

AE1241 Physics

Chapter 20 Second Law of Thermodynamics

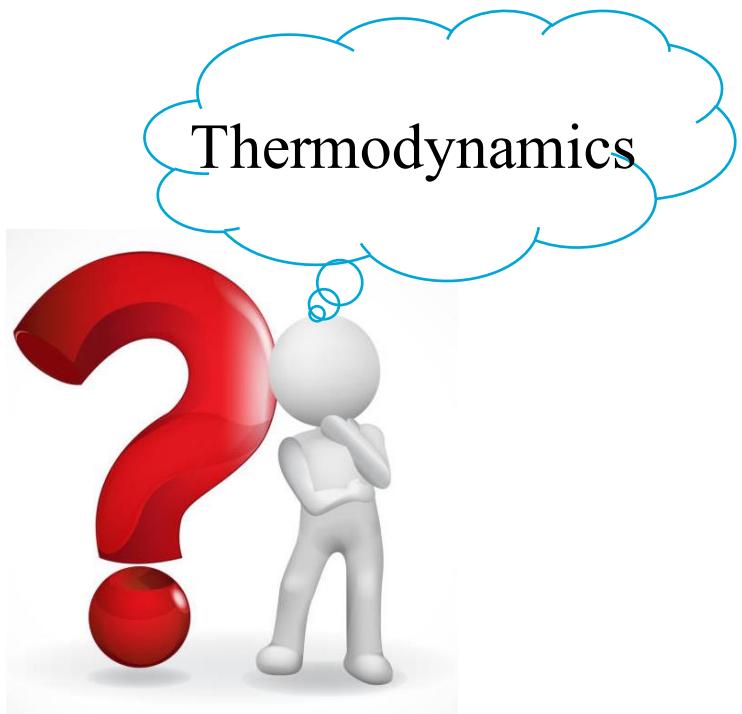


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Faculty of Aerospace Engineering**

18th March 2025

What do we focus on?



- ~~0th law of thermodynamics (temperature)~~ – Chapter 17
- ~~Kinetic Theory of Gases (temperature)~~ – Chapter 18
- ~~1st law of thermodynamics (energy)~~ – Chapter 19
- **2nd law of thermodynamics (entropy)** – Chapter 20
- **3rd law of thermodynamics (absolute 0 K)** – Chapter 20

Structure of this lecture

- The Second Law of Thermodynamics
- Heat Engines; The Carnot Engine; Reversible Processes
- Refrigerator, Air Conditioners, and Heat Pumps
- Concept of Entropy; Statistical Interpretation of Entropy
- Third law of Thermodynamics
- Thermal Pollution, Global Warming, and Energy Resources

Learning objective

After today's lecture, you should be able to:



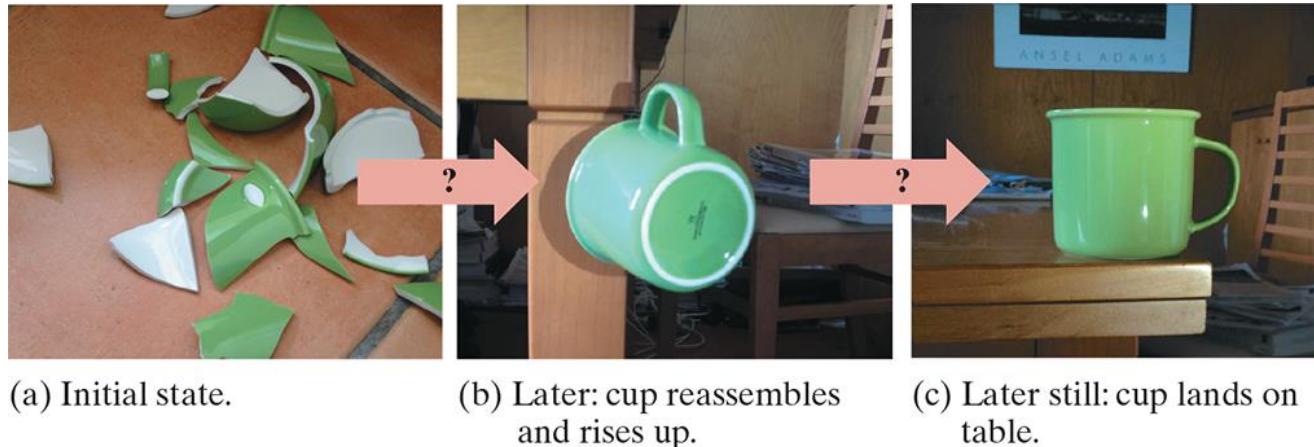
- Understand the concept of **entropy** and the **2nd law of thermodynamics**
- Understand the working principle of heat engines, refrigerator, air conditioning, heat pump
- Evaluate the **performance** of different applicants (e.g., refrigerator, air conditioning and heat pump)
- Calculate the **entropy change** of a given thermodynamic cycle (e.g., Canon cycle)
- Calculate **efficiency** of different thermodynamic cycles

Prior Knowledge

- 1st law of thermodynamics
- Basic mechanics (e.g., *Newton's law*)
- Calculus (e.g., *differential and integral*)
- Statistics (e.g., *distribution, probability*)

20-1 Second law of Thermodynamics

- Many processes can be imagined for which energy is conserved, but these are not observed to occur in nature, e.g.



- For the process “heat from colder object to hotter object” energy can be conserved, but it does ***not*** happen ***spontaneously***,
 - The second law of thermodynamics is about which processes occur in nature and which do not (**entropy**).

20-1 Second law of Thermodynamics - Clausius statement

Heat can flow spontaneously from a hot object to a cold object, heat will NOT flow spontaneously from a cold object to a hot object

- Limitation:

Applies to one particular process
- A *general* statement of 2nd law of thermodynamics based partly on the study of **heat engines**, which are devices that **change thermal energy into mechanical work** (e.g. steam engines, automobile engines)



20-2 Heat Engines

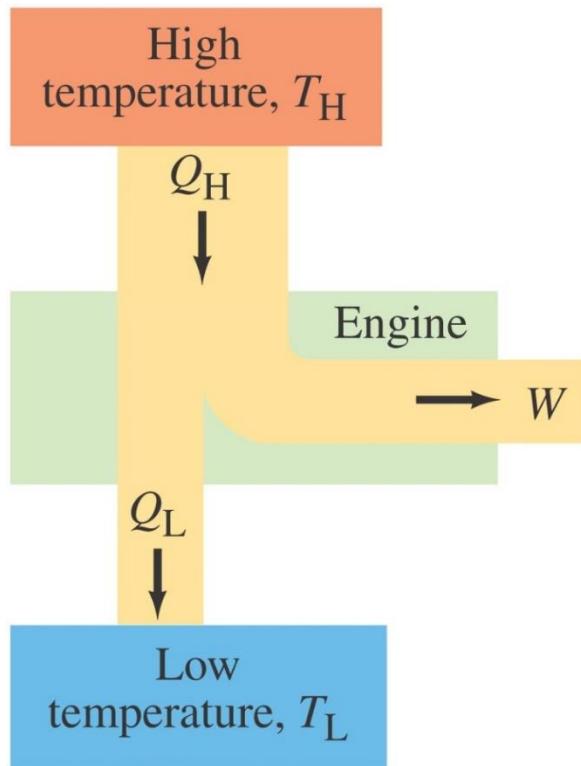
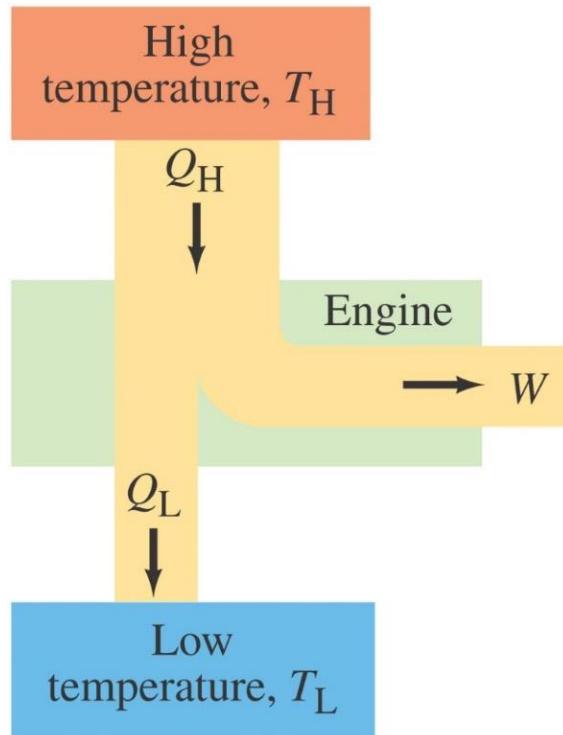


Figure 20-2 Schematic of energy transfer for a heat engine.

- Mechanical energy can be obtained from thermal energy *only* when heat is allowed to flow from a high to a low temperature. Some of the heat can then be transformed to work.
- Engines that run in a repeated cycle (then system returns repeatedly to its starting point) and thus can run *continuously*.
- In each cycle, conservation of energy
- Thus, $Q_H = W + Q_L$ (new sign convention (!), all positive)

Where Q_H is a heat input at high temperature T_H , W is work output; Q_L is heat exhausted at a lower temperature T_L .

20-2 Efficiency calculation



Efficiency (e) is the ratio of the work (W) a system does to the heat input (Q_H) at the high temperature (T_H)

$$e = \frac{W}{Q_H}$$

$e = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$

Output (what you get from the engine)

Input (what you pay for in burned fuel)

Please note: $e = 1$ (100 %) only if $Q_L = 0$ (i.e. when no heat is exhausted to environment)

20-2 Heat Engines

---Internal combustion engine

Otto Cycle

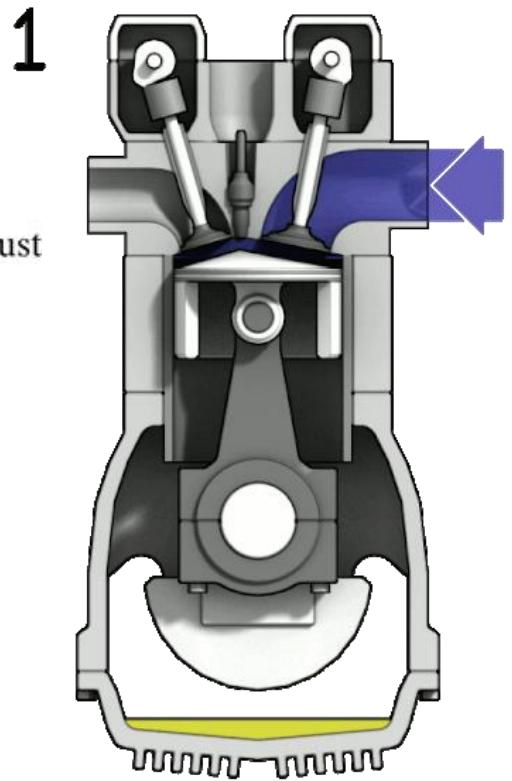
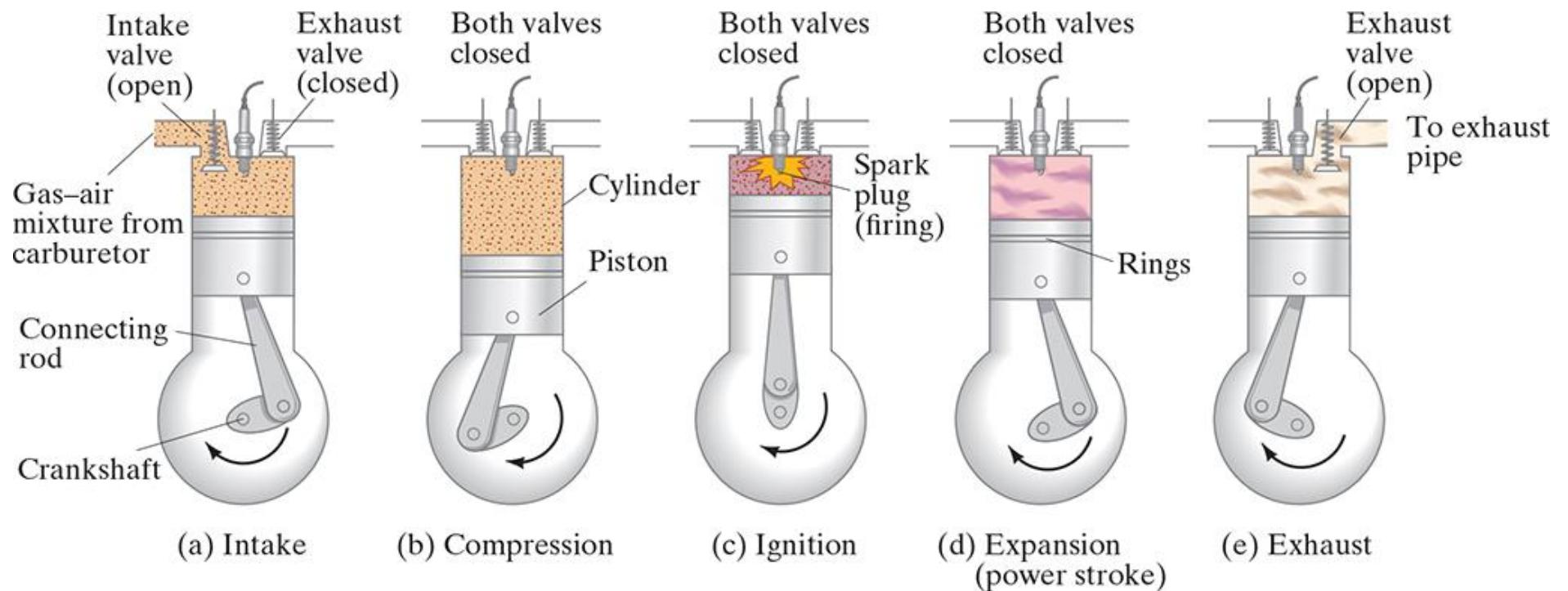
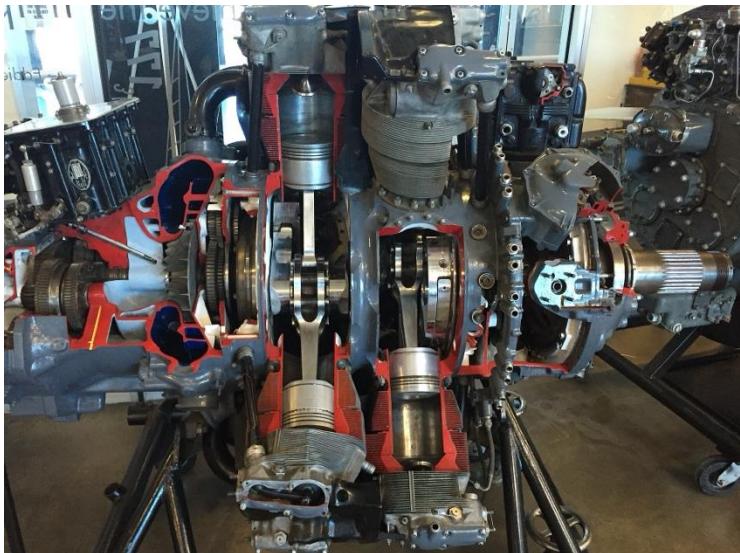


Figure 20-4 Four-stroke-cycle internal combustion engine.

