HEAT ENGINES AND REFRIGERATORS

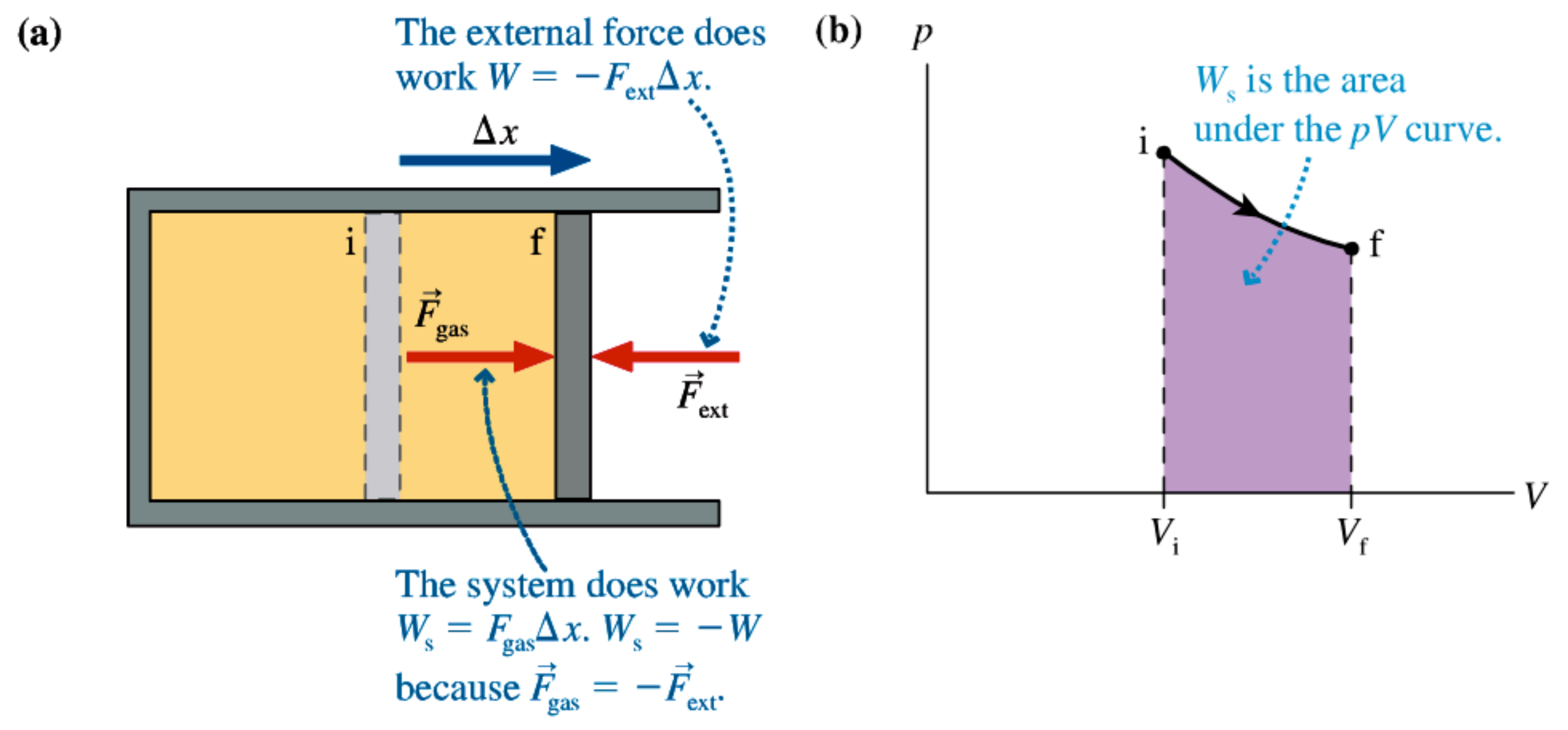
First Law

Energy is conserved; that is $Q = \Delta U + W$

Second Law

Most macroscopic processes are irreversible. In particular, heat energy is transferred spontaneously from a hotter to a colder system but never from a colder to a hotter system.

A car engine transforms the chemical energy stored in the fuel into work and ultimately into the car's kinetic energy.



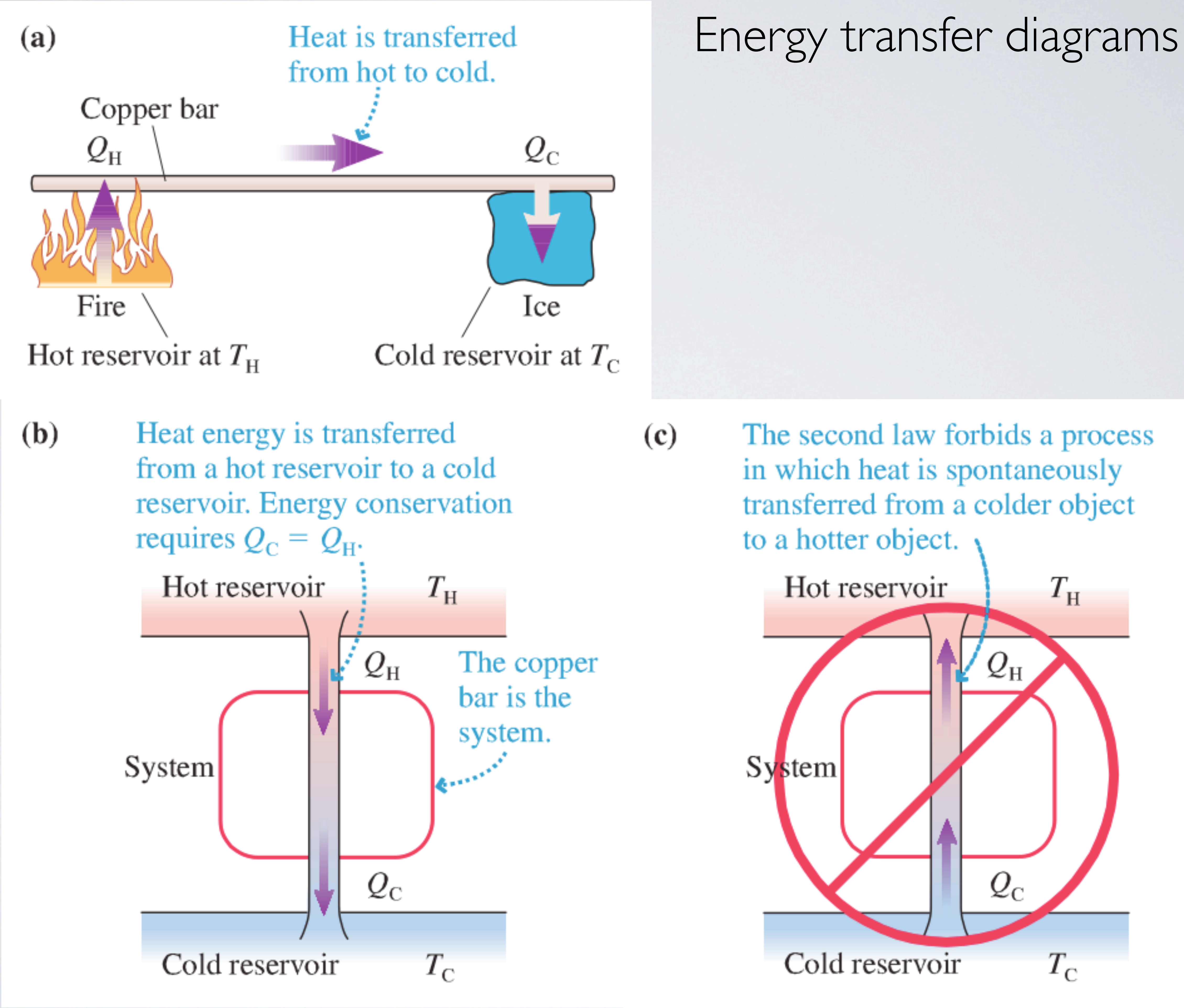
The external force does work $W = -F_{\text{ext}}\Delta x$.

