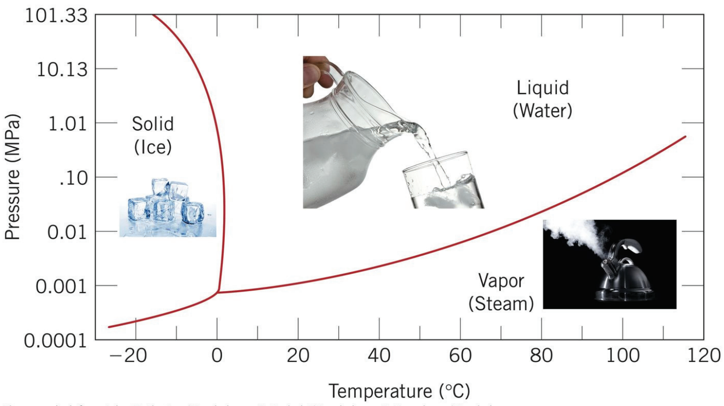
Chap. 11: Phase Diagrams

- **ISSUES TO ADDRESS**
  - When we combine two elements, what is the resulting equilibrium state?
  - In particular, if we specify, the composition (e.g., wt% Cu - wt% Ni), and the temperature (T), then
    - How many phases form?
    - What is the composition of each phase?
    - What is the amount of each phase?



Photographs left to right: © AlexStar/iStockphoto, © Canbalci/iStockphoto, © IJzendoorn/iStockphoto.

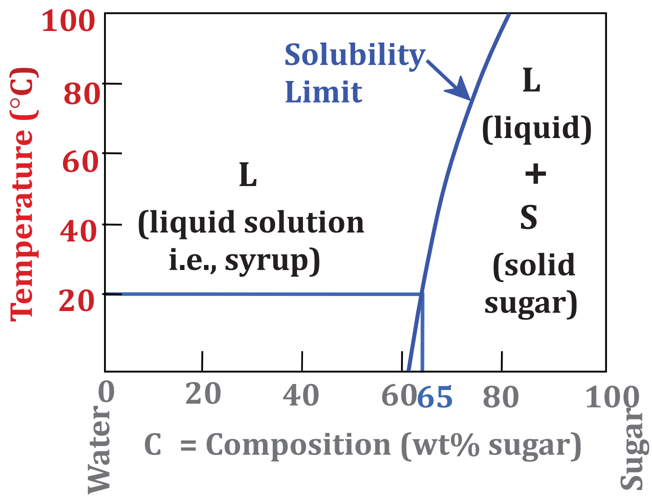
© Achim Baqué/Stockphoto/

11.2 Solubility Limit: Phase Equilibria

- **Solution – solid, liquid, or gas solutions, single phase**
- **Mixture – more than one phase**
- **Solubility Limit: Maximum concentration for which only a single phase solution exists.**

Adapted from Fig. 11.1, Callister & Rethwisch 9e.

Sugar/Water Phase Diagram



Question: What is the solubility limit for sugar in water at 20 °C?

Answer: 65 wt% sugar.

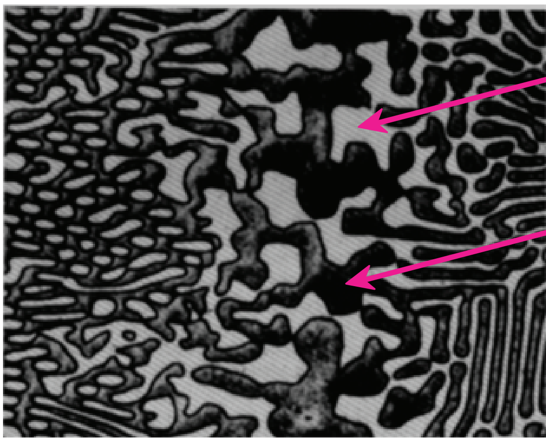
At 20 °C, if C < 65 wt% sugar: syrup

At 20 °C, if C > 65 wt% sugar: syrup + sugar

Components and Phases

- Components: The elements or compounds which are present in the alloy (e.g., Al and Cu)
- Phases: The physically and chemically distinct material regions that form (e.g., α and β).