Figure source: Wikipedia

Application of internal combustion engine

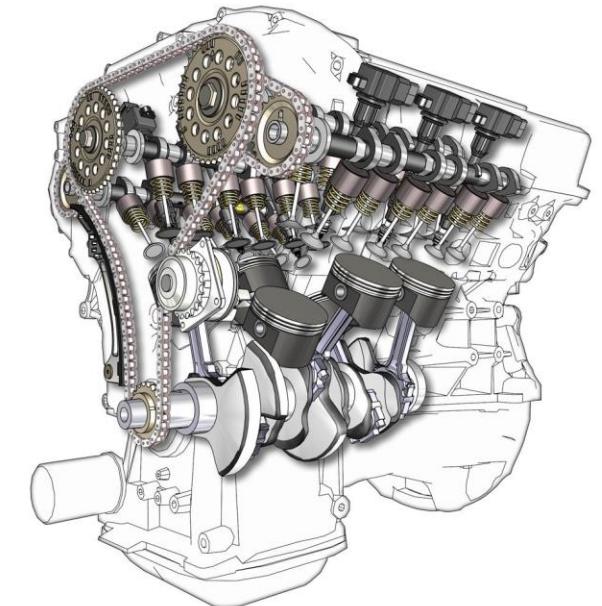
- Power generation
- Marine time
- Aircraft propulsion
- Auto mobile



Pratt&Whitney R2800 in 1939

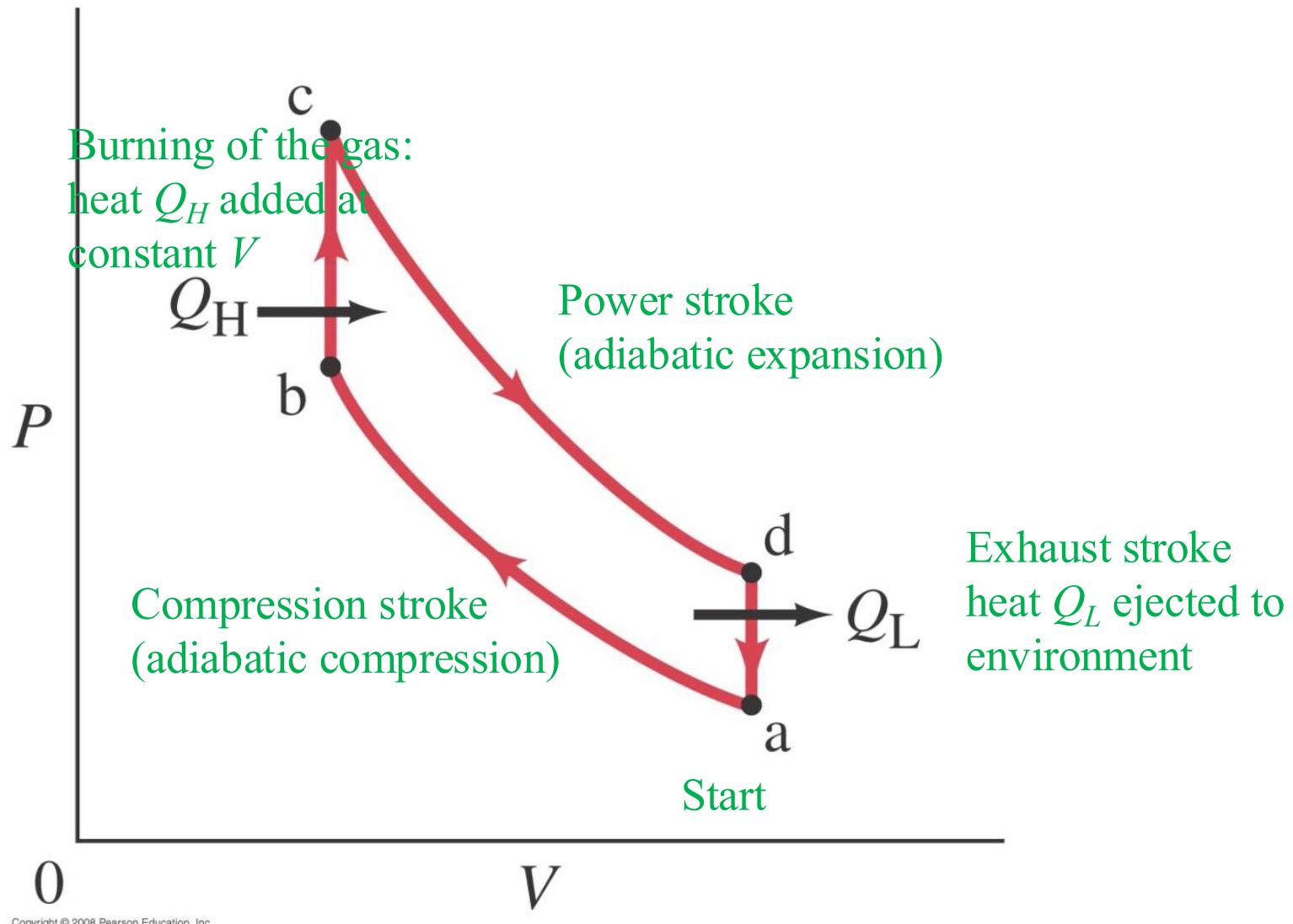


Used in ship

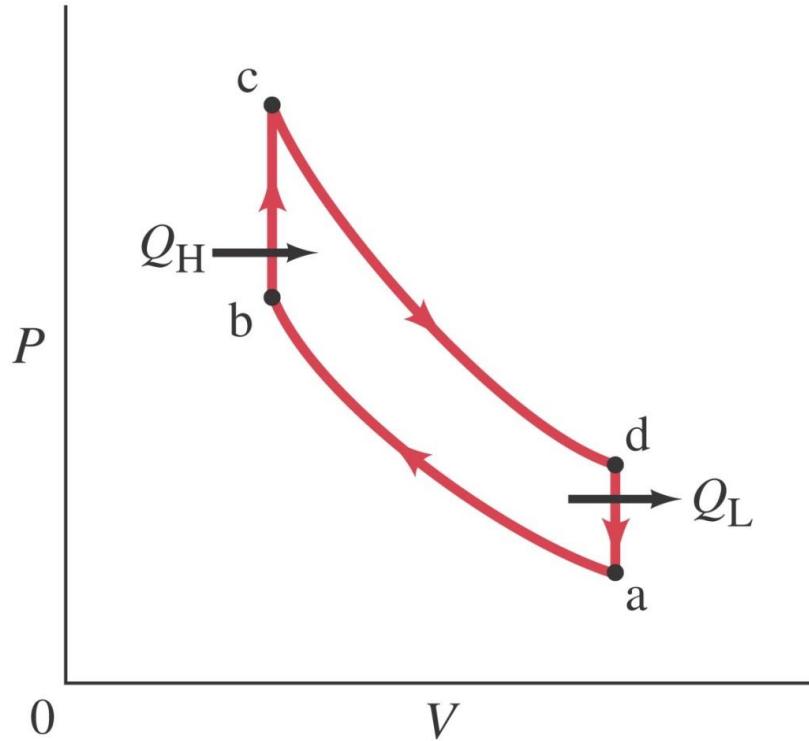


V6 engine model. Figure source:
[wikipedia](#)

20-2 Internal combustion engine cycle



Derive the efficiency of an internal combustion engine



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$$e = 1 - \left(\frac{V_a}{V_b} \right)^{1-\gamma}$$

Compression ratio

20-2 Steam engine

Rankine cycle

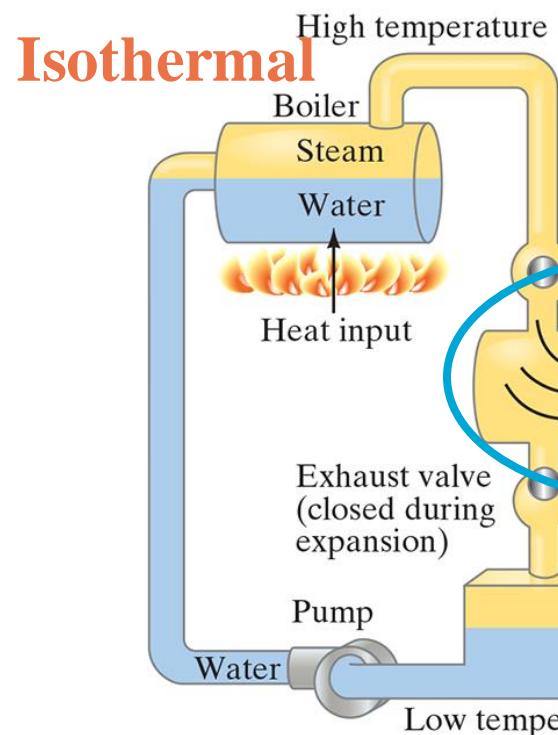
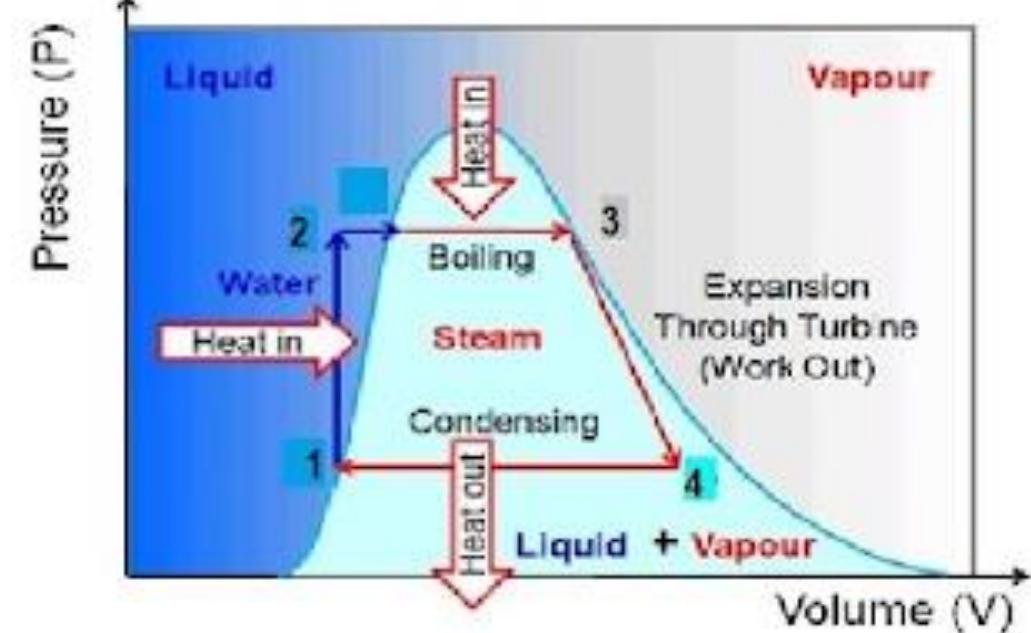
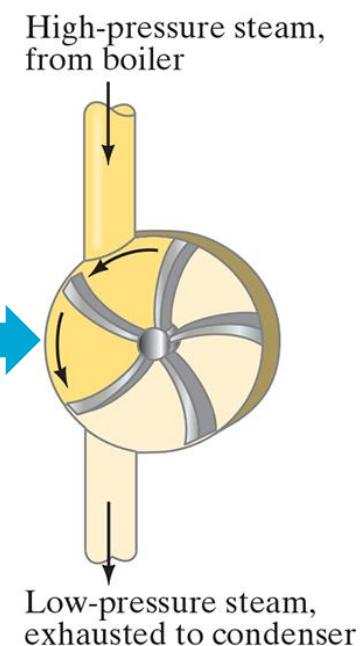
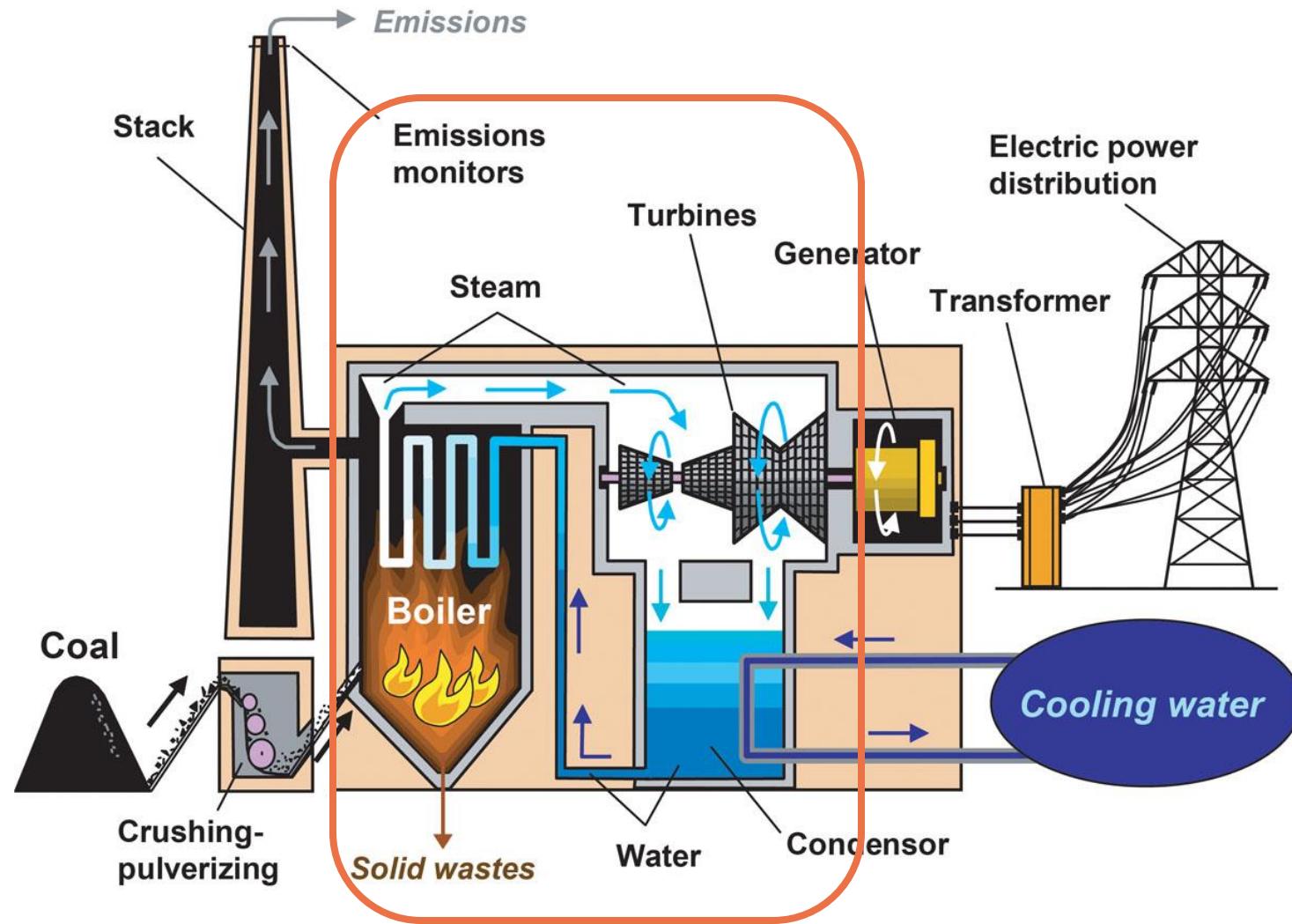


