Lecture 20

This week (chapter 19: Heat Engines and Refrigerators)

- physical principles for all heat engines (transform heat energy into work) and refrigerators (uses work to move heat from cold to hot)
- 2nd law: limit on efficiency (Carnot cycle)

Today

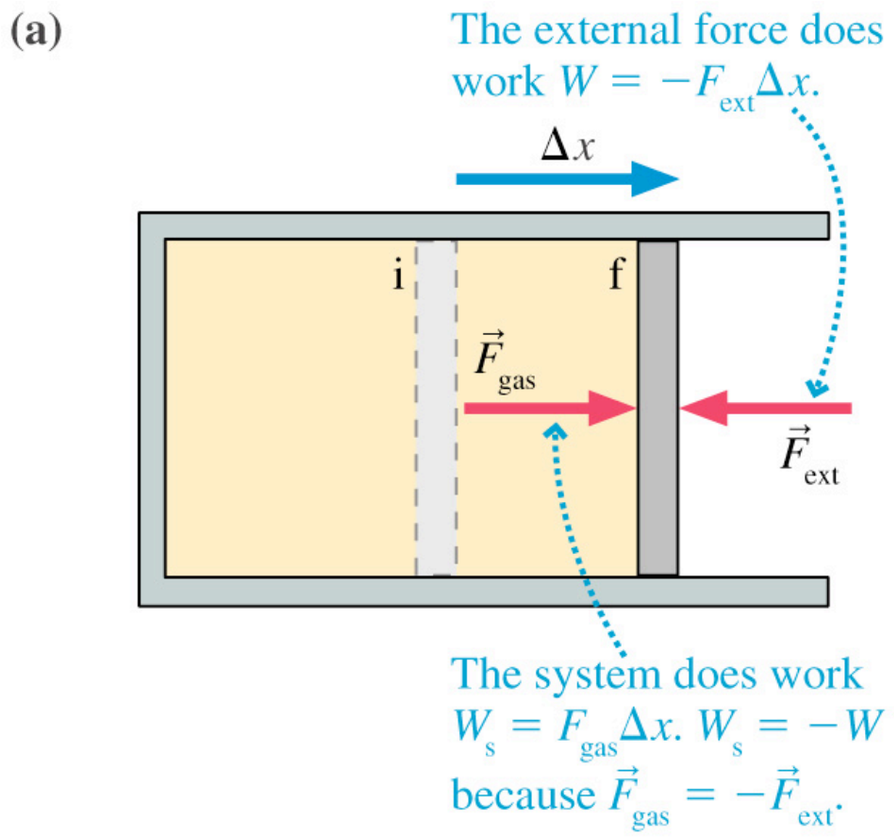
- general concepts of turning heat into work; heat engines and refrigerators

Heat ⟷ Work

- thermodynamics: transformation of energy e.g. heat into work
  obeys (i) 1st law (energy conservation): $\Delta E_{th} = W + Q$
  (ii) 2nd law: heat flows from hotter to colder (spontaneously)

- Work done <u>by</u> system, W_s (vs. work done <u>on</u> system by external force, W: heat and work are 2 ways to transfer energy to system)

equilibrium: $\bar{F}_{gas} = -\bar{F}_{ext} \Rightarrow W_s = -W =$ the area under the pV curve
$W_s > 0$ ($W < 0$) during expansion (energy transferred out of system)
1st law: $Q = W_s + \Delta E_{th}$ (heat used to do work or stored as thermal)



