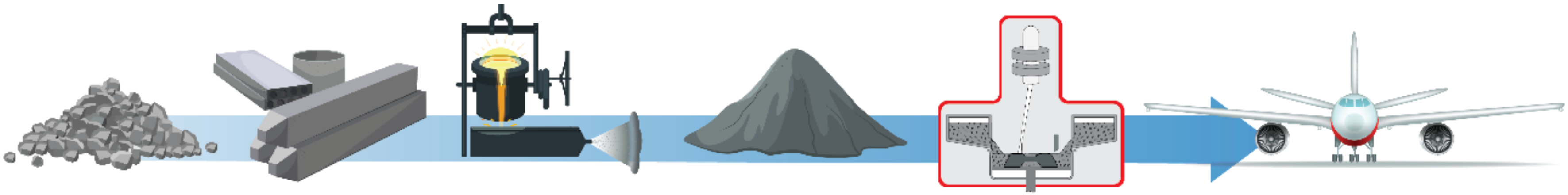
# Lecture 2A

## Phase Diagrams and Microstructures

Monday 9th November 2020

# Why do phases matter to manufacture?

Metals are melted and solidified during *casting* and *welding,* but also during *atomization* (metal powder making) and *powder bed fusion* **AM** by *laser* or *electron beam*



Equilibrium ***phase diagrams*** are one step towards understanding metal microstructures and properties after melting or heat treatments. ***Phase transformations*** another.

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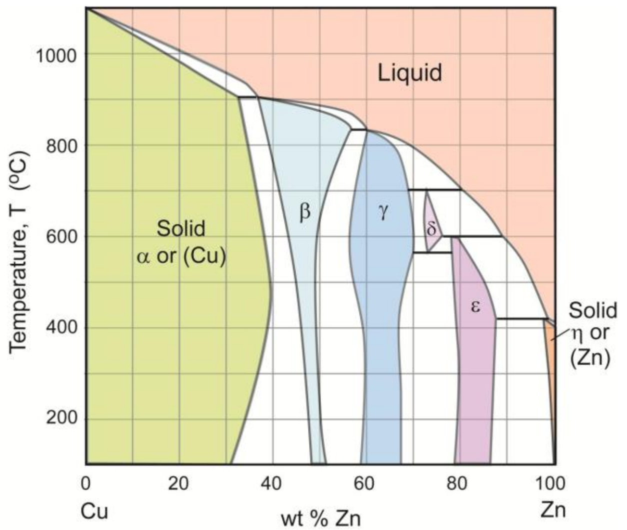
# Learning Outcomes




- Knowledge of microstructures and phases of binary alloys.
- Understanding of how to interpret phase diagram information.
- Ability to apply phase diagrams to define microstructures.

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# Study guide for lecture 2A

***Minimum reading:***

- Lecture slides 2A
- Teach yourself Phase Diagrams and Phase Transformations, part 1-3 and exercises within

**Supplementary recommended resources:**

- Phase diagram tool within GRANTA EduPack MS&E database
- Ashby Ch 3-4 (just up until and including iron-carbon)
- Callister (any edition): Chapter on Phase Diagrams
- For advanced understanding of calculations, some YouTube links
  https://www.youtube.com/watch?v=h5dwpTqacqc
  https://www.youtube.com/watch?v=AbXIiN8iAeU
  https://www.youtube.com/watch?v=IUMcbctDNtM

**Recommended extra exercises:**

Micro-projects 2A-B

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# *Outline*

- Introduction to Phase Diagrams
- Microstructures and binary alloys
- Isomorphous binary phase diagrams
- Eutectic binary phase diagrams
- Lever rule for phase fractions
- Iron – Carbon Phase Diagram and the Granta EduPack software tool

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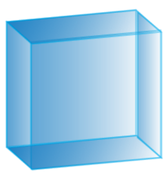
# What is a phase?

**DEF**: A *phase* is a homogeneous portion of a (material) system that has uniform physical and chemical characteristics

Solid phase: ice



Liquid phase: water

Gas phase: water vapor

## Classic example: Water

Metals are normally in the solid phase at room temperature but can be melted and even vaporized at high temperatures

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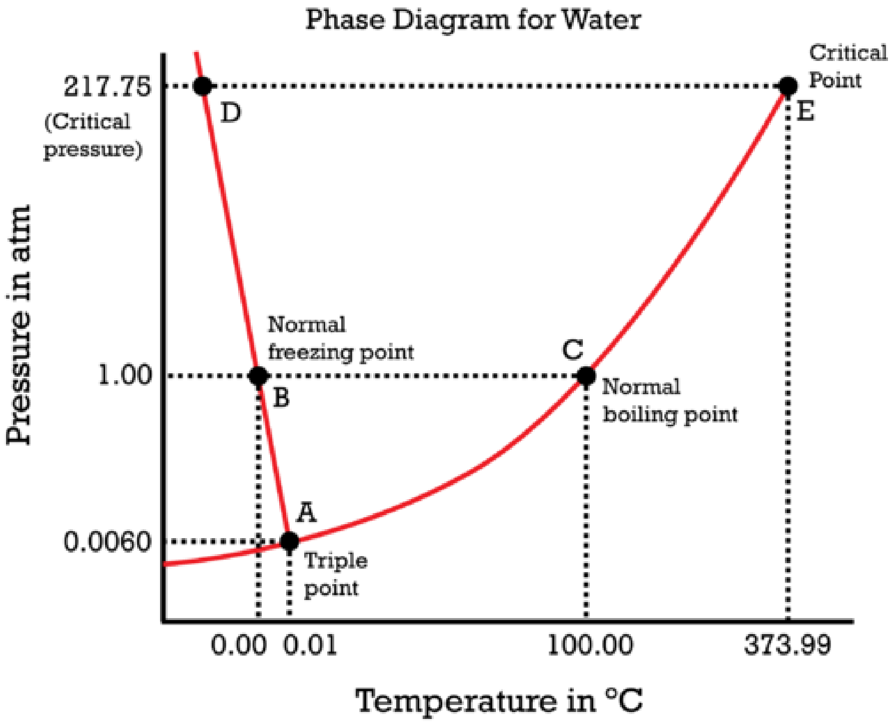
# Phase Diagrams help us understand materials