Figure 20-3 Steam Engine



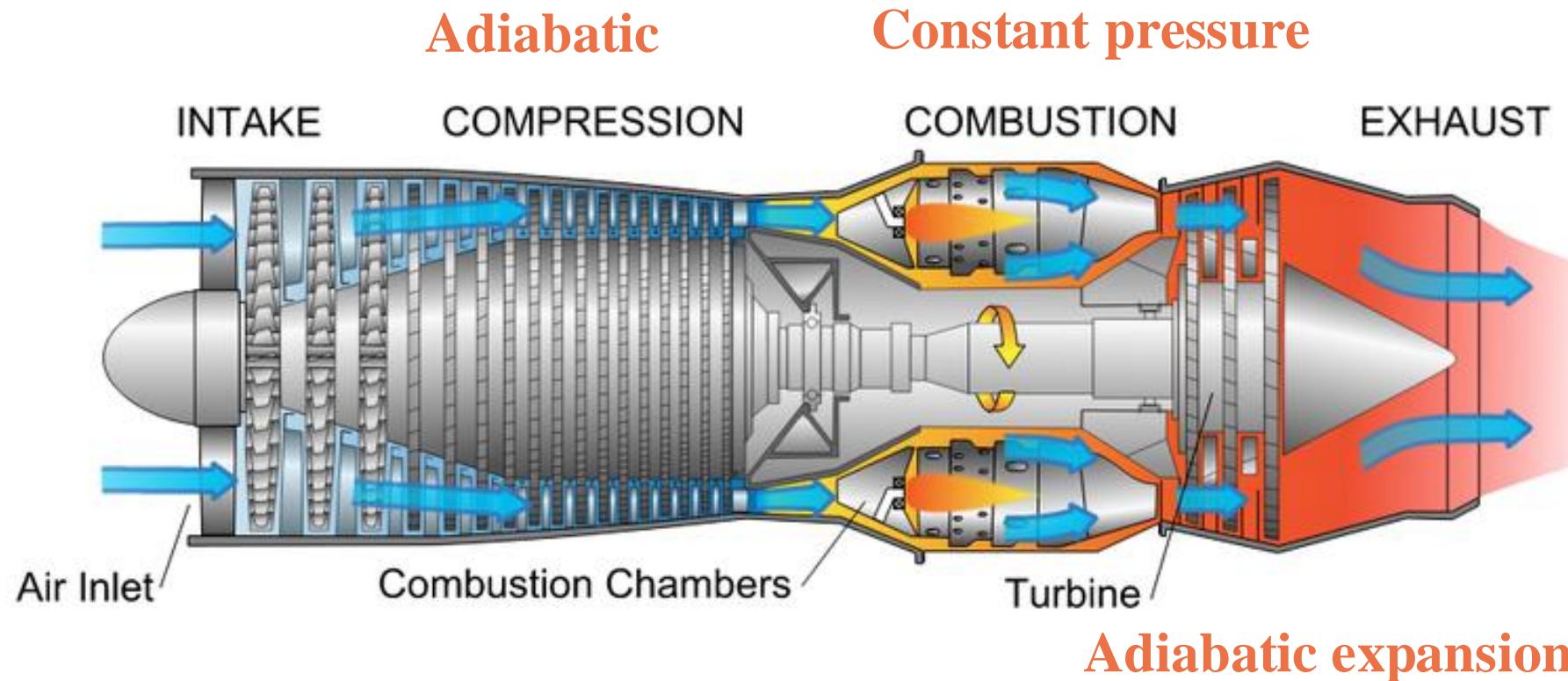
Coal power plant



Gas turbine engine

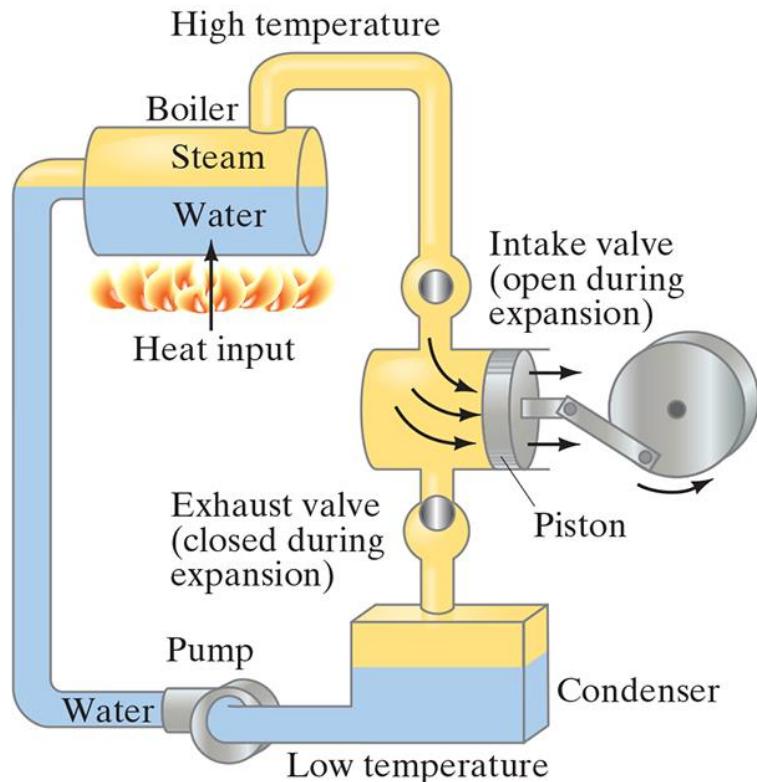
Brayton cycle

$$e = 1 - \frac{1}{\left(\frac{p_b}{p_a}\right)^{\frac{\gamma-1}{\gamma}}}$$



20-2 Heat Engines

---Why temperature difference needed



Suppose in a steam engine:

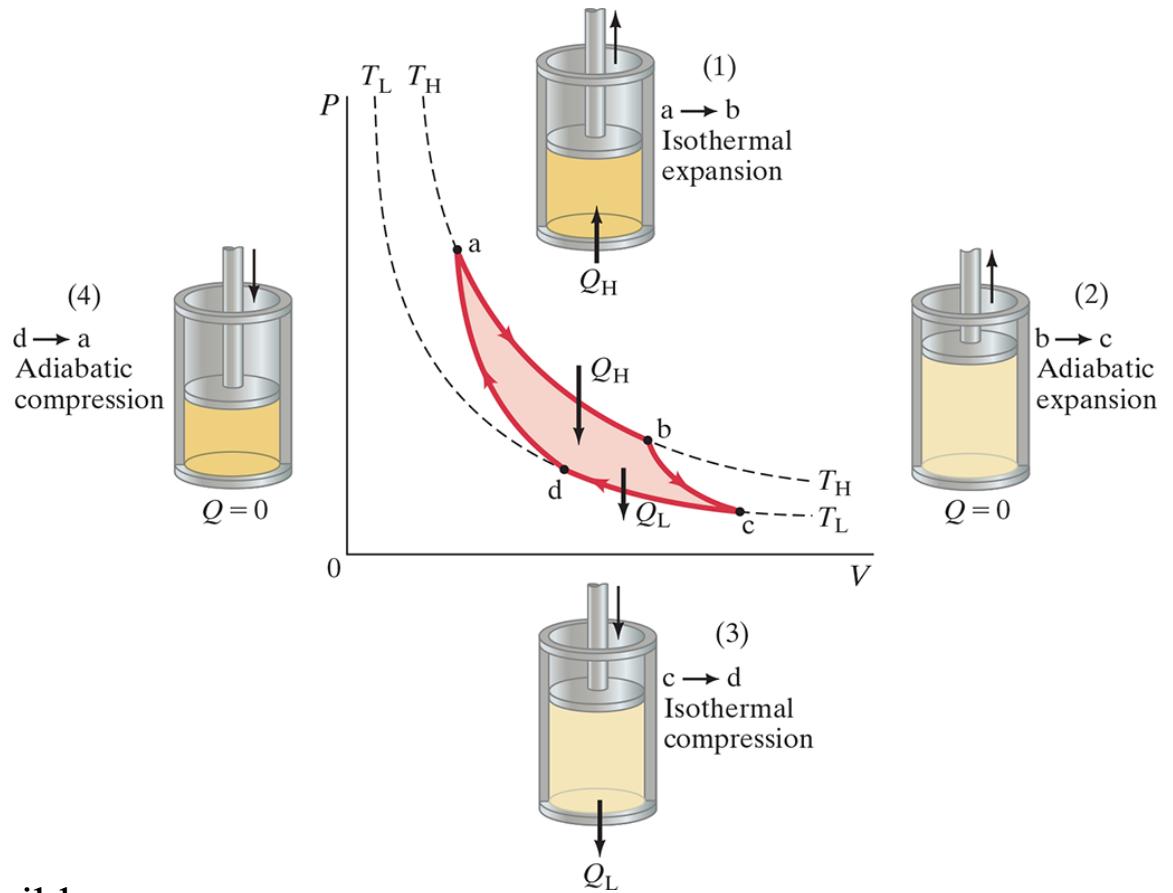
- No condenser or pump;
- The steam was at the same temperature.

Then:

- Pressure of the gas being exhausted is the same as that on intake,
i.e. work is done by the gas on the piston
during expansion = work done by the piston
on steam → **no net work!**

20-3 The Carnot Engine

- An idealized **Carnot engine** consists of four processes in a cycle:
 - Two adiabatic processes ($Q=0$)
 - Two isothermal processes ($\Delta T=0$)
- Each of the processes is **reversible**
 - Infinitely slow
 - The process can be considered as a series of equilibrium states;
 - The whole process can be reversed with no change in work or heat)



Note: All real processes are irreversible
(they are not done infinitely slowly and there is friction, turbulence in the gas, etc.)

Figure 20-5 The Carnot cycle.

20-3 Derivation Carnot efficiency

a→b isothermal expansion:

$$Q_H = W_{ab} \quad W_{ab} = nRT_H \ln\left(\frac{V_b}{V_a}\right)$$

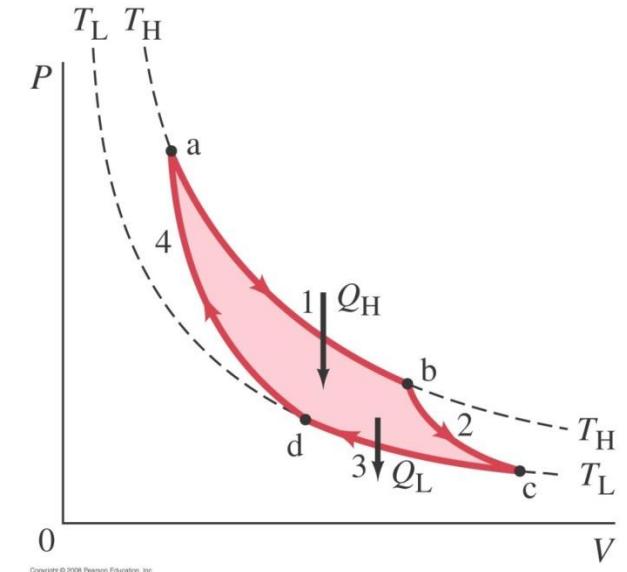
Similarly, c→d isothermal compression:

$$Q_L = W_{cd} \quad W_{cd} = nRT_L \ln\left(\frac{V_c}{V_d}\right)$$

b→c & d→a adiabatic processes: $P_b V_b^\gamma = P_c V_c^\gamma \quad P_d V_d^\gamma = P_a V_a^\gamma$

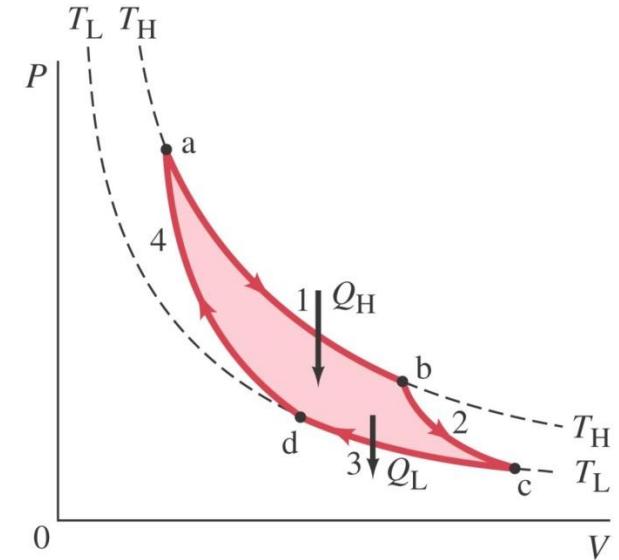
Ideal gas law: $\frac{P_b V_b}{T_H} = \frac{P_c V_c}{T_L} \quad \frac{P_d V_d}{T_L} = \frac{P_a V_a}{T_H}$

$$V_b^{\gamma-1} T_H = V_c^{\gamma-1} T_L \quad V_d^{\gamma-1} T_L = V_a^{\gamma-1} T_H \rightarrow \frac{V_b}{V_a} = \frac{V_c}{V_d} \rightarrow \frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$



20-3 Carnot's Theorem

All reversible engines operating between the same two constant temperatures T_H and T_L have the same efficiency. Any irreversible engine operating between the same two fixed temperatures will have an efficiency less than this.



The maximum possible efficiency for a real (irreversible) engine is:

$$e_{ideal} = 1 - \frac{T_L}{T_H}$$

The fundamental upper limit to the efficiency of any heat engine.

Practice: 60-80 % of the Carnot efficiency is reached

$e = 1$ (100 %) only if $T_L = 0$, which is practically (but also theoretically) impossible (see third law of thermodynamics 20-10)

20-3 Kelvin-Planck statement of 2nd law

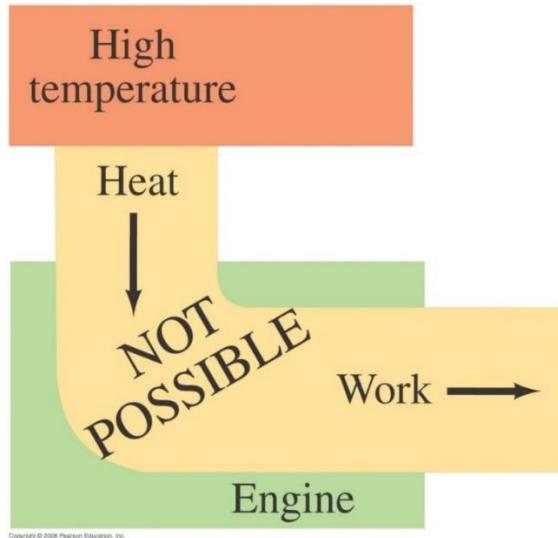


Figure 20-6 Diagram of an impossible perfect heat engine in which all heat input is used to do work.

$$e = 1 - \frac{Q_L}{Q_H}$$

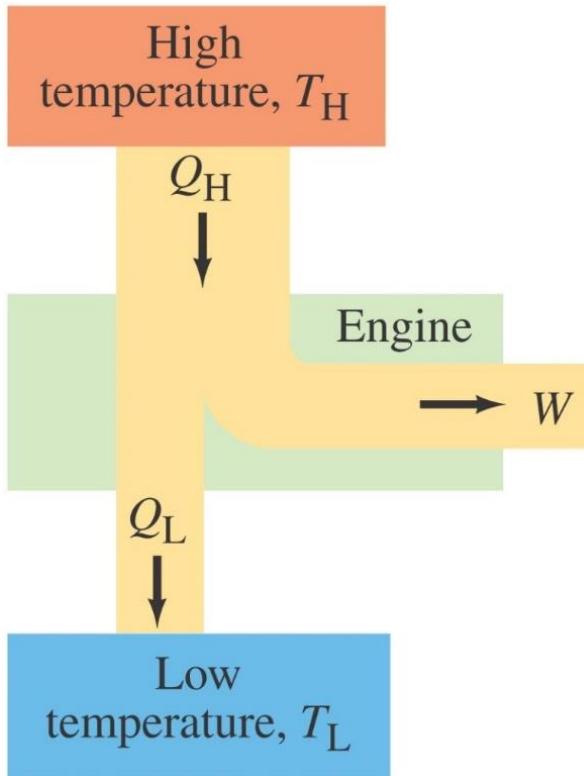
Kelvin-Planck statement of the second law of thermodynamics:

No device is possible whose sole effect is to transform a given amount of heat completely into work.



It is NOT possible to reduce Q_L to zero, i.e. a perfect engine (100 % efficiency) is NOT possible

20-4 Refrigerator vs. Heat Engine



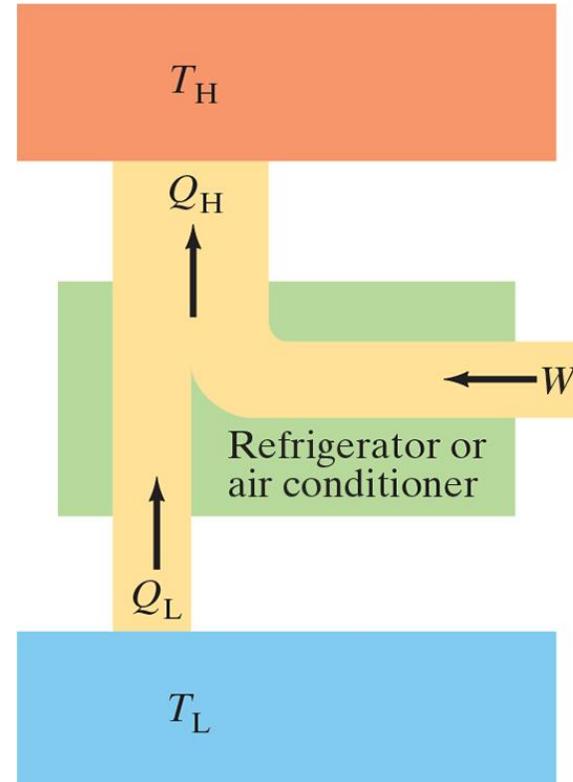
20-2 energy transfer for a heat engine.

