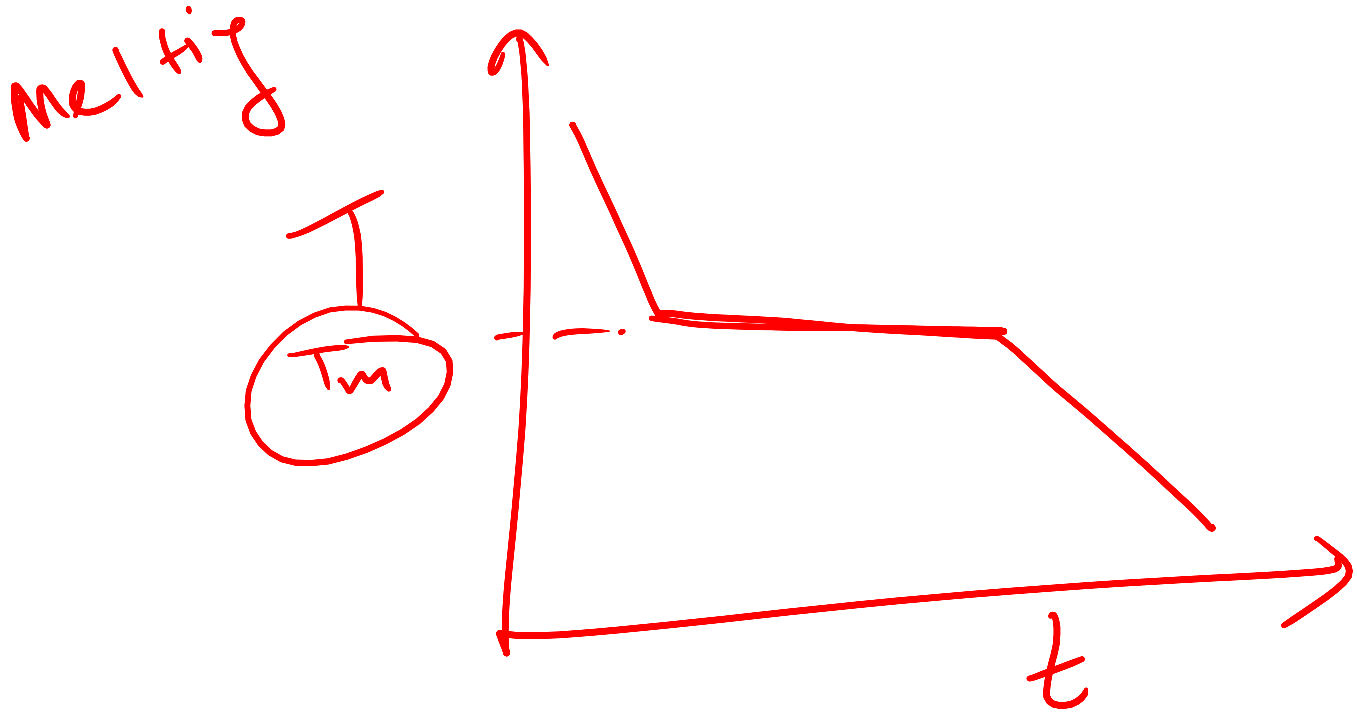
Binary mixture



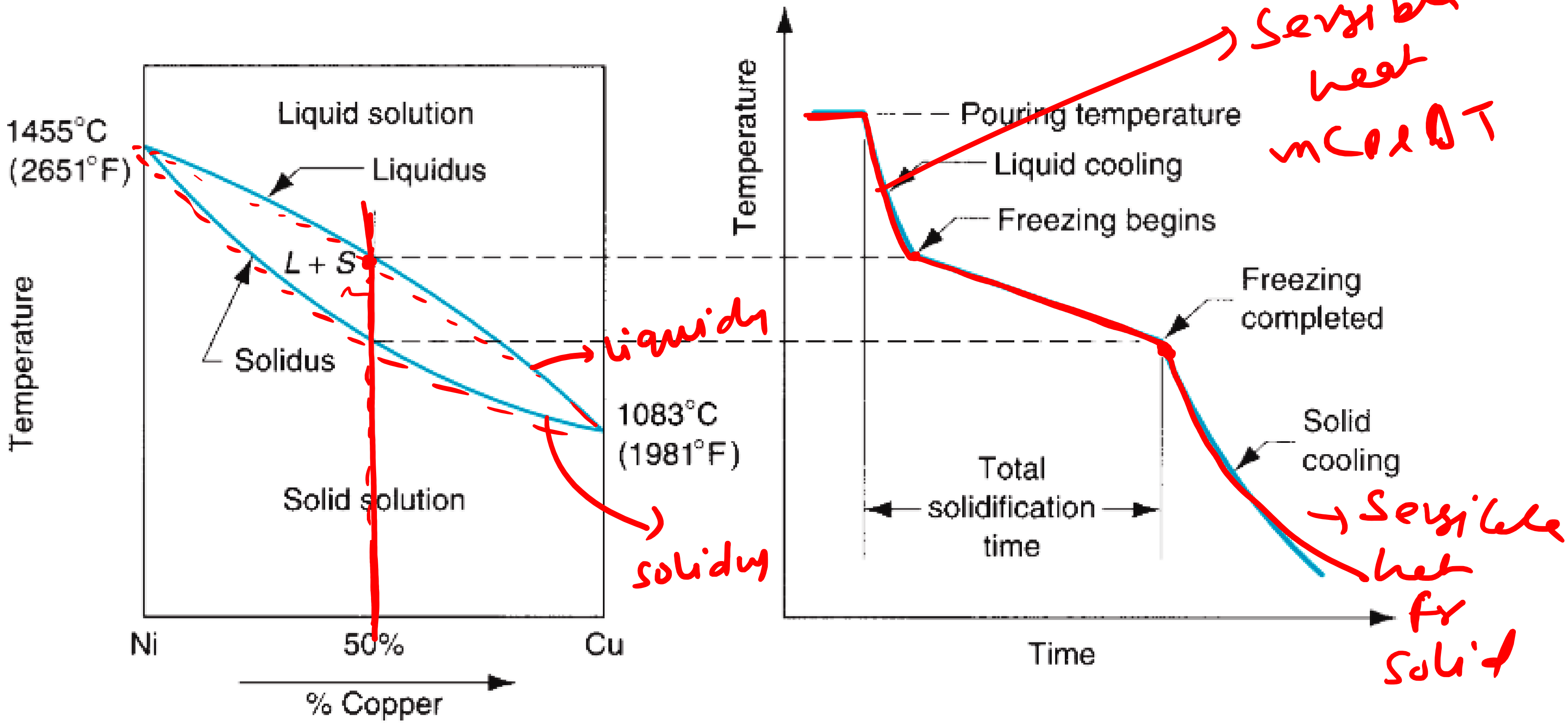
Binary mixture



Binary mixture

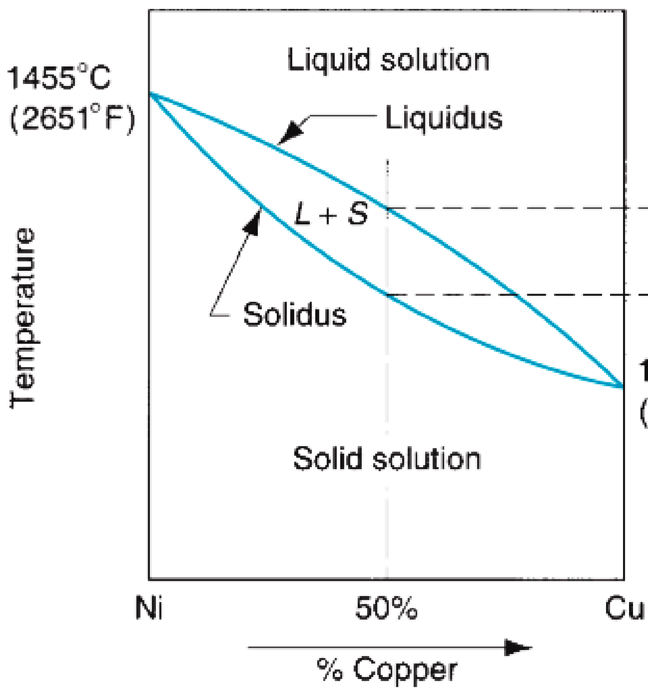


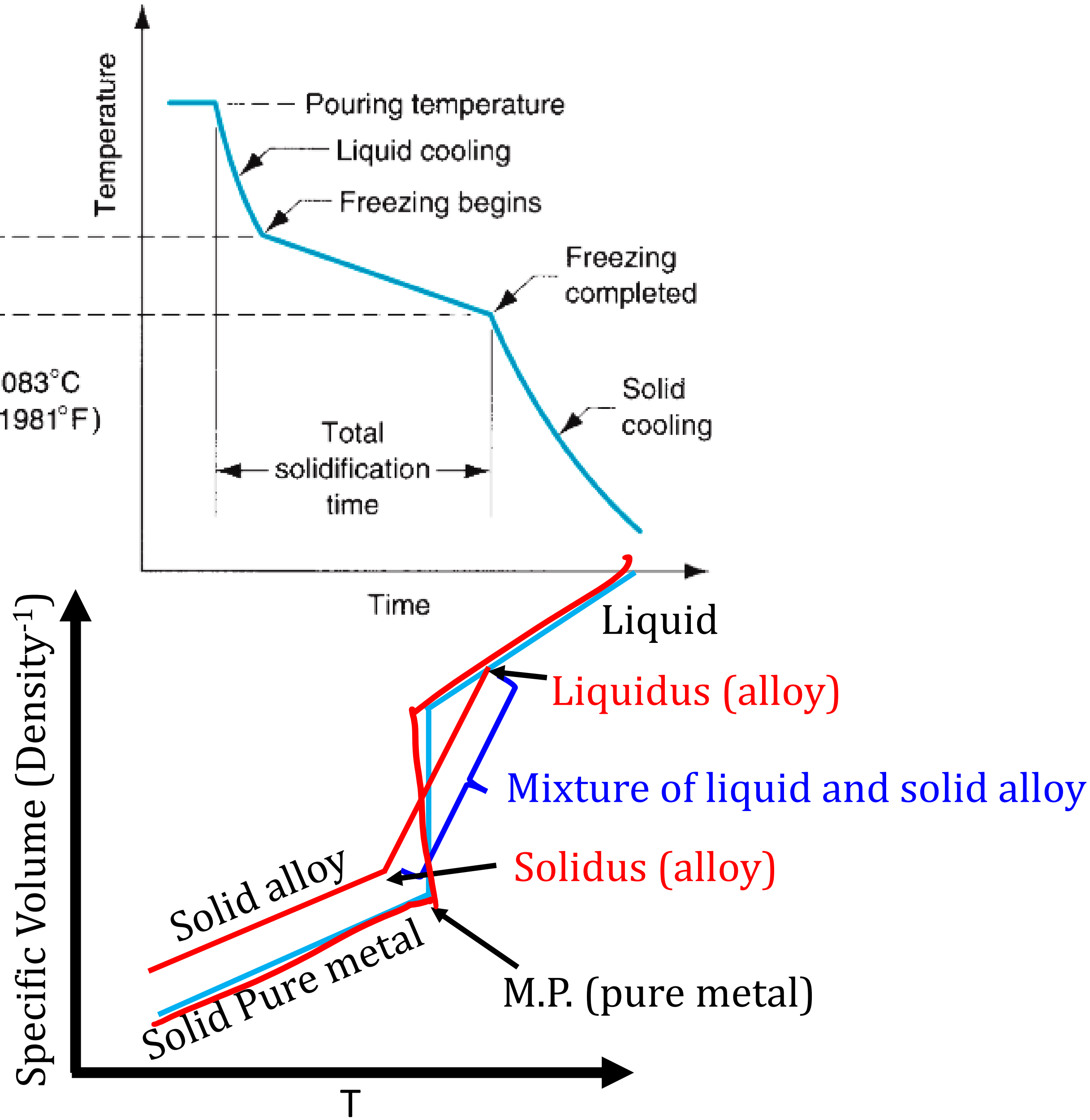
Binary mixture



Porus zone or mushy zone

Binary alloy: Isomorphous phase diagram

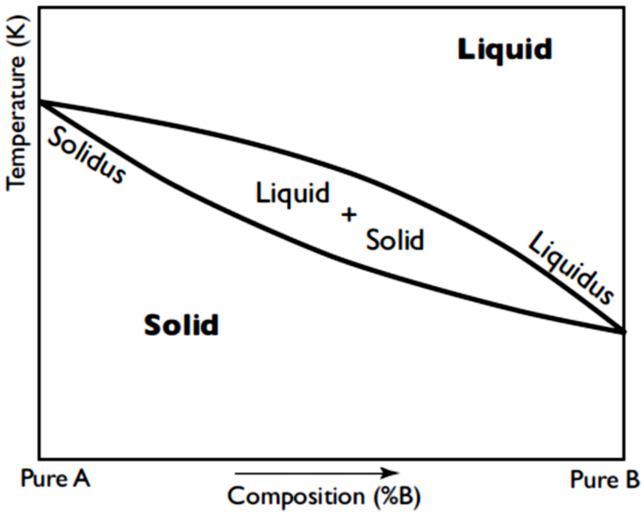


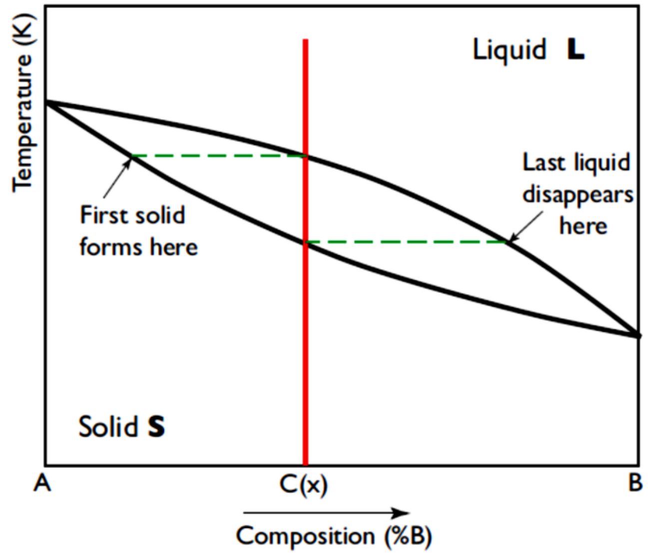


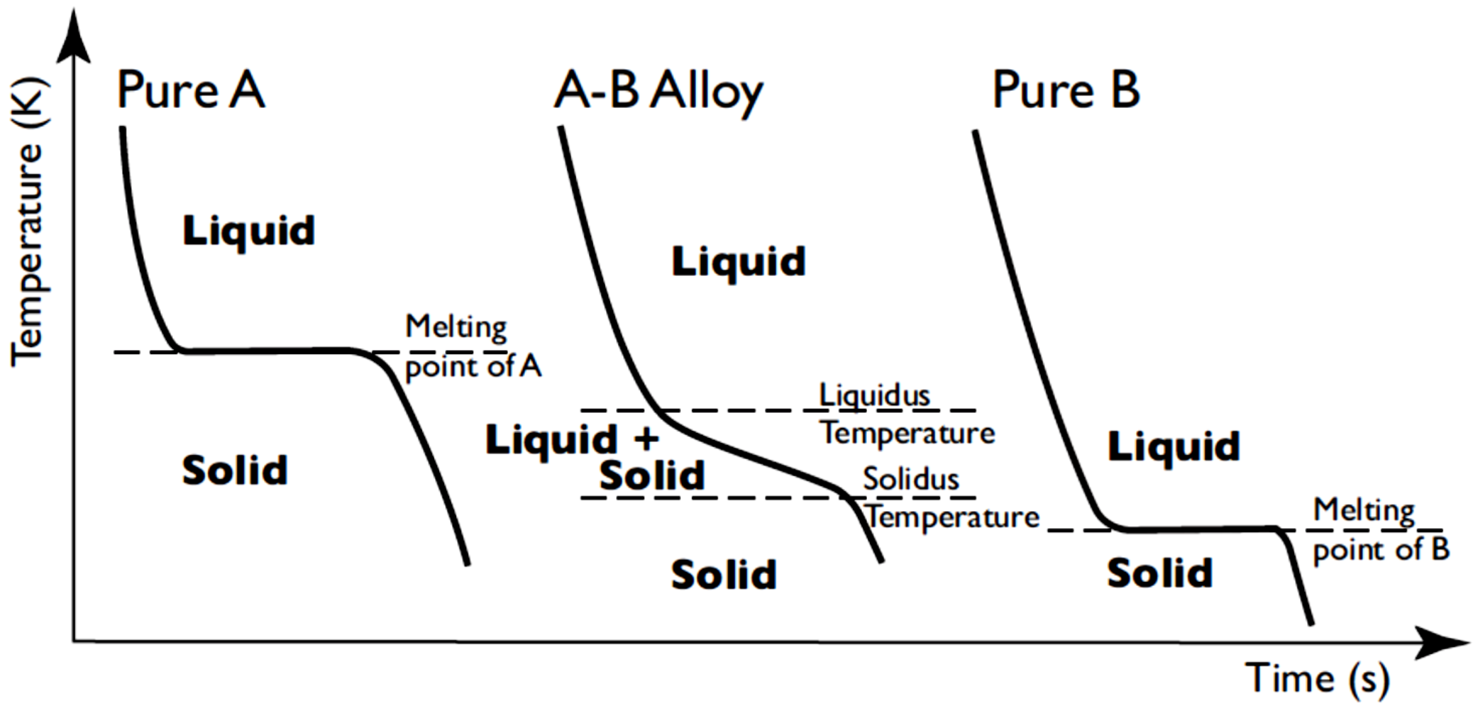
Gibbs Phase Rule:

$F = C-P+2$

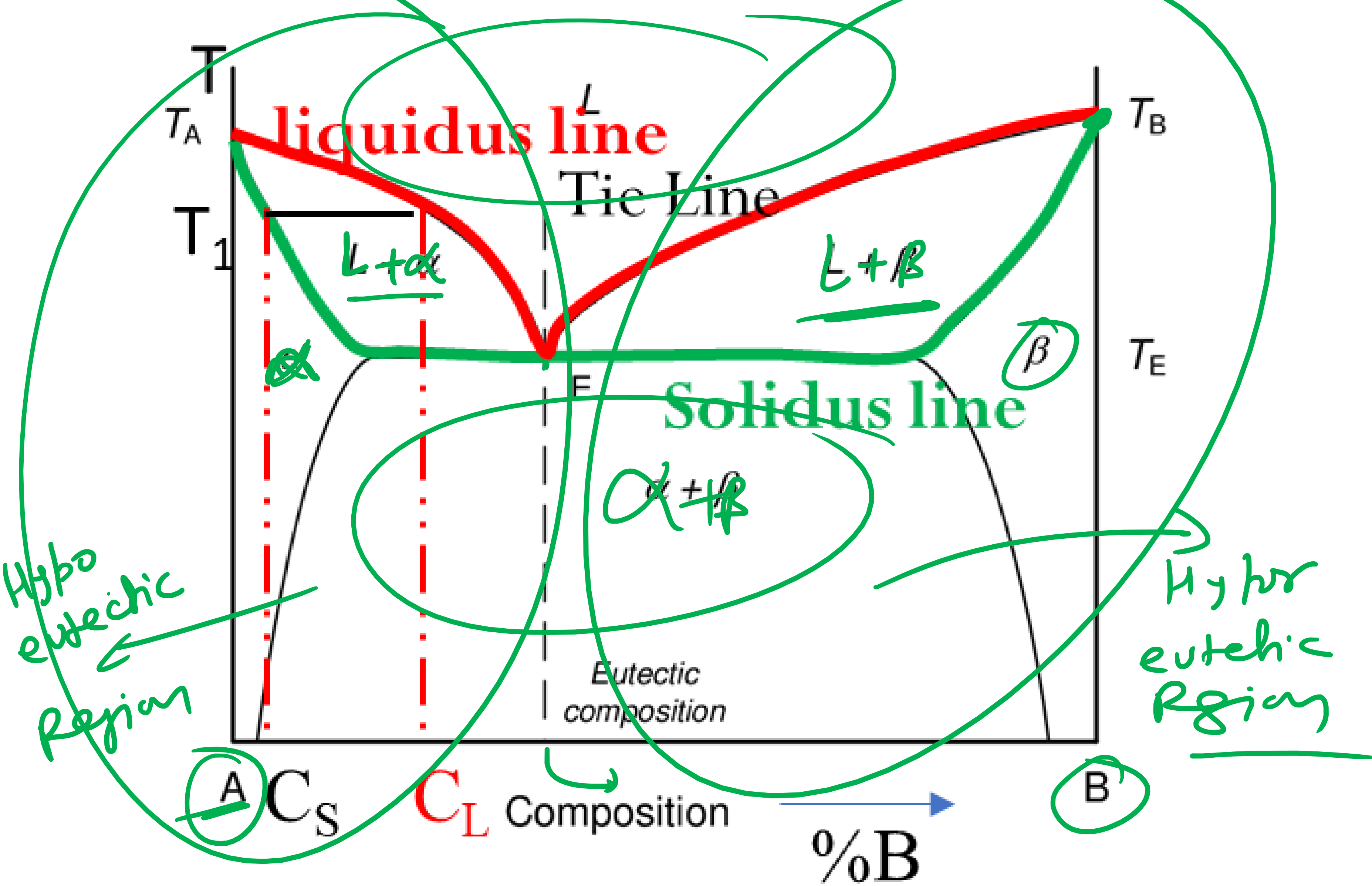
Binary alloy: Isomorphous phase diagram



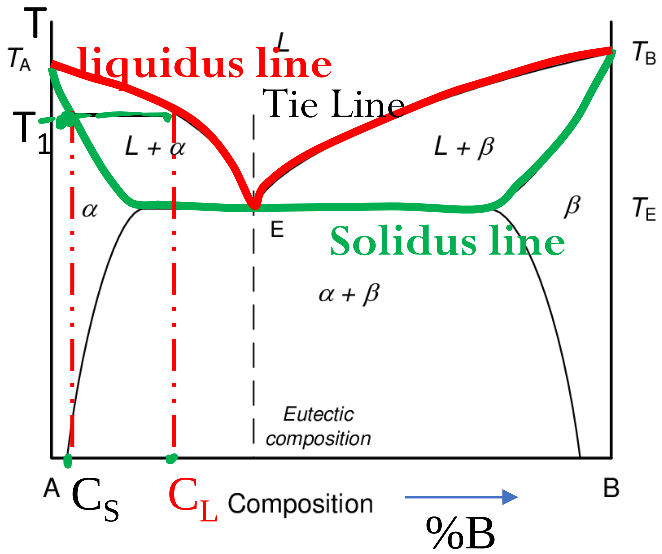




Binary eutectic phase diagram



Binary eutectic phase diagram



Growing solid cannot hold the same amount solute as that of the liquid due to solubility differences.

Diffusivity of solute in solid << Diffusivity of solute in liquid

$$D_S << D_L$$

$K = \frac{C_S}{C_L} < 1$

$C_S < C_L$

Therefore, an unavoidable disparity exists between the compositions of the primary solid and the bulk liquid.

