Laboratory of
Computational
Systems
Biotechnology

EPFL

Introduction to Chemical Engineering

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Office hours: Mondays 16h-19h (CH H4 625) or schedule by email

Fridays, 14 - 17h
2025-2026

Course Schedule

Date	Subject
12-Sep	**1. Fundamentals of Material Balances** 1.1. Process definition and classification 1.2. Material balance calculations 1.3. Balances on multiple-unit processes
19-Sep	Exercises
26-Sep	1.4. Chemical reaction stoichiometry 1.5. Balances on reactive Processes
03-Oct	Review on Material Balances
10-Oct	**1.6. Balances on multiple unit reactive processes**
17-Oct	**2. Fundamentals of Energy and Energy Balances** 2.1. Energy balances on closed systems 2.2. Open systems at steady state **3. Balances on Non-Reactive Processes** 3.1. Energy balance calculation 3.2. Changes in Pressure, Temperature, Phases
31-Oct	**4. Balances on Reactive Processes** 4.1. Introduction to the Enthalpy of Reaction 4.2. Heat of Reaction Method 4.3. Heat of Formation Method 4.4 General Procedure to solve energy balance in reactive systems
07-Nov	**Review on Balances on Non-Reactive & Reactive Processes** Problems: Mass Balances on reactive and non-reactive & Energy Balances on non-Reactive Systems
14-Nov	**Midterm Exam: Mass Balances on Non-Reactive & Reactive Processes & Energy Balances non-Reactive Processes**
21-Nov	**Review Midterm**

Date	Subject
28-Nov	**Review on Heat of Reaction vs Heat of Formation Methods** **4.5 Hess's Law to compute the Heat of Reaction** **4.6 Heat of Combustion**
05-Dec	**5. Energy balances on mixing processes** **5.1 Distinction between ideal and real solutions** **5.2 Heat of Solution**
12-Dec	**Review and Study Session** • **Summing up with Mass and Energy Balances on Reactive Systems with Recycle**

Recommended textbook:
Elementary Principles of Chemical Processes,
Richard M. Felder & Ronald W. Rousseau

Revision Session II: Friday 06 November 2025

During this session, we will review the following concepts

1. Material balances (Non-Reactive & Reactive)
2. Energy balances (Non-Reactive)

Material Balances

Material Balances: overview

It all starts with the mother of all equations:

Input	+	**generation**	-	**output**	-	**consumption**	=	**accumulation**
Entering through boundaries		Produced in the system		Leaving through boundaries		Consumed within system		Build up within system

Material Balances: overview

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(Almost) all the systems we study represent **steady-state continuous processes:**

Input	+	**generation**	-	**output**	-	**consumption**	=	**0**
Entering through boundaries		Produced in the system		Leaving through boundaries		Consumed within system		

Material Balances: overview

It all starts with the mother of all equations:

$$\underset{\left(\begin{array}{c}\text{Entering}\\ \text{through}\\ \text{boundaries}\end{array}\right)}{\textbf{Input}} + \underset{\left(\begin{array}{c}\text{Produced}\\ \text{in the}\\ \text{system}\end{array}\right)}{\textbf{generation}} - \underset{\left(\begin{array}{c}\text{Leaving}\\ \text{through}\\ \text{boundaries}\end{array}\right)}{\textbf{output}} - \underset{\left(\begin{array}{c}\text{Consumed}\\ \text{within}\\ \text{system}\end{array}\right)}{\textbf{consumption}} = \underset{\left(\begin{array}{c}\text{Build up}\\ \text{within}\\ \text{system}\end{array}\right)}{\textbf{accumulation}}$$

(Almost) all the systems we study represent **steady-state continuous processes:**

$$\underset{\left(\begin{array}{c}\text{Entering}\\ \text{through}\\ \text{boundaries}\end{array}\right)}{\textbf{Input}} + \underset{\left(\begin{array}{c}\text{Produced}\\ \text{in the}\\ \text{system}\end{array}\right)}{\textbf{generation}} - \underset{\left(\begin{array}{c}\text{Leaving}\\ \text{through}\\ \text{boundaries}\end{array}\right)}{\textbf{output}} - \underset{\left(\begin{array}{c}\text{Consumed}\\ \text{within}\\ \text{system}\end{array}\right)}{\textbf{consumption}} = \mathbf{0}$$

From there, we have seen 2 possible methods:

Species Material Balances

We perform balances for each molecular species

Atom Material Balances

We perform balances for each element

Material Balances: species vs atom balances

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Material Balances: species vs atom balances

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Species Material Balances

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We perform balances for each element

Non-reactive systems:

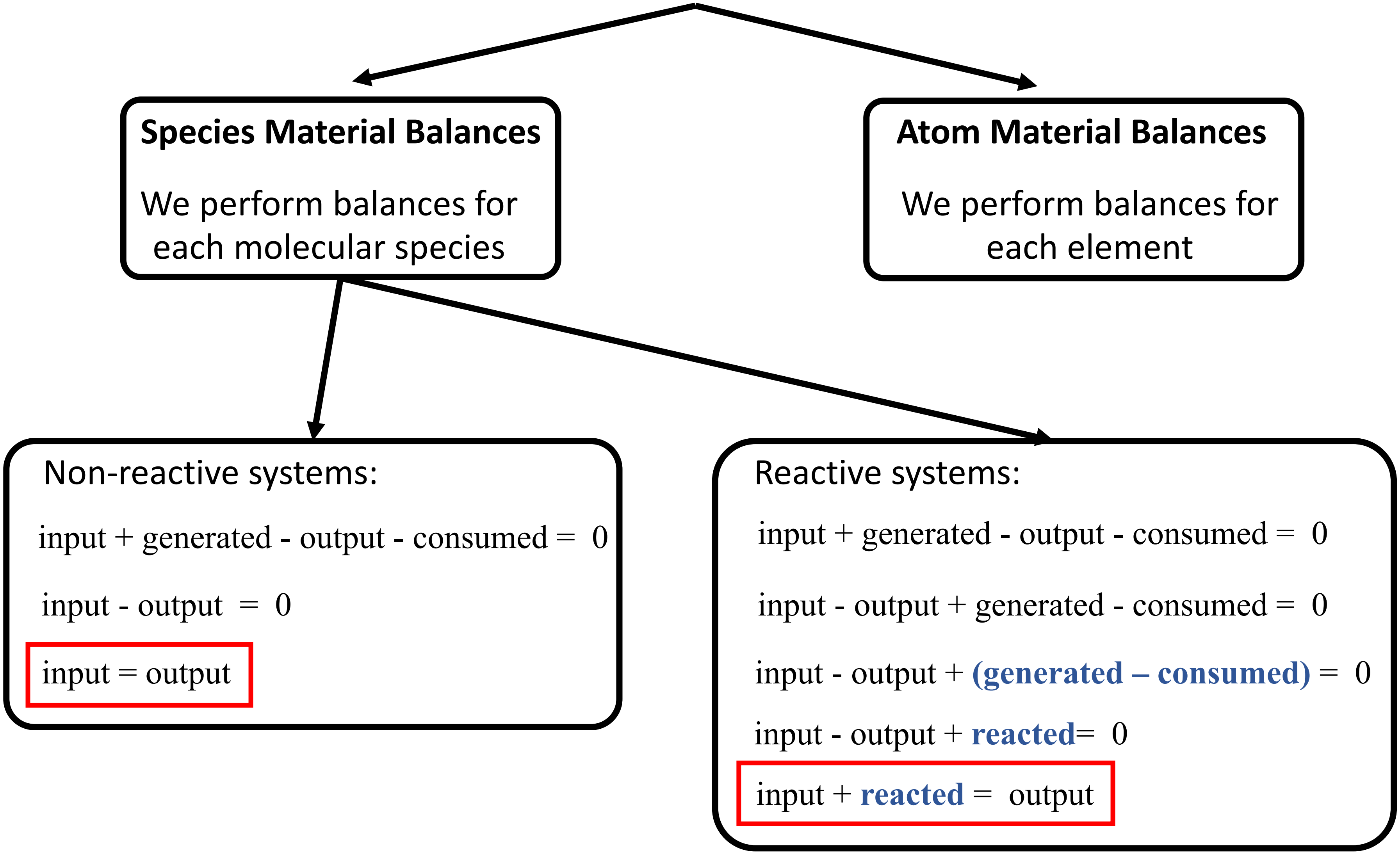
$$\text{input} + \text{generated} - \text{output} - \text{consumed} = 0$$

$$\text{input} - \text{output} = 0$$

$$\boxed{\text{input} = \text{output}}$$

Material Balances: species vs atom balances

From there, we have seen 2 possible methods:



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Non-reactive systems:

$$\text{input} + \text{generated} - \text{output} - \text{consumed} = 0$$

$$\text{input} - \text{output} = 0$$

$$\boxed{\text{input} = \text{output}}$$

Reactive systems:

$$\text{input} + \text{generated} - \text{output} - \text{consumed} = 0$$

$$\text{input} - \text{output} + \text{generated} - \text{consumed} = 0$$

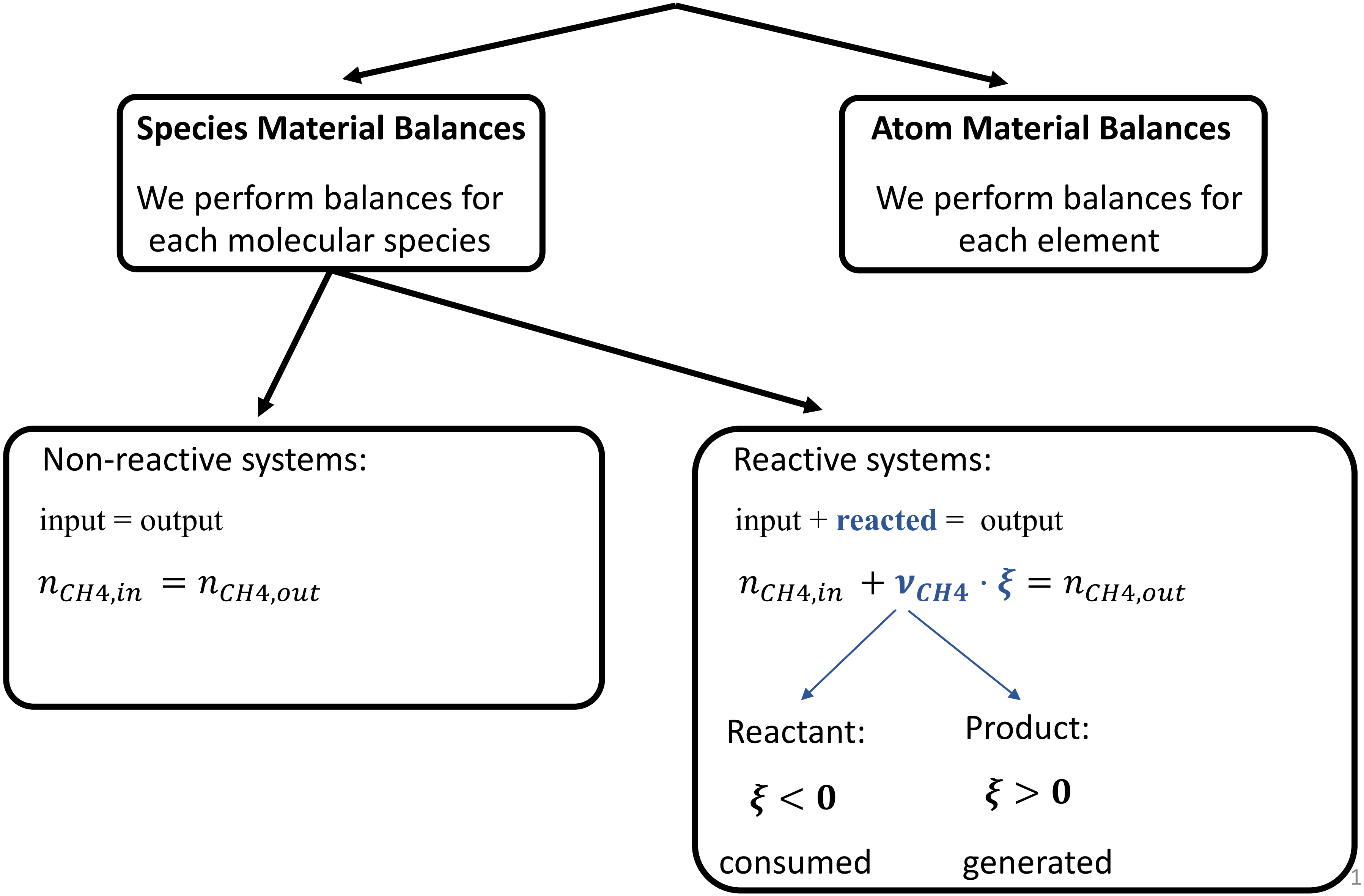
$$\text{input} - \text{output} + \mathbf{(generated - consumed)} = 0$$

$$\text{input} - \text{output} + \mathbf{reacted} = 0$$

$$\boxed{\text{input} + \mathbf{reacted} = \text{output}}$$

Material Balances: species vs atom balances

From there, we have seen 2 possible methods:



Species Material Balances

We perform balances for each molecular species

Atom Material Balances

We perform balances for each element

Non-reactive systems:

$$\text{input} = \text{output}$$

$$n_{CH4,in} = n_{CH4,out}$$

Reactive systems:

$$\text{input} + \textbf{reacted} = \text{output}$$

$$n_{CH4,in} + \boldsymbol{\nu_{CH4}} \cdot \xi = n_{CH4,out}$$

Reactant:

$$\xi < \mathbf{0}$$

consumed

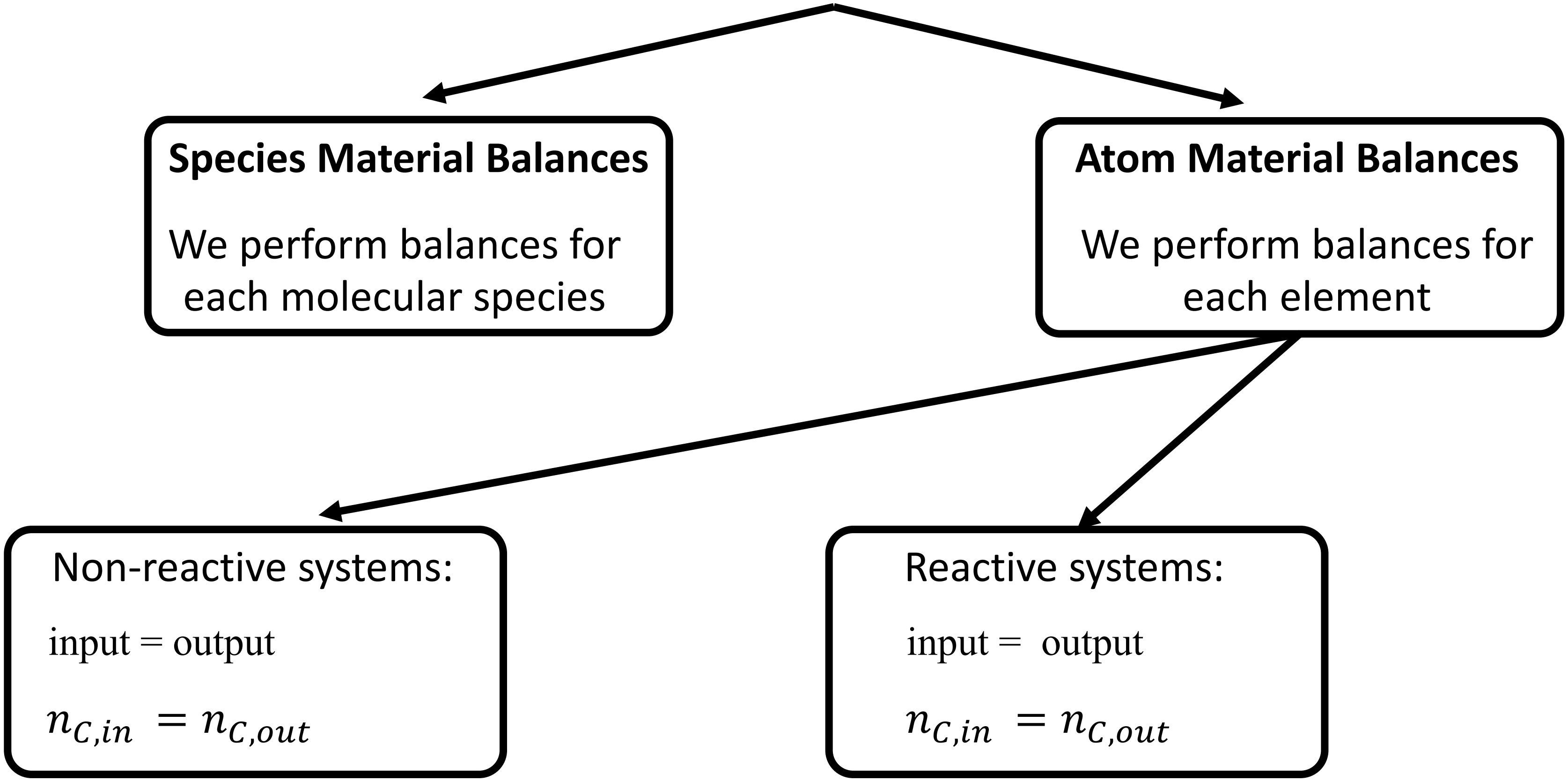
Product:

$$\xi > \mathbf{0}$$

generated

Material Balances: species vs atom balances

From there, we have seen 2 possible methods:



Species Material Balances

We perform balances for each molecular species

Atom Material Balances

We perform balances for each element

Non-reactive systems:

input = output

$n_{C,in} = n_{C,out}$

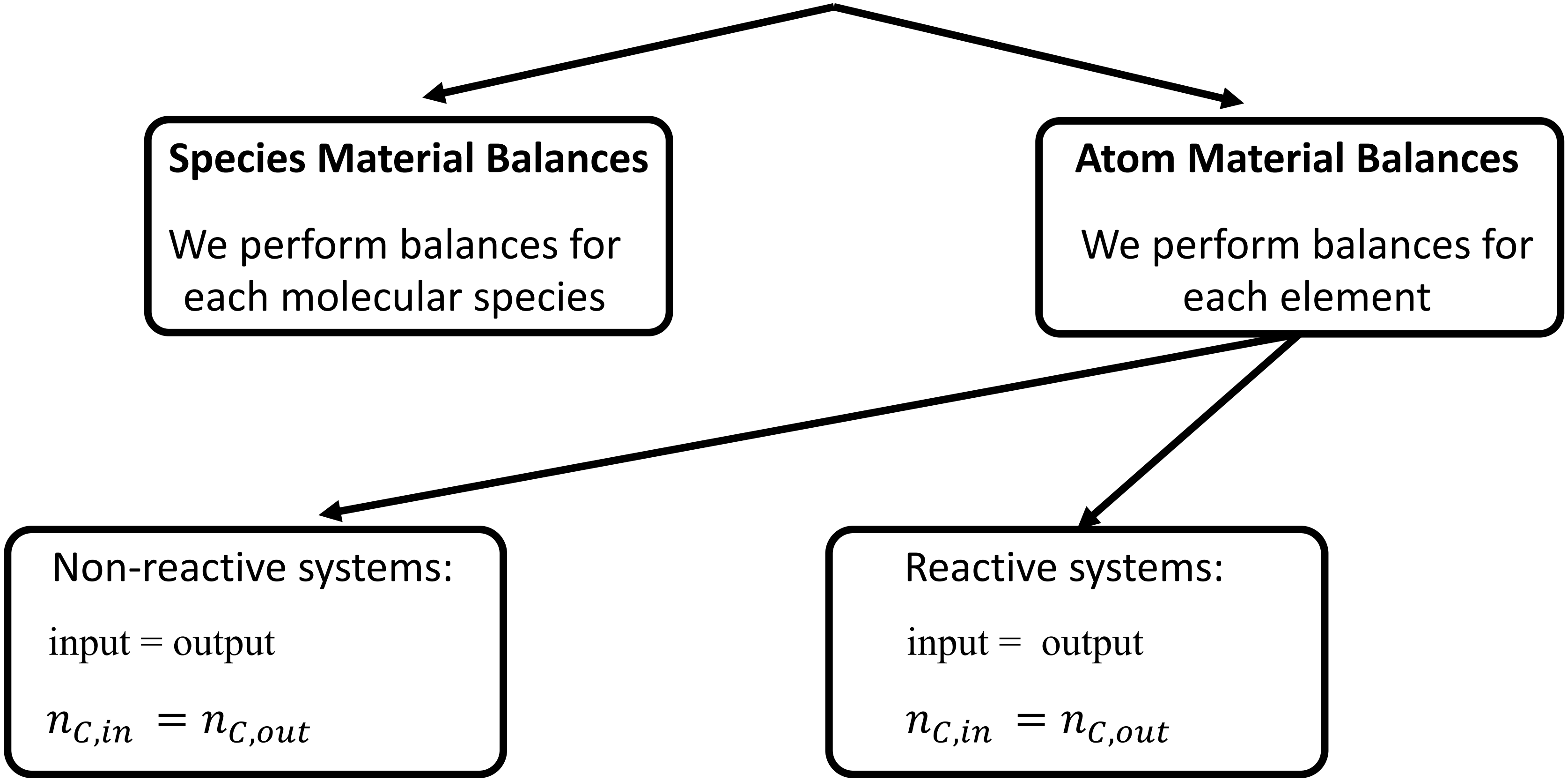
Reactive systems:

input = output

$n_{C,in} = n_{C,out}$

Material Balances: species vs atom balances

From there, we have seen 2 possible methods:



Species Material Balances

We perform balances for each molecular species

Atom Material Balances

We perform balances for each element

Non-reactive systems:

input = output

$n_{C,in} = n_{C,out}$

Reactive systems:

input = output

$n_{C,in} = n_{C,out}$

- No consideration of the extent of reaction with atom balance
- However, do not forget to multiply by the stoichiometric coefficient, e.g, in 1 mole of CH4, there is 1 mole of Carbon BUT 4 moles of Hydrogen!

Material Balances: Considerations on Reactive Systems

Multiple reactions → multiple extents of reactions (species material balance)

$$\left.\begin{array}{ll} R_1: 2\,CO_2 \rightarrow 2\,CO + O_2 & \longrightarrow \quad \xi_1 \\ R_2: O_2 + N_2 \rightarrow 2NO & \longrightarrow \quad \xi_2 \end{array}\right\} \quad n_i = n_{i0} + \sum_j \nu_{ij}\xi_j$$

Material Balances: Considerations on Reactive Systems

Multiple reactions → multiple extents of reactions (species material balance)

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If 2 reactions or more, it is generally easier to go with atomic material balance method

Material Balances: Considerations on Reactive Systems

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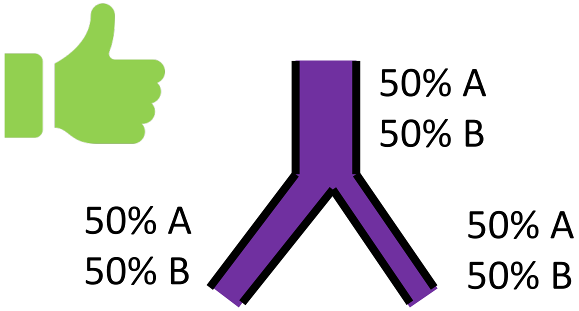
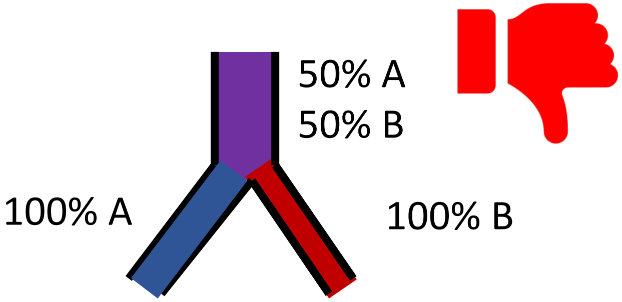
In **reactive systems, moles of species are not conserved** (look at reaction 1, we start with a total of 2 moles (CO2) and ends up with a total of 3 moles (2 moles CO and 1 mole O2). HOWEVER, the moles of elements are conserved → if we use the molecular species balance method**, do not forget to convert the moles to mass when solving your material balances!**

Material Balances: General Considerations

At a splitting point, the composition of the stream is maintained (unless mentioned otherwise)





Material Balances: Limiting and Excess Reactants

Limiting reactant in reactive process = reactant that would be **completely consumed if the reaction proceeded to completion**.

All other reactants must either be fed in (1) stoichiometric proportion to the limiting reactant (the feed rates are in the ratio of the stoichiometric coefficients) or (2) in excess of the limiting reactant (in greater than stoichiometric proportion to it).

$$\%\ excess = \frac{amount\ fed\ - amount\ theoretically\ required}{amount\ theoretically\ requied}$$

Material Balances: Procedure for Calculations

1. Choose **as basis of calculation** an amount or flow rate of one of the process streams
    1. Basis can already be given in the problem
    2. If no stream amount or flow rate is specified, take as a basis an arbitrary amount or flow rate of a stream with known composition
2. **Draw a flowchart** and fill in all known variable values, including the basis of calculation, then label the unknown stream variables on the chart
3. Express what the **problem statement asks you** to determine in terms of the labeled variables
4. If you are given mixed mass and mole units for a stream**, convert all quantities to one basis or the other**.
5. OPTIONNAL: Perform a degree-of-freedom analysis
6. OPTIONNAL: If the number of unknowns equals the number of equations relating them, write the equation in an efficient order (minimizing simultaneous equations), and circle the variables for which you will solve
7. **Solve the equations**
8. **Calculate the quantities requested in the problem statement** if they have not already been calculated
9. OPTIONNAL: Scale if you chose a different basis than the one initially suggested.

Energy Balances

Energy Balances: overview

Again, with the mother of all equations:

$$E_{\text{accumulated}} = E_{\text{input}} - E_{\text{output}} + E_{\text{gen}} + E_{\text{transferred}}$$

Where $E_{\text{transferred}} = Q - W$

<u>Conventions:</u>

- $Q > 0$ when heat is transferred **from the surrounding to the system**
- $W > 0$ when work is **done by the system on the surroundings** *

* The opposite convention is sometimes used. The choice is arbitrary, **if it is used consistently**

Energy Balances: overview

Again, with the mother of all equations:

$$E_{\text{accumulated}} = E_{\text{input}} - E_{\text{output}} + E_{\text{gen}} + E_{\text{transferred}}$$

Closed

$$\Delta U + \Delta E_k + \Delta E_p = Q - W$$

- Δ : final – initial

Open

$$\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

- Δ : output – input

Energy Balances: closed vs open systems

Closed

$$\Delta U + \Delta E_k + \Delta E_p = Q - W$$

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Why do we switch from **internal energy** to **enthalpy** when considering **an open system** (vs a closed system)?

Energy Balances: closed vs open systems

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1st law of thermodynamics for an open system at steady state

Energy Balances: closed vs open systems

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$$\Delta\dot{U} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - (\dot{W}_{fl} + \dot{W}_s)$$

Total Work Done by a system on its surrounding:

$$\boldsymbol{W = W_{fl} + W_s}$$

$\boldsymbol{W_{fl}}$**:** Flow Work Rate= rate of work done by the output streams – rate of work done on the input streams

$\boldsymbol{W_s}$**:** Shaft Work Rate = rate of work transferred across the system boundary by 1) moving part or 2) as electricity or 3) radiation

- **"Useful mechanical or electrical work"**
- Energy transferred **through moving parts or fields**, not by pushing fluid.
- Think of **shafts, paddles, pistons, motors, turbines or electrical devices**.
- Examples:
  - Pump or compressor driven by a motor (**work done *on* the system**)
  - Turbine driving a generator (**work done *by* the system**)
  - Stirred tank: mixer shaft doing work on the liquid
  - Electric heater: electrical work entering the system

Energy Balances: closed vs open systems

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- **"Pressure work to move fluid across boundaries"**
- The **"pressure push"** that forces mass to enter or leave the control volume.
- Each kilogram of fluid carries pv of flow energy (work of displacement).
- Examples:
  - Pump pushing liquid into a pressurised pipe
  - Compressed gas leaving a tank through a valve
  - Any inlet or outlet stream of a heat exchanger or reactor

Energy Balances: closed vs open systems

Closed

$$\Delta U + \Delta E_k + \Delta E_p = Q \; - W$$

- Δ : final – initial

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$$\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} \; - \dot{W}_s$$

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$$\Delta \dot{U} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} \; - (\dot{\boldsymbol{W}}_{\boldsymbol{fl}} + \dot{W}_s)$$

$$\Delta \dot{U} + \dot{\boldsymbol{W}}_{\boldsymbol{fl}} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} \; - \dot{W}_s$$

Energy Balances: closed vs open systems

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$$\Delta \dot{U} + \dot{W}_{fl} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

$$(\Delta \dot{U} + \dot{W}_{fl}) + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

$$\boldsymbol{\Delta \dot{H} = \Delta \dot{U} + \dot{W}_{fl}}$$

$$\Delta \dot{H} + \Delta \dot{E}_k + \Delta \dot{E}_p = \dot{Q} - \dot{W}_s$$

Energy Balances: closed vs open systems

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$$\Delta U+\Delta E_k+\Delta E_p=Q-W$$

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Why do we switch from **internal energy** to **enthalpy** when considering **an open system** (vs a closed system)?

$$\Delta\dot{U}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}$$

$$\Delta\dot{U}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-(\dot{W}_{fl}+\dot{W}_s)$$

$$\Delta\dot{U}+\dot{W}_{fl}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$$

$$(\Delta\dot{U}+\dot{W}_{fl})+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$$

$$\boldsymbol{\Delta\dot{H}=\Delta\dot{U}+\dot{W}_{fl}}$$

$$\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$$

$$\boldsymbol{\Delta\dot{U}+\dot{W}_{fl}}$$

$$\boldsymbol{=\sum_{output}\dot{U}_j-\sum_{input}\dot{U}_j+\sum_{output}P_j\dot{V}_j-\sum_{input}P_j\dot{V}_j}$$

$$\boldsymbol{=\sum_{output}\dot{U}_j+P_j\dot{V}_j-\sum_{input}\dot{U}_j+P_j\dot{V}_j}$$

$$\boldsymbol{=\sum_{output}\dot{m}_j\,(\hat{U}_j+P_j\hat{V}_j)-\sum_{input}\dot{m}_j\,(\hat{U}_j+P_j\hat{V}_j)}$$

$$\boldsymbol{=\sum_{output}\dot{m}_j\,(\hat{H}_j)-\sum_{input}\dot{m}_j\,(\hat{H}_j)}$$

$$\boldsymbol{=\Delta\dot{H}}$$

Energy Balances: overview

Again, with the mother of all equations:

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Energy Balances: overview

Again, with the mother of all equations:

$$E_{\text{accumulated}} = E_{\text{input}} - E_{\text{output}} + E_{\text{gen}} + E_{\text{transferred}}$$

Most common

Closed

$$\Delta U + \Delta E_k + \Delta E_p = Q - W$$

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Open

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- Δ : output – input

Energy Balances: overview

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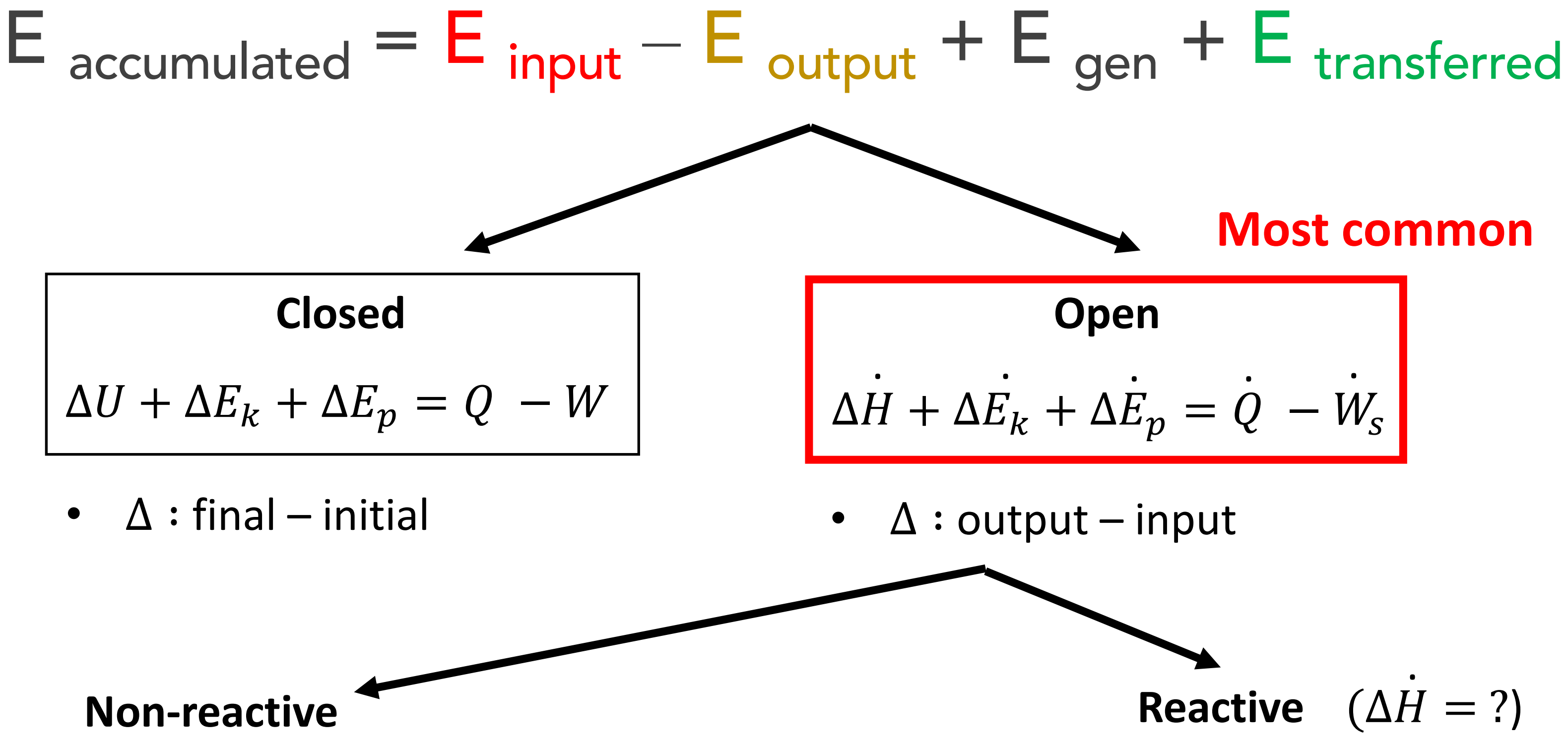

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Most common

Open

$$\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$$

- Δ : output – input

Non-reactive

Reactive $(\Delta\dot{H} = ?)$

Energy Balances: overview

Again, with the mother of all equations:

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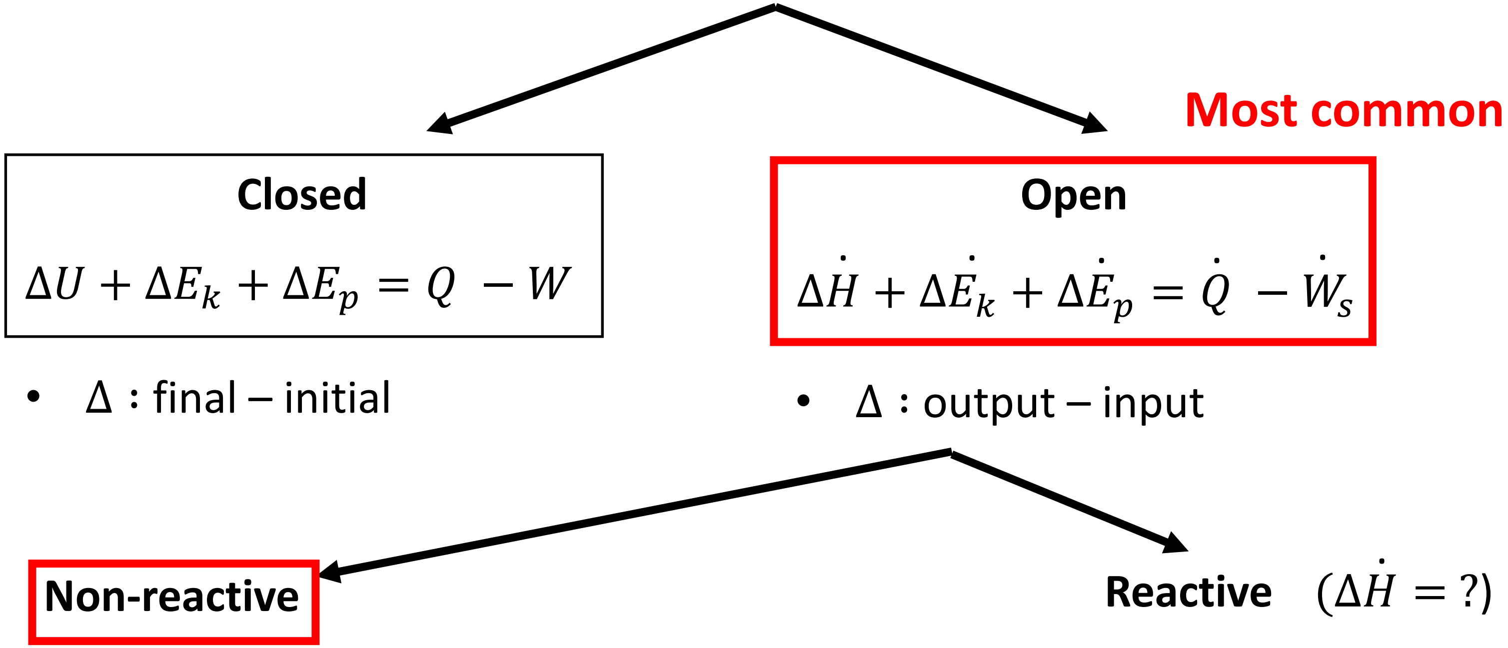

Most common

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Open

$$\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$$

- Δ : output – input

Non-reactive

Reactive $(\Delta\dot{H} = ?)$

Energy Balances: considerations for non-reactive system

Reference state

Arbitrarily designate a reference state for substance at which $\widehat{U}$ or $\widehat{H}$ is declared to equal zero.