Basis: $Q_L + W = Q_H$

Reverse of heat engine:
transfer heat out of a cool
environment into a warm one
Note: $Q_H > Q_L$ and work W is
needed for this

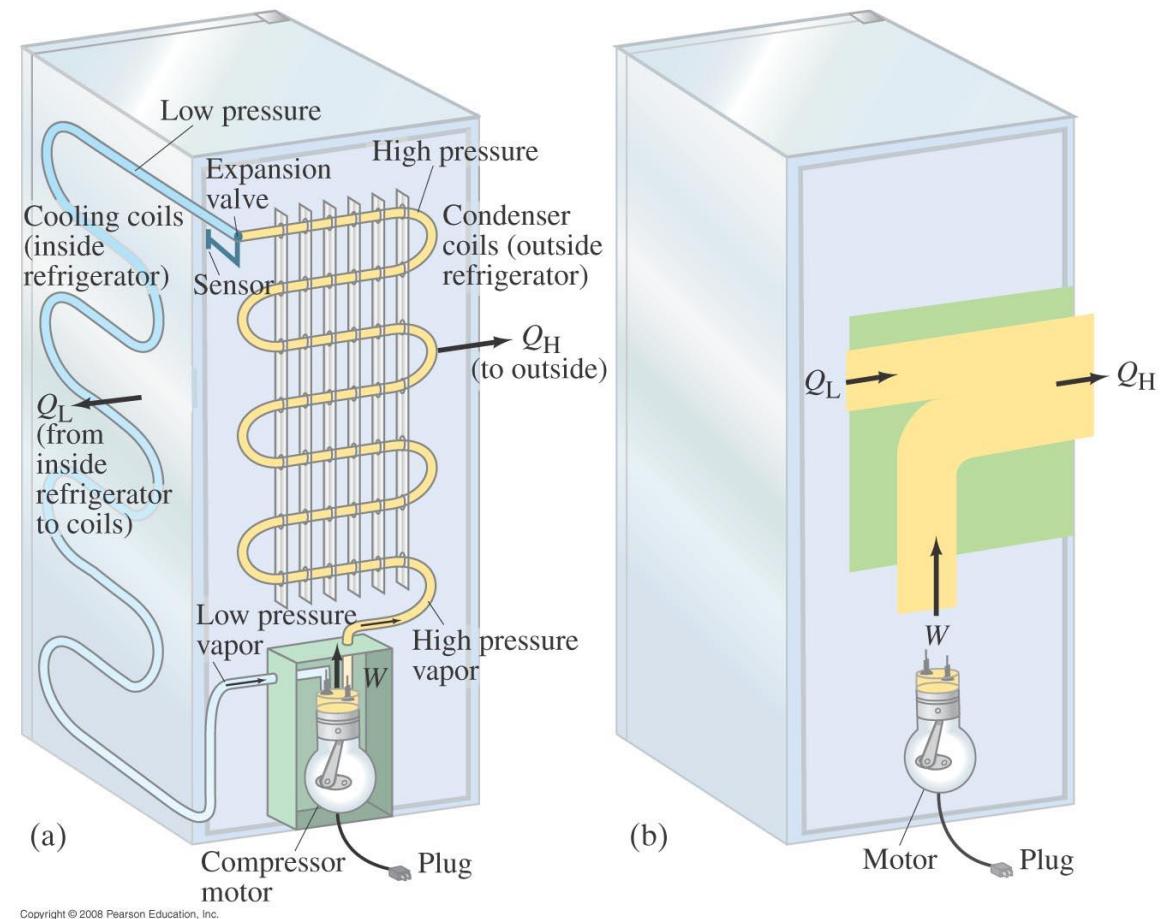
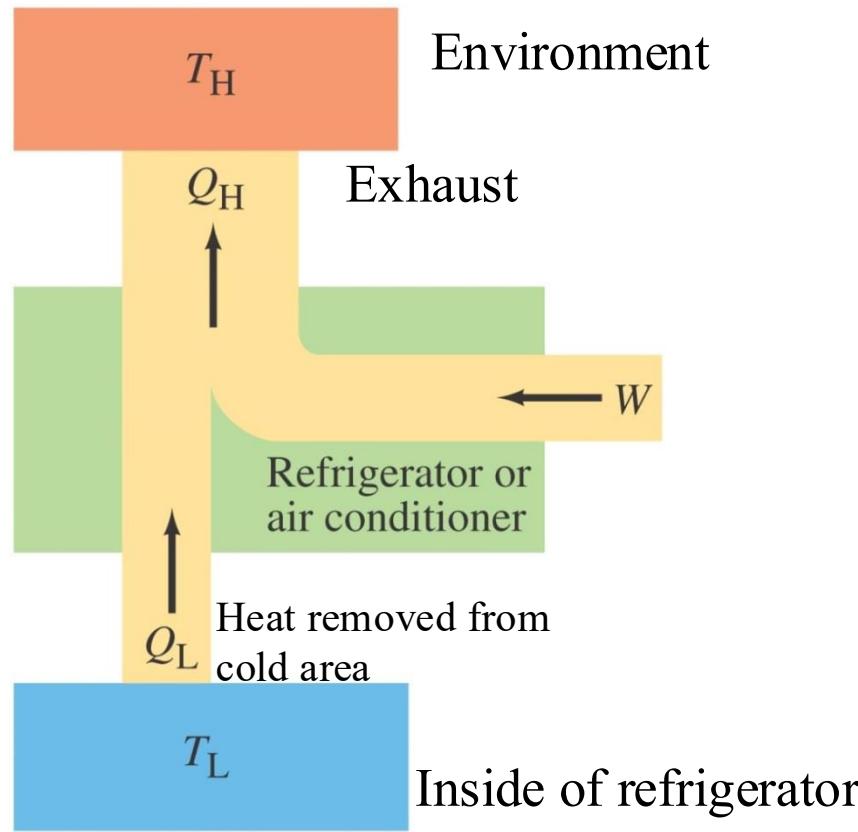


Clausius statement:
No device is possible whose sole effect
is to transfer heat from one region at a
temperature T_L into a second region at
a higher temperature T_H .

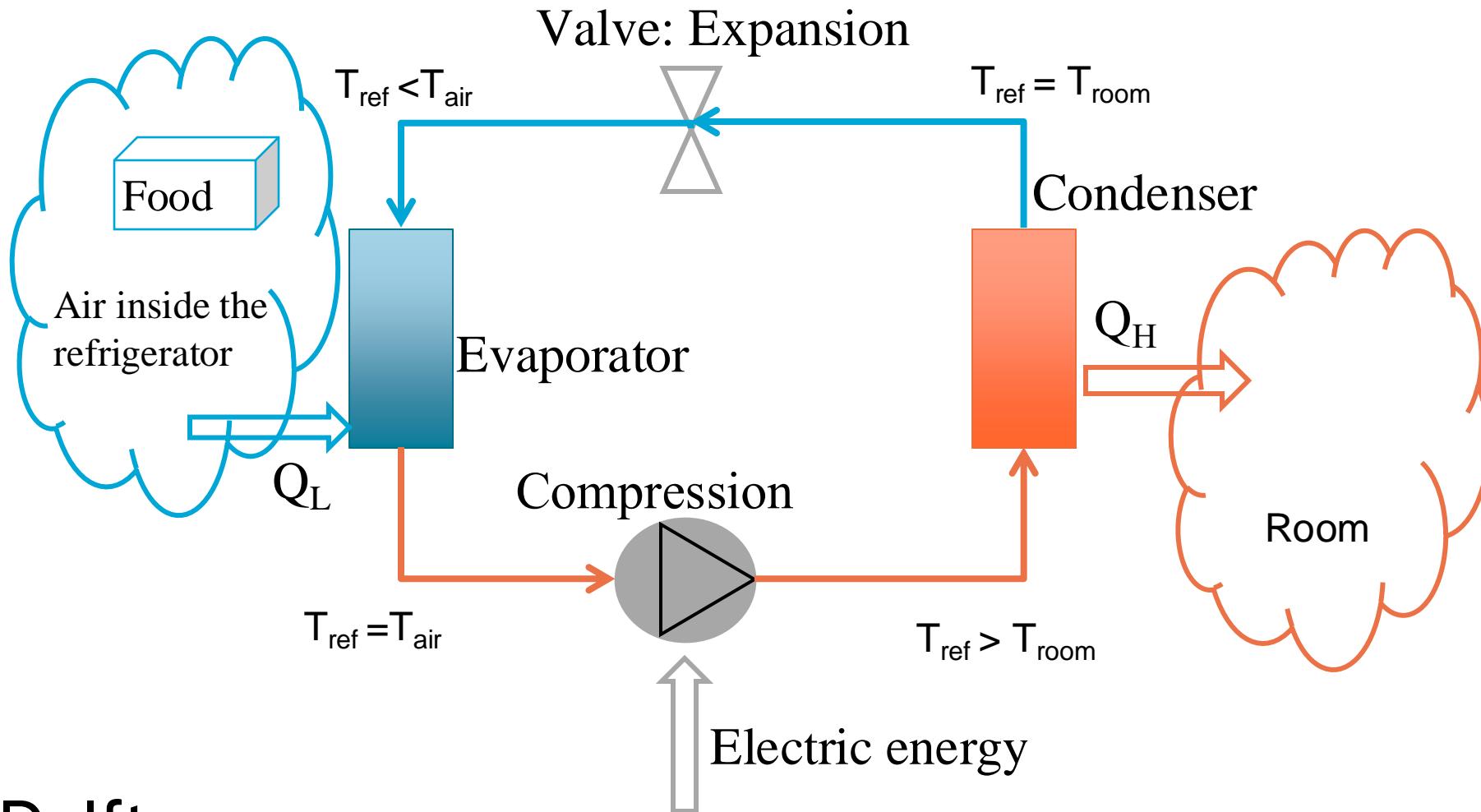


20-8 energy transfer for a refrigerator or AC.

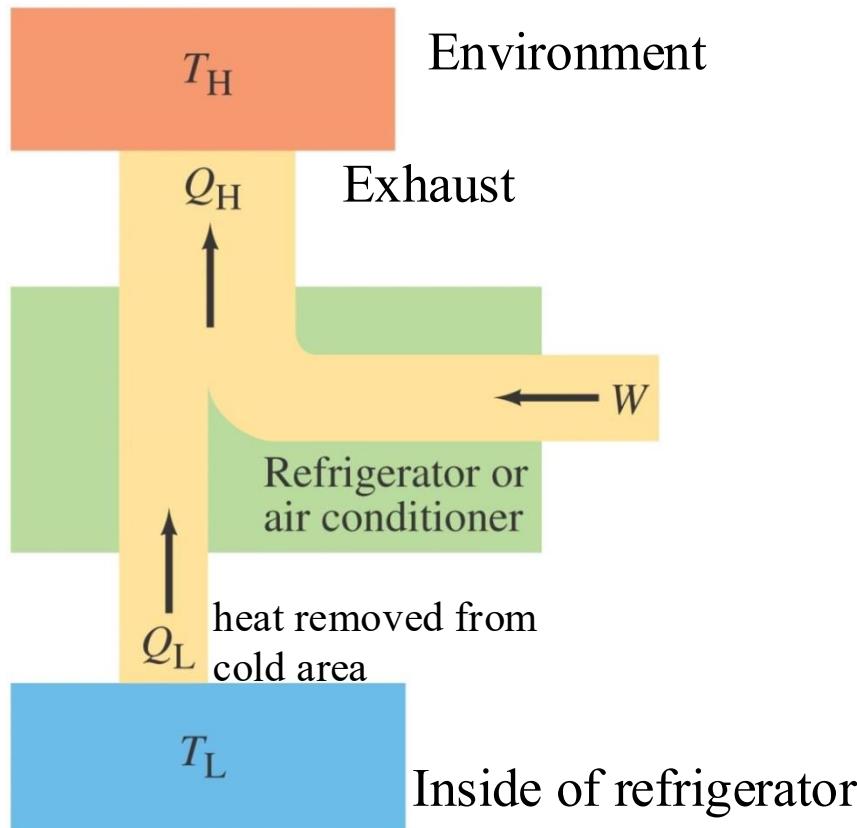
20-4 Refrigerator system (construction)



20-4 Working principle of refrigerator



20-4 Performance of Refrigerators



According to the Clausius statement of the 2nd law, a *perfect* refrigerator ($W = 0$) is NOT possible, i.e. work must be done.

Coefficient of performance (COP):

$$\text{COP} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}$$

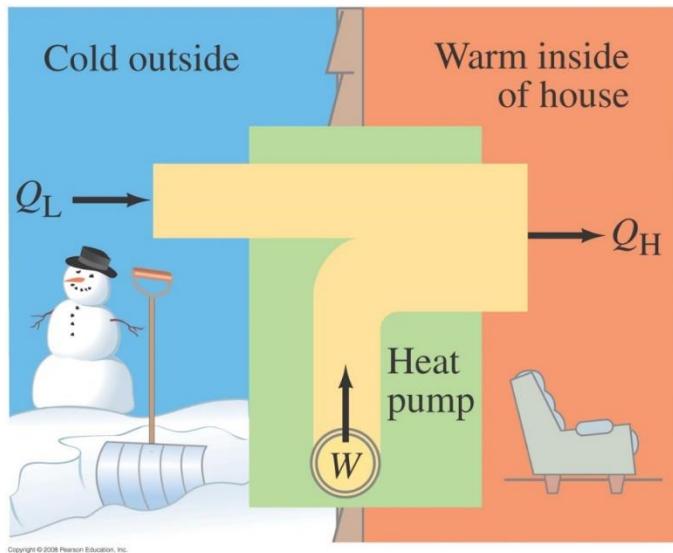
COP of *Ideal* refrigerator:

$$\text{COP}_{\text{ideal}} = \frac{T_L}{T_H - T_L}$$

Note: air conditioner works very much like a refrigerator.