The system does work $W_s = F_{\text{gas}}\Delta x$. $W_s = -W$ because $\vec{F}_{\text{gas}} = -\vec{F}_{\text{ext}}$.

W_s is the area under the pV curve.

Forces $\boldsymbol{F}_{\text{gas}}$ and $\boldsymbol{F}_{\text{ext}}$ both do work as the piston moves.

Energy transfer diagrams

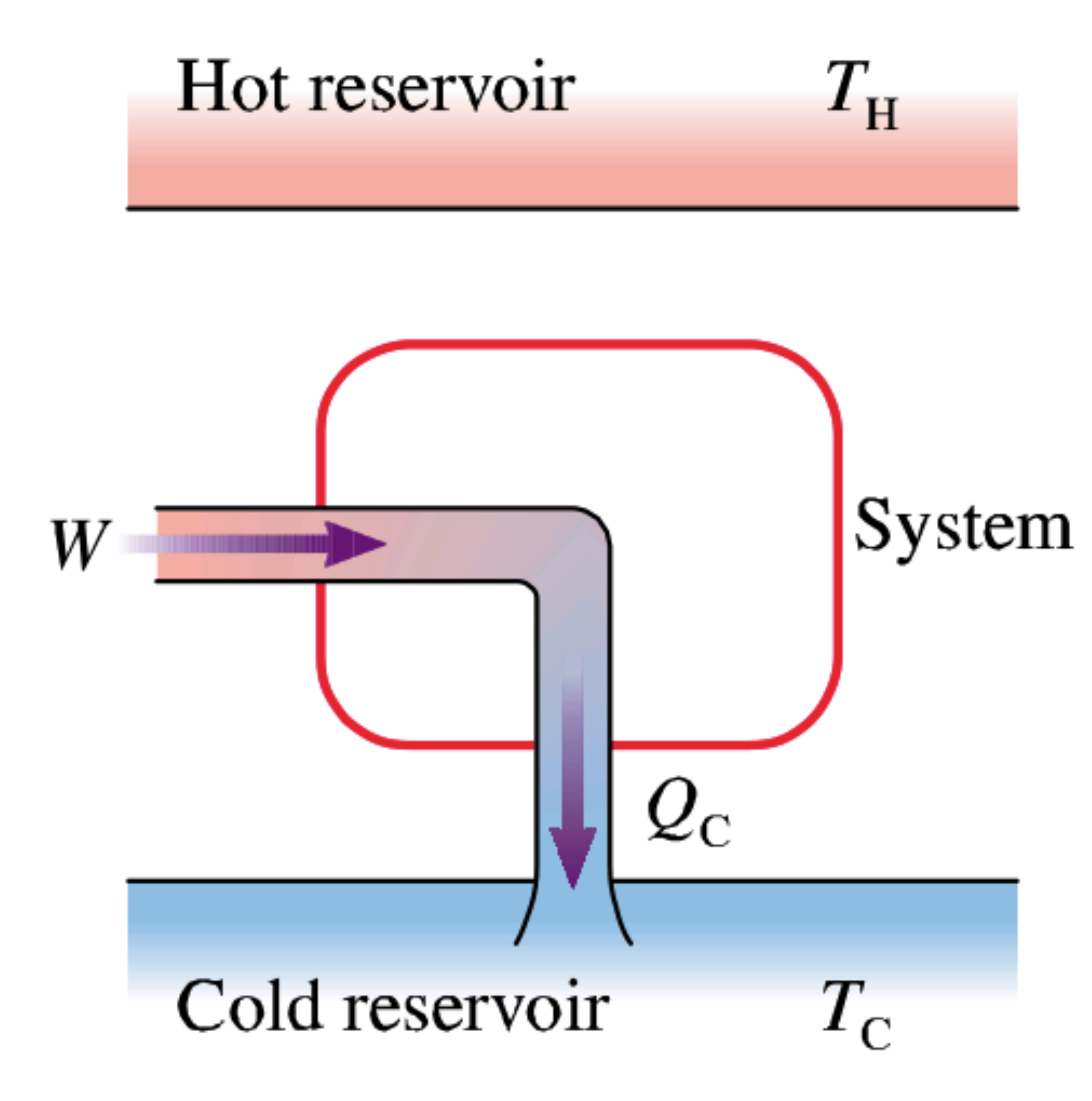


Heat is transferred from hot to cold.

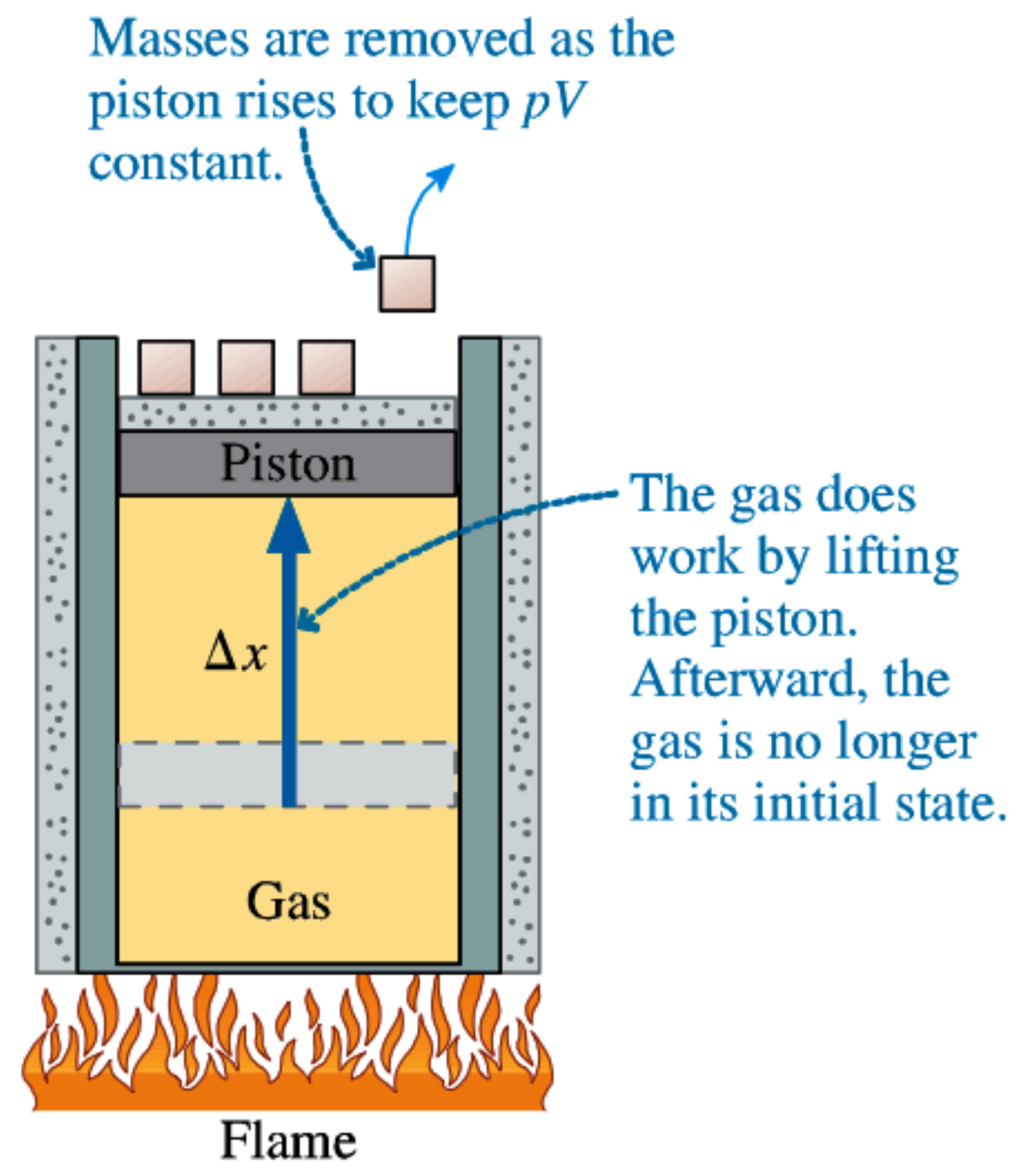
Heat energy is transferred from a hot reservoir to a cold reservoir. Energy conservation requires $Q_C = Q_H$.