Tabulate $\widehat{U}$ or $\widehat{H}$ for the substance relative to the reference state

Energy Balances: Hypothetical Process Paths

In the systems we study, there are internal energy and **enthalpy changes associated with key processes**. We are specifically interested in the following:

- Changes in P at constant T and state of aggregation
- Changes in T at constant P and state of aggregation
- Phase changes at constant T and P
- Mixing of 2 liquids or dissolving of a gas or a solid in a liquid at constant T and P
- Chemical reaction at constant T and P

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- Changes in T at constant P and state of aggregation
- Phase changes at constant T and P
- Mixing of 2 liquids or dissolving of a gas or a solid in a liquid at constant T and P **
- Chemical reaction at constant T and P

The ones you are expected to know for the midterm

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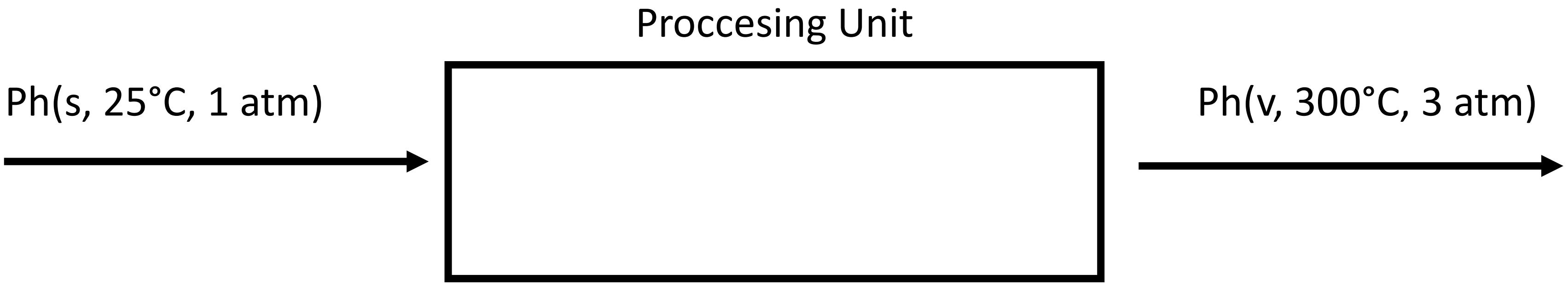
* For the processes and species seen in this class, we can neglect the enthalpy changes associated with changes in P(ressure).

** Enthalpy changes due to mixing were briefly covered in the last lecture. These will not be subject to examination

Energy Balances: Hypothetical Process Paths

Ph = phenol (C6H5OH)



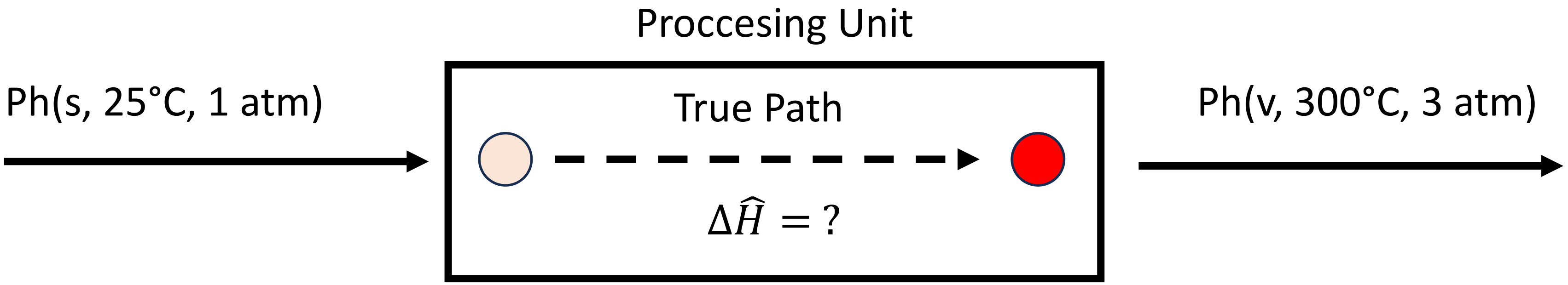
Proccesing Unit

Ph(s, 25°C, 1 atm)

Ph(v, 300°C, 3 atm)

Energy Balances: Hypothetical Process Paths

Ph = phenol (C6H5OH)



Proccesing Unit

Ph(s, 25°C, 1 atm)

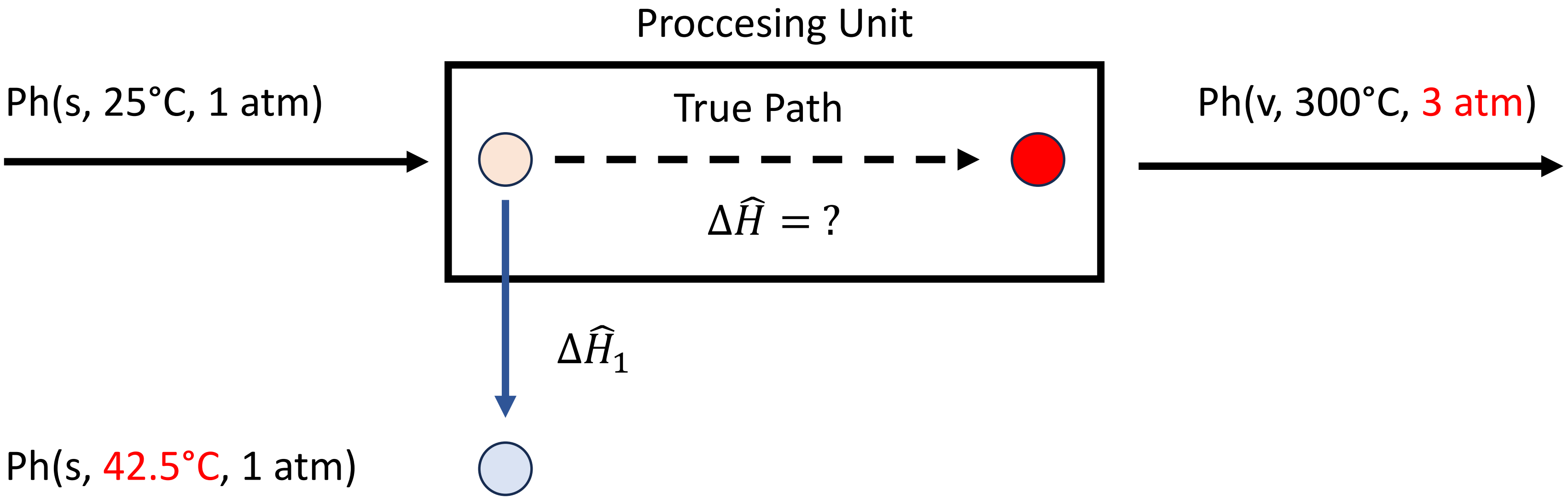
True Path

$\Delta\widehat{H} = ?$

Ph(v, 300°C, 3 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

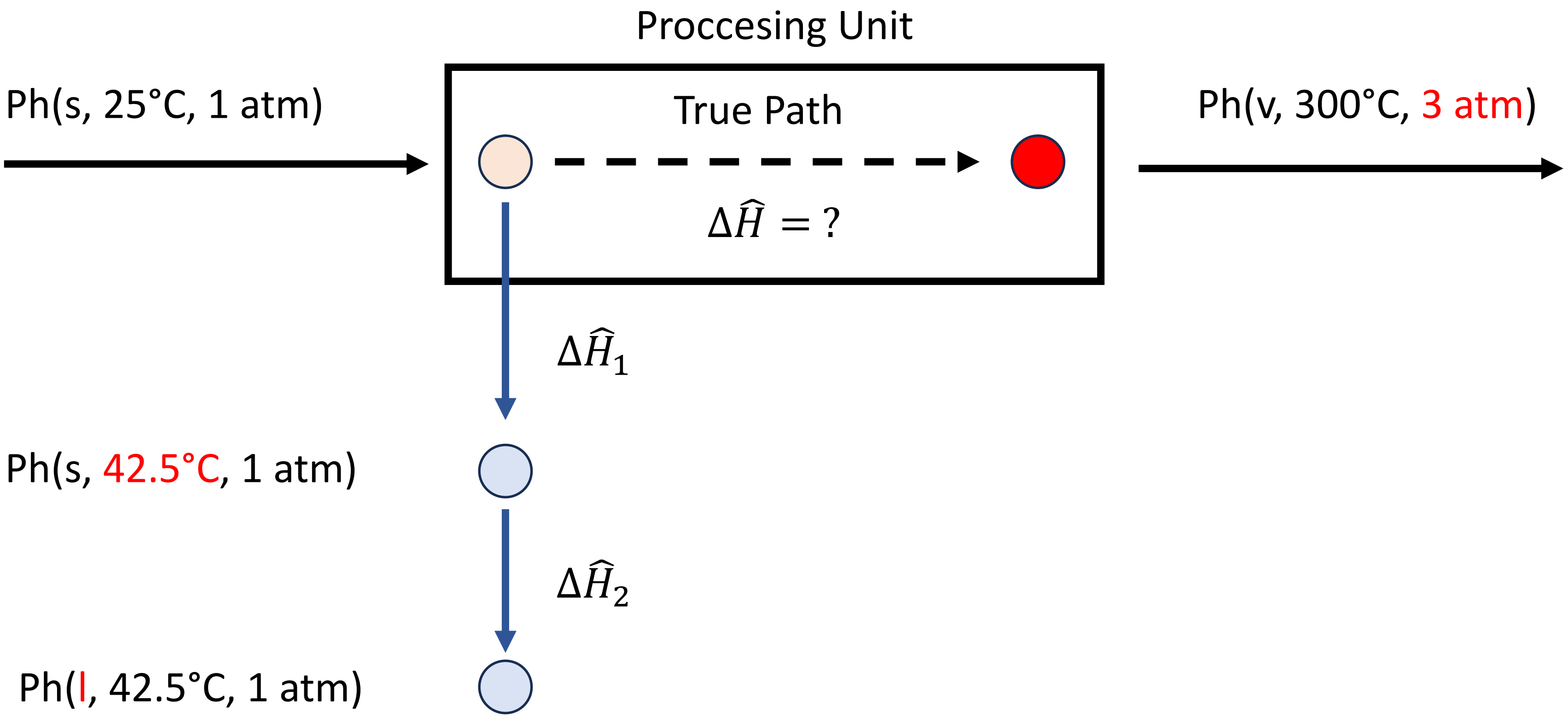
Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

Ph(s, 42.5°C, 1 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\widehat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\widehat{H}_1$

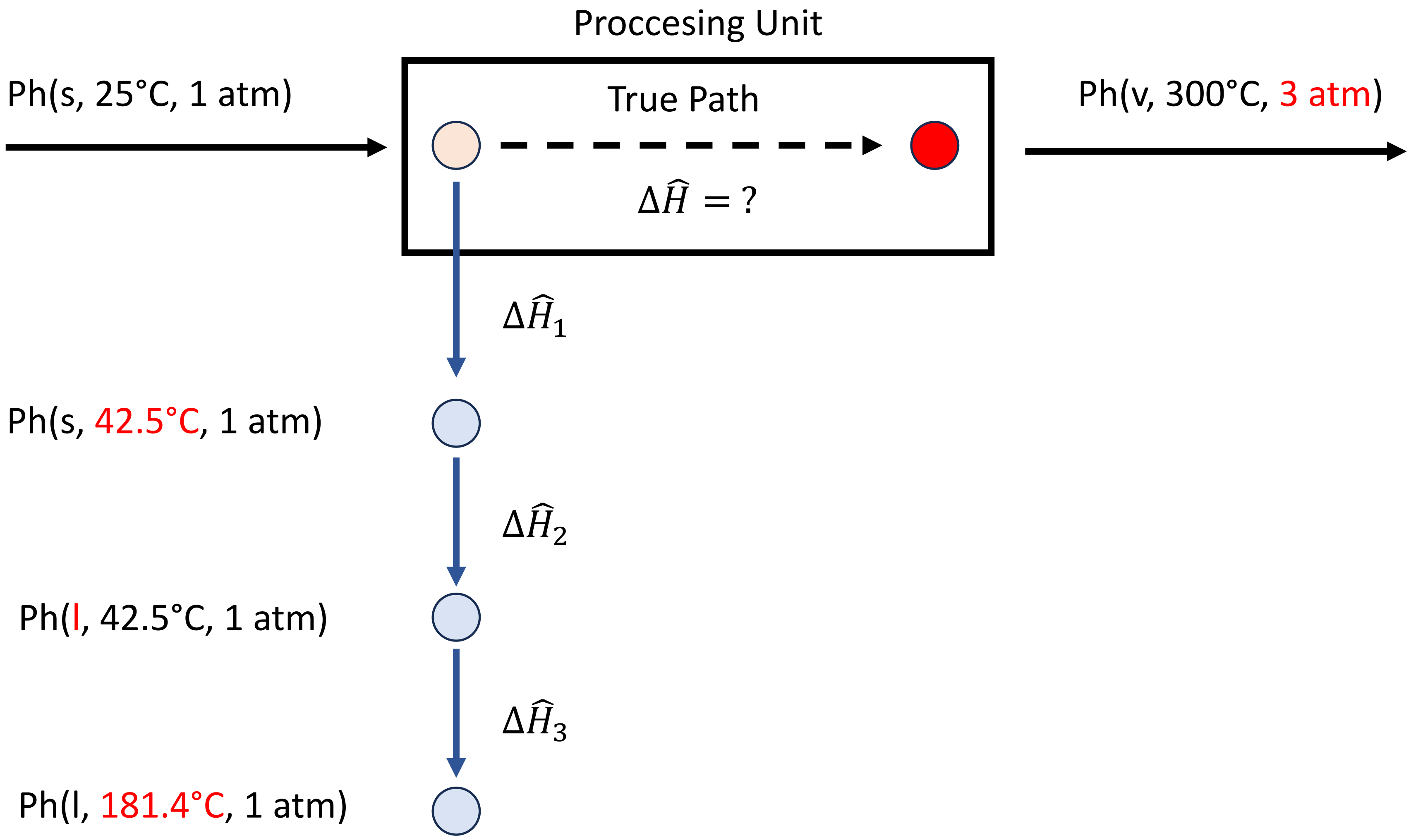
Ph(s, 42.5°C, 1 atm)

$\Delta\widehat{H}_2$

Ph(l, 42.5°C, 1 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

Ph(s, 42.5°C, 1 atm)

$\Delta\hat{H}_2$

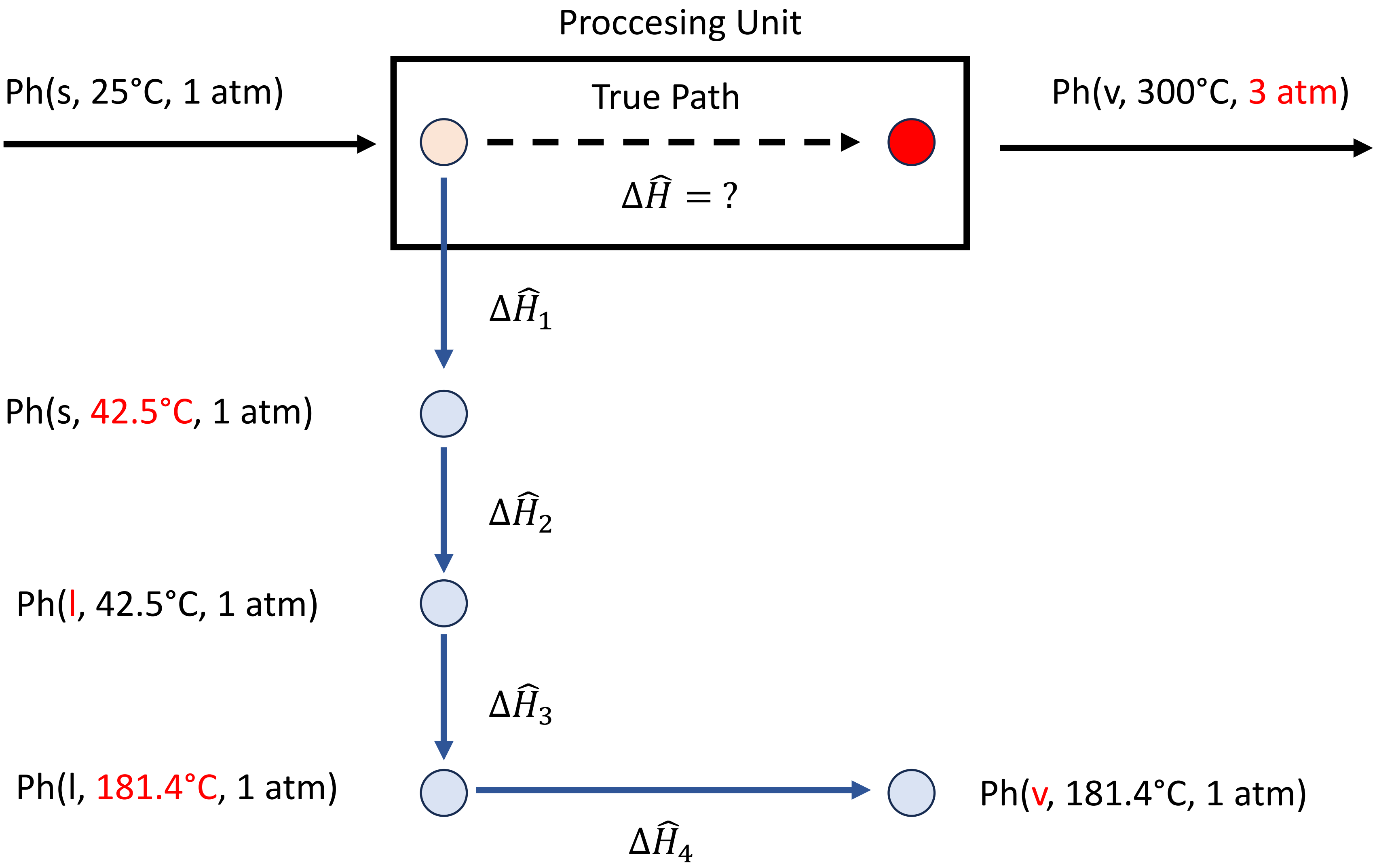
Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