Aluminum-
Copper
Alloy



Adapted from chapter-opening photograph, Chapter 9, Callister, Materials Science & Engineering: An Introduction, 3e.

Effect of Temperature & Composition

- Altering T can change # of phases: path A to B.
- Altering C can change # of phases: path B to D.

water-
sugar
system

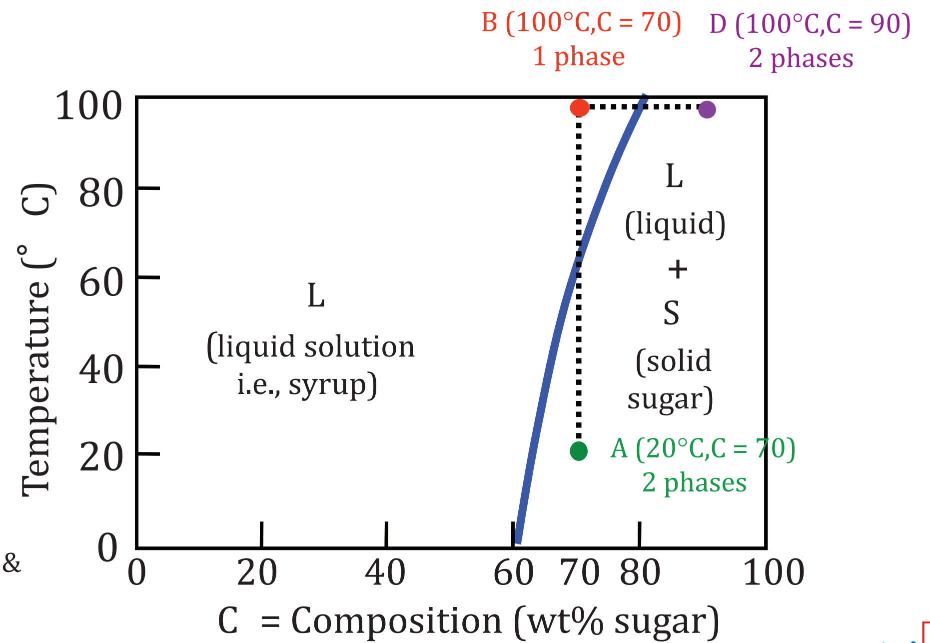
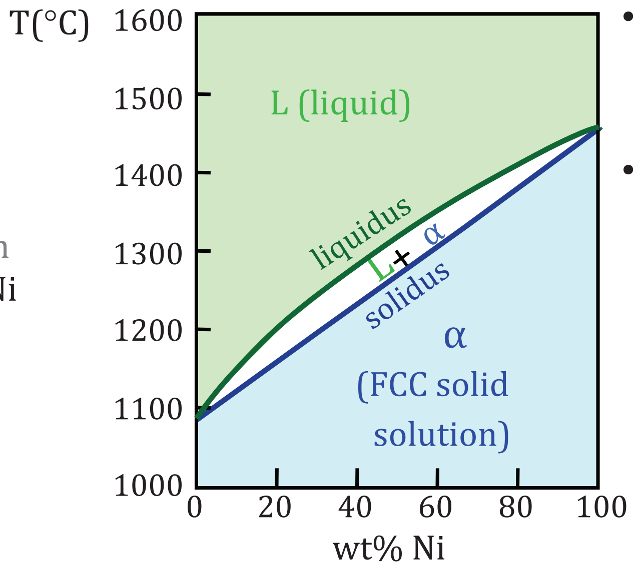


Fig. 11.1, Callister & Rethwisch 9e.

Phase Diagrams

- Indicate phases as a function of T, C, and P.
- For this course:
  - binary systems: just 2 components.
  - independent variables: T and C (P = 1 atm is almost always used).