20-4 Heat Pump

Operating principle of heat pump same as that of a refrigerator (or air conditioner), *but the objective is now to heat (Q_H) rather than to cool (Q_L).*



Hence, the **coefficient of performance (COP)** is

$$\text{COP} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} > 1$$

COP of ideal heat pump:

$$\text{COP}_{\text{ideal}}^{\text{heat pump}} = \frac{T_H}{T_H - T_L} = \frac{1}{1 - T_L / T_H} = 1 + \text{COP}_{\text{ideal}}^{\text{refrigerator}}$$

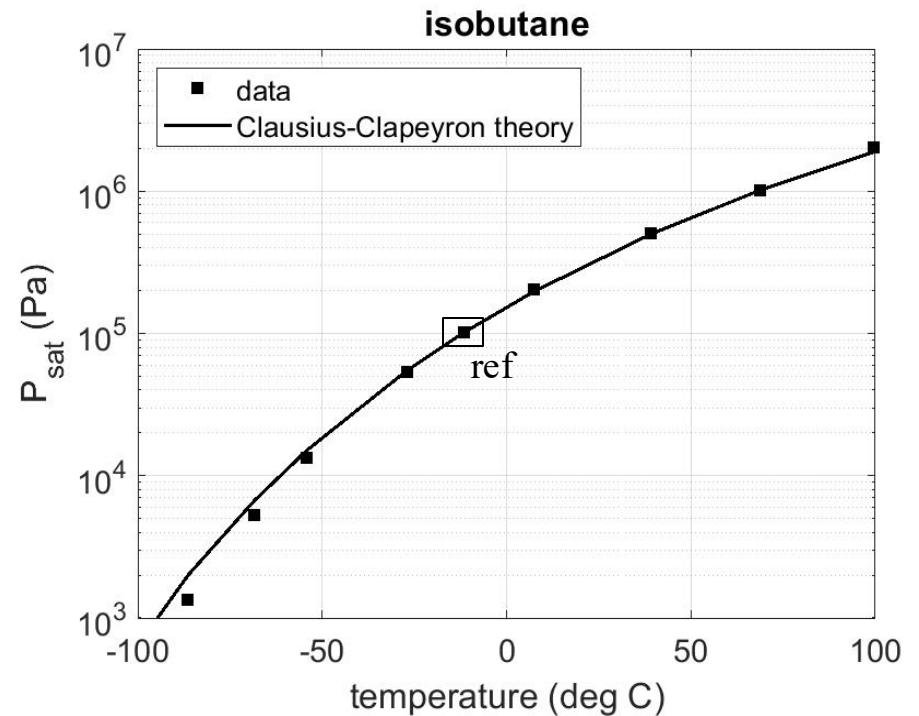
Note: a heat pump can be ‘turned around’ and used as an air conditioner (in summer)

20-4 Heat pump example

$$P = P_{ref} e^{-\frac{L_v}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)}$$

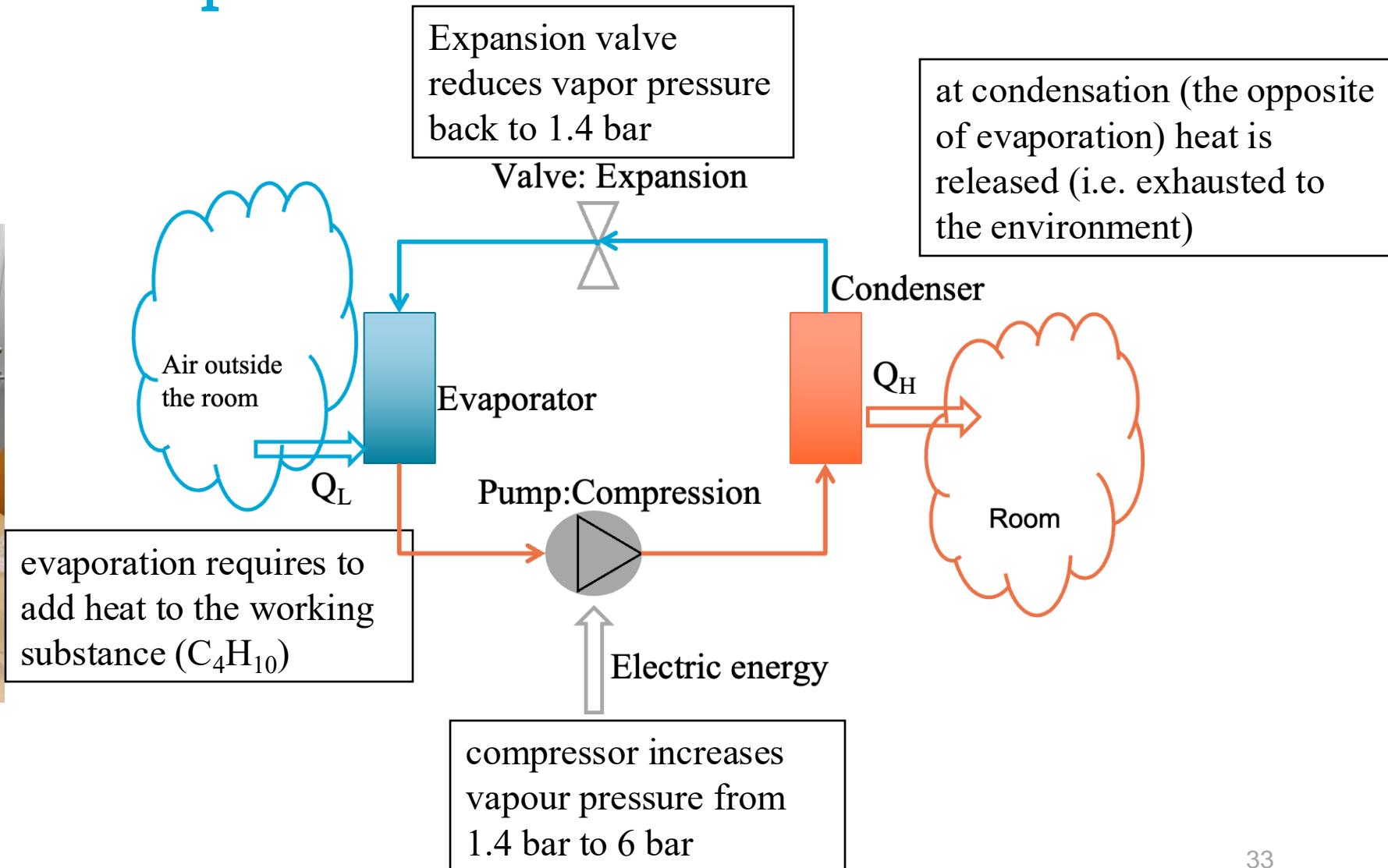


Pressure meter
Temperature sensor
Heat exchanger (filled with iso-butane (C_4H_{10}))



- Evaporator at 1.4 bar, -4.4 °C
- Condenser at 6 bar, 44.5 °C

20-4 Heat pump example



20-4 Heat pump example

Compressor power is 100 Watt. Calculate the COP of heat pump.



$$t = 60 \text{ s}$$

$$\text{Temperature at the start: } T_{\text{initial}} = 23.5 \text{ }^{\circ}\text{C}$$

$$\text{Temperature after 1 min: } T_{\text{end}} = 27 \text{ }^{\circ}\text{C}$$

$$c = 4186 \text{ J/kg} \cdot \text{K}$$

$$V = 900 \text{ ml}$$

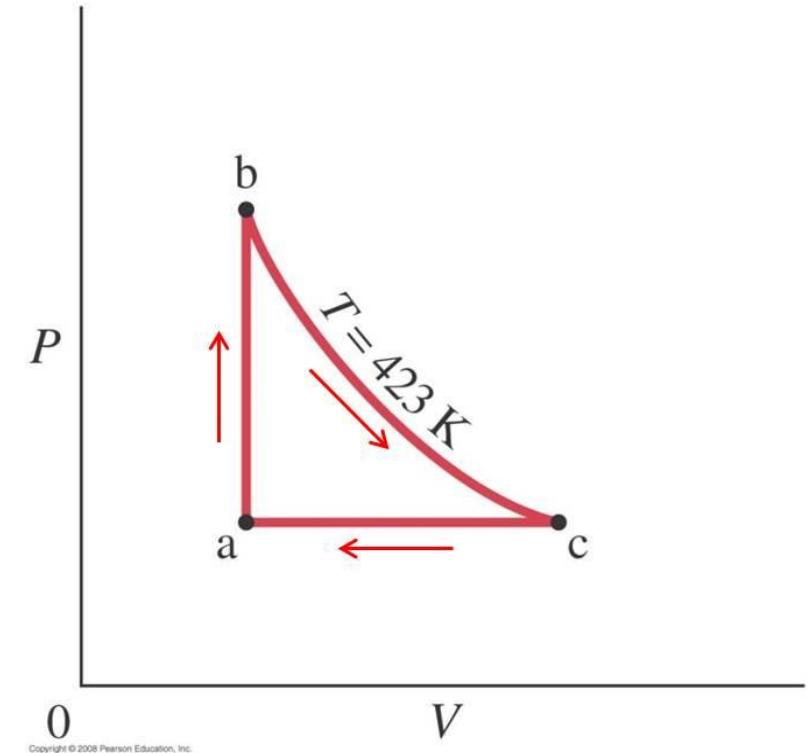
$$COP = \frac{Q_H}{W} = \frac{m \cdot c \cdot \Delta T}{100 \cdot t} = \frac{0.9 \text{ kg} * 4186 * 3.5 \text{ }^{\circ}\text{C}}{6000 \text{ J}} \approx 2.2$$

Recording of the experiments is available [here](#)

Exercise 1

The figure below is a PV diagram for a reversible heat engine in which 1.0 mol of argon (assumed to be an ideal gas) is initially at point a of STP ($T=0^\circ\text{ C}$, $P=101.3\text{ kPa}$). Points b and c are on an isotherm at 423 K. Process $a \rightarrow b$ is at constant volume, whereas process $c \rightarrow a$ is at constant pressure. The gas constant $R=8.314\text{ J/K/mol}$.

- (A) Determine the volume at point a, b and c.
- (B) Determine the work done during the entire process $a \rightarrow b \rightarrow c \rightarrow a$.
- (C) Determine the efficiency of this engine.



Exercise 1

$$V_a = \frac{nRT}{P} = 0.022 m^3$$

$$V_c = \frac{nRT}{P} = 0.035 m^3$$

$$V_b = V_a = 0.022 m^3$$

$$\Delta E_{ab} = Q_{ab} - W_{ab} = \frac{3}{2} nR(T_b - T_a) = 1.5 \times 1 mol \times 8.314 J/K \cdot mol \times (423 - 273) K = 1870.7 J = Q_{ab}$$

$$Q_{bc} = W_{bc} = 1632.9 J$$

$$Q_{ca} = \Delta E_{ca} + W_{ca} = \frac{3}{2} nR(T_a - T_c) - 1316.9 J = -3187.6 J$$

Work done a → b: $W_{ab} = \int P dV = 0 J$

Work done b → c: $W_{bc} = \int_{V_b}^{V_c} P dV = nRT \ln\left(\frac{V_c}{V_b}\right) = 1632.9 J$

Work done c → a: $W_{ca} = \int_{V_c}^{V_a} P dV = P(V_a - V_c) = -1316.9 J$

Total work done: $W_{tot} = W_{ab} + W_{bc} + W_{ca} = 316 J$

$$\eta = \frac{W_{tot}}{QH} = 9\%$$

Exercise 2 efficiency calculation

A typical A320 aircraft experiences 40 kN drag force in total when cruise at 11 km altitude with a speed of 850 km/hour. The aircraft is powered by two engines. Each engine burns 0.6 kg per second of Jet A fuel at this speed. The jet A releases 43 MJ per kilogram when burned. What is the efficiency per engine?

$$W = F \cdot v = \frac{40000N}{2} \times 850 \frac{km}{h} = 20000N \times \frac{236m}{s} = 4720 kW$$

$$Q/t = mf \cdot LHV = 0.25 \frac{kg}{s} \times 43000 \frac{kJ}{kg} = 10750 kW$$

$$\eta = \frac{W}{Q} = \frac{4720}{10750} \approx 44\%$$



CFM56 engine
for A320 aircraft

20-5 Entropy of reversible process—Clausius definition

- **Change in entropy** of a system when an amount of heat Q is added to it by a reversible process at constant T (Kelvin temperature):

$$\Delta S = \frac{Q}{T}$$

- When T is not constant then

$$dS = \frac{dQ}{T}$$

- Change in entropy of a system taken reversibly from state a to state b is

$$\Delta S = S_b - S_a = \int_a^b dS = \int_a^b \frac{dQ}{T}$$

This does not depend on the process: entropy is a state variable

Exercise 3: entropy calculation constant pressure

The volume of 2 mol of ideal diatomic gas doubles at a constant pressure. What is the entropy change?

$$dS = \frac{dQ}{T}$$

$$PV = nRT$$

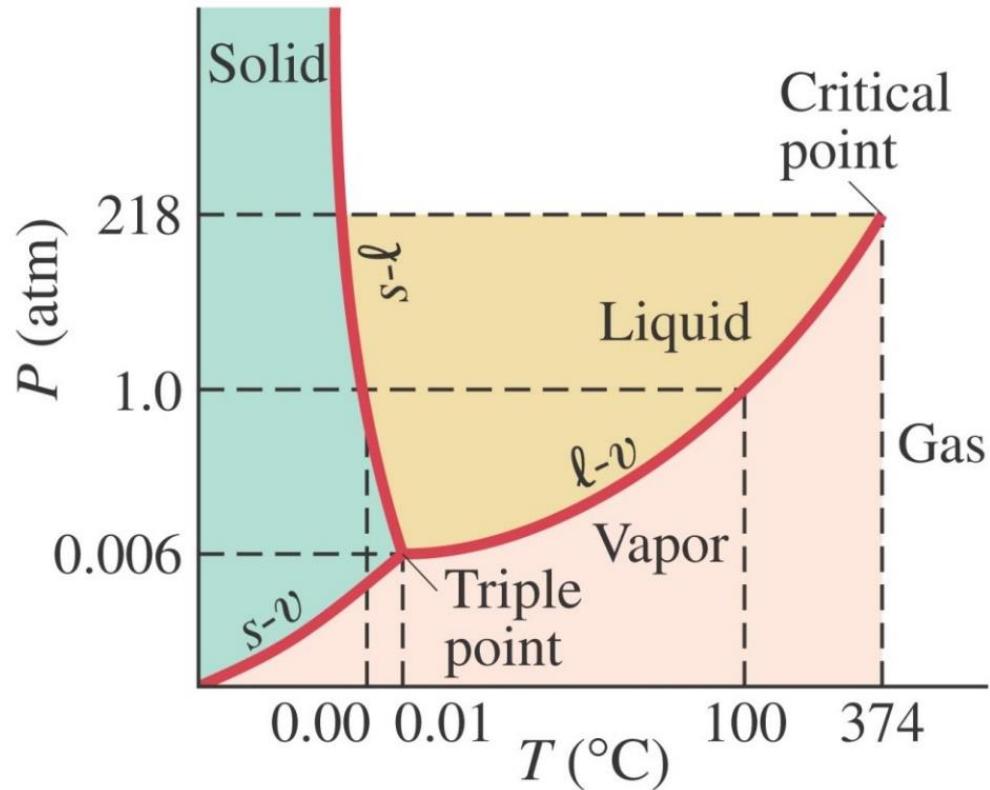
$$\frac{T_2}{T_1} = \frac{V_2}{V_1}$$

$$dQ = nCpdT$$

$$\Delta S = nCp \ln\left(\frac{T_2}{T_1}\right) = nCp \ln\left(\frac{V_2}{V_1}\right) = 2 * \frac{7}{2} R * \ln(2) = 40.3 \text{ J/K}$$

$$dS = nCp \frac{dT}{T}$$

Exercise 4: entropy change during phase change



Step 1: 1 kg of ice at -40 °C is heated to 0 °C
Step 2: Continue heating until all ice melts
Step 3: all liquid water is heated up to 100 °C
Step 4: Continue heating to evaporate

Calculate the entropy change per step.