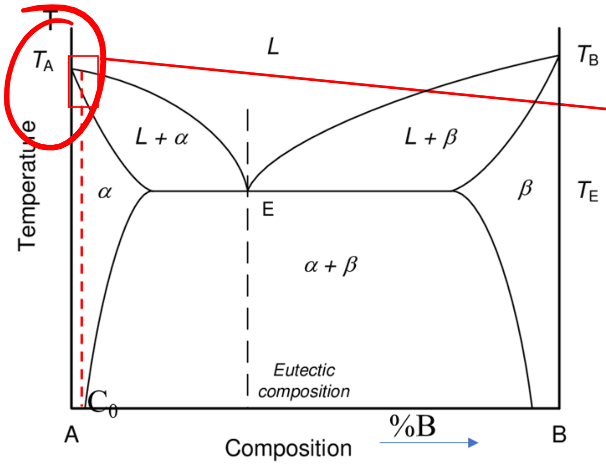
Partition coefficient (k)=*ratio of solute in solid and liquid*

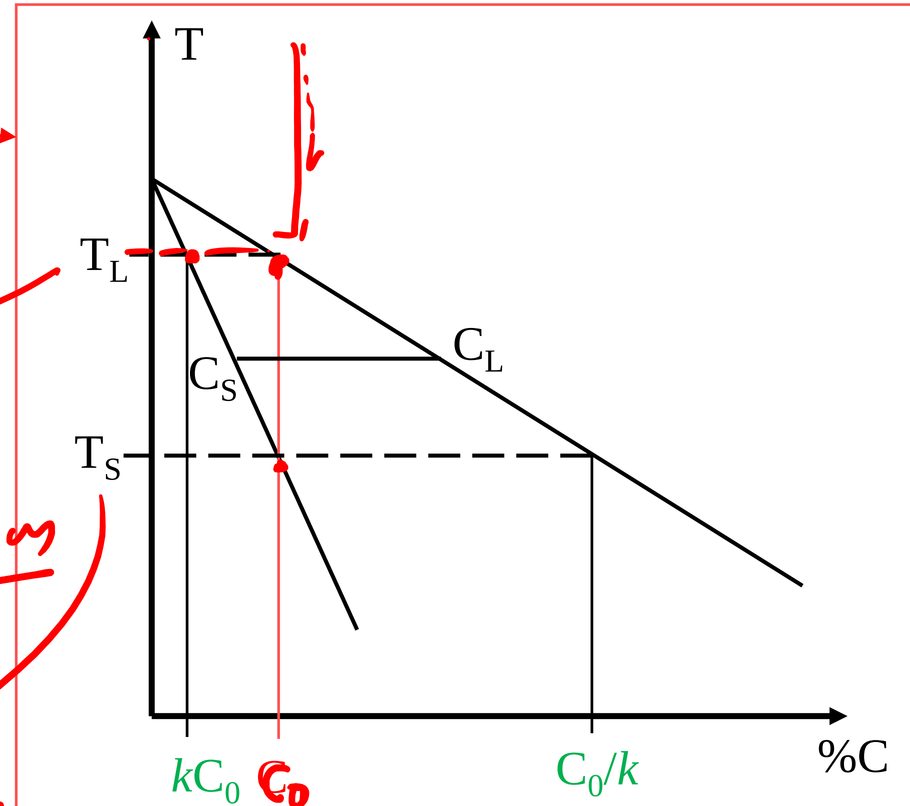
$K = \frac{C_S}{C_L} = \frac{\text{solute in growing solid}}{\text{solute in liquid}}$

$$k = \frac{C_S}{C_L}$$

https://www.youtube.com/watch?v=JSnM92b0_qg&ab_channel=bhadeshia123

Binary eutectic phase diagram





liquidus temp for Co concentration

solidus ~~line~~ temp for Co concentration

at T_l, $f_s = 0$

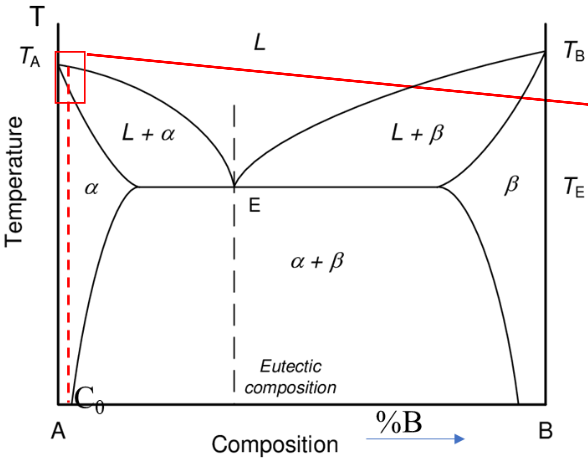
$f\,C$

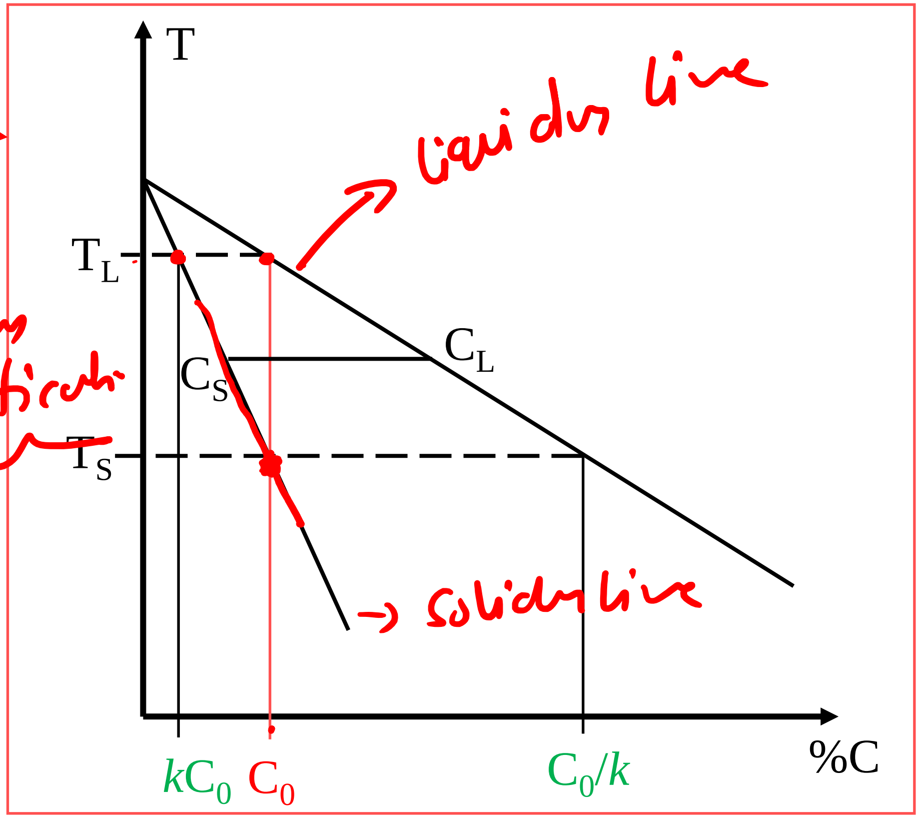
$f_l = 1$

$K = \frac{C_s}{C_l}$

$C_0 = C_l$

Binary eutectic phase diagram





at initiation of solidification or nucleation

$C_l = C_0$, $f_s = 0$, $f_l = 1$

$k=C_S/C_L$

$k = \frac{C_s}{C_l}$

$\boxed{C_s = k C_l = k C_0}$

At T_L,
Fraction of solid (f_S)~0,
Liquid composition=C_0
Solid composition= kC_0

at T_s , $f_s \to 1$, $f_l \to 0$

$C_s = C_0$

$\boxed{C_l = \frac{C_s}{k} = \frac{C_0}{k}}$

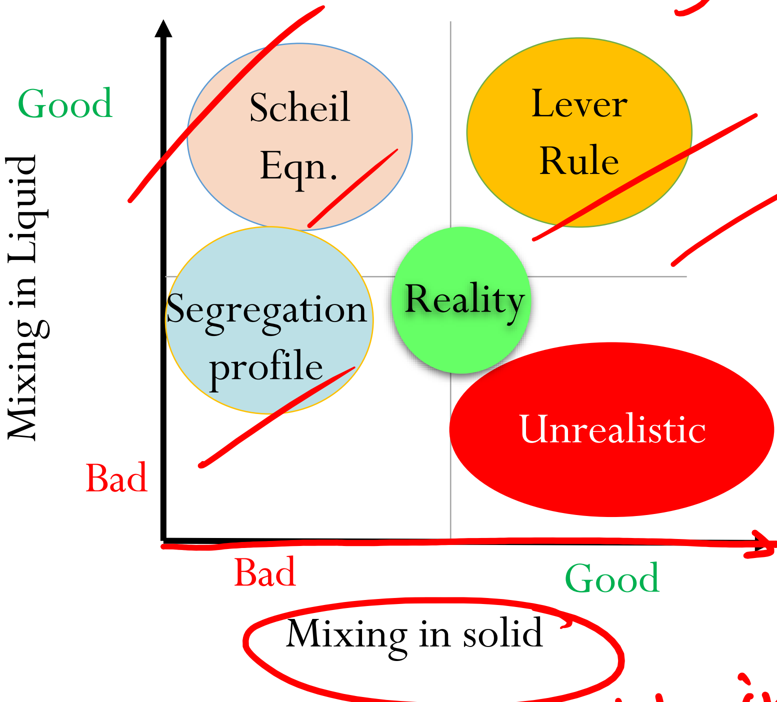
At T_S, f_S~1
Solid composition=C_0
liquid composition= C_0/k
Means last liquid to be solidify with the composition of C_0/k

$k = \frac{C_s}{C_l}$

Solute profiles based of Diffusivity

Based on the diffusivity condition (mixing) some of different type of solidification behaviour can be observed.

$D^s << D^l$



mixing of solute in solid

Good mixing in both solid and liquid is unrealistic case

Equilibrium solidification: Infinitely slow solidification. The composition of the phase is evaluated by **Lever Rule**.

Solidification with no diffusion in the solid but perfect mixing in the liquid. Composition is tracked by **Scheil Eqn.**

Solidification with no diffusion in the solid and only limited diffusion in the liquid: Composition tracked by Segregation Profile.

However, mixing in solid is poorer, and mixing in liquid is near to good but not perfect.

Case: I (Equilibrium Solidification): Lever Rule

Co

Initial uniform composition in liquid

Solid

Liquid

S

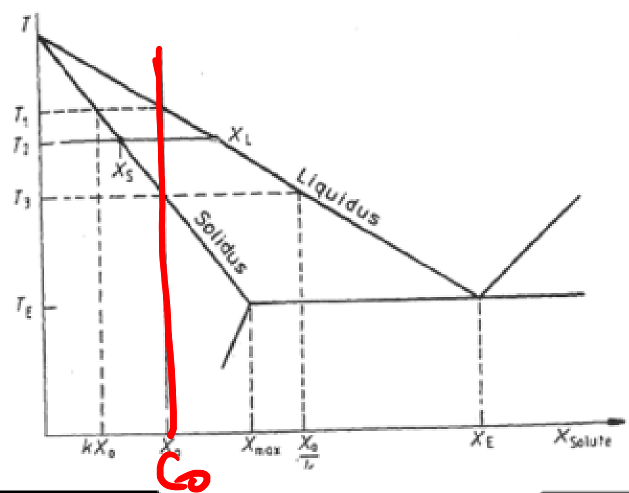
L

Two phases

Uniform composition in the both phases at all times due to infinite diffusion

fraction of phase 1 = $(C_2 - C) / (C_2 - C_1)$

fraction of phase 2 = $(C - C_1) / (C_2 - C_1)$

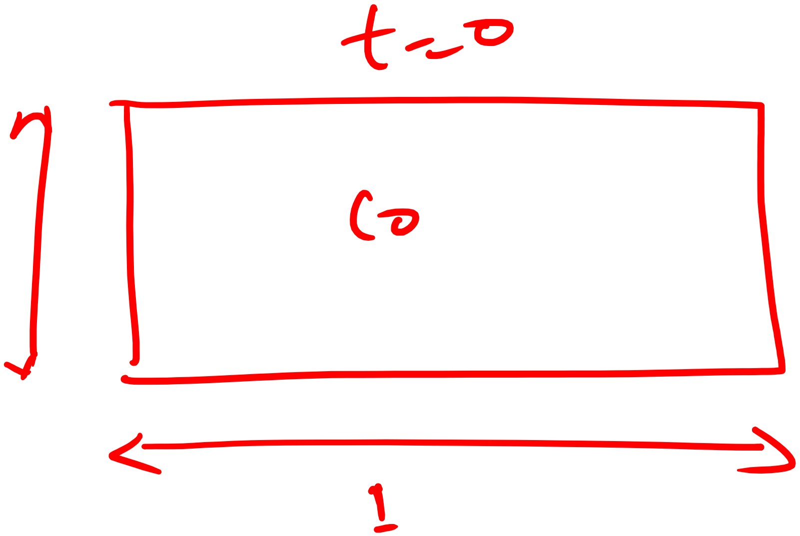


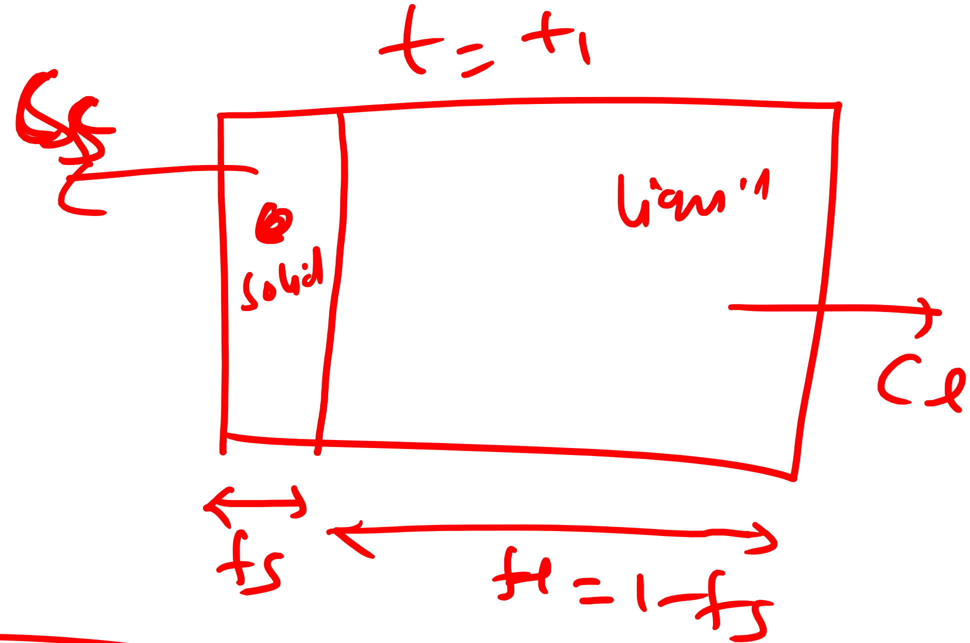
S

L

Final uniform composition in the solid

Case: I (Equilibrium Solidification): Lever Rule



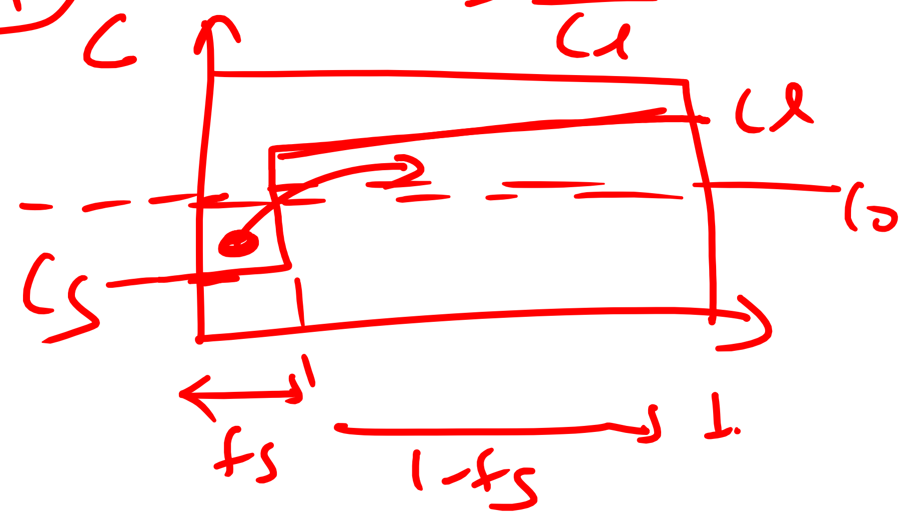


$k = \frac{C_s}{C_l}$

$\boxed{C_o = C_s \times f_s + C_l \times f_l}$

initial → C_o

$0 \times f_s + 1.0 \times f_l$ → $= 1$



Case: I (Equilibrium Solidification): Lever Rule

$$C_0 = C_s f_s + C_l f_l$$

$$= C_s f_s + C_l (1 - f_s)$$

$$C_0 = (C_s - C_l) f_s + C_l$$

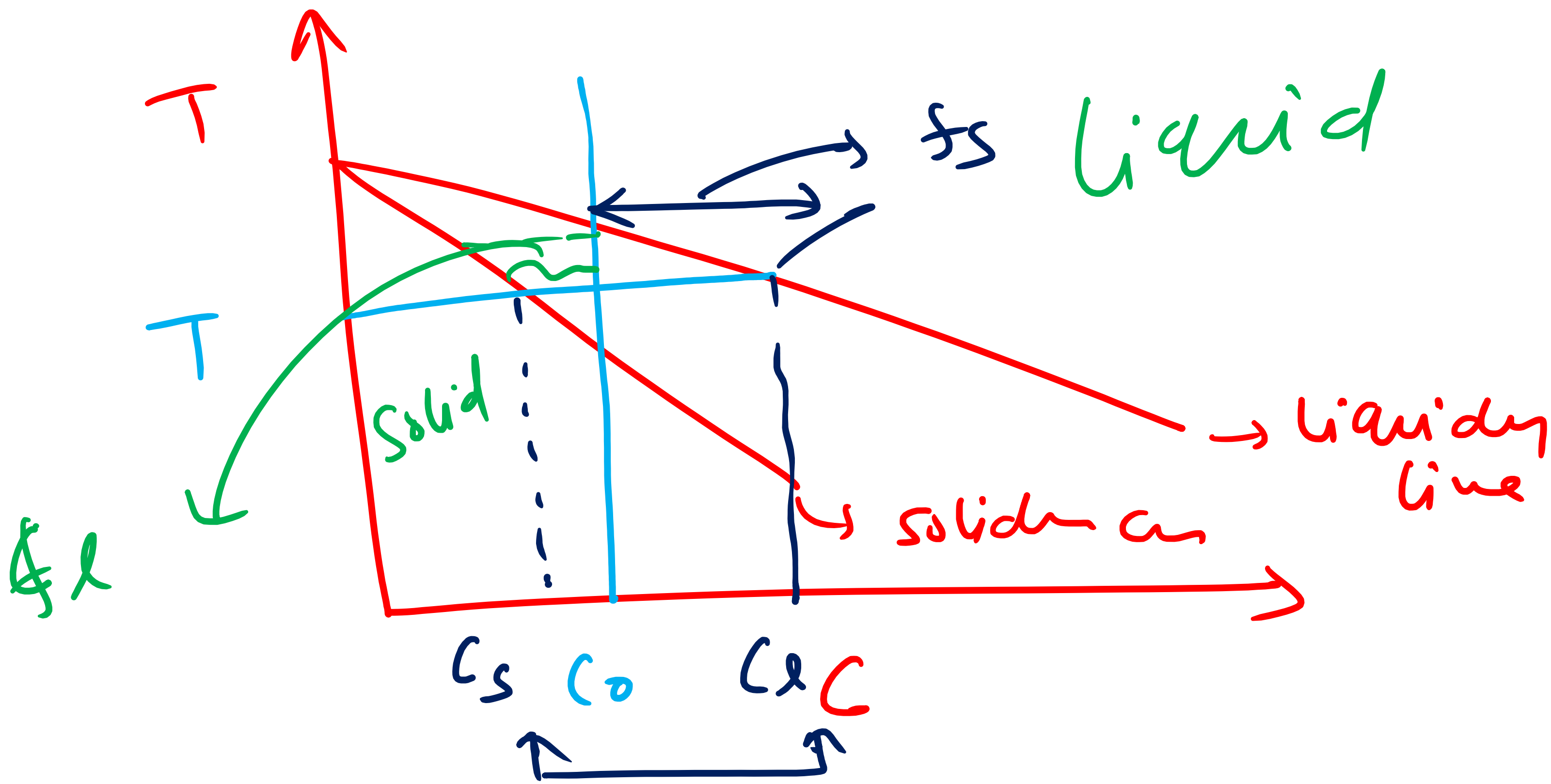
$$f_s = \frac{C_0 - C_l}{C_s - C_l} = \frac{C_l - C_0}{C_l - C_s}$$

$$f_l = 1 - f_s = 1 - \frac{C_l - C_0}{C_l - C_s} = \frac{\cancel{C_l} - C_s - \cancel{C_l} + C_0}{C_l - C_s}$$

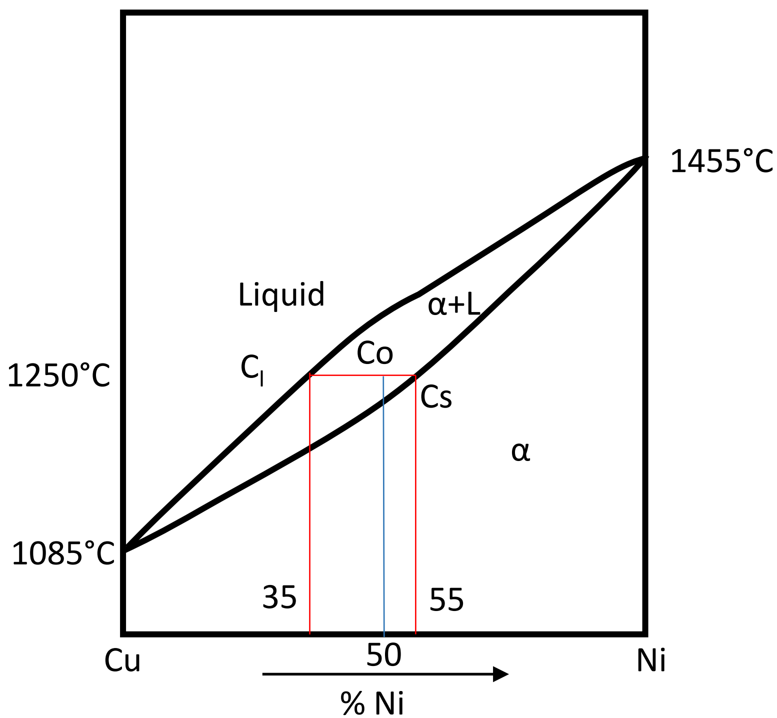
$$= \frac{C_0 - C_s}{C_l - C_s}$$

Case: I (Equilibrium Solidification): Lever Rule

$$f_s = \frac{C_l - C_o}{C_l - C_s} \qquad f_l = \frac{C_o - C_s}{C_l - C_s}$$



Lever Rule

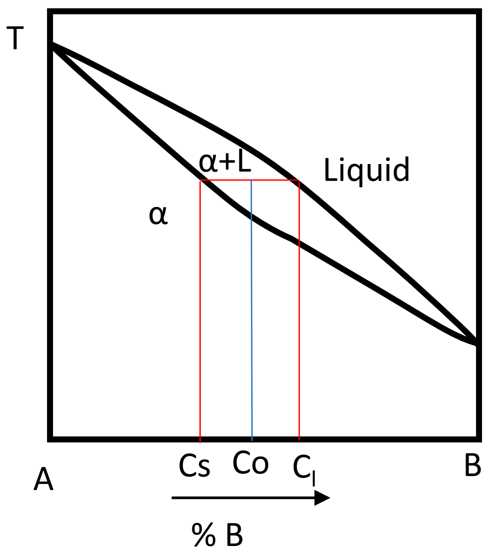


$$f_S = \frac{C_l - C_0}{C_l - C_S} \qquad f_l = 1 - f_S = \frac{C_0 - C_S}{C_l - C_S}$$