**DEF**: *Phase Diagrams* graphically show information about the ***equilibrium*** phase structure of a material system with respect to temperature, pressure, and composition

Single component phase diagrams show temperature and pressure

One composition → held constant




https://courses.lumenlearning.com/cheminter/chapter/phase-diagram-for-water/

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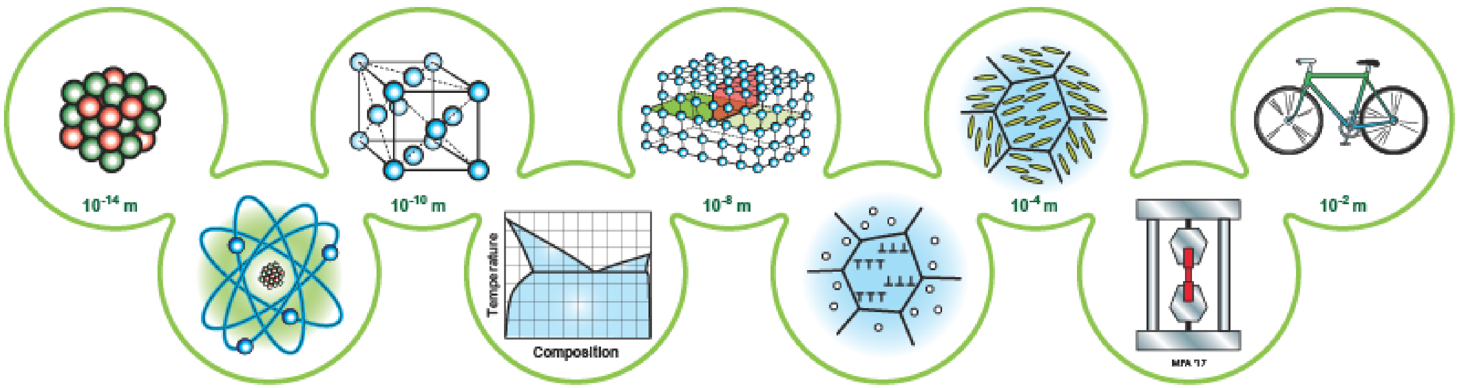
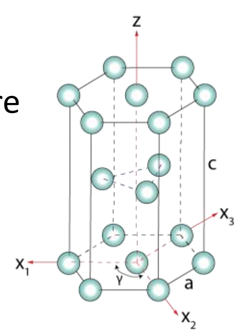
# For metals it is more than just liquid, solid, and gas!

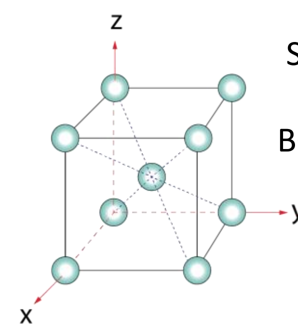
**DEF:** All parts of an alloy ***microstructure*** with the same atomic structure are a *single phase*




**Alpha Titanium**
Stable below 882˚C
HCP Crystal Structure




882°C




**Beta Titanium**
Stable between 882-1670˚C
BCC Crystal Structure

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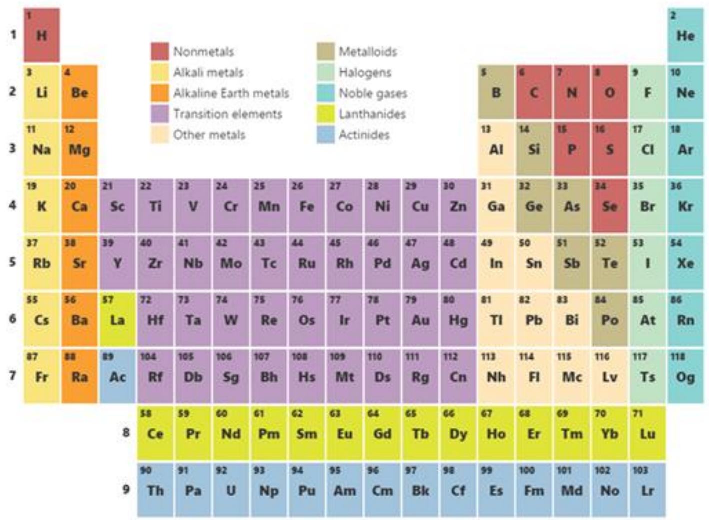
# What is a binary metal alloy?

**DEF**: A *metallic alloy* is a mixture of a metal with other metals or non-metals.




**DEF**: The *components* are the chemical elements that make up alloys (here, atoms)

**DEF**: A *binary alloy* contains two components. A *ternary alloy* contains three, etc.

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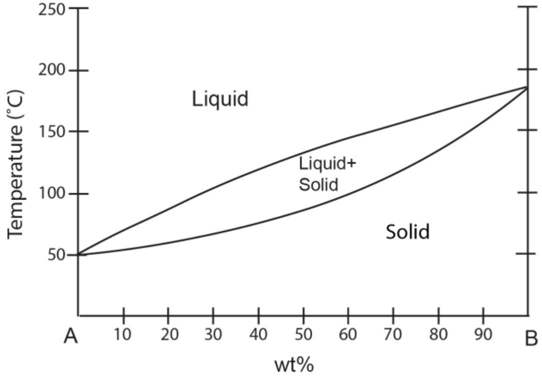
# Binary Phase Diagrams

**DEF**: The *constitution* of an alloy is described by:
(a) the phases present;
(b) the weight fraction of each phase;
(c) the composition of each phase.