Phase Diagram for Cu-Ni system

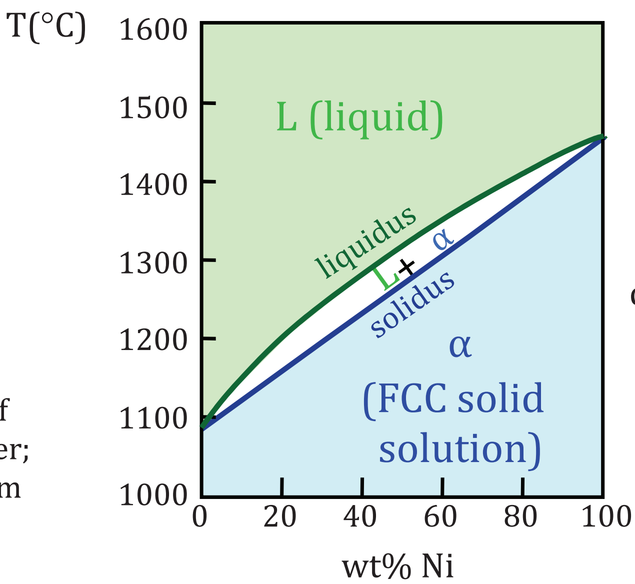


- 2 phases:
  - L (liquid)
  - α (FCC solid solution)
- 3 different phase fields:
  - L
  - L + α
  - α

Fig. 11.3(a), Callister & Rethwisch 9e. (Adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Isomorphous Binary Phase Diagram

- Phase diagram: Cu-Ni system.
- System is:
  - binary
    i.e., 2 components: Cu and Ni.
  - isomorphous
    i.e., complete solubility of one component in another; α phase field extends from 0 to 100 wt% Ni.



Cu-Ni phase diagram

Fig. 11.3(a), Callister & Rethwisch 9e. (Adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams: Determination of phase(s) present

- Rule 1: If we know T and C_o, then we know:
  - which phase(s) is (are) present.
- Examples:

  A(1100°C, 60 wt% Ni):

  1 phase: α

  B (1250°C, 35 wt% Ni):

  2 phases: L + α

Cu-Ni phase diagram

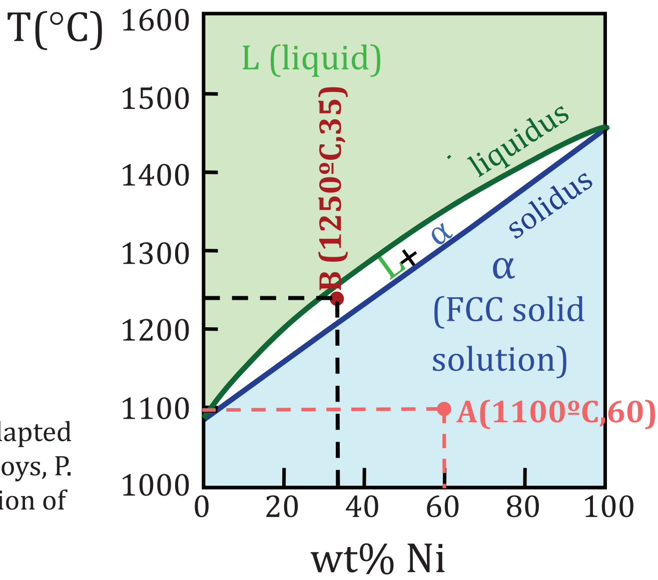


Fig. 11.3(a), Callister & Rethwisch 9e. (Adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams: Determination of phase compositions

- Rule 2: If we know T and C_0, then we can determine:
  - the composition of each phase.
- Examples:

  Consider C_0 = 35 wt% Ni

  At T_A = 1320°C:

  Only Liquid (L) present

  $C_L = C_0$ (= 35 wt% Ni)

  At T_D = 1190°C:

  Only Solid (α) present

  $C_\alpha = C_0$ (= 35 wt% Ni)

  At T_B = 1250°C:

  Both α and L present

  C_L = C liquidus (= 32 wt% Ni)