The copper bar is the system.

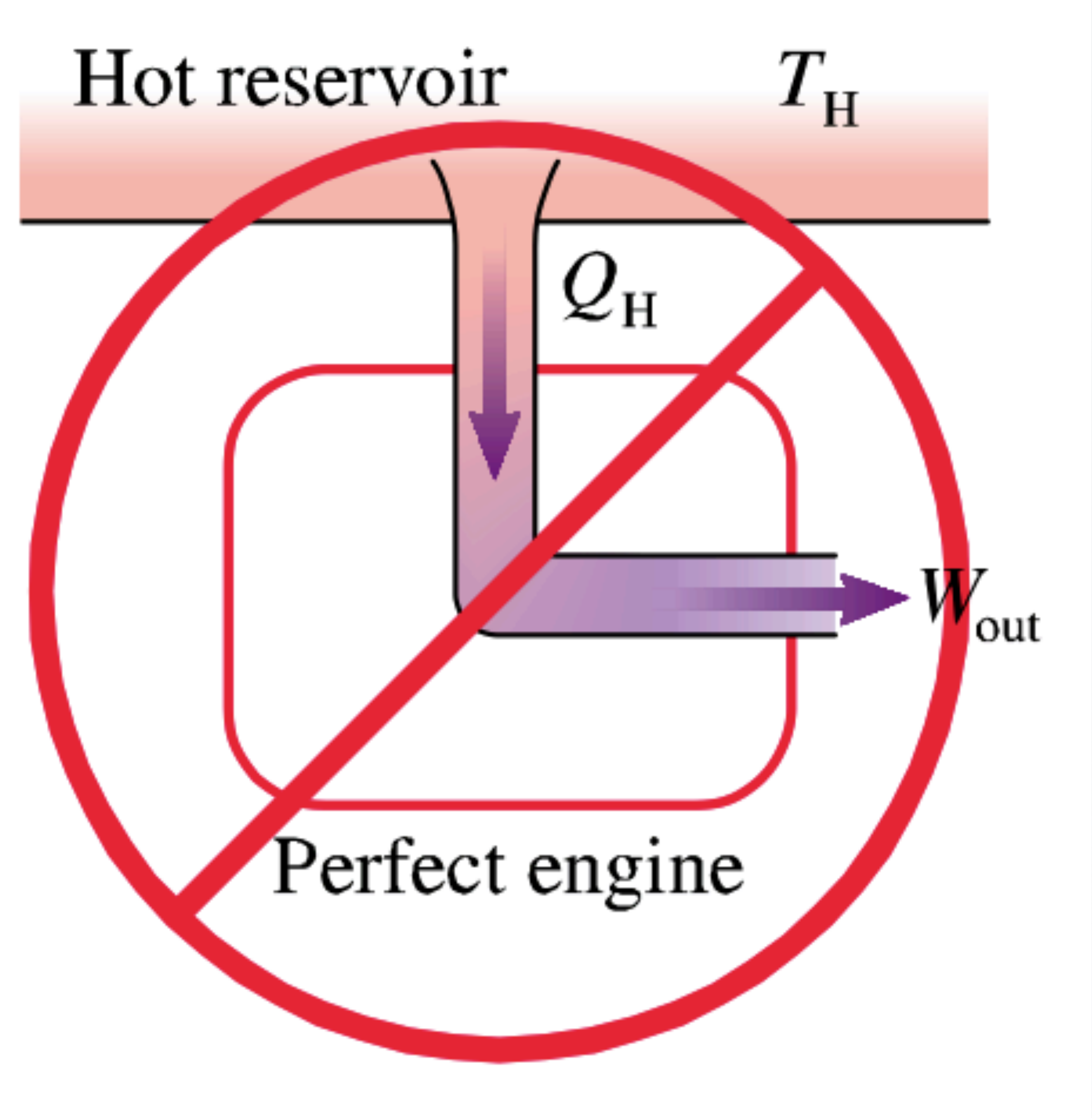
The second law forbids a process in which heat is spontaneously transferred from a colder object to a hotter object.



Work can be transformed into heat with 100% efficiency.

