

# Physics 101: Lecture 28

## Thermodynamics II

- Today's lecture will cover Textbook Chapter 15.6-15.9

Check Final Exam Room Assignment! Bring ID!

Be sure to check your gradebook!

# Final Exam Info!!

- ~ 45 Problems
- Roughly even distribution over lectures
- Study
  - Old hour exams
  - Discussion Quizzes
  - Homework
  - Practice problems

# Recap:

→ 1st Law of Thermodynamics

→ energy conservation

$$Q = \Delta U - W$$

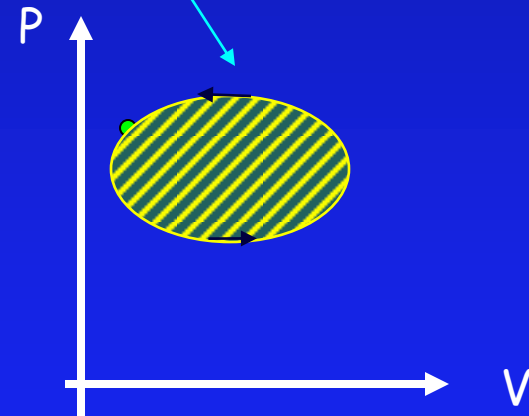
Heat flow  
into system

Increase in internal  
energy of system

Work done on system

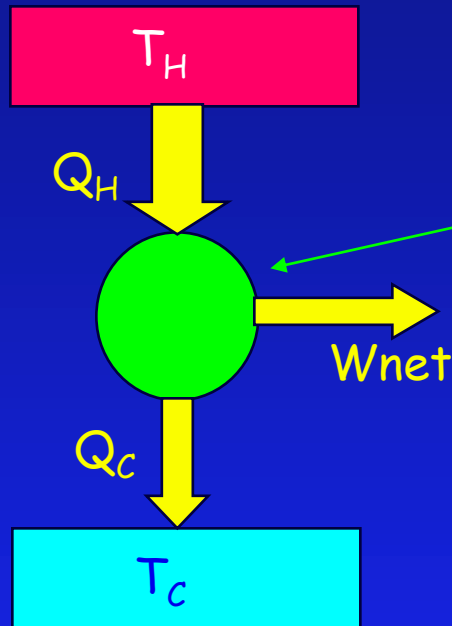
- $U$  depends only on  $T$  ( $U = 3nRT/2 = 3PV/2$ )
- point on  $p$ - $V$  plot completely specifies state of system ( $PV = nRT$ )
- work done is area under curve
- for complete cycle

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

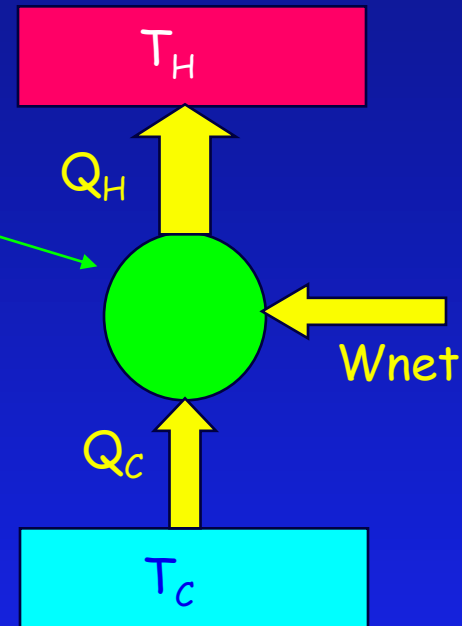


# Engines and Refrigerators

"HEAT ENGINE"