Ph(l, 181.4°C, 1 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

Ph(s, 42.5°C, 1 atm)

$\Delta\hat{H}_2$

Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

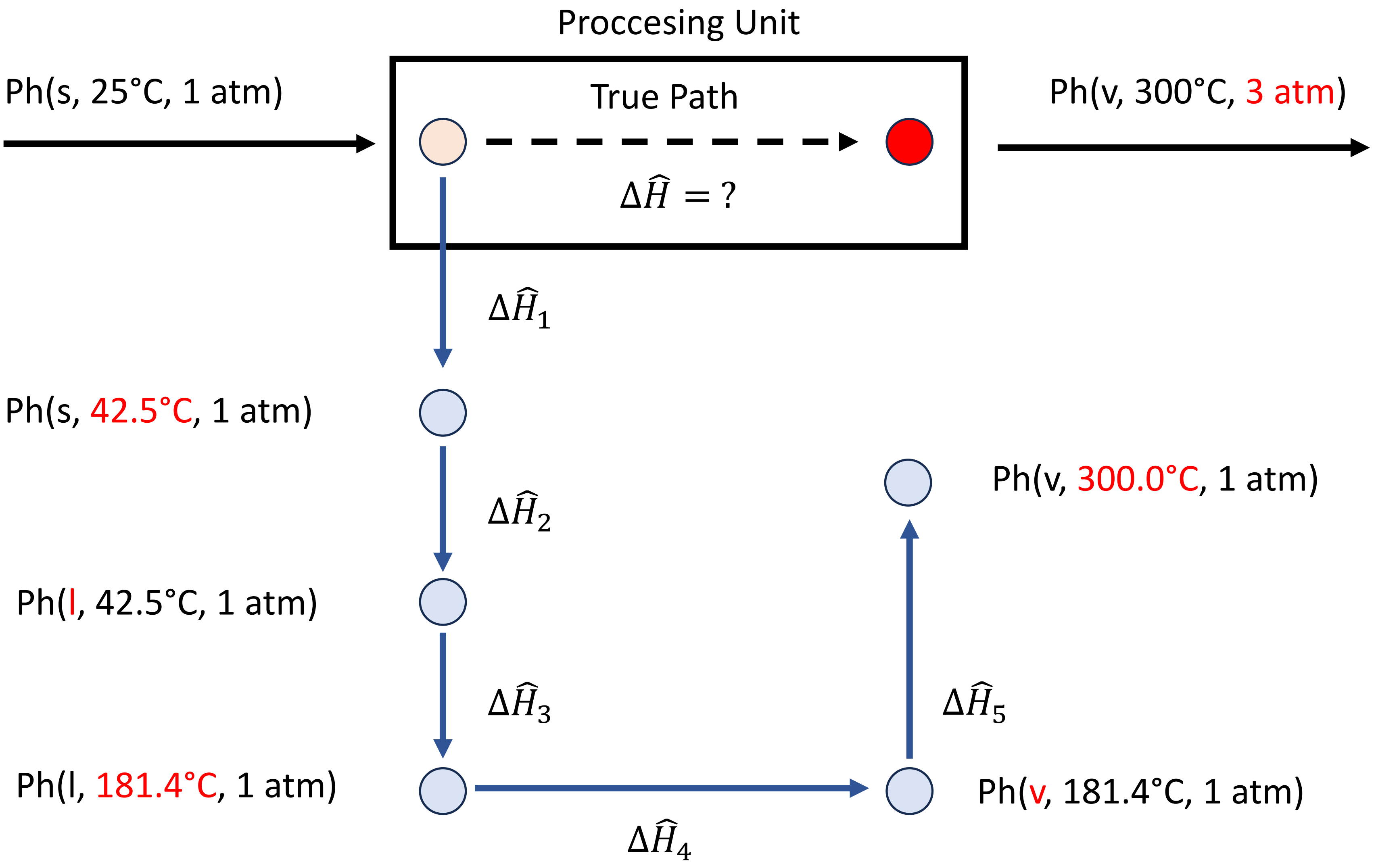
Ph(l, 181.4°C, 1 atm)

$\Delta\hat{H}_4$

Ph(v, 181.4°C, 1 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

Ph(s, 42.5°C, 1 atm)

$\Delta\hat{H}_2$

Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

Ph(l, 181.4°C, 1 atm)

$\Delta\hat{H}_4$

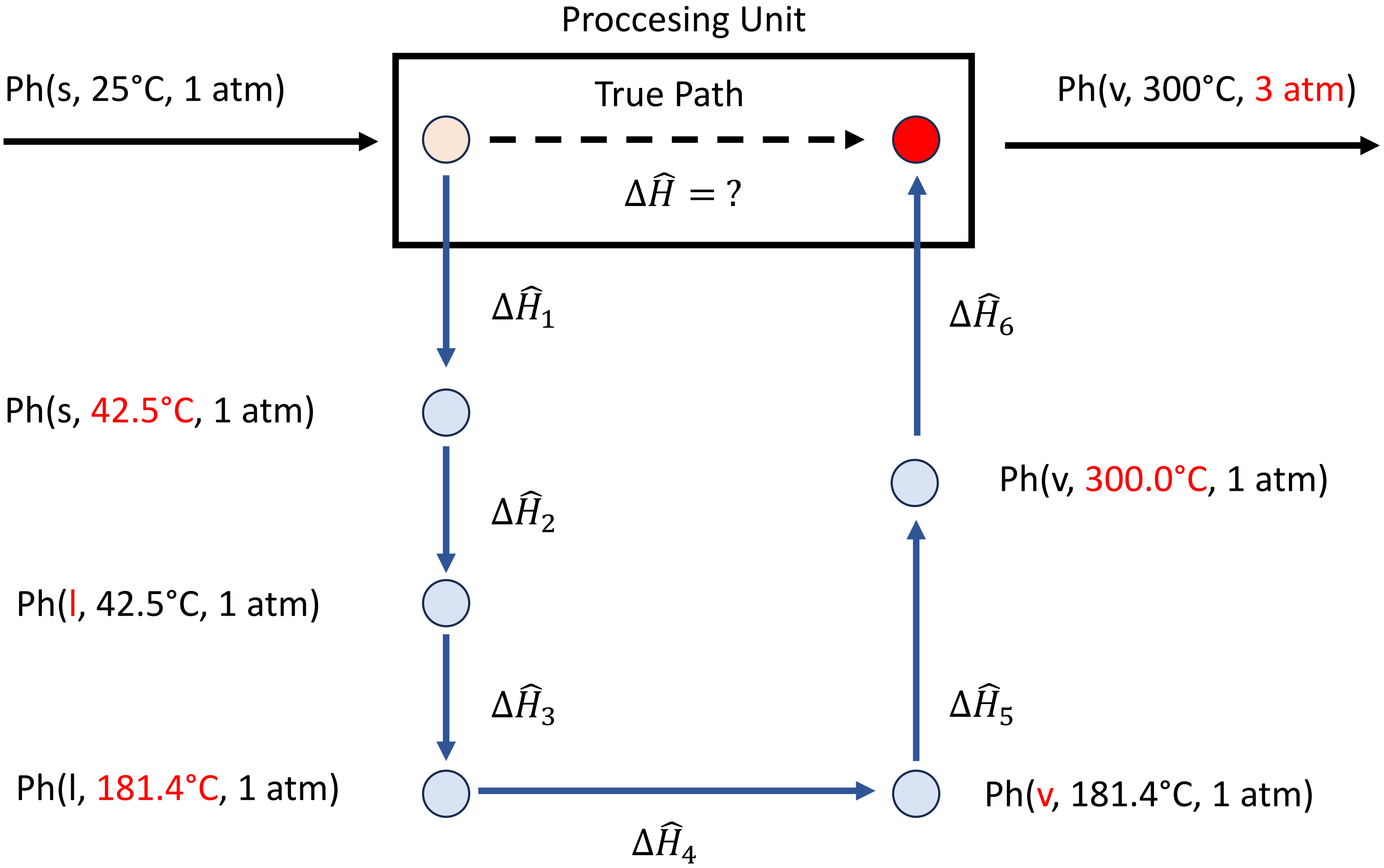
Ph(v, 181.4°C, 1 atm)

$\Delta\hat{H}_5$

Ph(v, 300.0°C, 1 atm)

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

$\Delta\hat{H}_6$

Ph(s, 42.5°C, 1 atm)

Ph(v, 300.0°C, 1 atm)

$\Delta\hat{H}_2$

Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

$\Delta\hat{H}_5$

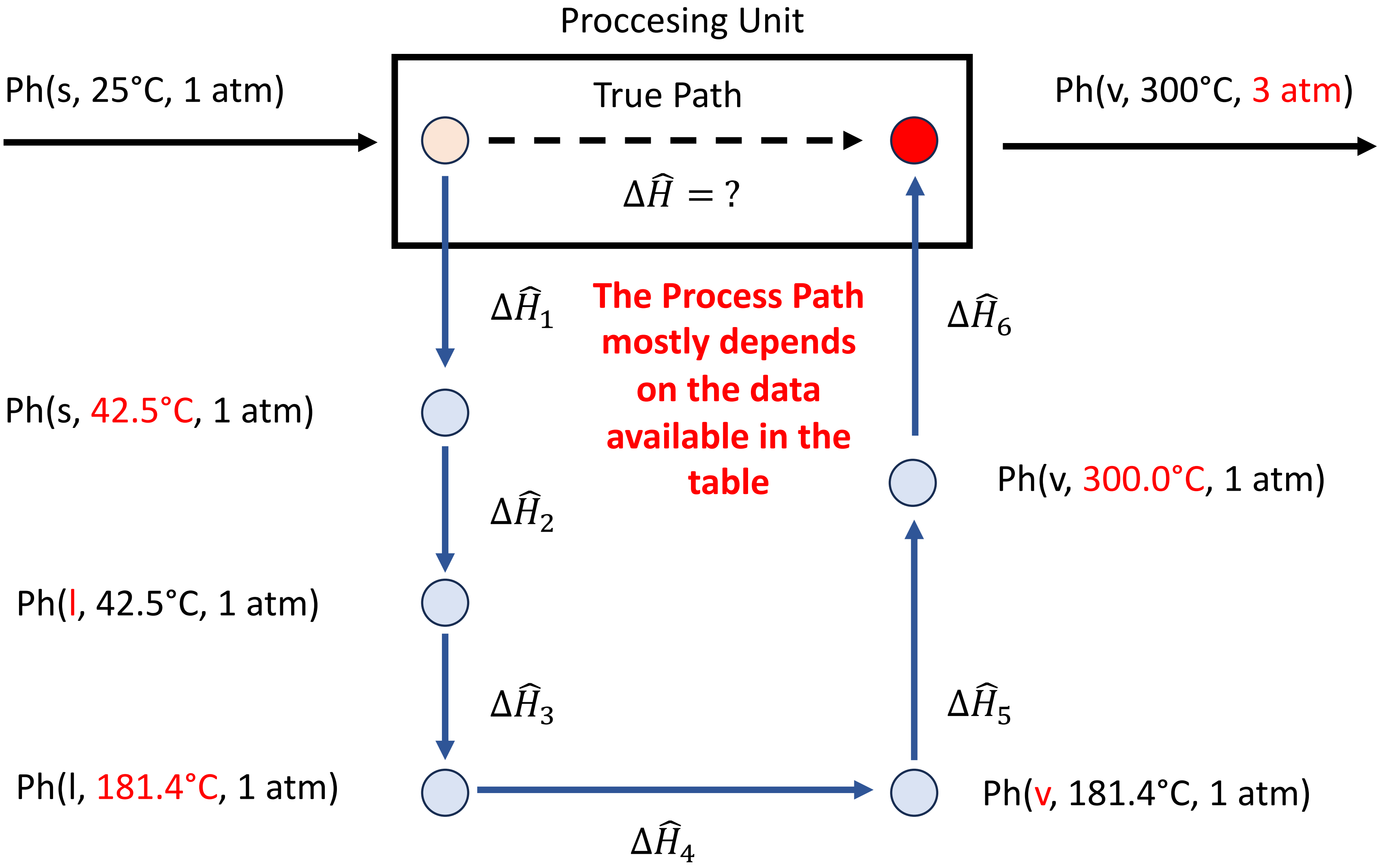
Ph(l, 181.4°C, 1 atm)

Ph(v, 181.4°C, 1 atm)

$\Delta\hat{H}_4$

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

$\Delta\hat{H} = ?$

Ph(v, 300°C, 3 atm)

$\Delta\hat{H}_1$

Ph(s, 42.5°C, 1 atm)

$\Delta\hat{H}_2$

Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

Ph(l, 181.4°C, 1 atm)

$\Delta\hat{H}_4$

Ph(v, 181.4°C, 1 atm)

$\Delta\hat{H}_5$

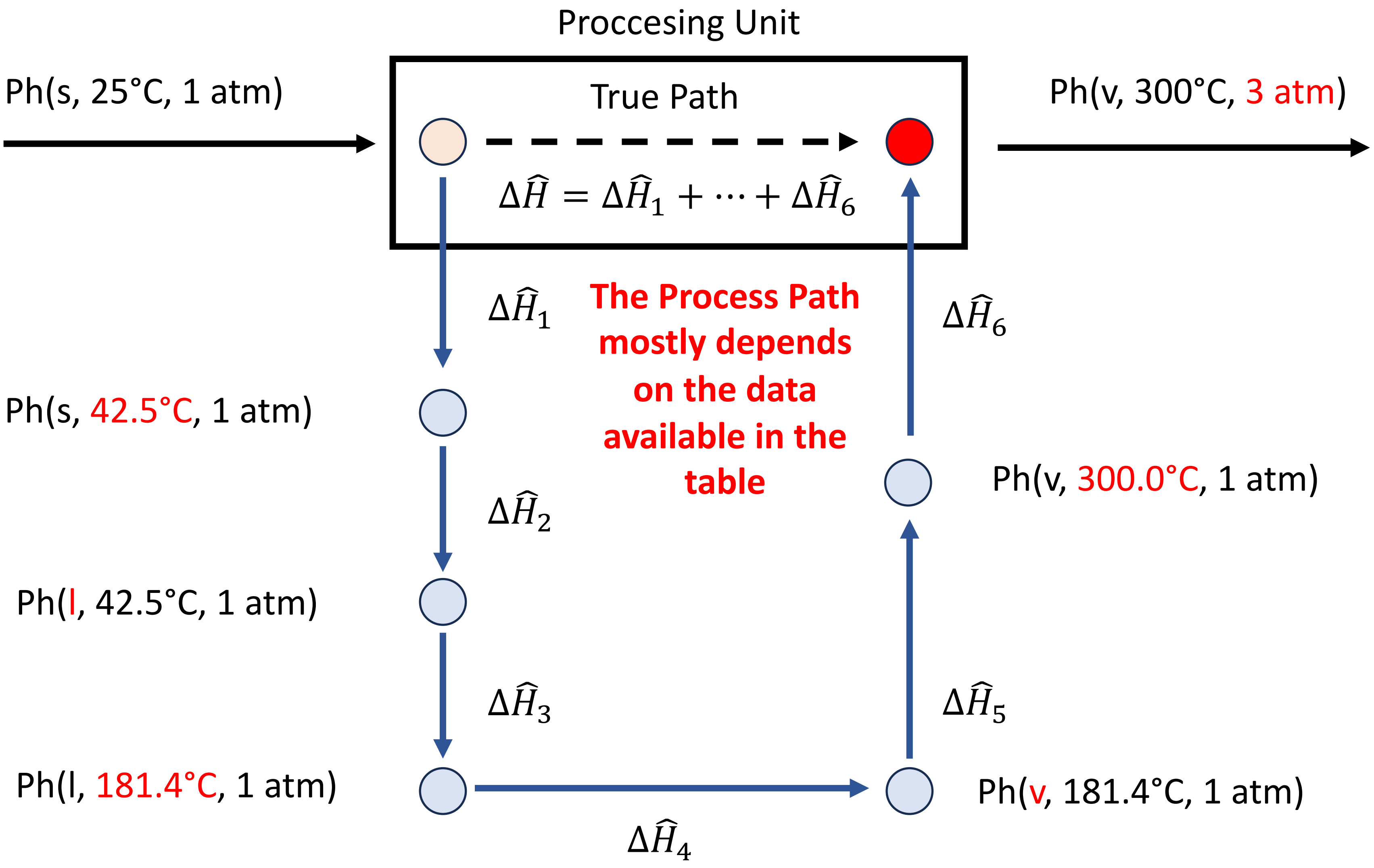
Ph(v, 300.0°C, 1 atm)

$\Delta\hat{H}_6$

The Process Path mostly depends on the data available in the table

Energy Balances: Hypothetical Process Paths

We create a hypothetical process path by changing 1 variable at a time



Proccesing Unit

Ph(s, 25°C, 1 atm)

True Path

Ph(v, 300°C, 3 atm)

$$\Delta\hat{H} = \Delta\hat{H}_1 + \cdots + \Delta\hat{H}_6$$

$\Delta\hat{H}_1$

The Process Path mostly depends on the data available in the table

$\Delta\hat{H}_6$

Ph(s, 42.5°C, 1 atm)

Ph(v, 300.0°C, 1 atm)

$\Delta\hat{H}_2$

Ph(l, 42.5°C, 1 atm)

$\Delta\hat{H}_3$

$\Delta\hat{H}_5$

Ph(l, 181.4°C, 1 atm)

Ph(v, 181.4°C, 1 atm)

$\Delta\hat{H}_4$

Changes in T at constant P and state of aggregation

There are 2 ways to calculate the enthalpy change associated to a change of temperature from T1 (initial temperature) to T2 (final temperature).

Let’s take an example: 15 kmol/min of air is cooled from 430 C to 100C. Calculate the required heat removal rate.

Changes in T at constant P and state of aggregation

There are 2 ways to calculate the enthalpy change associated to a change of temperature from T1 (initial temperature) to T2 (final temperature).

Let’s take an example: 15 kmol/min of air is cooled from 430 C to 100C. Calculate the required heat removal rate.

Most common (harder) way: Integrate the heat capacity formula from table B2

$$\Delta\hat{H}\,(\mathrm{kJ/mol}) = \int_{430^\circ C}^{100^\circ C} C_p(T)\,dT$$

$$C_p(T) = 0.02894 + (0.4147 \times 10^{-5})T + (0.3191 \times 10^{-8})T^2 - (1.965 \times 10^{-12})T^3$$

The integral expands to:

$$\Delta\hat{H} = \left[0.02894(T) + \frac{0.4147 \times 10^{-5}}{2}(T^2) + \frac{0.3191 \times 10^{-8}}{3}(T^3) - \frac{1.965 \times 10^{-12}}{4}(T^4)\right]_{430^\circ C}^{100^\circ C}$$

Plugging in the limits of integration ($T = 100^\circ C$ and $T = 430^\circ C$):

$$\Delta\hat{H} = \left[0.02894(100 - 430) + \frac{0.4147 \times 10^{-5}}{2}(100^2 - 430^2) + \frac{0.3191 \times 10^{-8}}{3}(100^3 - 430^3) - \frac{1.965 \times 10^{-12}}{4}(100^4 - 430^4)\right]$$

This evaluates to:

$$\Delta\hat{H} = (-9.5502 - 0.3627 - 0.0835 + 0.0167)\,\mathrm{kJ/mol} = -9.98\,\mathrm{kJ/mol}.$$

Changes in T at constant P and state of aggregation

There are 2 ways to calculate the enthalpy change associated to a change of temperature from T1 (initial temperature) to T2 (final temperature).