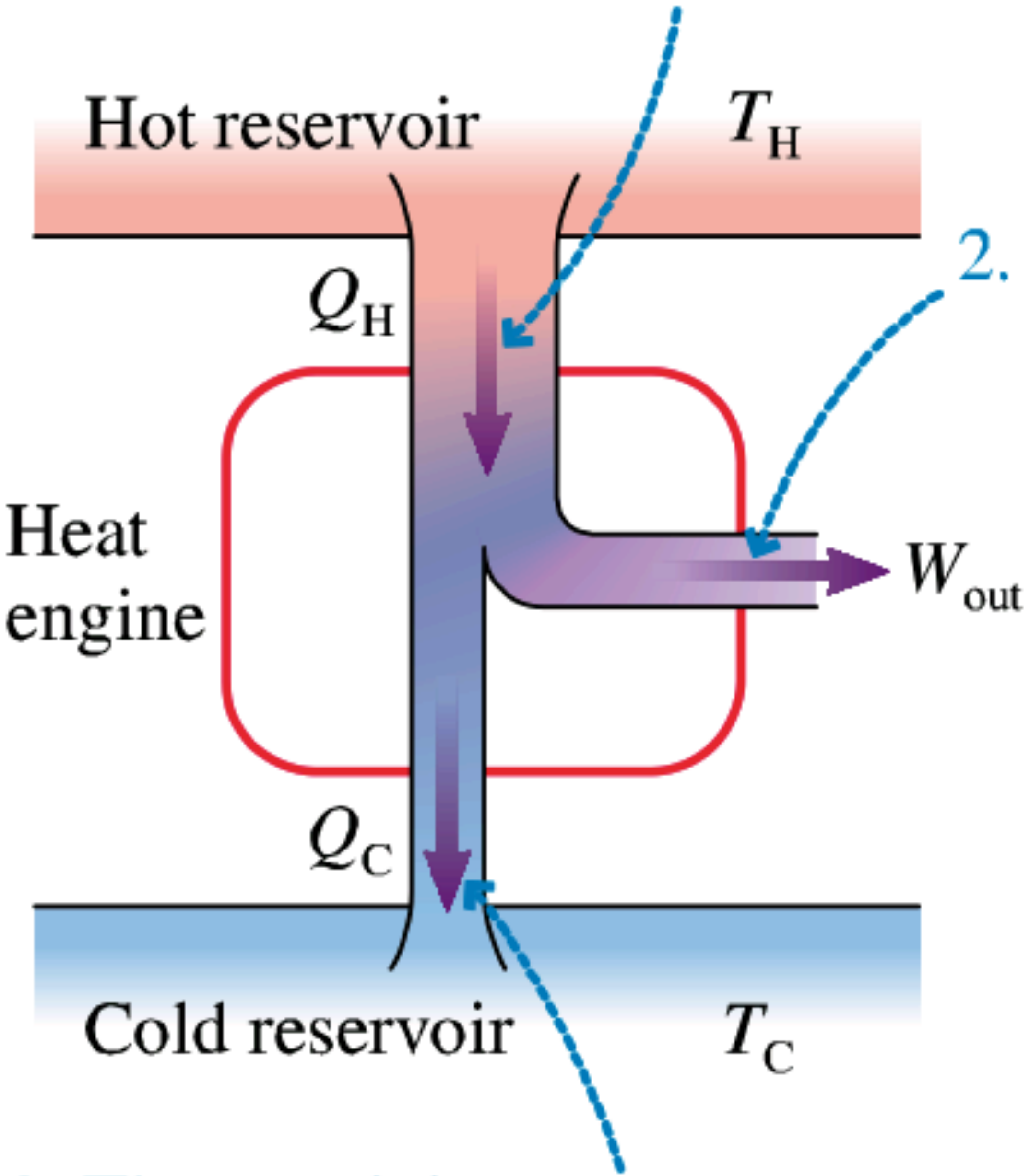


An isothermal process transforms heat into work, but only as a one-time event.



There are no perfect engines that turn heat into work with 100% efficiency.

The energy-transfer diagram of a heat engine.



1. Heat energy Q_H is transferred from the hot reservoir (typically burning fuel) to the system.
2. Part of the energy is used to do useful work W_{out}.
3. The remaining energy $Q_C = Q_H - W_{out}$ is exhausted to the cold reservoir (cooling water or the air) as waste heat.

