Lecture 16

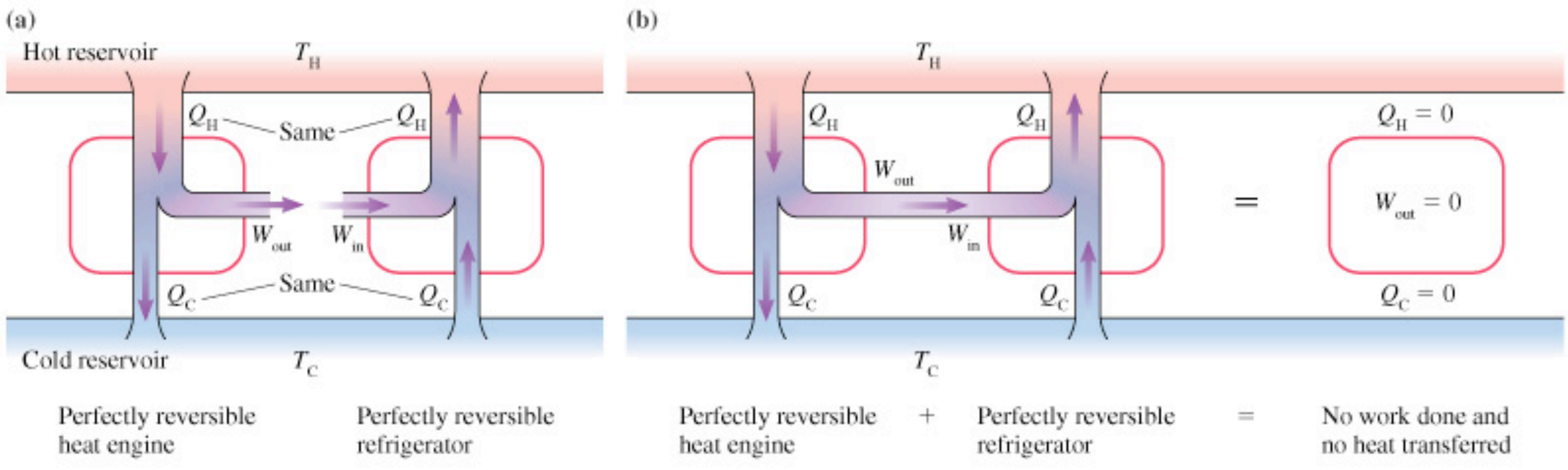
- Maximum efficiency for a perfectly reversible engine
- conditions for perfectly reversible engine
- efficiency for Carnot cycle

Reversible Engine

- What's most efficient heat engine/refrigerator operating between hot and cold reservoirs at temperatures T_C and T_H?

i.e., $\eta = 0.99$ allowed or is there an η_{max} (for given $T_{H,C}$) ?

- related: refrigerator is heat engine running "backwards"
- perfectly reversible engine: device can be operated between <u>same</u> two reservoirs, with <u>same</u> energy transfers (only direction reversed): can<u>not</u> be Brayton-cycle engine (need to change temperatures of reservoirs)
- use heat engine to drive refrigerator: no net heat transfer

