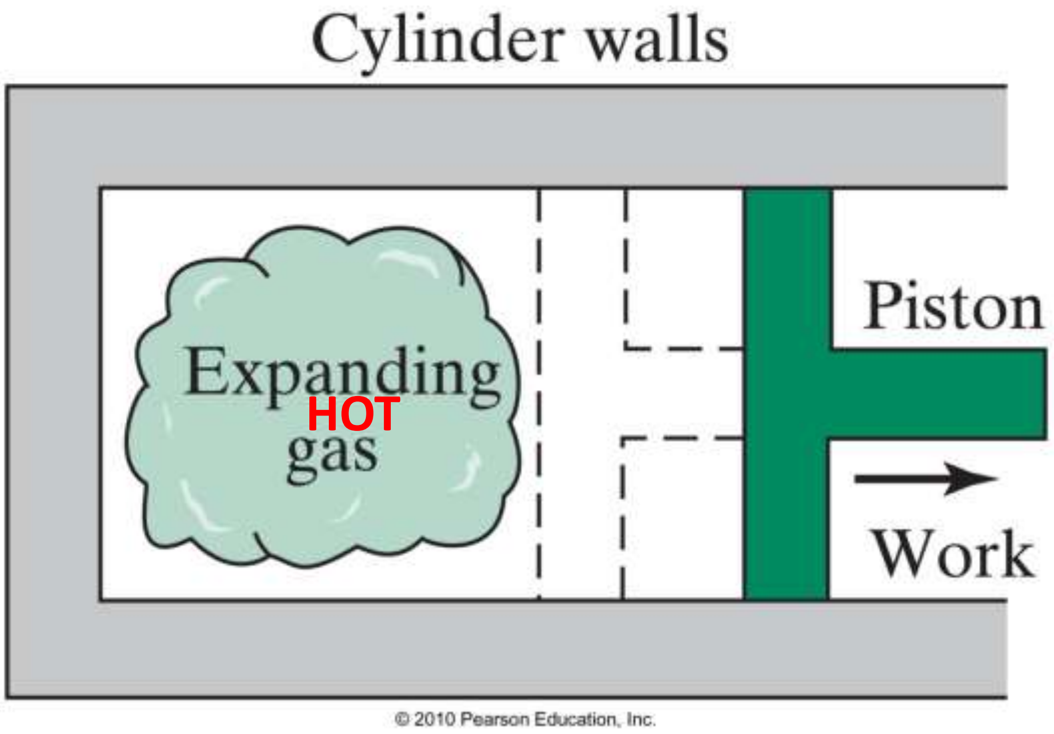
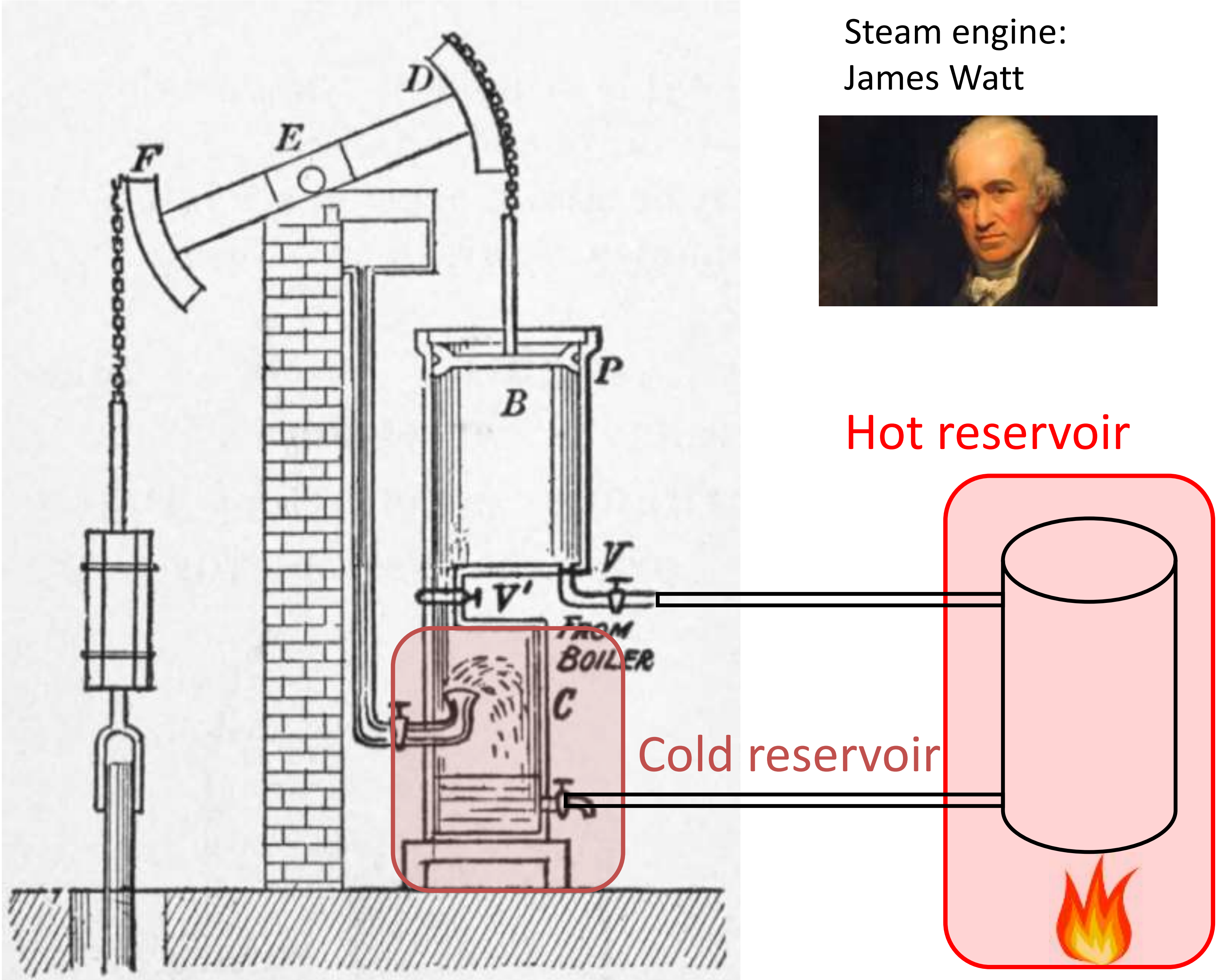
Heat Engines: Using Thermal Energy to Do Work

- Definition: a heat engine is any machine that converts thermal energy into mechanical forms of energy.
- How do we design such machines?

