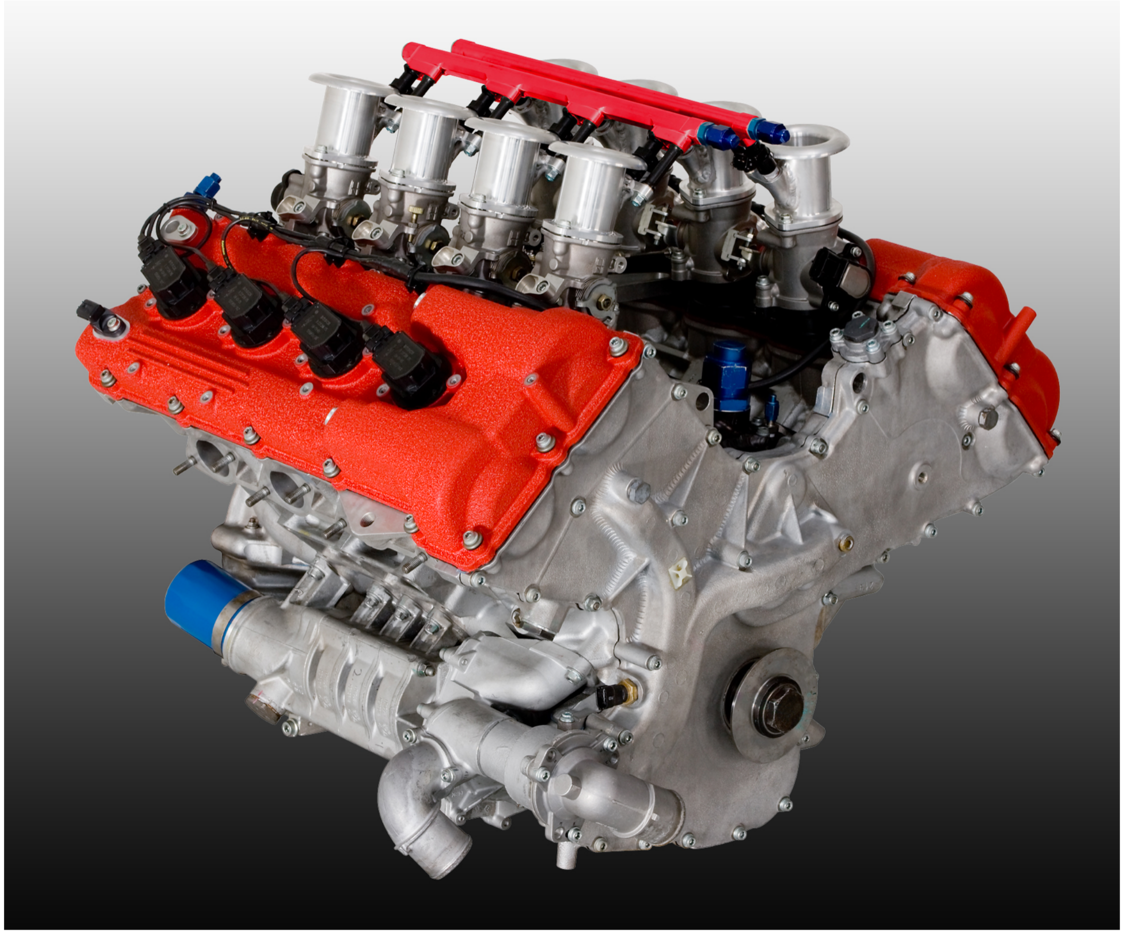
Physics 101: Lecture 29
Thermodynamics II



Recap:

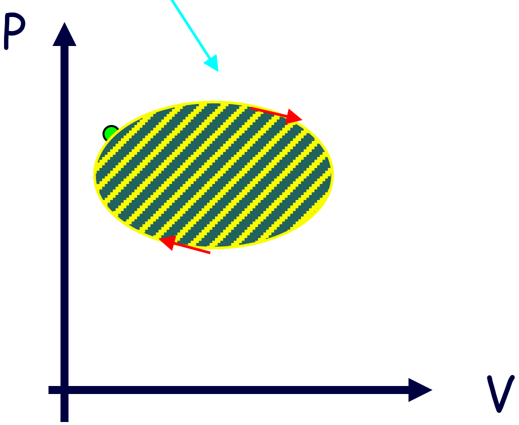
- 1st Law of Thermodynamics
- energy conservation

$$Q = \Delta U + W$$

Work done by system

Change in internal energy of system

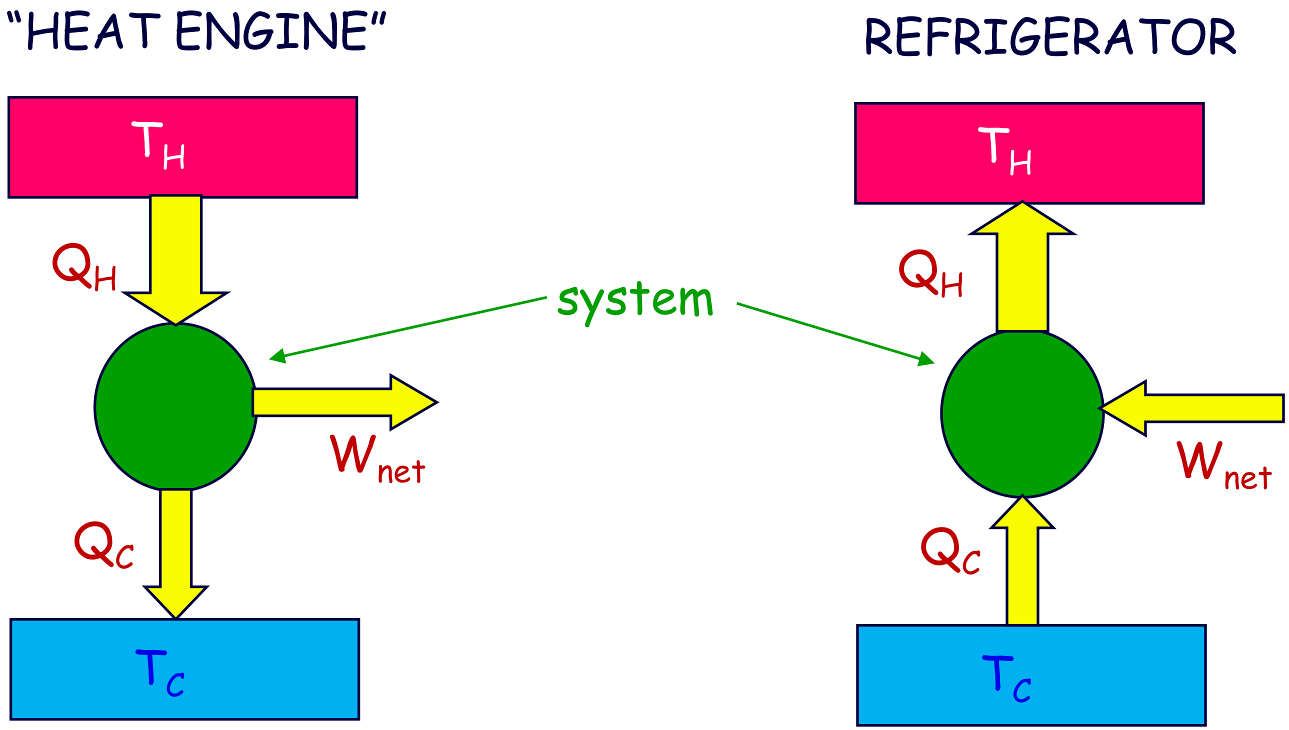
Heat flow into system



- 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"