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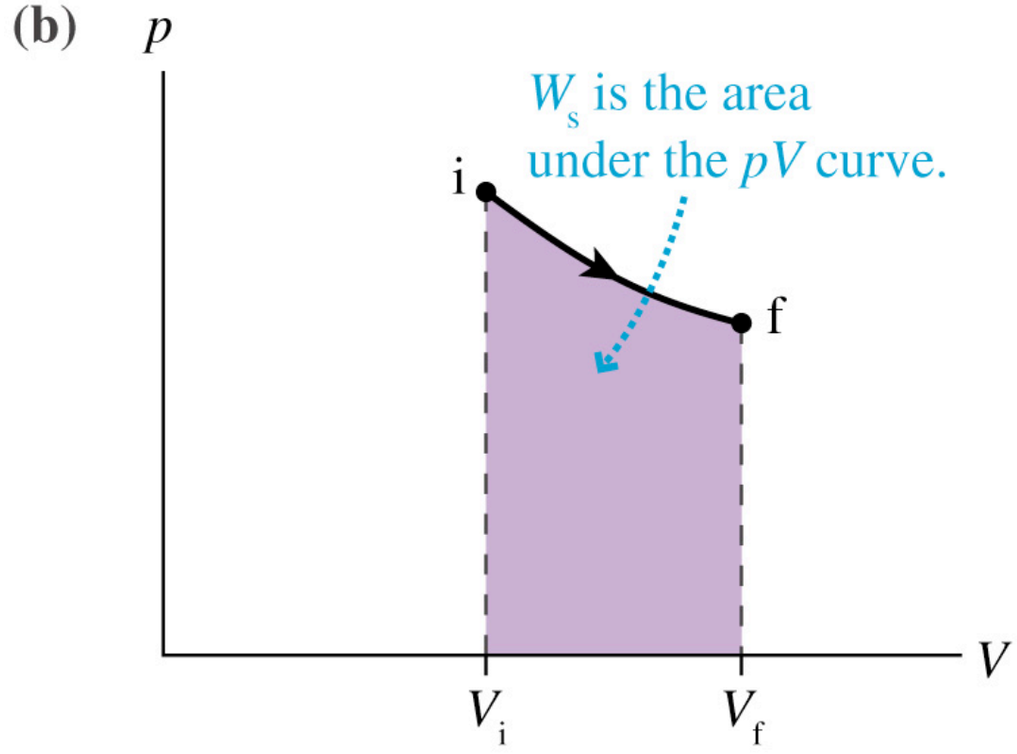

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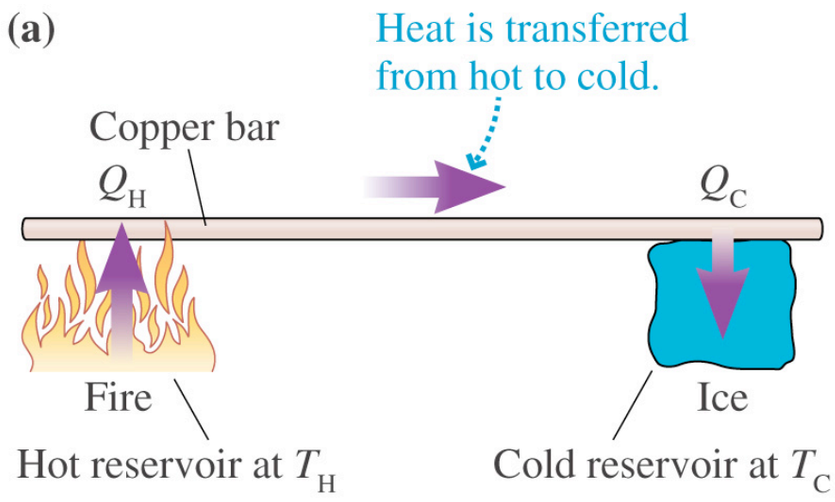
Energy Transfer diagrams



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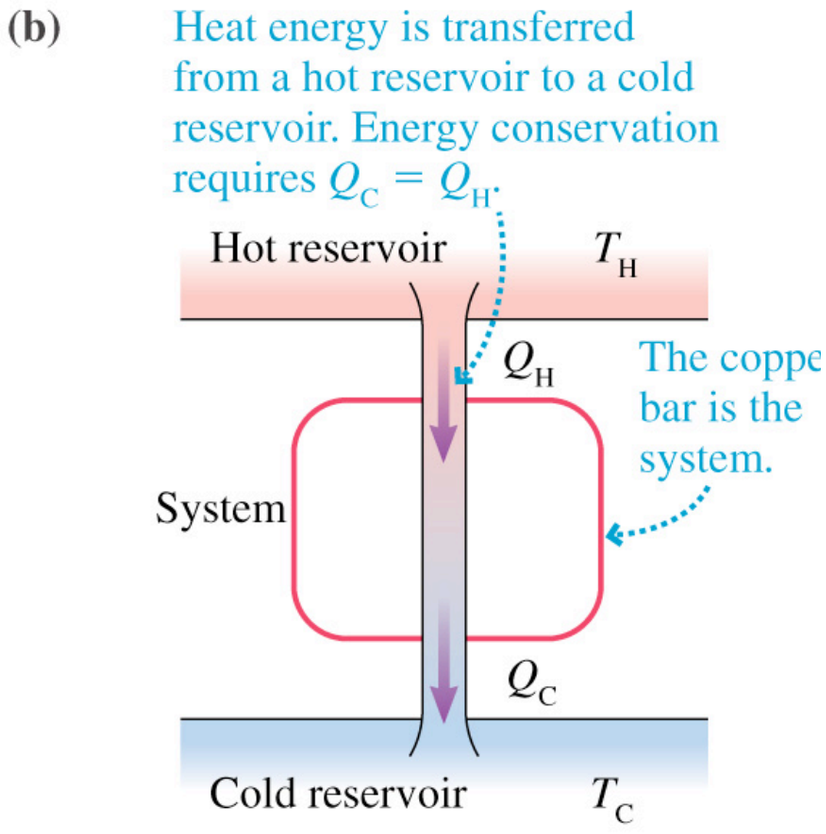

