Physics 101: Lecture 29
Thermodynamics II: Engines & refrigerators

Recap:

➔ 1st Law of Thermodynamics

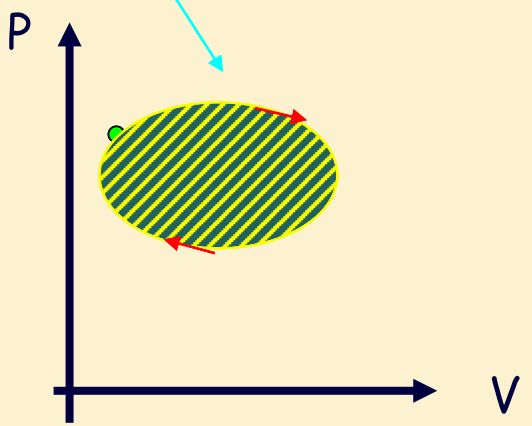
➔ energy conservation

$$Q = \Delta U + W$$

Work done by system

Change in internal energy of system

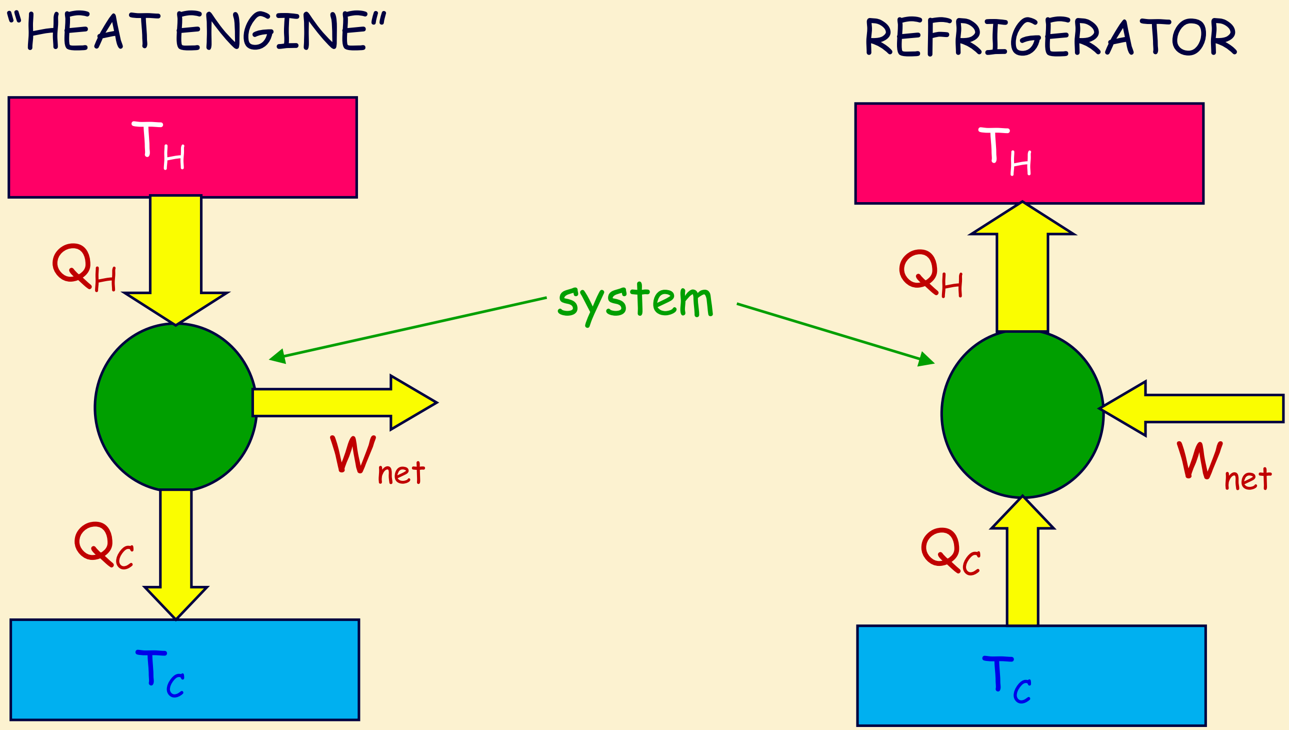
Heat flow into system



- U depends only on T ($U = 3nRT/2 = 3PV/2$)
- point on p-V plot completely specifies state of system ($PV = nRT$)
- work done is area under curve
- for a complete cycle

$$\Delta U=0 \Rightarrow Q=W$$

Engines and Refrigerators



- system taken in closed cycle $\Rightarrow \Delta U_{system} = 0$
- therefore, net heat absorbed = work done by system