Let’s take an example: 15 kmol/min of air is cooled from 430 C to 100C. Calculate the required heat removal rate.

Easy way (not always possible): Use tabulated enthalpies (with linear interpolation)

Initial

$$\left\{\begin{array}{l}\hat{H}(400\ C) = 11.24\frac{kJ}{mol} \\[2ex] \hat{H}(430\ C) = 11.24 + 0.3\ (14.37\ - 11.24) = 12.17 \\[2ex] \hat{H}(500\ C) = 14.37\frac{kJ}{mol}\end{array}\right.$$

Final

$$\left\{\hat{H}(100\ C) = 2.19\frac{kJ}{mol}\right.$$

$$\Delta\hat{H} = \widehat{H_{final}} - \widehat{H_{initial}}\ = 2.19\ - 12.17 = -9.98\frac{kJ}{mol}$$

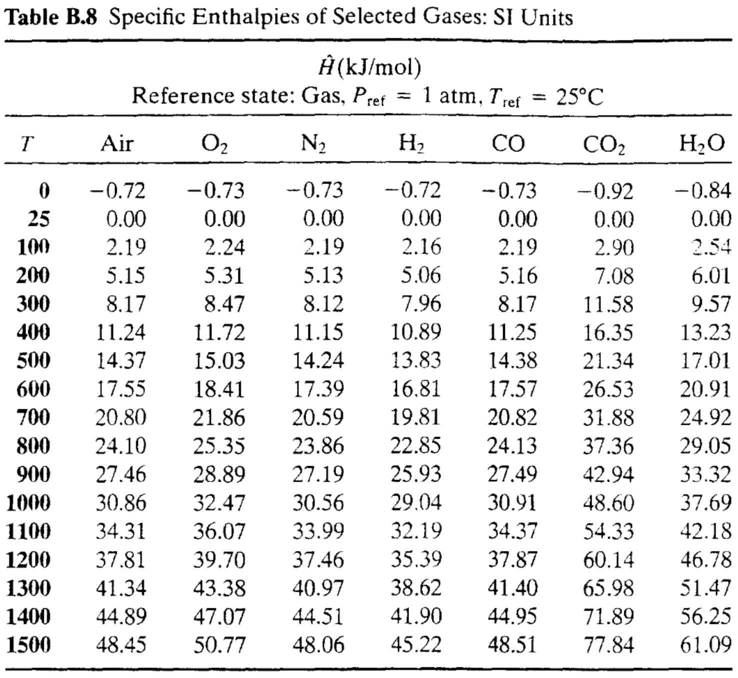


Table B.8 Specific Enthalpies of Selected Gases: SI Units

$\hat{H}$(kJ/mol)
Reference state: Gas, $P_{\text{ref}} = 1$ atm, $T_{\text{ref}} = 25$°C

T	Air	O_2	N_2	H_2	CO	CO_2	H_2O
0	−0.72	−0.73	−0.73	−0.72	−0.73	−0.92	−0.84
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	2.19	2.24	2.19	2.16	2.19	2.90	2.54
200	5.15	5.31	5.13	5.06	5.16	7.08	6.01
300	8.17	8.47	8.12	7.96	8.17	11.58	9.57
400	11.24	11.72	11.15	10.89	11.25	16.35	13.23
500	14.37	15.03	14.24	13.83	14.38	21.34	17.01
600	17.55	18.41	17.39	16.81	17.57	26.53	20.91
700	20.80	21.86	20.59	19.81	20.82	31.88	24.92
800	24.10	25.35	23.86	22.85	24.13	37.36	29.05
900	27.46	28.89	27.19	25.93	27.49	42.94	33.32
1000	30.86	32.47	30.56	29.04	30.91	48.60	37.69
1100	34.31	36.07	33.99	32.19	34.37	54.33	42.18
1200	37.81	39.70	37.46	35.39	37.87	60.14	46.78
1300	41.34	43.38	40.97	38.62	41.40	65.98	51.47
1400	44.89	47.07	44.51	41.90	44.95	71.89	56.25
1500	48.45	50.77	48.06	45.22	48.51	77.84	61.09

Note on interpolating from tabulated values

$$H(T) = H(T_1) + \frac{(T - T_1)}{(T_2 - T_1)} \times [H(T_2) - H(T_1)]$$

Where:

- $H(T)$ is the enthalpy at the desired temperature T,
- T_1 and T_2 are the temperatures between which the interpolation is performed,
- $H(T_1)$ and $H(T_2)$ are the enthalpy values at T_1 and T_2, respectively.

For the example

- $T = 430^\circ C$,
- $T_1 = 400^\circ C$,
- $T_2 = 500^\circ C$,
- $H(T_1) = 11.24\,\mathrm{kJ/mol}$,
- $H(T_2) = 14.37\,\mathrm{kJ/mol}$.

$$H(430^\circ C) = 11.24 + \frac{(430 - 400)}{(500 - 400)} \times (14.37 - 11.24)$$

$$H(430^\circ C) = 11.24 + 0.30 \times 3.13$$

$$H(430^\circ C) = 11.24 + 0.939 = 12.17\,\mathrm{kJ/mol}.$$

Phase changes at constant T and P

Latent Heat:
The specific enthalpy change ($\Delta\hat{H}$) during a phase transition (e.g., melting, vaporization) at constant temperature and pressure is called the **latent heat**. It is distinct from **sensible heat**, which involves temperature changes without a phase change (that we have just seen).

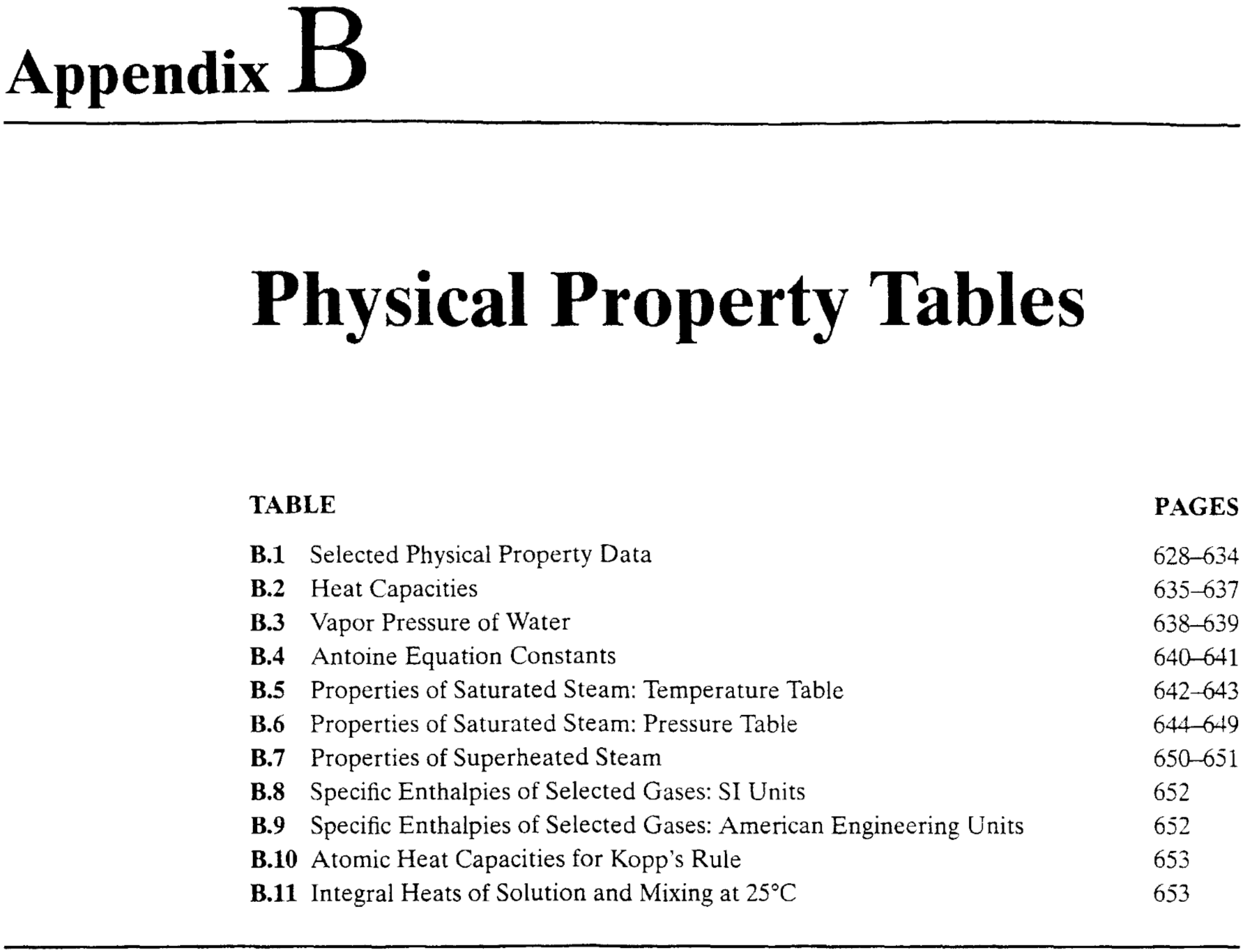
Heat of Vaporization (from liquid to gas):

- For water at 100°C and 1 atm, the latent heat of vaporization is 40.6 kJ/mol.
- The **heat of condensation** is the negative of the heat of vaporization (-40.6 kJ/mol) because condensation is the reverse process of vaporization.

Heat of Fusion (from solid to liquid):
The **heat of fusion** (or melting) is the enthalpy difference between the solid and liquid forms of a substance at a given T and P.
Similarly, the **heat of solidification** is the negative of the heat of fusion.

Tabulated Values:
Standard heats of fusion and vaporization are typically provided at the melting or boiling points of a substance at 1 atm. **These values can be found in Table B1 (more on this later)**

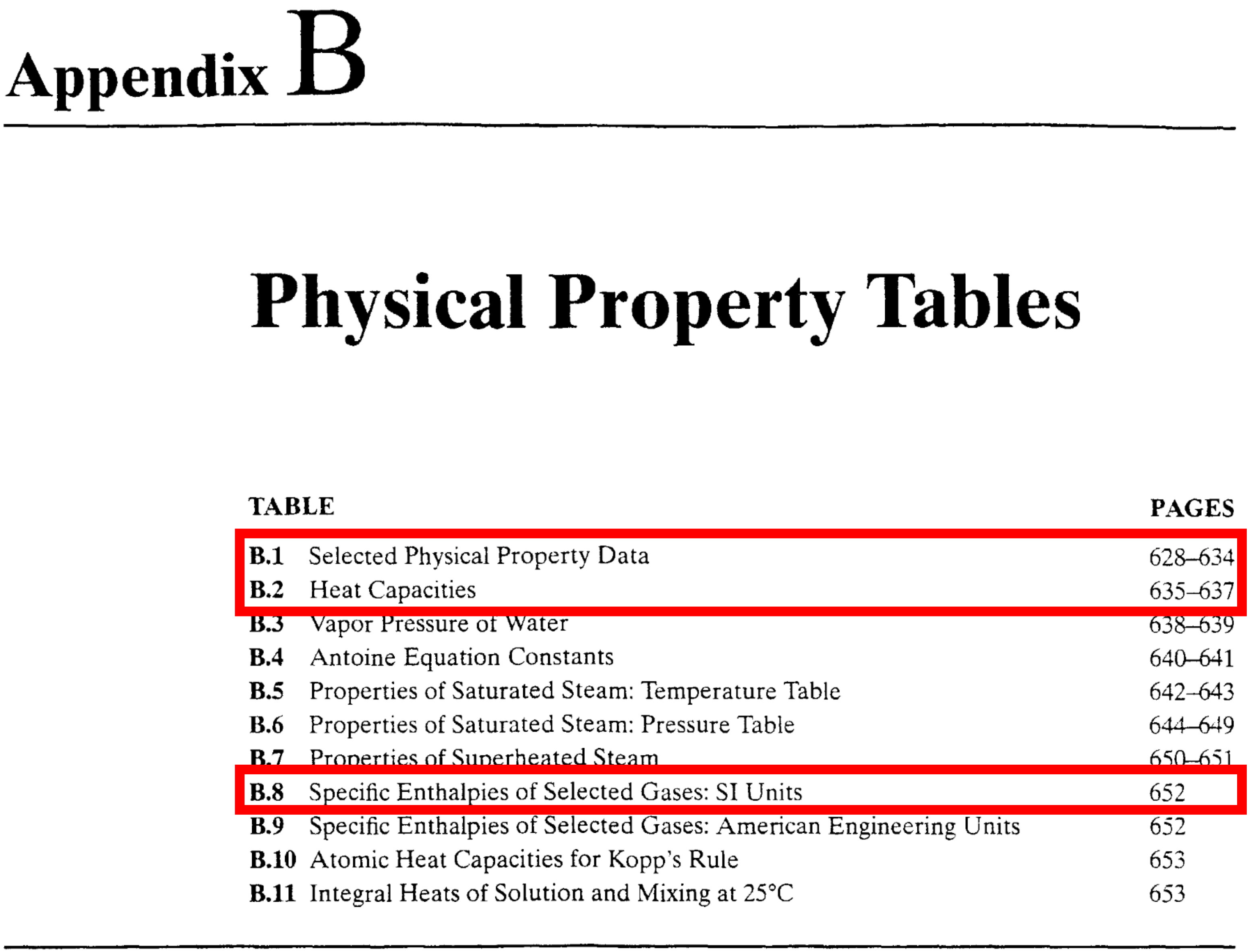
Know Thy Tables



Appendix B

Physical Property Tables

Know Thy Tables

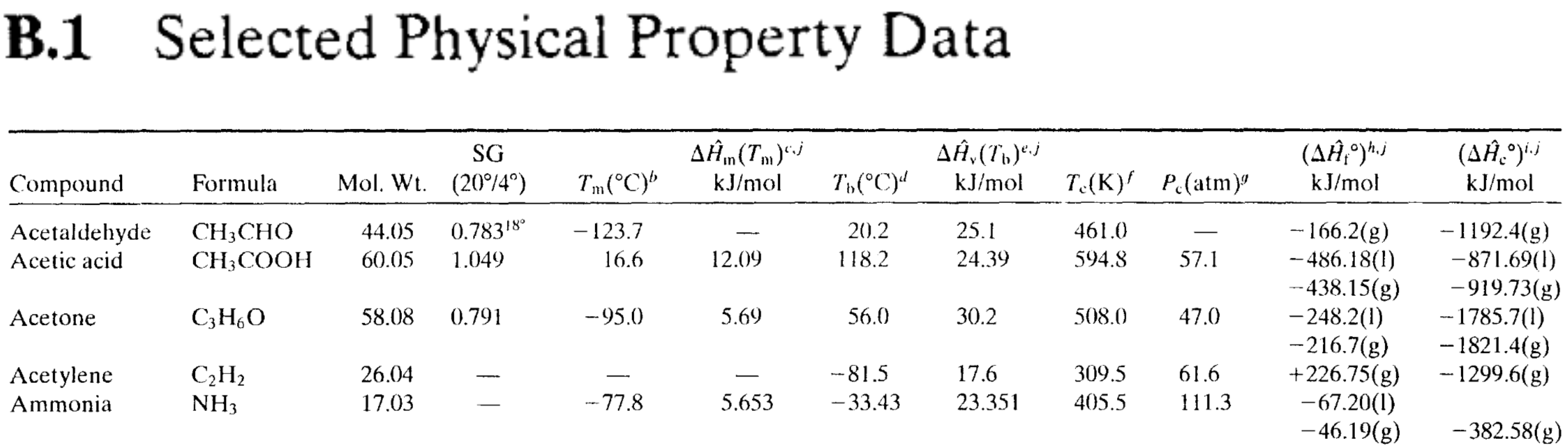


Appendix B

Physical Property Tables

TABLE **PAGES**

Know Thy Tables

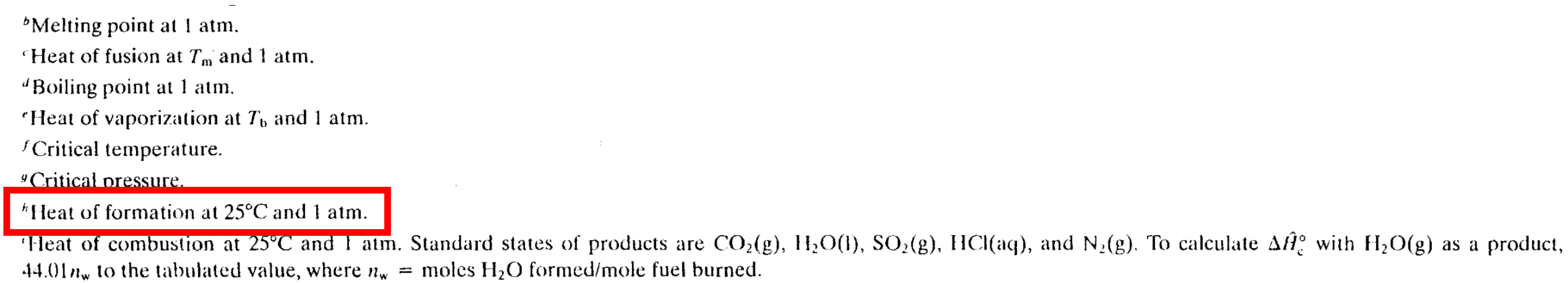


B.1 Selected Physical Property Data

Compound	Formula	Mol. Wt.	SG (20°/4°)	T_m(°C)[b]	$\Delta\hat{H}_m(T_m)$[c,j] kJ/mol	T_b(°C)[d]	$\Delta\hat{H}_v(T_b)$[e,j] kJ/mol	T_c(K)[f]	P_c(atm)[g]	$(\Delta\hat{H}_f^\circ)$[h,j] kJ/mol	$(\Delta\hat{H}_c^\circ)$[i,j] kJ/mol
Acetaldehyde	CH_3CHO	44.05	$0.783^{18°}$	−123.7	—	20.2	25.1	461.0	—	−166.2(g)	−1192.4(g)
Acetic acid	CH_3COOH	60.05	1.049	16.6	12.09	118.2	24.39	594.8	57.1	−486.18(l) −438.15(g)	−871.69(l) −919.73(g)
Acetone	C_3H_6O	58.08	0.791	−95.0	5.69	56.0	30.2	508.0	47.0	−248.2(l) −216.7(g)	−1785.7(l) −1821.4(g)
Acetylene	C_2H_2	26.04	—	—	—	−81.5	17.6	309.5	61.6	+226.75(g)	−1299.6(g)
Ammonia	NH_3	17.03	—	−77.8	5.653	−33.43	23.351	405.5	111.3	−67.20(l) −46.19(g)	−382.58(g)

(latent) heat of fusion/melting H_m : specific enthalpy from solid to liquid stage = - latent heat of solidification

(latent) heat of vaporization H_v: specific enthalpy change from liquid to gaseous stage = - latent heat of condensation



[b] Melting point at 1 atm.