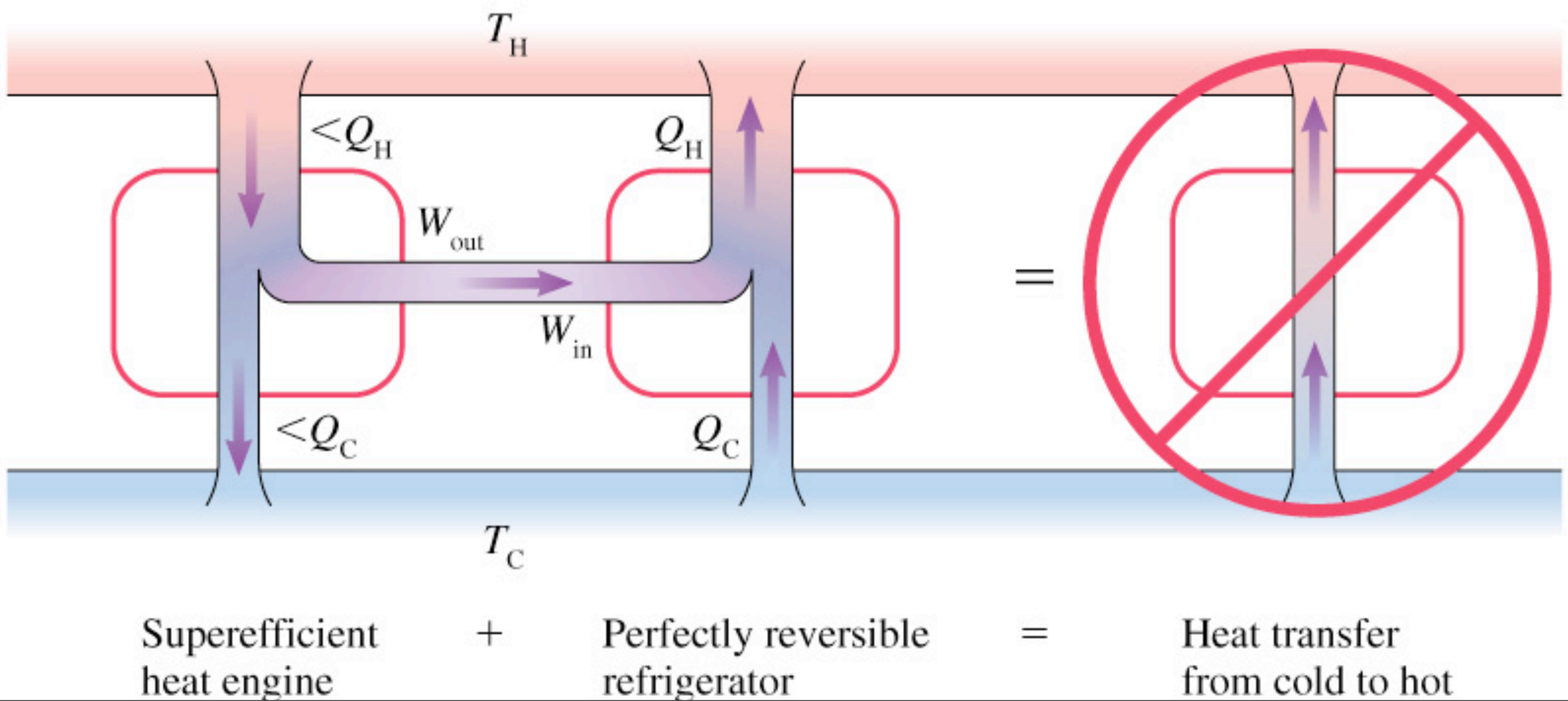


Limits of efficiency I

- Proof by Contradiction (II): suppose heat engine with more efficiency than perfectly reversible ⟶ for same W_{out}, new heat engine exhausts/needs less heat to/from cold/hot reservoir:

$$\eta = \frac{W_{out}}{Q_H} \text{ and } W_{out} = Q_H - Q_C$$

- use it to operate perfectly reversible refrigerator: engine extracts less heat from hot reservoir than refrigerator exhausts... heat transferred from cold to hot without outside assistance (forbidden by 2nd law)



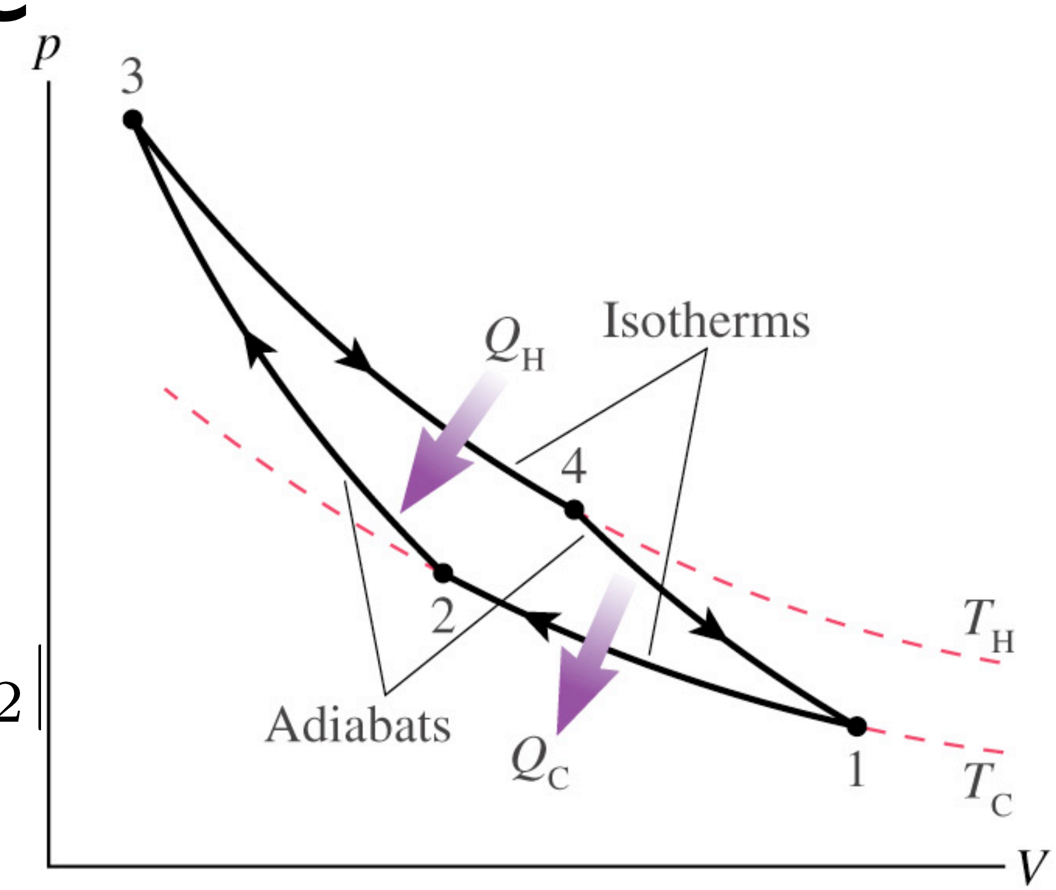
Limits of efficiency II

- 2nd law, informal statements # 5, 6: no heat engine more efficient than perfectly reversible engine operating between two reservoirs...no refrigerator has larger coefficient of performance