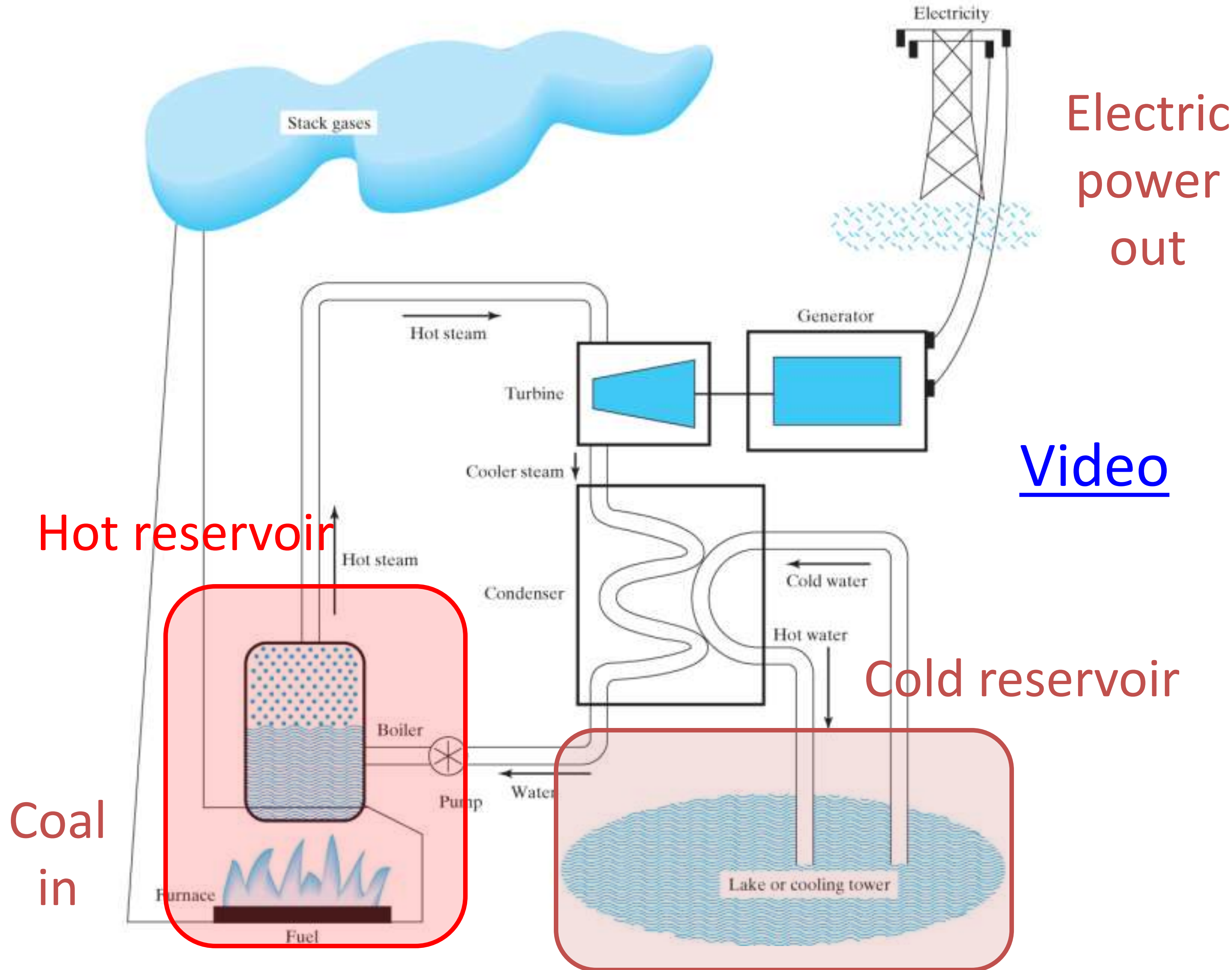


Basic principle of most heat engines

Steam engine:
James Watt

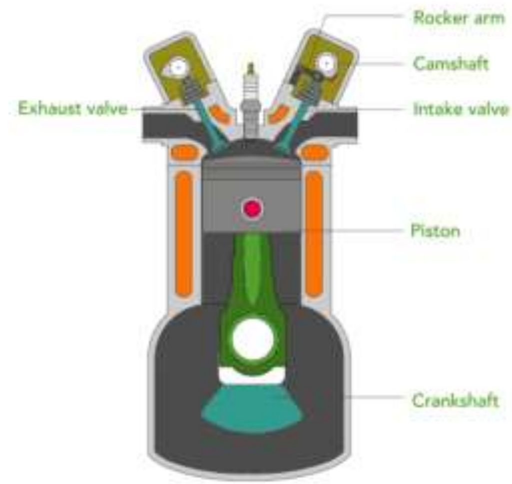


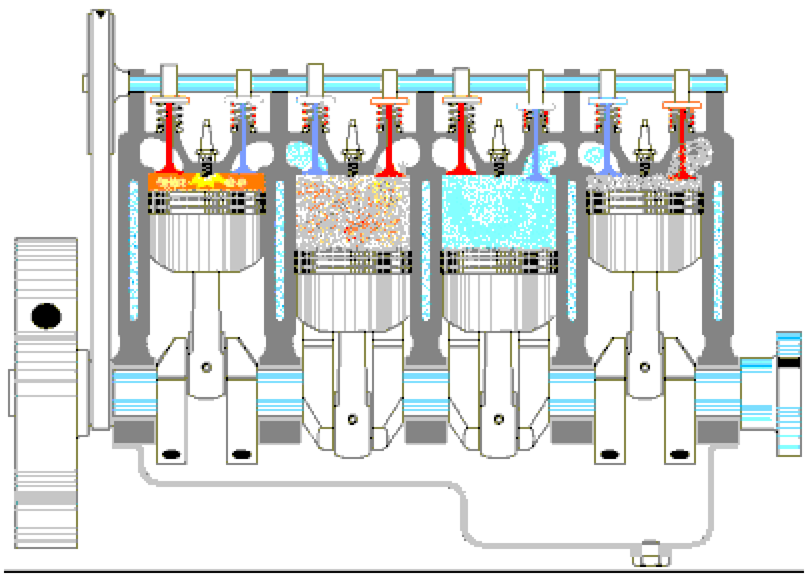
The Steam-Electric Power Plant



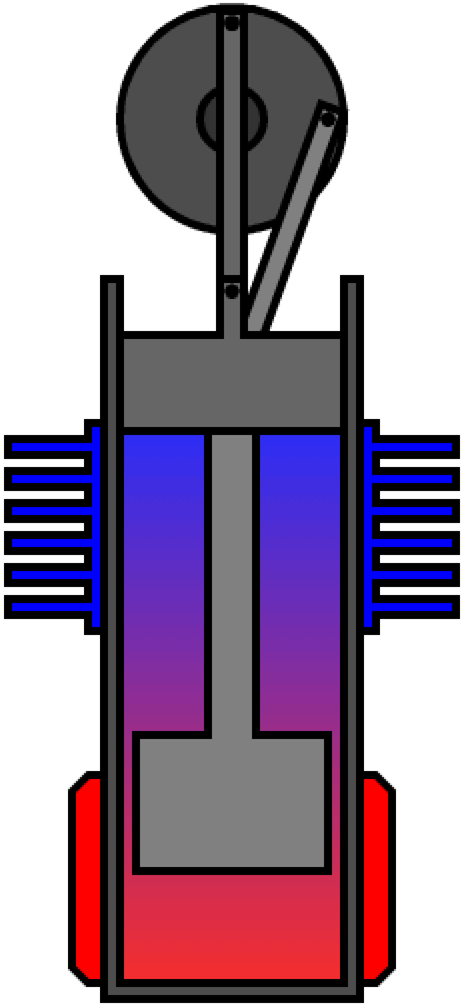
Internal Combustion Engine

- **Intake:** The intake valve opens, and fresh air (containing no fuel), is drawn into the cylinder.
- **Compression:** <u>As the piston rises, the air is compressed, causing its temperature to rise. At the end of the compression stroke, the air is hot enough to ignite fuel.</u>
- **Injection:** Near the top of the compression stroke, the fuel injector drives fuel into the cylinder. The fuel-air mixture is ignited with a spark plug.
- **Power:** <u>As the fuel burns, the gas in the cylinder heats and expands, driving the piston.</u>
- **Exhaust:** The exhaust valve opens, and the exhaust is driven out of the cylinder