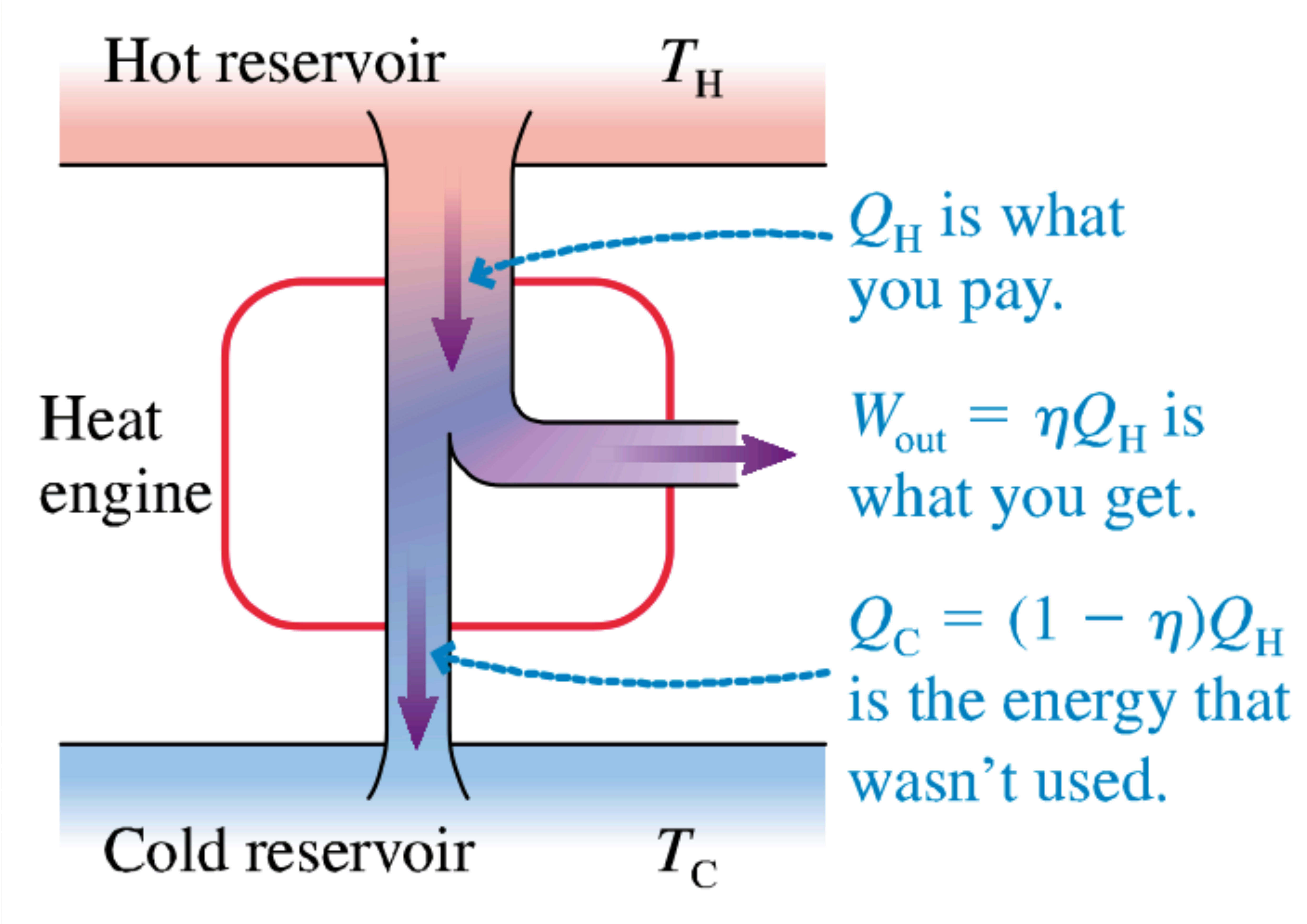
Useful work

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

Thermal efficiency

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

$$\eta = 1 - \frac{Q_{\text{C}}}{Q_{\text{H}}}$$



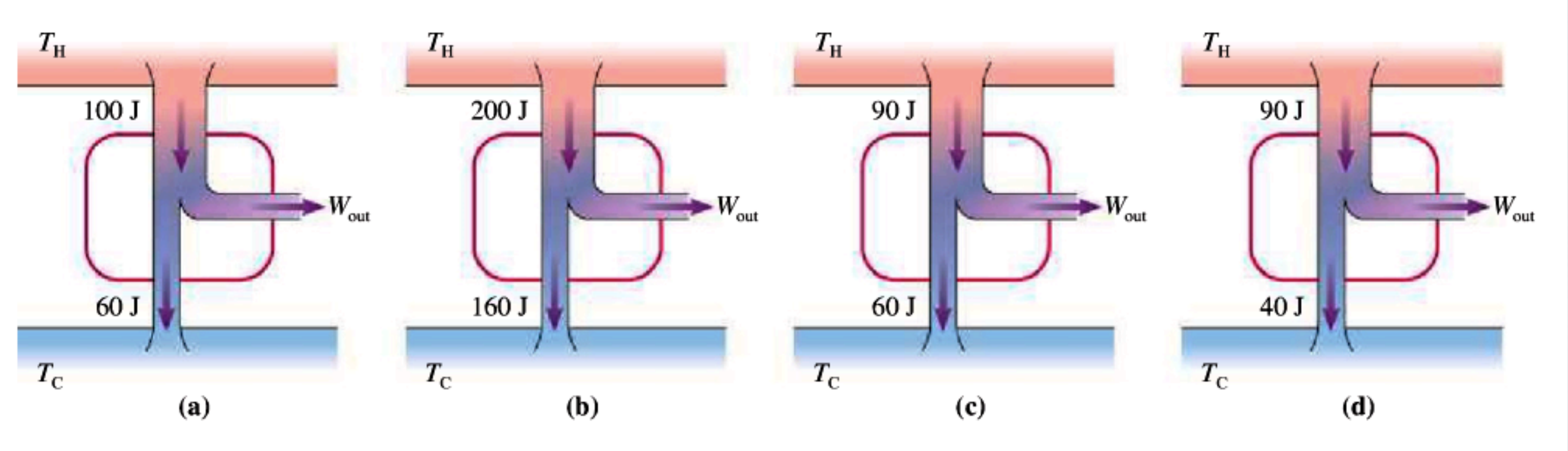
Q_H is what you pay.

$W_{out} = \eta Q_H$ is what you get.

$Q_C = (1 - \eta)Q_H$ is the energy that wasn't used.

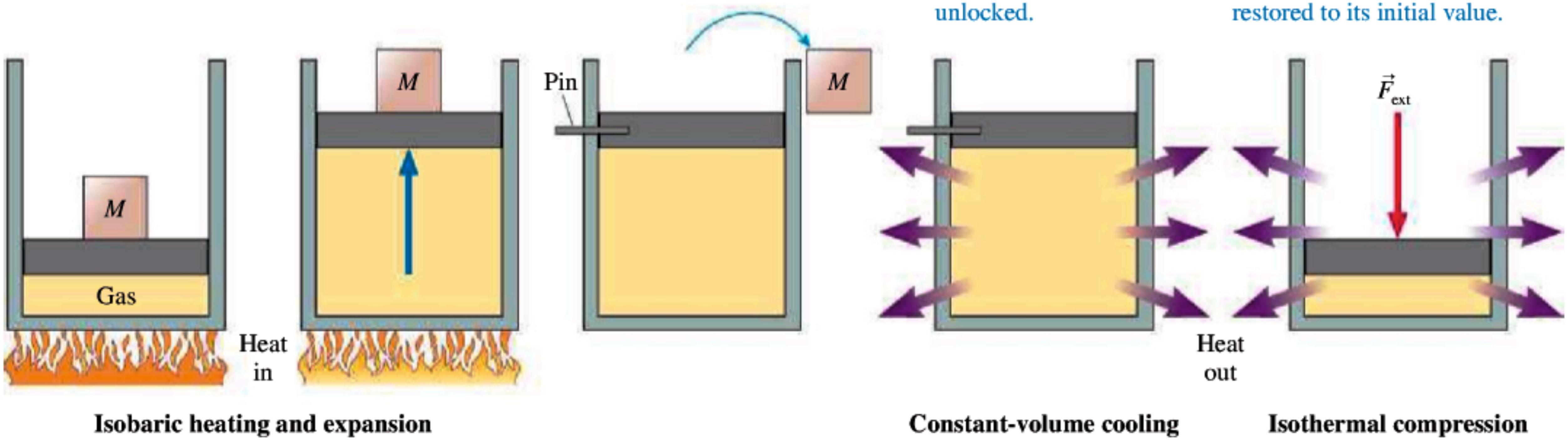
η is the fraction of heat energy that is transformed into useful work.

Rank in order, from largest to smallest, the work W_{out} performed by these four heat engines.



A heat-engine example

A simple heat engine transforms heat into work.



(a) Heat is transferred into the gas from the burning fuel.

(b) The gas does work by lifting the mass in an isobaric expansion.

(c) The piston is locked and the mass is removed. The heat is turned off.

(d) The gas cools back to room temperature at constant volume. Then the piston is unlocked.

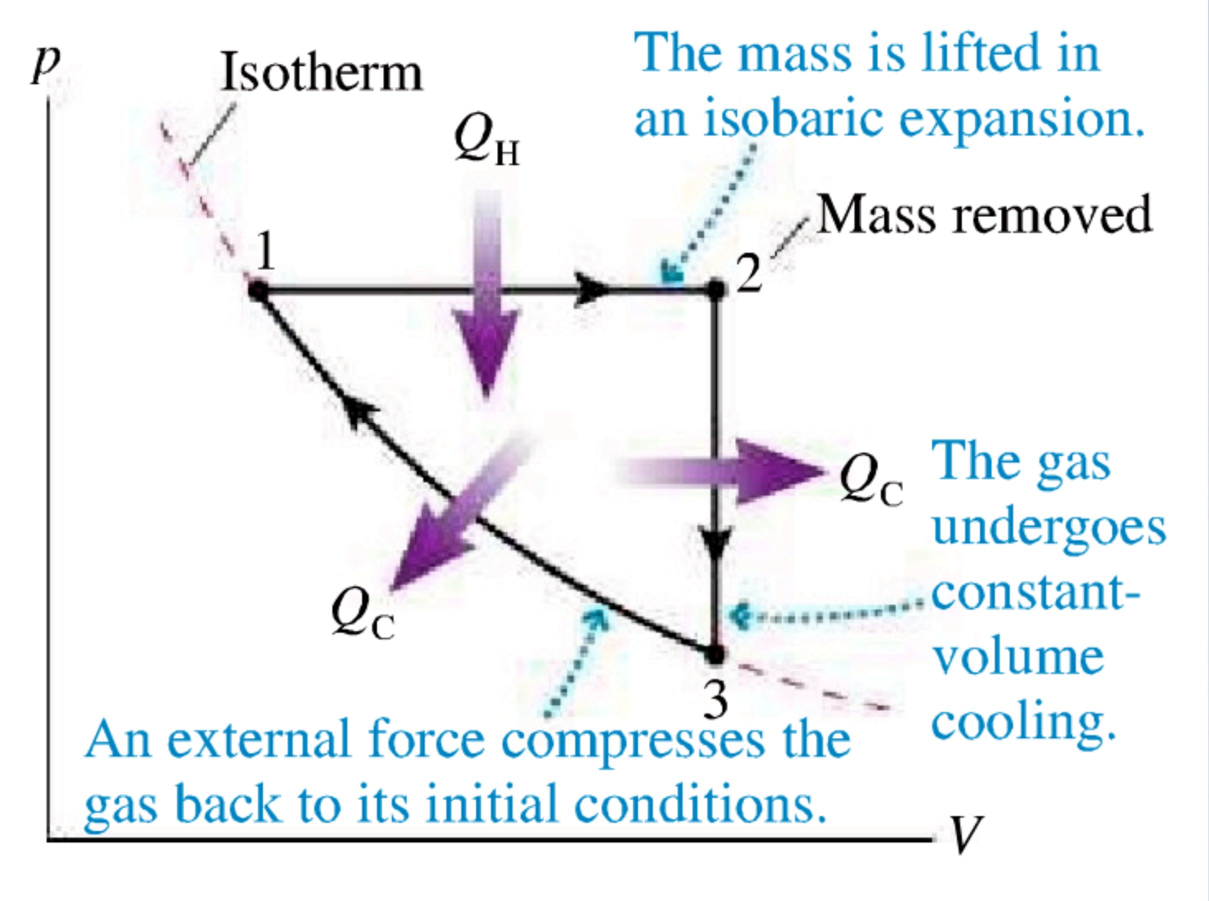
(e) A steadily increasing external force steadily raises the pressure in an isothermal compression until the pressure has been restored to its initial value.