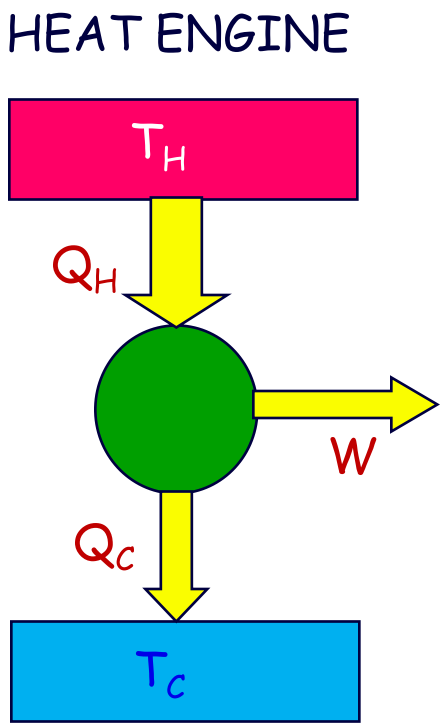
1st Law: $Q_H - Q_C = W$

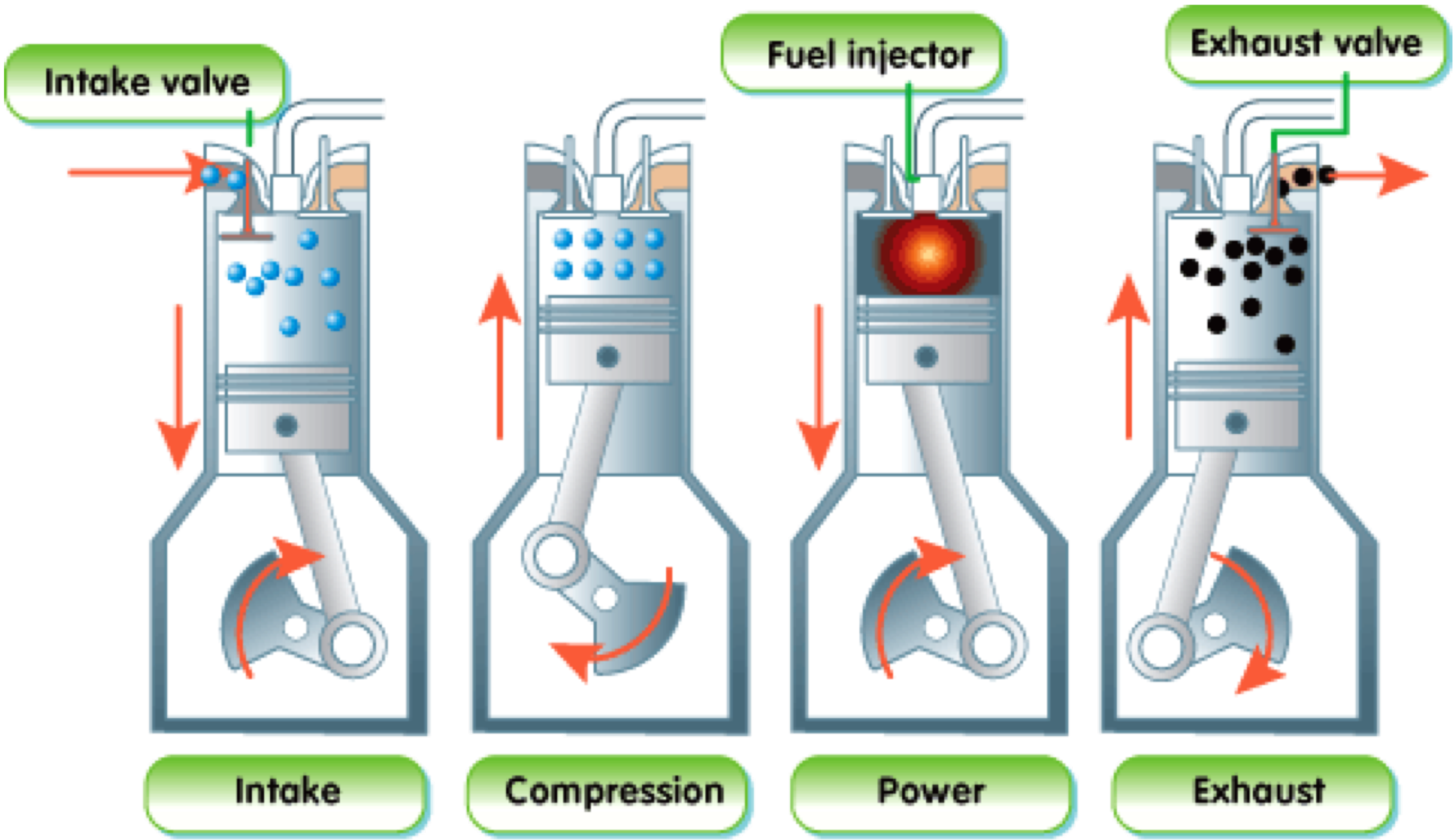
efficiency $e \equiv W/Q_H$

$= W/Q_H$

$= (Q_H - Q_C)/Q_H$

$= 1 - Q_C/Q_H$




Intake valve
Fuel injector
Exhaust valve
Intake
Compression
Power
Exhaust

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: $Q_H = W + Q_C$

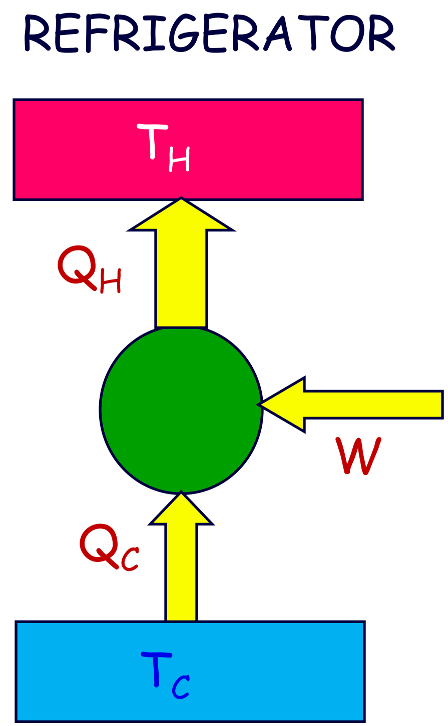
coefficient of performance

$$CP \equiv Q_C/W$$

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

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)

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.