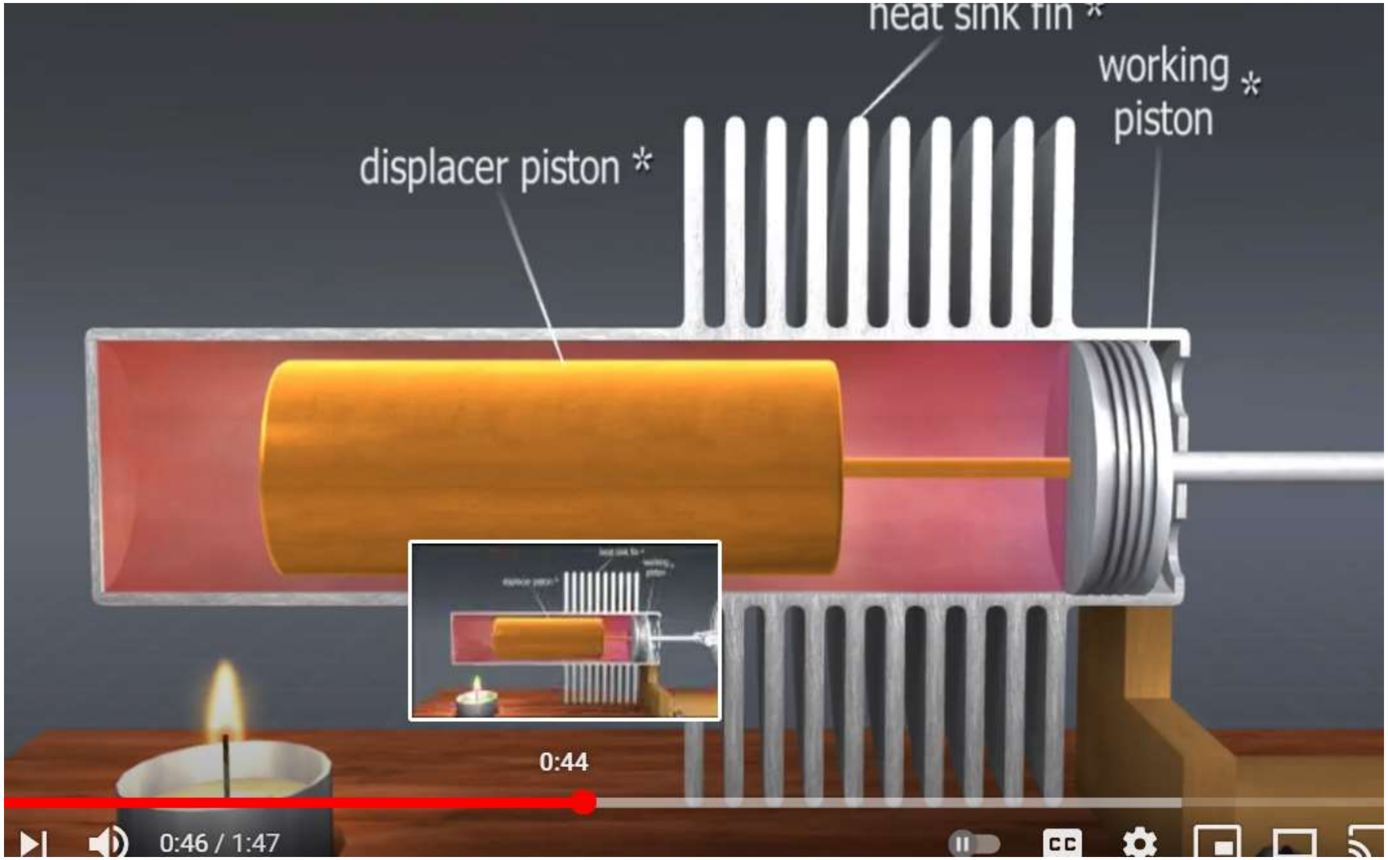




Demo: Sterling engine

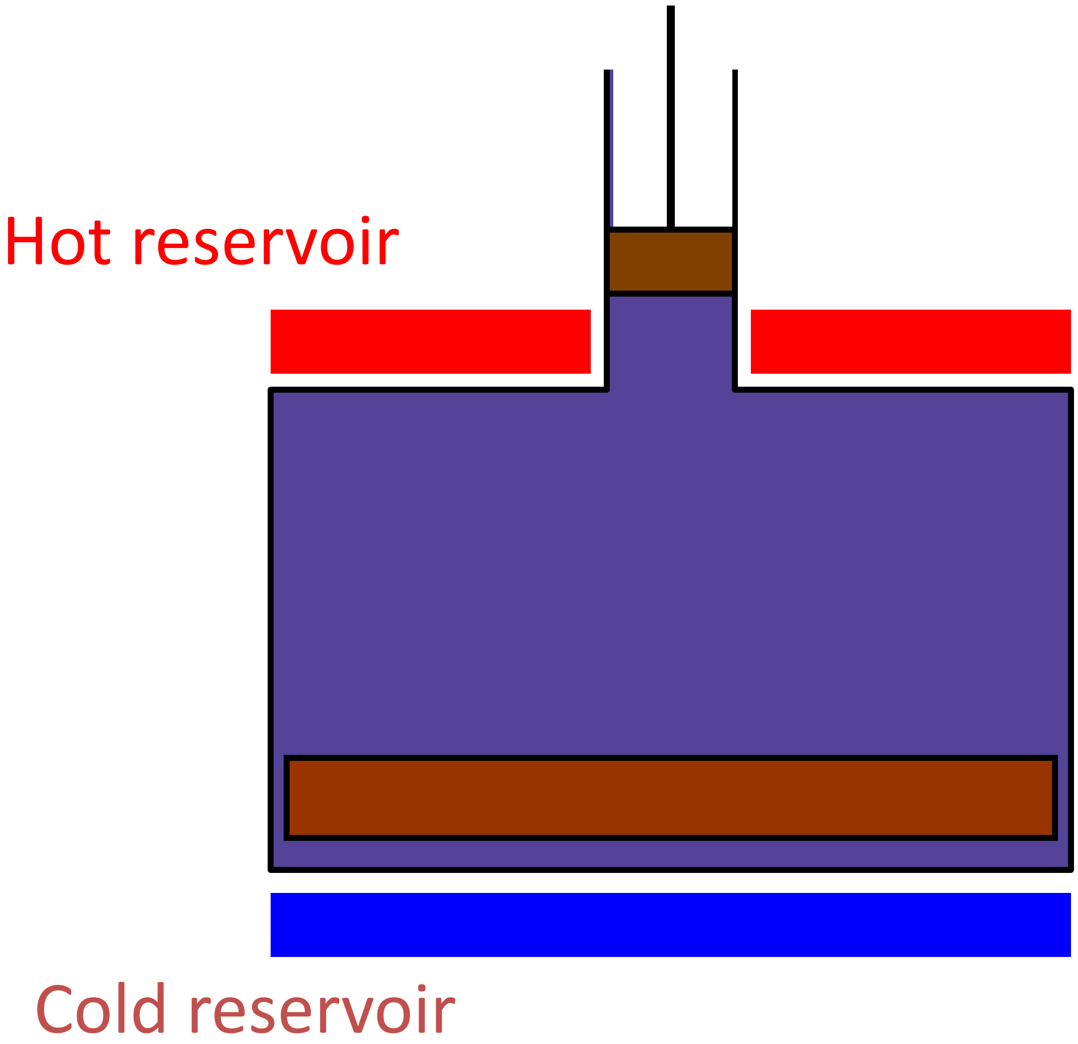


Video: Sterling engine



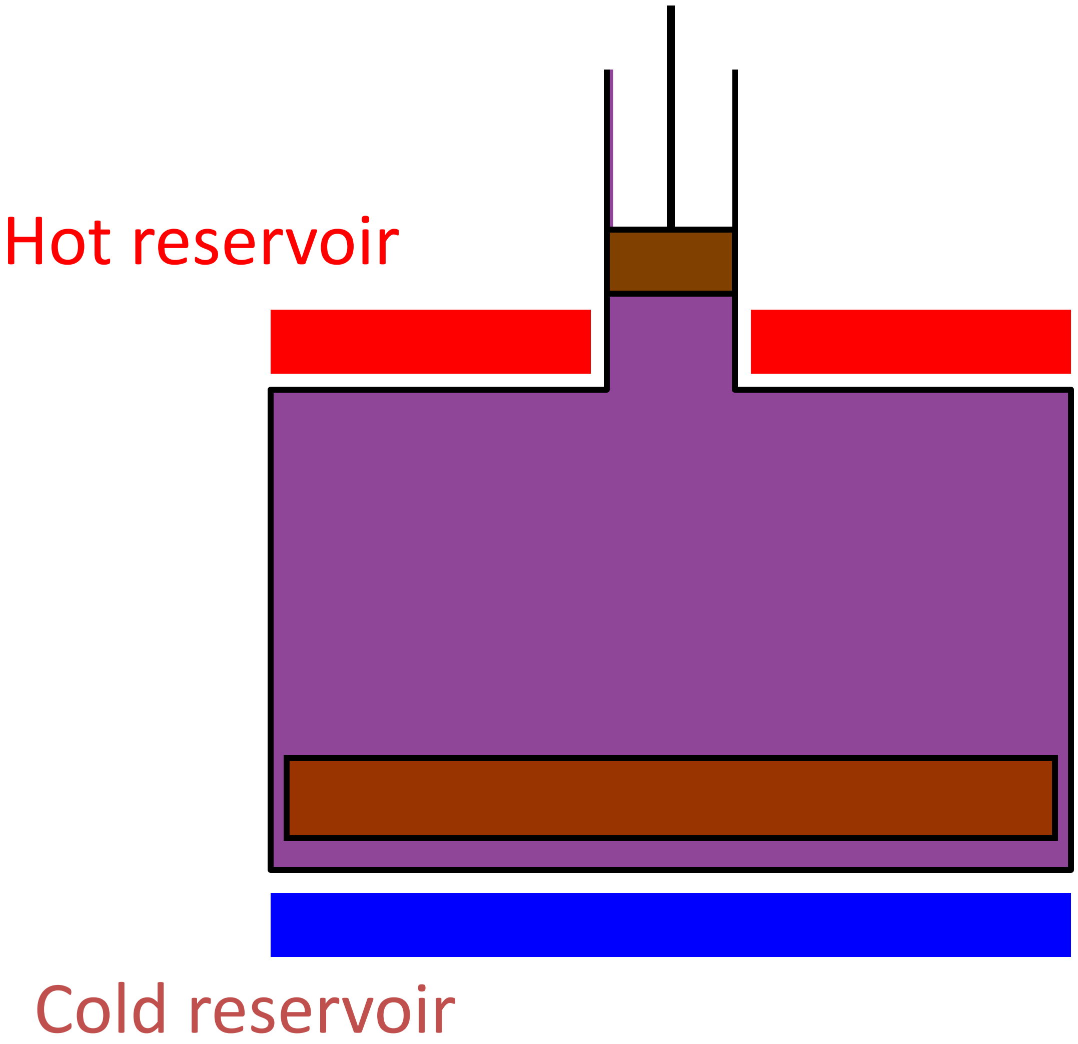
Sterling engine

Step 1