[c] Heat of fusion at T_m and 1 atm.

[d] Boiling point at 1 atm.

[e] Heat of vaporization at T_b and 1 atm.

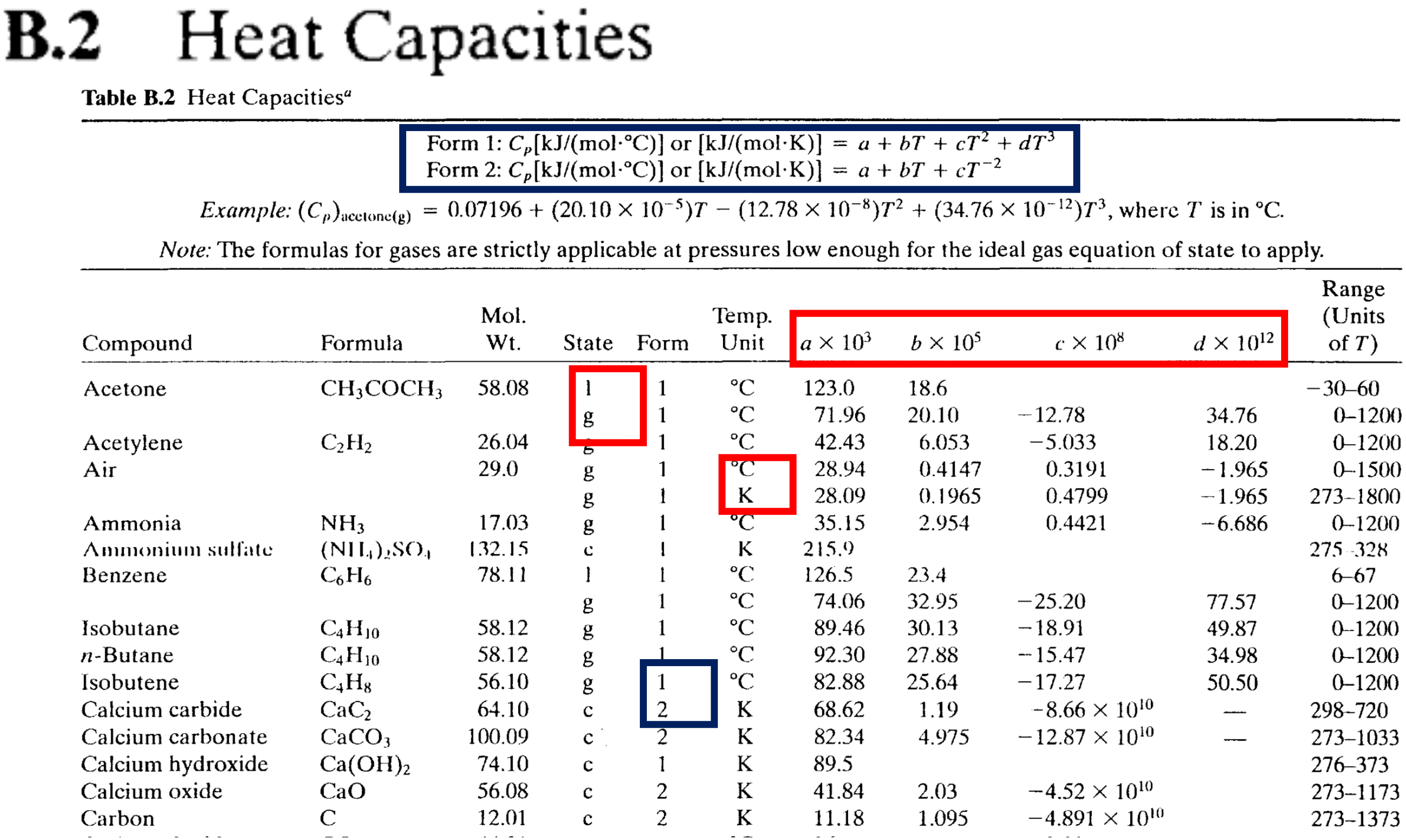
[f] Critical temperature.

[g] Critical pressure.

[h] Heat of formation at 25°C and 1 atm.

[i] Heat of combustion at 25°C and 1 atm. Standard states of products are $CO_2(g)$, $H_2O(l)$, $SO_2(g)$, $HCl(aq)$, and $N_2(g)$. To calculate $\Delta\hat{H}_c^\circ$ with $H_2O(g)$ as a product, $44.01 n_w$ to the tabulated value, where n_w = moles H_2O formed/mole fuel burned.

Know Thy Tables



B.2 Heat Capacities

Table B.2 Heat Capacities[a]

Form 1: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^2 + dT^3$
Form 2: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^{-2}$

Example: $(C_p)_{\text{acetone(g)}} = 0.07196 + (20.10 \times 10^{-5})T - (12.78 \times 10^{-8})T^2 + (34.76 \times 10^{-12})T^3$, where T is in °C.

Note: The formulas for gases are strictly applicable at pressures low enough for the ideal gas equation of state to apply.

Compound	Formula	Mol. Wt.	State	Form	Temp. Unit	$a \times 10^3$	$b \times 10^5$	$c \times 10^8$	$d \times 10^{12}$	Range (Units of T)
Acetone	CH_3COCH_3	58.08	l	1	°C	123.0	18.6			−30–60
			g	1	°C	71.96	20.10	−12.78	34.76	0–1200
Acetylene	C_2H_2	26.04	g	1	°C	42.43	6.053	−5.033	18.20	0–1200
Air		29.0	g	1	°C	28.94	0.4147	0.3191	−1.965	0–1500
			g	1	K	28.09	0.1965	0.4799	−1.965	273–1800
Ammonia	NH_3	17.03	g	1	°C	35.15	2.954	0.4421	−6.686	0–1200
Ammonium sulfate	$(NH_4)_2SO_4$	132.15	c	1	K	215.9				275–328
Benzene	C_6H_6	78.11	l	1	°C	126.5	23.4			6–67
			g	1	°C	74.06	32.95	−25.20	77.57	0–1200
Isobutane	C_4H_{10}	58.12	g	1	°C	89.46	30.13	−18.91	49.87	0–1200
n-Butane	C_4H_{10}	58.12	g	1	°C	92.30	27.88	−15.47	34.98	0–1200
Isobutene	C_4H_8	56.10	g	1	°C	82.88	25.64	−17.27	50.50	0–1200
Calcium carbide	CaC_2	64.10	c	2	K	68.62	1.19	-8.66×10^{10}	—	298–720
Calcium carbonate	$CaCO_3$	100.09	c	2	K	82.34	4.975	-12.87×10^{10}	—	273–1033
Calcium hydroxide	$Ca(OH)_2$	74.10	c	1	K	89.5				276–373
Calcium oxide	CaO	56.08	c	2	K	41.84	2.03	-4.52×10^{10}		273–1173
Carbon	C	12.01	c	2	K	11.18	1.095	-4.891×10^{10}		273–1373

Know Thy Tables

Some specific enthalpies are already computed for you → Gain of time during the exam!

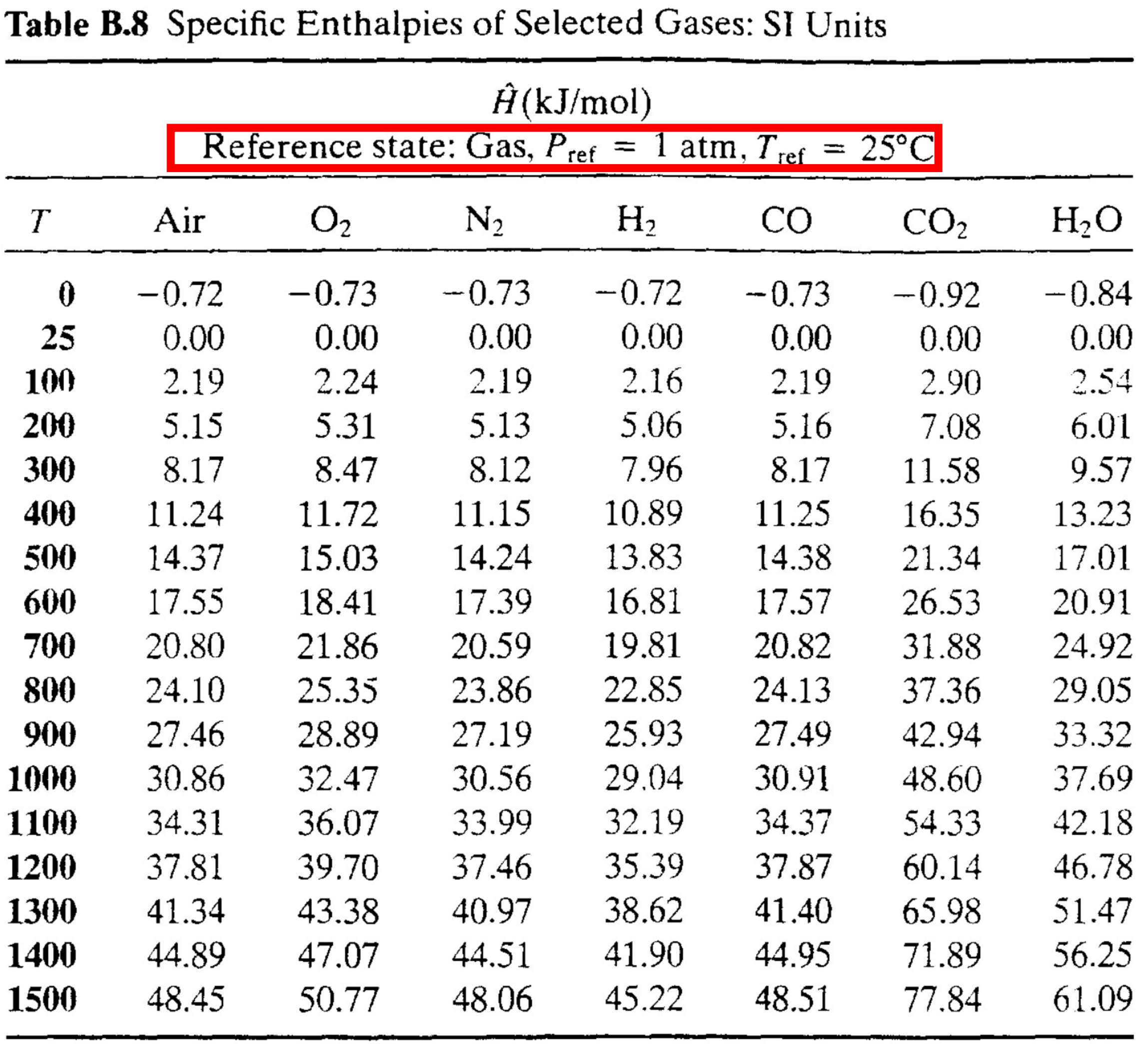


Table B.8 Specific Enthalpies of Selected Gases: SI Units

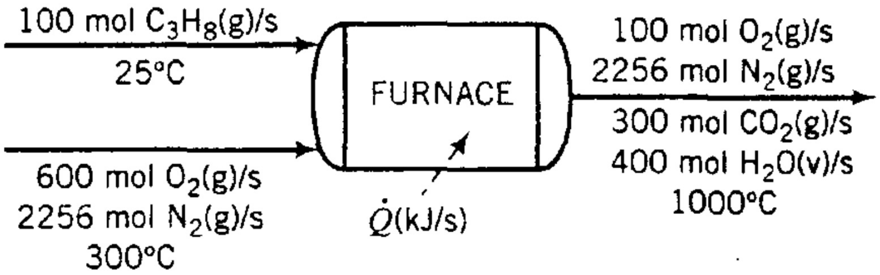
$\hat{H}$(kJ/mol)

Reference state: Gas, $P_{\text{ref}} = 1$ atm, $T_{\text{ref}} = 25°\text{C}$

T	Air	O_2	N_2	H_2	CO	CO_2	H_2O
0	−0.72	−0.73	−0.73	−0.72	−0.73	−0.92	−0.84
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	2.19	2.24	2.19	2.16	2.19	2.90	2.54
200	5.15	5.31	5.13	5.06	5.16	7.08	6.01
300	8.17	8.47	8.12	7.96	8.17	11.58	9.57
400	11.24	11.72	11.15	10.89	11.25	16.35	13.23
500	14.37	15.03	14.24	13.83	14.38	21.34	17.01
600	17.55	18.41	17.39	16.81	17.57	26.53	20.91
700	20.80	21.86	20.59	19.81	20.82	31.88	24.92
800	24.10	25.35	23.86	22.85	24.13	37.36	29.05
900	27.46	28.89	27.19	25.93	27.49	42.94	33.32
1000	30.86	32.47	30.56	29.04	30.91	48.60	37.69
1100	34.31	36.07	33.99	32.19	34.37	54.33	42.18
1200	37.81	39.70	37.46	35.39	37.87	60.14	46.78
1300	41.34	43.38	40.97	38.62	41.40	65.98	51.47
1400	44.89	47.07	44.51	41.90	44.95	71.89	56.25
1500	48.45	50.77	48.06	45.22	48.51	77.84	61.09

Energy Balances: Heat of Formation vs Heat of Reaction

$$C_3H_8(g) + 5\,O_2(g) \longrightarrow 3\,CO_2(g) + 4\,H_2O(l): \quad \Delta\hat{H}_r^\circ = -2220\ \text{kJ/mol}$$



$$\dot{\xi} = \frac{|(\dot{n}_{C_3H_8})_{out} - (\dot{n}_{C_3H_8})_{in}|}{|\nu_{C_3H_8}|}$$

$$= \frac{|0 - 100|\ \text{mol/s}}{1} = 100\ \text{mol/s}$$

Heat of reaction method

$$\boxed{\Delta\dot{H} = \dot{\xi}\,\Delta\hat{H}_r^\circ + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} \quad \text{(single reaction)}}$$

References given in terms of **molecules**

References: $C_3H_8(g)$, $O_2(g)$, $N_2(g)$, $CO_2(g)$, $H_2O(l)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	0	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

Heat of formation method

$$\boxed{\Delta H = \sum_{out} n_i\widehat{H_i} - \sum_{in} n_i\widehat{H_i}}$$

References given in terms of **elements**

References: $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C and 1 atm

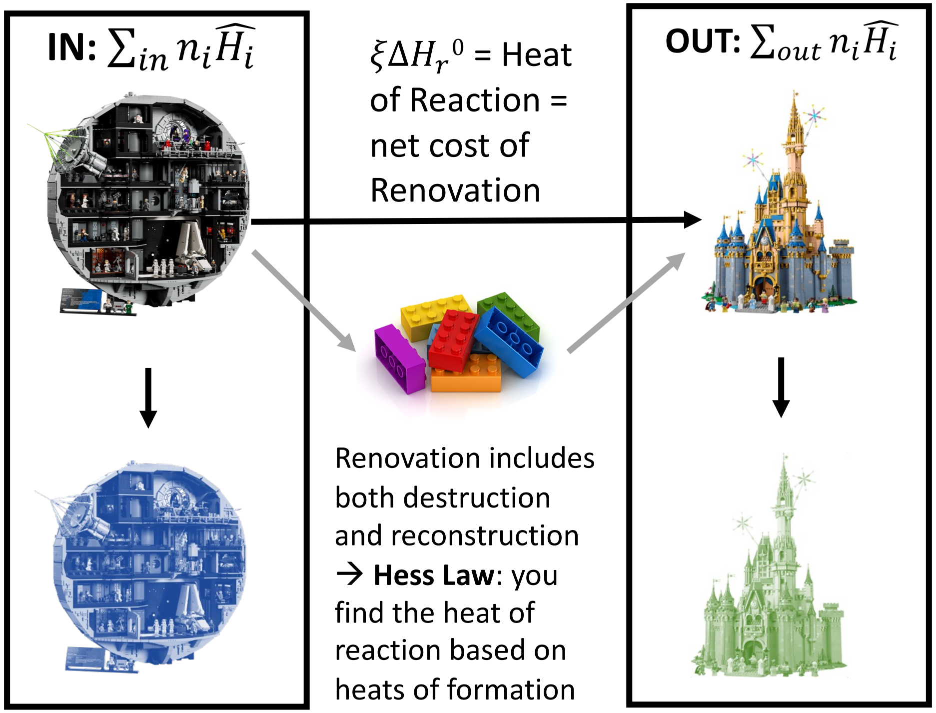
Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	$\hat{H}_1$	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

Energy Balances: Heat of Formation vs Heat of Reaction

The Remodelor: Heat of reaction method

$$\Delta \dot{H} = \dot{\xi}\,\Delta \hat{H}_r^\circ + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} \quad \text{(single reaction)}$$

References given in terms of **molecules**



IN: $\sum_{in} n_i \widehat{H_i}$

$\xi \Delta H_r{}^0$ = Heat of Reaction = net cost of Renovation

OUT: $\sum_{out} n_i \widehat{H_i}$

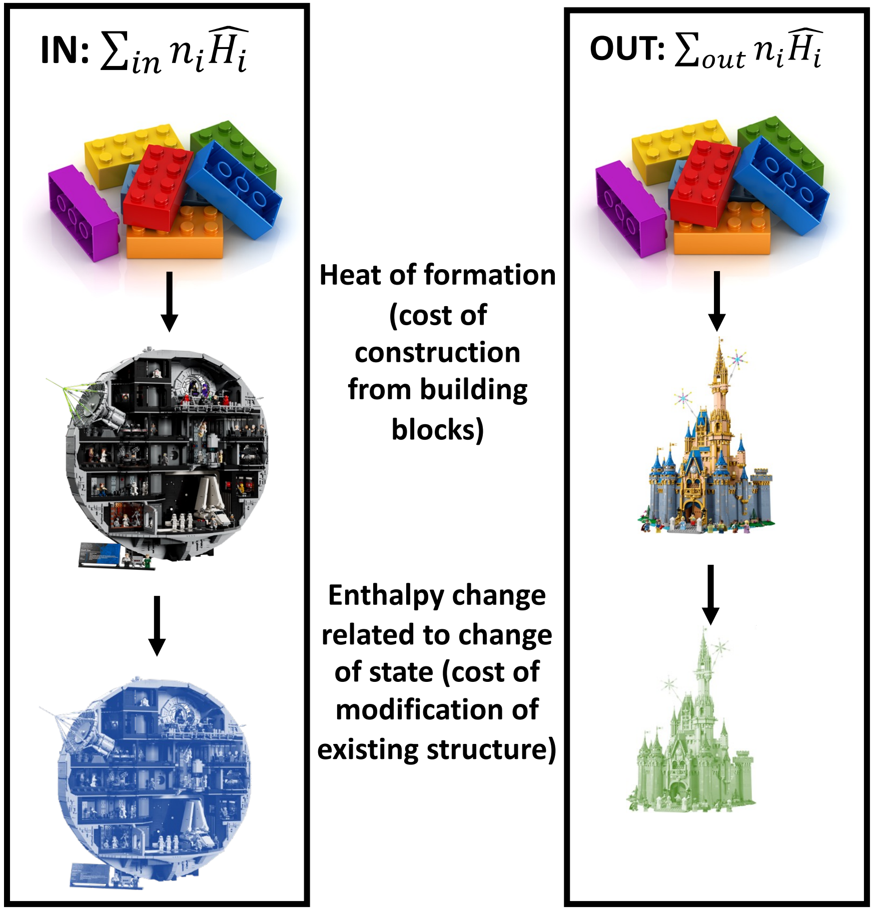
Renovation includes both destruction and reconstruction → **Hess Law**: you find the heat of reaction based on heats of formation

