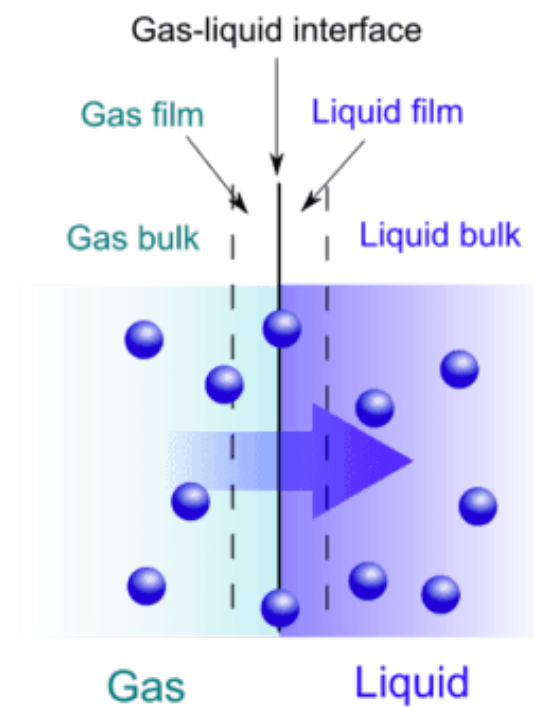


# Lecture 8

## Absorption-based separation processes



# Concepts which we will learn

## **Course Content**

Mass and Energy Balances

Thermodynamics of Separations/Phase Equilibria/Degree of Freedom

Flash Distillation

Column Distillation

Multicomponent Distillation

Absorption and Stripping

Liquid-Liquid Extraction

Diffusion and Mass Transfer

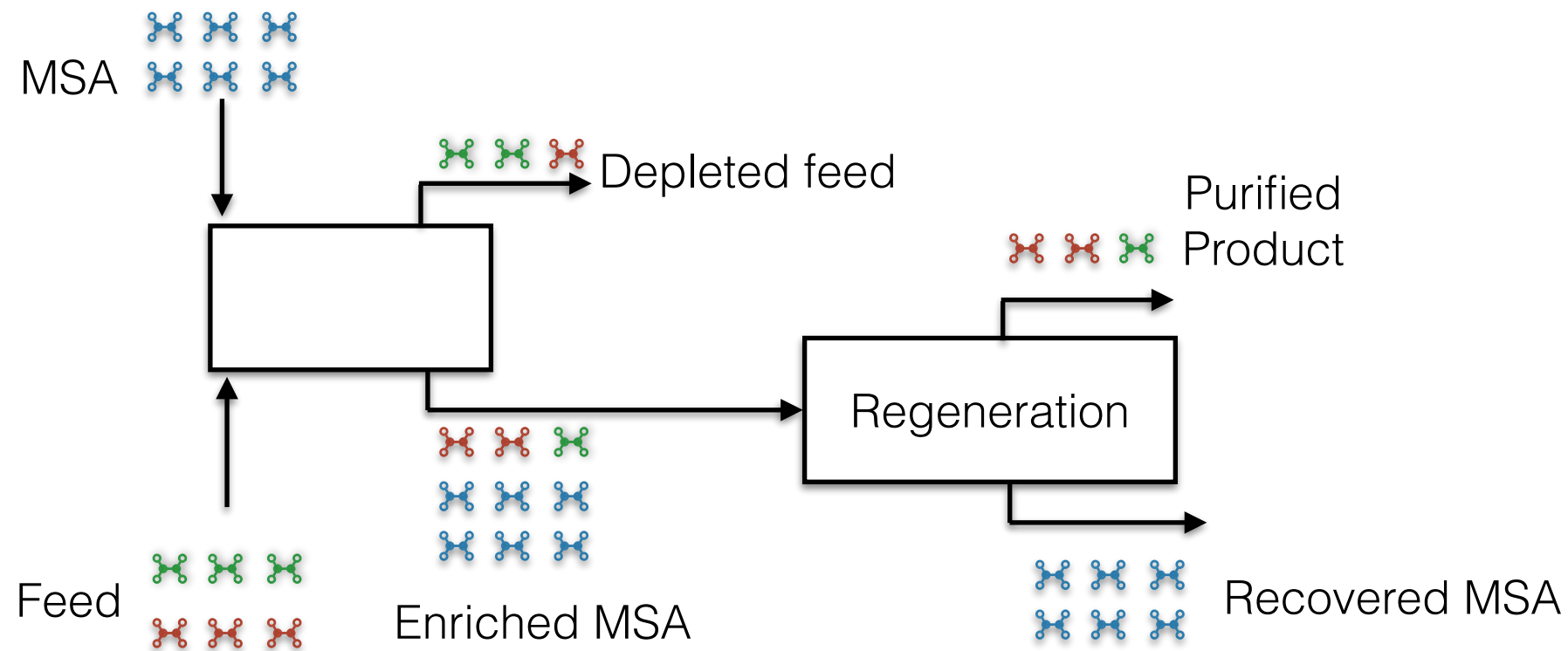
Adsorption Processes

Membrane Processes

# Intended Learning Outcome

1. Understand mass transfer in absorption and stripping processes.
2. Apply graphical method to solve absorption and stripping problem.
3. Apply Kremser equation to numerically calculate number of stages.
4. Learn the configuration similarity and differences between the absorption and stripping processes.

# Phase creation by adding mass separating agent (MSA)



Examples:

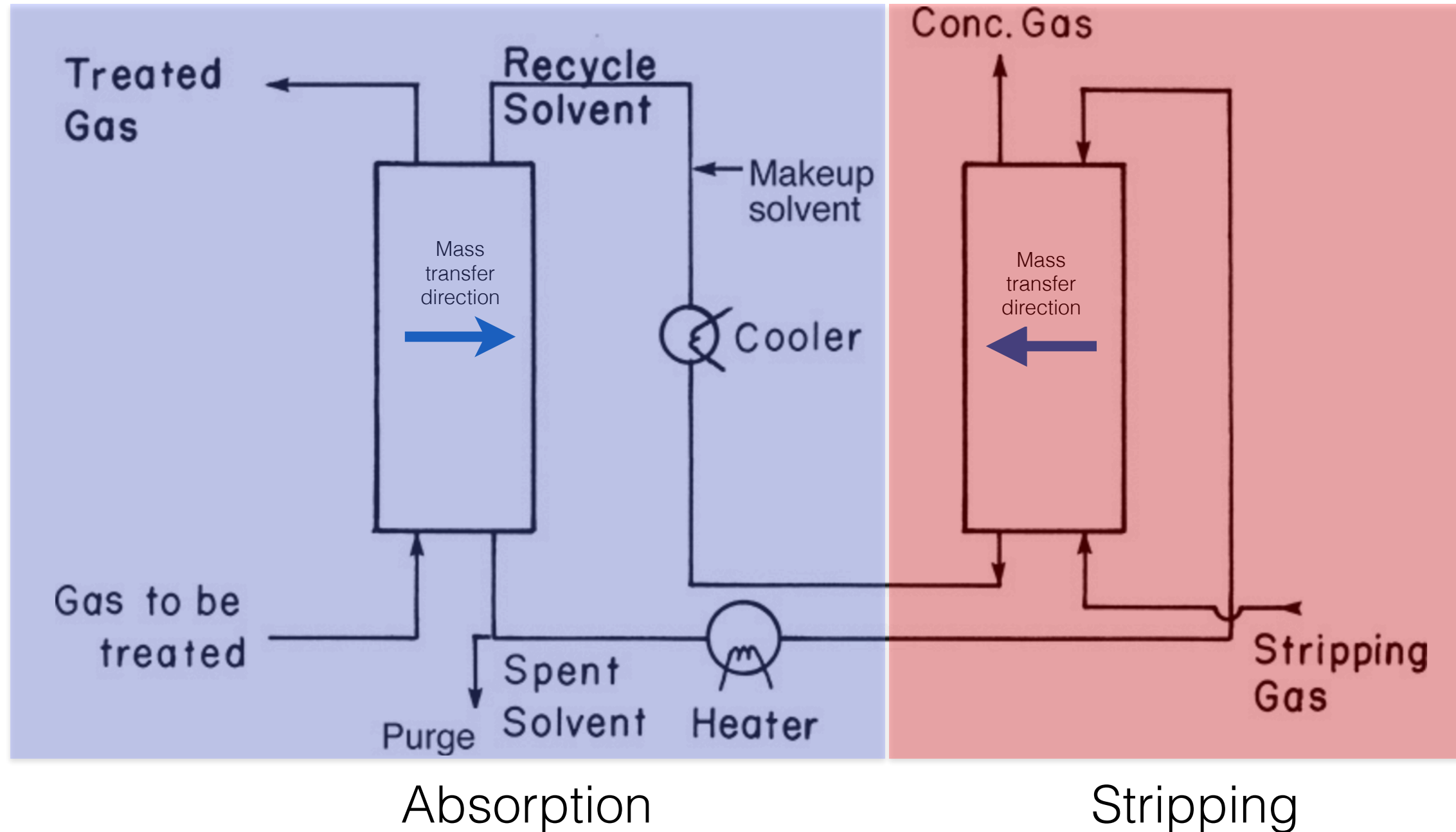
1. Absorption
2. Liquid-Liquid Extraction
3. Adsorption