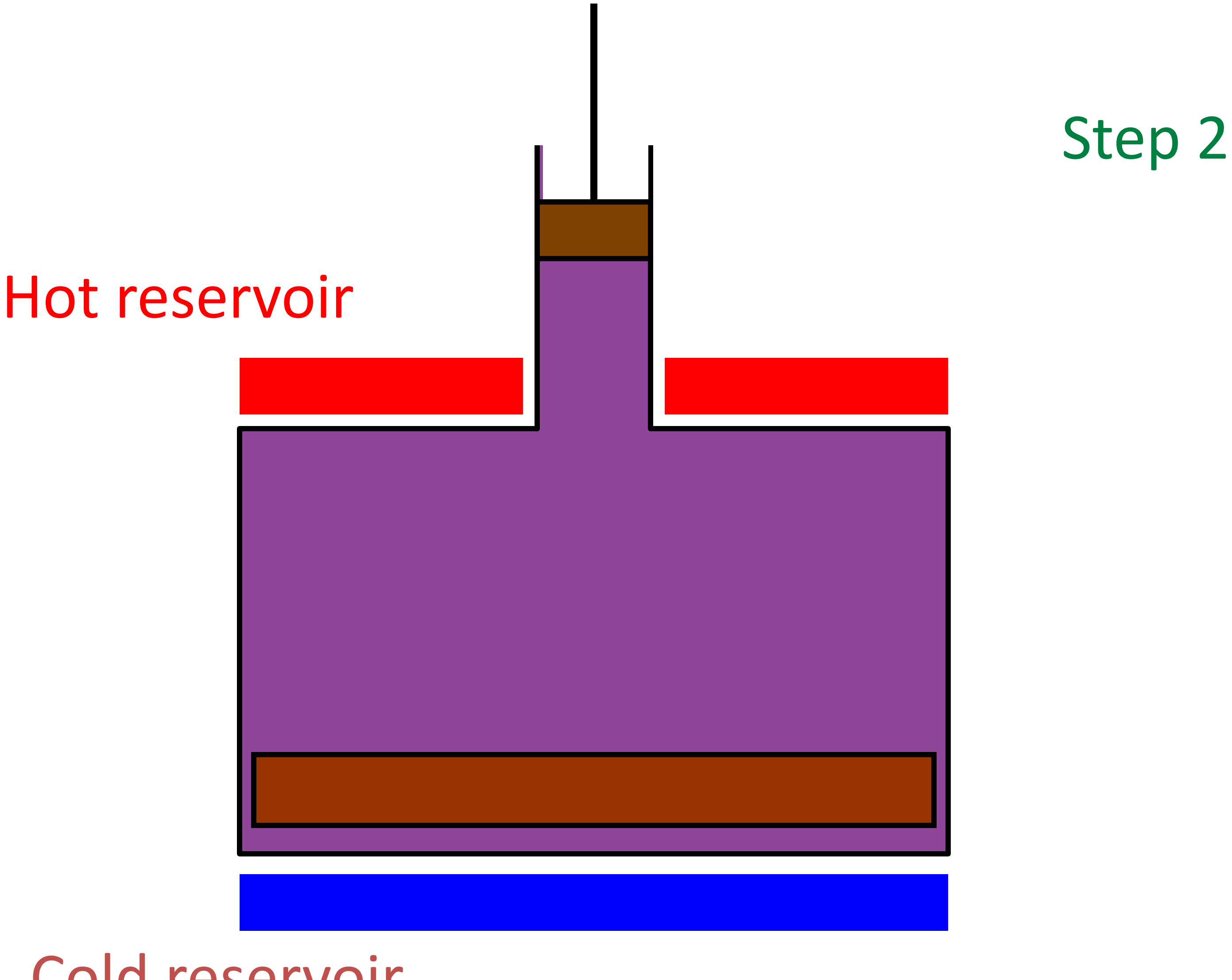


Sterling engine

Step 1



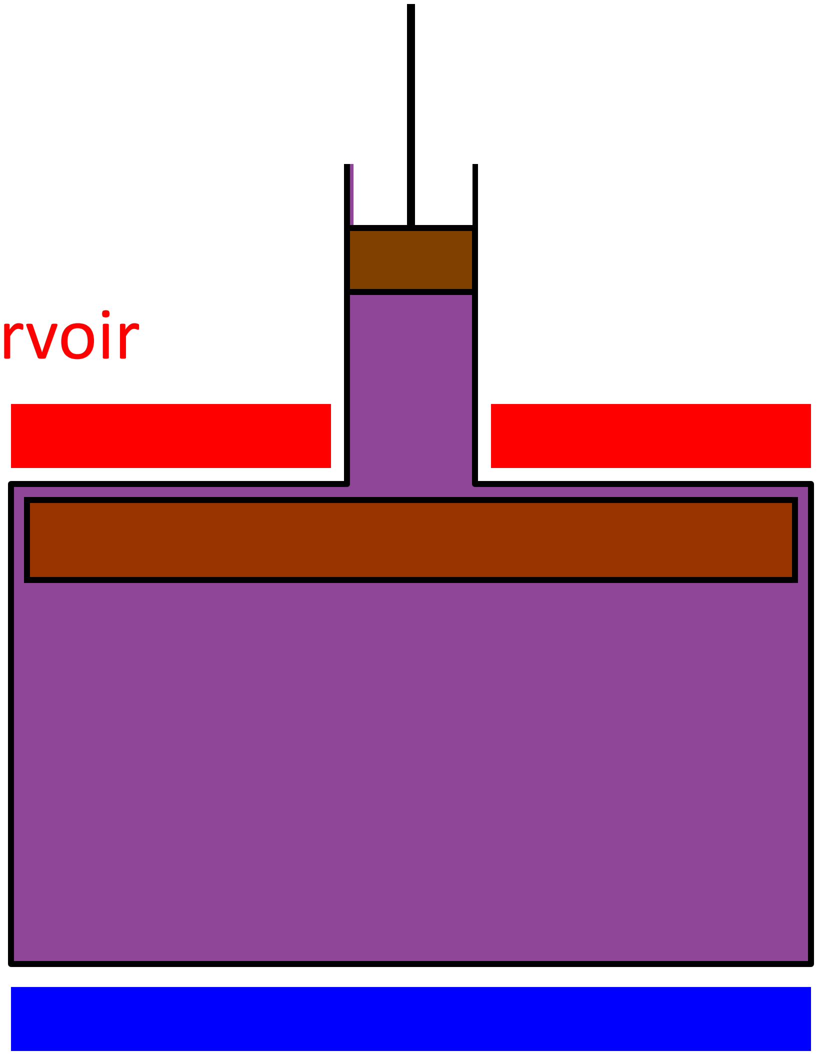
Sterling engine



Sterling engine

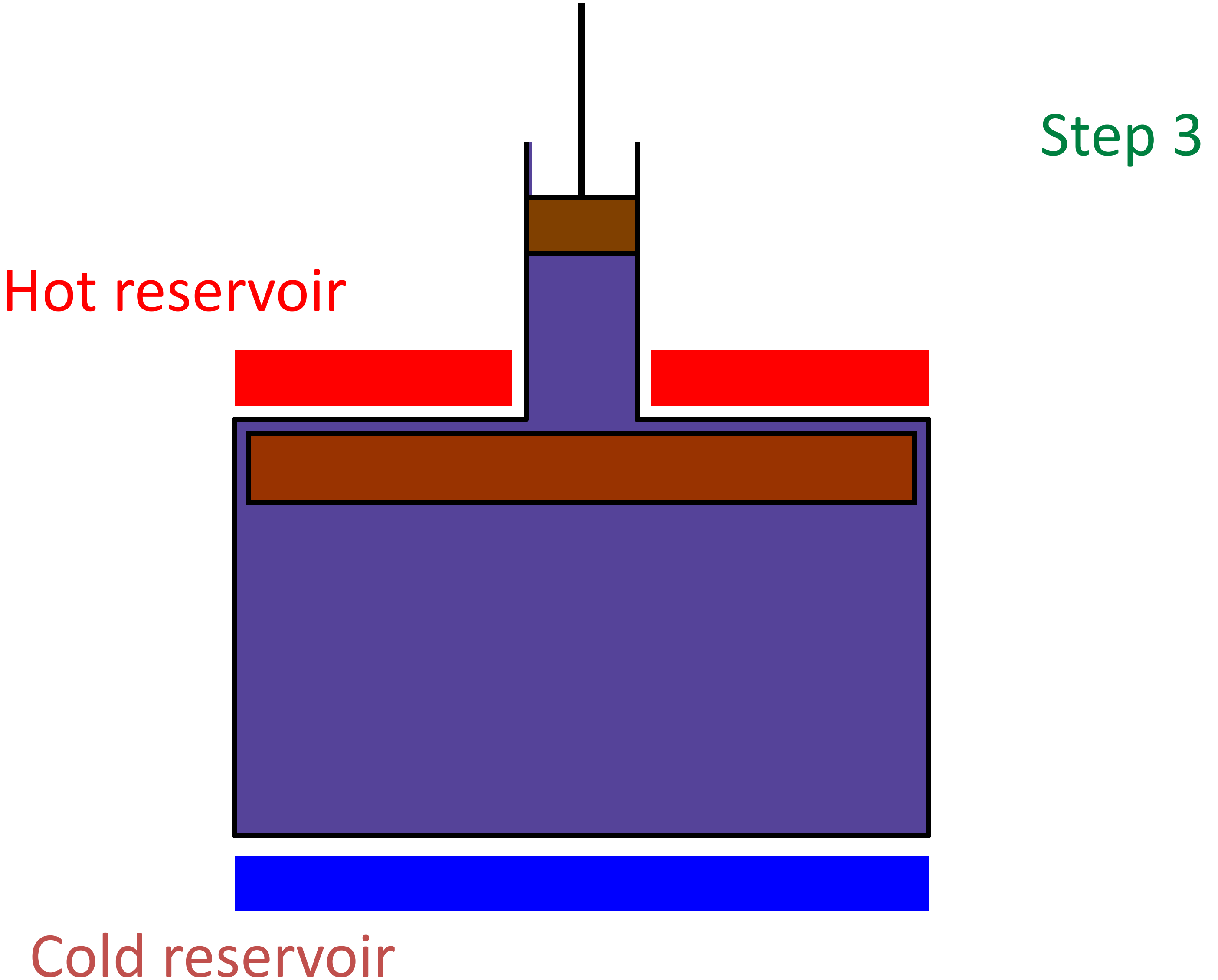
Step 3

Hot reservoir



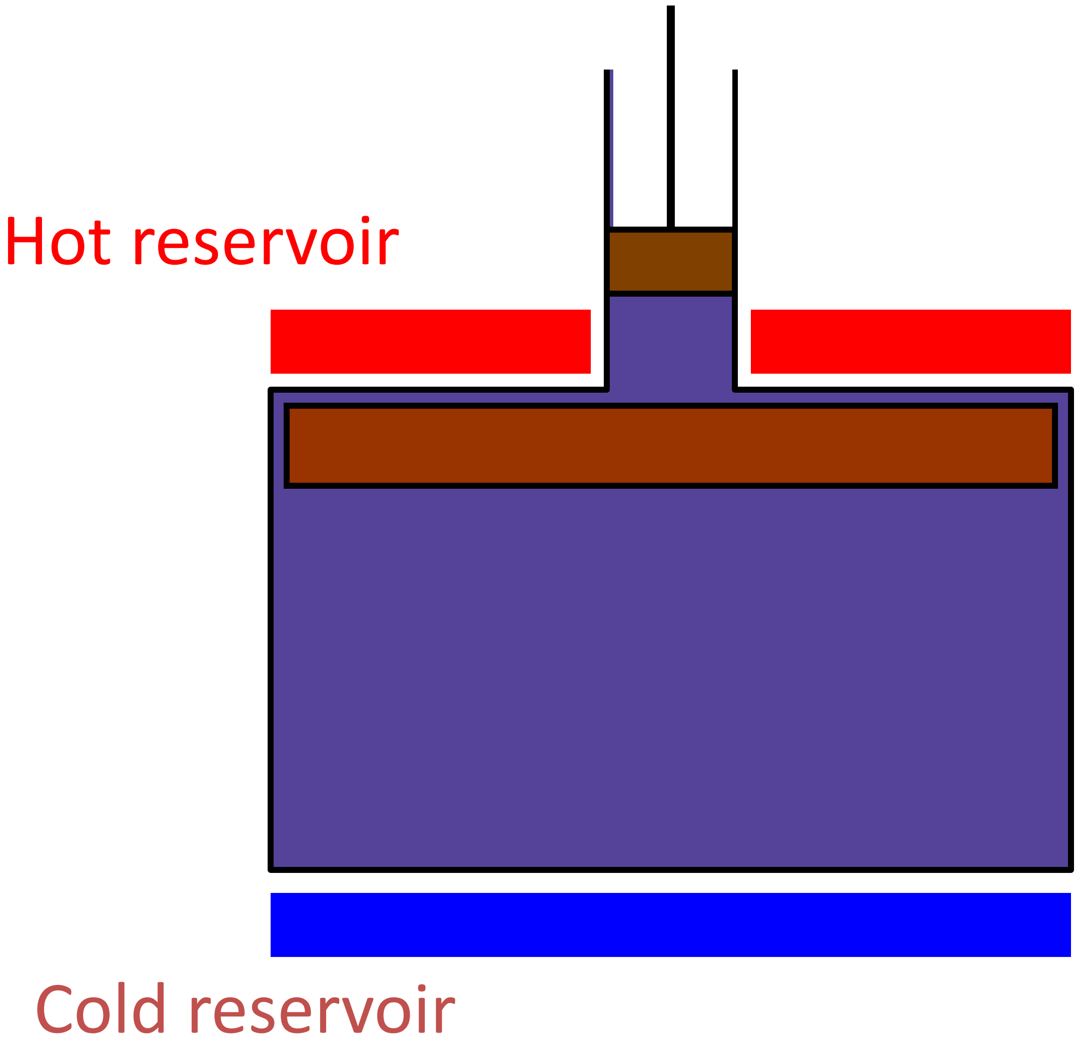