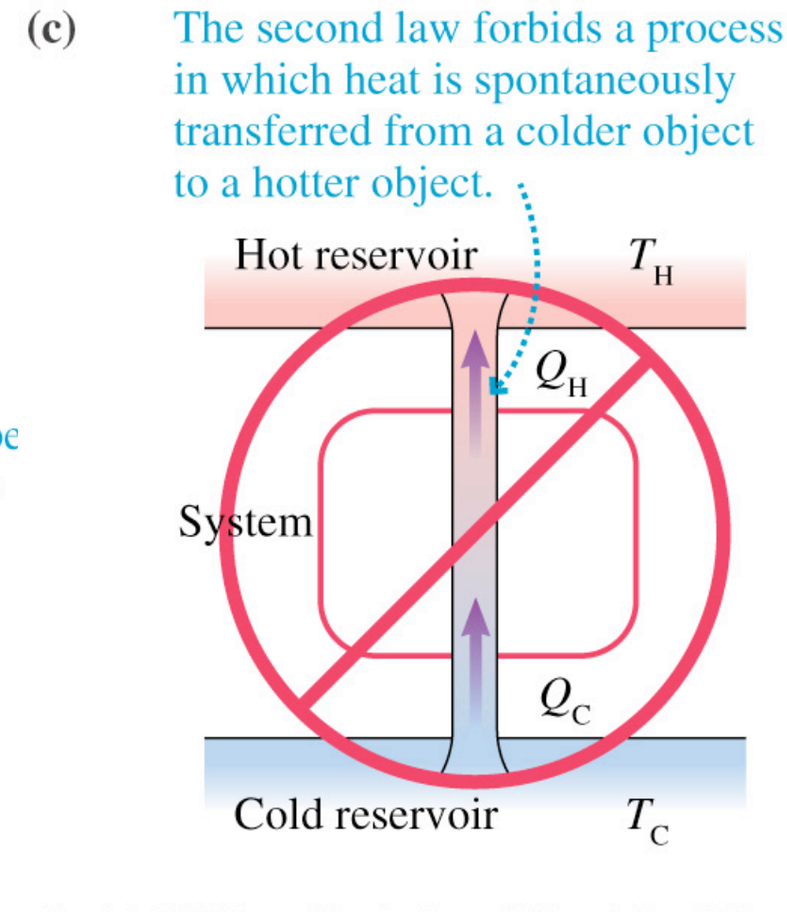

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- energy reservoir (hot or cold): much larger than system, temperature does not change when heat transferred between it and system due to difference in temperatures

$Q_{H,\,C}(>0)$ = heat transferred to/from a hot/cold reservoir

$Q = -Q_C$ in 1st law (heat transferred *from* system...)

1st law: $Q = W_s + \Delta E_{th}$ refers to system

$Q = Q_H - Q_C$; $W_s = 0$; $\Delta E_{th} = 0$ (steady state) $\Rightarrow$

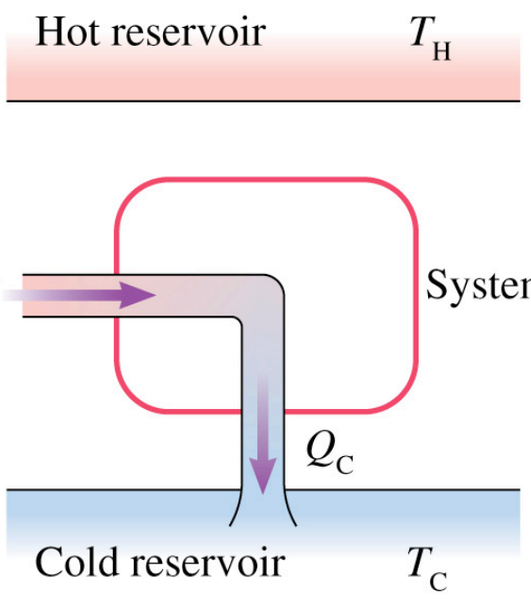
$Q_H = Q_C$ (system provides route for energy transfer from hot to cold)

heat transferred from cold to hot: 1st law not violated if $Q_H = Q_C$, but 2nd law does not allow spontaneous transfer...