# Absorption and stripping

## Example

Postcombustion capture ( $\text{CO}_2$  from  $\text{N}_2$ )

Natural gas processing (removal of  $\text{H}_2\text{S}$  from  $\text{CH}_4$ )



# Where absorption/stripping stands with other MSA process

Separation Process	Feed	MSA	Regeneration Step
Liquid-Liquid Extraction	Liquid (solute)	Liquid (solvent)	Distillation, Crystallization
Absorption	Gas/vapor	Liquid (low-volatility)	Stripping
Stripping	Liquid	Steam	Condensation

# Absorption and stripping are equilibrium-stage process

Separation process	Equilibrium-stage	Steady-state
Distillation	Yes	Yes
Liquid-Liquid Extraction	Yes	Yes
Absorption and stripping	Yes	Yes
Membranes	No (diffusion)	Yes
Adsorption	No (diffusion, convection)	No

# Absorption: some interesting facts

1. Tallest unit in a chemical plant are distillation column.
2. Second tallest units are absorption units.
3. Common absorption process: acid gases ( $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ ) from gas streams

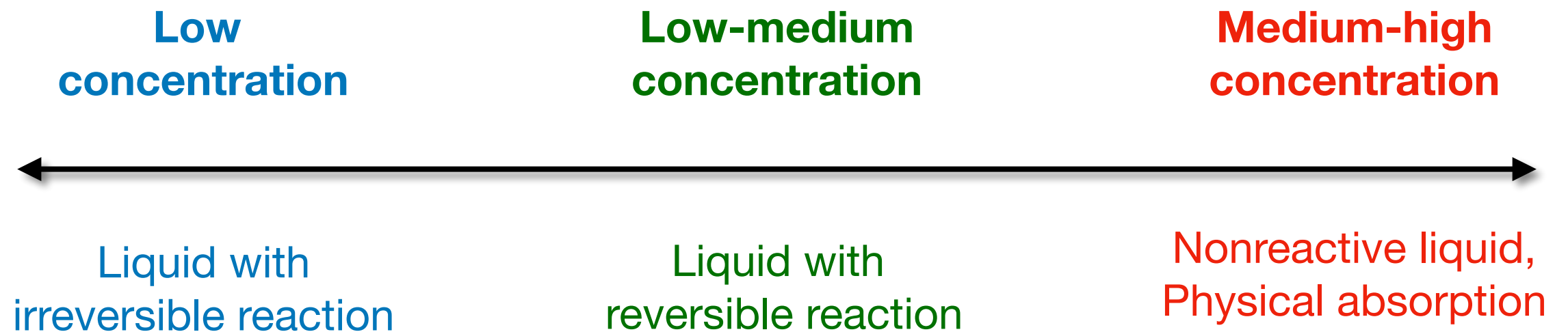
Table 10.1-1 *Gas treating in major industrial processes*

Process	Gases to be removed	Common targets (% Acid gas)
Ammonia manufacture	$\text{CO}_2$ , $\text{NH}_3$ , $\text{H}_2\text{S}$	< 10 ppm $\text{CO}_2$
Coal gas:		
High Btu gas	$\text{CO}_2$ , $\text{H}_2\text{S}$ , COS	500 ppm $\text{CO}_2$ ; 0.01 ppm $\text{H}_2\text{S}$
Low Btu gas	$\text{H}_2\text{S}$	100 ppm $\text{H}_2\text{S}$
Ethylene manufacture	$\text{H}_2\text{S}$ , $\text{CO}_2$	< 1 ppm $\text{H}_2\text{S}$ , 1 ppm $\text{CO}_2$
Flue gas desulfurization	$\text{SO}_2$	90% removal
Hydrogen manufacture	$\text{CO}_2$	< 0.1% $\text{CO}_2$
Natural gas upgrading	$\text{H}_2\text{S}$ , $\text{CO}_2$ , $\text{N}_2$ , RSH	< 4 ppm $\text{H}_2\text{S}$ ; < 1% $\text{CO}_2$
Oil desulfurization	$\text{H}_2\text{S}$	100 ppm $\text{H}_2\text{S}$
Refinery desulfurization	$\text{CO}_2$ , $\text{H}_2\text{S}$ , COS	10 ppm $\text{H}_2\text{S}$
Syn gas for chemicals feedstock	$\text{CO}_2$ , $\text{H}_2\text{S}$	< 500 ppm $\text{CO}_2$ ; < 0.01 ppm $\text{H}_2\text{S}$



# Absorption: choice of solvents

Depends upon the concentration of the component to be removed and target purity



**Example: H<sub>2</sub>S removal by absorption**

Aqueous NaOH

Alkylamine

Ethylene glycol

# Degree of freedom in absorption

**Gibbs phase rule:**  $f = C - P + 2$

**Components:** Carrier gas (from which the desired gas/vapor is removed)  
Solute (gas/vapor)  
Absorbent

**Phases:** 2

$$f = 3 - 2 + 2 = 3$$

1. Temperature (isothermal operation)
2. Pressure (isobaric operation)
3. Gas concentration in one of the phases

# Linear equilibrium relationship in dilute case: Henry's law

$$P_A = H_c C_A$$

Units of  $H_c$ : bar liter mol<sup>-1</sup>

$$P_A = H_x x_A$$

Units of  $H_x$ : bar

$$H'_x P_A = x_A$$

Units of  $H'_x$ : bar<sup>-1</sup>

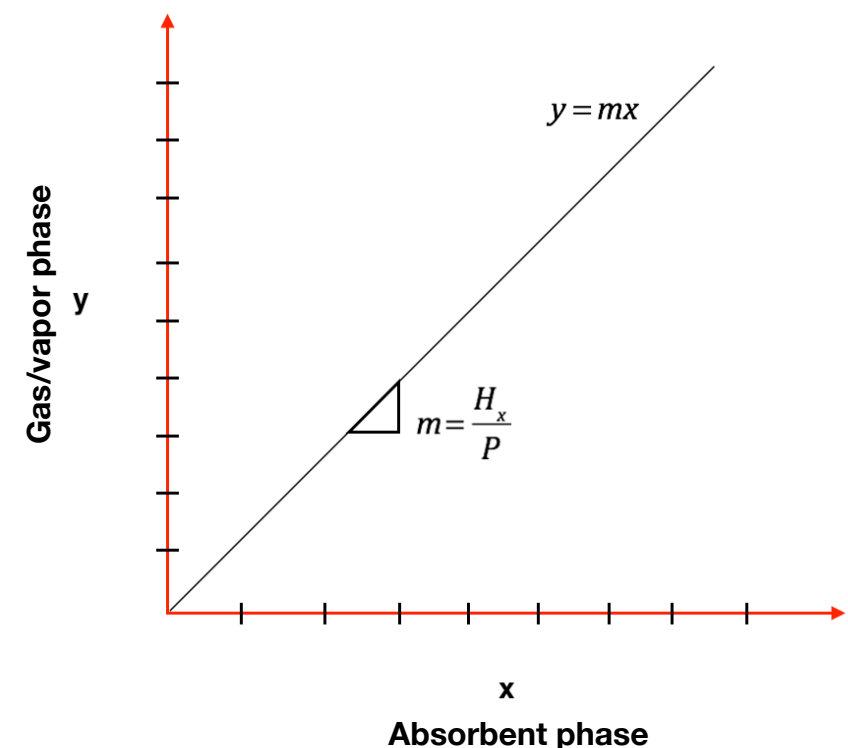
Alternate definition

$$P_A = y_A P$$

$$y_A P = H_x x_A$$

$$y_A = \left( \frac{H_x}{P} \right) x_A = m x_A$$

Which one is better: large m or small m?