At 1250°C
initial composition is Cu-50%Ni

α phase = (50-35)/(55-35)=0.75 or 75%
Liquid=(55-50)/(55-35)=0.25 or 25%

Lever Rule



$$f_l = 1 - f_S = \frac{C_0 - C_S}{C_l - C_S}$$

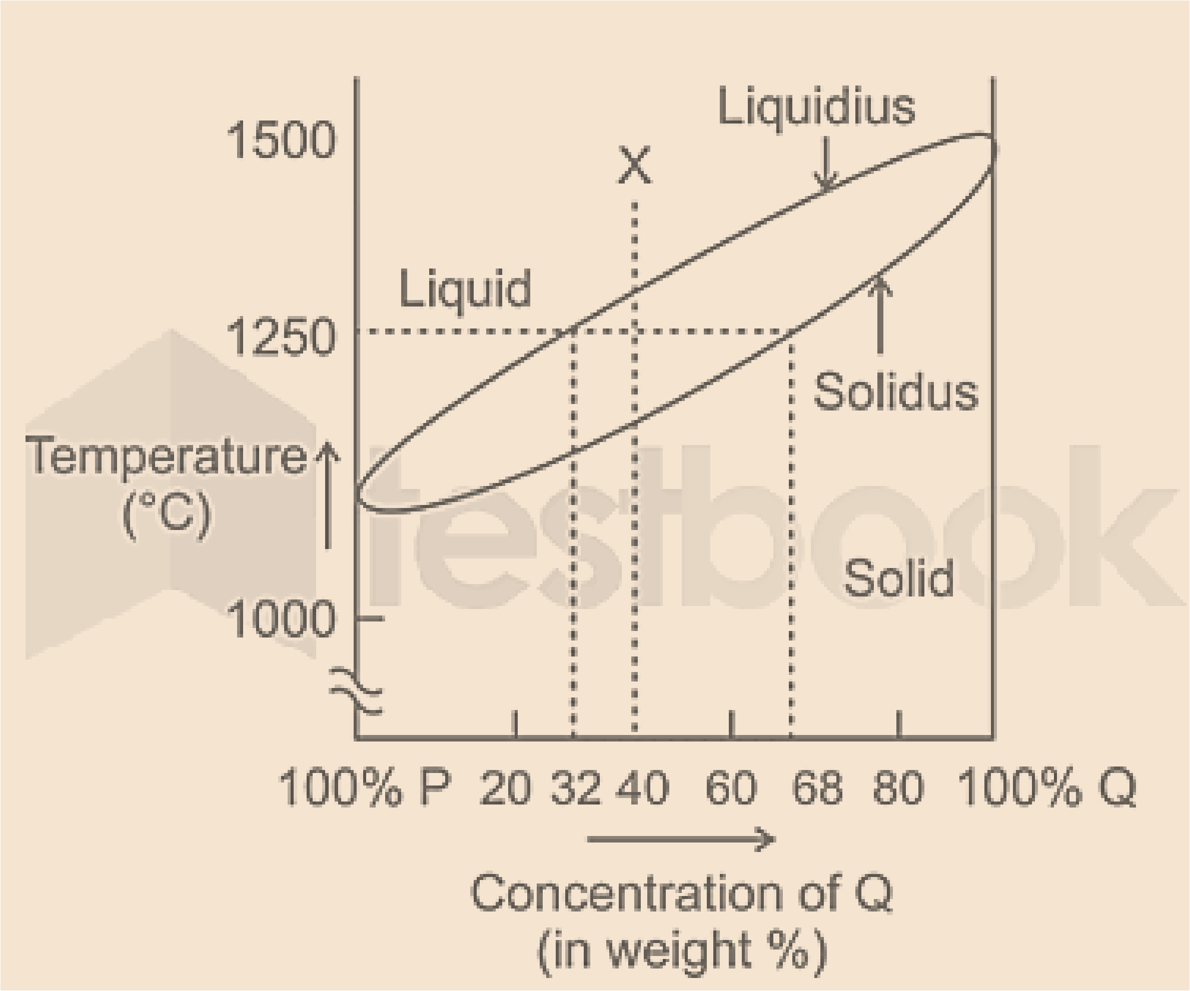
$$f_S \ or \ \alpha \ phase = \frac{C_l - C_0}{C_l - C_S}$$

At 1250°C
initial composition is Cu-50%Ni

α phase = (50-35)/(55-35)=0.75 or 75%
Liquid=(55-50)/(55-35)=0.25 or 25%

Numerical problems

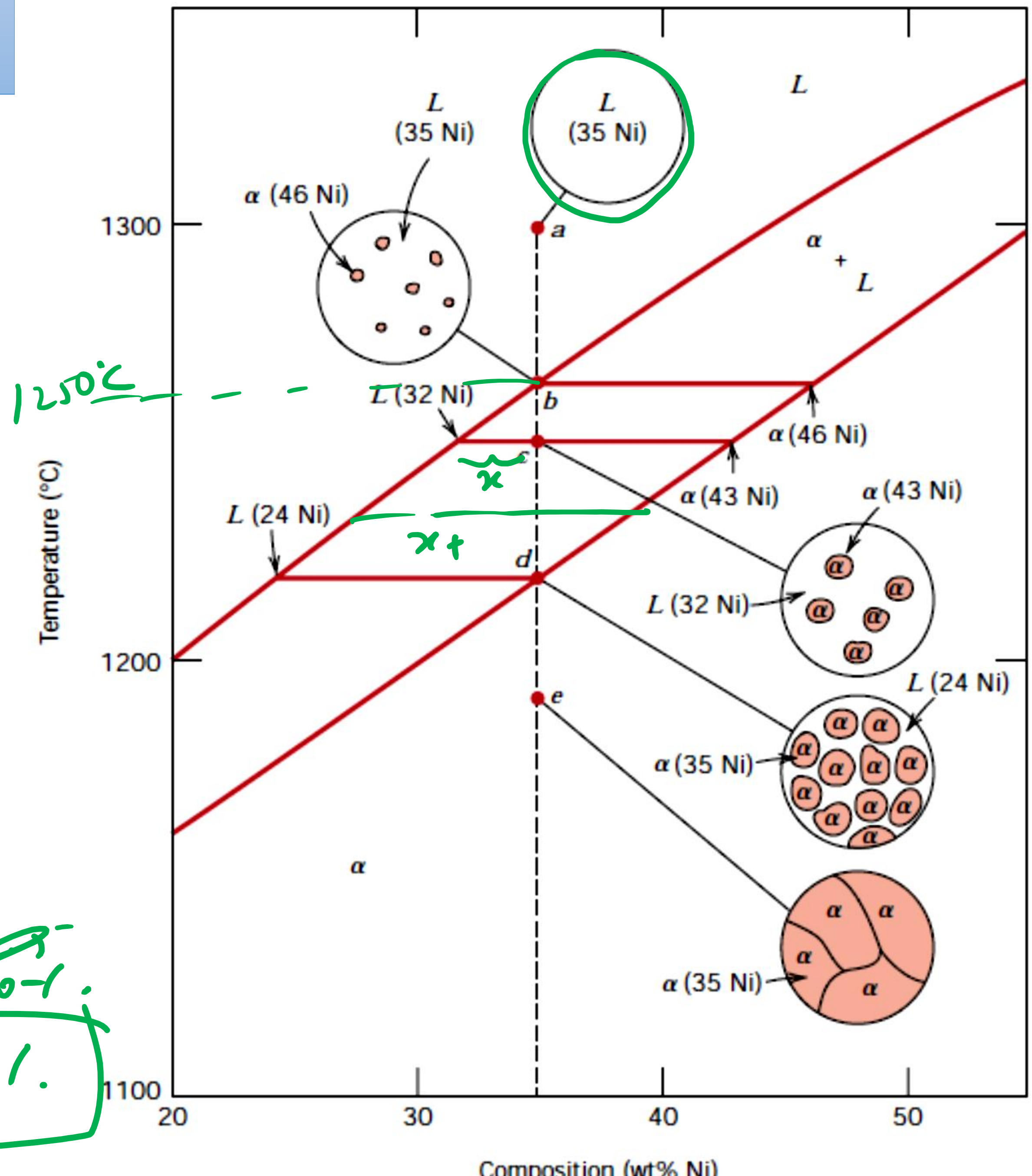
The binary phase diagram of metals P and Q is shown in the figure. An alloy X containing 60% P and 40% Q (by weight) is cooled from liquid to solid state. The fractions of solid and liquid (in weight percent) at 1250°C, respectively, will be



Microstructures

Micro structure of alloy depends on

1. Alloying elements
2. Concentration of elements
3. Grain size (controlled by heat treatment)

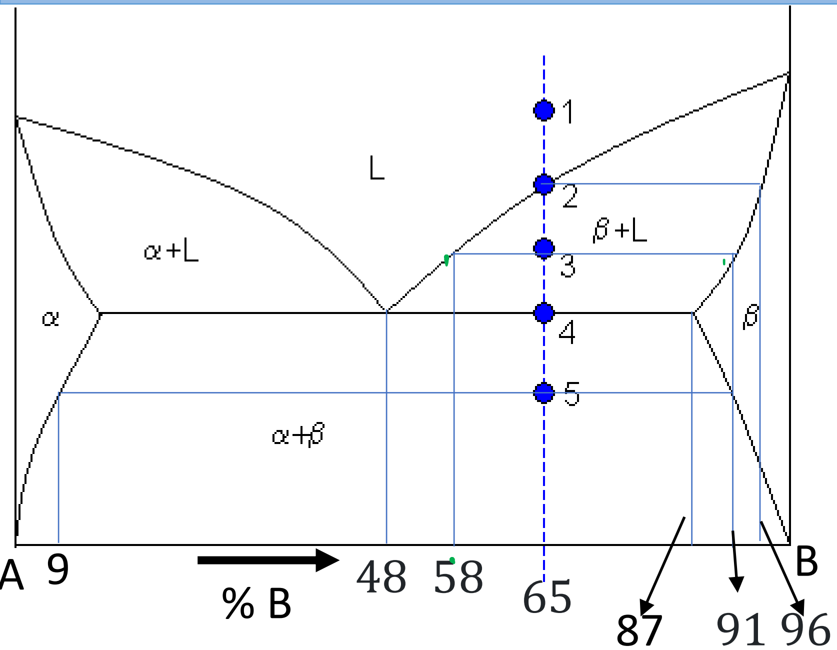


$K = 0.2$

$K = \frac{C_s}{C_l} \rightarrow 50\%$

$\boxed{C_s = 10\%}$

Case: I (Equilibrium Solidification): Lever Rule

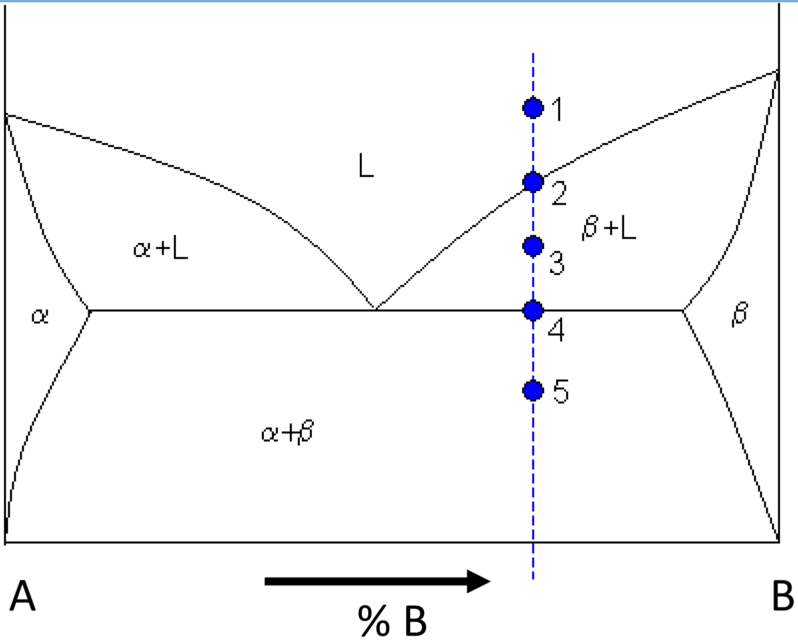


Point 1

At point 1 the alloy is completely liquid, with a composition C.

Let C = 65 weight% B.

Case: I (Equilibrium Solidification): Lever Rule

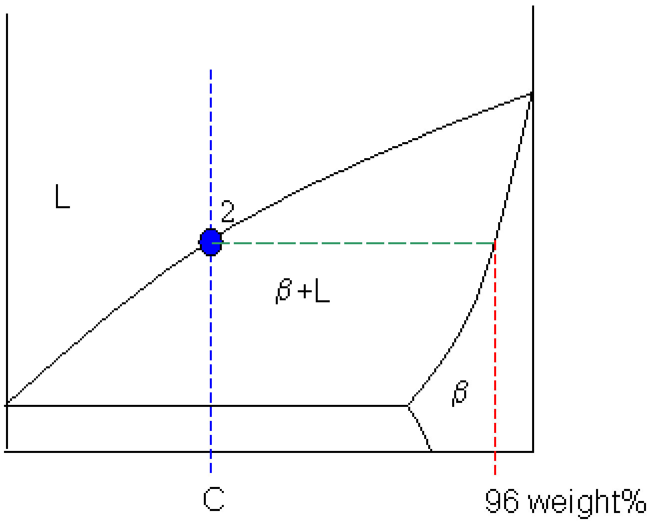


Point 2

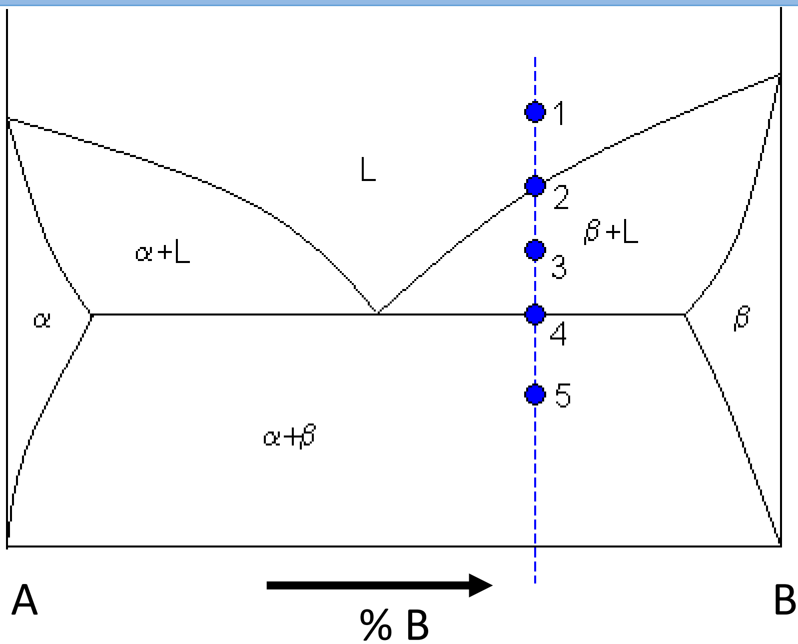
At point 2 the alloy has cooled as far as the liquidus, and solid phase β starts to form. Phase β first forms with a composition of 96 weight% B.

The green dashed line below is an example of a *tie-line*.

A tie-line is a horizontal (i.e., constant-temperature) line through the chosen point, which intersects the phase boundary lines on either side.



Case: I (Equilibrium Solidification): Lever Rule



Point 3

A tie-line is drawn through the point, and the lever rule is applied to identify the proportions of phases present.

Intersection of the lines gives compositions C_1 and C_2 as shown.Let

$C_1 = 58$ weight% B and $C_2 = 92$ weight% B

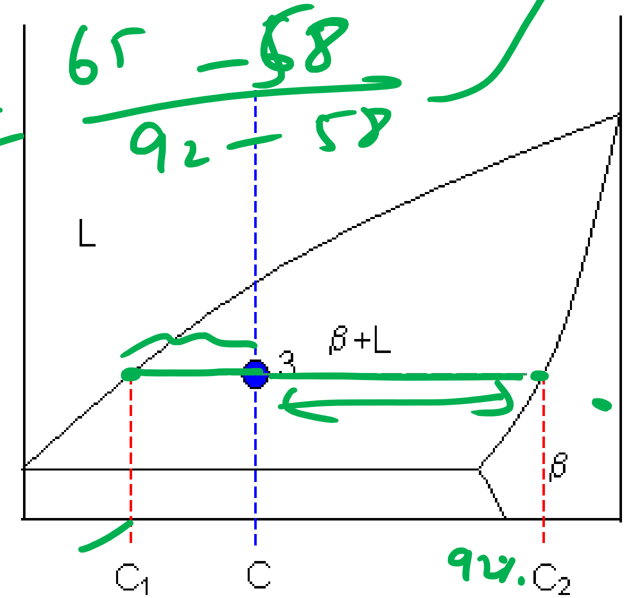
So,

fraction of solid β = (65 - 58) / (92 - 58) = 20 weight%

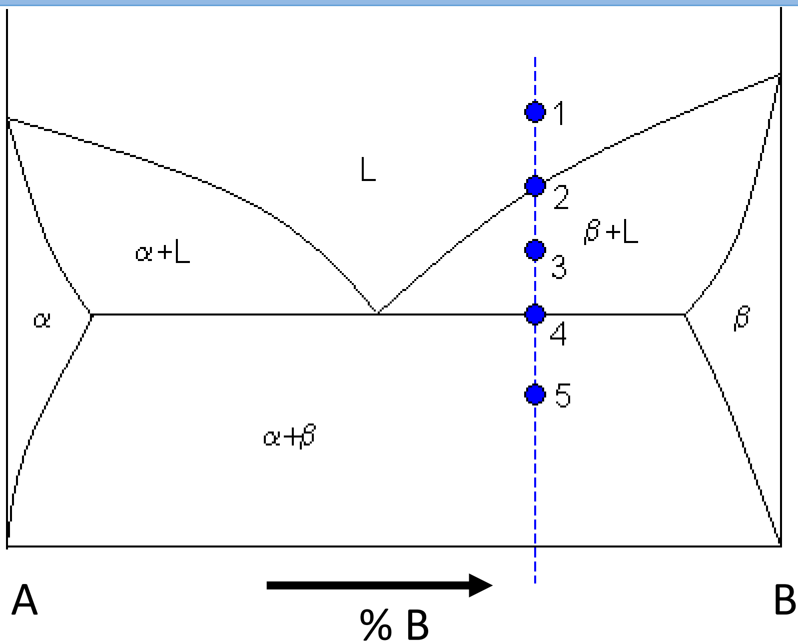
fraction of liquid = (92 - 65) / (92 - 58) = 80 weight%

fraction of β $= \dfrac{C - C_1}{C_2 - C_1} = \dfrac{65 - 58}{92 - 58}$

fraction of liquid $= \dfrac{C_2 - C}{C_2 - C_1} = \dfrac{92 - 65}{92 - 58}$



Case: I (Equilibrium Solidification): Lever Rule



Point 4

Let $C_3 = 48$ weight% B and $C_4 = 87$ weight% B

So

fraction of solid β = (65 - 48) / (87 - 48) = 44 weight%.

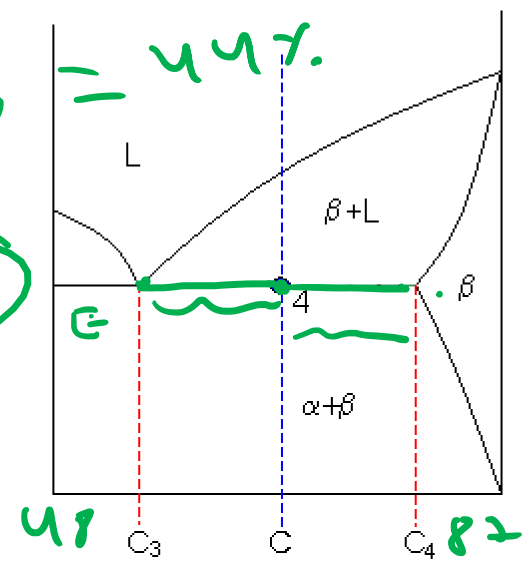
As the alloy is cooled, more solid β phase forms.

At point 4, the remainder of the liquid becomes a eutectic phase of α+ β and

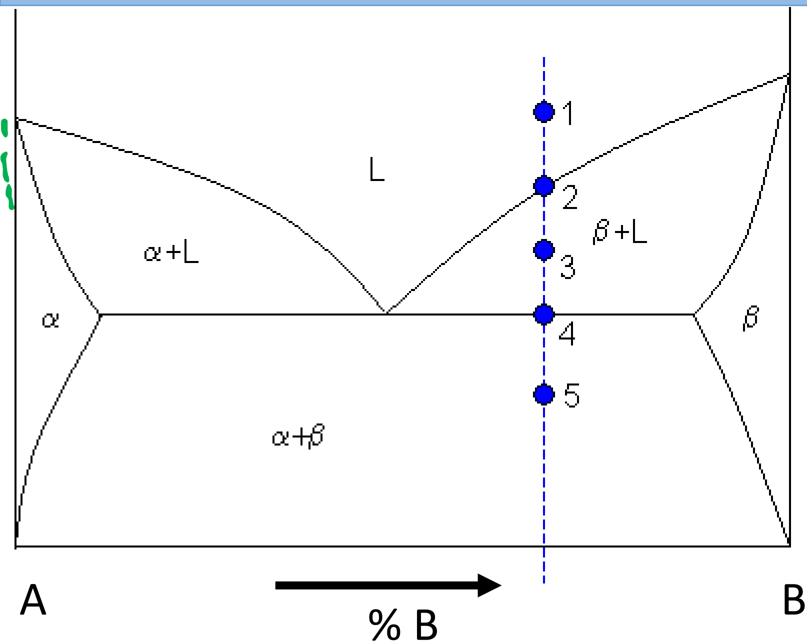
Fraction of eutectic = 56 weight%

$$\beta = \frac{C - C_3}{C_4 - C_3} = \frac{65-48}{87-48} = 44\%$$

$$E = \frac{87-65}{87-48} = 56\%$$



Case: I (Equilibrium Solidification): Lever Rule



Point 5

Let $C_5 = 9$ weight% B and $C_6 = 91$ weight% B

So

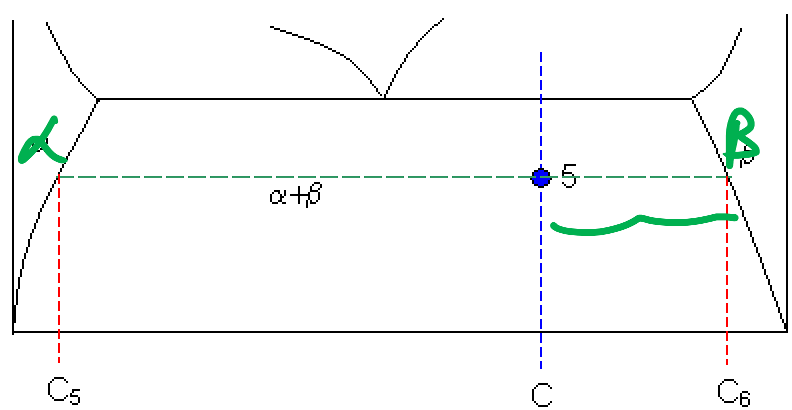
fraction of solid β $= (65 - 9) / (91 - 9) = 68$ weight%

and

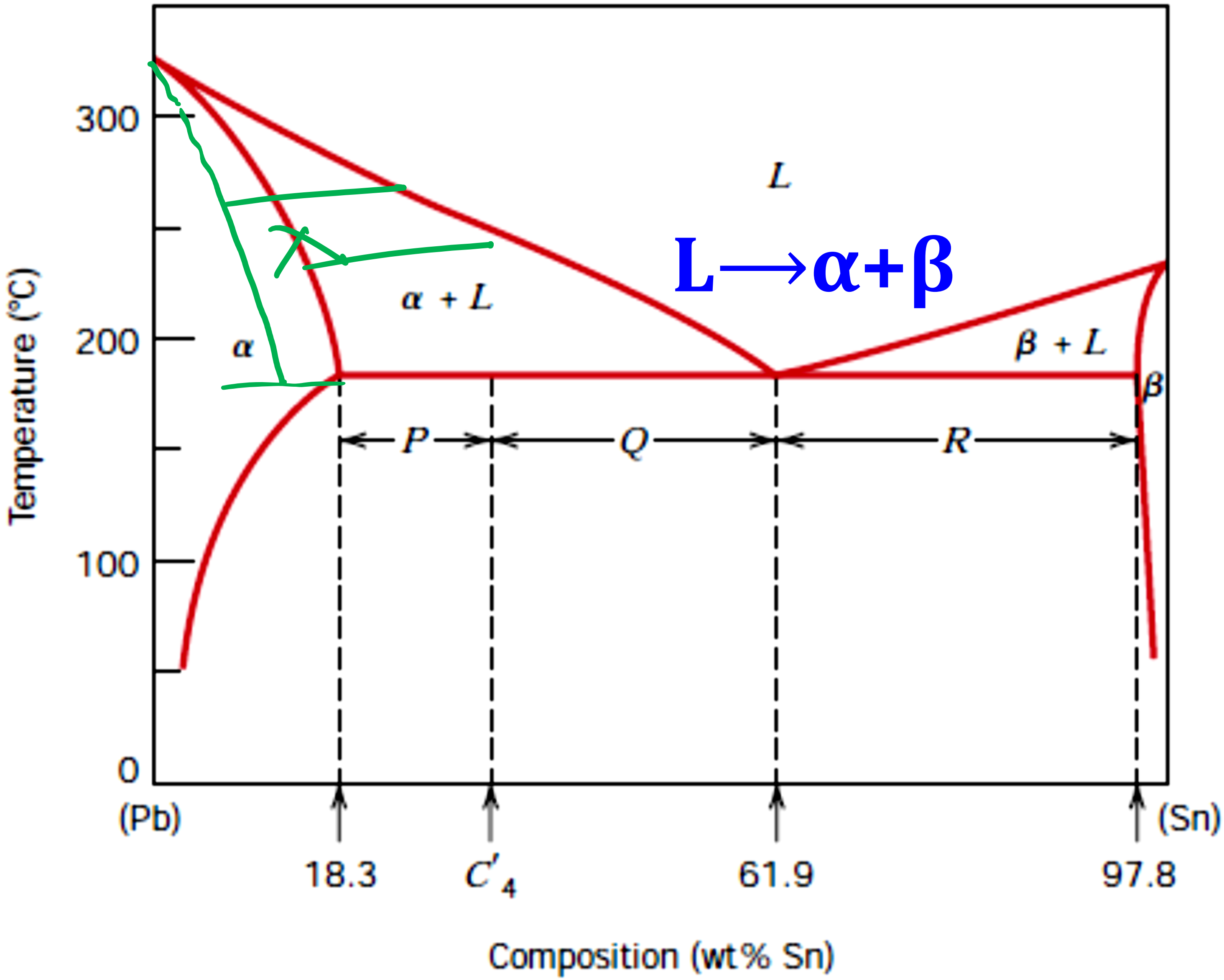
fraction of solid α$= (91 - 65) / (91 - 9) = 32$ weight%.