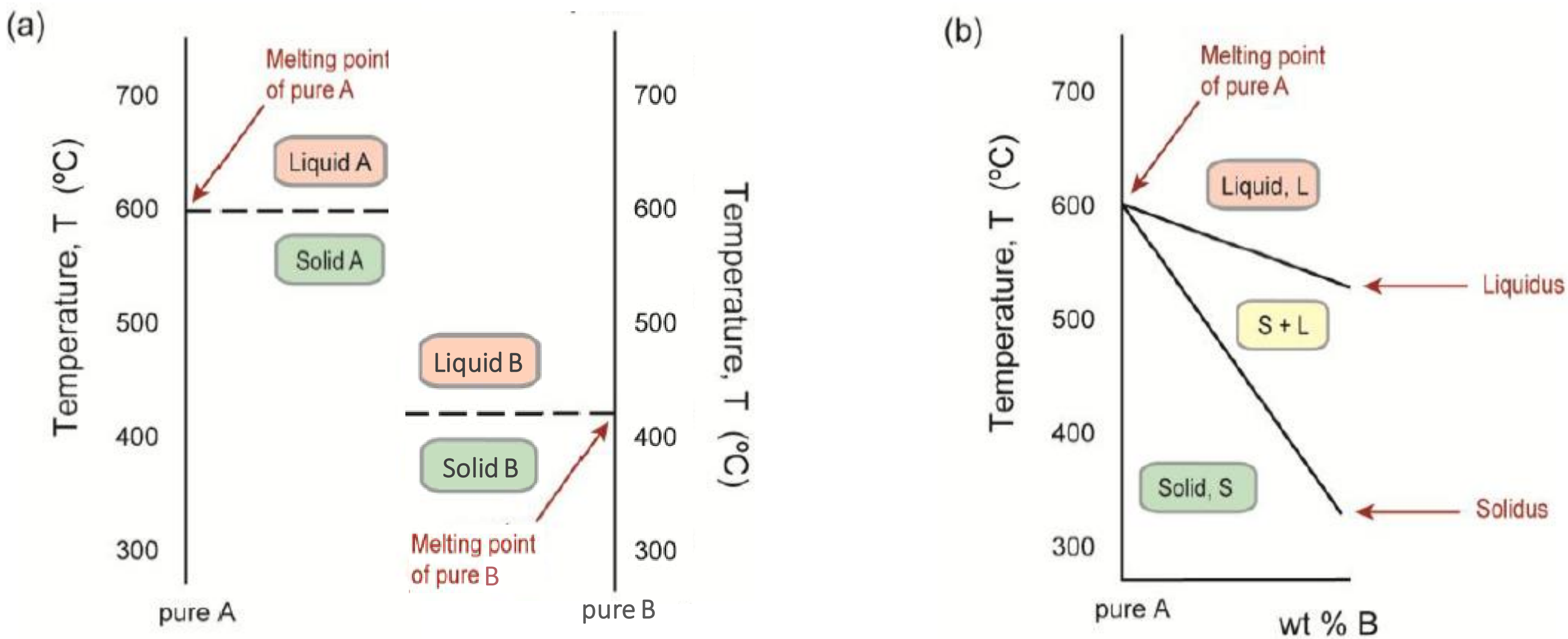
**DEF:** The *equilibrium constitution* is the state of lowest Gibbs free energy *G*, for a given composition, temperature and pressure. An alloy in this state shows no tendency to change – it is thermodynamically stable.

**DEF**: A binary *phase diagram* (or equilibrium diagram) is a diagram with *T* and composition as axes, showing the equilibrium constitution.

- Graphical representation of the phases present for a two-component system
- Two axis are temperature (y-axis) and composition (x-axis)
- Third variable pressure, is assumed to be one atmosphere
- Most common in materials engineering



# Mixing two metals with different melting point

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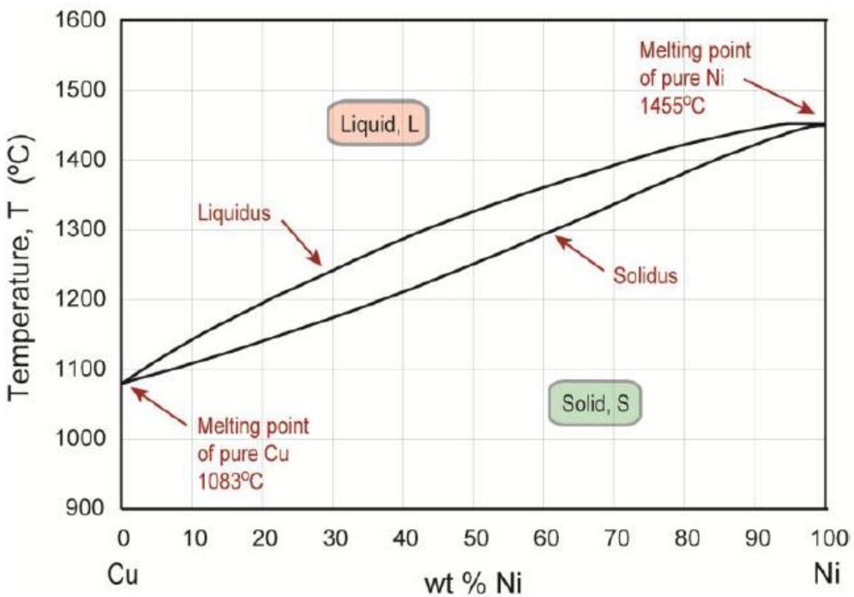
# Binary Isomorphous Phase Diagrams

- Complete liquid and solid solubility
- Only one liquid and solid phase across the complete composition range
- Often due to similar atomic crystal structures of the two components
- E.g. Copper and Nickel