Exercise 4: phase change

Step 1: $dS = \frac{mcdT}{T}$ $\Delta S = m \ln\left(\frac{T_2}{T_1}\right) = 332 J/K$

Step 2 constant temperature:

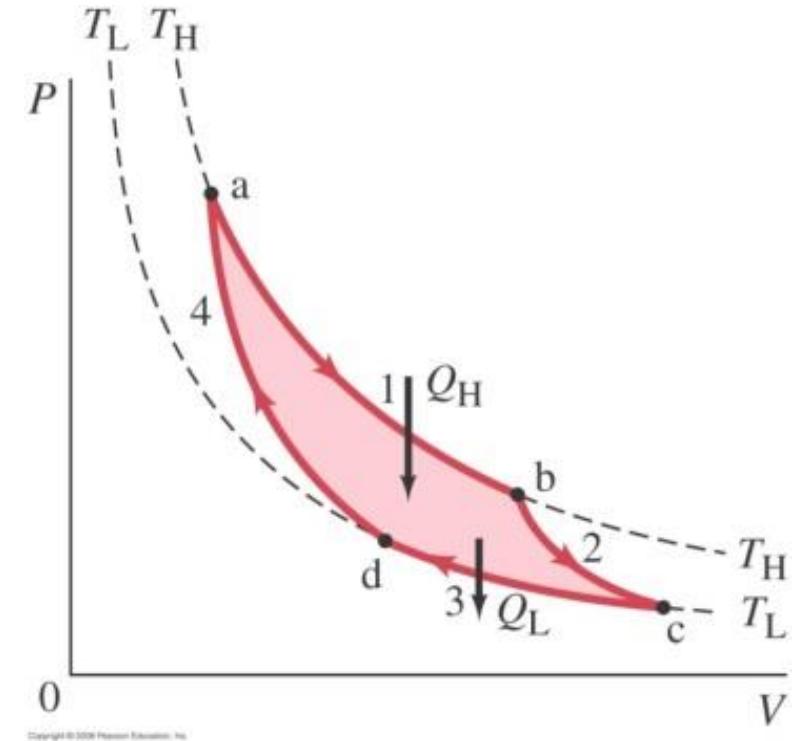
$$\Delta S = \frac{Q}{T} = \frac{mL}{T} = 1219 J/K$$

Step 3: $dS = \frac{mcdT}{T}$ $\Delta S = m \ln\left(\frac{T_2}{T_1}\right) = 1306 J/K$

Step 4 constant temperature: $\Delta S = \frac{Q}{T} = \frac{mL}{T} = 6059 J/K$

20-5 Entropy---state variable

- Consider a Carnot cycle with paths abc and adc .
- Path abc in the PV diagram: $\Delta S_{abc} = \frac{Q_H}{T_H} + 0$
- Path adc in the PV diagram: $\Delta S_{adc} = \frac{Q_L}{T_L} + 0$
- We already derived: $\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$

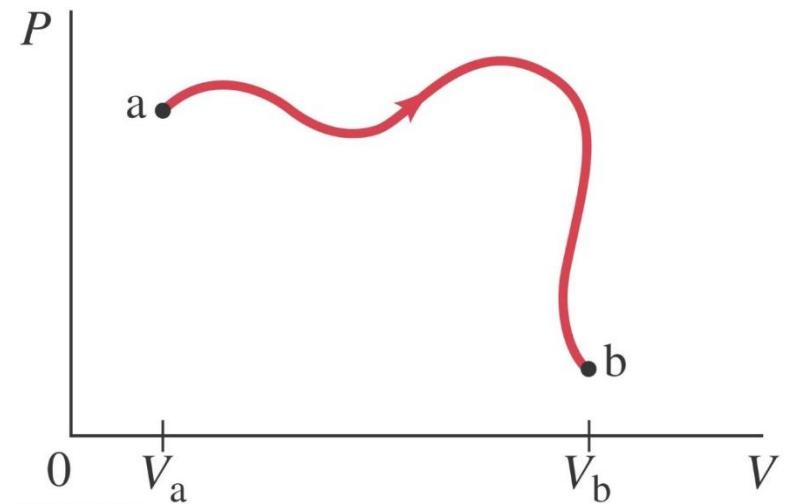


Hence, change in entropy is path independent.

Exercise 5: entropy calculation

Ideal gas of n moles undergoes a reversible process shown in the PV diagram. The temperature of the gas at points a and b is the same

what is the change in entropy of the gas?



Along the isothermal connecting a and b we have $\Delta E_{int} = 0$

and

$$Q = W = nRT \ln\left(\frac{V_b}{V_a}\right)$$

hence

$$\Delta S = \frac{Q}{T} = \frac{W}{T} = nR \ln\left(\frac{V_b}{V_a}\right)$$

20-6 Entropy of irreversible process

- Equation for entropy change ΔS can only be applied to reversible processes

$$\Delta S = S_b - S_a = \int_a^b \frac{dQ}{T}$$

- For real (i.e. irreversible) processes we take a reversible process that takes the system between the same two states
- This ΔS then also holds for the irreversible process, as ΔS only depends on the initial and final states

20-6 Entropy and the Second Law of Thermodynamics

- Entropy of the system plus that of the environment either stays constant (for any *reversible* process):

$$\Delta S_{total} = \Delta S_{sys} + \Delta S_{env} = 0$$

Or increase (real, i.e. *irreversible*, processes) $\Delta S_{total} = \Delta S_{sys} + \Delta S_{env} > 0$

General statement of the 2nd law of thermodynamics (which processes are observed in nature and which are not? tells us about the direction processes go)

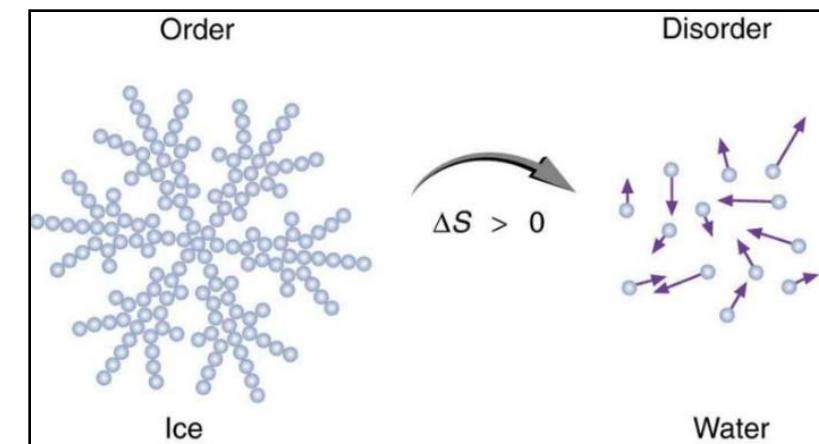
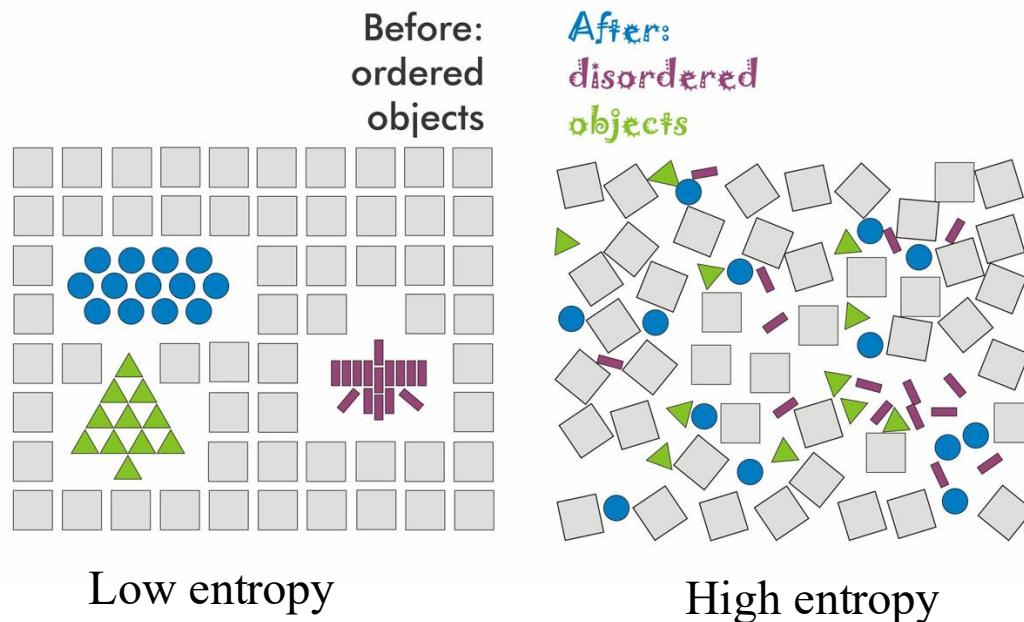
The entropy of an isolated system never decreases. It either stays constant (reversible process) or increases (irreversible process).

or (as all real processes are irreversible)

The total entropy of any system plus that of its environment increases as a result of any natural process: $\Delta S_{total} = \Delta S_{sys} + \Delta S_{env} > 0$

20-7 Entropy as description of disorder

- The entropy of a system can be considered a *measure of the disorder* of the system, i.e. the 2nd law can be stated as:
natural processes tend to move toward a state of greater disorder



Example: melting of ice at 0 °C:
entropy increases.

20-7 Order to Disorder

Hot object in contact with a colder object (see the previous example):

- Beginning: two classes of molecules can be distinguished (high and lower average kinetic energy)
- After the heat has flown: one class with the same average kinetic energy (less orderly)
- Further: when hot and cold objects serve as the two ‘regions’ of a heat engine, useful work can be obtained. when the two objects have reached the same temperature, no work can be obtained

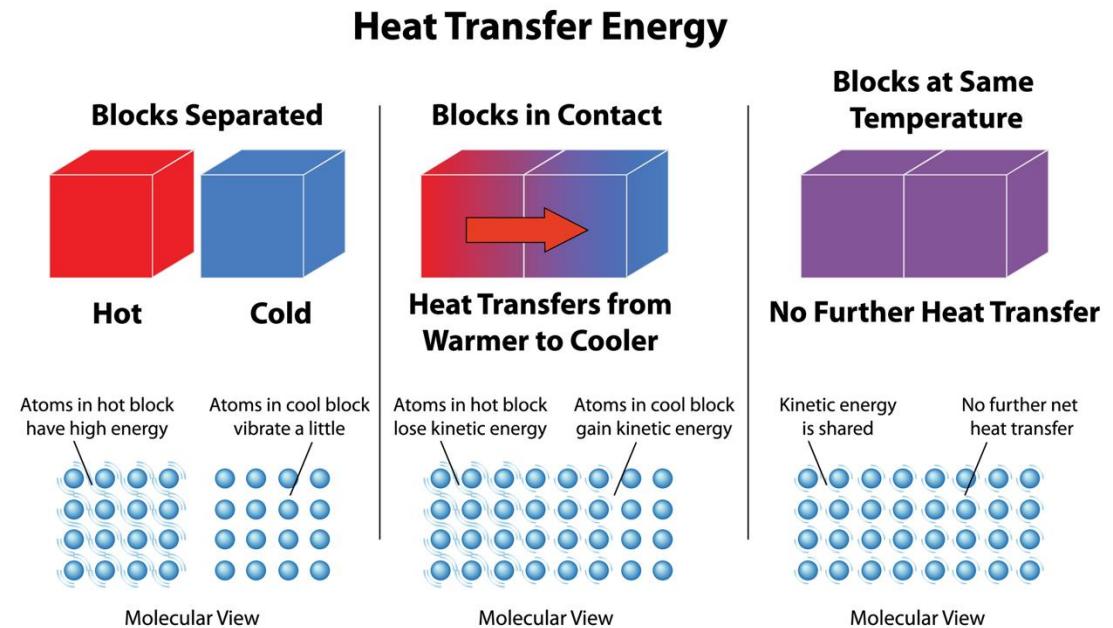


Image: OSweetNature/Shutterstock

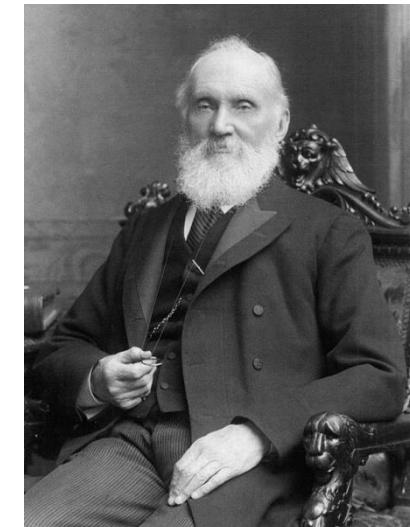
→ *a system that can perform work must have higher order than a system that cannot*

20-8 Unavailability of Energy; Heat Death

- In any natural process, some energy becomes unavailable to do useful work
- Energy is never lost (it is conserved cf. 1st law), but becomes less useful (i.e. can do less work).
- Energy is *degraded*, as it goes from more orderly forms (mechanical) to least orderly forms (thermal)
The amount of energy that becomes unavailable to do work is proportional to the change in entropy during any process

Consequence: as time goes on, the universe should approach a state of maximum disorder, the universe is then at one temperature, and no work could be done, as all energy is degraded to thermal energy

→ heat death of the universe



Lord Kelvin originated the idea of universal heat death in 1852

20-9 Statistical Interpretation of Entropy

Boltzmann makes a distinction between ‘macrostate’ and ‘microstate’ of a system.

- *microstate* is specified by giving the position and velocity of every molecule
- *macrostate* is specified by giving macroscopic properties like temperature and pressure

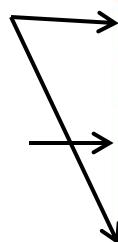
(we can only know the macrostate of a system, we **assume each microstate is equally probable**)

General: a large number of microstates correspond to the same macrostate.

Questions: How random are the possible microstates given a macrostate?

least probable,
highest order

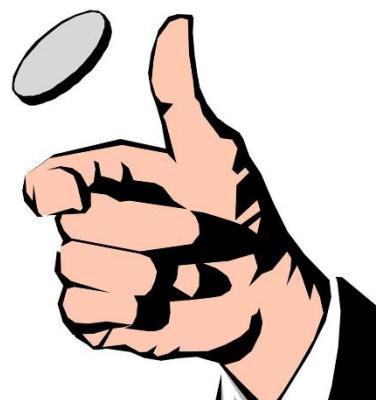
most probable,
lowest order



Macrostate	Possible Microstates (H = heads, T = tails)	Number of Microstates
4 heads	H H H H	1
3 heads, 1 tail	H H H T, H H T H, H T H H, T H H H	4
2 heads, 2 tails	H H T T, H T H T, T H H T, H T T H, T H T H, T T H H	6
1 head, 3 tails	T T T H, T T H T, T H T T, H T T T	4
4 tails	T T T T	1

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total # of microstates = 16



20-9 Statistical Interpretation of Entropy

least probable,
highest order

Macrostate		Number of Microstates	Probability
Heads	Tails		
100	0	1	7.9×10^{-31}
99	1	1.0×10^2	7.9×10^{-29}
90	10	1.7×10^{13}	1.4×10^{-17}
80	20	5.4×10^{20}	4.2×10^{-10}
60	40	1.4×10^{28}	0.01
55	45	6.1×10^{28}	0.05
50	50	1.0×10^{29}	0.08
45	55	6.1×10^{28}	0.05
40	60	1.4×10^{28}	0.01
20	80	5.4×10^{20}	4.2×10^{-10}
10	90	1.7×10^{13}	1.4×10^{-17}
1	99	1.0×10^2	7.9×10^{-29}
0	100	1	7.9×10^{-31}

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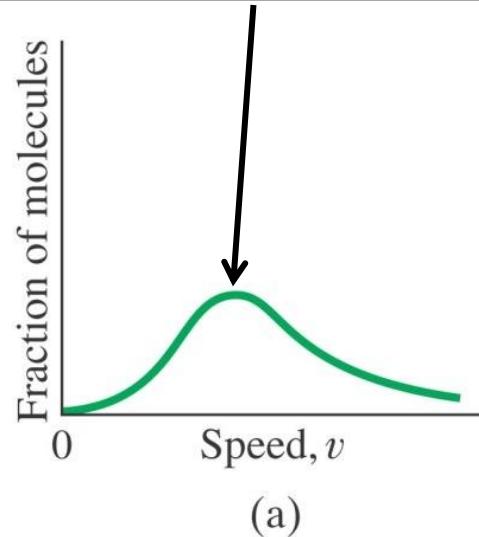


most probable,
lowest order

$$\text{total # of microstates} = 2^{100} = 1.3 \times 10^{30}$$

20-9 Statistical Interpretation of Entropy – Boltzmann description

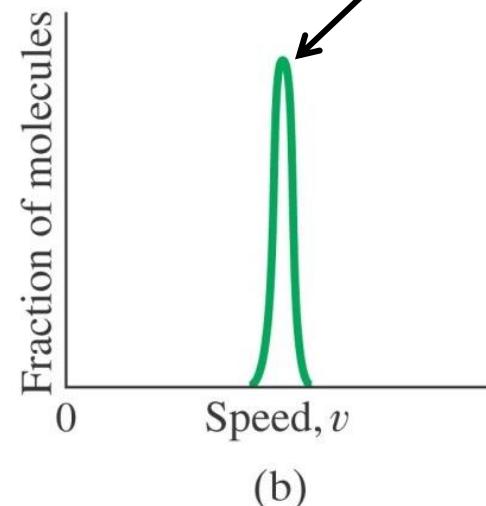
most probable state of a gas: molecules take up whole space and move randomly (Maxwell velocity distribution)