# Typical value of Henry's constant in water

Units of  $H_x$ : bar

$T\text{ }^{\circ}\text{C}$	$\text{CO}_2$	$\text{CO}$	$\text{H}_2\text{S}$
0	728	35,200	268
5	876	39,600	315
10	1040	44,200	367
15	1220	48,900	423
20	1420	53,600	483
25	1640	58,000	545
30	1860	62,000	609
35	2090	65,900	676
40	2330	69,600	745
45	2570	72,900	814
50	2830	76,100	884
60	3410	82,100	1030
70	—	84,500	1190
80	—	84,500	1350
90	—	84,600	1440
100	—	84,600	1480

Source: Perry et al. (1963), pp. 14-4 and 14-6, and Green and Perry (2008), pp. 2-130 ( $\text{H}_2\text{S}$ ).

# Where do we experience Henry's law in daily life?

$$y_A = \left( \frac{H_x}{P} \right) x_A = m x_A$$



- Liquid phase: Coke
- Dissolved gas: CO<sub>2</sub>

# Dilute case

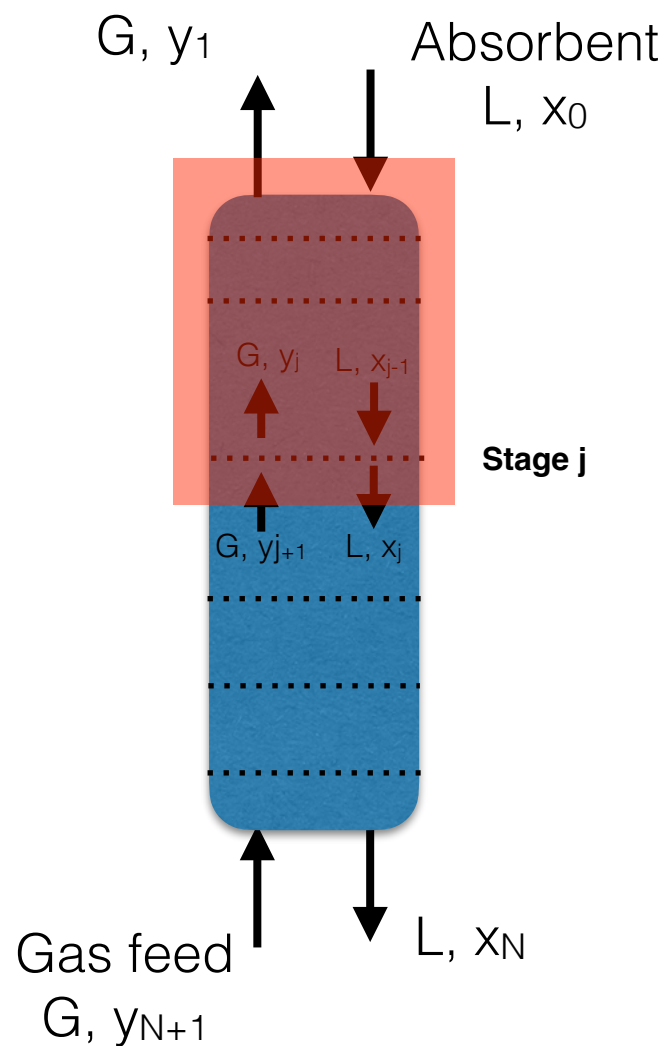
## **Key assumptions:**

1. Carrier gas is insoluble (carrier does not transfer to the absorbent phase).
2. Absorbent is nonvolatile (absorbent does not transfer to the carrier phase).
3. System is isothermal and isobaric (the heat of absorption is negligible).

## **Implication:**

1. Linear equilibrium relationship between concentration in gas phase and in absorbed phase (Henry's law).
2. Net flow rate of the liquid phase does not change.
3. Net flow rate of the gas phase does not change.

# Mass balance for the dilute case



## Balance around stage j

$$In = out$$

$$Gy_{j+1} + Lx_0 = Lx_j + Gy_1$$

$$y_{j+1} = \frac{L}{G}x_j + \left(y_1 - \frac{L}{G}x_0\right)$$




$$y_{N+1} = \frac{L}{G}x_N + \left(y_1 - \frac{L}{G}x_0\right)$$

## Operating line

$$y = \frac{L}{G}x + \left(y_1 - \frac{L}{G}x_0\right)$$

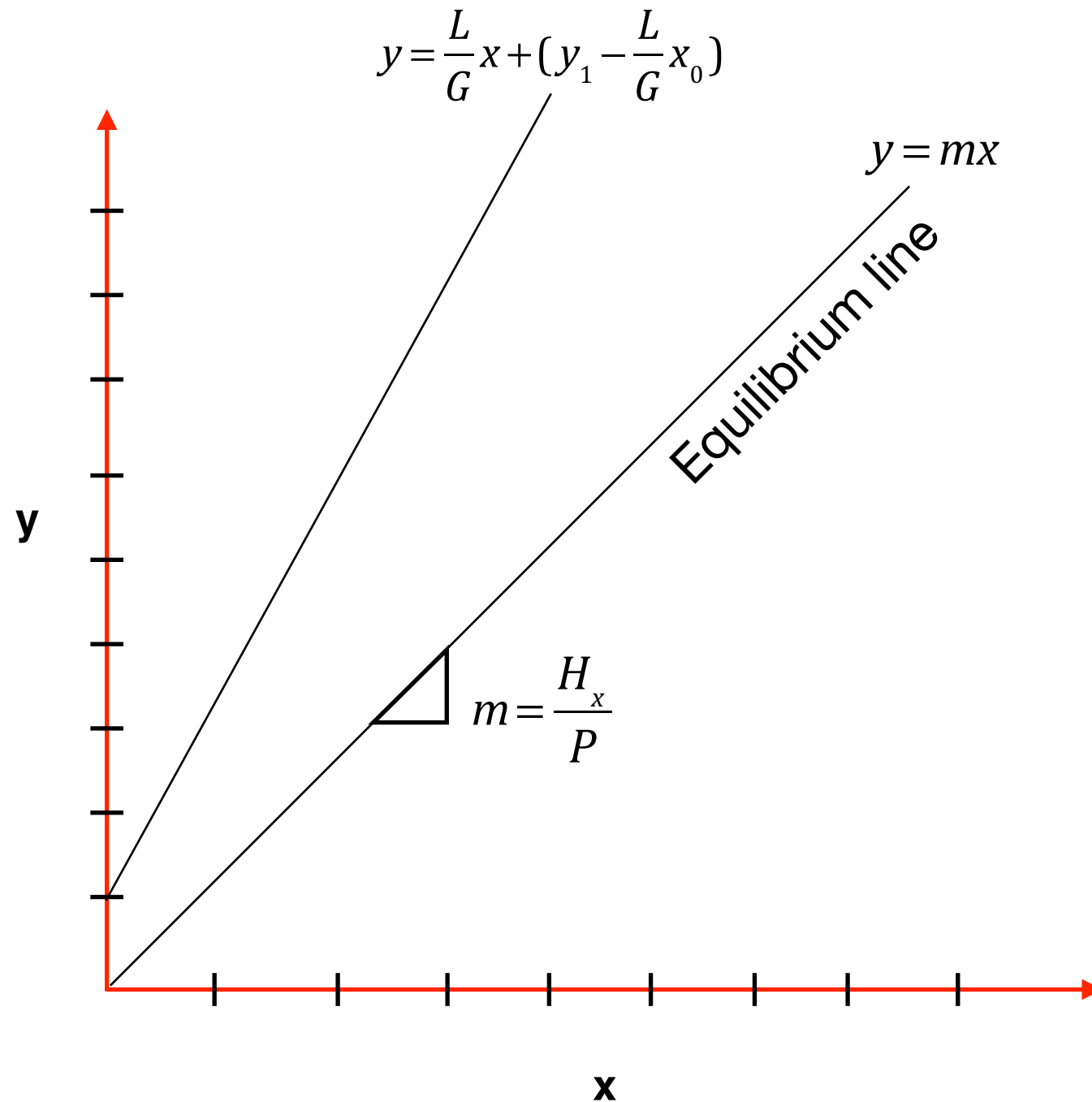
$$y = \frac{L}{G}x + \left(y_{N+1} - \frac{L}{G}x_N\right)$$