$$\alpha = \frac{C_6 - C}{C_6 - C_5} = \frac{91 - 65}{91 - 9} = 0.32$$

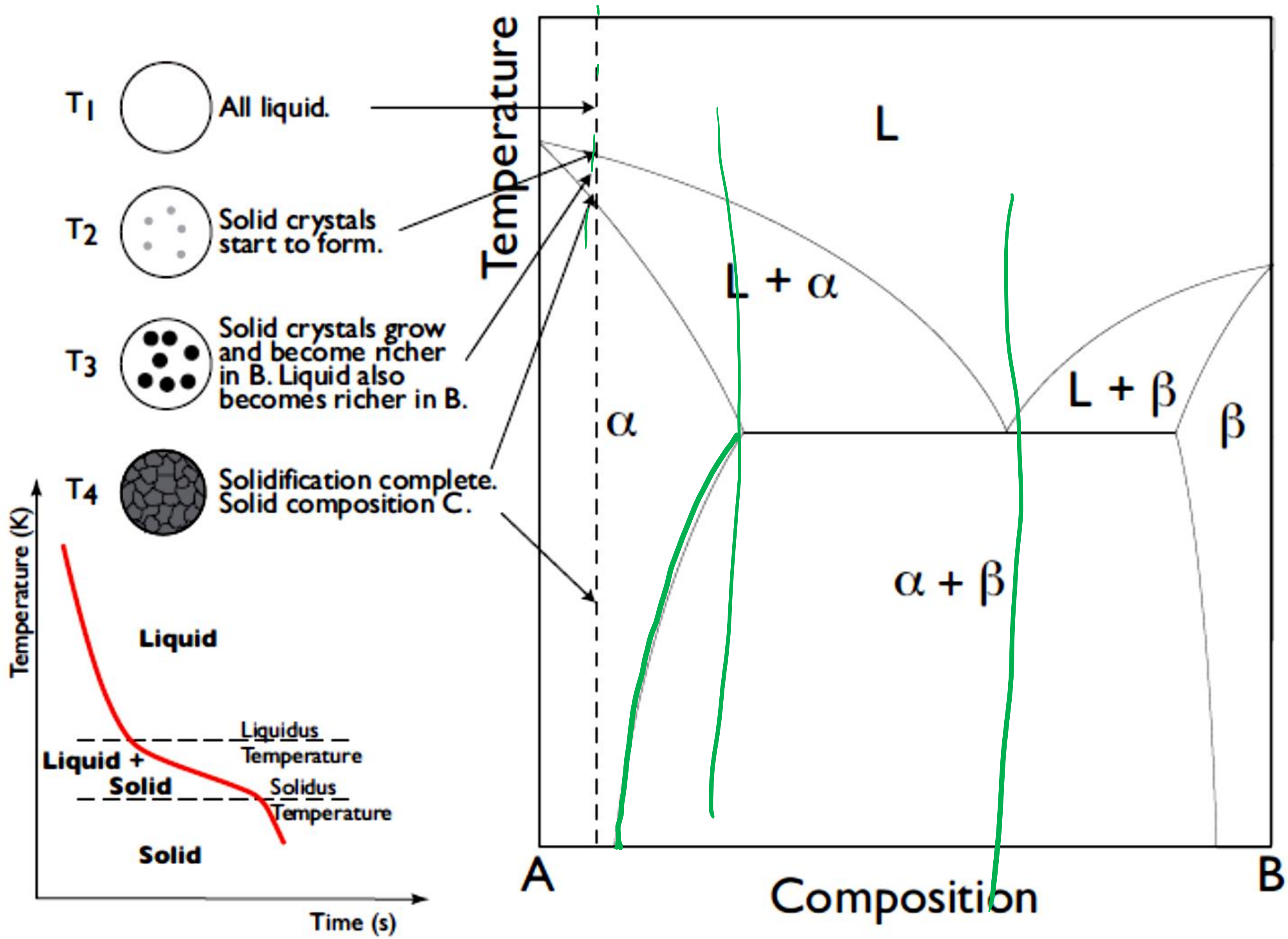
$$\beta = 68\%$$



Eutectic phase diagram – Tin-lead alloy system

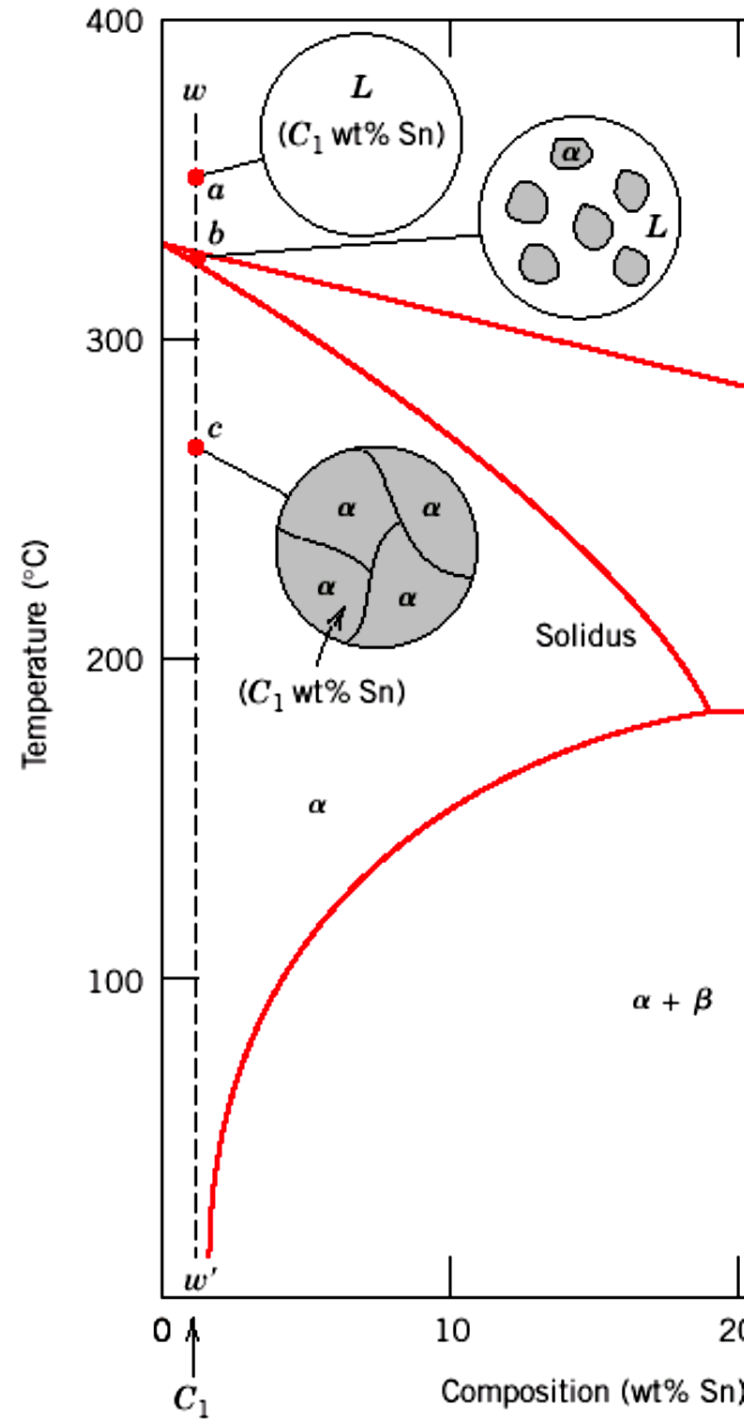


Solidification sequence for a single-phase alloy

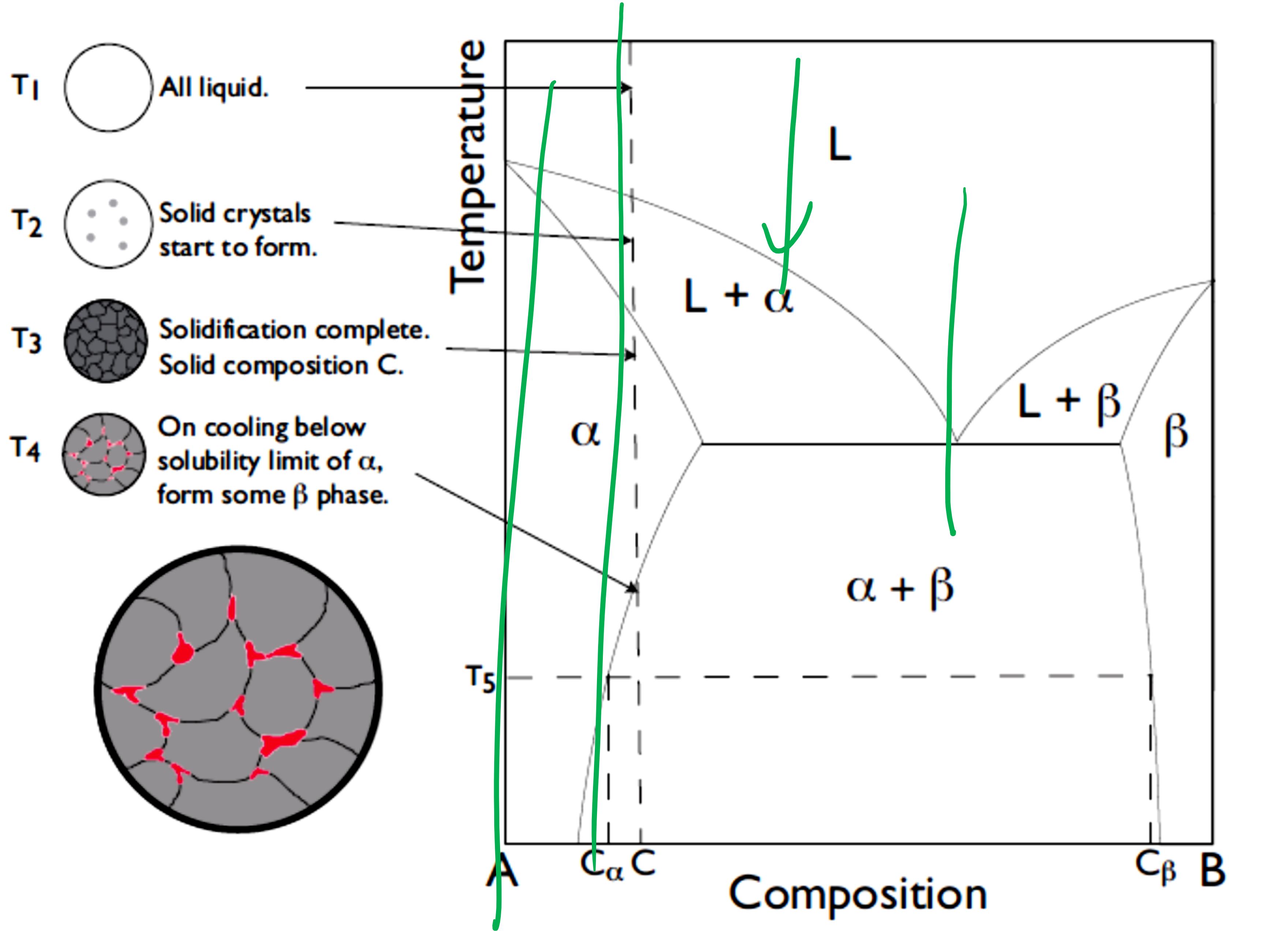


Tin-lead alloy system

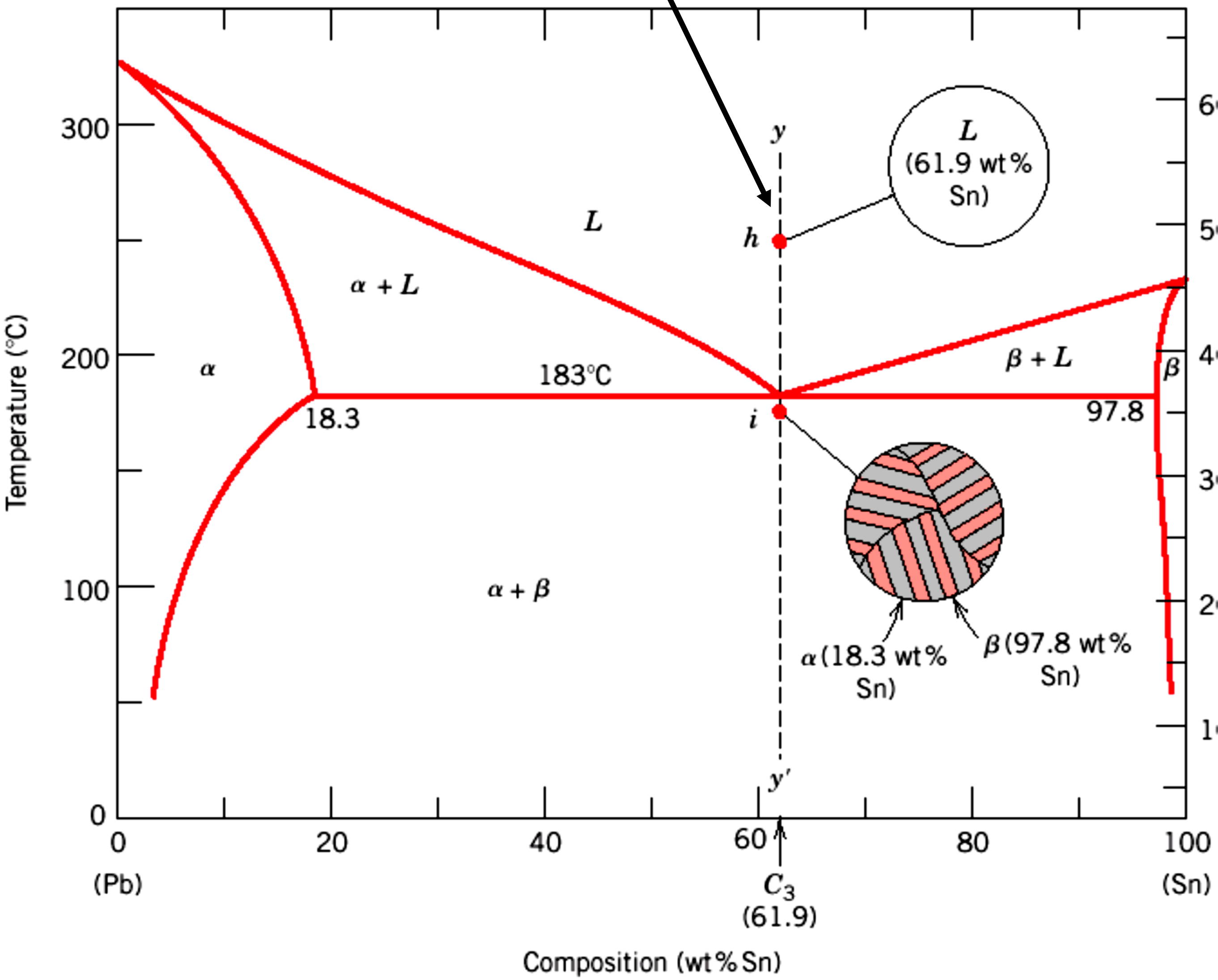
Solidification of a low composition – similar to isomorphous phase, No precipitation

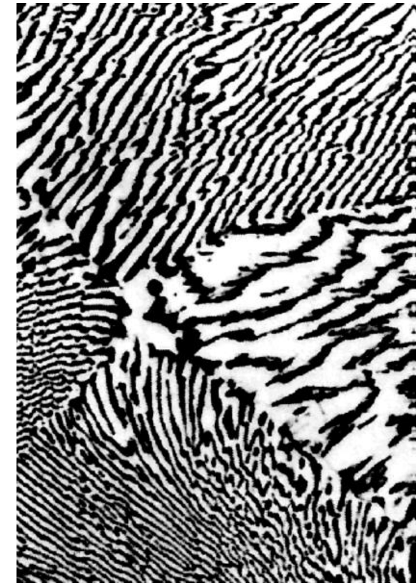


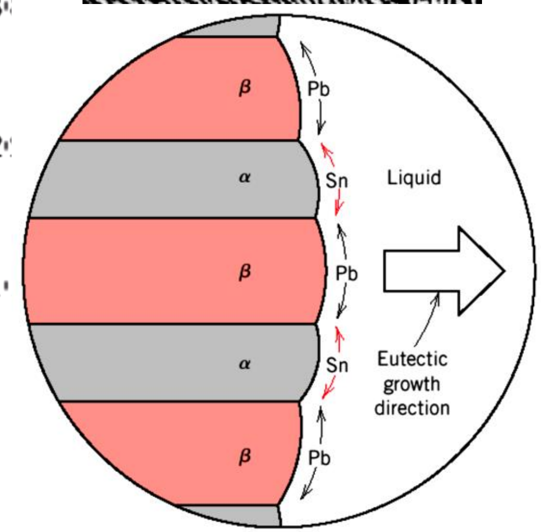
Solidification sequence for a two-phase alloy



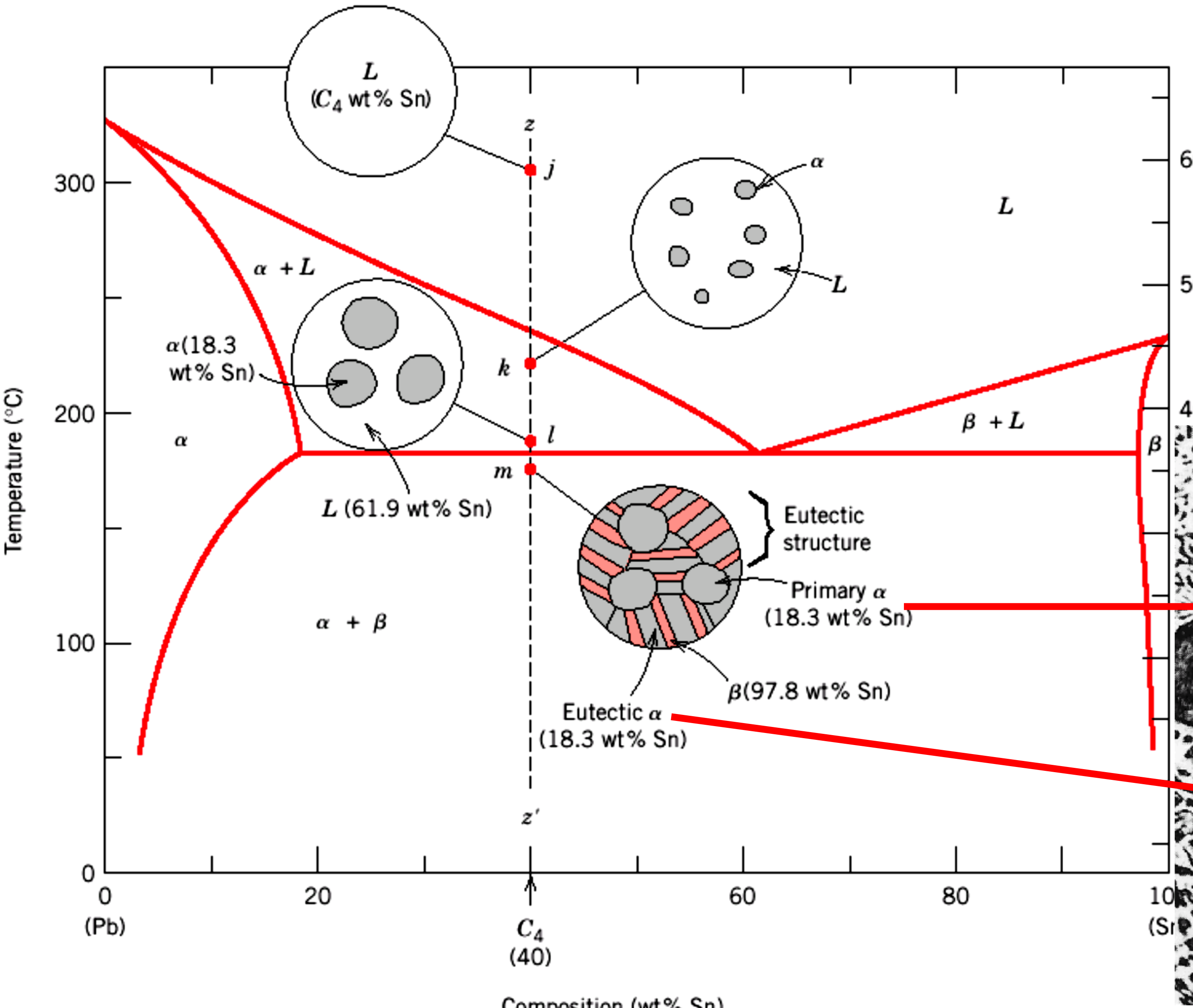
Eutectic microstructure development

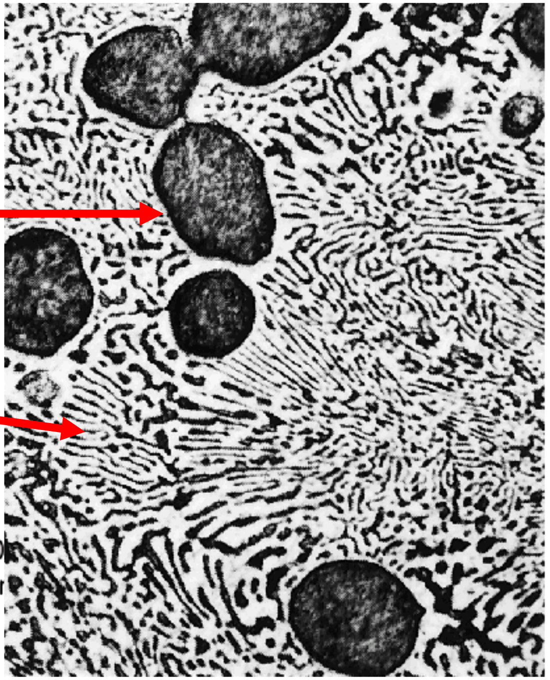




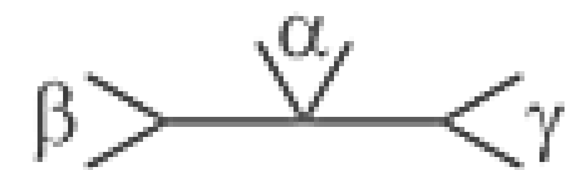
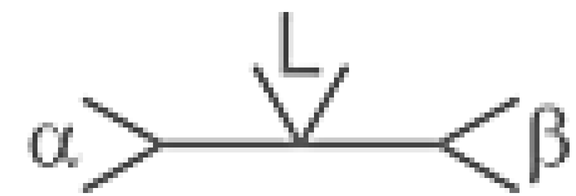
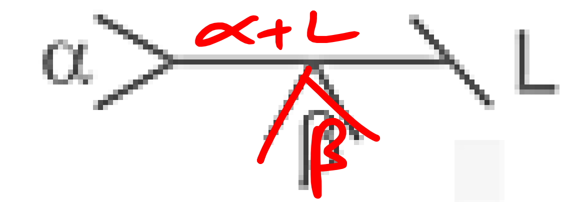
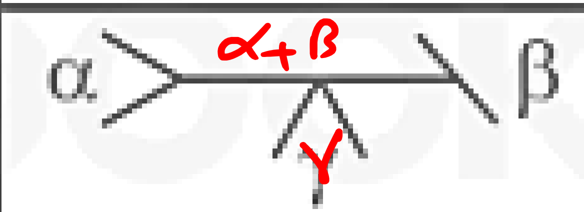