Efficiency of Heat ↔ Work

Work into heat

- 100 % efficient: e.g. warm up rocks from ocean by rubbing ($W \rightarrow \Delta E_{th}$); back into ocean ($\Delta E_{th} \rightarrow Q_C$); continue as long as there is motion



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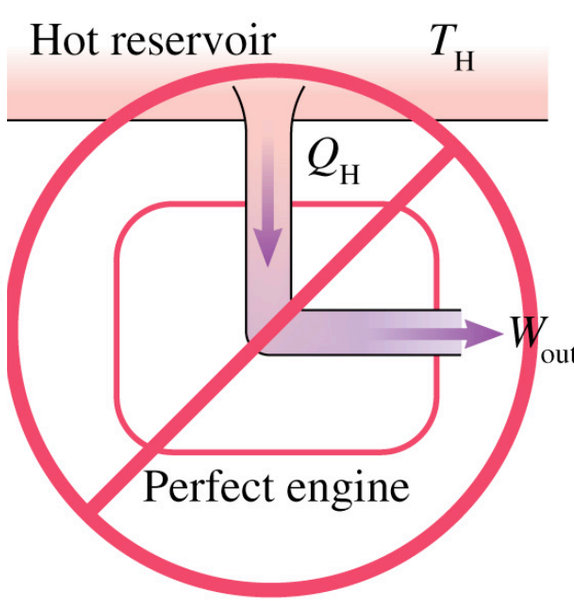

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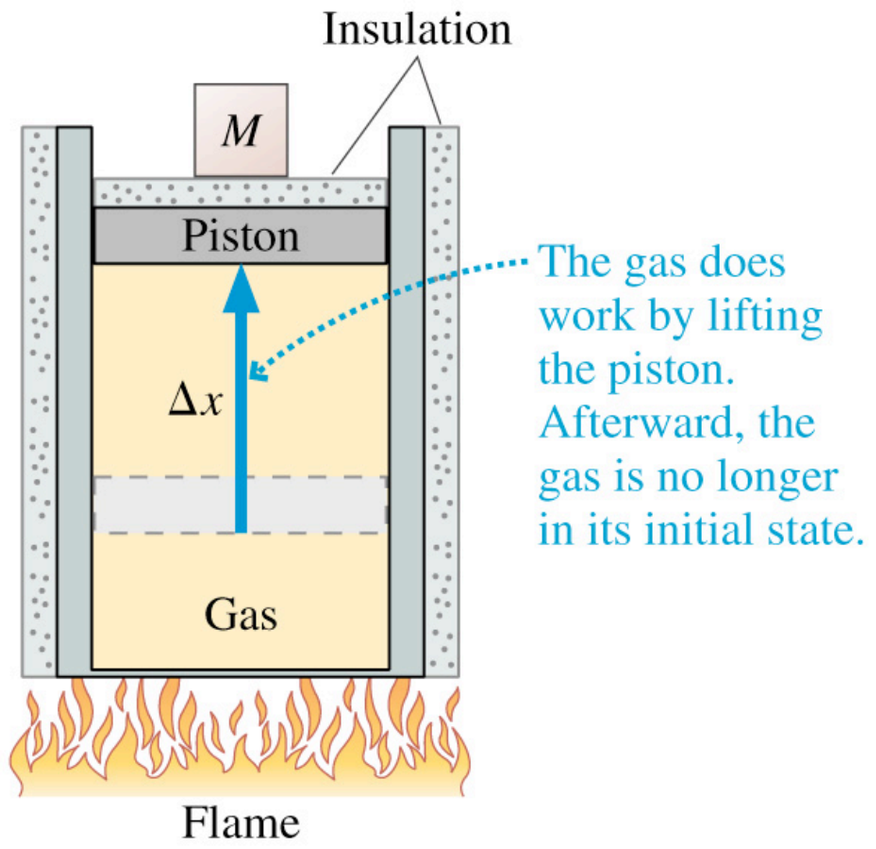
Heat into Work