REFRIGERATOR



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

$$Q_H - Q_C = -W_{on} \text{ (engine)} = W_{by} = W_{net}$$

$$Q_C - Q_H = -W_{on} \text{ (refrigerator)} = -W_{net}$$

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:**  $Q_H - Q_C = W$

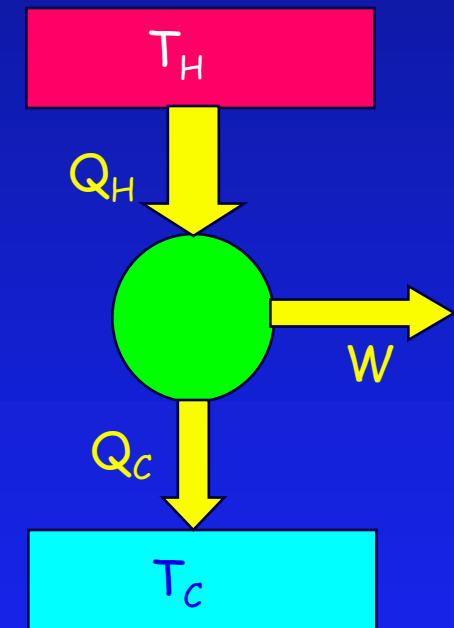
**efficiency  $e \equiv W/Q_H$**

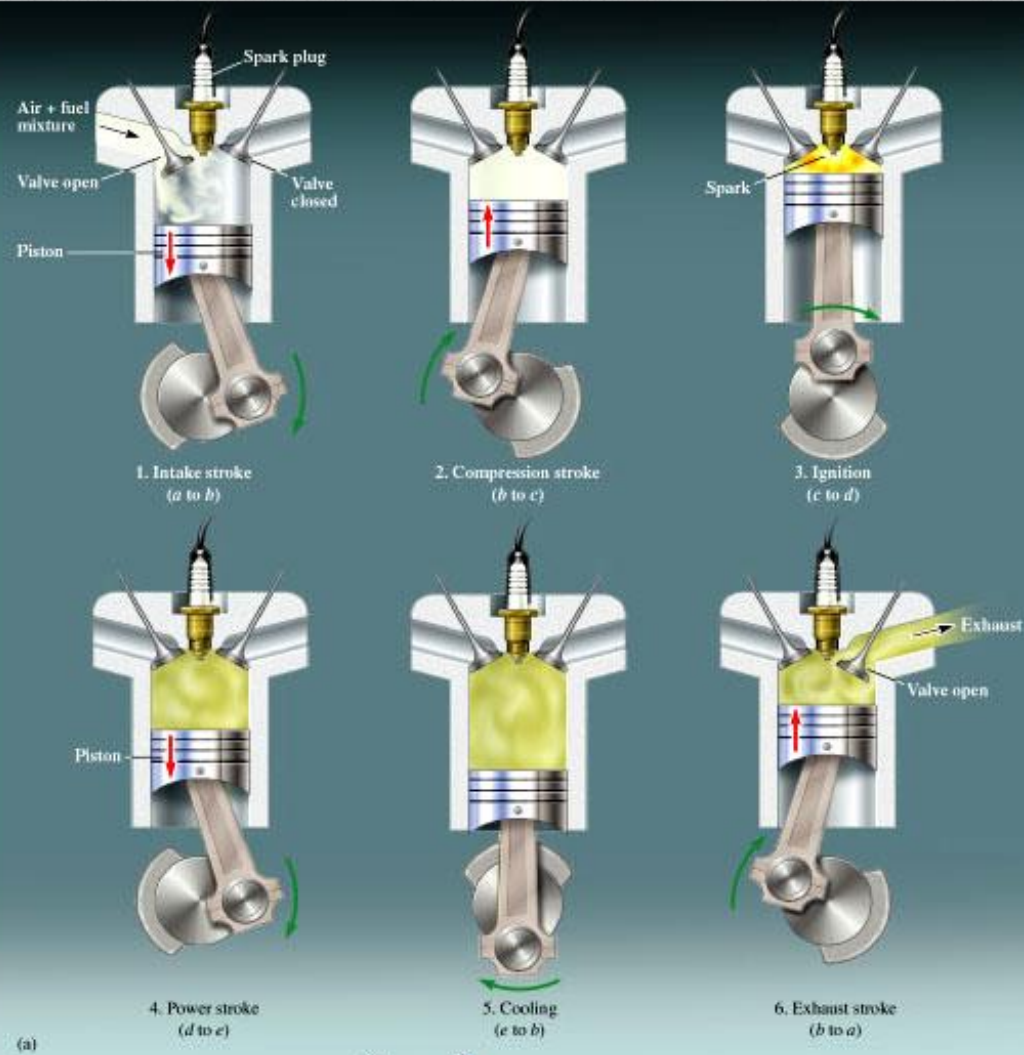
$$= W/Q_H$$

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

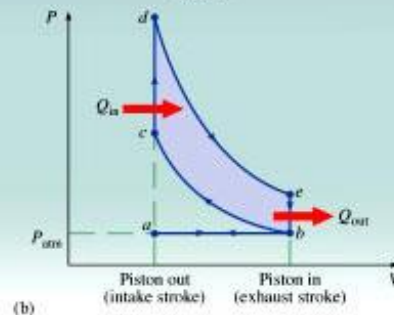
$$= 1 - Q_C/Q_H$$

HEAT ENGINE





(a)