Conditions for reversible engine: Carnot

- so far, exists; next, design it and calculate efficiency (η_{max})
- exchange of energy in mechanical interactions (pushes on piston) reversible if (i) $W_{out} = W_{in}$ and (ii) system returns to initial T...only if motion is frictionless
- heat transfer thru' an <u>finite</u> temperature difference is <u>ir</u>reversible
- <u>reversible</u> if heat transferred infinitely slowly (<u>infinitesimal</u> temperature difference) in isothermal process
- must use (i) frictionless, no heat transfer ($Q = 0$) and (ii) heat transfer in isothermal processes ($\Delta E_{th} = 0$):
  Carnot engine (maximum η and K)

Carnot cycle



- enough to determine efficiency of Carnot engine using <u>ideal gas</u>
- ideal-gas cycle: 2 isothermal ($\Delta E_{th} = 0$) and 2 adiabatic processes ($Q = 0$)
- slow isothermal compression (1→2): $|Q_{12}|$ removed; adiabatic compression (2→3) till T_H; isothermal expansion (3→4): Q_{34} transferred; adiabatic expansion (4→1) to T_C
- work during 4 processes; heat transferred during 2 isothermal...
- Find 2 Q's for thermal efficiency: $\eta = 1 - \frac{Q_C}{Q_H}$

$$Q_{12} = -nRT_C \ln \frac{V_1}{V_2};\ Q_C = |Q_{12}|$$

$$Q_{34} = nRT_H \ln \frac{V_4}{V_3}$$

$$\Rightarrow \eta_{Carnot} = 1 - \frac{T_C}{T_H} \frac{\ln(V_1/V_2)}{\ln(V_4/V_3)}$$

Maximum (Carnot) efficiency

Using $TV^{\gamma-1} = \text{constant}$ for adiabatic, $\frac{V_1}{V_2} = \frac{V_4}{V_3} \Rightarrow$

$$\eta_{\text{Carnot}} = 1 - \frac{T_\text{C}}{T_\text{H}} \qquad \text{(Carnot thermal efficiency)}$$

- Similarly, for refrigerator

$$K_{\text{Carnot}} = \frac{T_\text{C}}{T_\text{H} - T_\text{C}} \qquad \text{(Carnot coefficient of performance)}$$

- Earlier: $\eta = 1$ <u>not</u> allowed by 2nd law, but 0.99 is...
- Next, can't be more efficient than perfectly reversible
- Now, result for Carnot thermal efficiency
- 2nd law informal statements #7, 8: no heat engine/refrigerator can exceed $\eta_{Carnot} = 1 - \frac{T_C}{T_H}$ and $K_{Carnot} = \frac{T_C}{T_H - T_C}$
- high efficiency requires $T_H \gg T_C$, difficult in practice...
- $\eta \not> 1$ expected from energy conservation vs. limits from 2nd law

Example

- A Carnot engine operating between energy reservoirs at temperatures 300 K and 500 K produces a power output of 1000 W. What are (a) the thermal efficiency of this engine, (b) the rate of heat input, in W, and (c) the rate of heat output, in W?

Electricity (chapters 26-32)

- going beyond Newton's laws
- charges at rest and in motion (currents): less experience, e.g., don't see movement of charges
- electricity and magnetism connected (PHY 270)
- new concept of "field" to describe interactions (macroscopic description)
- microscopic level: relation of charges to atoms/molecules; atoms (neutral) made of charged particles (electrons and protons): can be separated and moved; atoms held by electric force...; macroscopic mechanical forces due to electric at atomic level
- this week: chapter 26 (Electric Charges and Forces) "charge model" to describe basic electric phenomena; how charges behave in insulators and conductors; calculate forces using Coulomb's law; "field model" (review properties of vectors)

Charge Model I

- Rubbing objects causes forces, e.g. plastic comb picks up paper; shock on touching metal doorknob after walking across carpet..
- understand electric phenomena in terms of charges and forces between them (without reference to atoms/electrons)
- experiments with rubbing of plastic/glass rods on wool/silk: no forces originally (neutral); both attractive and repulsive (cf. gravity), long range forces (like gravity) after rubbing (charging)
- attractive force between charged and neutral object → test for object being charged: picks up paper

Postulates of Charge Model

- Rubbing adds/removes charge (larger for more vigorous)
- Two kinds of charges: "plastic" and "glass" (others can be charged too: "positive" and "negative")
- Two like charges repel, two opposite charges attract
- Force between charges is long-range; increases with quantity of charge, decreases with distance
- Neutral objects equal mixture of 2 charges: rubbing separates...

...more experiments with metal spheres...

- Charge can be <u>transferred</u> by contact (removing charge: <u>discharging</u>)
- <u>Conductors</u> (charges move easily, e.g., metal) vs, <u>Insulators</u> (charges remain fixed, e.g., plastic): both can be charged