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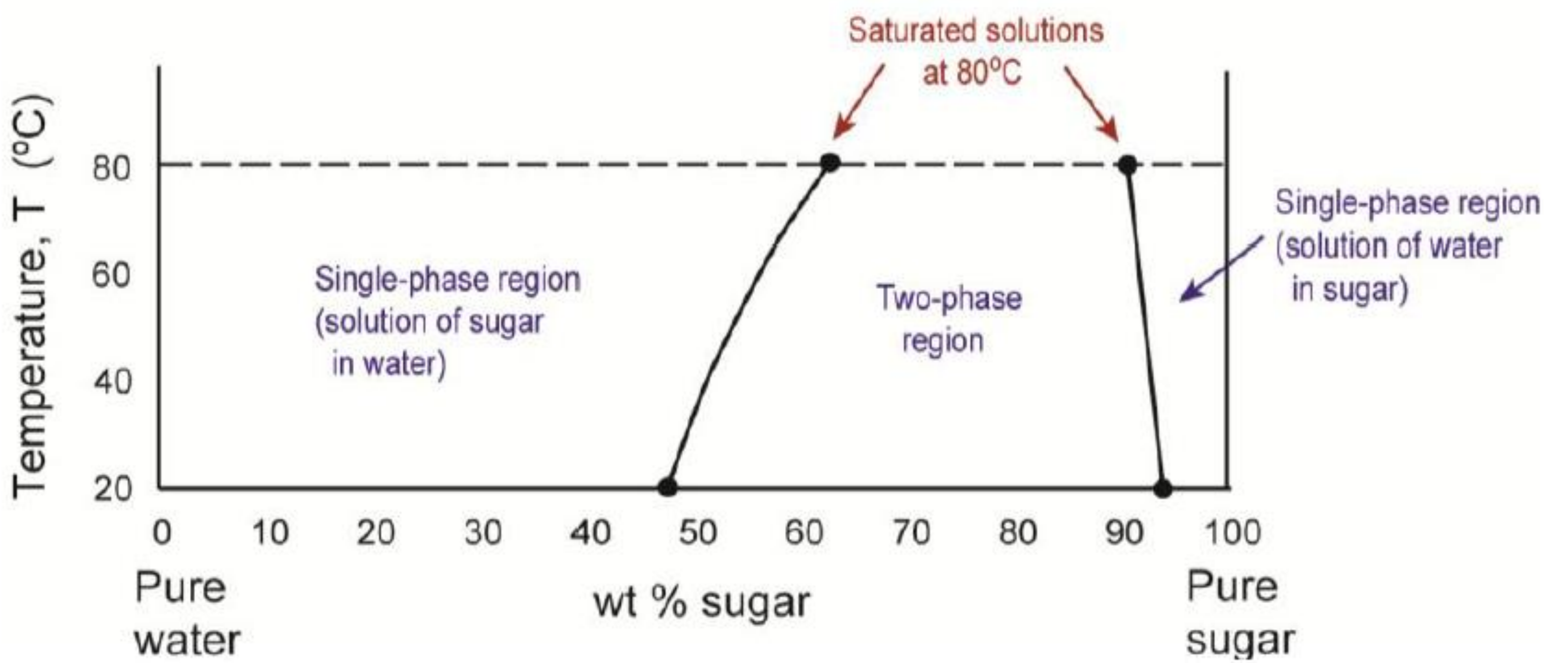
# Incomplete solubility of components – sweet tea

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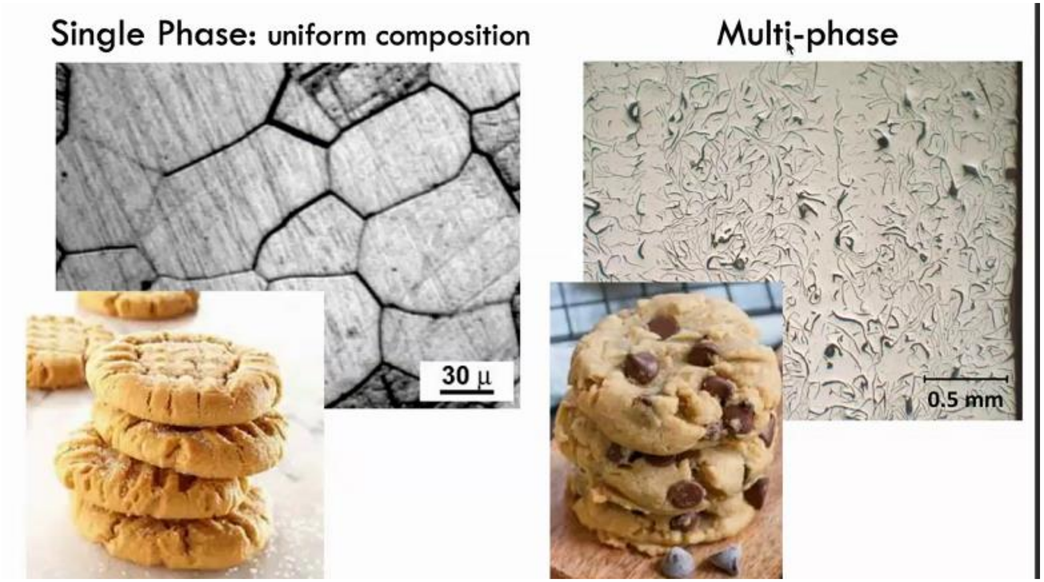
# Single and two-phase solid systems