# Comparison of separation processes

	Absorption	Liquid-liquid extraction	Distillation
<b>Operating line</b>	$y = \frac{L}{G}x + (y_1 - \frac{L}{G}x_0)$	$y = \frac{R}{E}x + (y_1 - \frac{R}{E}x_0)$	$y = \frac{L}{V}x + \frac{D}{V}x_D$ $y = \frac{L}{V}x + (y_1 - \frac{L}{V}x_D)$
<b>Phase description</b>	Gas (y) Liquid, Absorbent (x) <div>  </div>	Liquid, Raffinate (x) Liquid, Extract (y) <div>  </div>	Vapor (y) Liquid (x) <div>  </div>
<b>Equilibrium relationship</b>	$m = \frac{H_x}{P}$	$m = K_D$	$m = K_i = \frac{\gamma_i P_i^{sat}}{P}$



# Graphical method for number of stages




Operating line

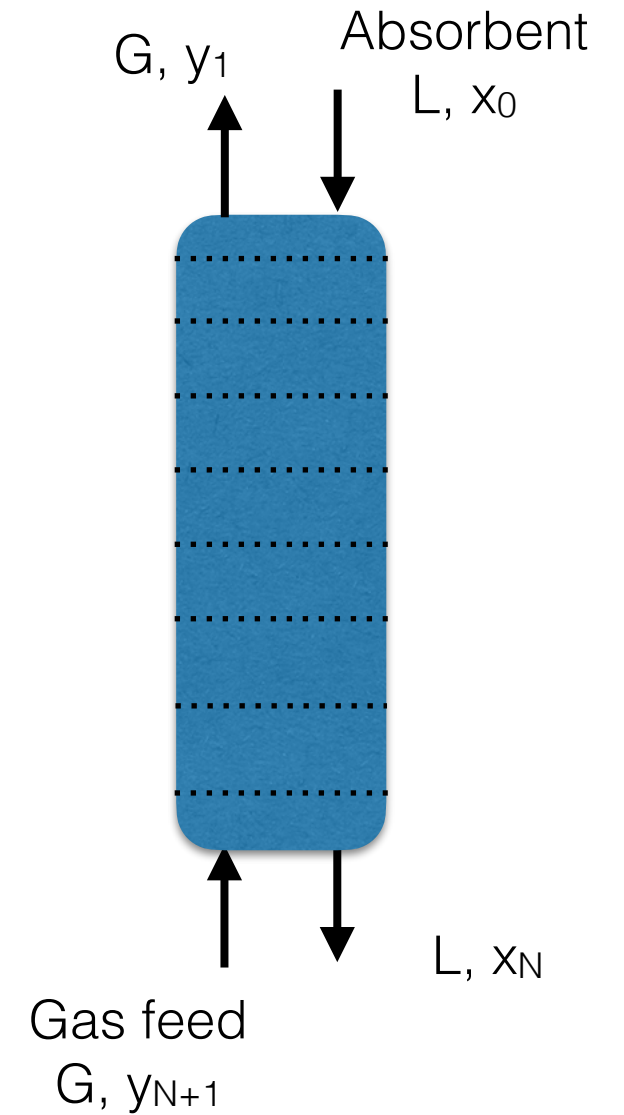
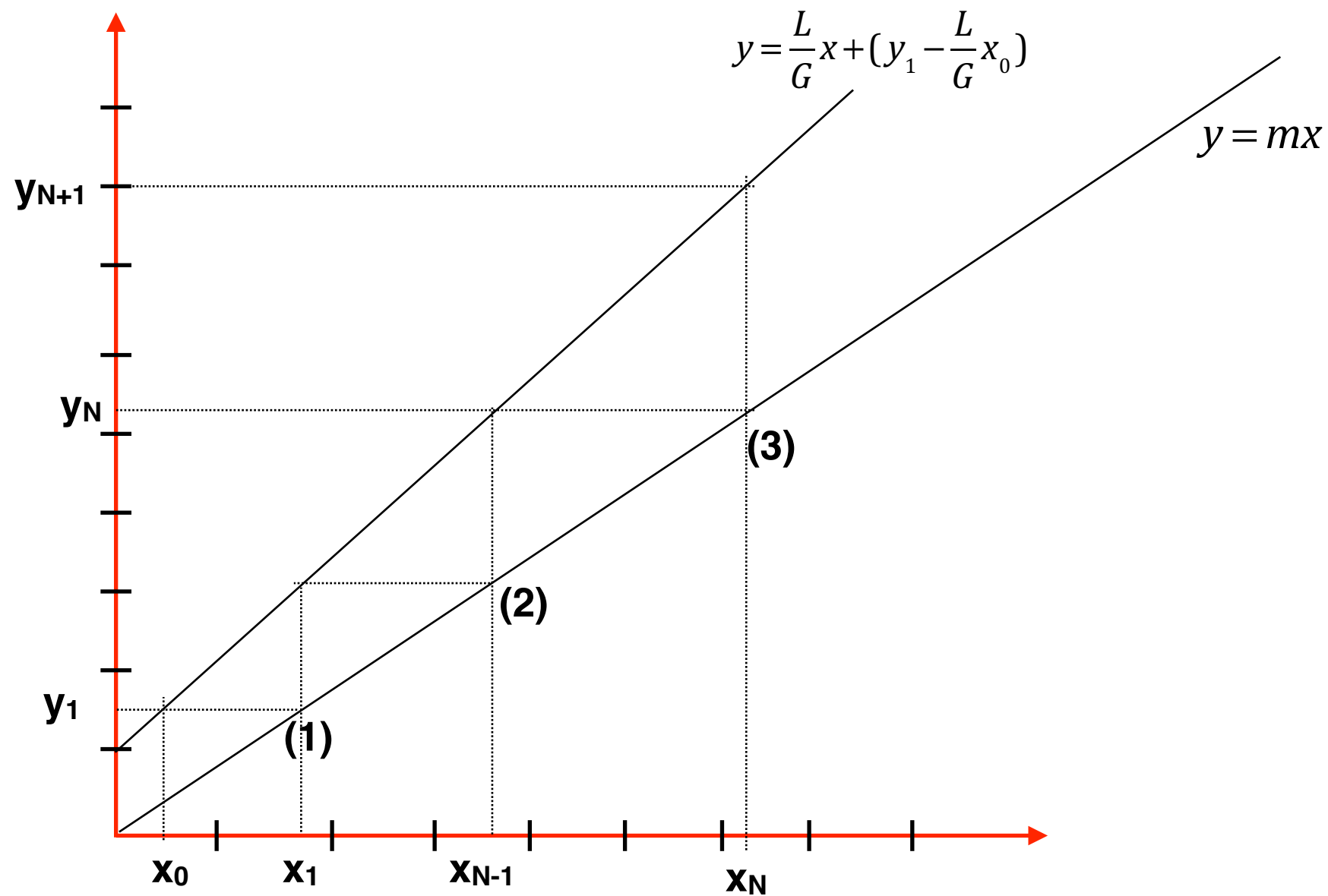
$$y = \frac{L}{G}x + (y_1 - \frac{L}{G}x_0)$$

Gas ( $y$ )  
Liquid ( $x$ )