Hypo-Eutectic microstructure development





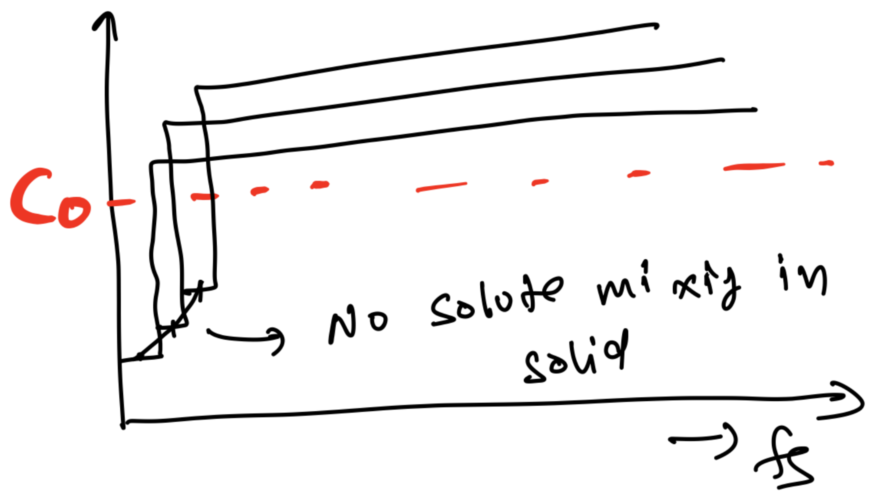
Invariant Reactions

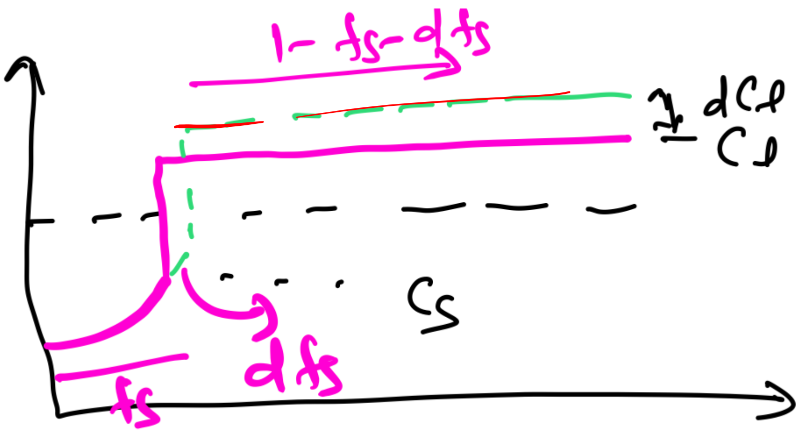
Reaction	Symbolic equation	Schematic Presentation
Eutetoid	$\alpha \leftrightarrow \beta + \gamma$	
Eutectic	$L \leftrightarrow \alpha + \beta$	
Peritectic	$L + \alpha \leftrightarrow \beta$	
Peritetoid	$\alpha + \beta \leftrightarrow \gamma$	

SCHEIL'S Eq^n

Complete mixing in Liquid
& No mixing in solid

— X —





Solute area
Balance $\Rightarrow$

$$d f_s (C_l - C_s) = dC_l (1 - f_s - df_s)$$

$$\frac{df_s}{1-f_s} = \frac{dC_l}{C_l - C_s}$$

$$k = \frac{C_s}{C_l} \Rightarrow dC_l = \frac{dC_s}{k}$$

$$\int_{f_s=0}^{f_s} \frac{df_s}{1-f_s} = \frac{\frac{dC_s}{k}}{\frac{C_s}{k} - C_s} = \int_{kC_o}^{C_s} \frac{dC_s}{C_s(1-k)}$$

$$\left[\ln(1-f_s)\right]_{f_s}^{0} = \frac{1}{1-k}\left[\ln C_s\right]_{kC_o}^{C_s}$$

$$0 - \ln(1-f_s) = \frac{1}{1-k} \ln \frac{C_s}{kC_o}$$

$$\ln \frac{1}{1-f_s} = \ln \left(\frac{C_s}{kC_o}\right)^{\frac{1}{1-k}}$$

SCHEIL'S Eqn

Complete mixing in Liquid & No mixing in Solid

X

$$\left(\frac{1}{1-f_s}\right)^{1-k} = \frac{C_l}{C_o}$$

$$C_l = \frac{C_o}{(1-f_s)^{1-k}}$$

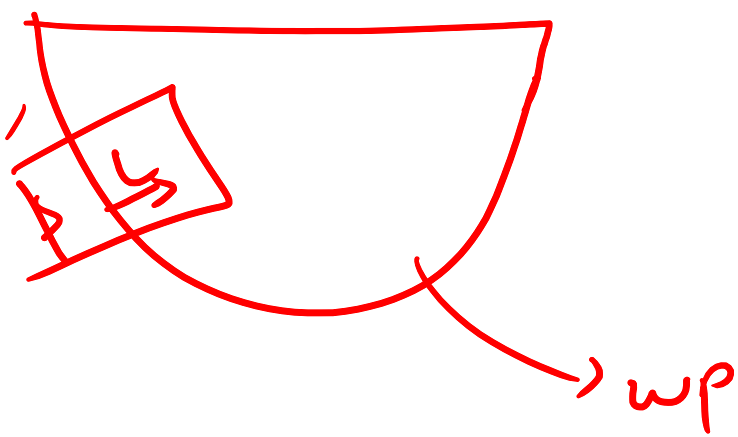
$$\boxed{C_l = C_o f_l^{k-1}}$$

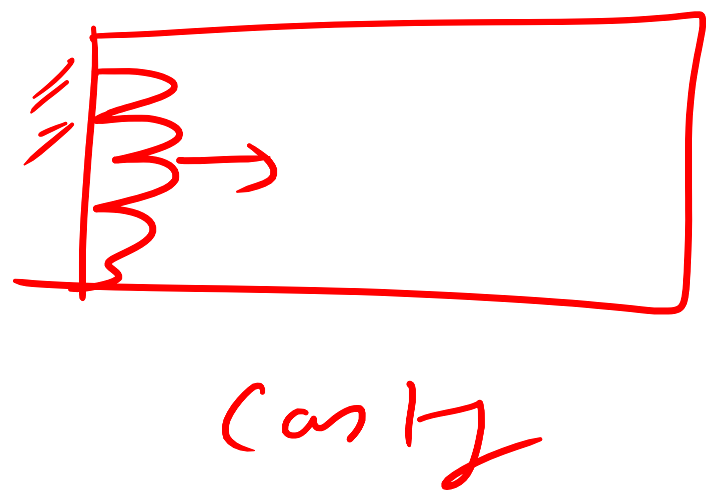
$$\boxed{C_s = k C_o f_l^{k-1}}$$

Segregation profiles in solidification

Solute has limiting diffusion in liquid and no diffusion in solid

Solute has limitig diffusion in liquid & no mixig in solid





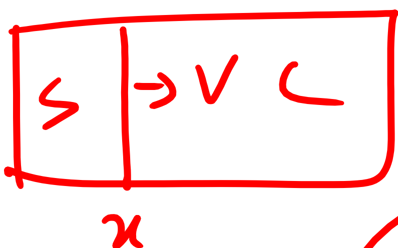
Segregation profiles in solidification

Ficks' 2nd law

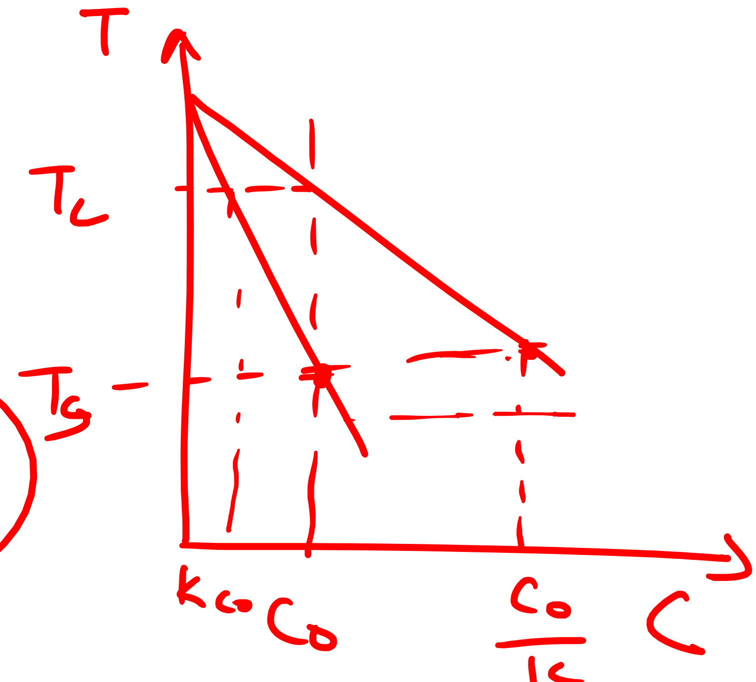
in liquid $$D\frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t}$$

$C = C_l$ = solute concentration in liquid

$$\cancel{\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t}}$$



$$x = x' - Vt$$
$$= x_0 - Vt$$



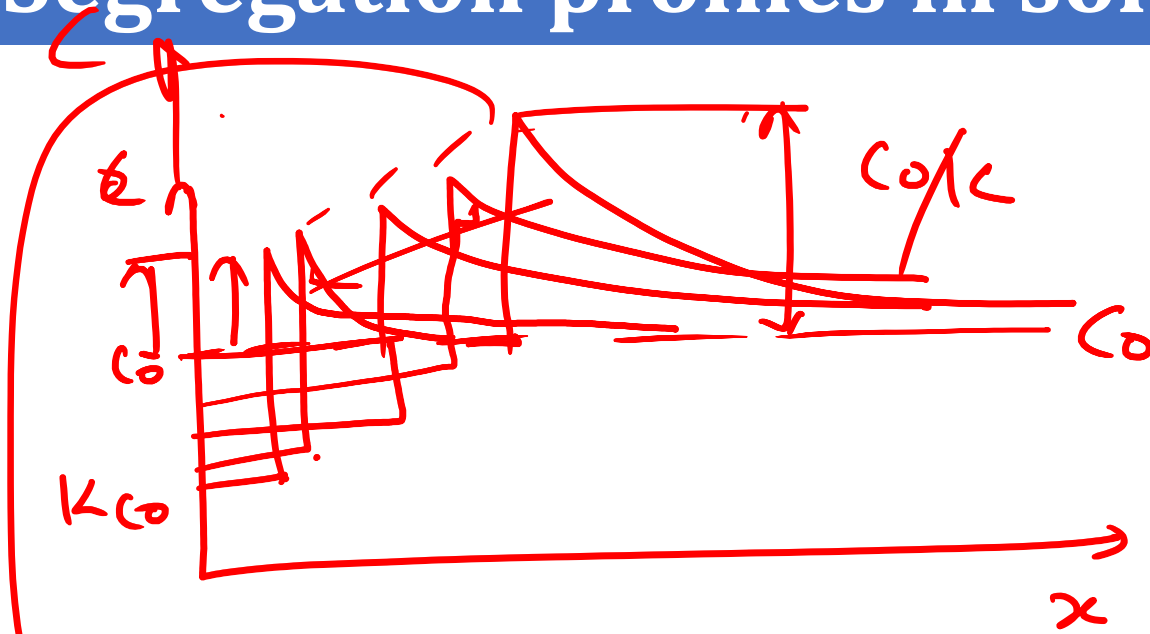
Segregation profiles in solidification

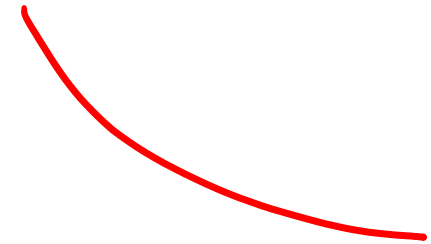
$$D\frac{\partial^2 c}{\partial x^2} = \frac{\partial c}{\partial t} = \frac{\partial c}{\partial x}\frac{\partial x}{\partial t}$$

$$\boxed{D\frac{\partial^2 c}{\partial x^2} = -v\frac{\partial c}{\partial x}}$$

$$\boxed{\begin{aligned} x &= x_0 - vt \\ \frac{\partial x}{\partial t} &= -v \end{aligned}}$$

Segregation profiles in solidification



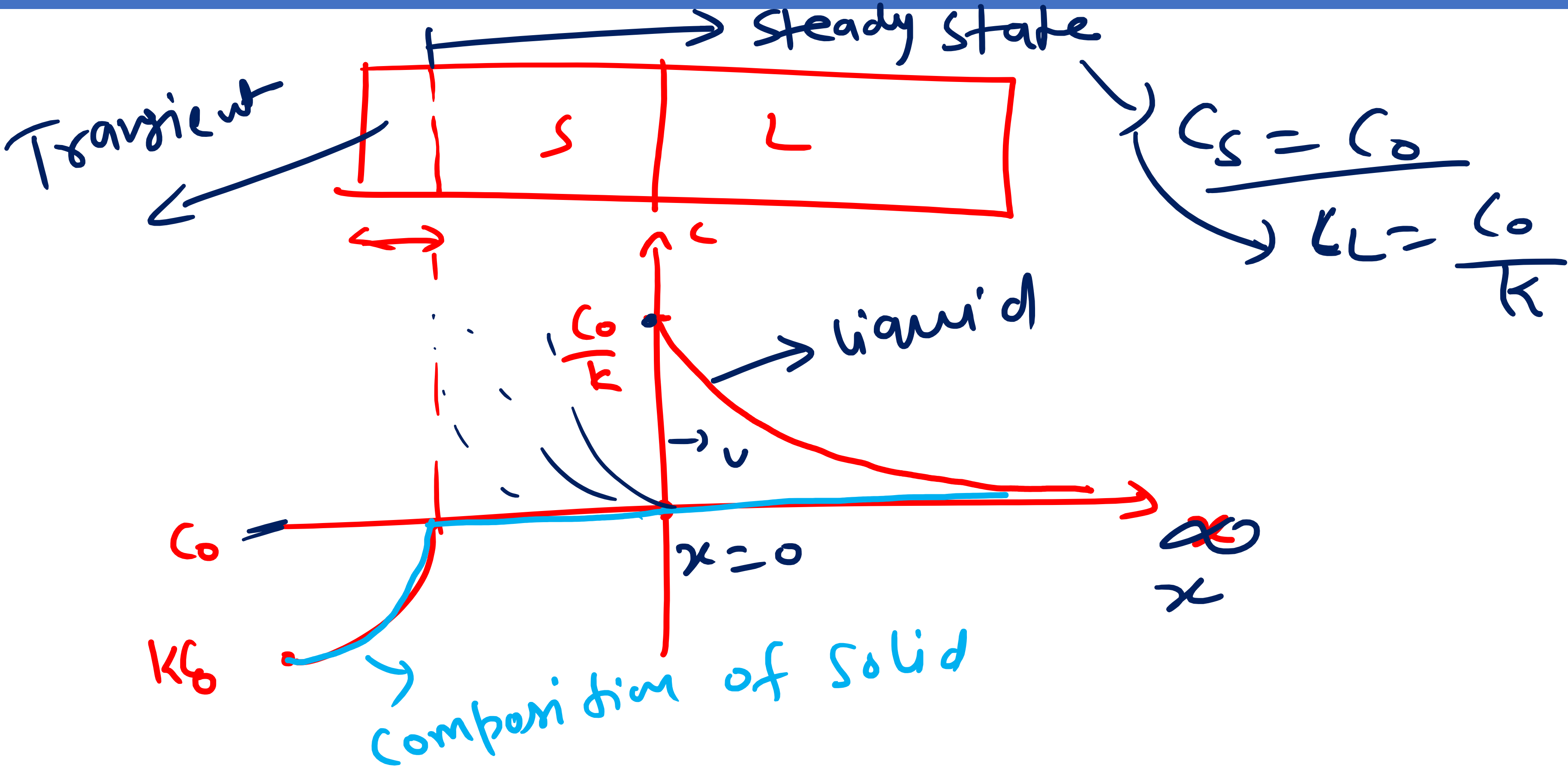


Solid Concentration = C_0

Liquid composition = $\frac{C_0}{k}$

then Steady state condition

Segregation profiles in solidification



$$D\frac{\partial^2 C}{\partial x^2} = -v\frac{\partial C}{\partial x}$$

Segregation profiles in solidification

$$D\frac{\partial^2 C}{\partial x^2} + V\frac{\partial C}{\partial x} = 0$$

liquid concentration

B.C.

at $x = 0$ $C = \frac{C_0}{K}$

at $x \to \infty$

$C = C_0$

$$\frac{\partial^2 C}{\partial x^2} = -\frac{V}{D}\frac{\partial C}{\partial x}$$

$$\frac{\partial\left(\frac{\partial C}{\partial x}\right)}{\partial x} = -\frac{V}{D}\frac{\partial C}{\partial x}$$

$$\frac{\partial\left(\frac{\partial C}{\partial x}\right)}{\frac{\partial C}{\partial x}} = -\frac{V}{D}\partial x$$

$$\ln\frac{\partial C}{\partial x} = -\frac{V}{D}x + P$$

$$\frac{\partial C}{\partial x} = e^{-\frac{Vx}{D}} \times P'$$

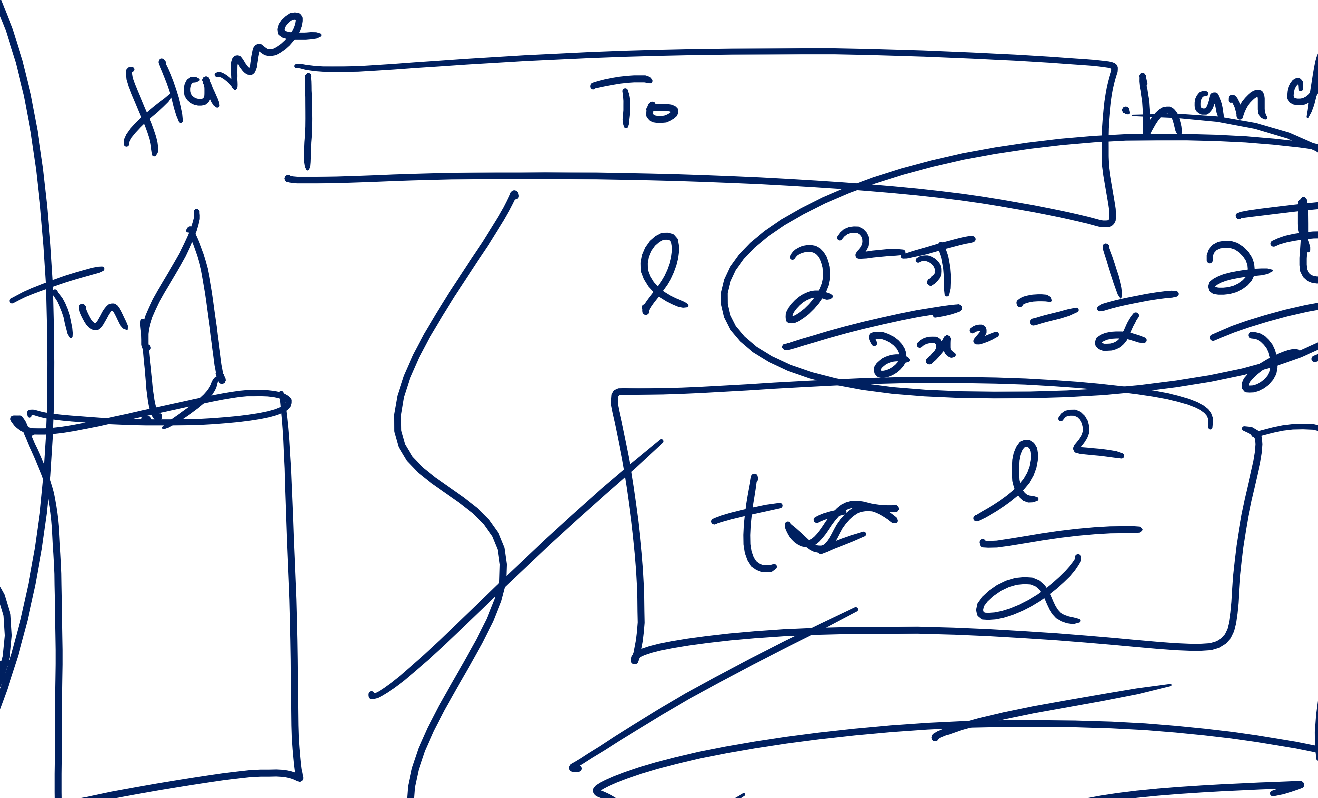
Segregation profiles in solidification

$$v = \frac{l}{t} \Rightarrow t = \frac{l}{v}$$

$$l = \frac{D}{V}$$

$$l = \frac{\alpha}{V}$$

$$t = \frac{\alpha}{V^2}$$



l $\quad \frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$

$$\boxed{t \sim \frac{l^2}{\alpha}}$$

$$\boxed{l \sim \sqrt{\alpha t}}$$

Segregation profiles in solidification

$$\frac{\partial C}{\partial x} = P' \exp\left(-\frac{vx}{D}\right)$$

$$C = \frac{P' \exp\left(-\frac{vx}{D}\right)}{-\frac{v}{D}} + B$$

B. C.

at $x = 0$, $C = \frac{C_0}{K}$

$x \to \infty$ $C = C_0$

$$C = A \exp\left(-\frac{vx}{D}\right) + B$$

$$C_0 = B, \quad \frac{C_0}{K} = A + C_0$$

$$A = \frac{C_0}{K} - C_0 = \frac{C_0(1-K)}{K}$$

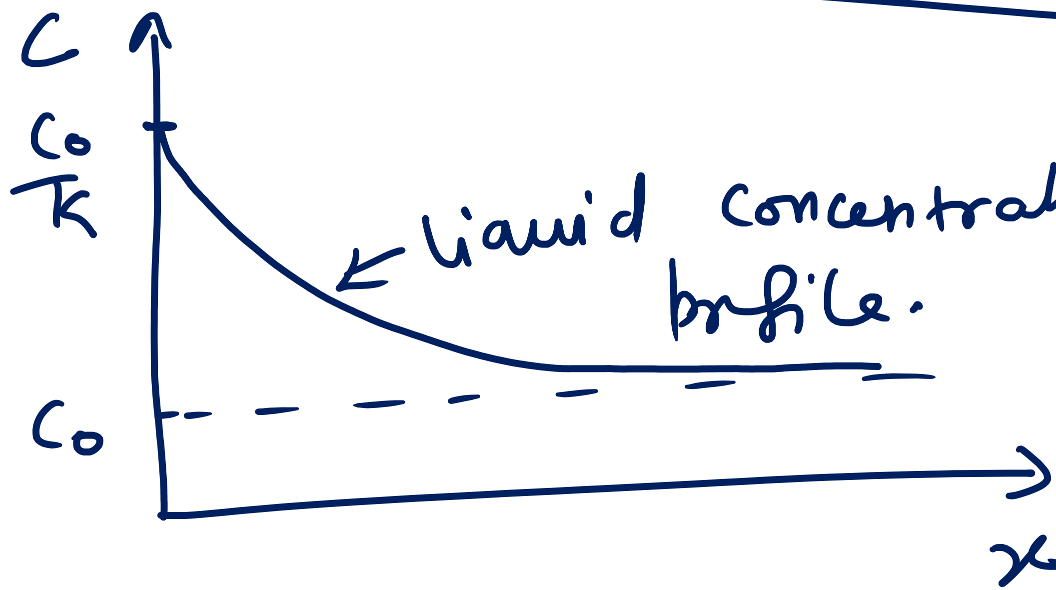
$C =$

Segregation profiles in solidification

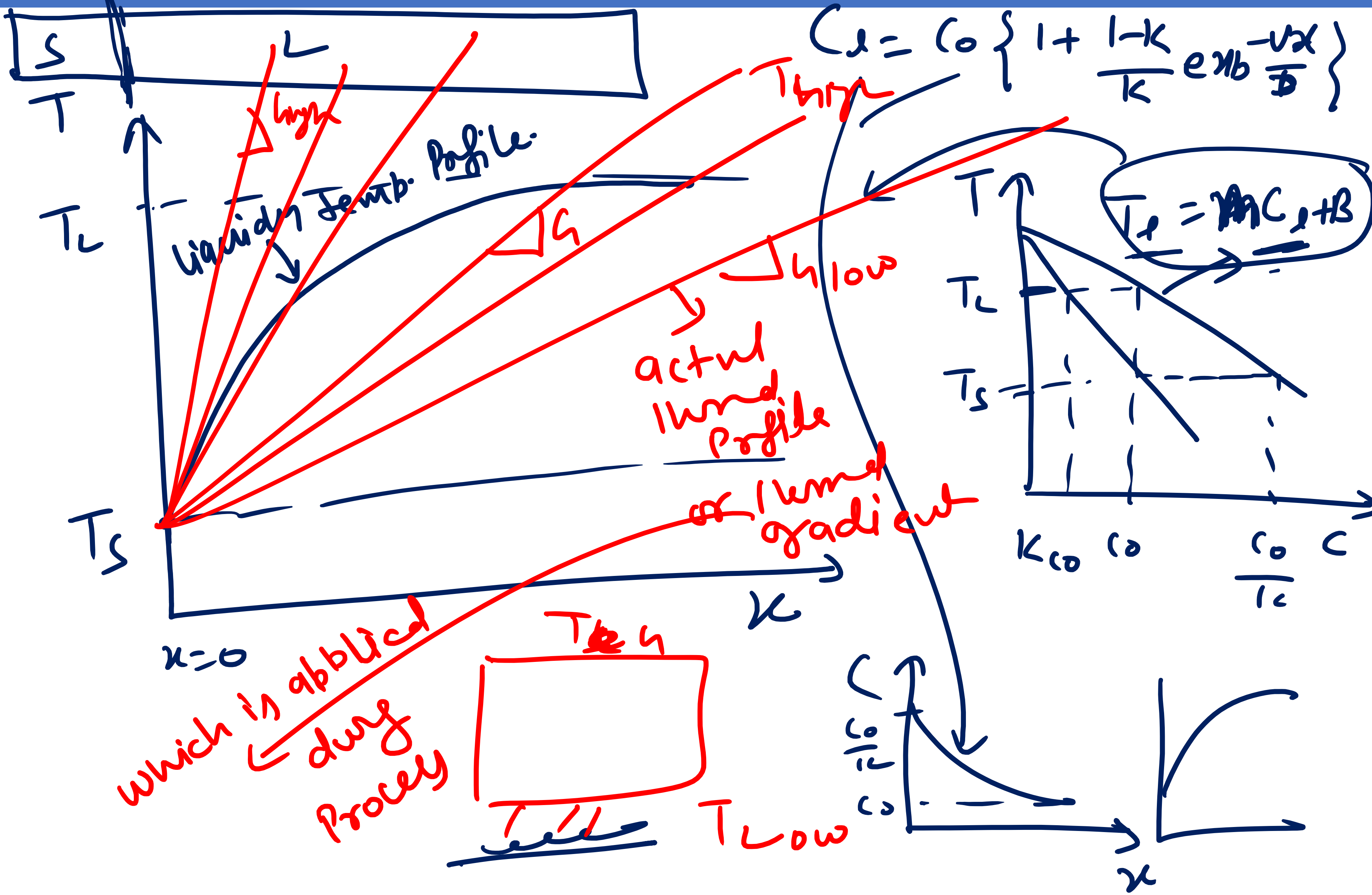
$$C = \frac{C_0(1-k)}{k} \exp\left(-\frac{Vx}{D}\right) + C_0$$

$$\boxed{C_l = C = C_0\left\{1 + \frac{1-k}{k}\exp\left(-\frac{Vx}{D}\right)\right\}}$$