$Q_H = Q_C + W_{net}$ (Engine)

$Q_C + W_{net} = Q_H$ (Refrigerator)

energy into green blob = energy leaving green blob

Heat Engine: Efficiency

The objective: turn heat from hot reservoir into work

The cost: "waste heat"

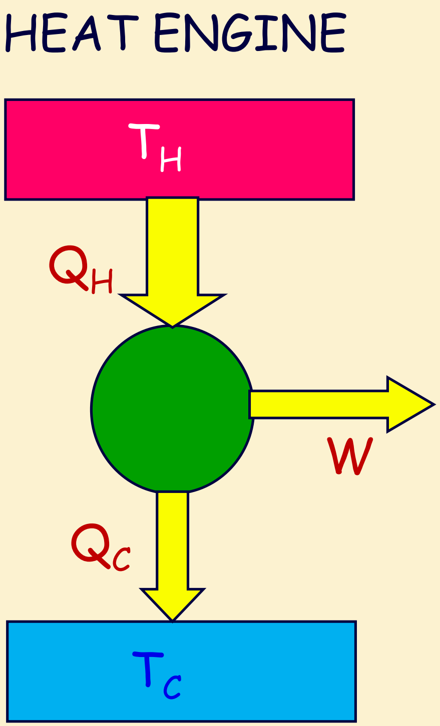
1st Law: $Q_H - Q_C = W$

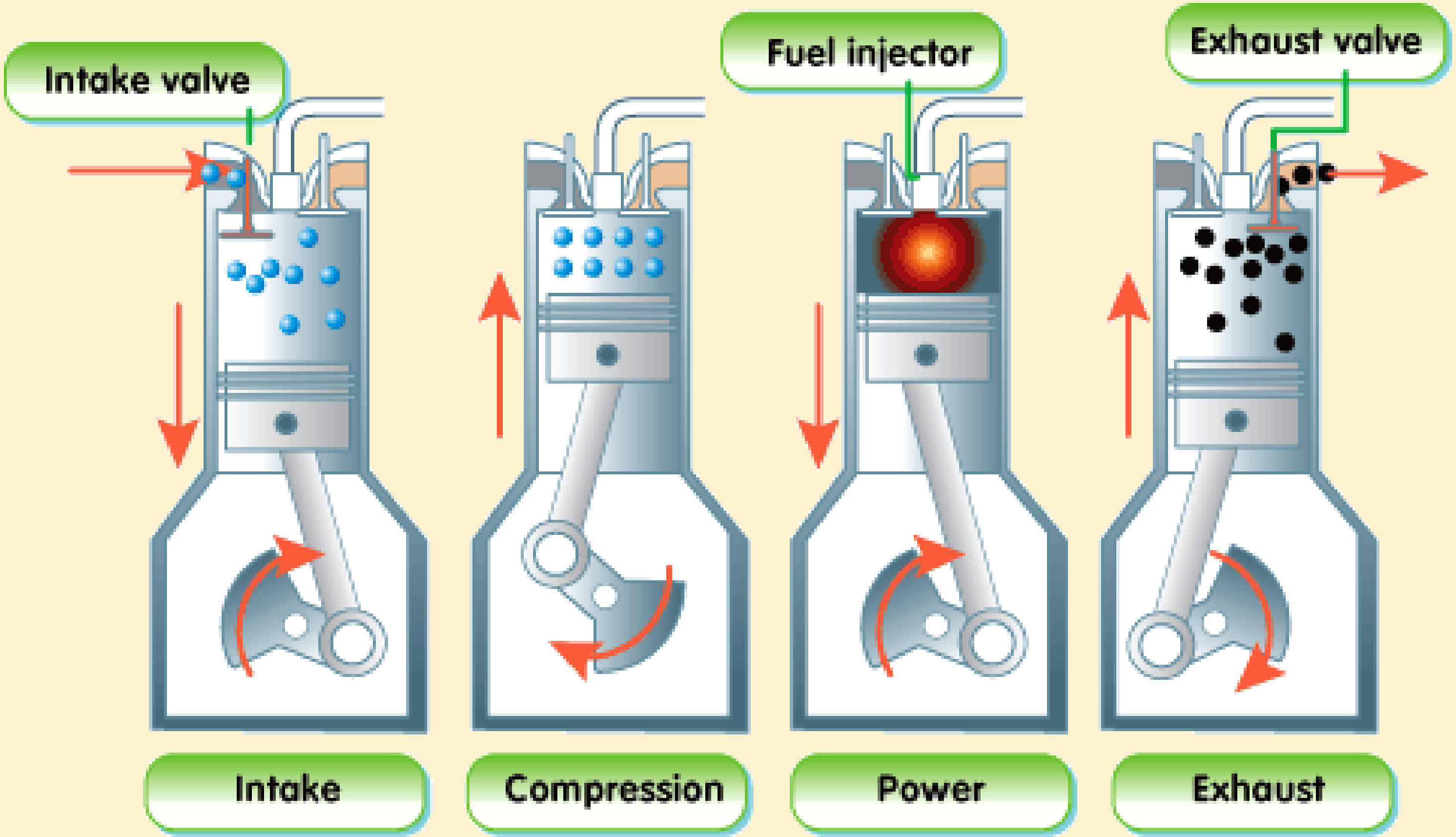
efficiency *definition*: $e \equiv W/Q_H$