Mass transfer



# Calculation of number of stages



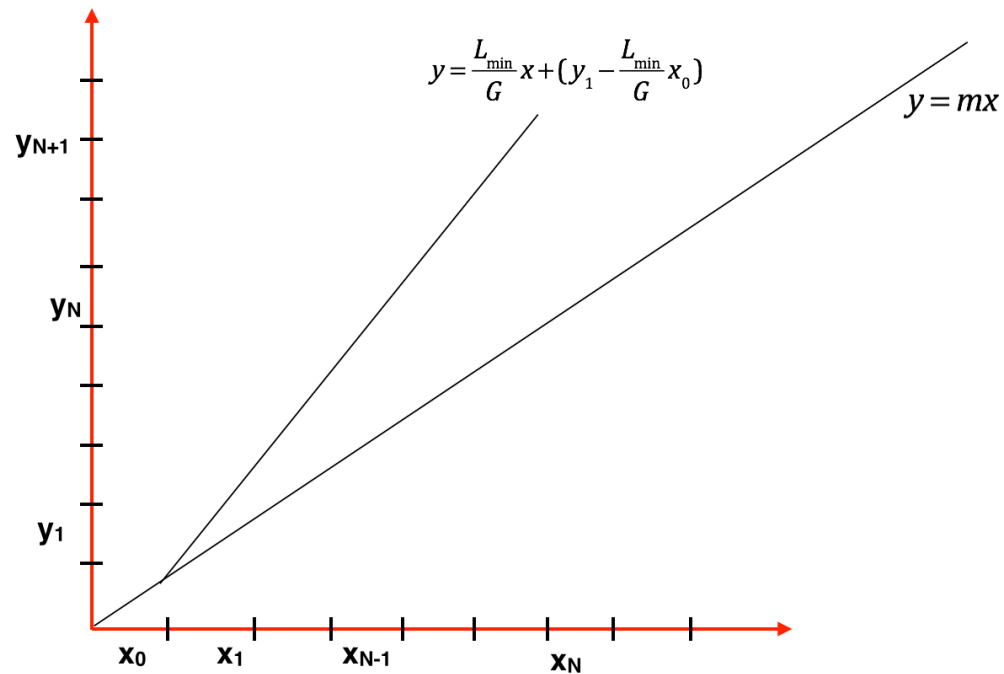
$$y_1 < y_{N+1}$$

$$x_0 < x_N$$

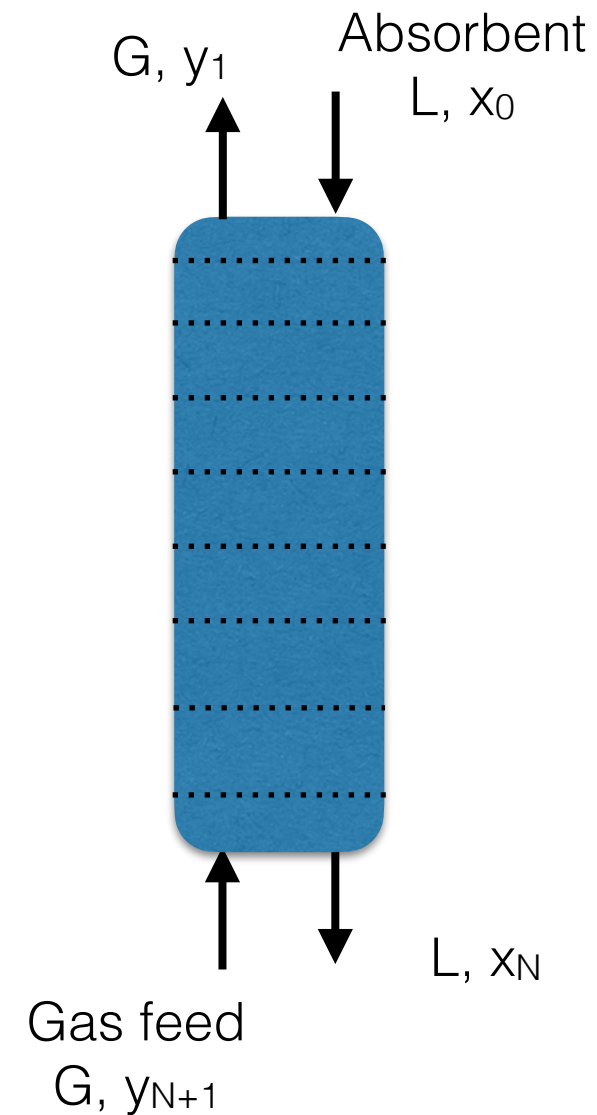
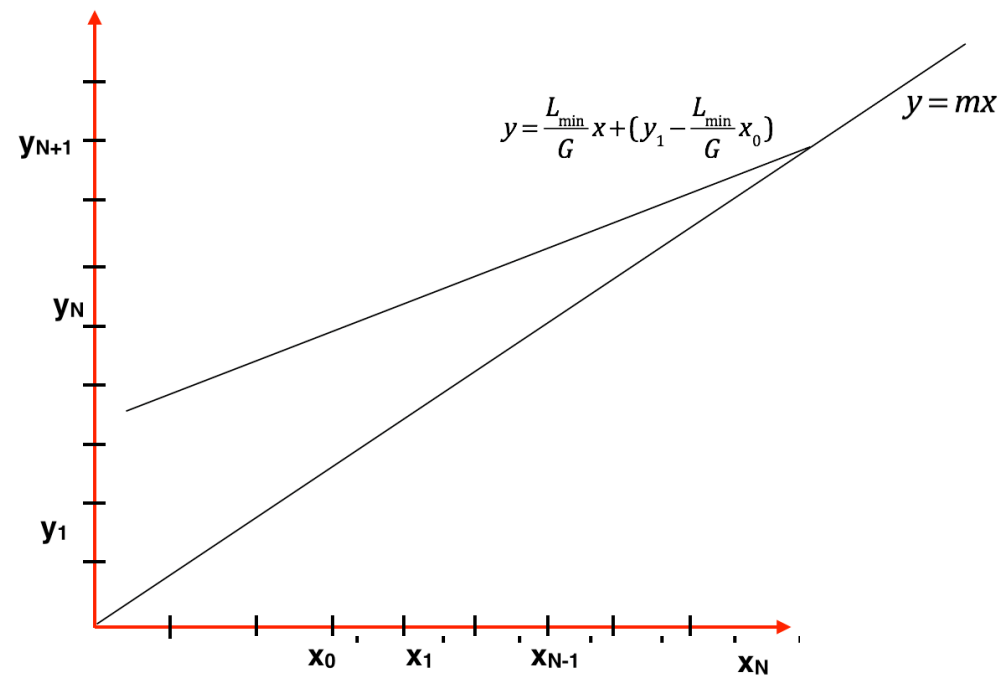
# Minimum absorbent flow rate

Which one is the correct representation??

A



B

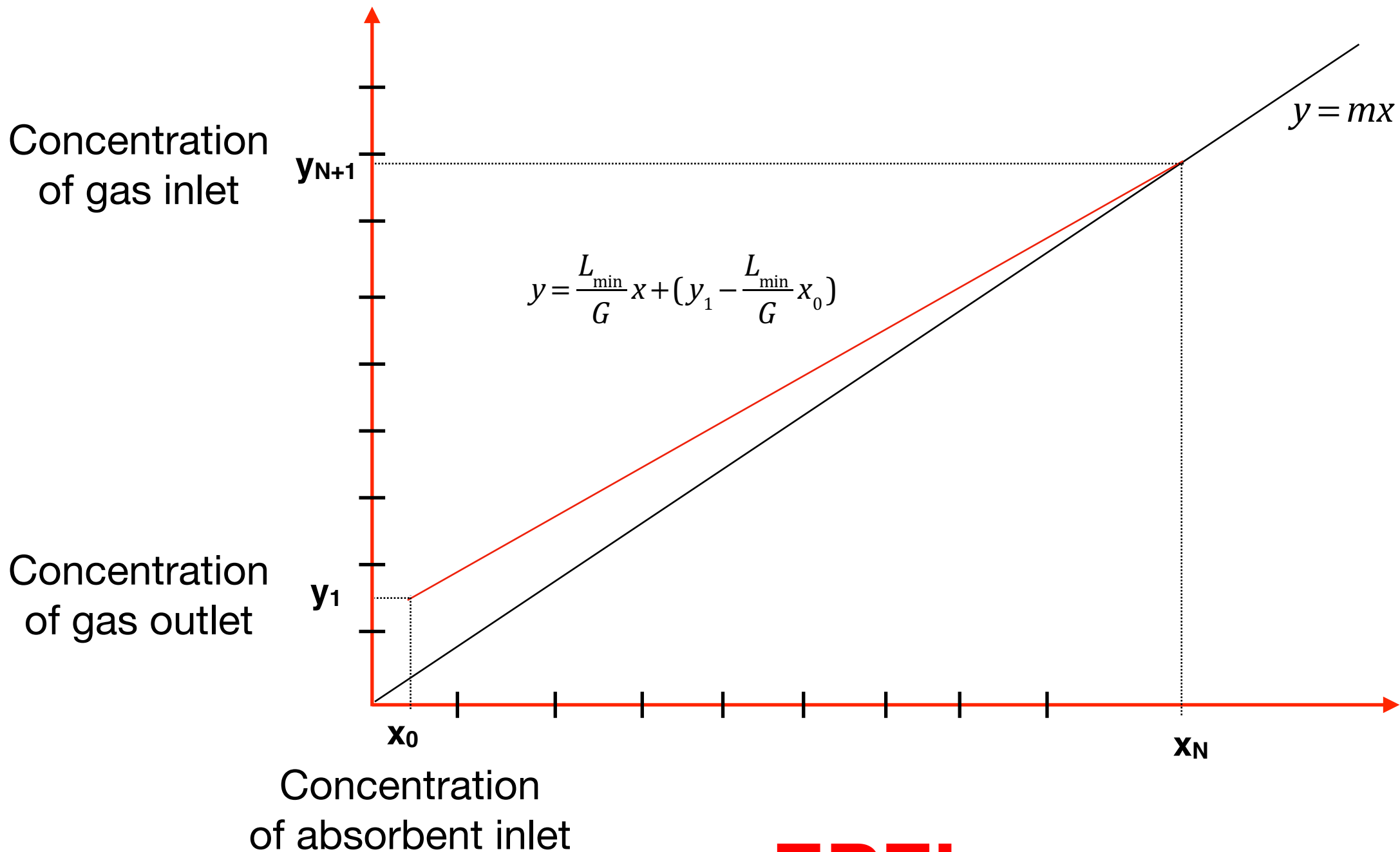


The slope of the operating line,  $L/G$ , is minimum

# Minimum absorbent flow rate

The slope of the operating line,  $L/G$ , is minimum

Number of stages is infinity



# Use of Kremser equation

## **Key assumptions:**

1. Equilibrium line is a straight line (when low concentration, Henry's equation).
2. Carrier gas is insoluble (carrier does not transfer to the solvent phase).
3. Absorbent is nonvolatile (solvent does not transfer to the carrier phase).
4. System is isothermal and isobaric (the heat of absorption is negligible).