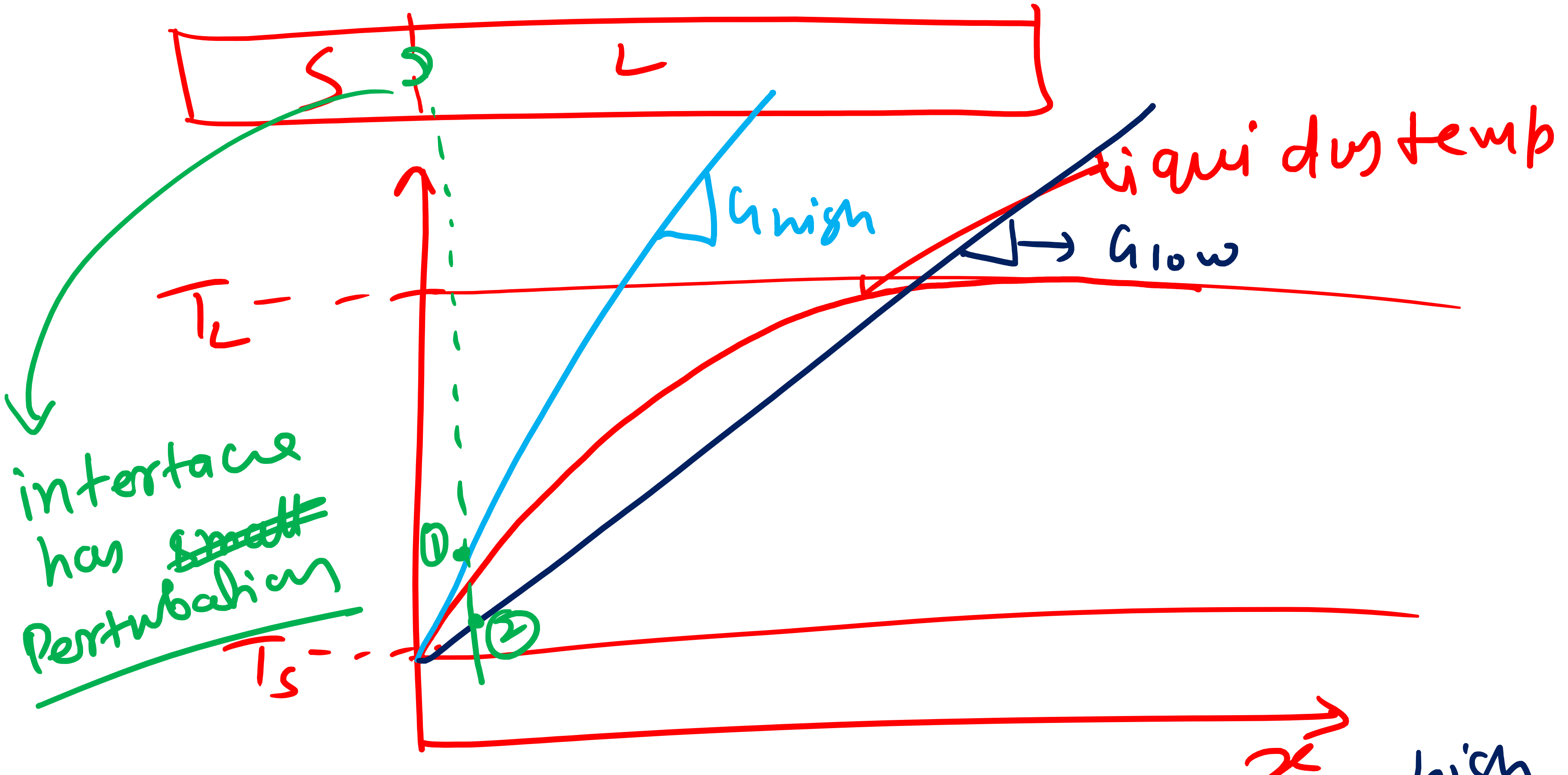
$$k = \frac{C_s}{C_l}$$



Segregation profiles in solidification



Segregation profiles in solidification



high
G high - thermal gradient

G low = low thermal gradient

Segregation profiles in solidification

case 1

gf temp. near growth solid > $T_{liquidus}$

$T_{actual} > T_{liquidus}$

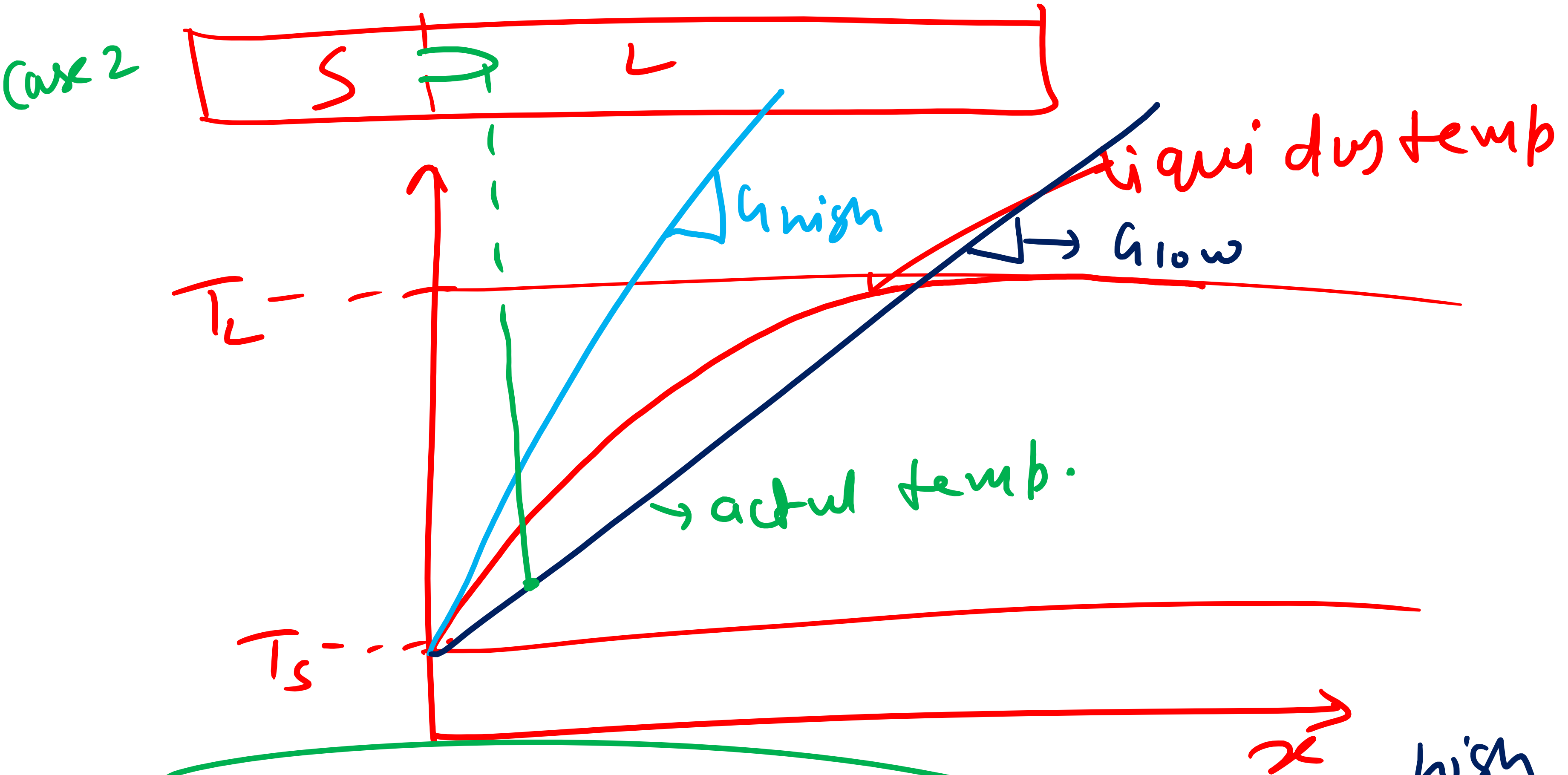
so, no perturbation grow. / Planar interface,

high

G_{high} - thermal gradient

G_{low} = low thermal gradient

Segregation profiles in solidification



$T_{actual} < T_{liquidus}$

Perturbation will grow

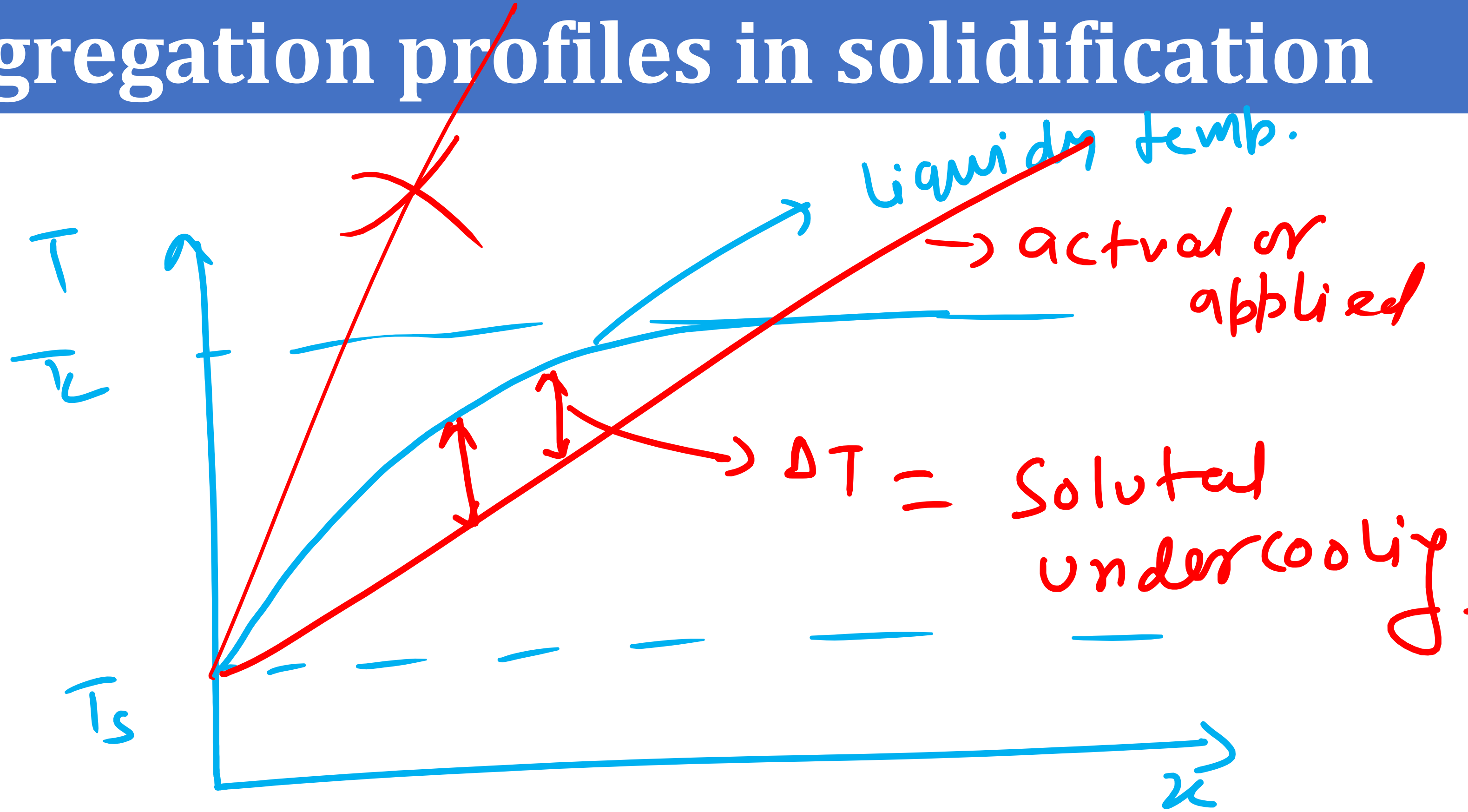
Cellular / dendrite / equiaxed grain

high

G high - thermal gradient

G low = low thermal gradient

Segregation profiles in solidification



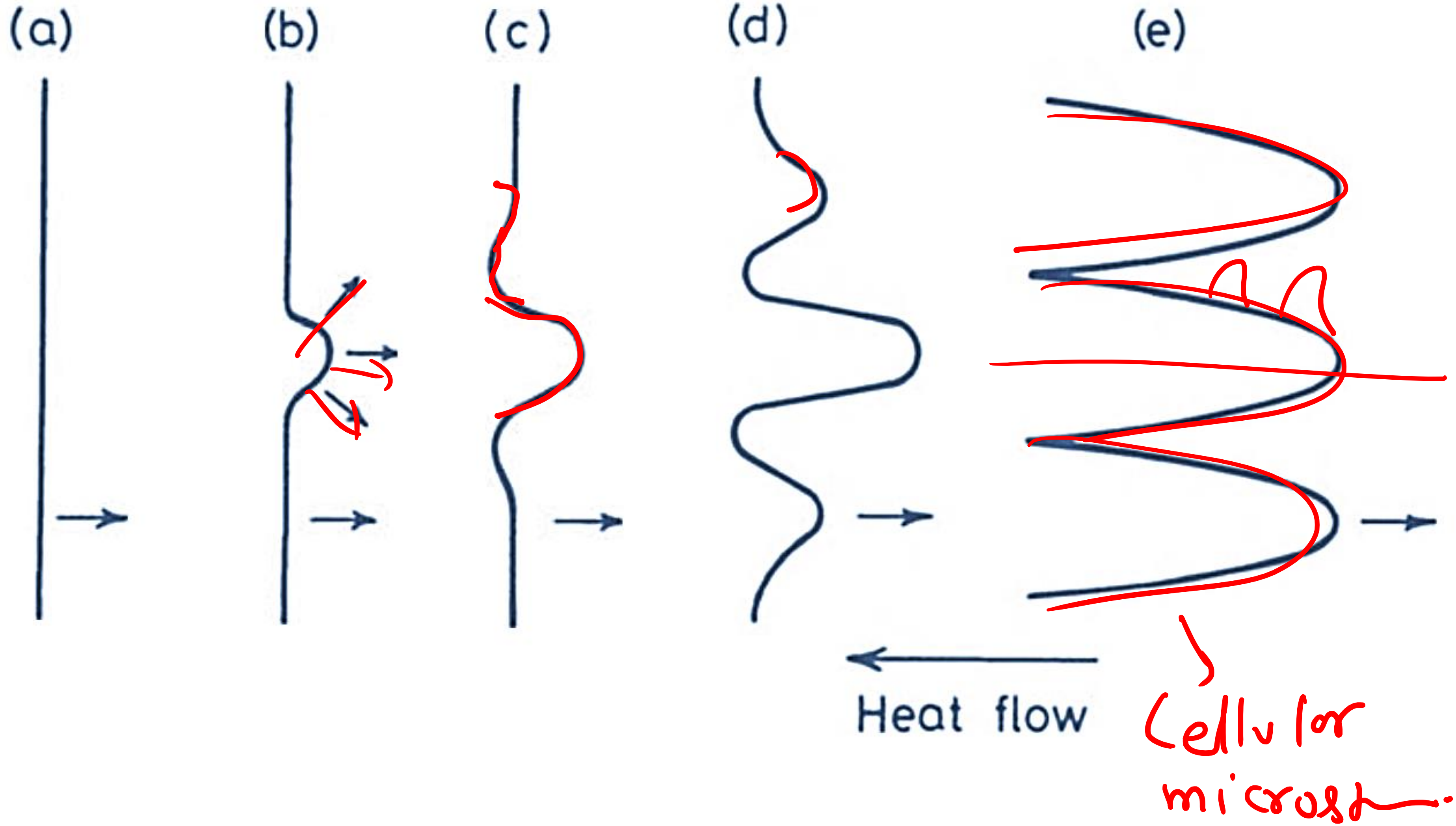
ΔT = 0

ΔT low value

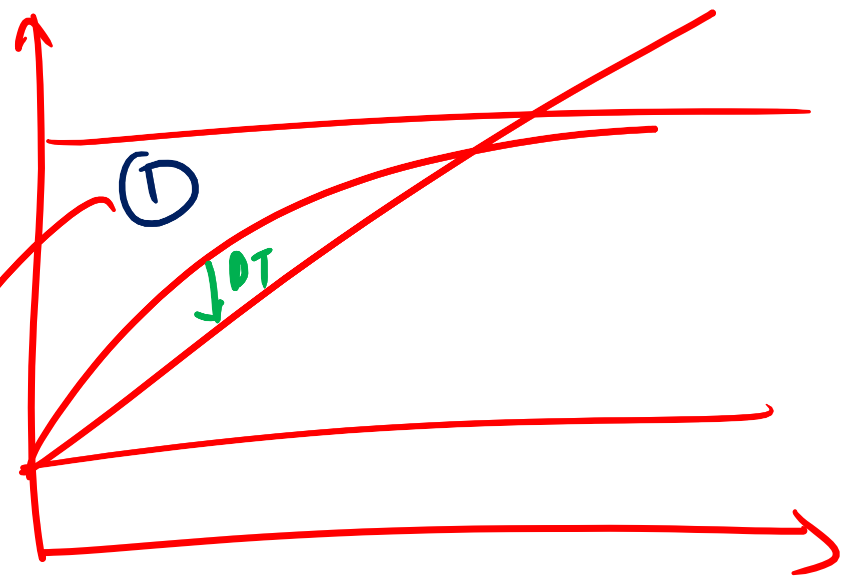
ΔT = moderate value

ΔT = high

Segregation profiles in solidification



Segregation profiles in solidification



planar interface

~~ΔT_m~~

① No solute undercooling.