Cold reservoir

Sterling engine



Sterling engine

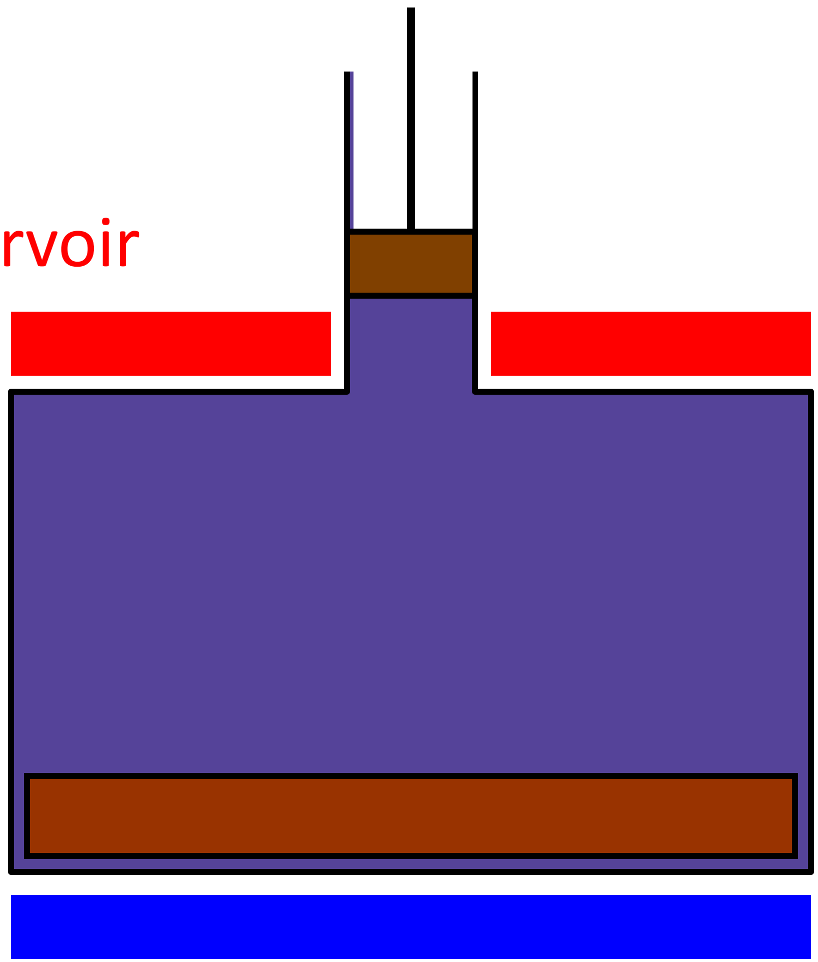
Step 4



Sterling engine

Step 1

Hot reservoir



Cold reservoir

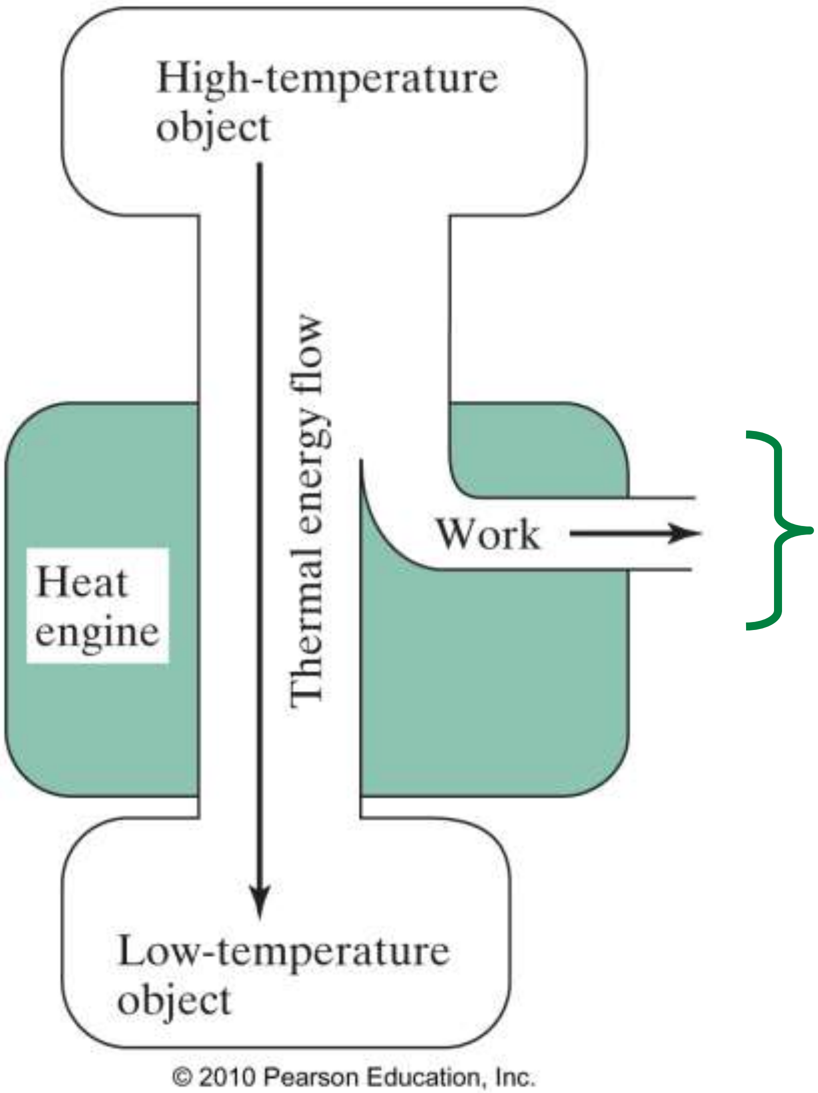