# Kremser equation for analytical calculation

$$y_1 - y_{N+1} = (y_1 - y_2) + (y_2 - y_3) + (y_3 - y_4) + \dots + (y_{N-1} - y_N) + (y_N - y_{N+1})$$

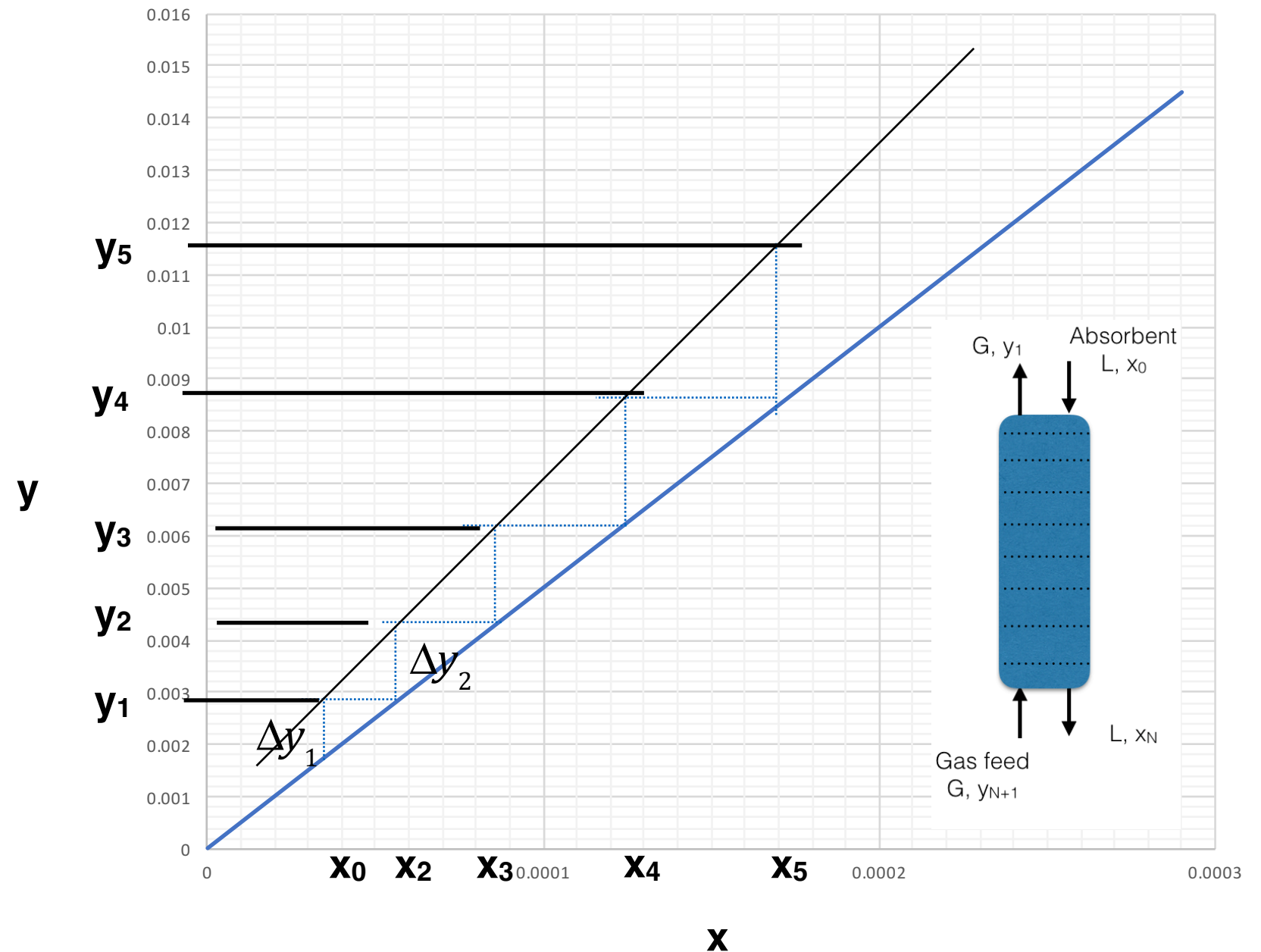
$$y_1 - y_2 = \Delta y_1$$

$$y_j - y_{j+1} = \Delta y_j$$

Use equilibrium and operating lines

$$y_j = mx_j$$

$$y_{j+1} = \frac{L}{G}x_j + \left( y_{N+1} - \frac{L}{G}x_N \right)$$



# Kremser equation for analytical calculation

$$\Delta y_{j+1} = \left( \frac{L}{mG} \right) \Delta y_j$$

$$y_1 - y_{N+1} = \left( \frac{1 - A^N}{1 - A} \right) \Delta y_1$$

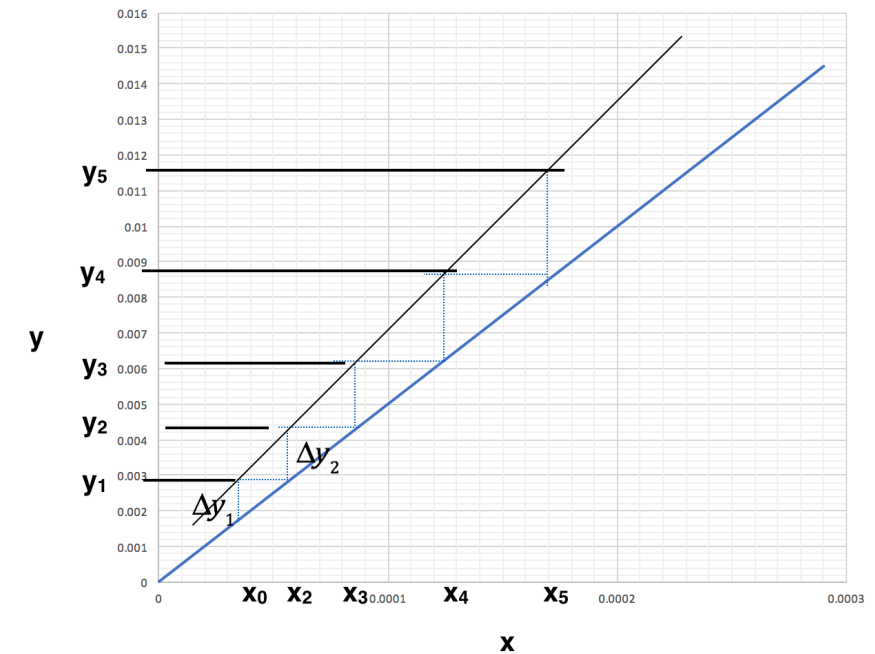
$$N = \frac{\ln \left[ \frac{1}{A} + \left( 1 - \frac{1}{A} \right) \left( \frac{y_{N+1} - y_0}{y_1 - y_0} \right) \right]}{\ln A}$$

**Kremser Equation**

$$y_0 = mx_0$$

$$A = \frac{L}{mG}$$

$$m = \left( \frac{H_x}{P} \right)$$



# Concentrated case

## Key assumptions:

1. Carrier gas is insoluble (carrier does not transfer to the solvent phase).
2. Absorbent is nonvolatile (solvent does not transfer to the carrier phase).
3. System is isothermal and isobaric (the heat of absorption is negligible).