- isothermal expansion: 100% efficient, but one-time process (piston reaches end of cylinder)

- practical device must return to initial state for continued use, but 2nd law does not allow perfect engine (100% efficient): asymmetry of 2 conversions similar to heat transfer



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Heat engines

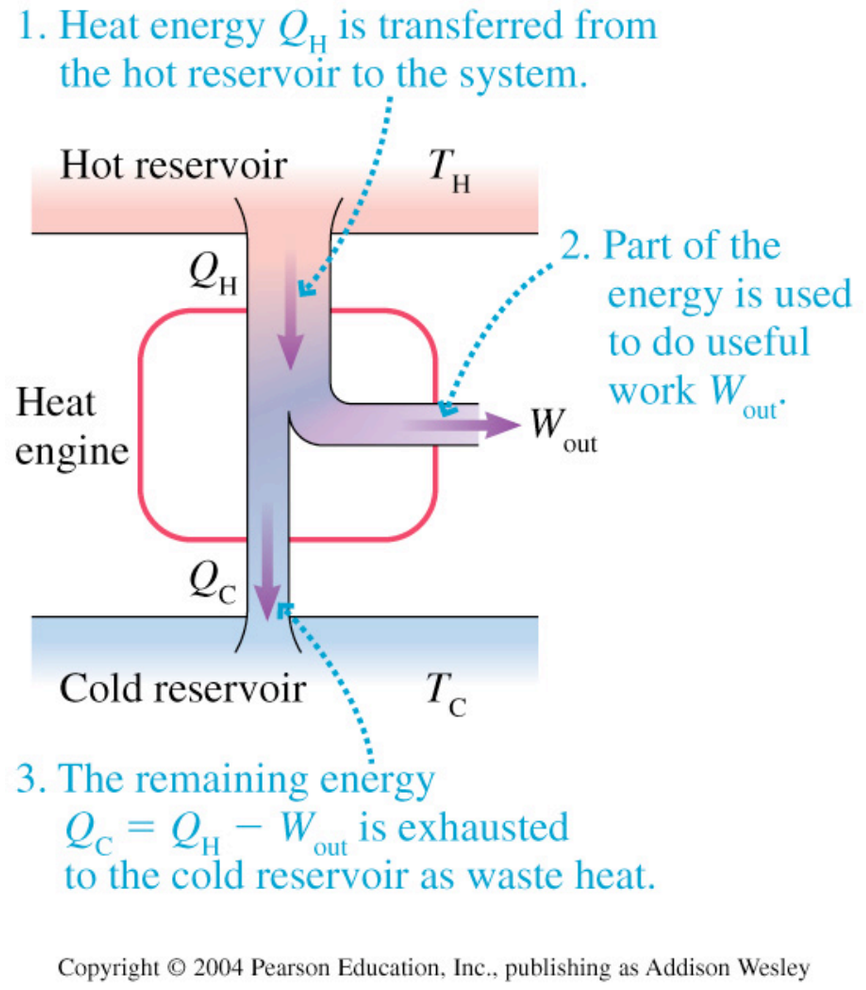
- closed cycle device (e.g. car engine: p, T inside cylinder repeated) extracts heat (combustion of fuel); does useful work (move pistons...); exhausts heat (radiator...): all state variables return to initial once every cycle

$(\Delta E_{th})_{net} = 0$ (over 1 full cycle)

1st law: $(\Delta E_{th})_{net} = Q_{net} - W_{out}$

with $Q_{net} = Q_H - Q_C \Rightarrow$ (energy conservation)

$W_{\text{out}} = Q_{\text{net}} = Q_{\text{H}} - Q_{\text{C}}$ (work per cycle done by a heat engine)