Isobaric heating and expansion

Constant-volume cooling

Isothermal compression

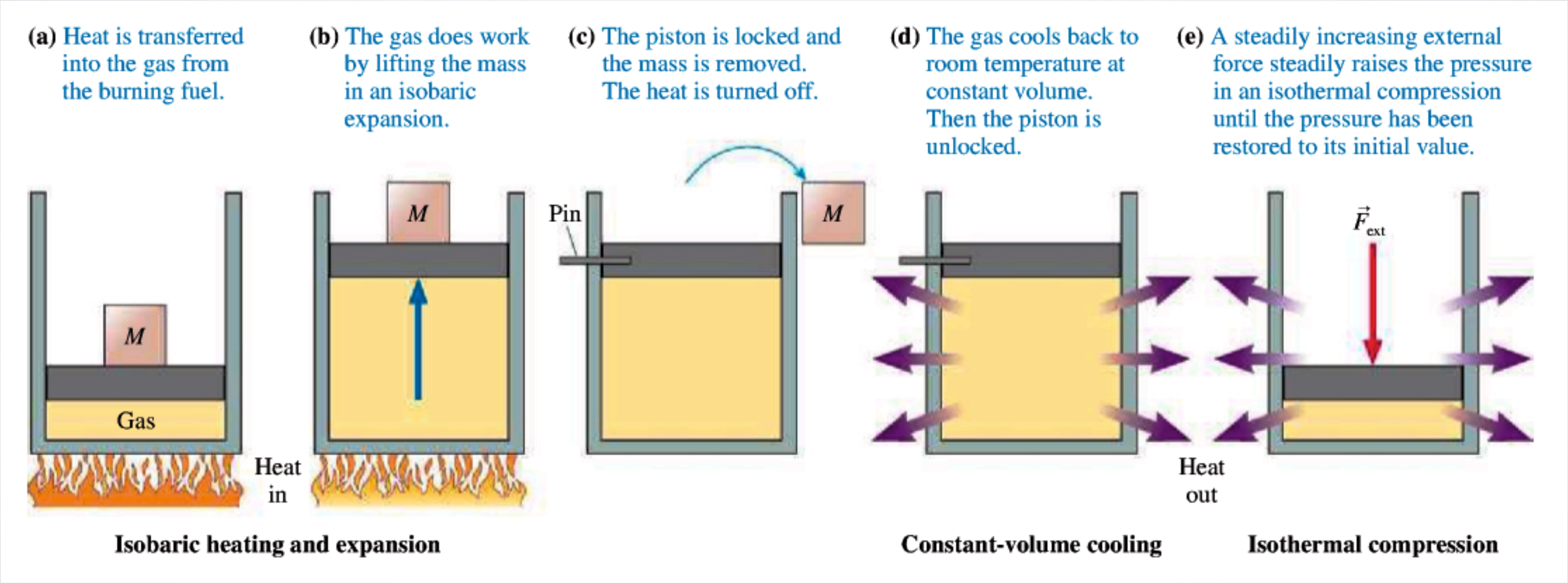
The closed-cycle *pV* diagram for the heat engine described.



The mass is lifted in an isobaric expansion.

The gas undergoes constant-volume cooling.

An external force compresses the gas back to its initial conditions.



(a) Heat is transferred into the gas from the burning fuel.

(b) The gas does work by lifting the mass in an isobaric expansion.

(c) The piston is locked and the mass is removed. The heat is turned off.

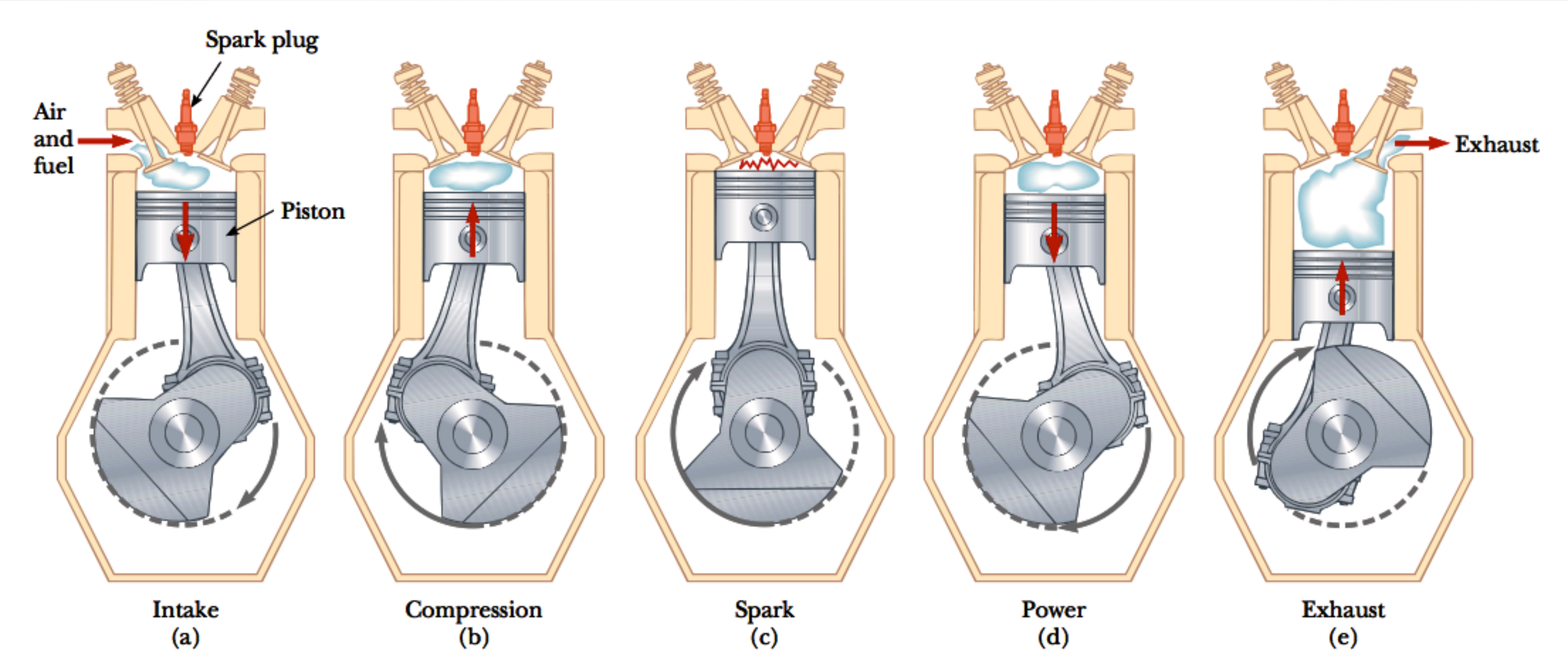
(d) The gas cools back to room temperature at constant volume. Then the piston is unlocked.