  C_α = C solidus (= 43 wt% Ni)

Cu-Ni sy stem

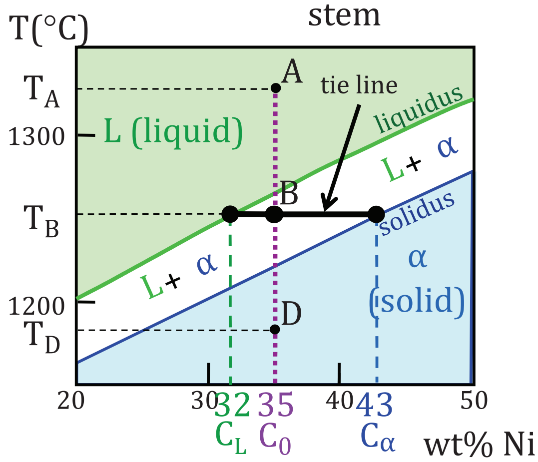


Fig. 11.3(b), Callister & Rethwisch 9e. (Adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams: Determination of phase weight fractions

- Rule 3: If we know T and C_0, then can determine:
  -- the weight fraction of each phase.
- Examples:

Consider C_0 = 35 wt% Ni

At T_A : Only Liquid (L) present

W_L = 1.00, W_a = 0

At T_D : Only Solid (α) present

W_L = 0, W_α = 1.00

At T_B : Both α and L present

$$W_L = \frac{S}{R+S} = \frac{43-35}{43-32} = 0.73$$

$$W_\alpha = \frac{R}{R+S} = 0.27$$

Cu-Ni system

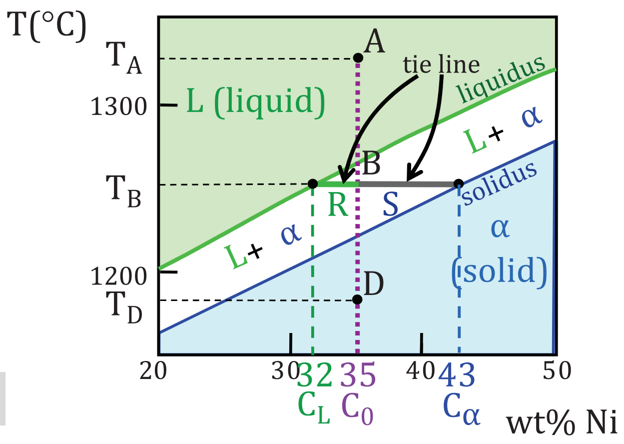
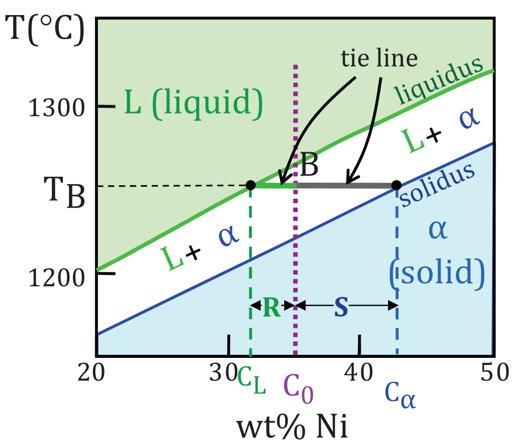


Fig. 11.3(b), Callister & Rethwisch 9e.
(Adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash, Editor, 1991.

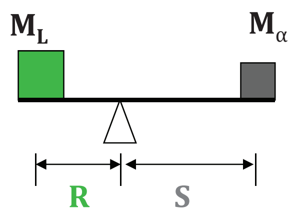
The Lever Rule

- Tie line – connects the phases in equilibrium with each other – also sometimes called an isotherm

Adapted from Fig. 11.3(b), Callister & Rethwisch 9e.