Total Enthalpy = (Cost of the Renovation Job) + (Temperature adjustments)

The Deconstructor: Heat of formation method

$$\Delta H = \sum_{out} n_i \widehat{H_i} - \sum_{in} n_i \widehat{H_i}$$

References given in terms of **elements**



IN: $\sum_{in} n_i \widehat{H_i}$

OUT: $\sum_{out} n_i \widehat{H_i}$

Heat of formation (cost of construction from building blocks)

Enthalpy change related to change of state (cost of modification of existing structure)

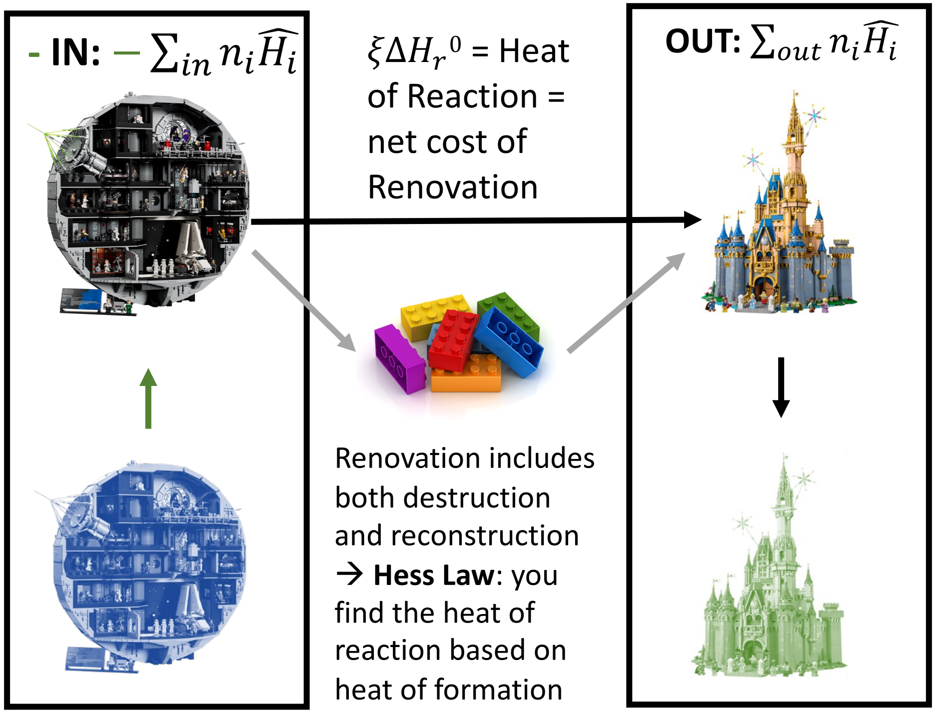
Total Enthalpy = (Value of Castle from Scratch) - (Value of Death Star from Scratch)

Energy Balances: Note on Sign

The Remodelor: Heat of reaction method

$$\Delta\dot{H} = \dot{\xi}\,\Delta\hat{H}_r^\circ + \sum \dot{n}_{\text{out}}\hat{H}_{\text{out}} - \sum \dot{n}_{\text{in}}\hat{H}_{\text{in}} \quad \text{(single reaction)}$$

References given in terms of **molecules**



- **IN:** $-\sum_{in} n_i\widehat{H_i}$

$\xi\Delta H_r{}^0$ = Heat of Reaction = net cost of Renovation

OUT: $\sum_{out} n_i\widehat{H_i}$

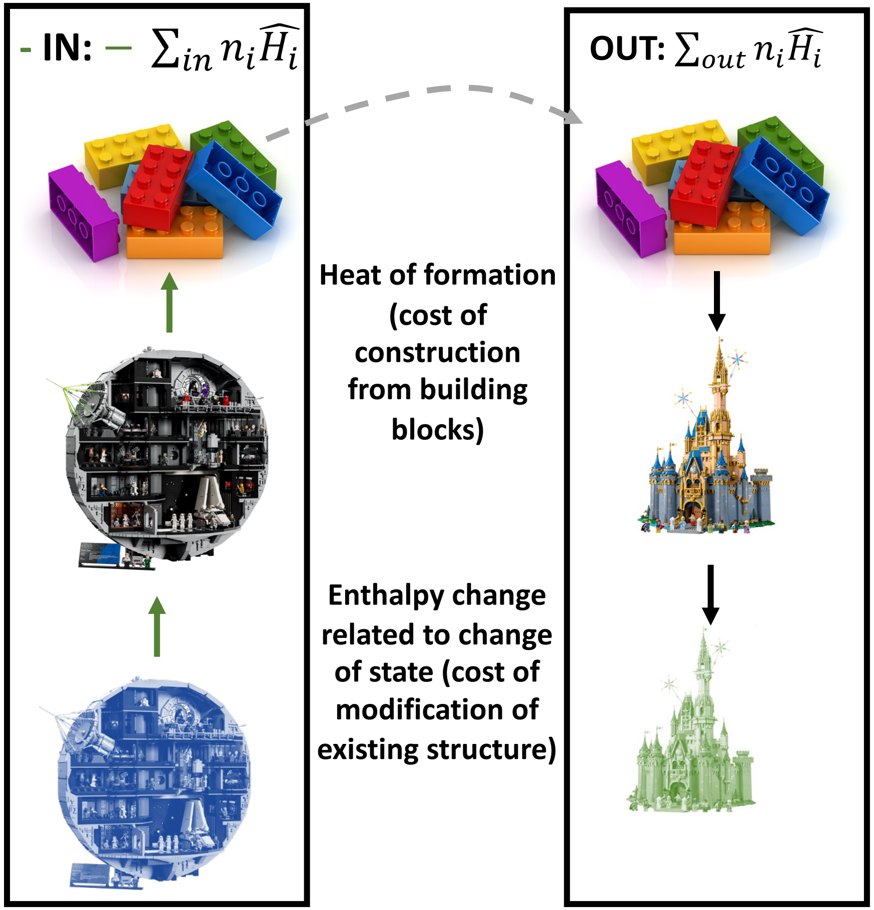
Renovation includes both destruction and reconstruction → **Hess Law**: you find the heat of reaction based on heat of formation

Total Enthalpy = (Cost of the Renovation Job) + (Temperature adjustments)

The Deconstructor: Heat of formation method

$$\Delta H = \sum_{out} n_i\widehat{H_i} - \sum_{in} n_i\widehat{H_i}$$

References given in terms of **elements**



- **IN:** $-\sum_{in} n_i\widehat{H_i}$

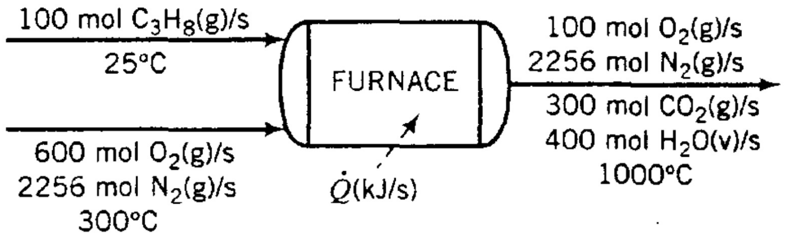
OUT: $\sum_{out} n_i\widehat{H_i}$

Heat of formation (cost of construction from building blocks)

Enthalpy change related to change of state (cost of modification of existing structure)

Total Enthalpy = (Value of Castle from Scratch) - (Value of Death Star from Scratch)

Energy Balances: Heat of Reaction Approach



$$\Delta \hat{H}_r^\circ = -2220 \text{ kJ/mol} \qquad \dot{\xi} = 100 \text{ mol/s}$$

Know your tables!

Heat of reaction method

References: C_3H_8(g), O_2(g), N_2(g), CO_2(g), H_2O(l) at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	0	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

$$\hat{H}_2 = \Delta\hat{H} \text{ for } O_2(25°C) \rightarrow O_2(300°C) = 8.47 \text{ kJ/mol (from Table B.8)}$$

$$\hat{H}_3 = 8.12 \text{ kJ/mol}$$

$$\hat{H}_4 = 32.47 \text{ kJ/mol}$$

$$\hat{H}_6 = 48.60 \text{ kJ/mol}$$

$$\hat{H}_7 = \Delta\hat{H} \text{ for } H_2O(\text{l}, 25°C) \rightarrow H_2O(\text{g}, 1000°C)$$

$$\int_{25°C}^{100°C} C_{pl}\, dT + \Delta\hat{H}_v(100°C) + \int_{100°C}^{1000°C} C_{pv}\, dT.$$

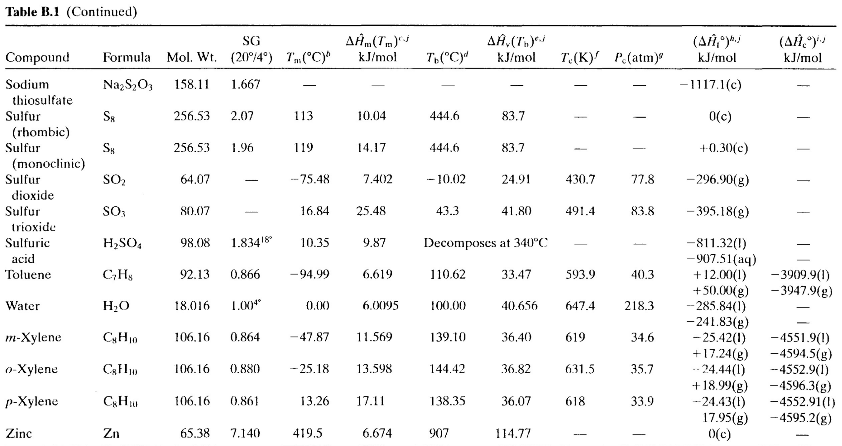


Table B.1 (Continued)

Compound	Formula	Mol. Wt.	SG (20°/4°)	T_m(°C)[b]	$\Delta\hat{H}_m(T_m)$[c,j] kJ/mol	T_b(°C)[d]	$\Delta\hat{H}_v(T_b)$[e,j] kJ/mol	T_c(K)[f]	P_c(atm)[g]	$(\Delta\hat{H}_f^\circ)$[h,j] kJ/mol	$(\Delta\hat{H}_c^\circ)$[i,j] kJ/mol
Sodium thiosulfate	$Na_2S_2O_3$	158.11	1.667	—	—	—	—	—	—	−1117.1(c)	—
Sulfur (rhombic)	S_8	256.53	2.07	113	10.04	444.6	83.7	—	—	0(c)	—
Sulfur (monoclinic)	S_8	256.53	1.96	119	14.17	444.6	83.7	—	—	+0.30(c)	—
Sulfur dioxide	SO_2	64.07	—	−75.48	7.402	−10.02	24.91	430.7	77.8	−296.90(g)	—
Sulfur trioxide	SO_3	80.07	—	16.84	25.48	43.3	41.80	491.4	83.8	−395.18(g)	—
Sulfuric acid	H_2SO_4	98.08	1.834[18°]	10.35	9.87	Decomposes at 340°C		—	—	−811.32(l) −907.51(aq)	— —
Toluene	C_7H_8	92.13	0.866	−94.99	6.619	110.62	33.47	593.9	40.3	+12.00(l) +50.00(g)	−3909.9(l) −3947.9(g)
Water	H_2O	18.016	1.00[4°]	0.00	6.0095	100.00	40.656	647.4	218.3	−285.84(l) −241.83(g)	— —
m-Xylene	C_8H_{10}	106.16	0.864	−47.87	11.569	139.10	36.40	619	34.6	−25.42(l) +17.24(g)	−4551.9(l) −4594.5(g)
o-Xylene	C_8H_{10}	106.16	0.880	−25.18	13.598	144.42	36.82	631.5	35.7	−24.44(l) +18.99(g)	−4552.9(l) −4596.3(g)
p-Xylene	C_8H_{10}	106.16	0.861	13.26	17.11	138.35	36.07	618	33.9	−24.43(l) 17.95(g)	−4552.91(l) −4595.2(g)
Zinc	Zn	65.38	7.140	419.5	6.674	907	114.77	—	—	0(c)	—

2 different Cps for 2 different phases

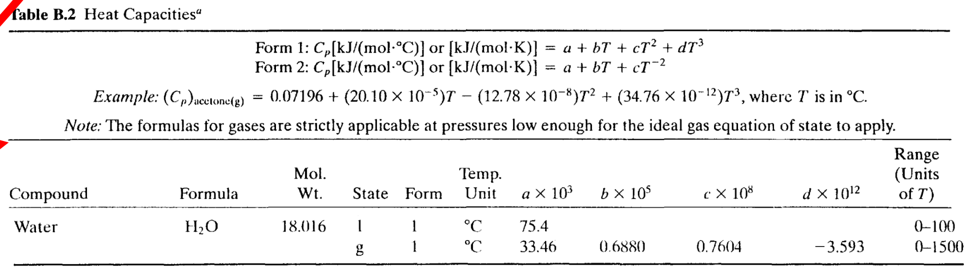


Table B.2 Heat Capacities[a]

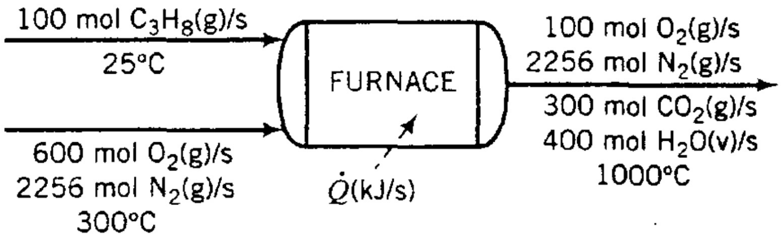
Form 1: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^2 + dT^3$
Form 2: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^{-2}$

Example: $(C_p)_{\text{acetone(g)}} = 0.07196 + (20.10 \times 10^{-5})T - (12.78 \times 10^{-8})T^2 + (34.76 \times 10^{-12})T^3$, where T is in °C.

Note: The formulas for gases are strictly applicable at pressures low enough for the ideal gas equation of state to apply.

Compound	Formula	Mol. Wt.	State	Form	Temp. Unit	$a \times 10^3$	$b \times 10^5$	$c \times 10^8$	$d \times 10^{12}$	Range (Units of T)
Water	H_2O	18.016	l	1	°C	75.4				0–100
			g	1	°C	33.46	0.6880	0.7604	−3.593	0–1500

Energy Balances: Heat of Reaction Approach



$$\Delta \hat{H}_r^\circ = -2220 \text{ kJ/mol} \qquad \dot{\xi} = 100 \text{ mol/s}$$

Know your tables!

Heat of reaction method

References: $C_3H_8(g)$, $O_2(g)$, $N_2(g)$, $CO_2(g)$, $H_2O(l)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	0	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

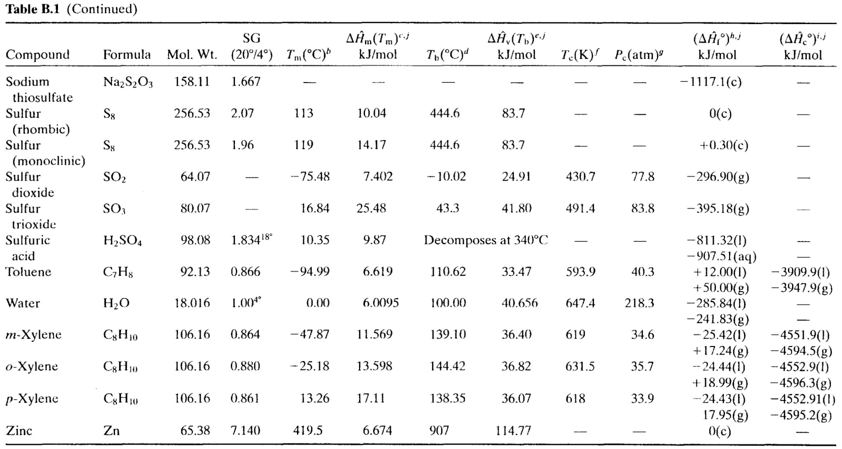


Table B.1 (Continued)

Compound	Formula	Mol. Wt.	SG (20°/4°)	T_m(°C)^b	$\Delta\hat{H}_m(T_m)^{c,j}$ kJ/mol	T_b(°C)^d	$\Delta\hat{H}_v(T_b)^{e,j}$ kJ/mol	T_c(K)^f	P_c(atm)^g	$(\Delta\hat{H}_f^\circ)^{h,j}$ kJ/mol	$(\Delta\hat{H}_c^\circ)^{i,j}$ kJ/mol
Sodium thiosulfate	$Na_2S_2O_3$	158.11	1.667	—	—	—	—	—	—	−1117.1(c)	—
Sulfur (rhombic)	S_8	256.53	2.07	113	10.04	444.6	83.7	—	—	0(c)	—
Sulfur (monoclinic)	S_8	256.53	1.96	119	14.17	444.6	83.7	—	—	+0.30(c)	—
Sulfur dioxide	SO_2	64.07	—	−75.48	7.402	−10.02	24.91	430.7	77.8	−296.90(g)	—
Sulfur trioxide	SO_3	80.07	—	16.84	25.48	43.3	41.80	491.4	83.8	−395.18(g)	—
Sulfuric acid	H_2SO_4	98.08	1.834$^{18°}$	10.35	9.87	Decomposes at 340°C		—	—	−811.32(l) −907.51(aq)	— —
Toluene	C_7H_8	92.13	0.866	−94.99	6.619	110.62	33.47	593.9	40.3	+12.00(l) +50.00(g)	−3909.9(l) −3947.9(g)
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m-Xylene	C_8H_{10}	106.16	0.864	−47.87	11.569	139.10	36.40	619	34.6	−25.42(l) +17.24(g)	−4551.9(l) −4594.5(g)
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Zinc	Zn	65.38	7.140	419.5	6.674	907	114.77	—	—	0(c)	—

$$\hat{H}_2 = \Delta\hat{H} \text{ for } O_2(25°C) \rightarrow O_2(300°C) = 8.47 \text{ kJ/mol (from Table B.8)}$$

$$\hat{H}_3 = 8.12 \text{ kJ/mol}$$

$$\hat{H}_4 = 32.47 \text{ kJ/mol}$$

$$\hat{H}_6 = 48.60 \text{ kJ/mol}$$

$$\hat{H}_7 = \Delta\hat{H} \text{ for } H_2O(l,\ 25°C) \rightarrow H_2O(g, 1000°C)$$

$$\Delta\dot{H} = \dot{\xi}\,\Delta\hat{H}_r^\circ + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} = -1.26 \times 10^5 \text{ kJ/s.}$$

2 different Cps for 2 different phases

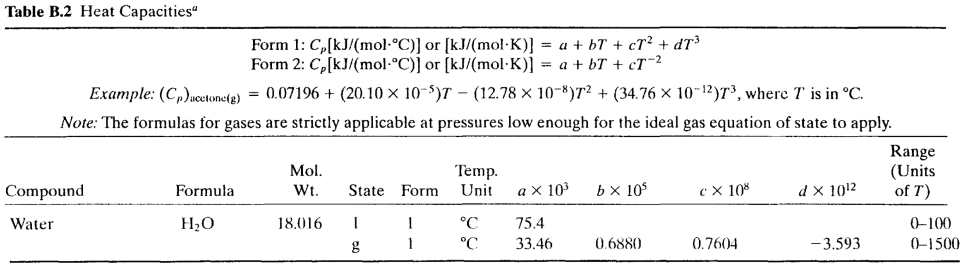


Table B.2 Heat Capacities^a

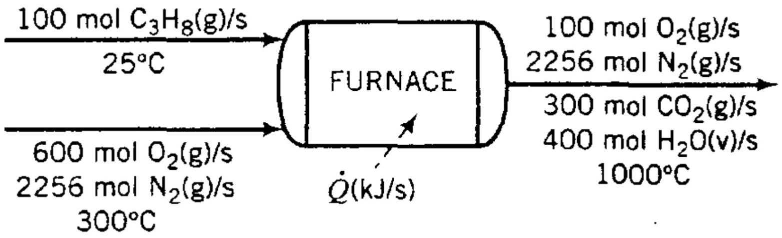
Form 1: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^2 + dT^3$
Form 2: C_p[kJ/(mol·°C)] or [kJ/(mol·K)] $= a + bT + cT^{-2}$

Example: $(C_p)_{\text{acetone(g)}} = 0.07196 + (20.10 \times 10^{-5})T - (12.78 \times 10^{-8})T^2 + (34.76 \times 10^{-12})T^3$, where T is in °C.