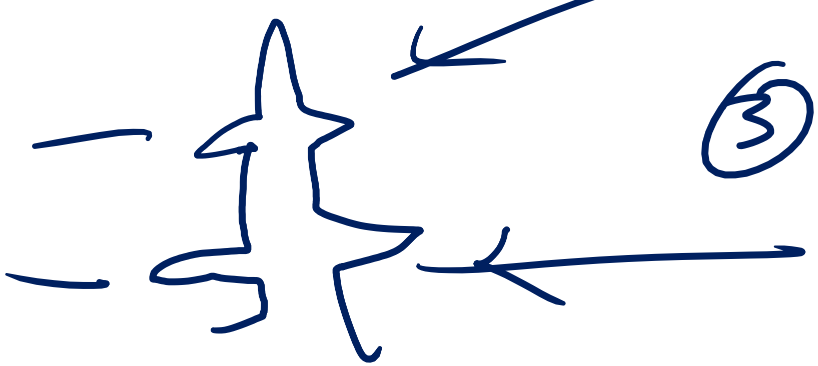
→ planar interface

② ΔT is low

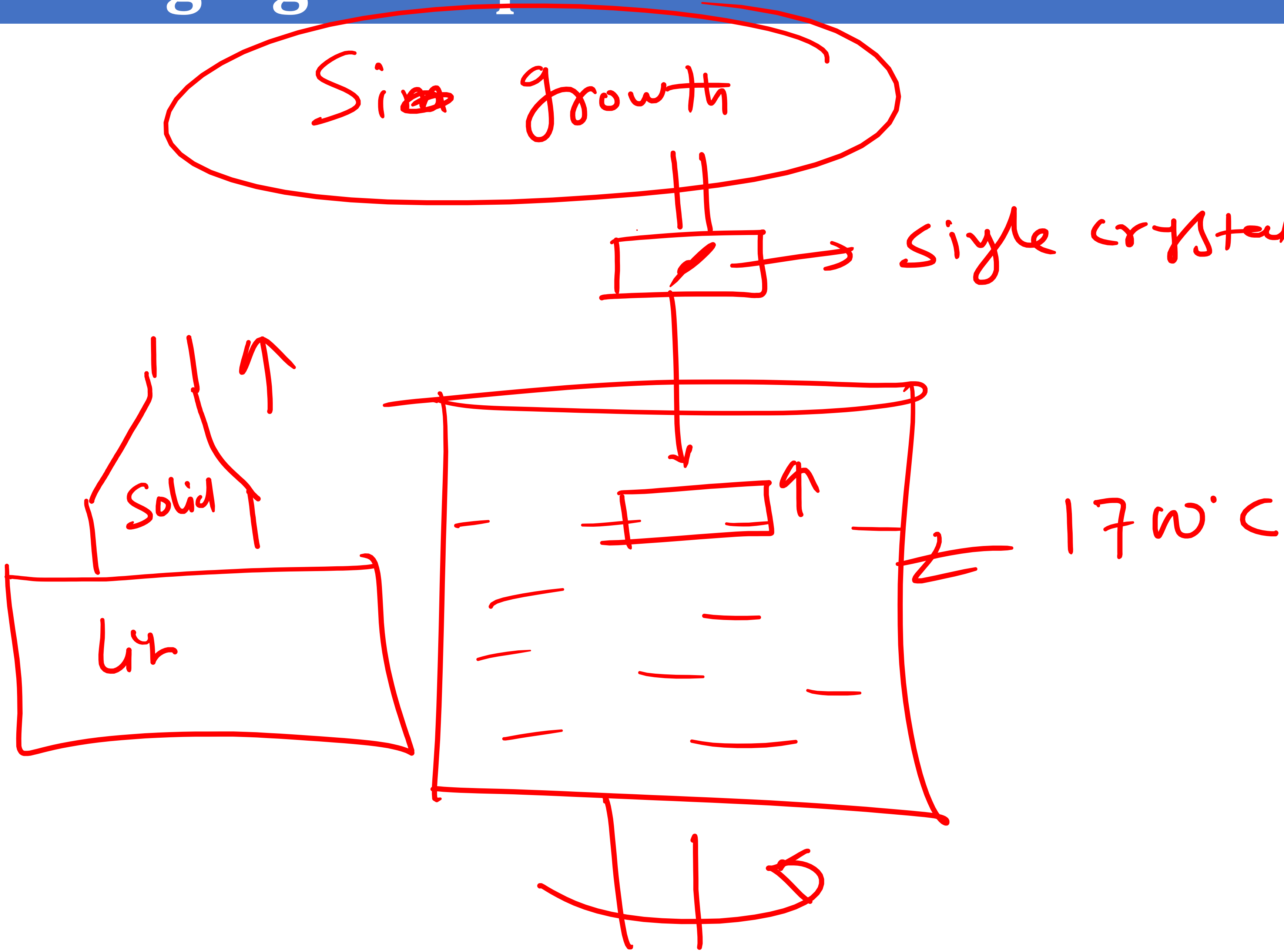
→ Cellular interface

③ ΔT is high

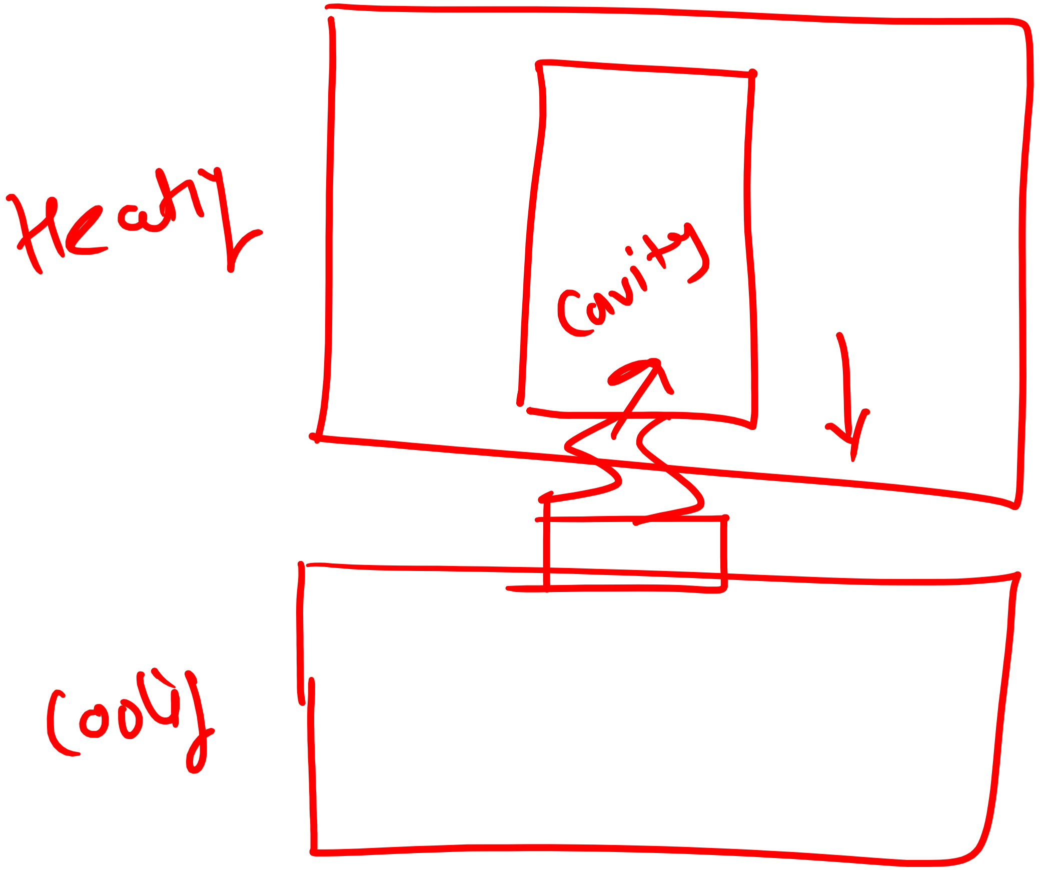
Columnar / dendrite



Segregation profiles in solidification



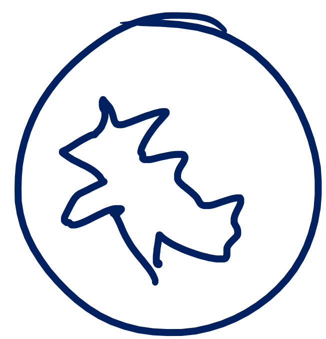
Segregation profiles in solidification

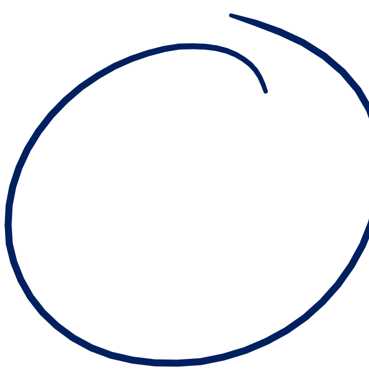


Segregation profiles in solidification

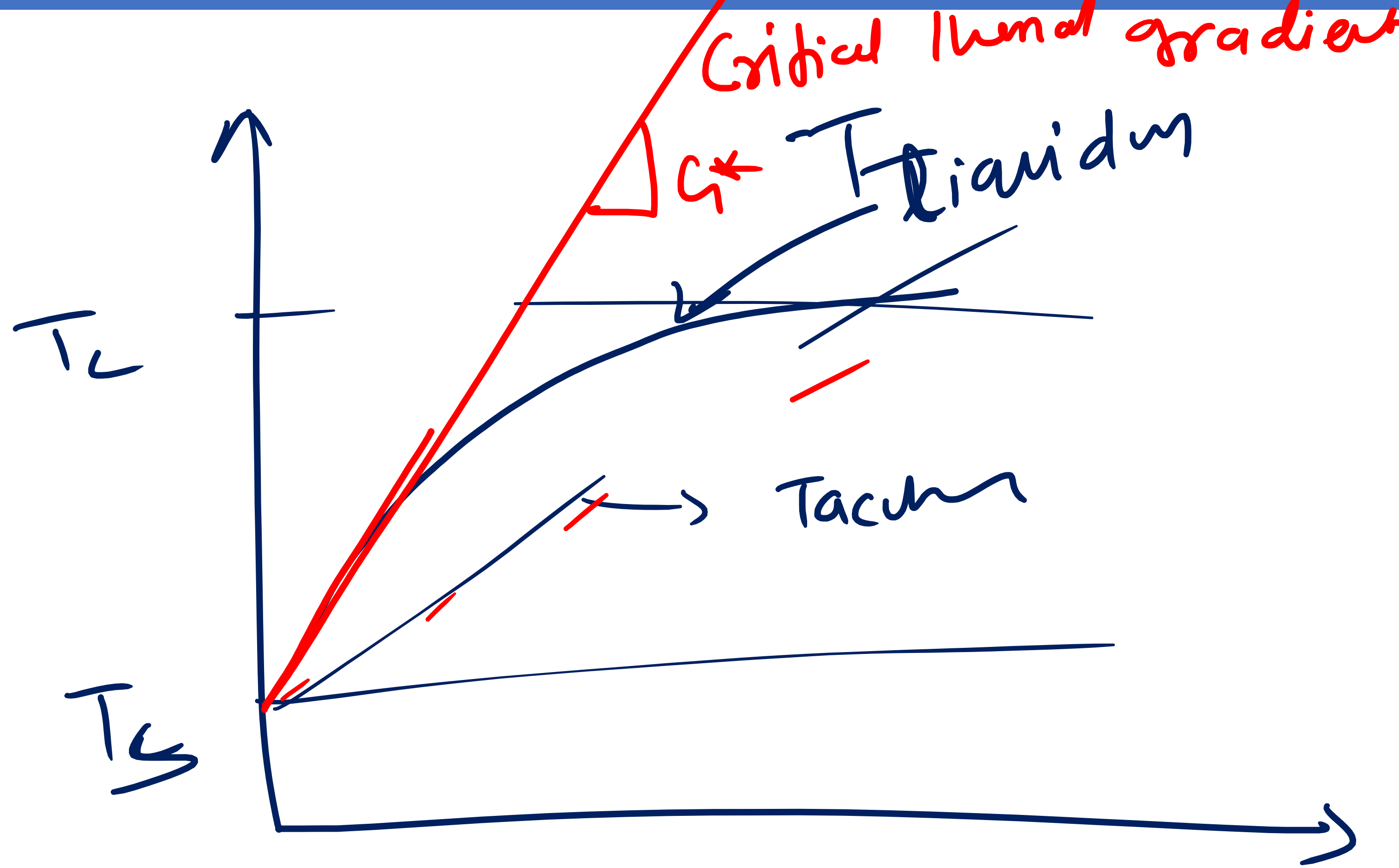
If ΔT is very high
then equiaxed grain

actual gradn is very low





Segregation profiles in solidification



$G > G^* \Rightarrow$ planar interface

$G < G^* \Rightarrow$ cellular / dendritic / equiaxed

Segregation profiles in solidification

$$G^* = \left.\frac{\partial T_{liq}}{\partial x}\right|_{x=0}$$

$$T_{liq} = -mC_l + B$$

$$= \frac{\partial}{\partial x}\left(-mC_l\right)$$

$$= \frac{\partial}{\partial x}\left(-mC_0\left\{1 + \frac{1-k}{k}e^{-\frac{vx}{D}}\right\}\right)$$

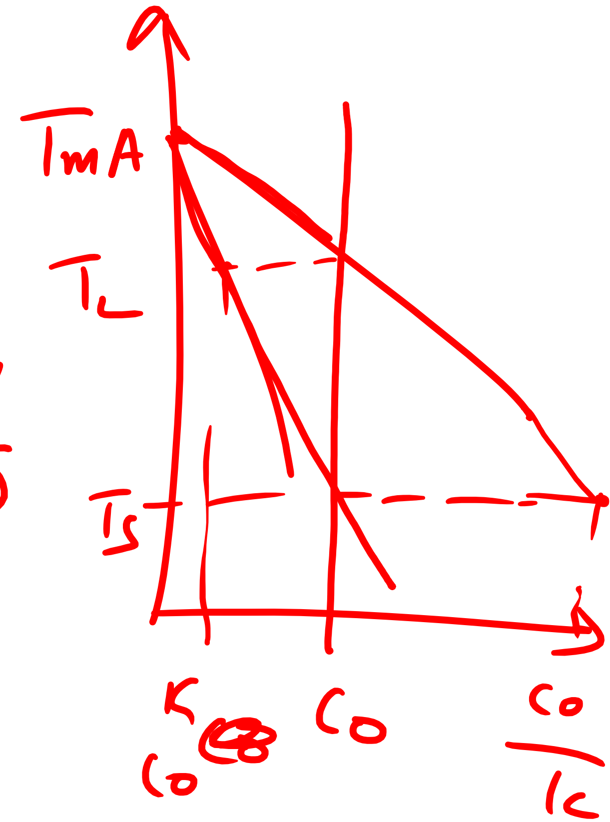
$$= -mC_0\,\frac{(1-k)}{k}\,e^{-vx/D}\left.\left(-v/D\right)\right|_{x=0}$$

Segregation profiles in solidification

$$= \frac{m C_0 (1-k)}{k} \frac{V}{D}$$

$$C^* = m\left(\frac{C_0}{k} - C_0\right)\frac{V}{D}$$

$$= (T_L - T_S)\frac{V}{D}$$

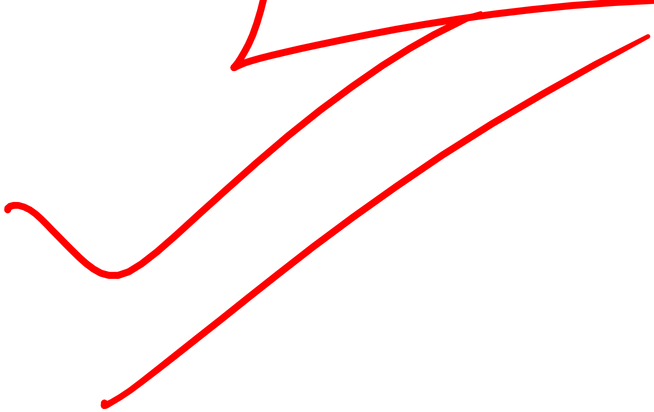


$$m C_0 = T_{mA} - T_L \quad \Big| \quad \frac{m C_0}{k} = T_{mA} - T_S$$

Segregation profiles in solidification

$$G^* = (T_L - T_S)\,/\,\frac{v}{D}$$

$$\boxed{\frac{G^*}{v} = \frac{T_L - T_S}{D}}$$



Segregation profiles in solidification

Segregation profiles in solidification

Segregation profiles in solidification

Microstructure

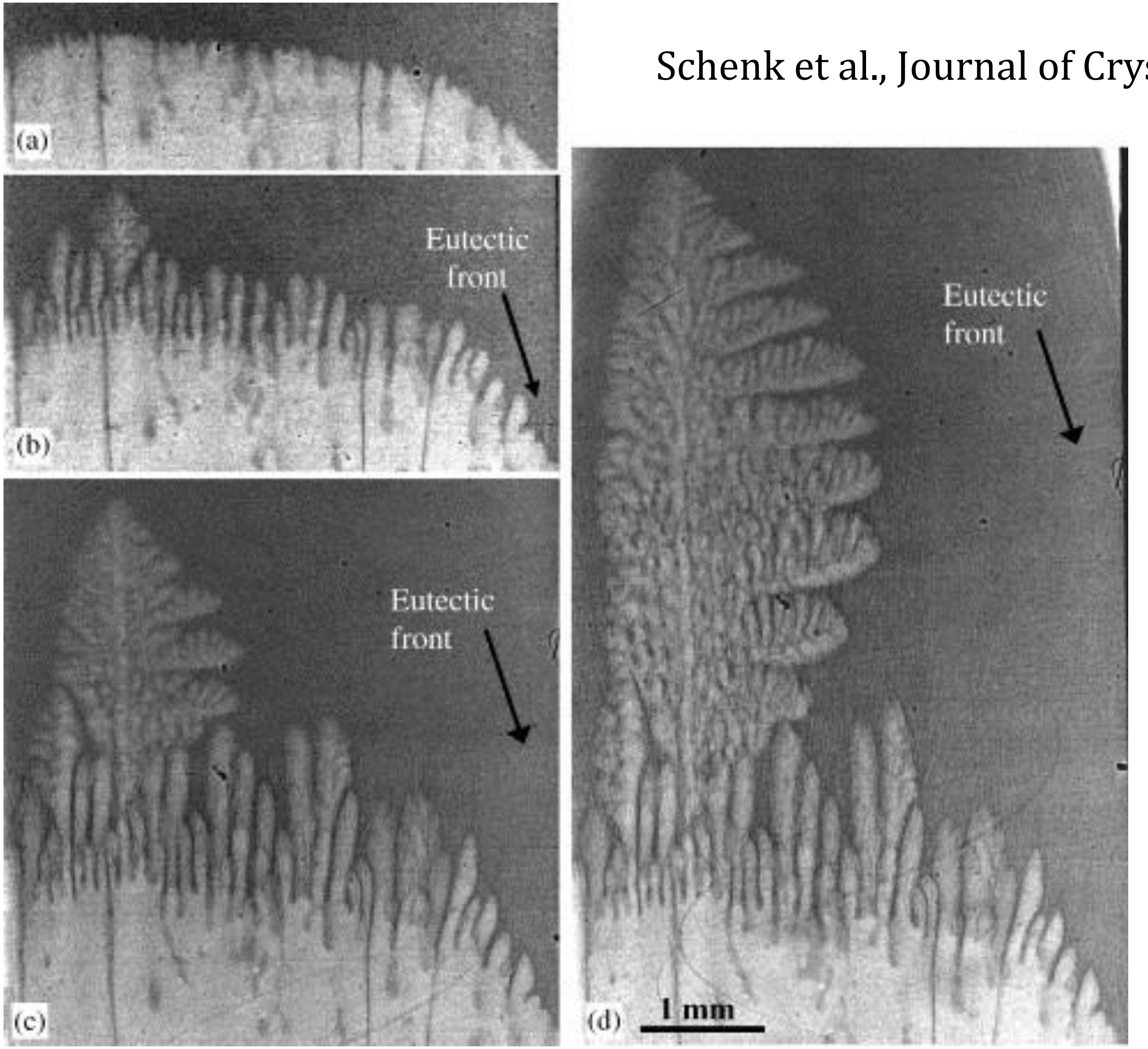
https://www.doitpoms.ac.uk/tlplib/solidification_alloys/undercooling.php

Microstructure

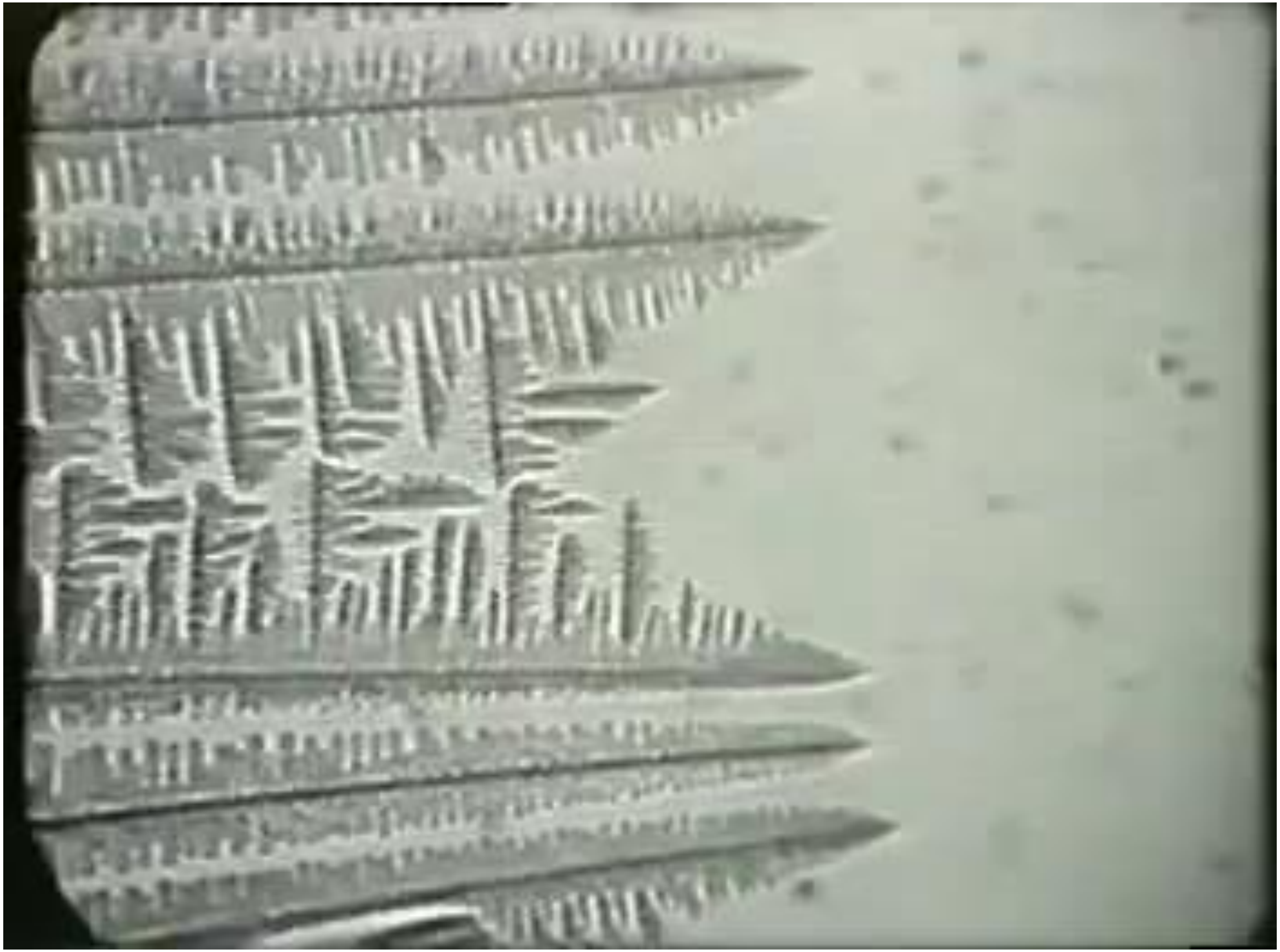
https://www.youtube.com/watch?v=coPRtatC2B0&ab_channel=E-FoundryIITBombay

Microstructure

Schenk et al., Journal of Crystal Growth, 2005

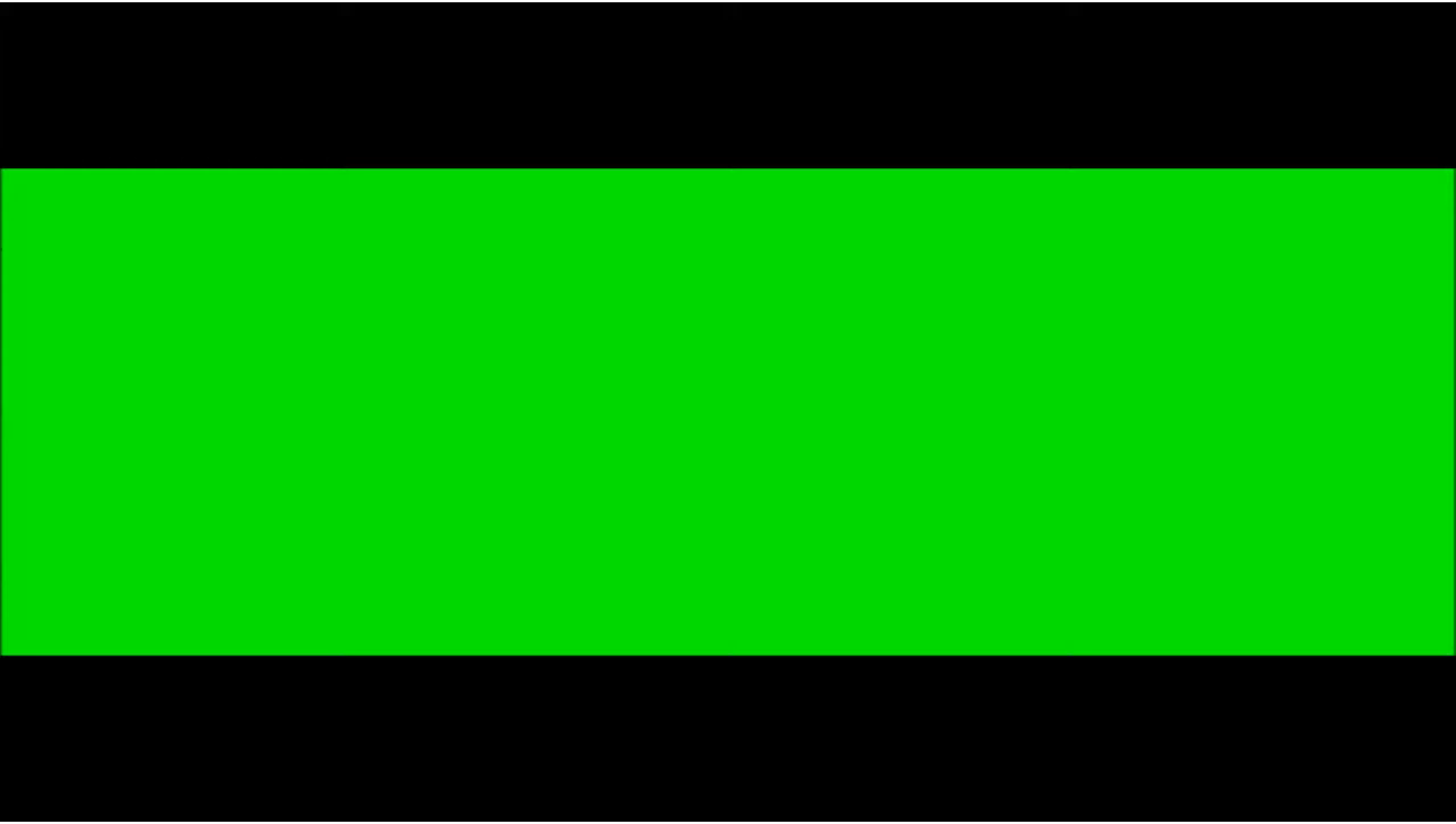


Microstructure



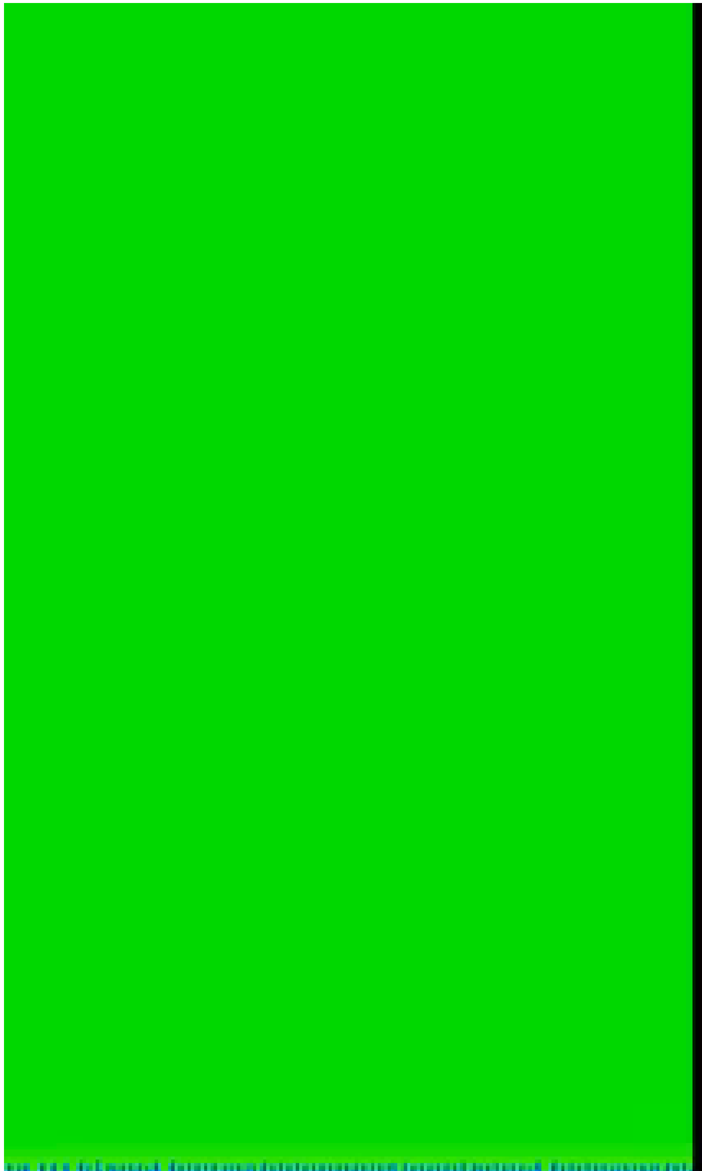
https://www.youtube.com/watch?v=S07fPo45BvM&ab_channel=JallepalliSATYASUNITHA