What fraction of each phase?
Think of the tie line as a lever (teeter-totter)



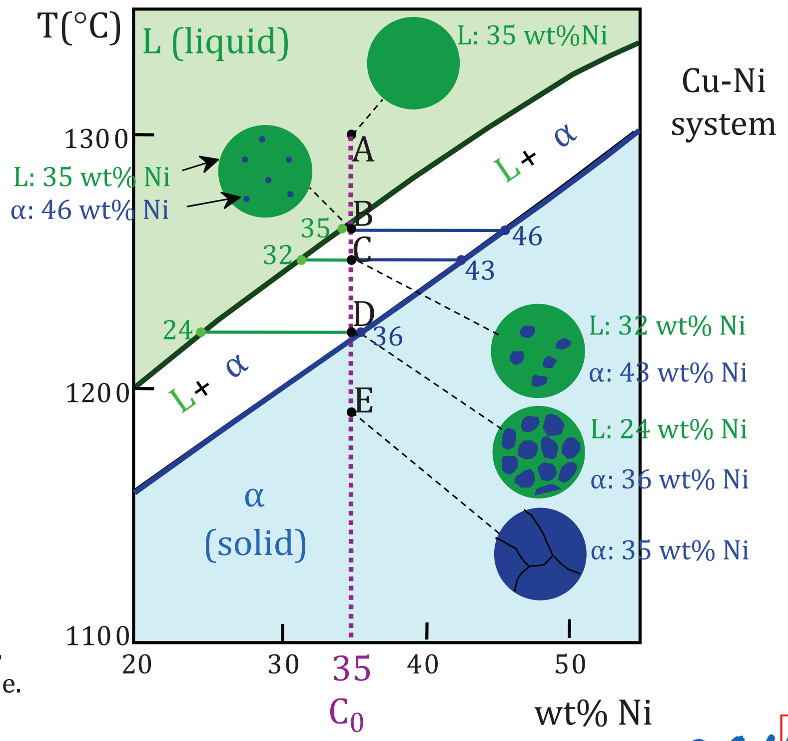
$$M_\alpha \text{ x } S = M_L \text{ x } R$$

$$W_L = \frac{M_L}{M_L + M_\alpha} = \frac{S}{R+S} = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{R}{R+S} = \frac{C_0 - C_L}{C_\alpha - C_L}$$

Ex: Cooling of a Cu-Ni Alloy

- Phase diagram: Cu-Ni system.
- Consider microstructural changes that accompany the cooling of a C_0 = 35 wt% Ni alloy

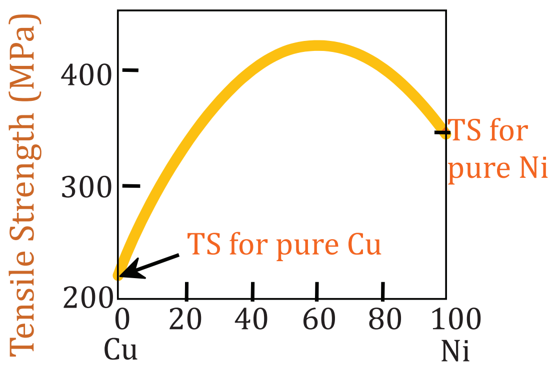


Adapted from Fig. 11.4, Callister & Rethwisch 9e.

Mechanical Properties: Cu-Ni System

- Effect of solid solution strengthening on:

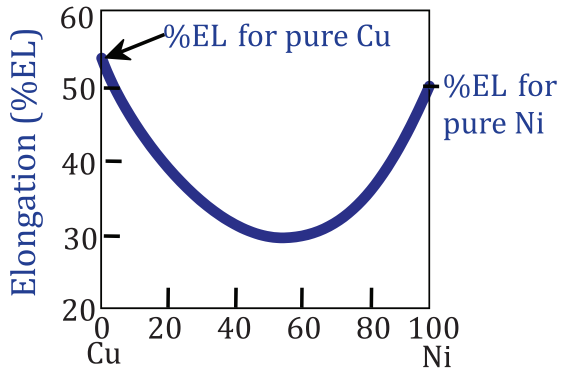
Tensile strength (TS)



Composition, wt% Ni

Adapted from Fig. 11.5(a), Callister & Rethwisch 9e.