## Implication:

1. Nonlinear equilibrium relationship between concentration in gas phase and in absorbed phase (Henry's law may or may not be valid).
2. Net flow rate of the liquid phase changes. However, the absorbent flow rate,  $L_A$ , does not change.
3. Net flow rate of the gas phase changes. However, the carrier flow rate,  $G_C$ , does not change.

$$X_j = \left( \frac{\text{flow rate of gas / vapor}}{\text{flow rate of absorbent, } L_A} \right)_j = \frac{x_j}{1 - x_j}$$

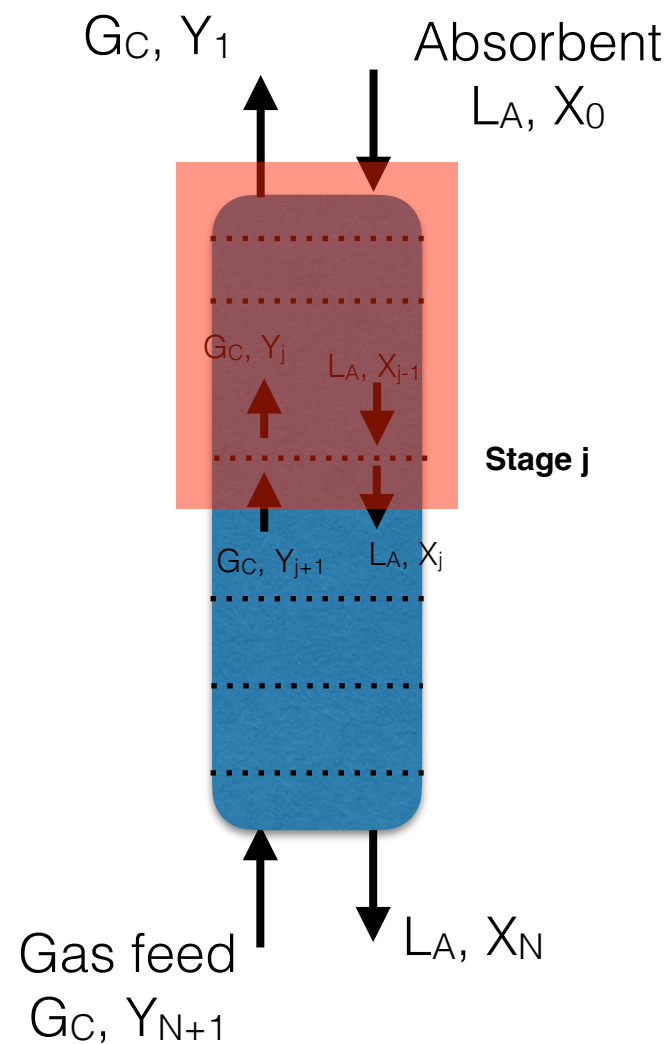
$$Y_j = \left( \frac{\text{flow rate of gas / vapor}}{\text{flow rate of carrier gas, } G_C} \right)_j = \frac{y_j}{1 - y_j}$$



# Mass balance for the concentrated case

$$X_j = \left( \frac{\text{flow rate of gas / vapor}}{\text{flow rate of absorbent, } L_A} \right)_j = \frac{x_j}{1 - x_j}$$

$$Y_j = \left( \frac{\text{flow rate of gas / vapor}}{\text{flow rate of carrier gas, } G_c} \right)_j = \frac{y_j}{1 - y_j}$$



## Balance around stage $j$

*In = out*

$$G_c Y_{j+1} + L_A X_0 = L_A X_j + G_c Y_1$$

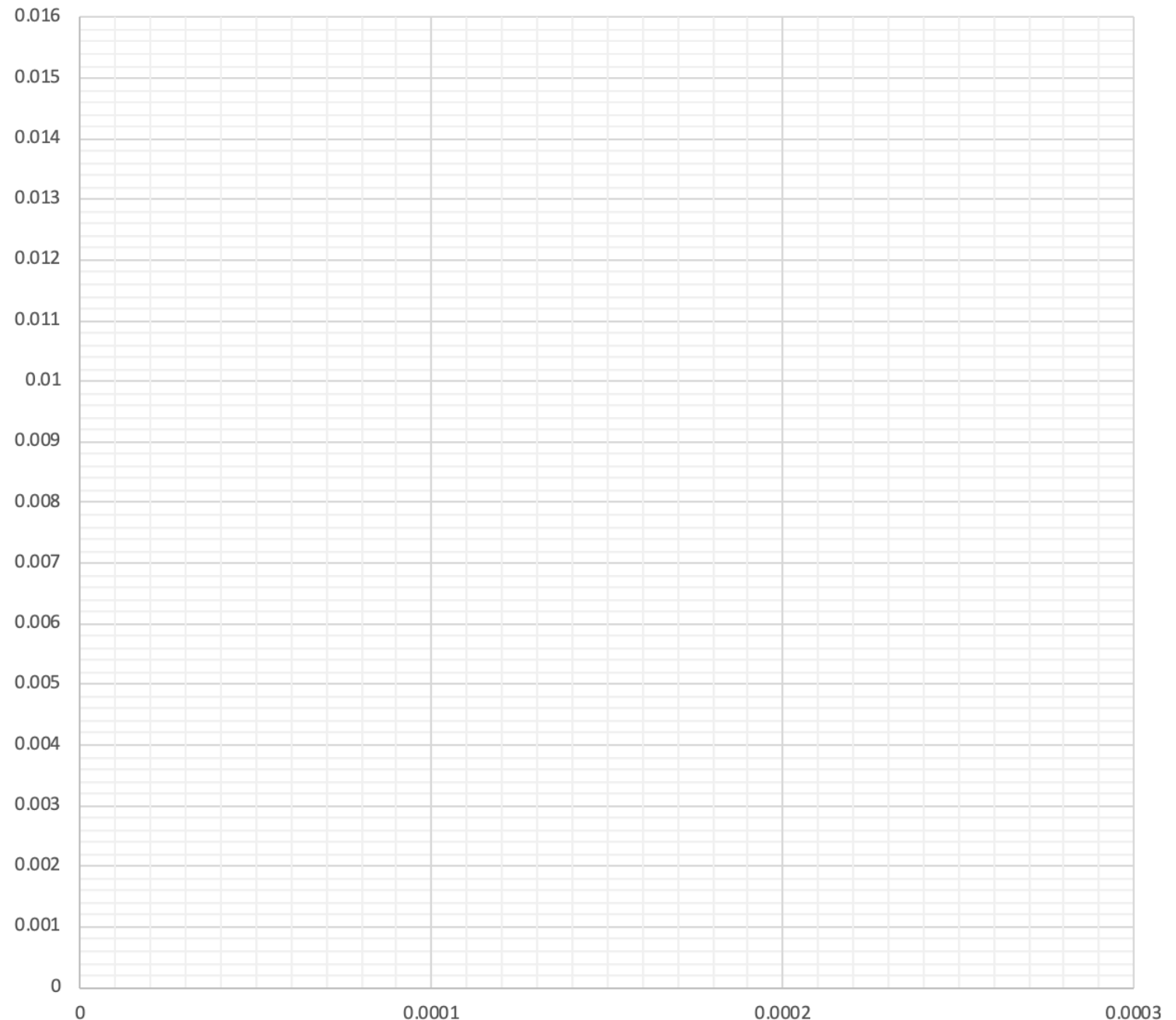
$$Y_{j+1} = \frac{L_A}{G_c} X_j + \left( Y_1 - \frac{L_A}{G_c} X_0 \right)$$

$$Y_{j+1} = \frac{L_A}{G_c} X_j + \left( Y_{N+1} - \frac{L_A}{G_c} X_N \right)$$

# Exercise problem 1: dilute gas absorption

100 mol/hr of flue gas containing 1.2% CO at 1 atm is to be cleaned of the CO such that at the end, its concentration is reduced by 20 fold. A pure absorbent is being used to remove CO. Calculate number of stages if  $L/G = 1.265 (L/G)_{\min}$ . Calculate exit concentration of absorbent.

$$H_x = 50 \text{ bar}$$



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$$y_A = \left( \frac{H_x}{P} \right) x_A = m x_A$$