(b)

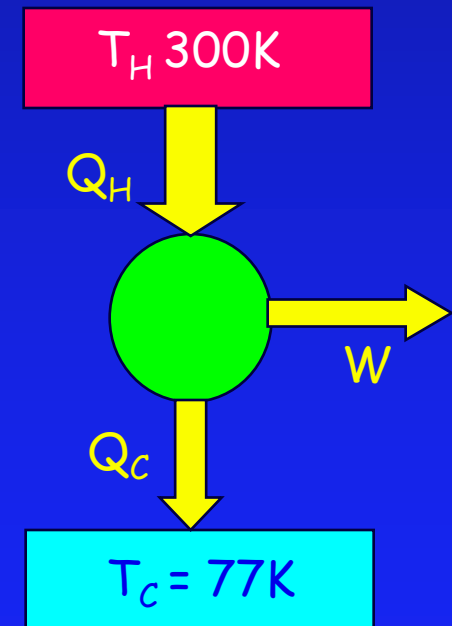
# Heat Engine ACT

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

1) Yes

2) No

HEAT ENGINE



# Rate of Heat Exhaustion

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

- Efficiency:  $e = \frac{W_{net}}{Q_{in}} \Rightarrow Q_{in} = \frac{W_{net}}{e}$
- Total heat flux:  $Q_{net} = Q_{in} - Q_{out}$ .

This question is about Power =  $Q_{out}/\Delta t$ .

- Energy conservation:

- $W_{net} = Q_{net}$

- Power:

1.  $\frac{W_{net}}{\Delta t} = \frac{Q_{net}}{\Delta t} = \frac{Q_{in} - Q_{out}}{\Delta t}$

2.  $\frac{Q_{out}}{\Delta t} = \frac{Q_{in}}{\Delta t} - \frac{W_{net}}{\Delta t} = \frac{\frac{W_{net}}{e}}{\Delta t} - \frac{W_{net}}{\Delta t}$

3.  $\frac{Q_{out}}{\Delta t} = \frac{\left[ \frac{W_{net} - eW_{net}}{e} \right]}{\Delta t} = \frac{\frac{W_{net}}{\Delta t} - \frac{eW_{net}}{\Delta t}}{e} \rightarrow \frac{Q_{out}}{\Delta t} = \frac{0.1 \text{ MW} - 0.25 \cdot 0.1}{0.25} = 0.30 \text{ MW}$



# Refrigerator: Coefficient of Performance

The objective: remove heat from cold reservoir

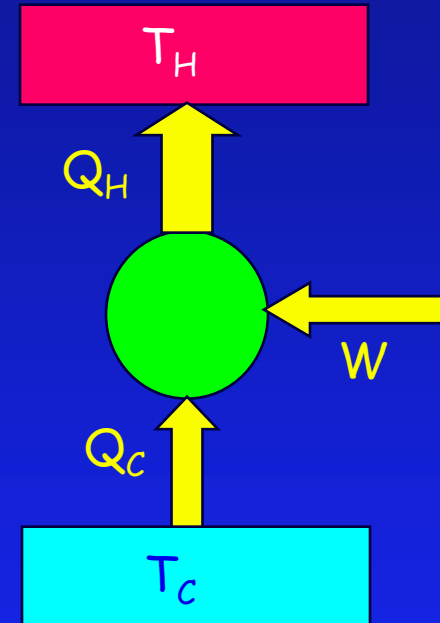
The cost: work

1st Law:  $Q_H = W + Q_C$

coefficient of performance

$$K_r \equiv Q_C / W \\ = Q_C / (Q_H - Q_C)$$

REFRIGERATOR



# New concept: Entropy (S)

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

# ACT

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) Increase    B) Same    C) Decreases

Heat leaves metal:  $Q < 0$

What happens to the entropy of the water?