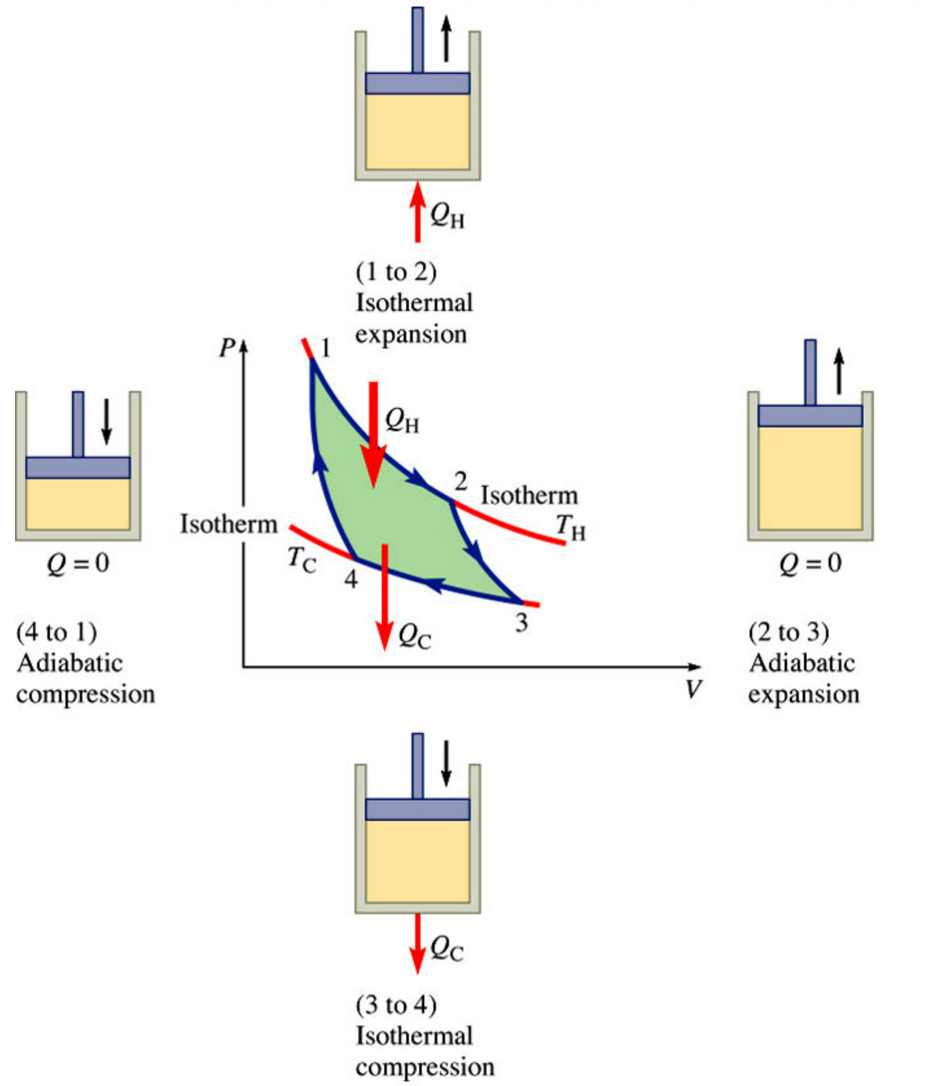
- Answers to Checkpoint: 1. A   2. D   3. A
- (To answer 3, use last equation is slide 8: "refrigerators" from the last prelecture, or last eqn on slide 8 in this lecture, to compare impact of raising T_C by 10 or lowering T_H by 10)

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



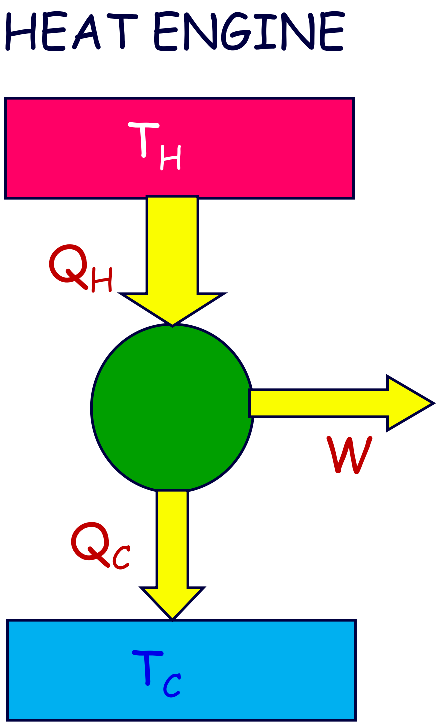
Engines and the 2nd Law

The objective: turn heat from hot reservoir into work

The cost: "waste heat"

1st Law: $Q_H - Q_C = W$

efficiency $e \equiv W/Q_H = (Q_H - Q_C)/Q_H = 1 - Q_C/Q_H$



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

$\Delta S = 0$ 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!

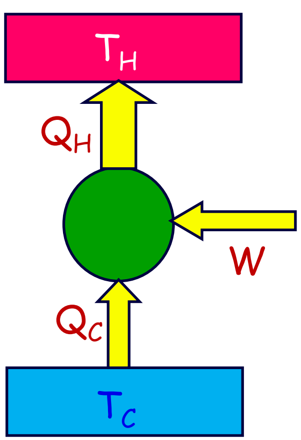
e largest if $T_C \ll T_H$

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

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

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

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

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

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!