

Physics 101: Lecture 28

Thermodynamics II

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

Check Final Exam Room Assignment! (Should be up by Fri)

Bring ID!

Be sure to check your gradebook!

Final Exam Info!!

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

Recap:

1st Law of Thermodynamics: energy conservation

$$\Delta U = Q + W$$

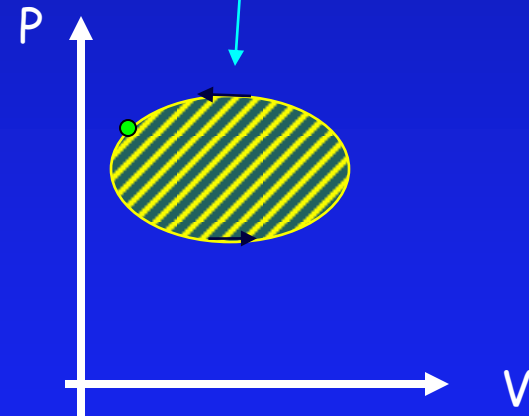
Increase in internal energy of system

Heat flow into system

Work done on system

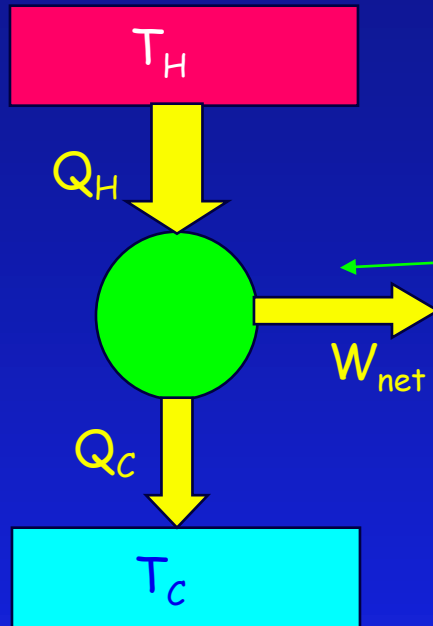
- U depends only on T ($U = 3nRT/2 = 3PV/2$)
- point on P - V plot completely specifies state of system ($PV = nRT$)
- work done is area under curve
- for complete cycle, $P_f V_f = P_0 V_0 \Rightarrow T_f = T_0$

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



Engines and Refrigerators

"HEAT ENGINE"

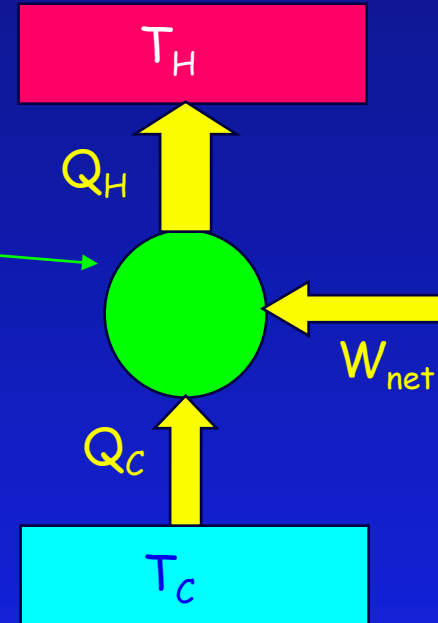


$$Q_H = Q_C + W_{net}$$

Energy Input

Energy Output

REFRIGERATOR



$$Q_C + W_{net} = Q_H$$

Energy Input

Energy Output

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

ENGINE:

$$Q_H - Q_C = W_{net}$$

REFRIGERATOR:

$$Q_C - Q_H = -W_{net}$$

Heat Engine: Efficiency

The objective: turn heat from hot reservoir (Q_H) into work (W)

The cost: "waste heat" (Q_C)

