1) Distillation Column (Continuous Fractionation)

Principle:
Separation is based on the difference in volatility of components through repeated vapor–liquid contact.

Key Relations:

- **Vapor–liquid equilibrium (VLE):**
  $y_i = K_i x_i$ where $K_i = \frac{P_i^*}{P}$ (Raoult's law).
- **Mass balances:**
  $$F = D + B$$
  $$F z_F = D x_D + B x_B$$
- **Operating line equations:**
  Rectifying section: $y = \frac{R}{R+1} x + \frac{x_D}{R+1}$
  Stripping section: $y = \frac{q}{q-1}(x - z_F) + z_F$
- **Stage design (McCabe–Thiele):**
  Number of theoretical stages obtained graphically using equilibrium and operating lines.
- **Reflux ratio:**
  Minimum reflux ratio R_{min}occurs when the operating line touches the equilibrium curve.
  Actual reflux ratio $R = f(R_{min})$(typically 1.2–1.5 × Rmin).
- **Actual plates:**
  $$N_{actual} = \frac{N_{theoretical}}{\text{Efficiency}}$$
- **Energy duties:**
  $Q_C = D\lambda_D$ (Condenser)
  $Q_R = V\lambda_B$ (Reboiler)

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2) Batch Distillation

Principle:
Feed is charged once into a still; vapor is withdrawn and condensed continuously, while liquid composition changes over time.

Key Relations:

- Instantaneous VLE: $y_i = K_i x_i$
- Total mass balance: $dW = -dD$
- Component balance: $W\,dx = -y\,dD$
- **Integrated Rayleigh equation:**
  $$\ln\left(\frac{W_F}{W}\right) = \int_{x_F}^{x} \frac{dx}{y^* - x}$$

- For binary mixtures, the distillate composition varies continuously.
- Total reflux operation is used to determine the number of equilibrium stages.
- **Reboiler duty:** $Q = \dot{m}_V \lambda$

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3) Flash Drum / Flash Distillation

Principle:
A liquid mixture is partially vaporized at constant pressure; vapor and liquid phases are in equilibrium.

Key Relations:

- **Equilibrium:** $y_i = K_i x_i$
- **Overall mass balance:** $F = V + L$
- **Component balance:** $F z_i = V y_i + L x_i$
- **Rachford–Rice equation:**

$$\sum_i \frac{z_i(K_i - 1)}{1 + \beta(K_i - 1)} = 0$$

where $\beta = \frac{V}{F}$ (vapor fraction).

- **Compositions:**

$$x_i = \frac{z_i}{1 + \beta(K_i - 1)}$$
$$y_i = K_i x_i$$

- **Energy balance (if required):**

$$F h_F = V h_V + L h_L$$

Applications: flash separators, flash drums, and first-stage distillation calculations.