$= W/Q_H$

$= (Q_H - Q_C)/Q_H$

$= 1 - Q_C/Q_H$




Intake valve
Fuel injector
Exhaust valve
Intake
Compression
Power
Exhaust

Heat Engine Clicker Q

- Can you get "work" out of a heat engine, if the hottest thing you have is at room temperature?

1) Yes

2) No

Rate of Heat Exhaustion

An engine operating at 25% efficiency produces work at a rate of 0.10 MW. At what rate is heat exhausted into the surrounding?

Efficiency $e = W_{net}/Q_H \Rightarrow Q_H = W_{net}/e$

The question is asking for $Q_C/\Delta t$.

$Q_H/t = (W_{net}/t)/e = 0.10\ \text{MW}/0.25 = 0.40\ \text{MW}$

From 1st Law of Thermo: $W_{net} = Q_H - Q_C$; divide by Δt:

$W_{net}/\Delta t = (Q_H - Q_C)/\Delta t$

$0.10\ \text{MW} = 0.40\ \text{MW} - Q_C/\Delta t$

$Q_C/\Delta t = 0.40\ \text{MW} - 0.10\ \text{MW} = 0.3\ \text{MW}$

Refrigerator: Coefficient of Performance

The objective: remove heat from cold reservoir

The cost: work

1st Law: $Q_H = W + Q_C$

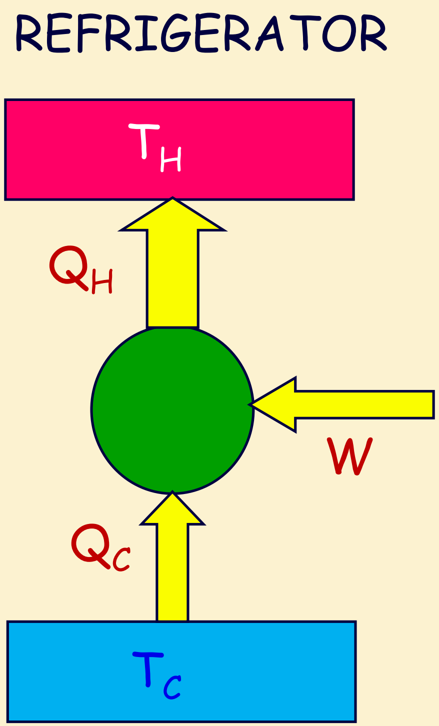
coefficient of performance

$$CP \equiv Q_C/W$$

$$= Q_C/(Q_H - Q_C)$$

Best CP you can have is Carnot coeff. of performance (more on Carnot in 4 slides):

$$CP_{Carnot} = T_C/(T_H - T_C)$$



Entropy (S)

- A measure of "disorder" (more entropy means more disorder)
- A property of a system (just like P, V, T, U)
  - ➔related to number of number of different possible "states" of system
- Examples of increasing entropy:
  - ➔ice cube melts
  - ➔gases expand into vacuum (recall demo of vacuum cannon)
- Change in entropy:
  - ➔$\Delta S = Q/T$
    - » > 0 if heat flows into system ($Q > 0$)
    - » < 0 if heat flows out of system ($Q < 0$)

Clicker Questions

A hot (98 C) slab of metal is placed in a cool (5C) bucket of water.

$\Delta S = Q/T$

What happens to the entropy of the metal?

A) Increases B) Same C) Decreases

What happens to the entropy of the water?

A) Increases B) Same C) Decreases

What happens to the total entropy (water+metal)?

A) Increases B) Same C) Decreases

A word on the Checkpoint Q on mixing yellow and blue water

- Process is irreversible—the mixing creates a batch of green water that we cannot separate back into two batches of blue and yellow water, so entropy increases.
- Another way to look at it. Big batch of water has more space for molecules to move around than the two smaller batches so it is more disordered.