Ductility (%EL)



Composition, wt% Ni

Adapted from Fig. 11.5(b), Callister & Rethwisch 9e.

Binary-Eutectic Systems

- **Eutectic systems: 2-component system having a special composition with a min. melting temperature.**

Ex.: Cu-Ag system

- 3 single phase regions (L, α, β)
- Limited solubility:
  - α: mostly Cu
  - β: mostly Ag
- T_E : No liquid below T_E
- C_E : Composition at temperature T_E

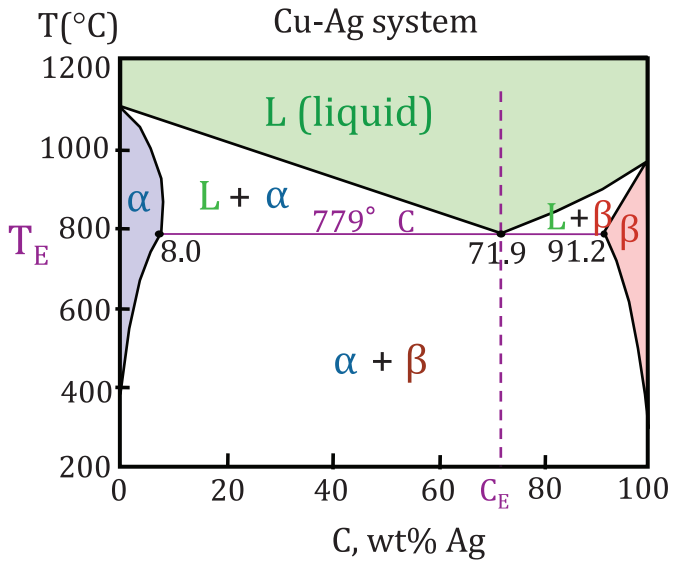


Fig. 11.6, Callister & Rethwisch 9e

- **Eutectic reaction**

$L(C_E) \rightleftharpoons \alpha(C_{\alpha E}) + \beta(C_{\beta E})$

$$L(71.9 \text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0 \text{ wt\% Ag}) + \beta(91.2 \text{ wt\% Ag})$$

Ex: Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, determine the phases present.

Answer: α + β

- the phase compositions

Answer: C_α = 11 wt% Sn

C_β = 99 wt% Sn

- the relative amount of each phase

Answer:

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

$$= \frac{99 - 40}{99 - 11} = \frac{59}{88} = 0.67$$

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

$$= \frac{40 - 11}{99 - 11} = \frac{29}{88} = 0.33$$

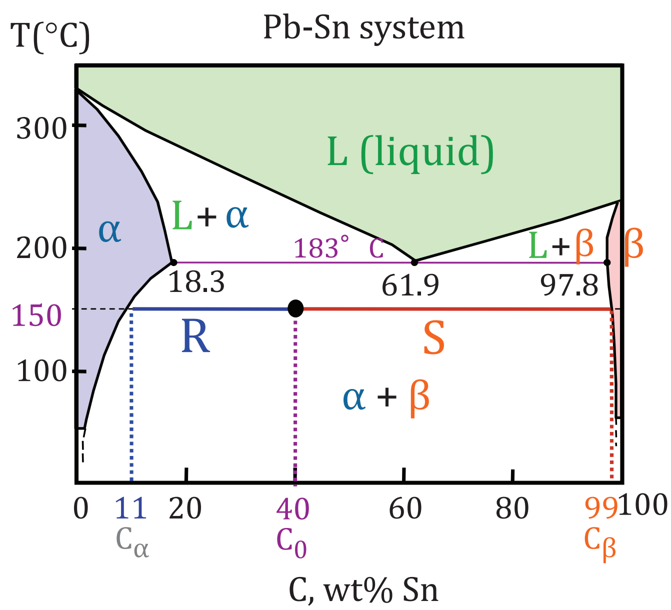


Fig. 11.7, Callister & Rethwisch 9e.