(e) A steadily increasing external force steadily raises the pressure in an isothermal compression until the pressure has been restored to its initial value.

Isobaric heating and expansion

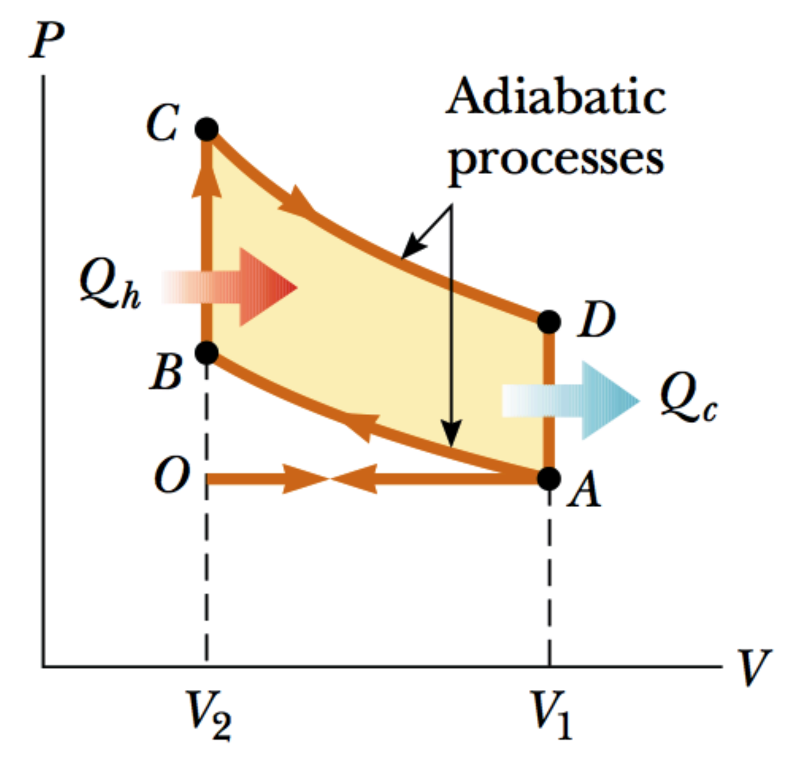
Constant-volume cooling

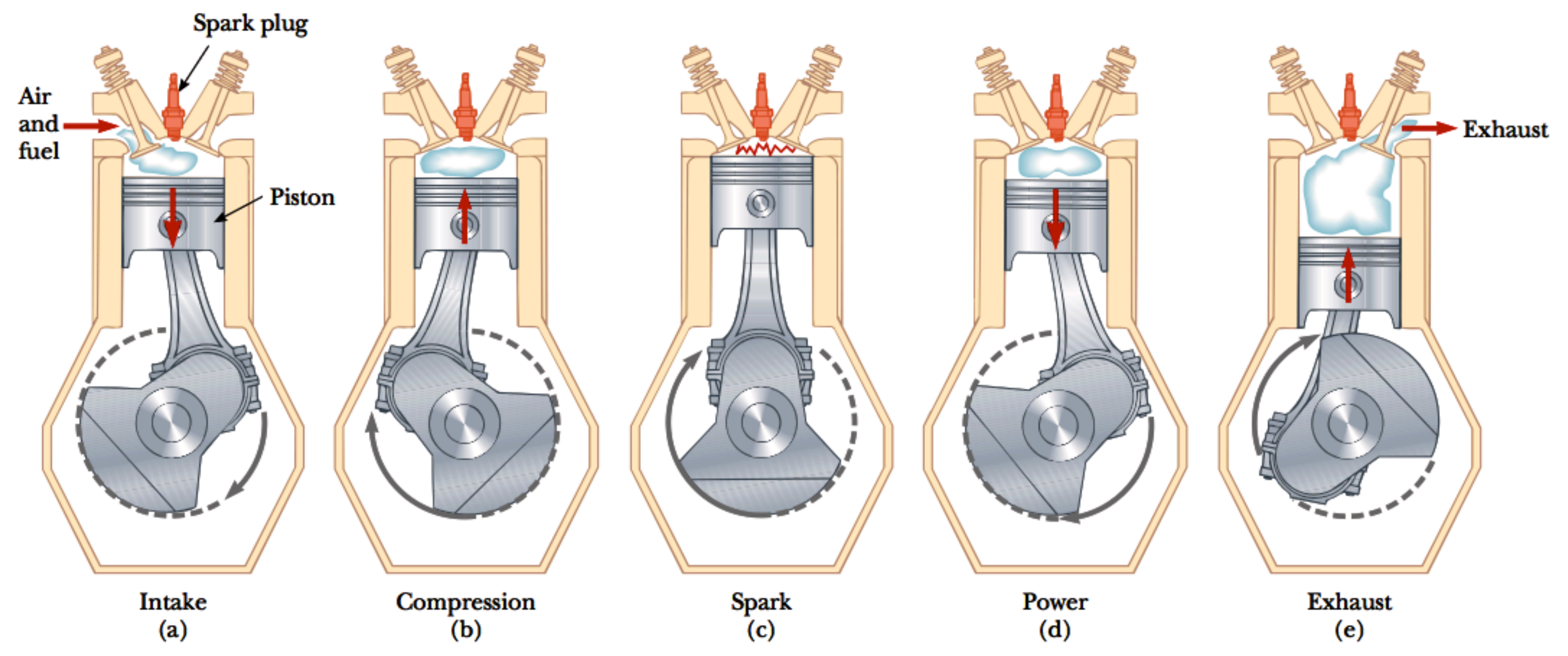
Isothermal compression



The four-stroke cycle of a conventional gasoline engine. (a) In the intake stroke, air is mixed with fuel. (b) The intake valve is then closed, and the air–fuel mixture is compressed by the piston. (c) The mixture is ignited by the spark plug, with the result that the temperature of the mixture increases. (d) In the power stroke, the gas expands against the piston. (e) Finally, the residual gases are expelled, and the cycle repeats.

PV diagram for the Otto cycle, which approximately represents the processes occurring in an internal combustion engine.