Note: The formulas for gases are strictly applicable at pressures low enough for the ideal gas equation of state to apply.

Compound	Formula	Mol. Wt.	State	Form	Temp. Unit	$a \times 10^3$	$b \times 10^5$	$c \times 10^8$	$d \times 10^{12}$	Range (Units of T)
Water	H_2O	18.016	l	1	°C	75.4				0–100
			g	1	°C	33.46	0.6880	0.7604	−3.593	0–1500

Energy Balances: Heat of Reaction Approach



$$\Delta \hat{H}_r^\circ = -2220 \text{ kJ/mol} \qquad \dot{\xi} = 100 \text{ mol/s}$$

Heat of reaction method

References: $C_3H_8(g)$, $O_2(g)$, $N_2(g)$, $CO_2(g)$, $H_2O(l)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	0	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

$$\hat{H}_2 = \Delta \hat{H} \text{ for } O_2(25°\text{C}) \rightarrow O_2(300°\text{C}) = 8.47 \text{ kJ/mol (from Table B.8)}$$

$$\hat{H}_3 = 8.12 \text{ kJ/mol}$$

$$\hat{H}_4 = 32.47 \text{ kJ/mol}$$

$$\hat{H}_6 = 48.60 \text{ kJ/mol}$$

$$\hat{H}_7 = \Delta \hat{H} \text{ for } H_2O(\text{l}, 25°\text{C}) \rightarrow H_2O(\text{g}, 1000°\text{C})$$

$$\boxed{\Delta \dot{H} = \dot{\xi}\, \Delta \hat{H}_r^\circ + \sum \dot{n}_{out} \hat{H}_{out} - \sum \dot{n}_{in} \hat{H}_{in} = -1.26 \times 10^5 \text{ kJ/s.}}$$

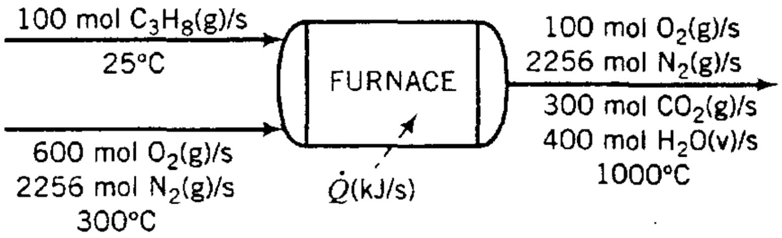
Heat of formation method

References: C(s), $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	$\hat{H}_1$	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

For a reactant or product, start with the elemental species at 25°C and 1 atm (the references) and form 1 mol of the process species at 25°C and 1 atm at **gaseous stage** (from Table B.1). Then bring the species from 25°C and 1 atm to its process state, calculating using the appropriate heat capacities from Tables

Energy Balances: Heat of Formation vs Heat of Reaction



Next, we calculate the specific enthalpy of O_2 at 300°C (the process state) relative to O_2 at 25°C (the reference state) as:

$$\hat{H}_2 = 8.47\,\mathrm{kJ/mol}\,(\text{from Table B.8}).$$

There is no heat of formation term since O_2 is an elemental species. We proceed in the same manner to calculate:

$$\hat{H}_3 = 8.12\,\mathrm{kJ/mol},\ \hat{H}_4 = 32.47\,\mathrm{kJ/mol},\ \hat{H}_5 = 30.56\,\mathrm{kJ/mol},$$

$$\hat{H}_6 = -344.9\,\mathrm{kJ/mol},\ \text{and}\ \hat{H}_7 = -204.1\,\mathrm{kJ/mol}.$$

To calculate $\hat{H}_6$ and $\hat{H}_7$, we form the corresponding species ($CO_2(g)$ and $H_2O(v)$) at 25°C from their elements ($\Delta\hat{H} = \Delta\hat{H}_f^\circ$), then heat them from 25°C to 1000°C ($\Delta\hat{H} = \hat{H}_{1000^\circ C}$ from Table B.8), and add the formation and heating terms.

$$\Delta\hat{H}_r^\circ = -2220\ \mathrm{kJ/mol} \qquad \dot{\xi} = 100\ \mathrm{mol/s}$$

Heat of formation method

References: C(s), $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	$\hat{H}_1$	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

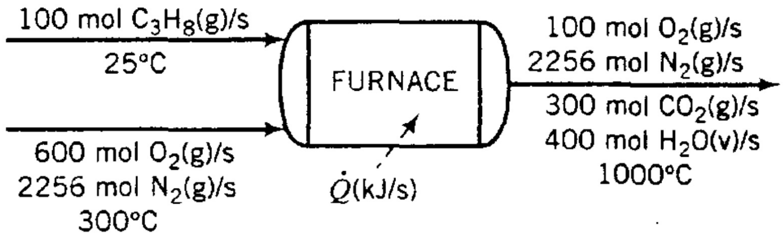
$$3\,C(s)(25^\circ C,\ 1\ \mathrm{atm}) + 4\,H_2(g)(25^\circ C,\ 1\ \mathrm{atm}) \rightarrow C_3H_8(g)(25^\circ C,\ 1\ \mathrm{atm})$$

$$\Downarrow$$

$$\hat{H}_1 = (\Delta\hat{H}_f^\circ)_{C_3H_8(g)} = -103.8\ \mathrm{kJ/mol}\ (\text{from Table B.1})$$

This is the enthalpy of propane at 25°C (the process state) relative to C(s) and H2(g) at 25°C (the reference states). If the propane had entered at a temperature T_0 other than 25°C, a term of the form $\int_{25^\circ C}^{T0} C_p\,dT$ would be added to the heat of formation of propane.

Energy Balances: Heat of Formation vs Heat of Reaction



Next, we calculate the specific enthalpy of O_2 at 300°C (the process state) relative to O_2 at (the reference state) as:

$$\hat{H}_2 = 8.47\,\mathrm{kJ/mol}\,(\text{from Table B.8}).$$

There is no heat of formation term since O_2 is an elemental species. We proceed in the sam manner to calculate:

$$\hat{H}_3 = 8.12\,\mathrm{kJ/mol},\ \hat{H}_4 = 32.47\,\mathrm{kJ/mol},\ \hat{H}_5 = 30.56\,\mathrm{kJ/mol},$$

$$\hat{H}_6 = -344.9\,\mathrm{kJ/mol},\ \text{and}\ \hat{H}_7 = -204.1\,\mathrm{kJ/mol}.$$

To calculate $\hat{H}_6$ and $\hat{H}_7$, we form the corresponding species ($CO_2(g)$ and $H_2O(v)$) at 25°C from their elements ($\Delta\hat{H} = \Delta\hat{H}_f^\circ$), then heat them from 25°C to 1000°C ($\Delta\hat{H} = \hat{H}_{1000^\circ C}$ f Table B.8), and add the formation and heating terms.

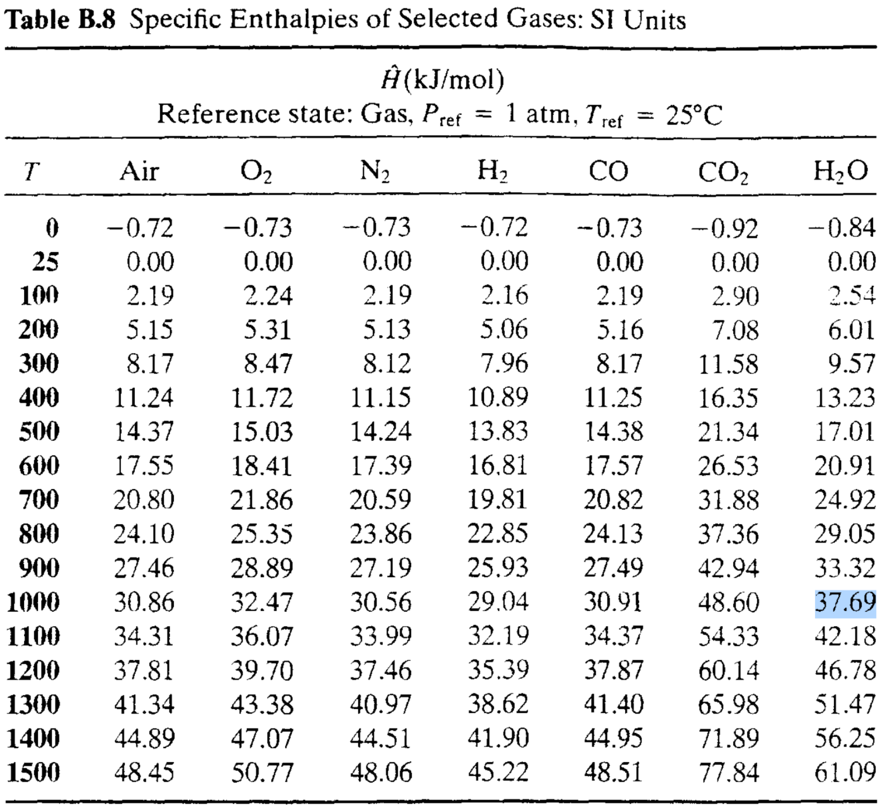
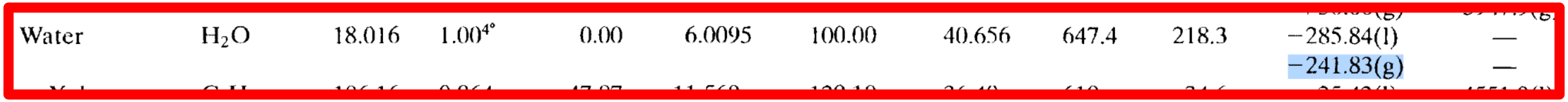


Table B.8 Specific Enthalpies of Selected Gases: SI Units

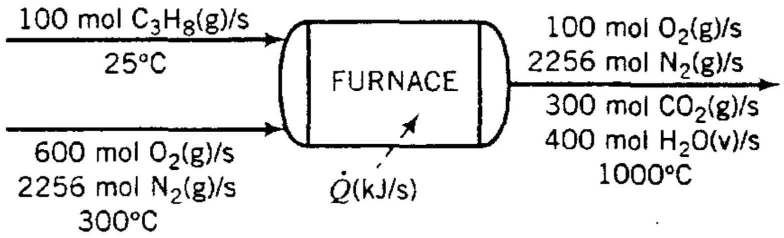
$\hat{H}$(kJ/mol)
Reference state: Gas, P_{ref} = 1 atm, T_{ref} = 25°C

T	Air	O_2	N_2	H_2	CO	CO_2	H_2O
0	−0.72	−0.73	−0.73	−0.72	−0.73	−0.92	−0.84
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	2.19	2.24	2.19	2.16	2.19	2.90	2.54
200	5.15	5.31	5.13	5.06	5.16	7.08	6.01
300	8.17	8.47	8.12	7.96	8.17	11.58	9.57
400	11.24	11.72	11.15	10.89	11.25	16.35	13.23
500	14.37	15.03	14.24	13.83	14.38	21.34	17.01
600	17.55	18.41	17.39	16.81	17.57	26.53	20.91
700	20.80	21.86	20.59	19.81	20.82	31.88	24.92
800	24.10	25.35	23.86	22.85	24.13	37.36	29.05
900	27.46	28.89	27.19	25.93	27.49	42.94	33.32
1000	30.86	32.47	30.56	29.04	30.91	48.60	37.69
1100	34.31	36.07	33.99	32.19	34.37	54.33	42.18
1200	37.81	39.70	37.46	35.39	37.87	60.14	46.78
1300	41.34	43.38	40.97	38.62	41.40	65.98	51.47
1400	44.89	47.07	44.51	41.90	44.95	71.89	56.25
1500	48.45	50.77	48.06	45.22	48.51	77.84	61.09



Water	H_2O	18.016	$1.00^{4°}$	0.00	6.0095	100.00	40.656	647.4	218.3	−285.84(l) −241.83(g)	— —

Energy Balances: Heat of Formation vs Heat of Reaction



$$\Delta \hat{H}_r^\circ = -2220 \text{ kJ/mol} \qquad \dot{\xi} = 100 \text{ mol/s}$$

Heat of reaction method

References: $C_3H_8(g)$, $O_2(g)$, $N_2(g)$, $CO_2(g)$, $H_2O(l)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	0	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

$$\hat{H}_2 = 8.47 \text{ kJ/mol} \qquad \hat{H}_5 = 30.56 \text{ kJ/mol}$$
$$\hat{H}_3 = 8.12 \text{ kJ/mol} \qquad \hat{H}_6 = 48.60 \text{ kJ/mol}$$
$$\hat{H}_4 = 32.47 \text{ kJ/mol} \qquad \hat{H}_7 = 81.71 \text{ kJ/mol}$$

$$\Delta H = \xi \Delta H_r{}^0 + \sum_{out} n_i \widehat{H}_i - \sum_{in} n_i \widehat{H}_i = -1.26\times 105 \frac{kJ}{s}$$

Heat of formation method

References: $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C and 1 atm

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
C_3H_8	100	$\hat{H}_1$	—	—
O_2	600	$\hat{H}_2$	100	$\hat{H}_4$
N_2	2256	$\hat{H}_3$	2256	$\hat{H}_5$
CO_2	—	—	300	$\hat{H}_6$
H_2O	—	—	400	$\hat{H}_7$

$$\hat{H}_1 = -103.8 \text{ kJ/mol} \qquad \hat{H}_5 = 30.56 \text{ kJ/mol}$$
$$\hat{H}_2 = 8.47 \text{ kJ/mol} \qquad \hat{H}_6 = -344.9 \text{ kJ/mol}$$
$$\hat{H}_3 = 8.12 \text{ kJ/mol} \qquad \hat{H}_7 = -204.1 \text{ kJ/mol}$$
$$\hat{H}_4 = 32.47 \text{ kJ/mol}$$

$$\Delta H = \sum_{out} n_i \widehat{H}_i - \sum_{in} n_i \widehat{H}_i = -1.26\times 105 \frac{kJ}{s}$$

Energy Balances: Procedure for Calculations

1. Perform all required material balances calculations (as much as possible)
2. Write the appropriate form of the energy balance (closed or open systems) and delete any of the terms that are either zero or negligible for the given process system
3. Choose a reference state (phase, temperature and pressure) for each species involved in the process
    1. If H or U for a species will be looked up in a table (such as the steam tables for water) choose the reference state used to generate the table
    2. Otherwise, choose one of the inlet or outlet steates as the reference states for the species (so that at least one H or U may be set equal to zero)
4. Construct a table with columns for number of species and specific enthalpies/internal energies) relative to the chosen reference states
5. Calculate all the required values
6. Use the final energy balance formula to find the desired quantities

Reminders

The Midterm grade (M) **only benefits** your Overall grade (O)

- Two cases, depending on your final exam grade (F):
  1. M > F: O = M*0.3 + F*0.7
  2. M < F: O = F

No electronic devices, except for calculators

- Print physical property tables

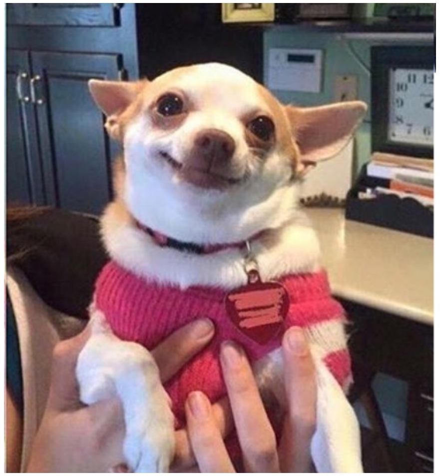
If more questions/clarifications needed, still Q&A session!

Think Like an Examiner

Maximize your points at the exam by understanding how you are graded and who grades you:

- Examiner/Grader = PhD student
- ~80 exams to correct → significant time not dedicated to research projects
- What Examiner wants: Grade Fast

- Exam sheets have a clear structure and every piece of information is noted down:
  - Flowchart
  - Basis
  - Detailed computations
  - Units



Think Like an Examiner

How to minimize your points

- Your exam sheet is messy and unclear:
  - No explanations
  - No detailed computations (if nothing is shown, how can we know you didn't just guess?)
  - Missing flowchart, basis, or units

- Make Correction Harder → 😡 Make Examiner Angrier

- ❌ YOU LOSE POINTS!

Questions?

The Midterm grade (M) **only benefits** your Overall grade (O)

- Two cases, depending on your final exam grade (F):
  1. M > F: O = M*0.3 + F*0.7
  2. M < F: O = F

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