- A) Increase    B) Same    C) Decreases

Heat enters water:  $Q > 0$

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

- A) Increase    B) Same    C) Decreases

$$\Delta S = Q/T_{\text{water}} - Q/T_{\text{metal}}$$

# Second Law of Thermodynamics

- The entropy change ( $Q/T$ ) of the system+environment  $\geq 0$ 
  - 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

- $DS = Q/T = 0$

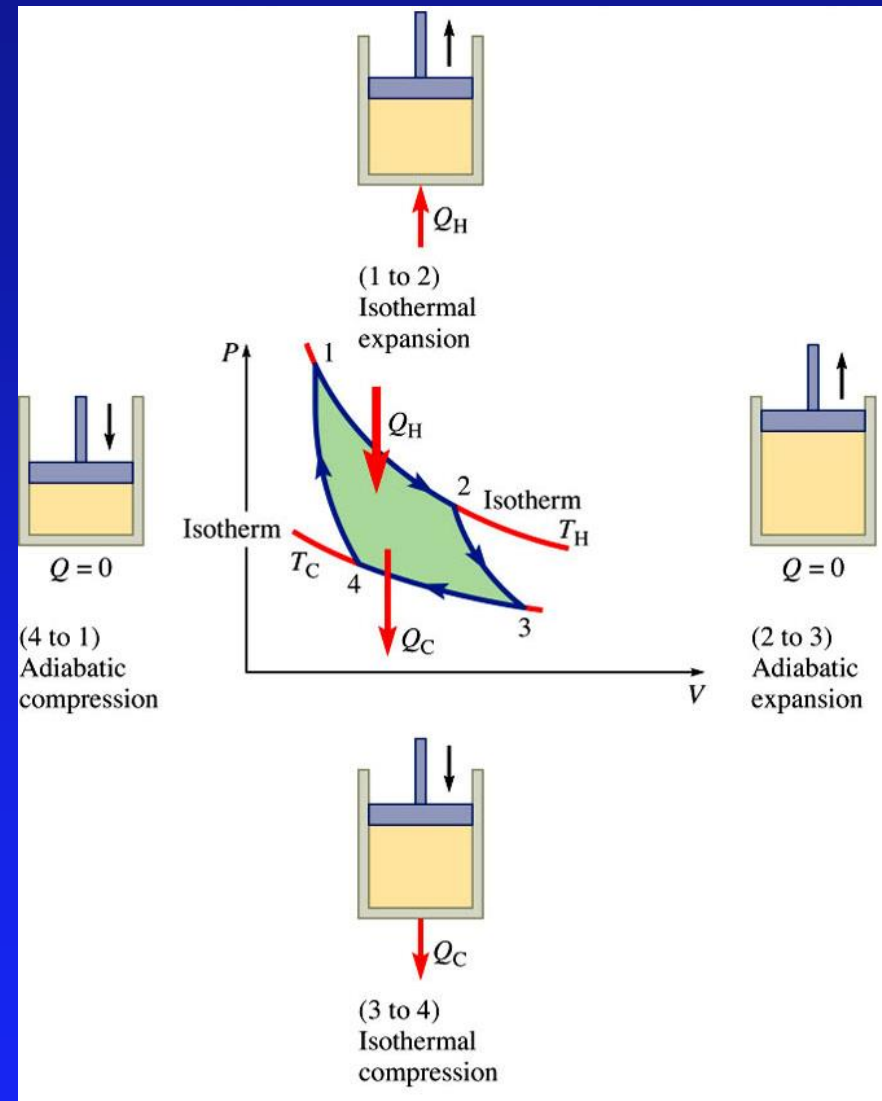
- Reversible Process

- » 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  $e \equiv W/Q_H = W/Q_H = 1 - Q_C/Q_H$