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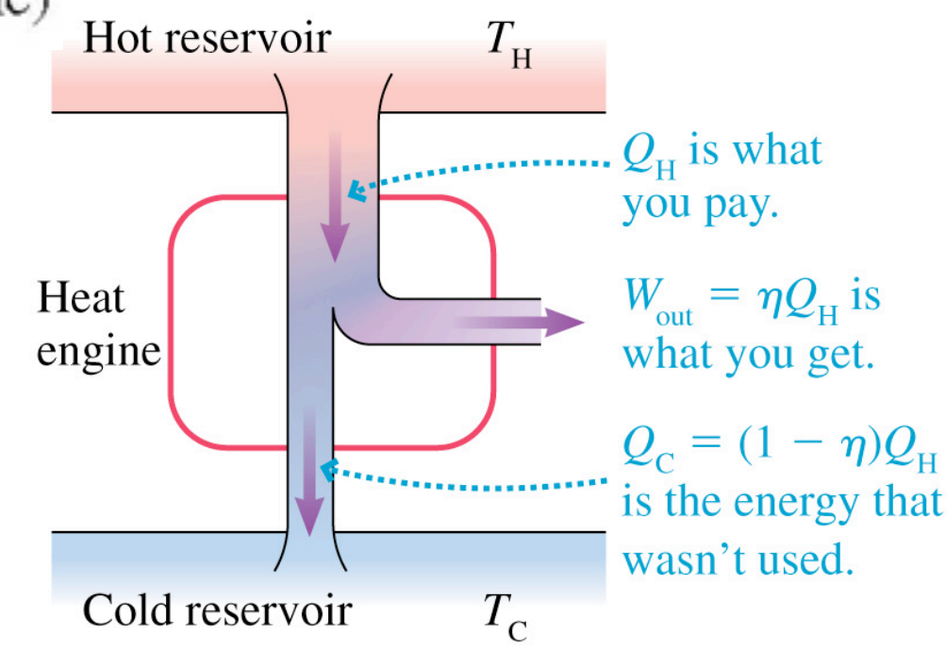
- thermal efficiency

$$\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

$$= 1 - \frac{Q_C}{Q_H}$$



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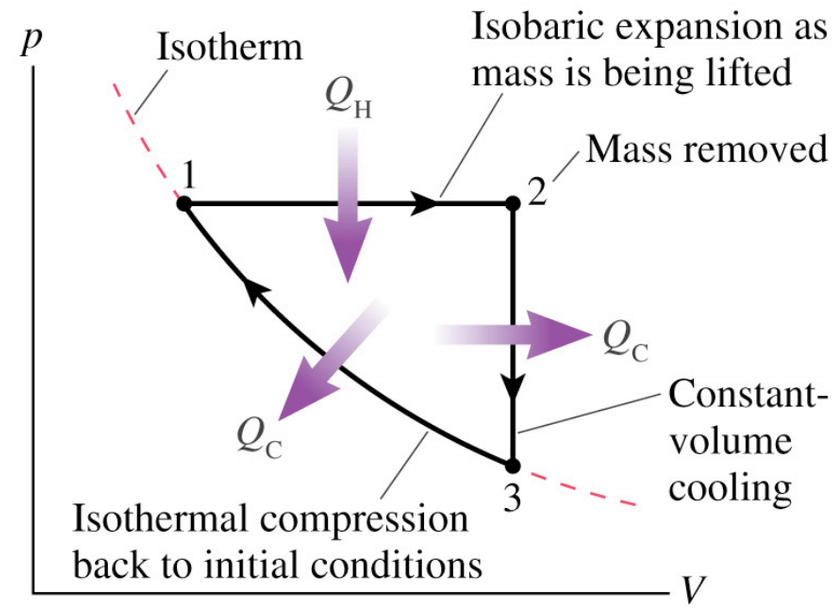
- perfect engine ($\eta = 1$) not possible: must exhaust energy (waste heat: energy extracted from hot reservoir, not transformed into work)

A Heat-Engine Example

- useful work of lifting mass during isobaric expansion...step (e): no net change in gas (start lifting mass again)
- heat engines require source and sink
- reservoirs not explicitly shown: $T_H >$ highest system temperature; $T_C <$ coldest...