*Images from: Dr Amber Genau, University of Alabama, Birmingham*

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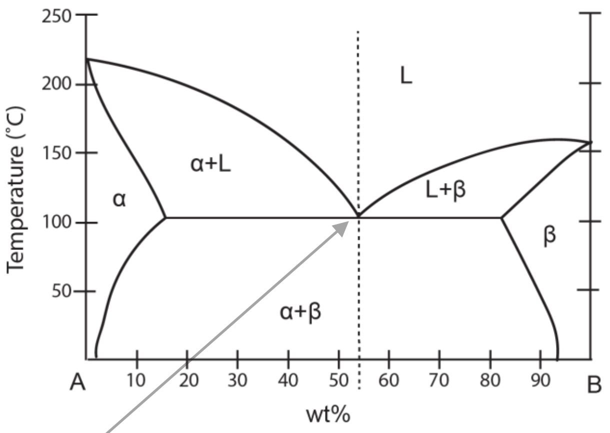
# Binary Eutectic Phase Diagram

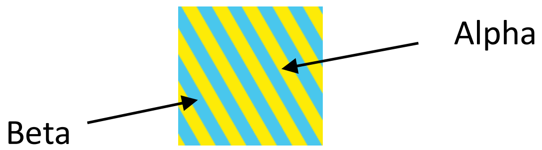
**DEF**: The lower limit of the single-phase liquid field formed by the intersection of two liquidus lines is called the *eutectic point*.

- Incomplete solubility within the solid phases
- Leads to a *eutectic reaction* at a specific composition and temperature
- Where the liquid solidifies into two unique solids, alpha and beta




*Reaction*:
$L \leftrightarrow \alpha + \beta$

Microstructure:

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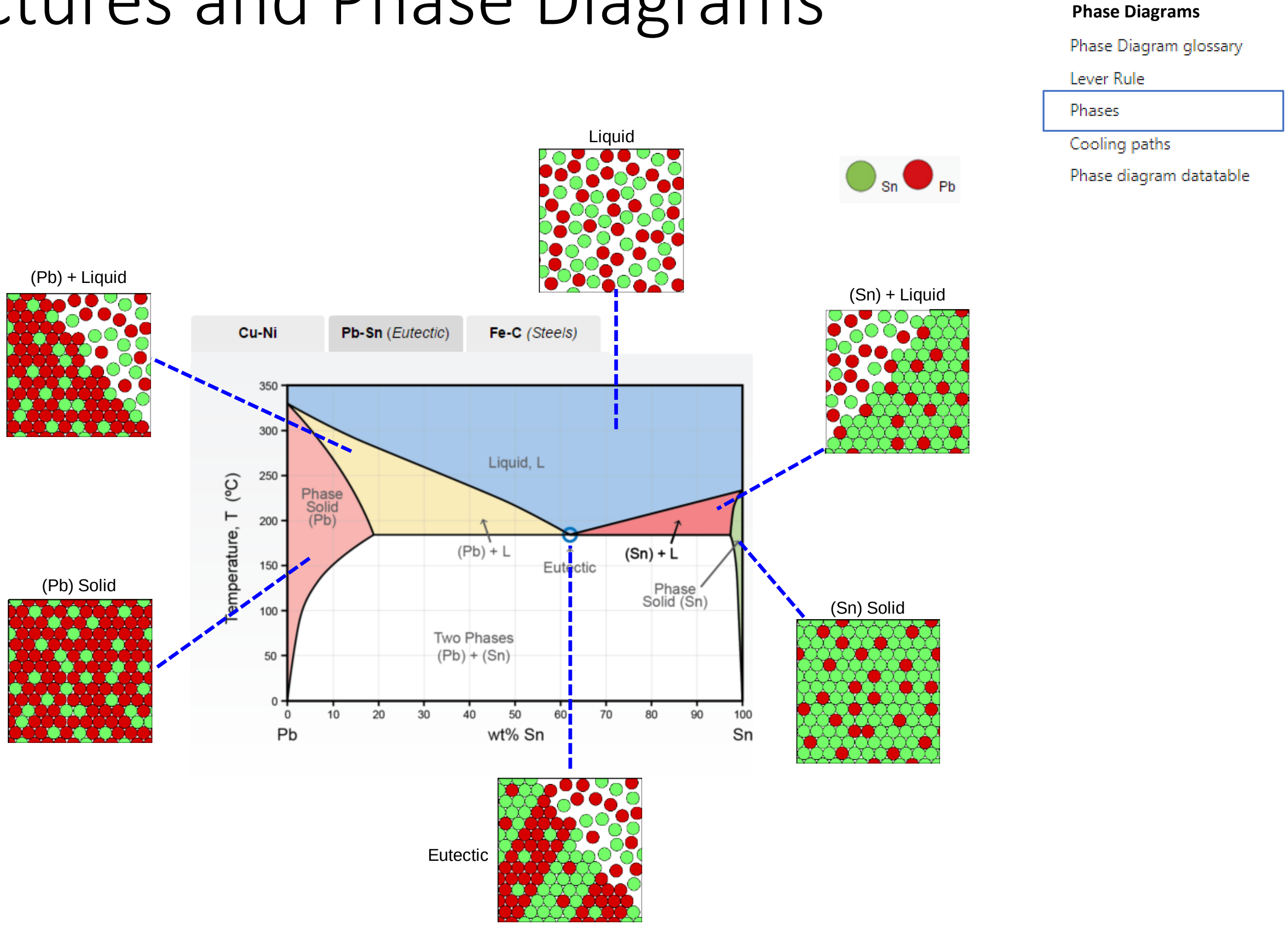
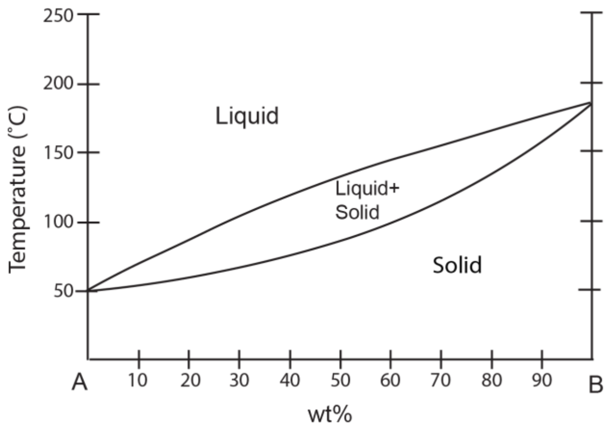
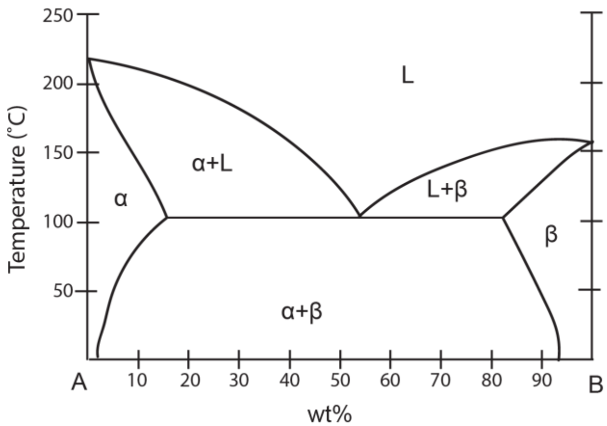
# Microstructures and Phase Diagrams