1st Law: $Q_H - Q_C = W$

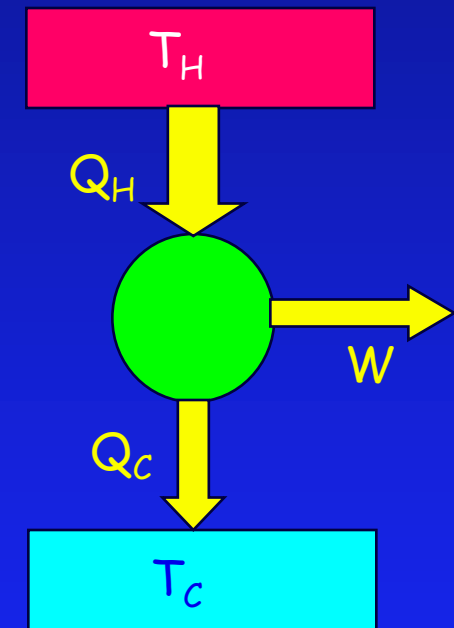
efficiency $e \equiv W/Q_H$

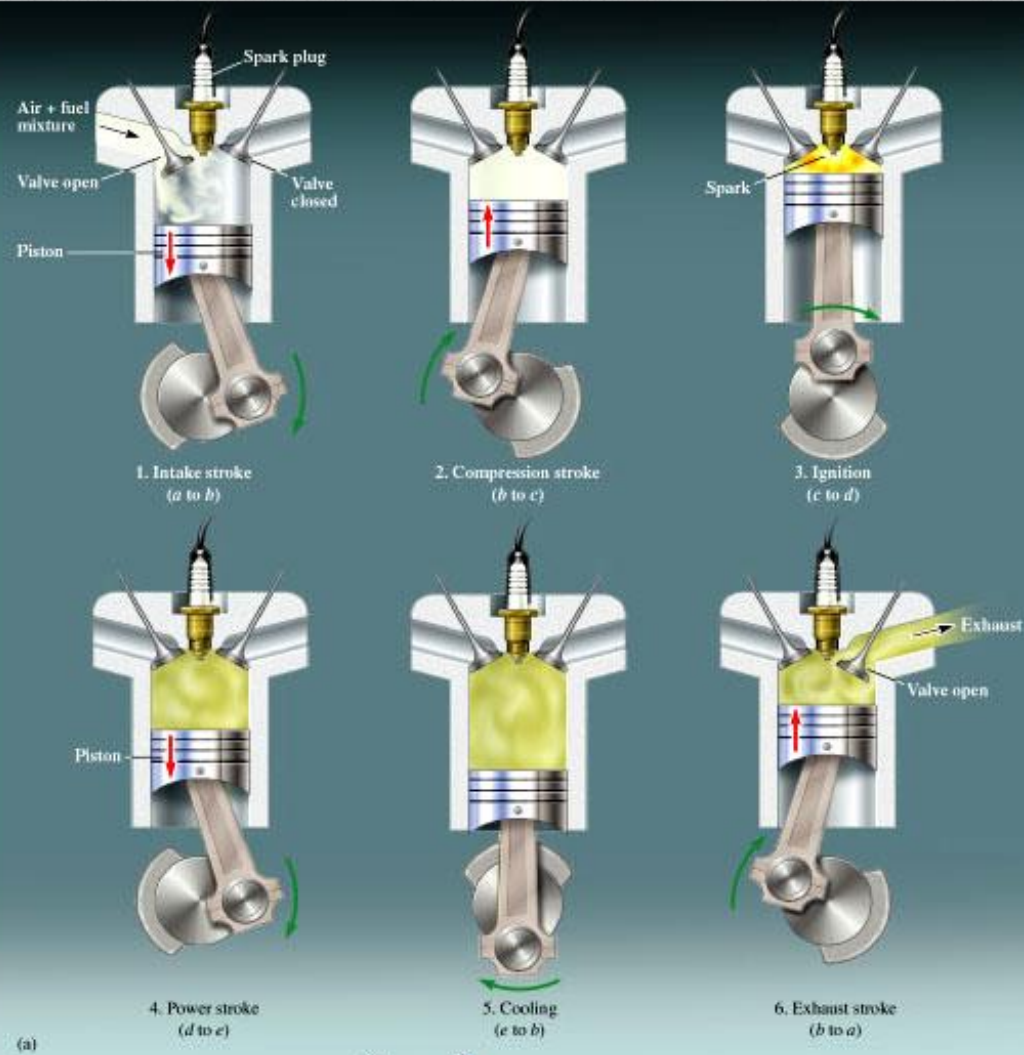
$$= W/Q_H$$

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

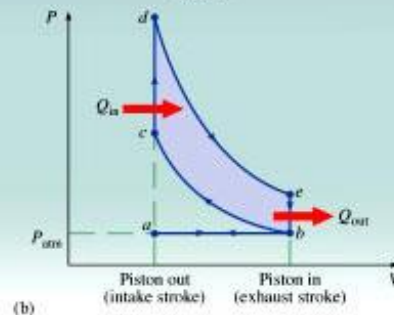
$$= 1 - Q_C/Q_H$$

HEAT ENGINE





(a)



(b)

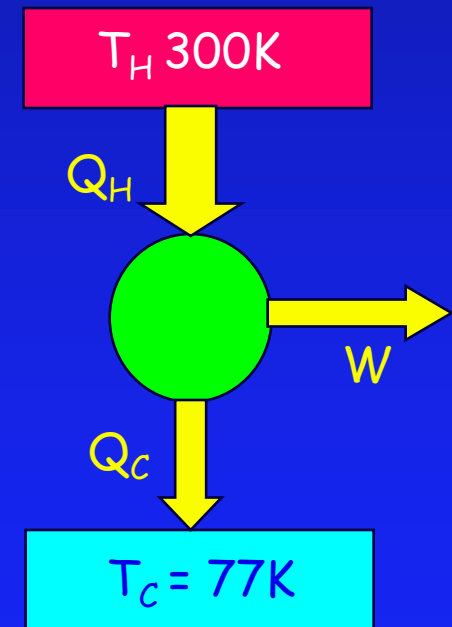
Heat Engine ACT

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

Efficiency: $e = W/Q_H \Rightarrow Q_H = W/e$

Total heat flow: $Q_{\text{net}} = Q_H - Q_C$

The question is about $Q_C/\Delta t$.