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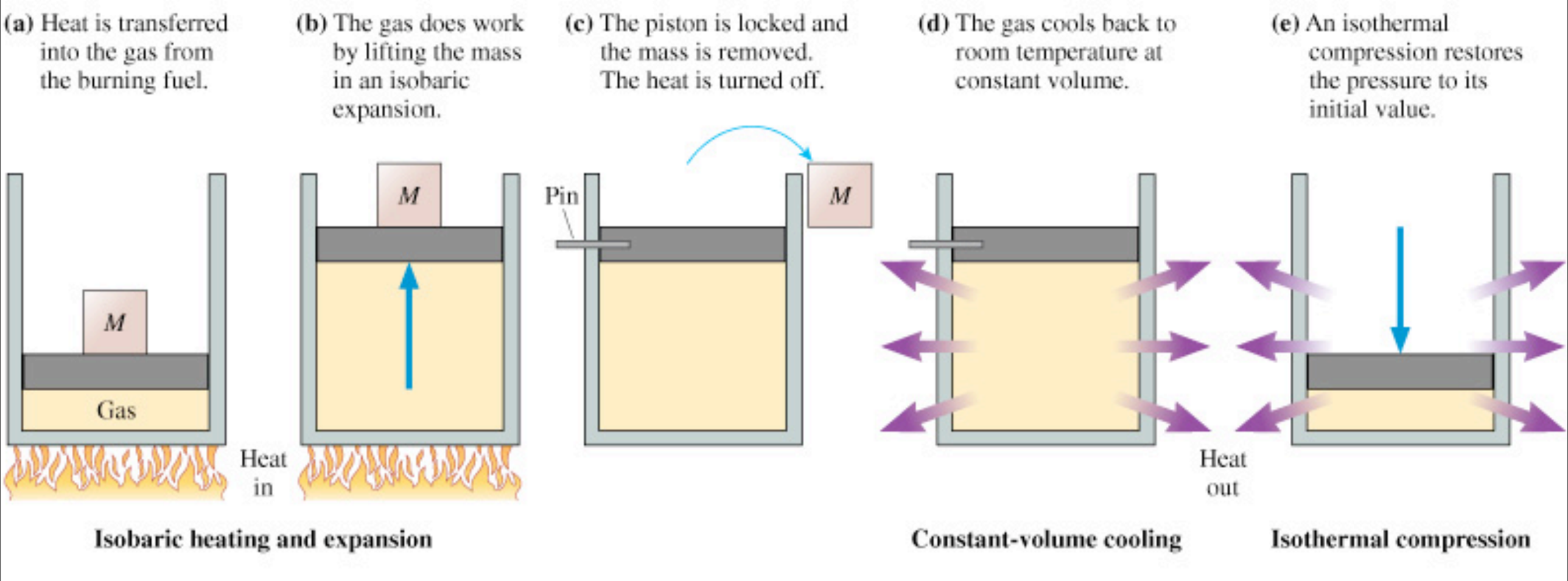
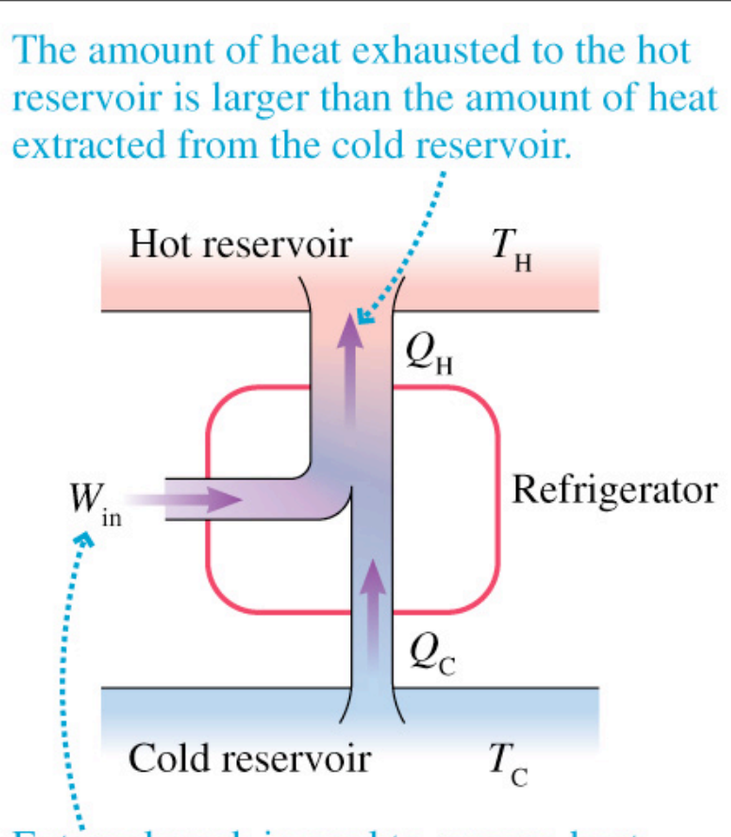