# Key Phase Diagram Terminology




**DEF**: The *constitution* of an alloy is described by:
(a) the phases (α, β) present;
(b) the weight fraction of each phase;
(c) the composition of each phase.

**DEF**: The lower limit of the single-phase liquid field formed by the intersection of two liquidus lines is called the *eutectic point*.

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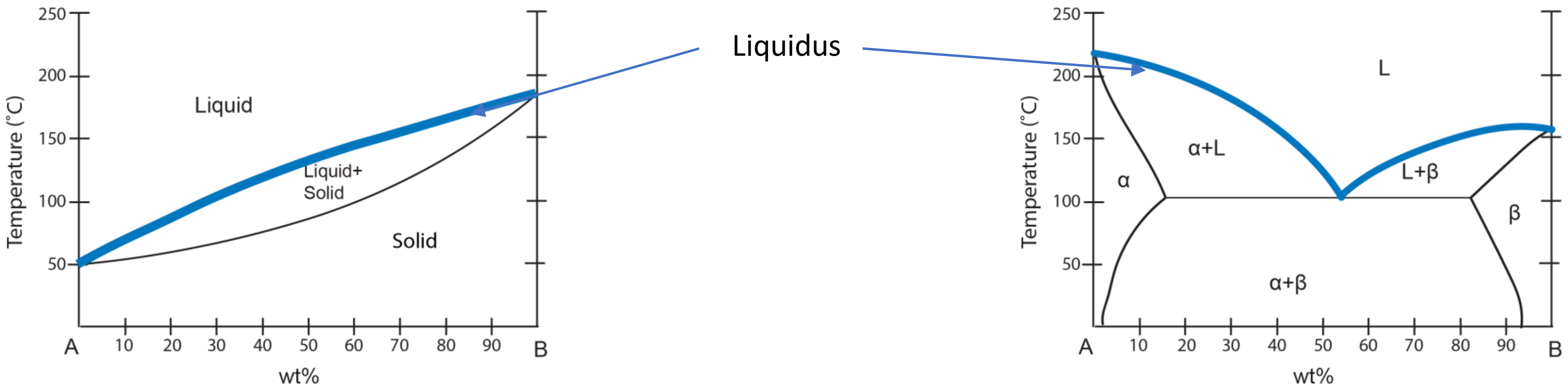


**DEF**: The phase boundary which limits the bottom of the *liquid* field is called the *liquidus line.*

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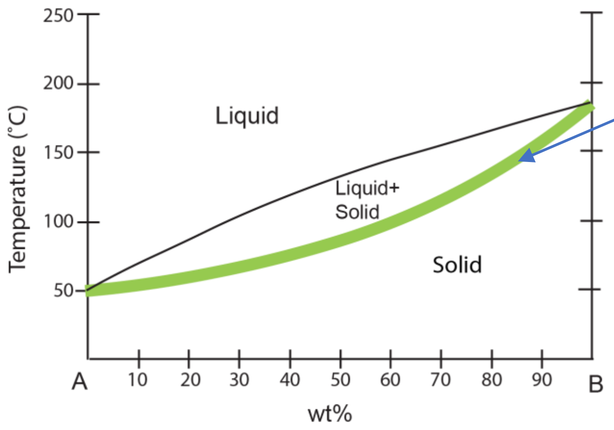
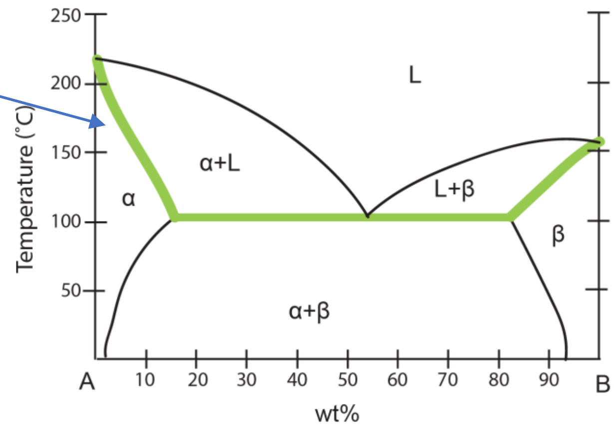
# Key Phase Diagram Terminology