Toy “Heat Engine”

Hot reservoir

Cold reservoir

Generic Heat Engine

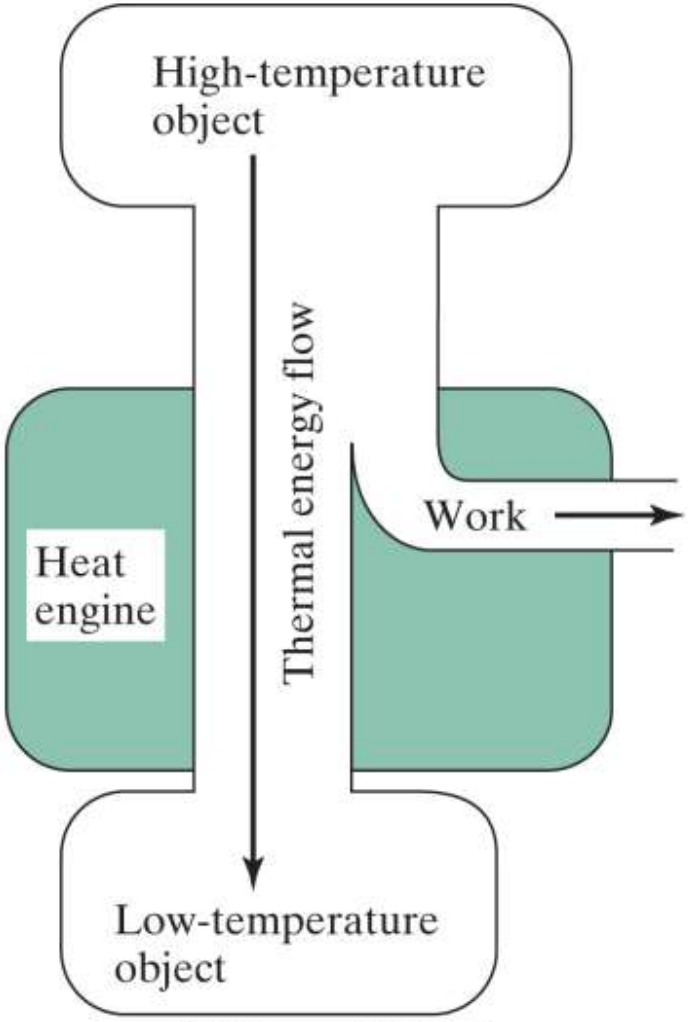
Hot reservoir



Cold reservoir

Note that only a fraction of the thermal energy goes into mechanical work!