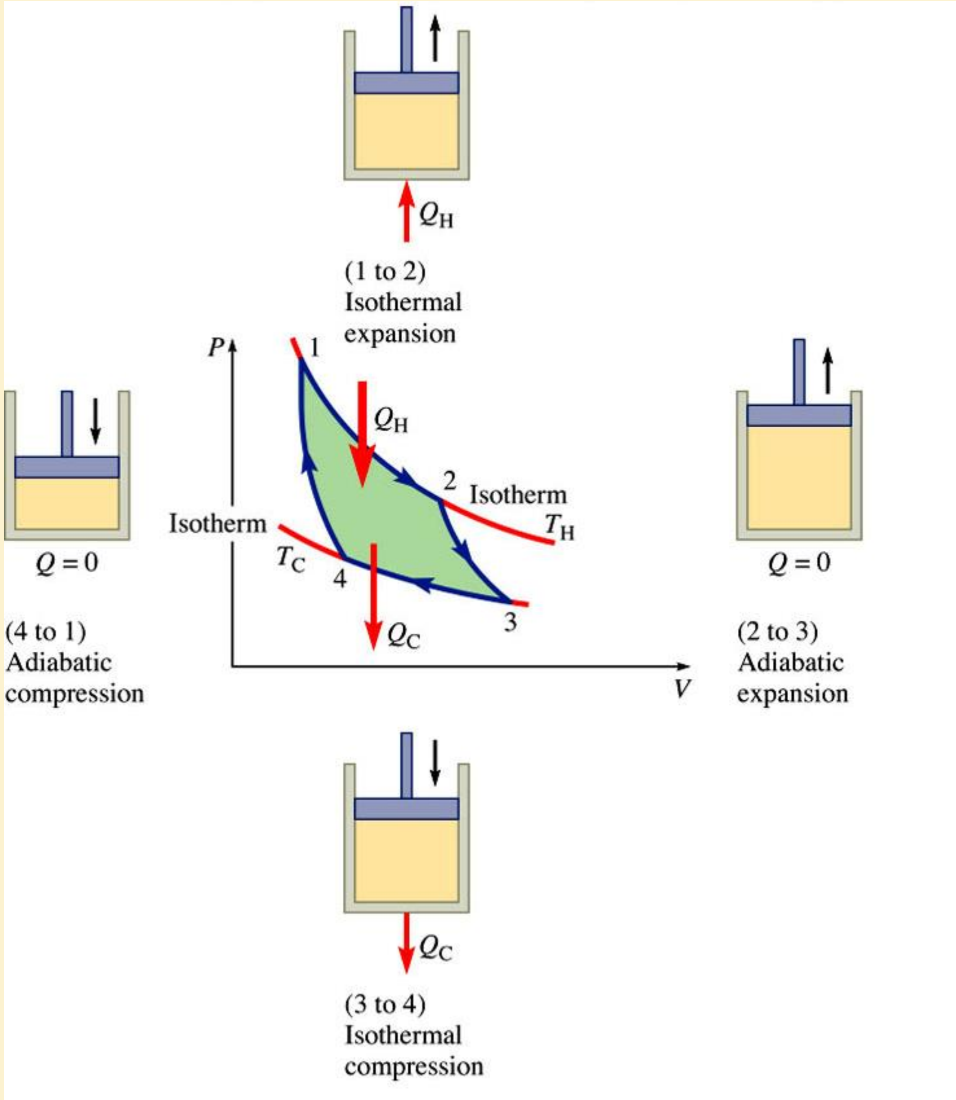
- Answers to Checkpoint: 1. A 2. D 3. A
- (To answer 3, use last equation is slide 8: “refrigerators” from the last prelecture, or last eqn on slide 8 in this lecture, to compare impact of raising T_C by 10 or lowering T_H by 10)

Second Law of Thermodynamics

- The entropy change (Q/T) of the system+**environment** ≥ 0
  - ➔ never < 0
  - ➔ order to disorder
- Consequences
  - ➔ A “disordered” state cannot spontaneously transform into an “ordered” state
  - ➔ No engine operating between two reservoirs can be more efficient than one that produces 0 change in entropy. This is called a “Carnot engine”

Carnot Cycle

- Idealized Heat Engine
  - ➔ No Friction
  - ➔ $\Delta S = Q/T = 0$
  - ➔ Reversible Process
    - » Isothermal Expansion
    - » Adiabatic Expansion
    - » Isothermal Compression
    - » Adiabatic Compression