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

$\Delta S = 0$  for Carnot

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

$Q_C/Q_H = T_C/T_H$  for Carnot

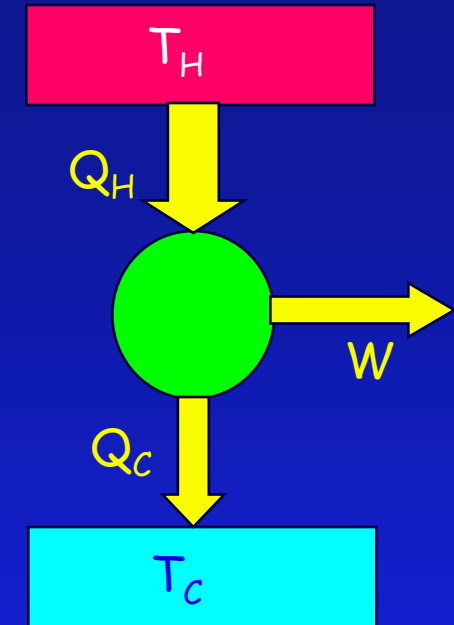
Therefore  $e = 1 - Q_C/Q_H \leq 1 - T_C/T_H$

$e = 1 - T_C/T_H$  for Carnot

$e = 1$  is forbidden!

$e$  largest if  $T_C \ll T_H$

HEAT ENGINE



# Example

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**.

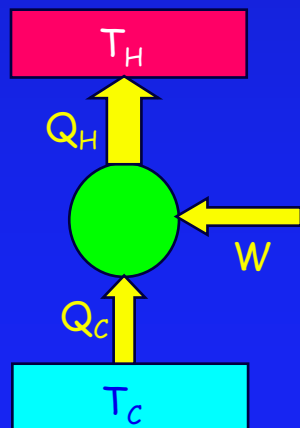
1. How much work does the refrigerator do?
2. What happens to the entropy of the universe?
3. Does this violate the 2nd law of thermodynamics?

Answers:

200 J

Decreases

yes



$$Q_C = 1000 \text{ J} \quad \text{Since } Q_C + W = Q_H, W = 200 \text{ J}$$
$$Q_H = 1200 \text{ J}$$

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

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

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

# Prelecture

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

total entropy decreases.

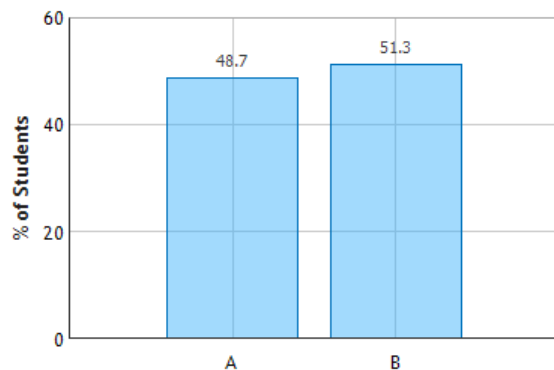
2. No

$$\Delta S_H = Q_H/T_H = (-1000 \text{ J}) / (300 \text{ K}) = -3.33 \text{ J/K}$$

$$\Delta S_C = +Q_C/T_C = (+200 \text{ J}) / (100 \text{ K}) = +2 \text{ J/K}$$

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

Is the Engine Possible?: Question 1 (N = 306)



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

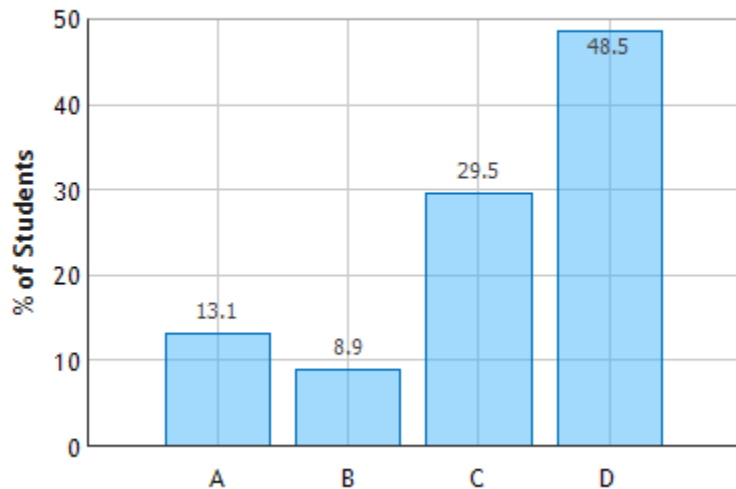


# Prelecture 3

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

Is the Engine Possible?: Question 3 (N = 305)



Answer: 3

# 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  $e = 1 - T_c/T_h$