Solidus




**DEF**: The line giving the upper limit of the single phase *solid* field is called the *solidus line*.

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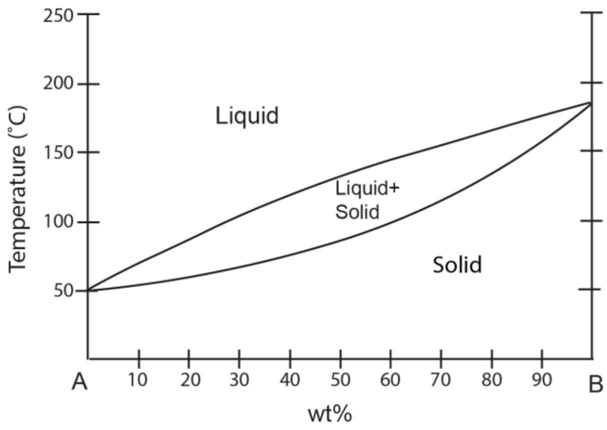
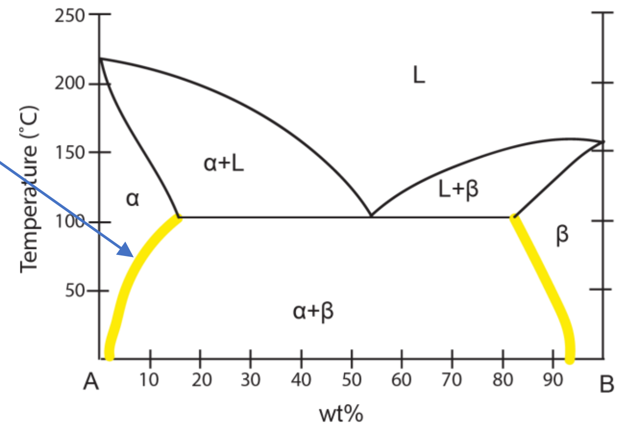
# Key Phase Diagram Terminology




Solvus

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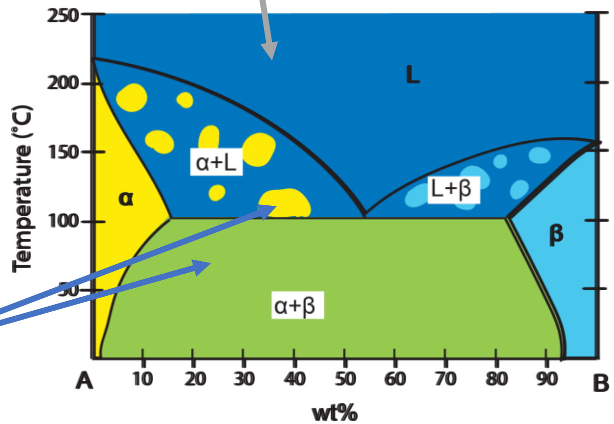
# Phase Fractions within Systems

Understanding what phases will be found at specific composition and temperature is incredibly important for alloy development

In a single-phase regions, identifying phase fractions is simple




In two-phase regions, the Lever Rule is needed to calculate the phase fractions

**DEF:** In a single-phase region, phase and alloy compositions coincide. In a two-phase region the phase compositions lie on the phase boundaries at either end of a horizontal tie-line through the constitution point.

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# What can the Lever Rule Determine?

**Weight fraction of single phases**

Liquid, alpha, beta, etc.

**Weight fraction of microconstituents**

Eutectic, Pro-eutectic phase alpha or beta, etc.

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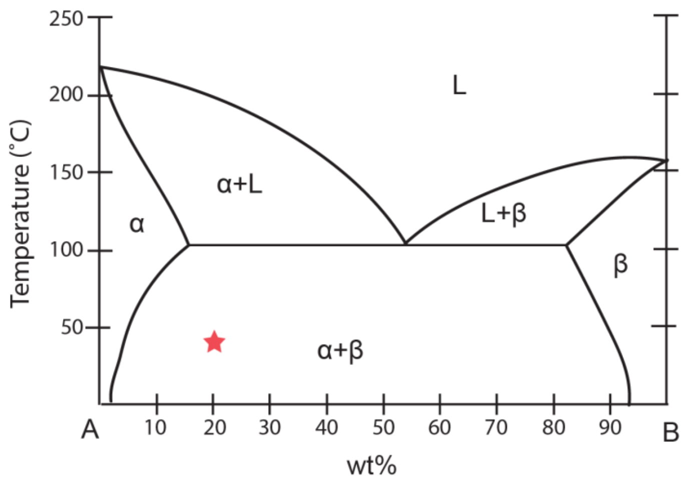
# Lever Rule

Used to calculate various phase and microconstituent fractions for two phase regions of binary phase diagrams




$$W_{\beta} = \frac{C_0 - C_{\alpha}}{C_{\beta} - C_{\alpha}}$$

$$W_{\alpha} = \frac{C_0 - C_{\beta}}{C_{\alpha} - C_{\beta}}$$

**Information needed:**
composition and temperature of interest.
e.g.: 20 wt.% B and 50 ˚C

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# Derivation

Assumptions:

- For a two-phase region, the weight fractions must add up to 1

$$W_\alpha + W_\beta = 1$$

- The mass of component B in both phases must add up to the total amount of B in the alloy