Intake
(a)

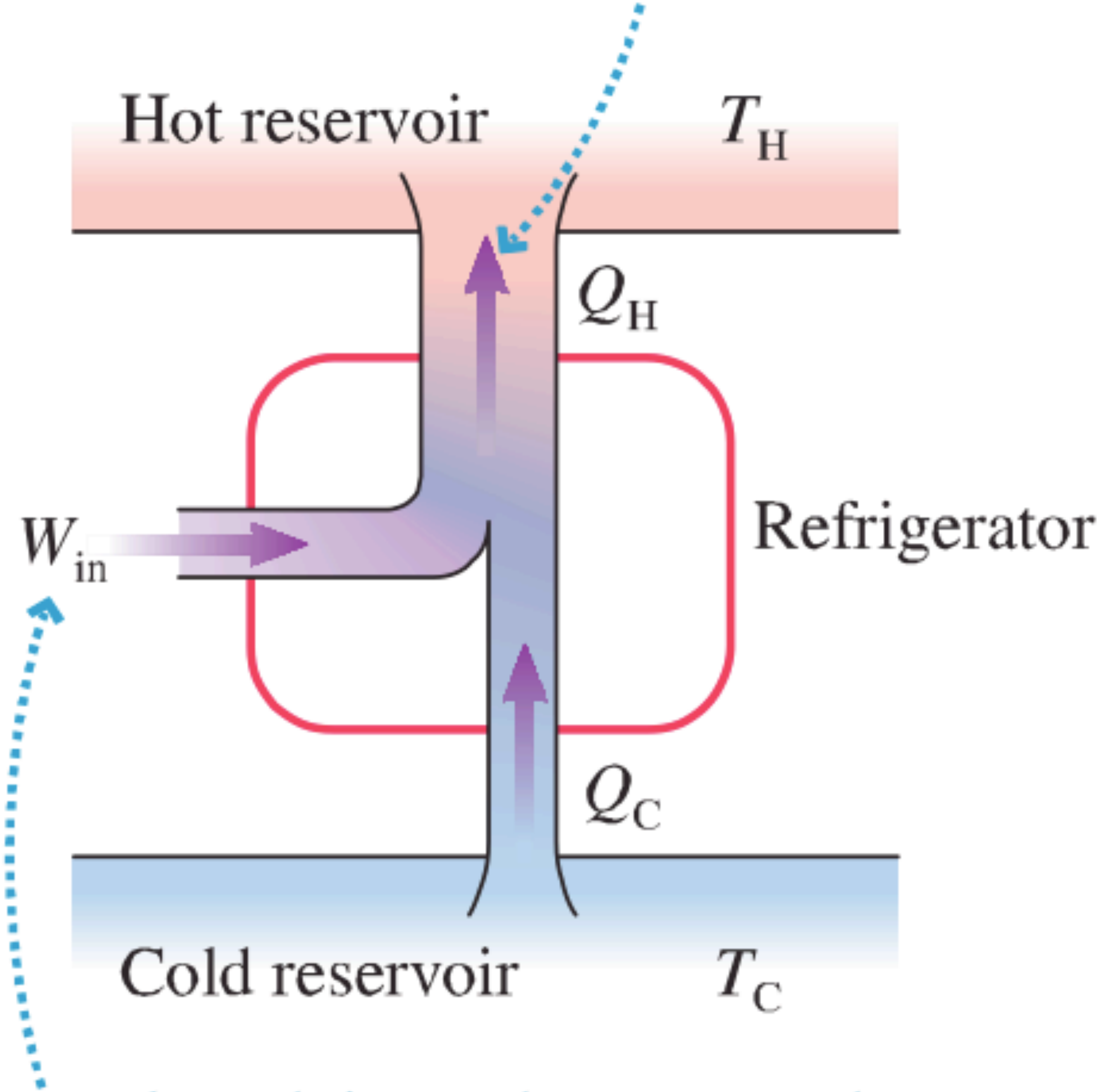
Compression
(b)

Spark
(c)

Power
(d)

Exhaust
(e)

The energy-transfer diagram of a refrigerator.



The amount of heat exhausted to the hot reservoir is larger than the amount of heat extracted from the cold reservoir.

External work is used to remove heat from a cold reservoir and exhaust heat to a hot reservoir.

Useful work

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

Thermal efficiency

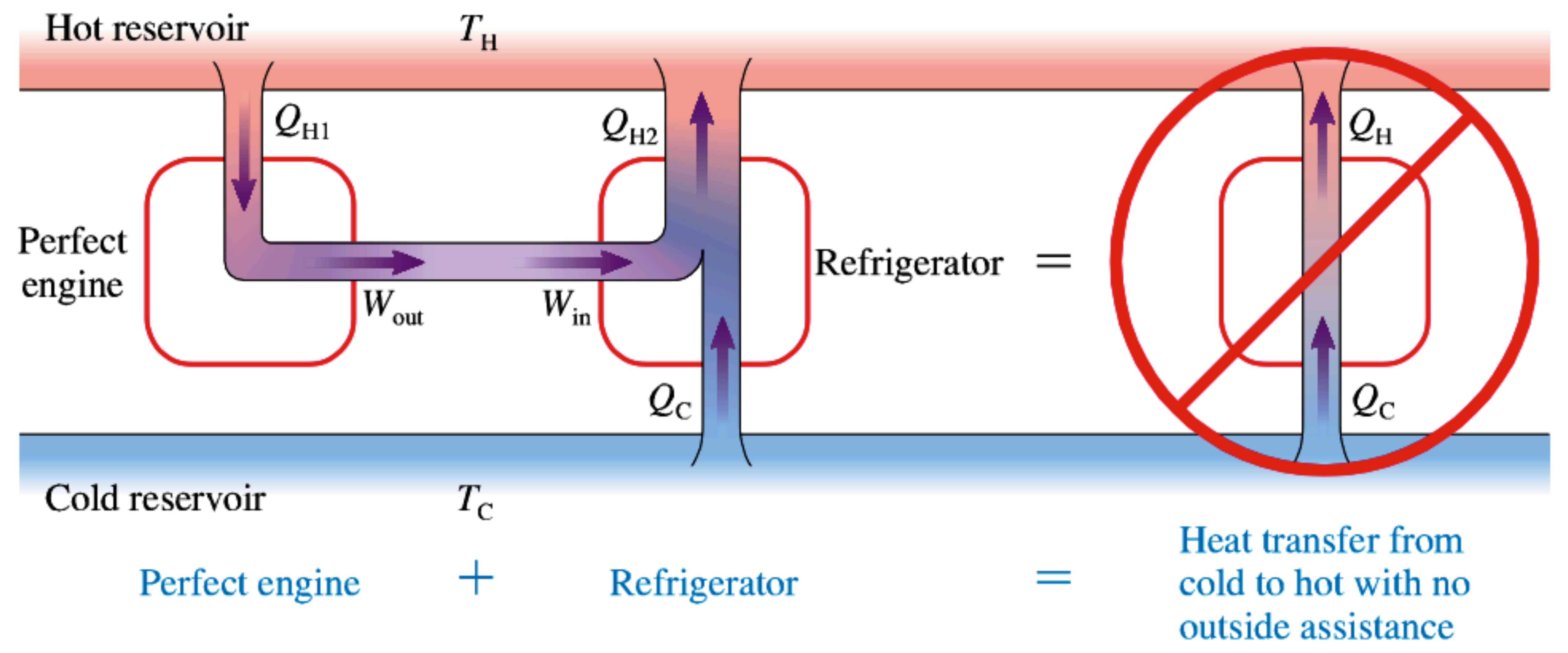
$$\eta = \frac{W_{\text{out}}}{Q_{\text{H}}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

$$\eta = 1 - \frac{Q_{\text{C}}}{Q_{\text{H}}}$$

Coefficient of performance

$$K = \frac{Q_{\text{C}}}{W_{\text{in}}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

A perfect engine driving an ordinary refrigerator would be able to violate the second law of thermodynamics.



It’s a hot day and your air conditioner is broken. Your roommate says, “Let’s open the refrigerator door and cool this place off.” will this work?

a. Yes.

b. No.

c. It might, but it will depend on how hot the room is.