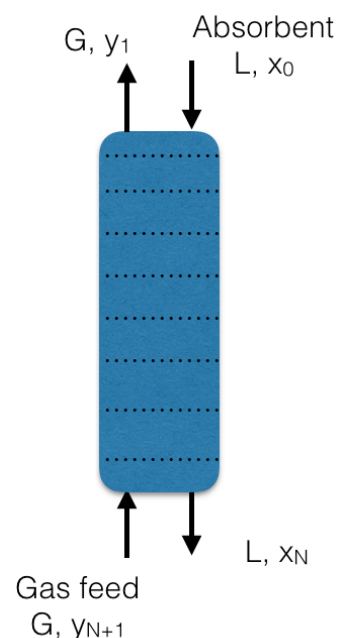
$$H_x = 50 \text{ bar}$$

$$m = \left( \frac{H_x}{P} \right) = 50$$

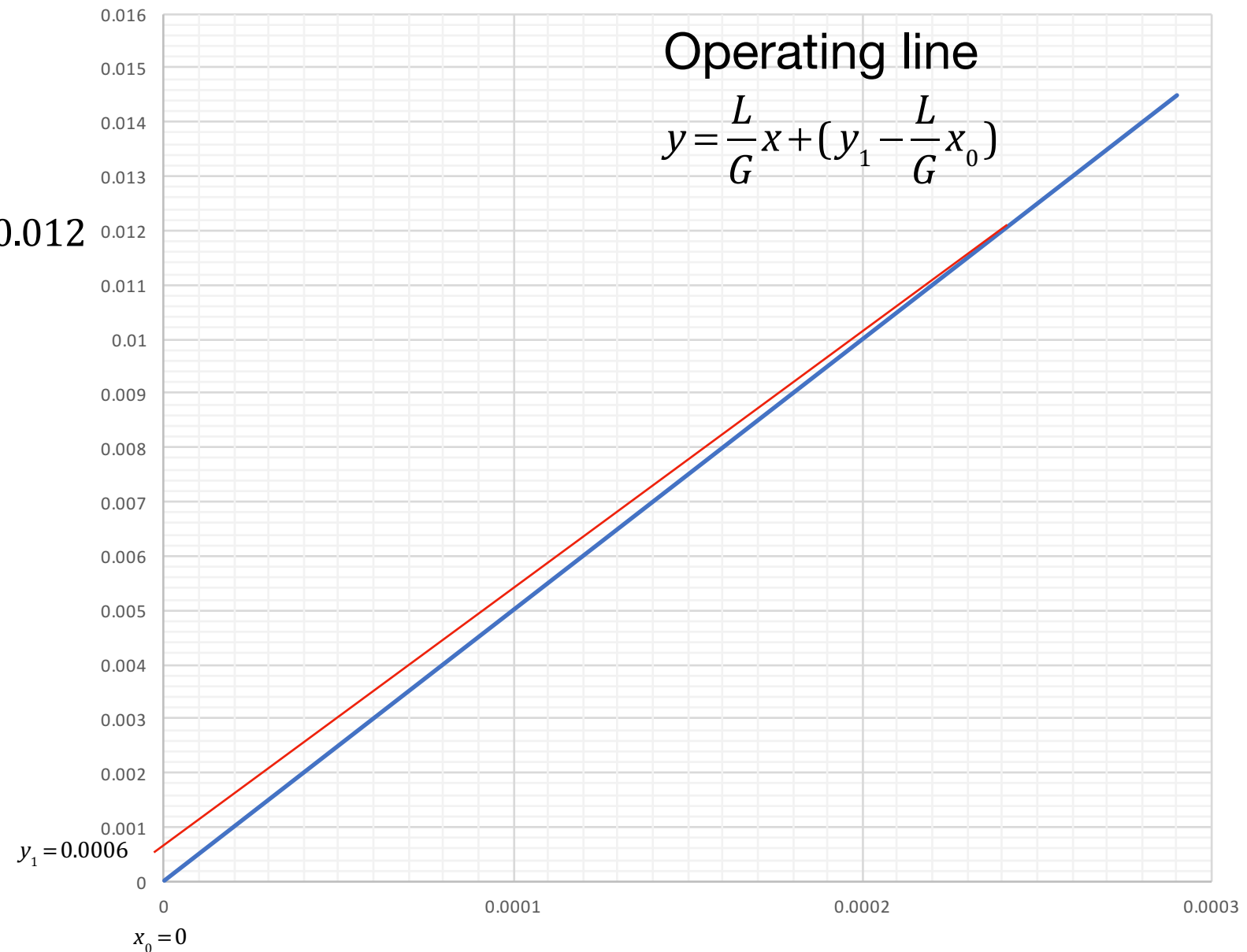
$$y_{N+1} = 0.012$$

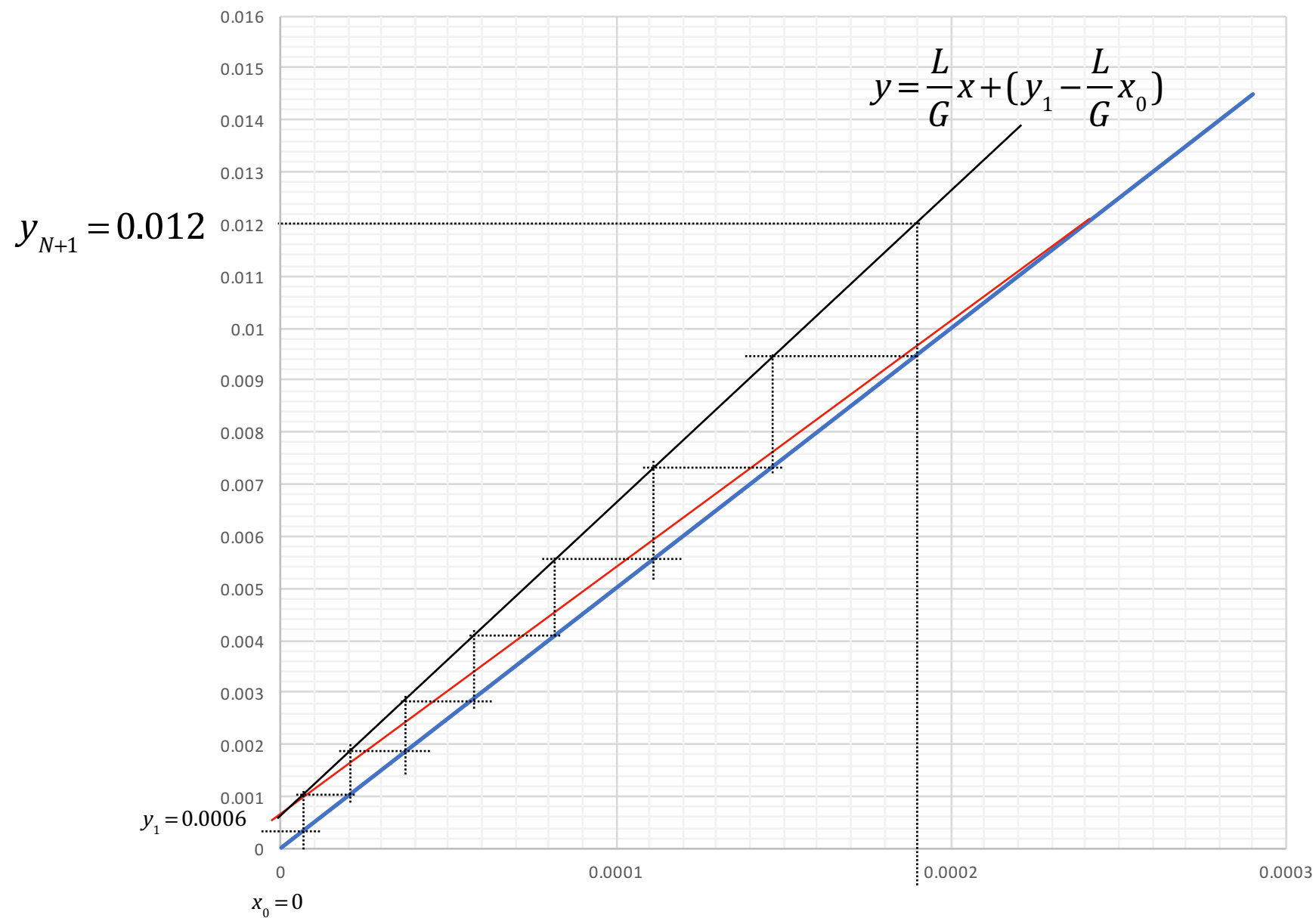
$$y_1 = 0.0006$$

$$x_0 = 0$$



$$y_{N+1} = 0.012$$





$$\frac{L_{\min}}{G} = \frac{0.012 - 0.0006}{0.00024 - 0} = 47.5$$

$$\frac{L}{G} = 1.265 * \frac{L_{\min}}{G} = 60$$

**$x_N = 0.00019$ , number of stages = 8**