$$W_\alpha C_\alpha + W_\beta C_\beta = C_0$$

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# Derivation

α phase

$$W_\alpha + W_\beta = 1 \Rightarrow W_\beta = 1 - W_\alpha$$

$$\Rightarrow W_\alpha\, C_\alpha + (1 - W_\alpha) C_\beta = C_0$$

$$\Rightarrow W_\alpha\, C_\alpha + C_\beta - W_\alpha C_\beta = C_0$$

$$\Rightarrow W_\alpha\, (C_\alpha - C_\beta) = C_0 - C_\beta$$

$$\Rightarrow \boldsymbol{W_\alpha = \frac{C_0 - C_\beta}{C_\alpha - C_\beta}}$$

β phase

$$W_\alpha + W_\beta = 1 \Rightarrow W_\alpha = 1 - W_\beta$$

$$(1 - W_\beta) C_\alpha + W_\beta C_\beta = C_0$$

$$\Rightarrow C_\alpha - W_\beta\, C_\alpha + W_\beta C_\beta = C_0$$

$$\Rightarrow W_\beta\, (C_\beta - C_\alpha) = C_0 - C_\alpha$$

$$\Rightarrow \boldsymbol{W_\beta = \frac{C_0 - C_\alpha}{C_\beta - C_\alpha}}$$

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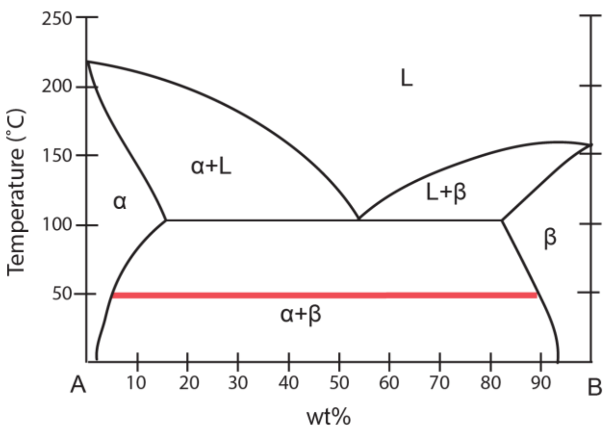
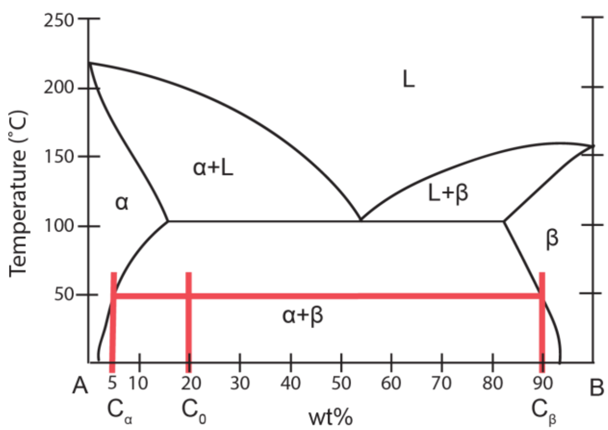
# Lever Rule Steps

**Step 1:**
Draw a tie line across the two-phase region




**Step 2:**
Identify points of interest

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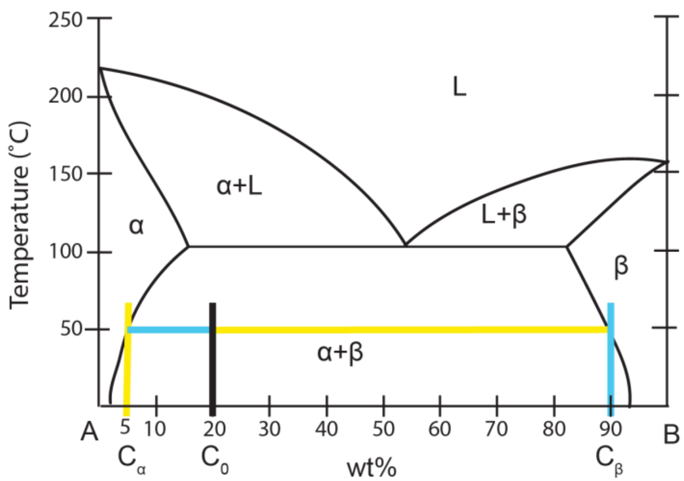
# Lever Rule Steps

**Step 3:**
To determine the phase fraction, take the distance from the composition to the *other* phase divided by the total




$$W_\alpha = \frac{C_0 - C_\beta}{C_\alpha - C_\beta} = \frac{20 - 90}{5 - 90} = \frac{-70}{-85}$$

$$= 0.824 = 82.4 \text{ wt\%}$$

$$W_\beta = \frac{C_\alpha - C_0}{C_\alpha - C_\beta} = \frac{5 - 20}{5 - 90} = \frac{-15}{-85}$$

$$= 0.176 = 17.6 \text{ wt\%}$$

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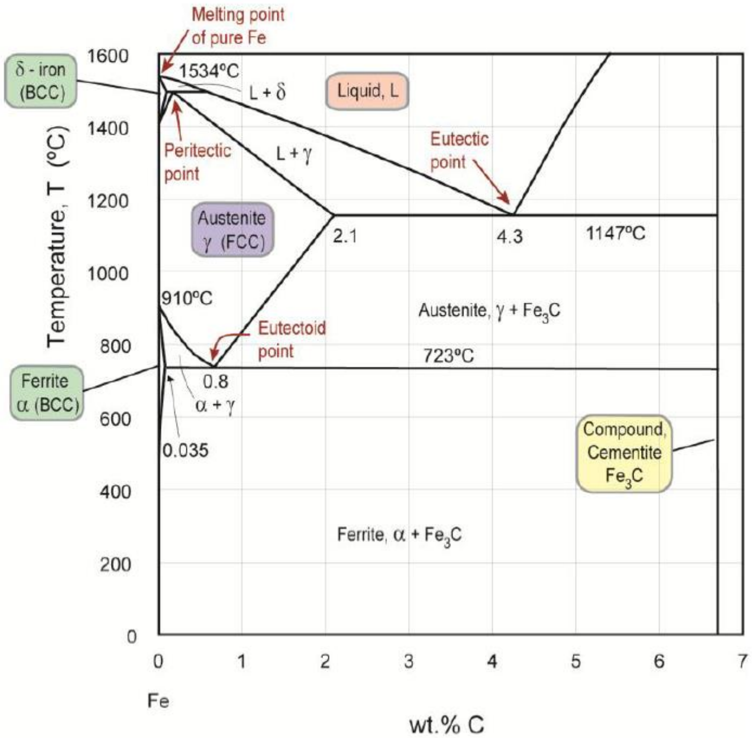
# The Iron – Carbon phase diagram: EduPack MS&E

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# *Any Questions ???*

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