Microstructure

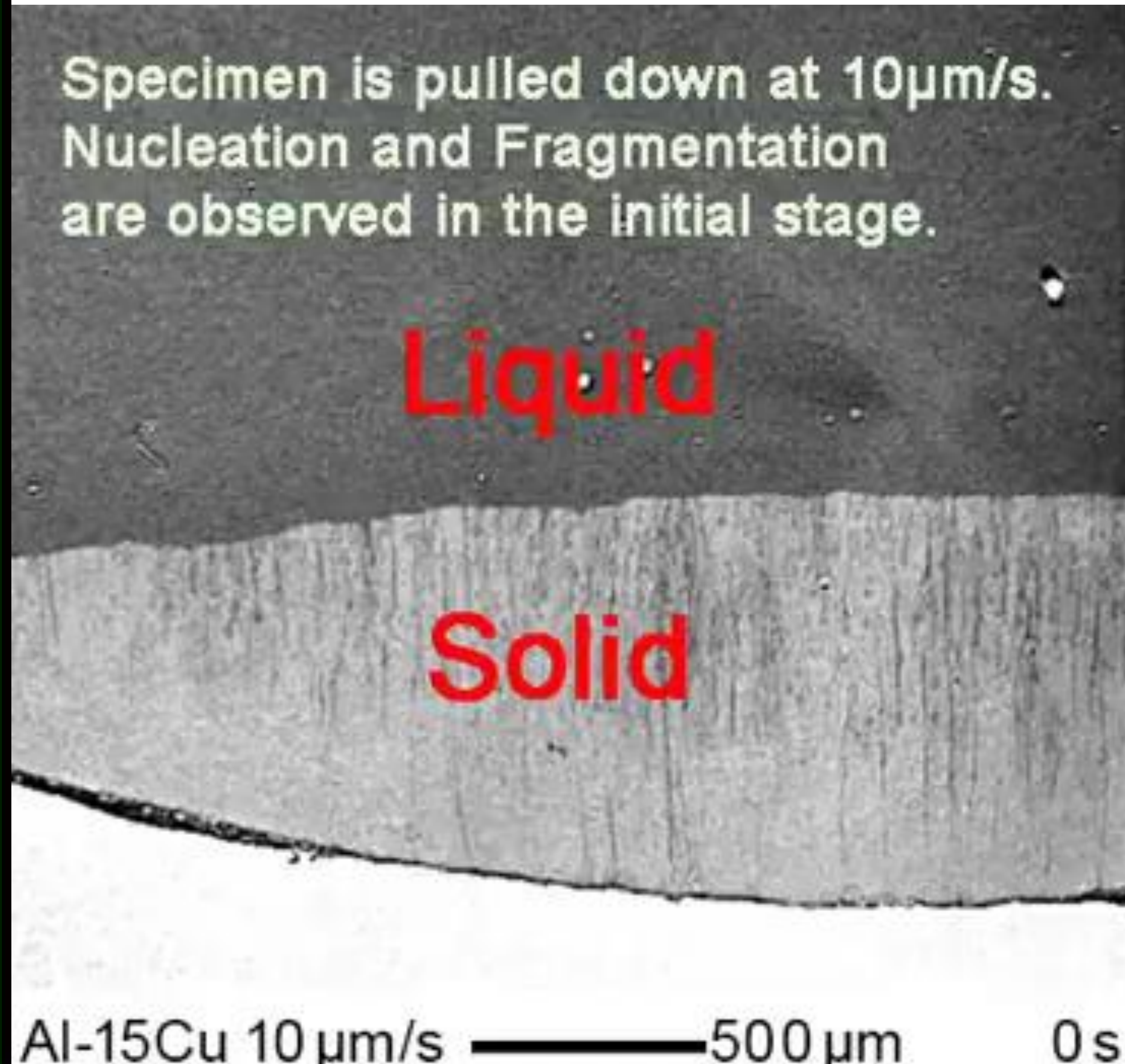


https://www.youtube.com/watch?v=mdTsKgS_wCQ&ab_channel=DmytroYermolenko

Microstructure



https://youtube.com/shorts/1Dboh3A8V78?si=KRhwyFpIjqey6msE

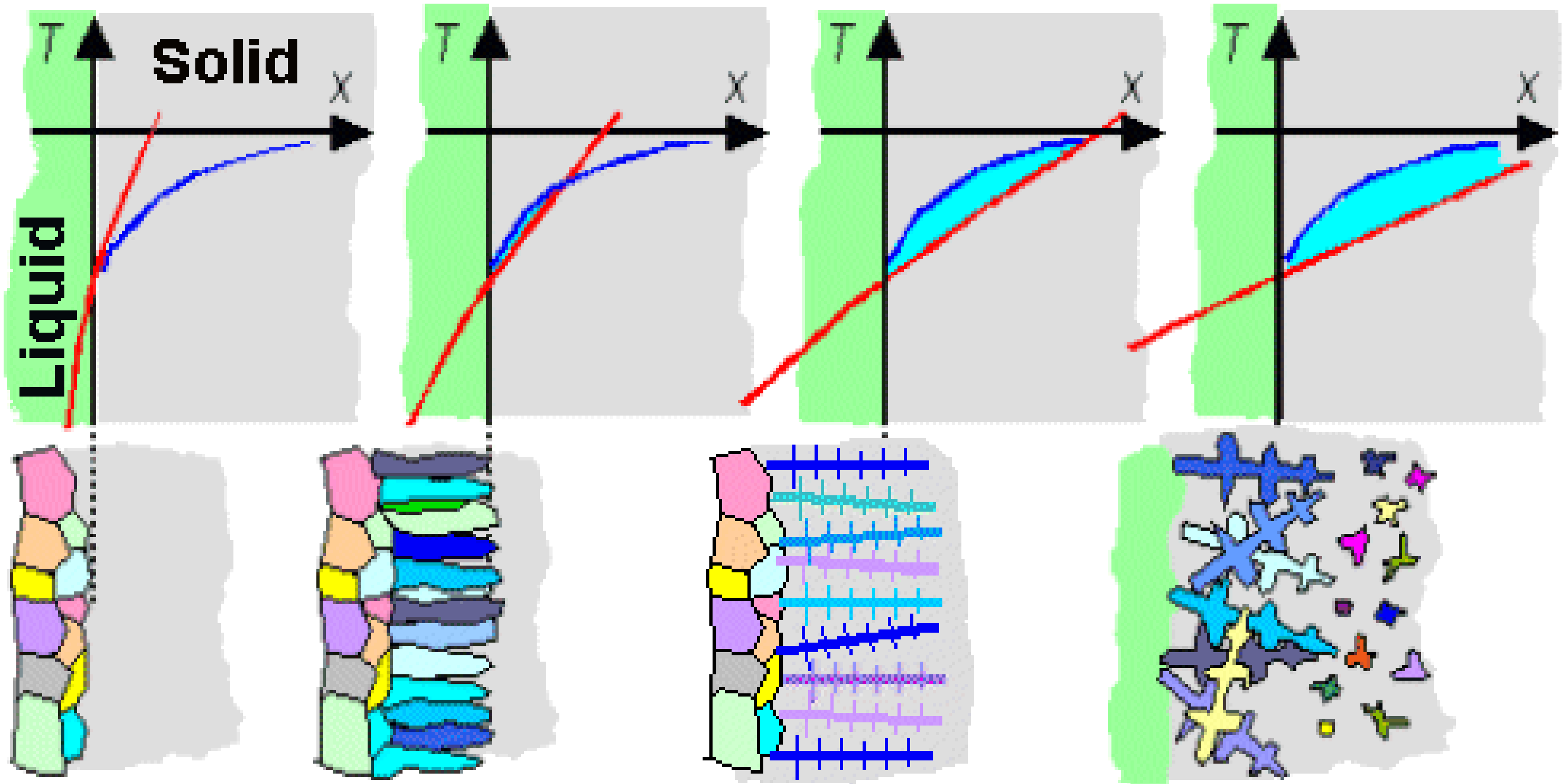


https://www.youtube.com/watch?v=LMqWWVzOMuA&ab_channel=Let%27ssolidify

Microstructure

Microstructure

Microstructure



https://www.tf.uni-kiel.de/matwis/amat/iss/kap_6/illustr/s6_2_1b.html

Planar interface	Cellular interface	Columnar dendrite interface	Equiaxed dendrite interface

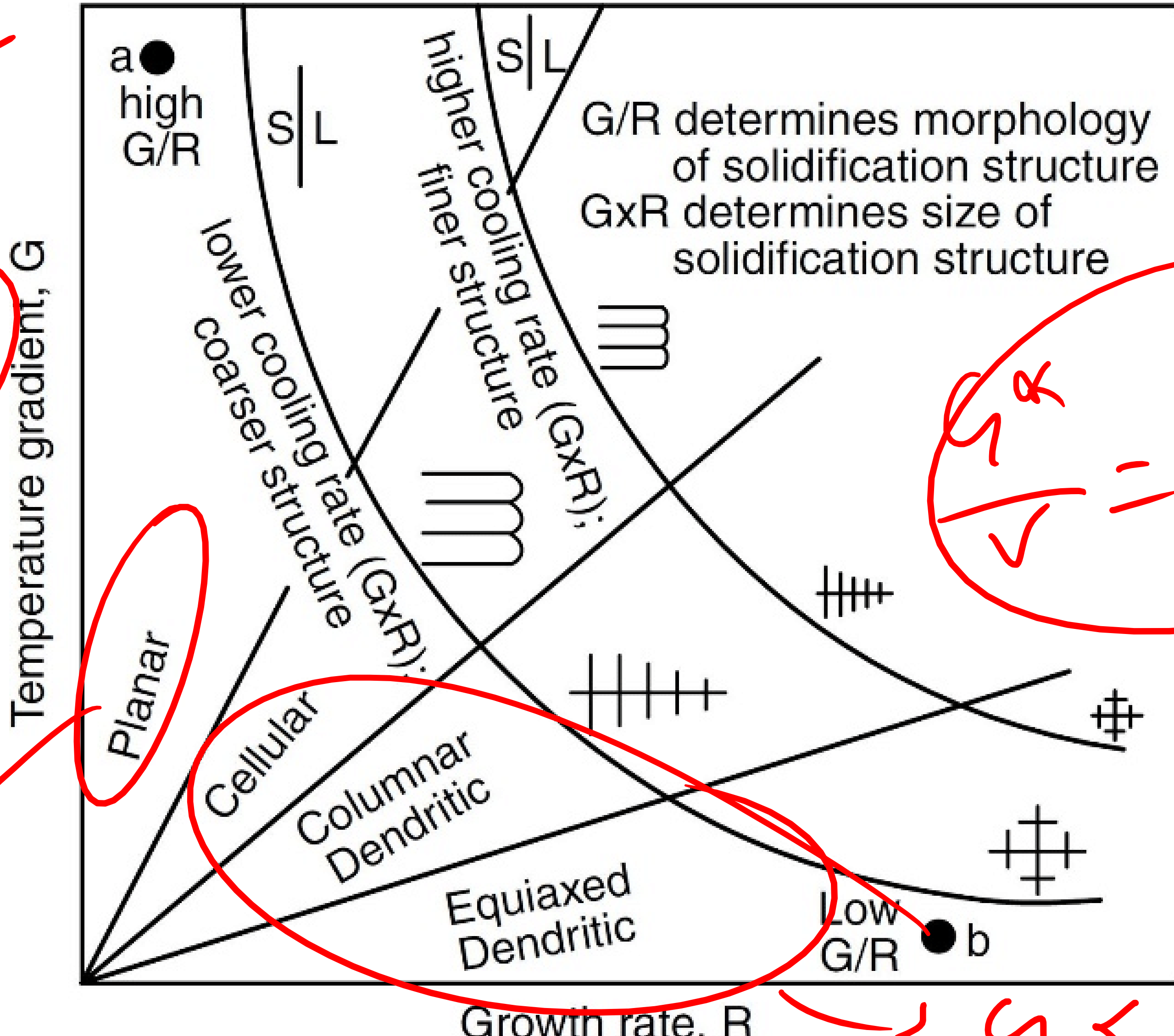
Microstructure

Microstructure

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial x} \times \frac{\partial x}{\partial t}$$

$G \cdot R$

$$-\frac{\partial T}{\partial x}$$



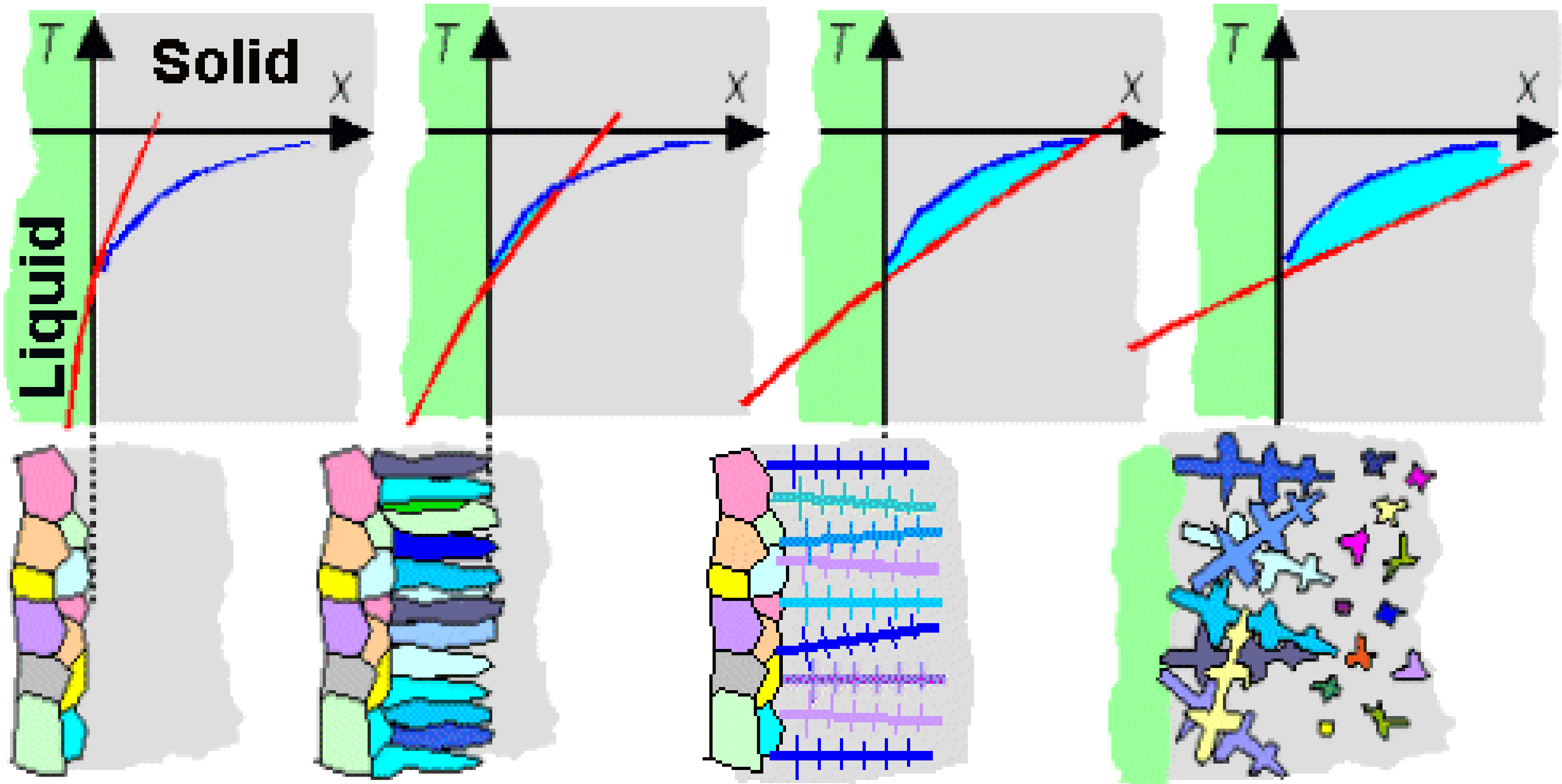
$G > G^*$

$$\frac{G^*}{V} = \frac{T_L - T_S}{D}$$

$G < G^*$

Microstructure

Solidification of Binary material



https://www.tf.uni-kiel.de/matwis/amat/iss/kap_6/illustr/s6_2_1b.html

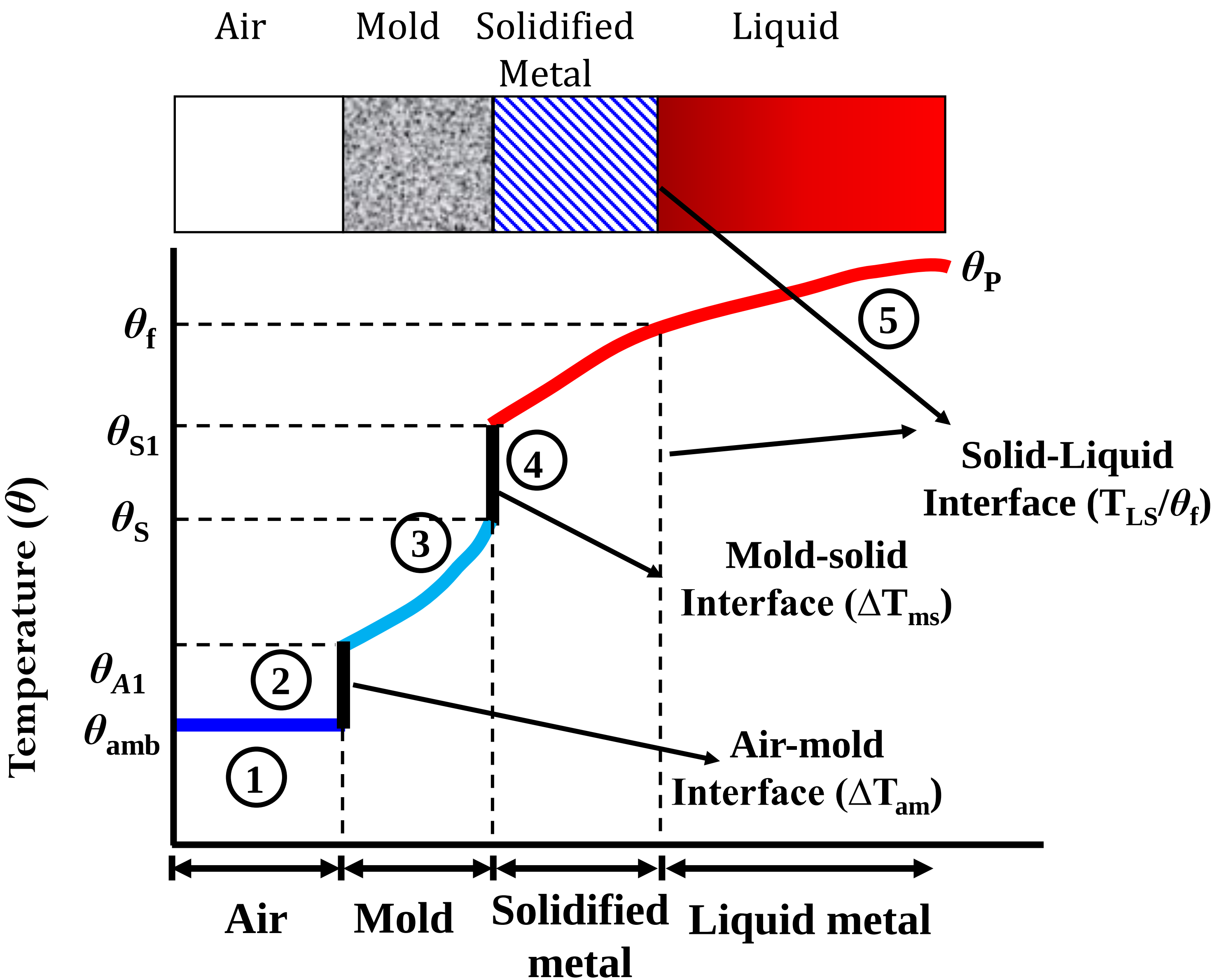
Planar interface	Cellular interface	Columnar dendrite interface	Equiaxed dendrite interface

Solidification time

- Solidification is a transient process involving heat and mass transfer.
- Solidification phenomena is complex due to multi-physics at the interface
  - Diffusion of latent heat at the interface
  - Movement of the solid-liquid interface

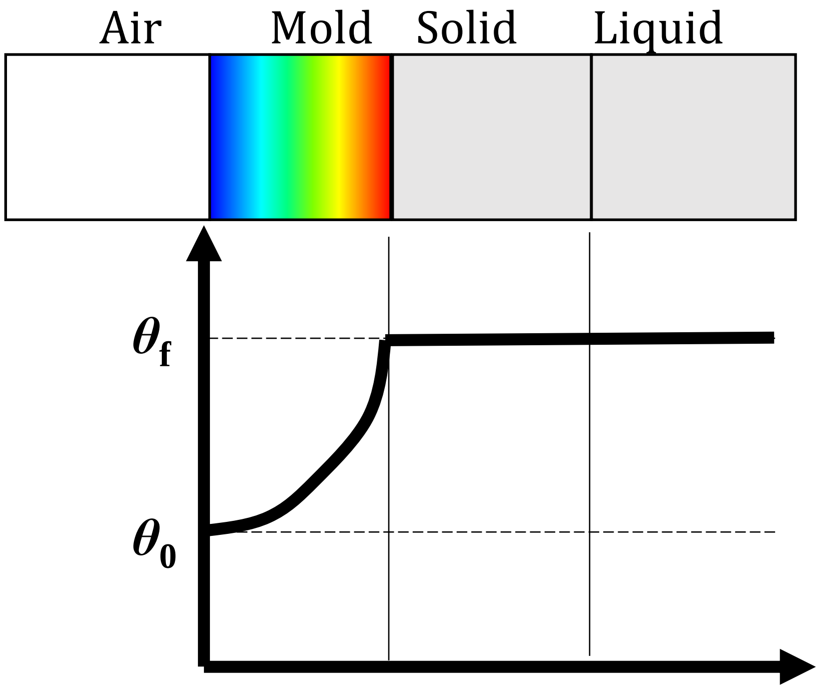
- Solidification time decides the design of riser.
  - Riser used to feed liquid metal in solidifying component to compensate the shrinkage due to phase change.
- For a sound casting, the solidification time of riser ~1.2(solidification time)

Temperature distribution in casting



Sand casting: Solidification time

- Insulated molding : Sand moulding, investment casting and Pit mould casting
- The sand mold thermal profile is main cause for heat transfer.



Assumptions

- Large mold (Semi-infinite region) and maintained at T_O (a fix temperature)
- Liquid metal poured at pouring temperature T_p ($T_p > T_f$)
- Liquid metal just contact with mould they solidifies instantaneously : Solid-mould interface reaches T_f
- Metal-mould interface is plane