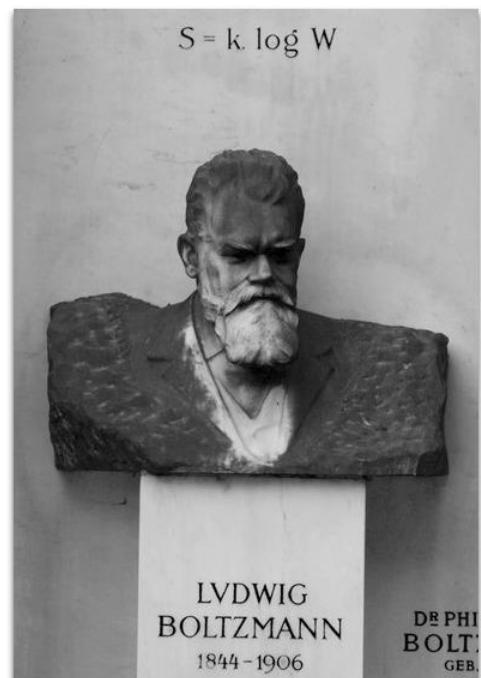
(a)

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Very unlikely: orderly arrangement of all molecules in a corner of the space, all moving with same velocity



(b)

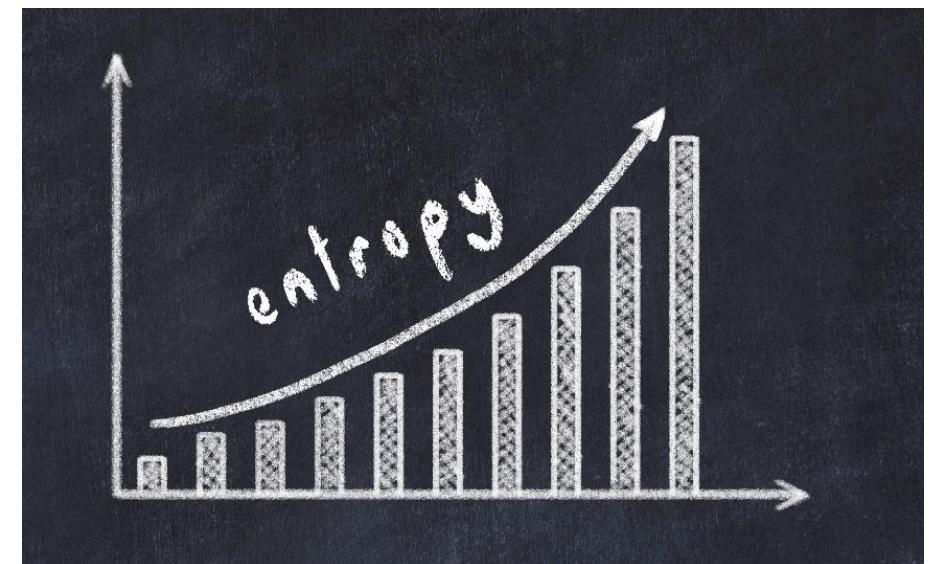


Most probable state = state with greatest entropy = state with greatest disorder

$$S = k \ln w$$

20-9 Statistical Interpretation of Entropy and the Second Law

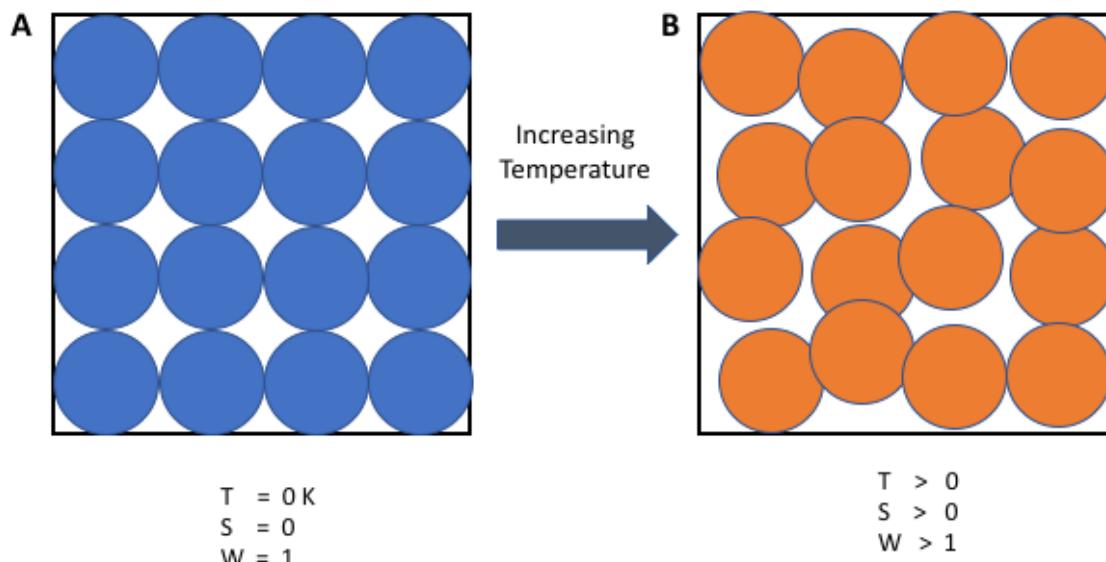
In terms of probability, 2nd law states that processes occur which are most probable and *does not forbid* a decrease in entropy, rather it says that the probability is extremely low



20-10 Thermodynamic Temperature; Third Law of Thermodynamics

The third law of thermodynamics:

It is not possible to reach absolute zero in any finite number of processes



$$e = 1 - \frac{T_L}{T_H} < 1$$

20-11 Thermal Pollution

Solar energy installation



(a)

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fossil fuel steam plants



(b)

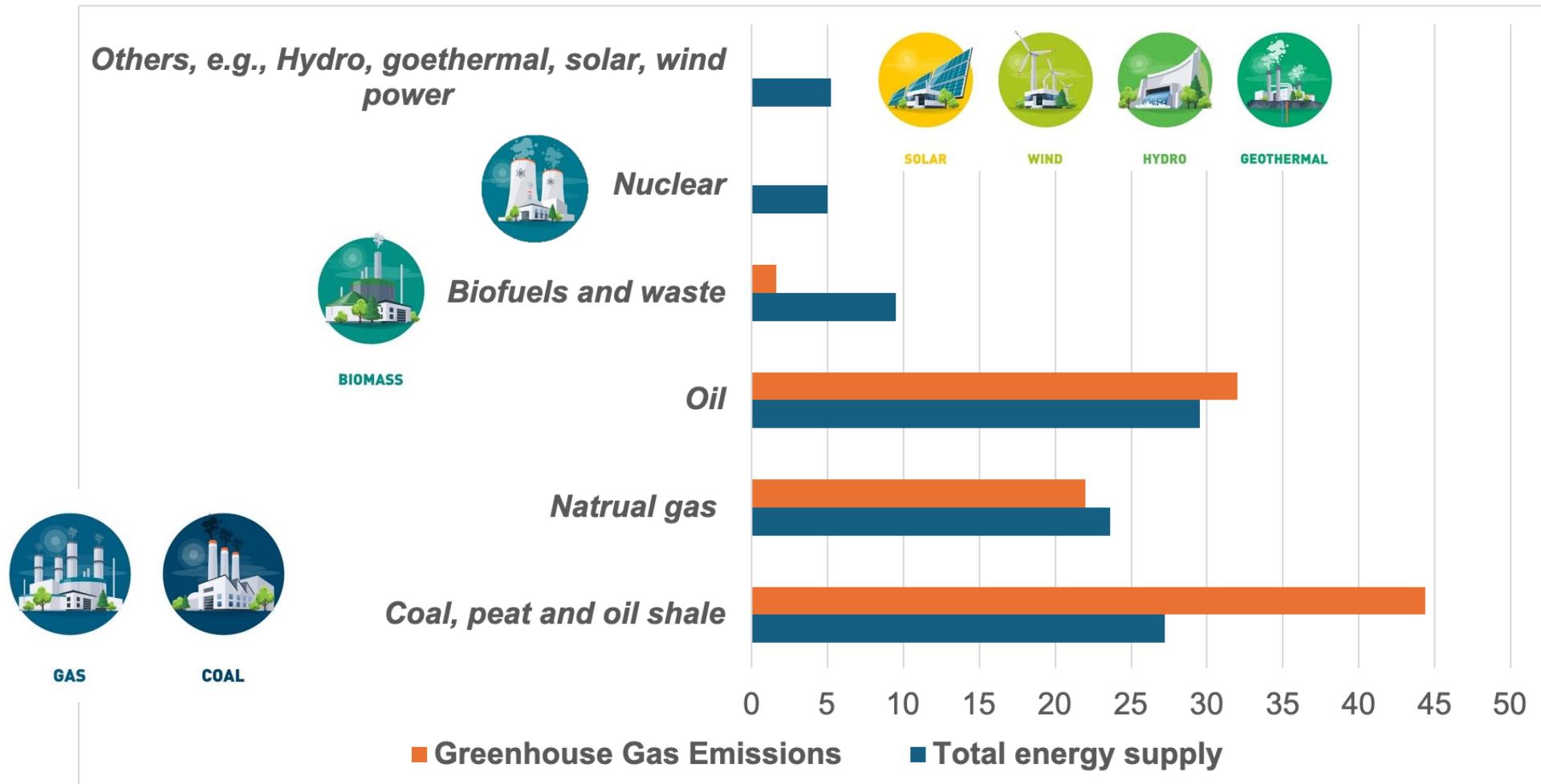
cooling towers electric generating plant



(c)

- Most of the energy we utilize makes use of a heat engine (fossil fuel steam plants, nuclear power plants)
- Q_L (absorbed by the environment), called *thermal pollution* (unavoidable)

20-11 Electric energy resources world in 2021 (compare to Table 20-3)



Global CO₂ emission

Annual CO₂ emissions

Carbon dioxide (CO₂) emissions from fossil fuels and industry¹. Land-use change is not included.

40 billion t

35 billion t

30 billion t

25 billion t

20 billion t

15 billion t

10 billion t

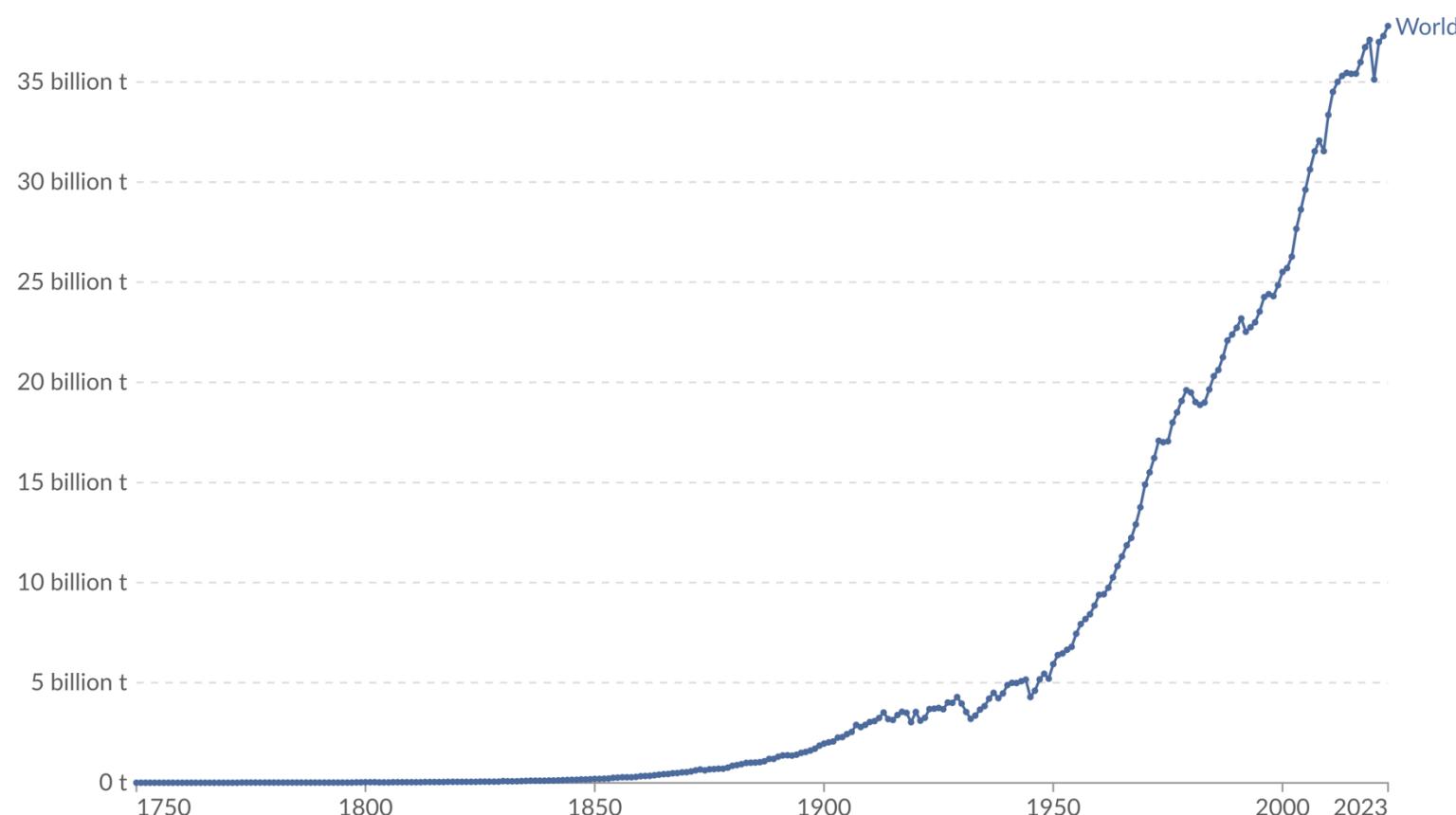
5 billion t

0 t

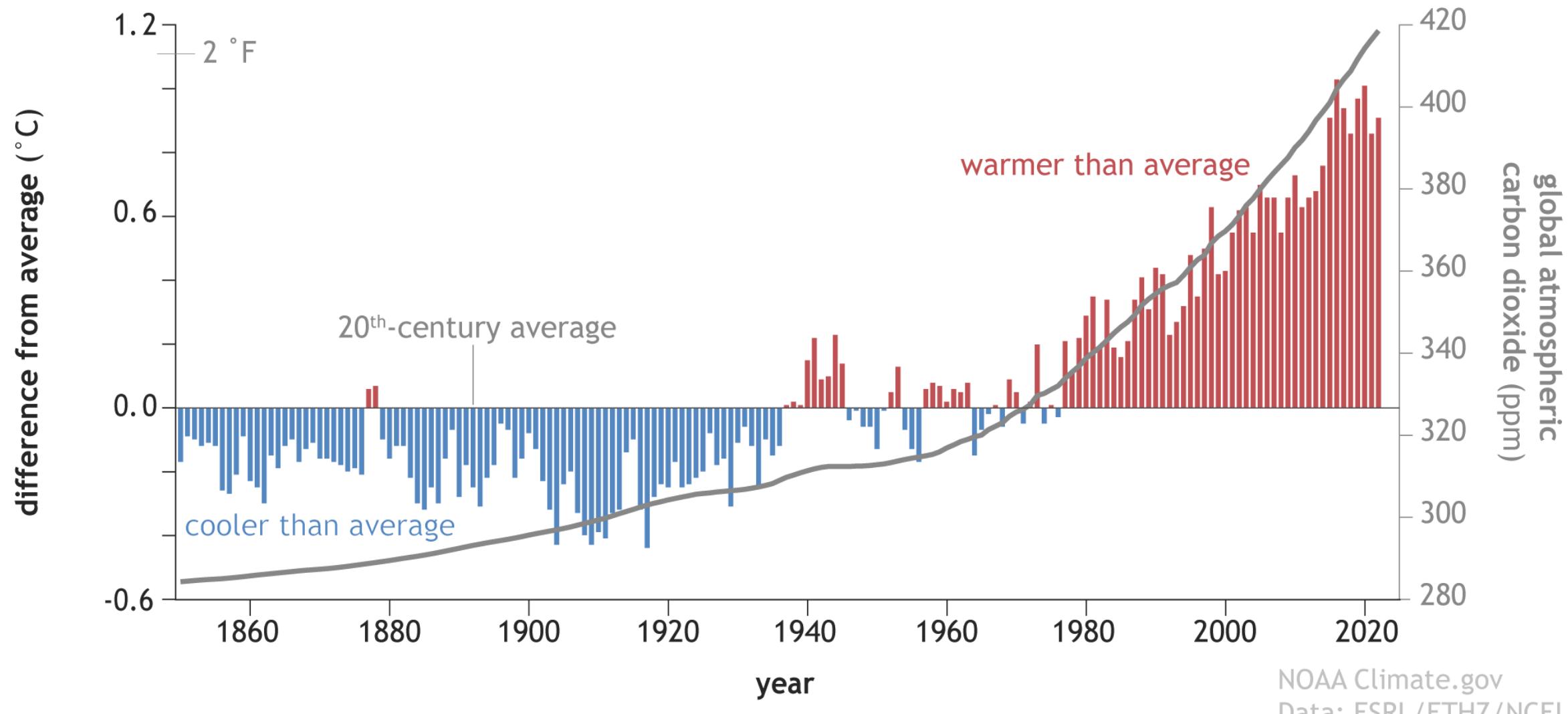
Data source: Global Carbon Budget (2024)

OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

1. **Fossil emissions:** Fossil emissions measure the quantity of carbon dioxide (CO₂) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO₂ includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.