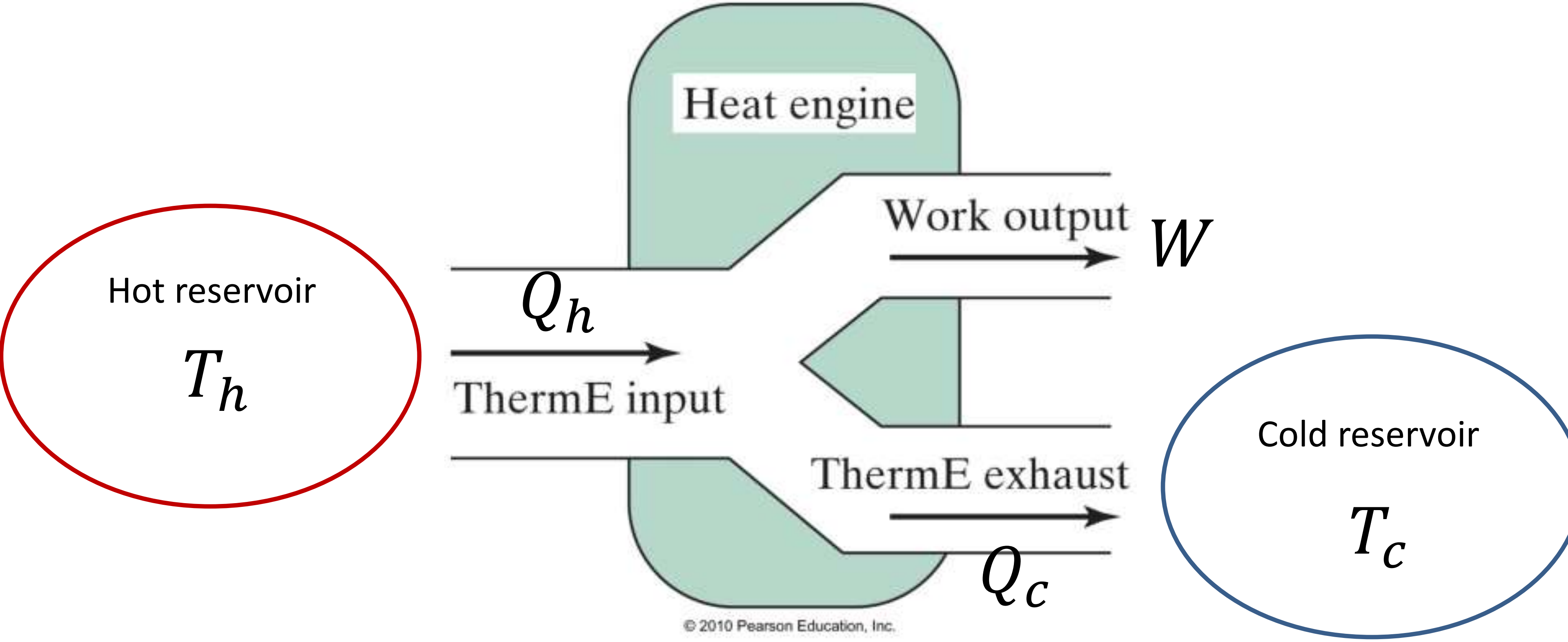
Heat Engine Efficiency



Efficiency

The fraction of the thermal energy that goes into mechanical work

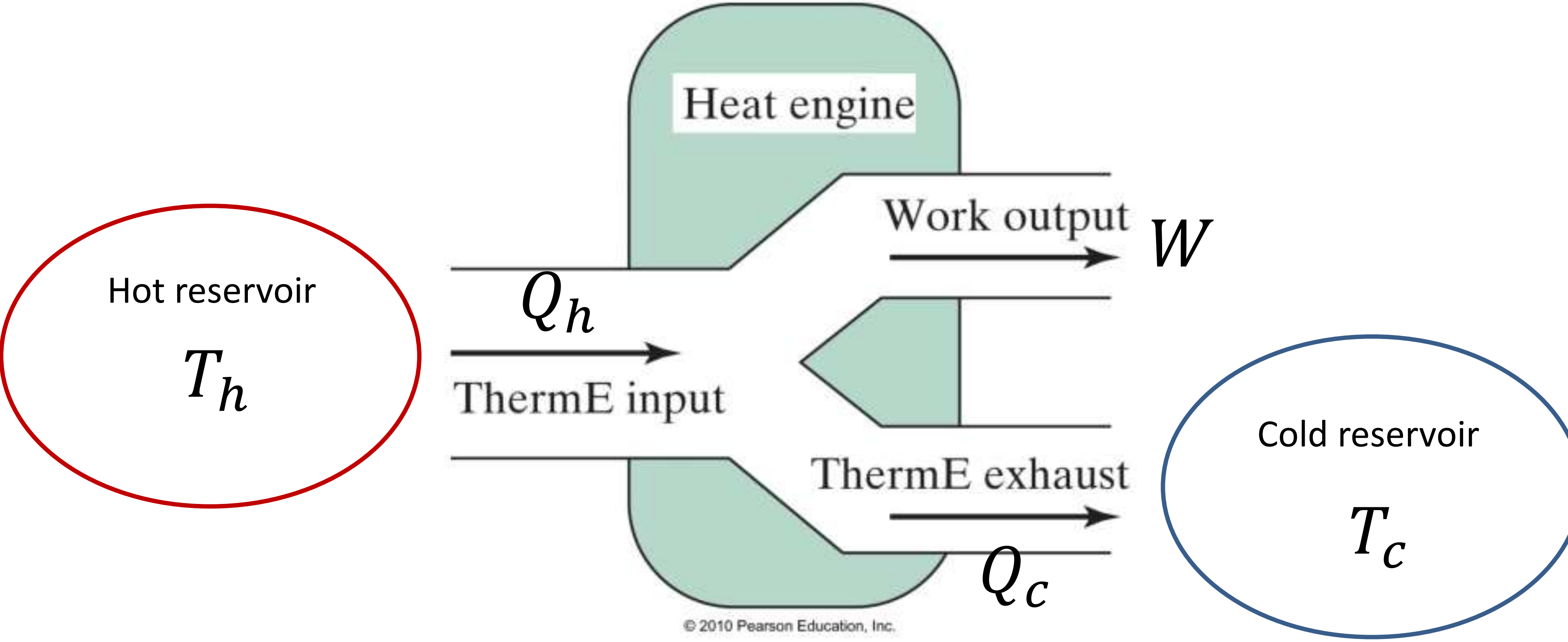
Heat Engine Efficiency



The energy efficiency of a heat engine is its <u>useful output</u> divided by the <u>total input</u>:
energy efficiency = (work output)/(thermal energy input)

$$\eta = \frac{W}{Q_h}$$

Heat Engine Efficiency



Energy conservation:

$$Q_h = Q_c + W$$

$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

Clicker Question

A heat engine consumes 100 W of thermal input power, produces 85 W of thermal output power, and does 15 Nm of work each second. What is the efficiency of this heat engine, in percent?

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$$\eta = \frac{W}{Q_h} \quad = \frac{15\ Nm/s}{100\ W} = \frac{15\ W}{100\ W} = 15\%$$

Clicker Question

Imagine a heat engine that consumes 100 W of thermal input power, produces 75 W of thermal output power, and does 35 Nm of work each second. Such a heat engine would

A. have a very high efficiency
B. have a very low efficiency
C. would violate the first law of thermodynamics
D. would violate the second law of thermodynamics
E. would not violate any laws of physics

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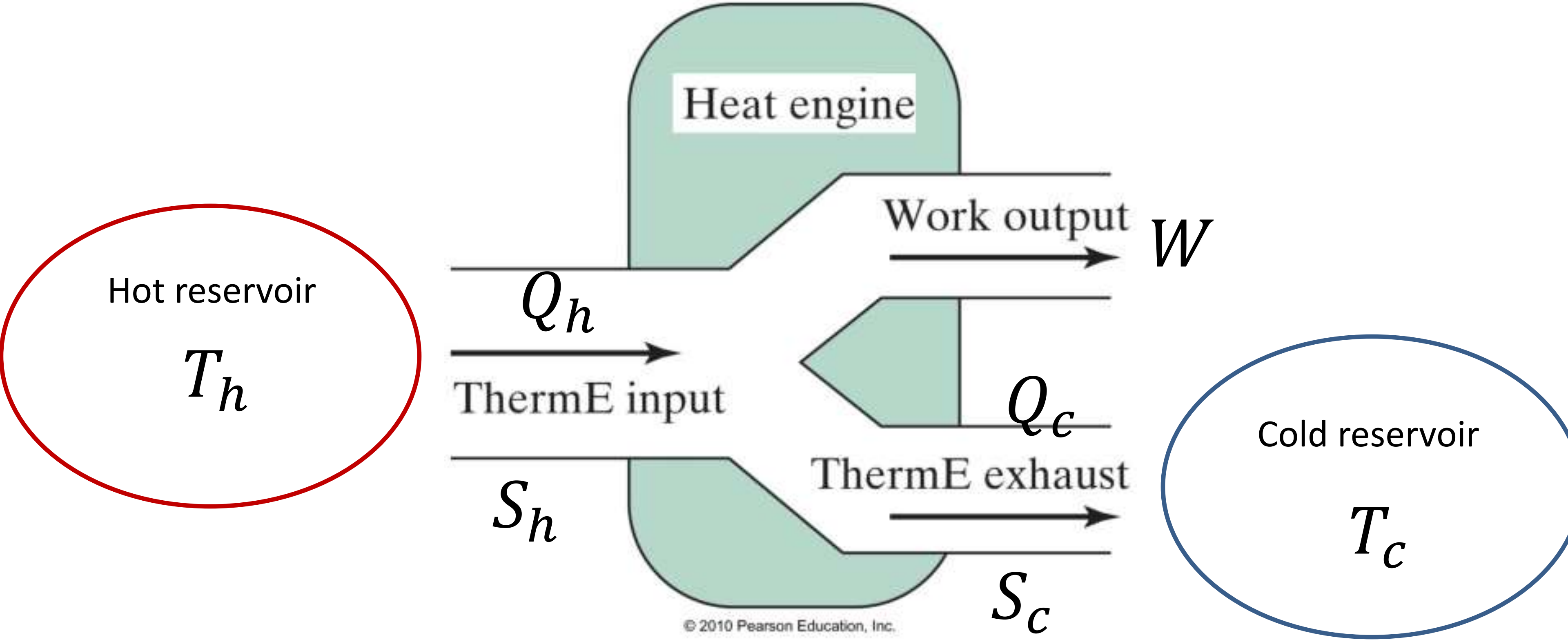
Heat Engine Efficiency