Refrigerators

- closed cycle uses <u>external</u> work to remove heat from cold reservoir and exhaust heat to hot reservoir (2nd law does not allow <u>spontaneous</u>): e.g. air-conditioner or kitchen...make air that is cooler than environment even <u>colder</u>

$$\Delta E_{th} = 0 \; (cyclical) : Q_H = Q_C + W_{in}$$



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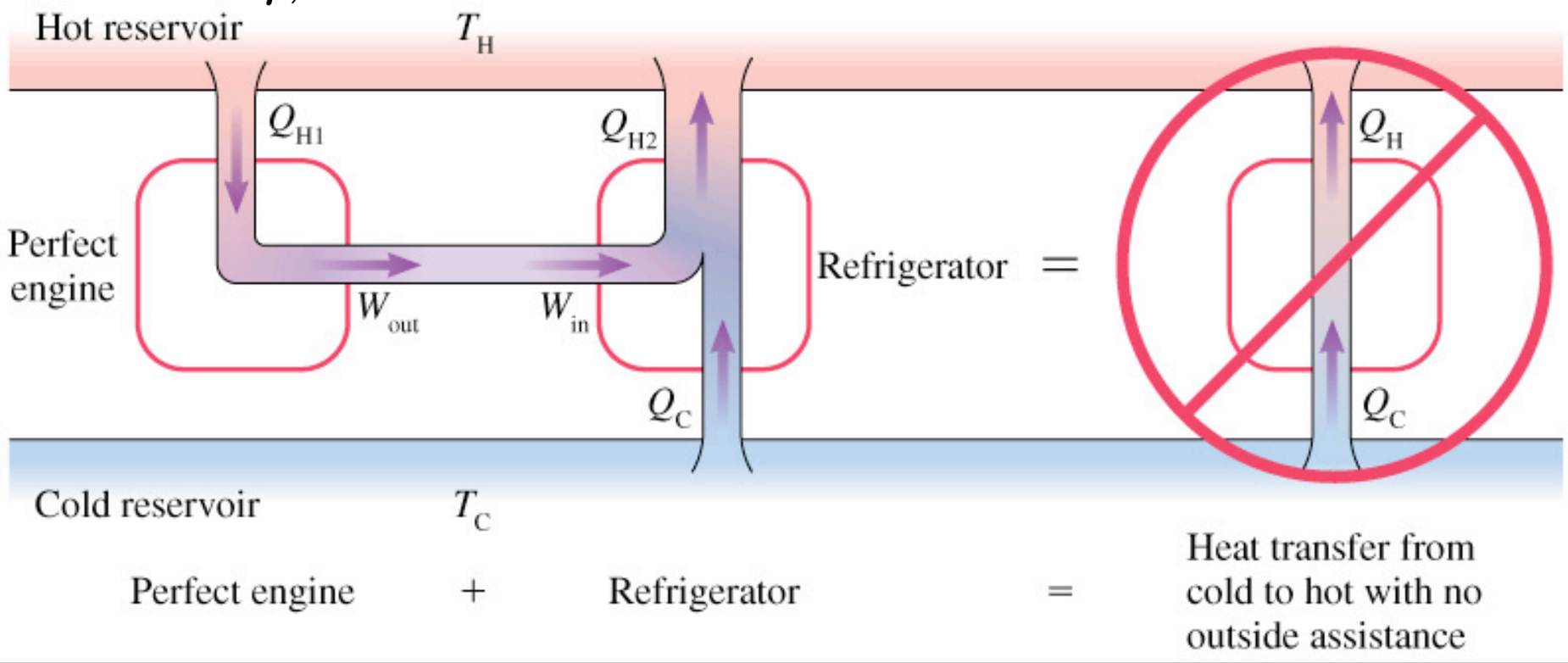
- exhaust <u>more</u> heat than removed from inside (cool room by leaving refrigerator door open?)

- coefficient of performance: $$K = \frac{Q_C}{W_{in}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

- perfect refrigerator ($W_{in} = 0;\ K = \infty$) forbidden by 2nd law (informal statement # 3): real refrigerator uses work ($K < \infty$)

No perfect Heat Engine

- connect perfect engine to refrigerator: no net work for 2 combined, but heat transferred from cold to hot (not by 2nd law)
- informal statement # 4: no perfect heat engine, must waste heat...
- Using only energy conservation and heat not transferred from cold to hot, deduce heat engines and refrigerators exist; must use closed-cycle processes; no perfect...

Unanswered questions

- upper limit on $\eta,\ K$?