Yearly global surface temperature and atmospheric carbon dioxide (1850-2022)



Global warming Solar radiation

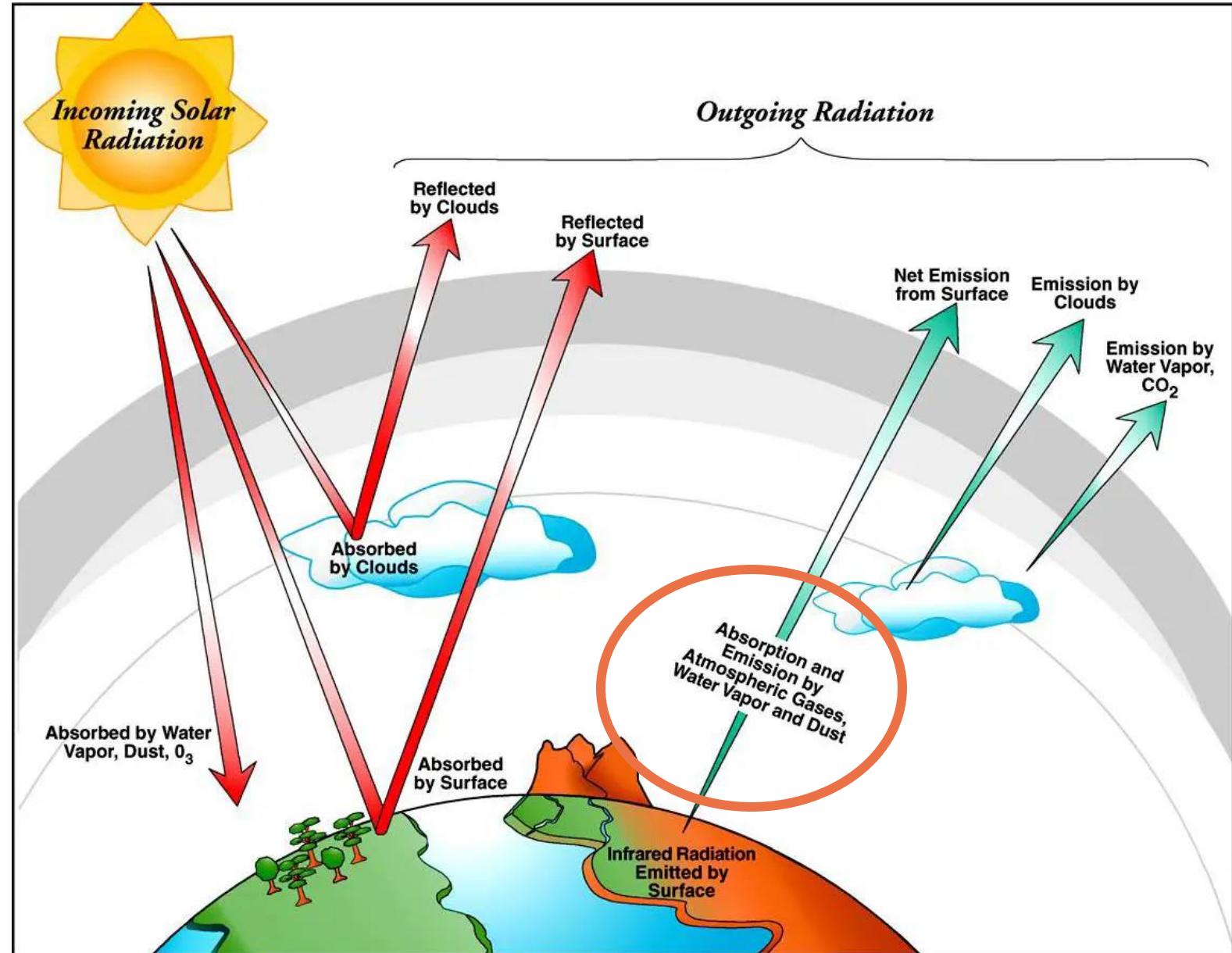
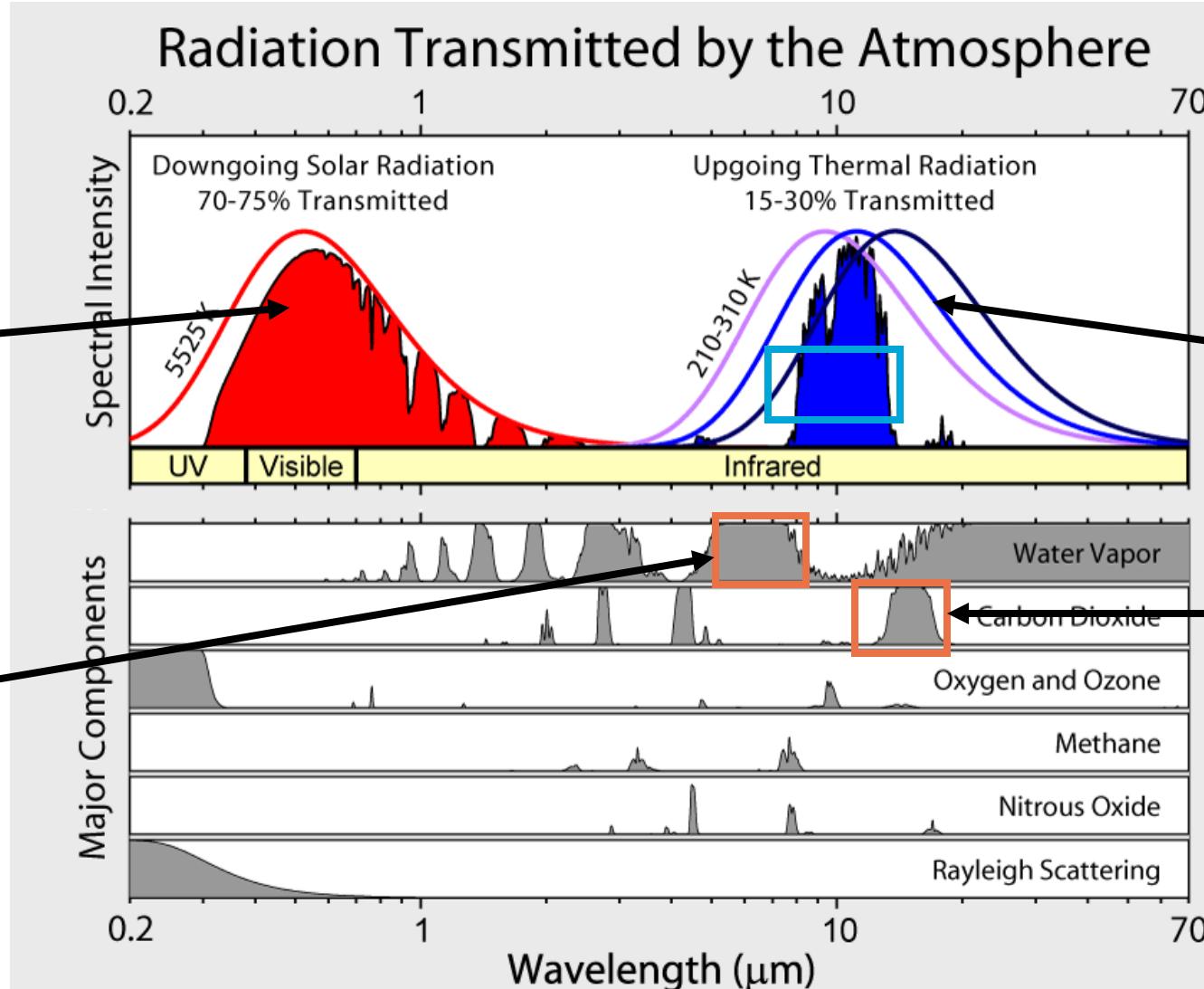


Image courtesy of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility

Global warming

Incoming shortwave radiation

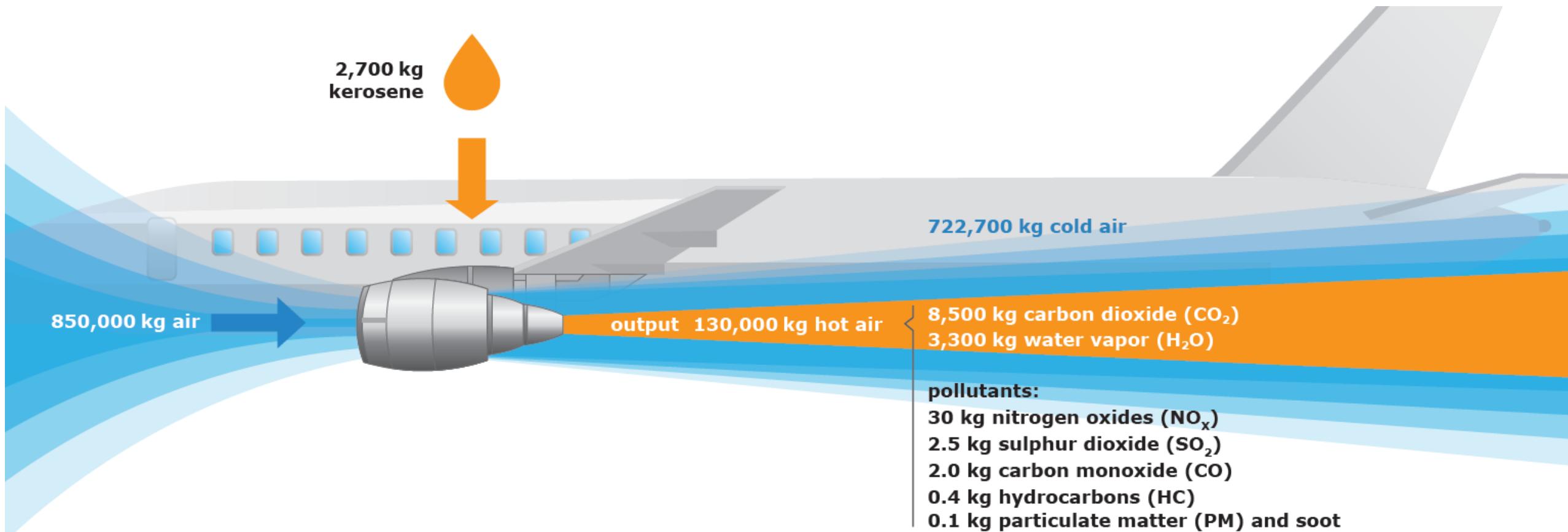
Absorption by water vapor



Outgoing longwave radiation

Absorption by CO₂

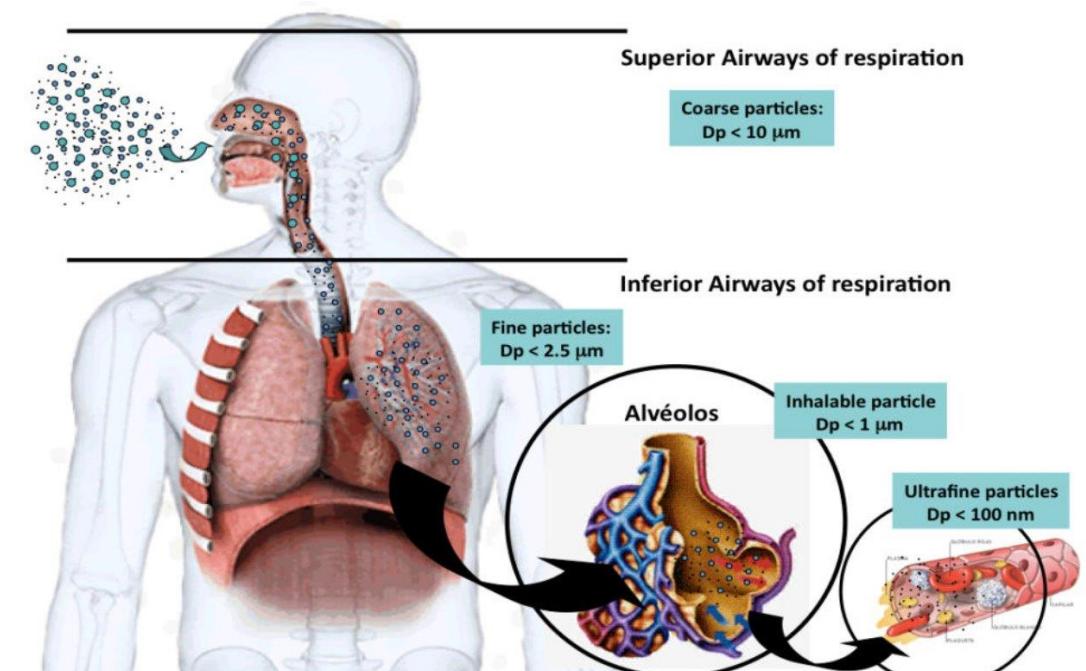
Typical aircraft emissions



20-11 Air Pollution

Particulate Matter (PM)

- Premature mortality
- Aggravation of respiratory and cardiovascular disease
- Changes in lung function
- Increased respiratory symptoms
- Changes to lung tissues and structure
- Altered respiratory defense mechanisms



Guarieiro & Guarieiro 2013

Common distinguish:

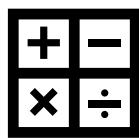
- PM0.1 – Sum of all particles smaller 0.1 μm (ultra fine particles, UFPs)
- PM2.5 – Sum of all particles smaller 2.5 μm
- PM10 – Sum of all particles smaller 10 μm

Wrap up: Learning objective

After today's lecture, you should be able to:



- Understand the concept of **entropy** and the **2nd law of thermodynamics**
→ Spontaneous heat flow; no 100% efficient heat engine; order vs. disorder
- Understand the working principle of heat engines, refrigerator, air conditioning, heat pump
- Evaluate the **performance** of different applicants (e.g., refrigerator, air conditioning and heat pump)



$$COP_{ref} = \frac{Q_L}{W}$$

$$COP_{heat\ pump} = \frac{Q_H}{W}$$

- Calculate the **entropy change** of a given thermodynamic cycle (e.g., Canon cycle)

$$\Delta S = \frac{Q}{T} \quad dS = \frac{dQ}{T}$$

- Calculate **efficiency** of different thermodynamic cycles $\eta = 1 - \frac{Q_L}{Q_H} = \frac{W}{Q_H}$



Thank you for your attention!

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