Engines and the 2nd Law

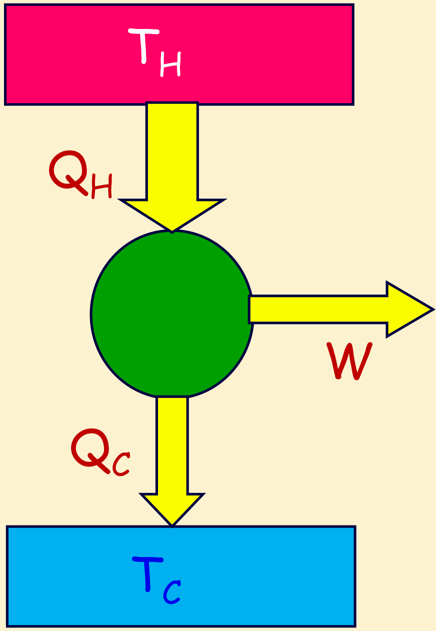
The objective: turn heat from hot reservoir into work

The cost: “waste heat”

1st Law: $Q_H - Q_C = W$

efficiency $e \equiv W/Q_H = (Q_H - Q_C)/Q_H$

HEAT ENGINE



$\Delta S = Q_C/T_C - Q_H/T_H \geq 0$

$\Delta S = 0$ for Carnot

Therefore, $Q_C/Q_H \geq T_C/T_H$

$Q_C/Q_H = T_C/T_H$ for Carnot

Therefore $e = 1 - Q_C/Q_H \leq 1 - T_C/T_H$

$e = 1 - T_C/T_H$ for Carnot

$e = 1$ is forbidden!

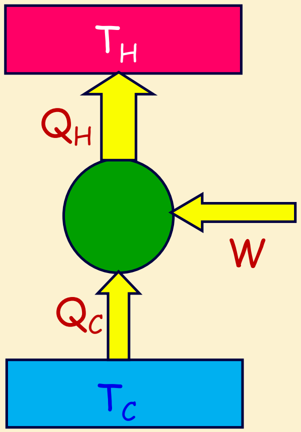
e largest if $T_C \ll T_H$

Example 1

Consider a hypothetical refrigerator that takes 1000 J of heat from a cold reservoir at 100K and ejects 1200 J of heat to a hot reservoir at 300K.

Answers:

1. How much work does the refrigerator do? — 200 J
2. What happens to the entropy of the universe? — Decreases
3. Does this violate the 2nd law of thermodynamics? — yes



$Q_C = 1000$ J

$Q_H = 1200$ J

Since $Q_C + W = Q_H$, $W = 200$ J

$\Delta S_H = Q_H/T_H = (1200\ \text{J}) / (300\ \text{K}) = 4\ \text{J/K}$

$\Delta S_C = -Q_C/T_C = (-1000\ \text{J}) / (100\ \text{K}) = -10\ \text{J/K}$

$\Delta S_{TOTAL} = \Delta S_H + \Delta S_C = -6\ \text{J/K}$ ➔ decreases (violates 2nd law)

Example 2

Consider a hypothetical device that takes 1000 J of heat from a hot reservoir at 300K, ejects 200 J of heat to a cold reservoir at 100K, and produces 800 J of work.

Does this device violate **the second law** of thermodynamics ?

1. Yes ⟵ correct

2. No

total entropy decreases.

$\Delta S_H = Q_H/T_H = (1000\ J) / (300\ K) = 3.33\ J/K$

$\Delta S_C = Q_C/T_C = (200\ J) / (100\ K) = 2\ J/K$

$\Delta S_{TOTAL} = \Delta S_C - \Delta S_H = -1.33\ J/K$ → (violates 2nd law)

- $W (800) = Q_{hot} (1000) - Q_{cold} (200)$
- Efficiency = $W/Q_{hot} = 800/1000 = 80\%$
- Max eff = $1 - T_c/T_h = 1 - 100/300 = 67\%$

Clicker Q

Which of the following is forbidden by the second law of thermodynamics?

1. Heat flows into a gas and the temperature falls
2. The temperature of a gas rises without any heat flowing into it
3. Heat flows spontaneously from a cold to a hot reservoir
4. All of the above

Summary

- **First Law** of thermodynamics: Energy Conservation
  - ➔ $Q = \Delta U + W$
- Heat Engines
  - ➔ Efficiency = = 1- Q_C/Q_H
- Refrigerators
  - ➔ Coefficient of Performance = $Q_C/(Q_H - Q_C)$
- Entropy $\Delta S = Q/T$
- **Second Law**: Entropy always increases!
- Carnot Cycle: Reversible, Maximum Efficiency $e = 1 – T_c/T_h$

It has been a pleasure teaching this class!