Energy conservation: $W = Q_{\text{net}}$; divide by Δt :

Rate of work production: $W/\Delta t = Q_{\text{net}}/\Delta t = (Q_H - Q_C)/\Delta t$

$$Q_C/\Delta t = Q_H/\Delta t - W/\Delta t$$

$$= (W/e)/\Delta t - W/\Delta t$$

$$= (1/e - 1)W/\Delta t$$

$$= (1/0.25 - 1)(0.1 \text{ MW}) = 0.3 \text{ MW}$$

Refrigerator: Coefficient of Performance

The objective: remove heat from cold reservoir

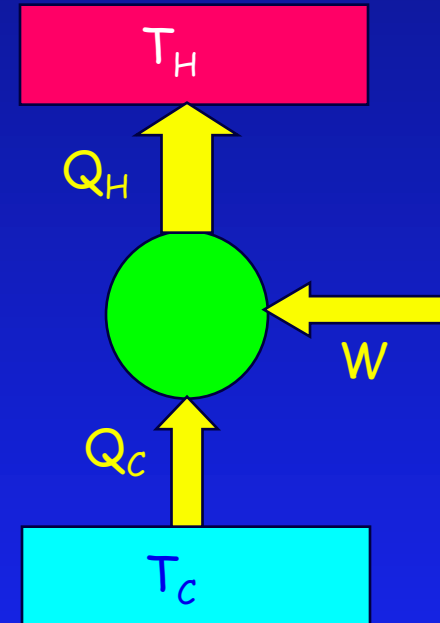
The cost: work

1st Law: $Q_H = W + Q_C$

coefficient of performance

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

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 ≥ 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

- $\Delta S = Q/T = 0$

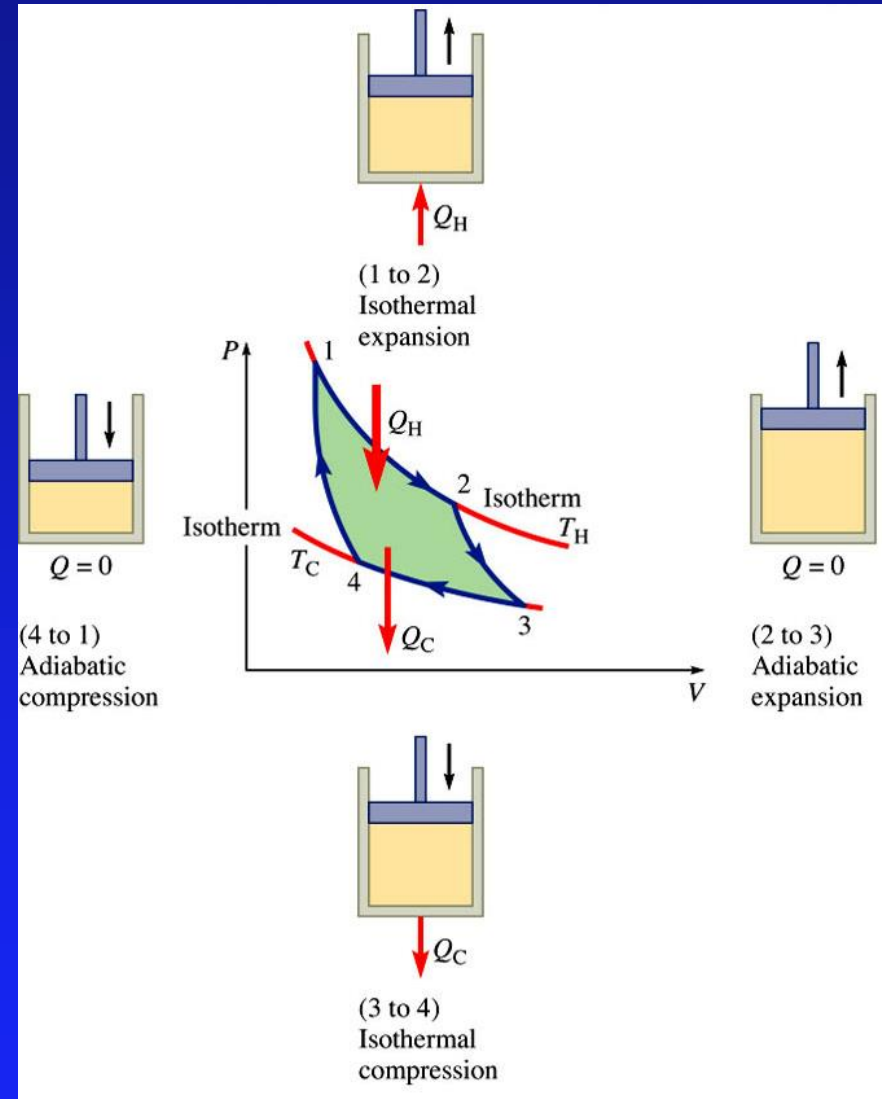
- Reversible Process

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

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

$\Delta S = 0$ for Carnot

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

$Q_C/Q_H = T_C/T_H$ for Carnot

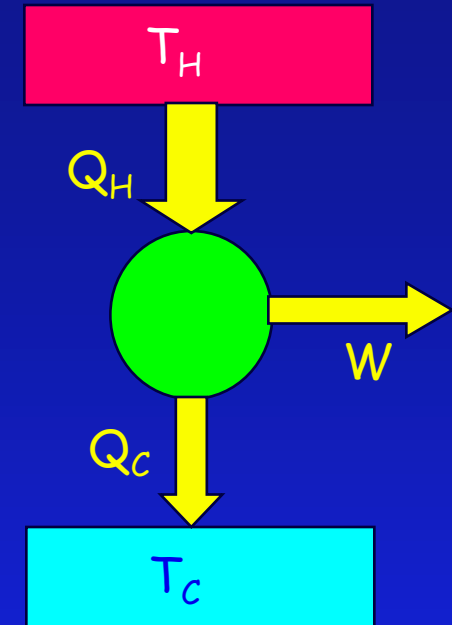
Therefore $e = 1 - Q_C/Q_H \leq 1 - T_C/T_H$

$e = 1 - T_C/T_H$ for Carnot

$e = 1$ is impossible!

e largest if $T_C \ll T_H$

HEAT ENGINE



Example

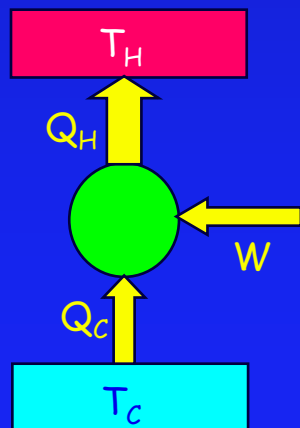
Consider a hypothetical refrigerator that takes **1000 J** of heat from a cold reservoir at **100K** and ejects **1200 J** of heat to a hot reservoir at **300K**.

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 i.e., does total entropy decrease?

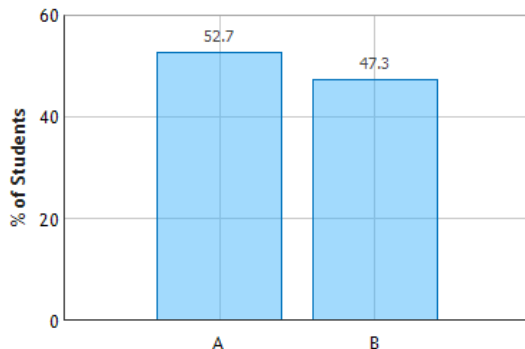
2. No

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

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

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

Is the Engine Possible?: Question 1 (N = 429)



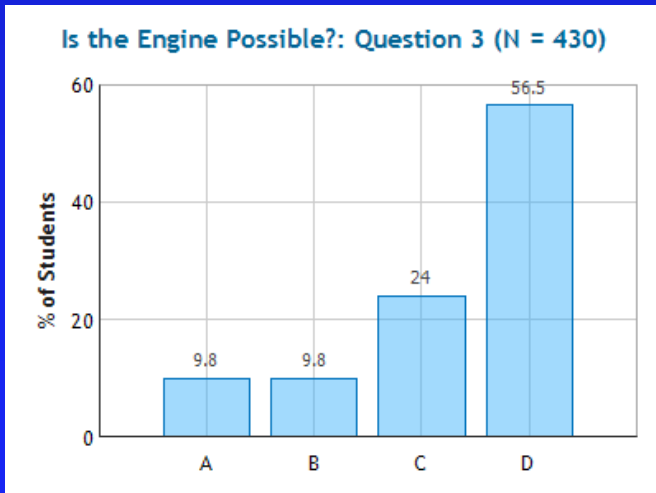
- $W (800) = Q_{\text{hot}} (1000) - Q_{\text{cold}} (200)$
- $\text{Efficiency} = W/Q_{\text{hot}} = 800/1000 = 80\%$
- $\text{Max eff} = 1 - T_c/T_h = 1 - 100/300 = 67\%$

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

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 $e = 1 - T_c/T_h$