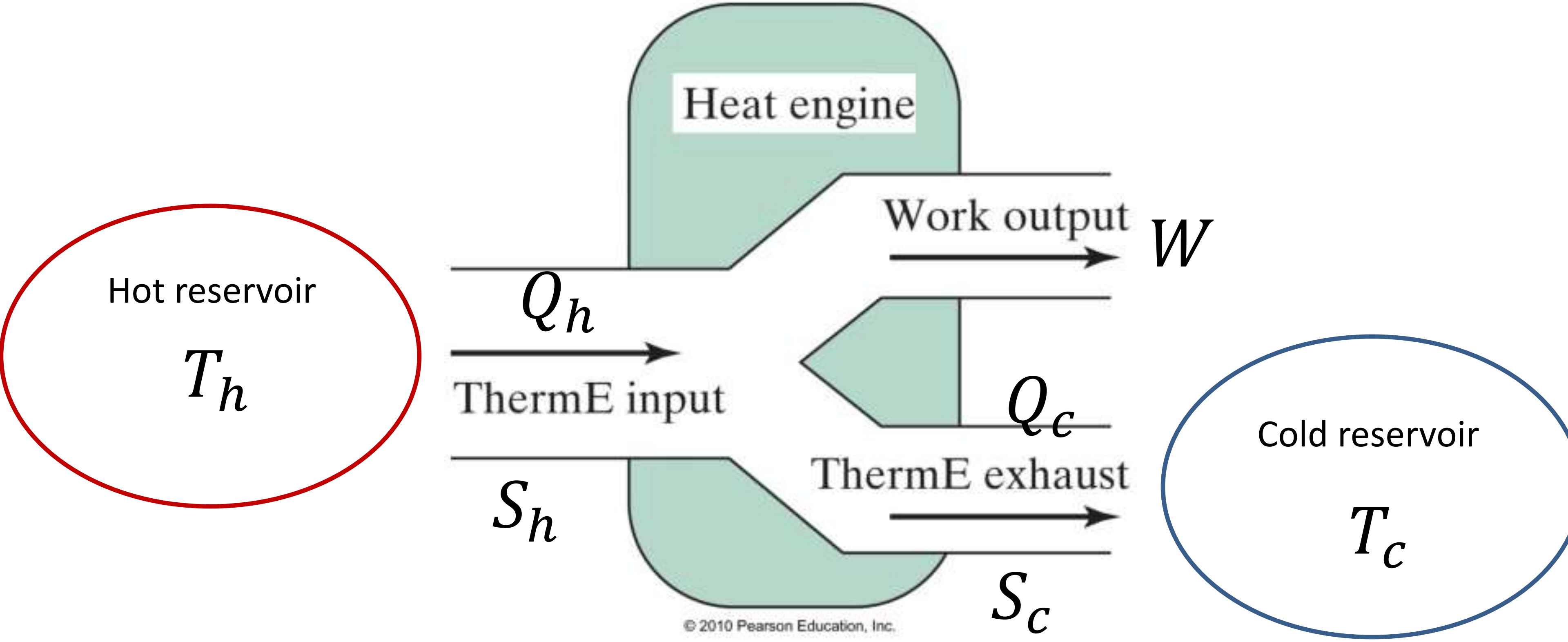
Entropy flow S is related to heat flow Q:

$$Q = TS$$

(absolute temperature, measured in Kelvin)

$$\eta = 1 - \frac{Q_c}{Q_h} = 1 - \frac{T_c\, S_c}{T_h S_h}$$

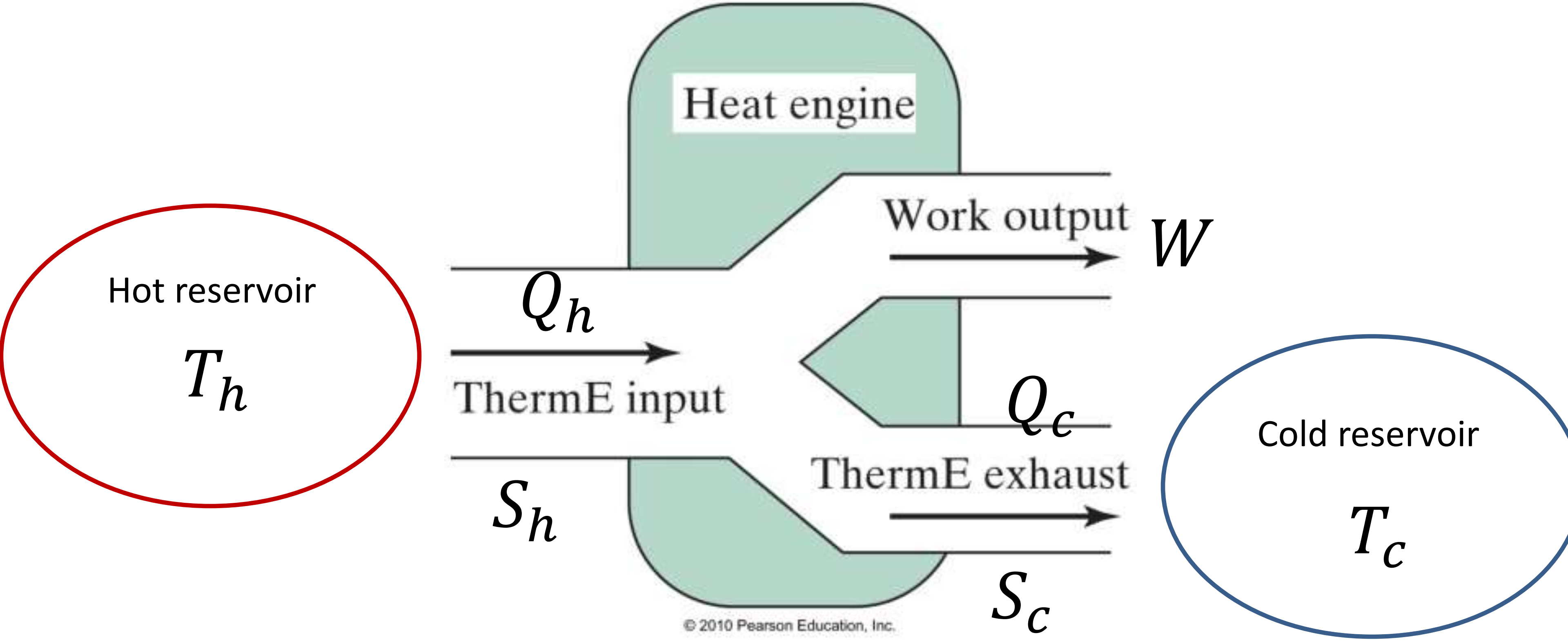
Heat Engine Efficiency



2nd Law of Thermodynamics:
Total entropy increases

⇨ $S_{out} \geq S_{in}$ $\quad S_c \geq S_h$ $\quad \eta = 1 - \frac{T_c\, S_c}{T_h S_h} \leq 1 - \frac{T_c}{T_h}$

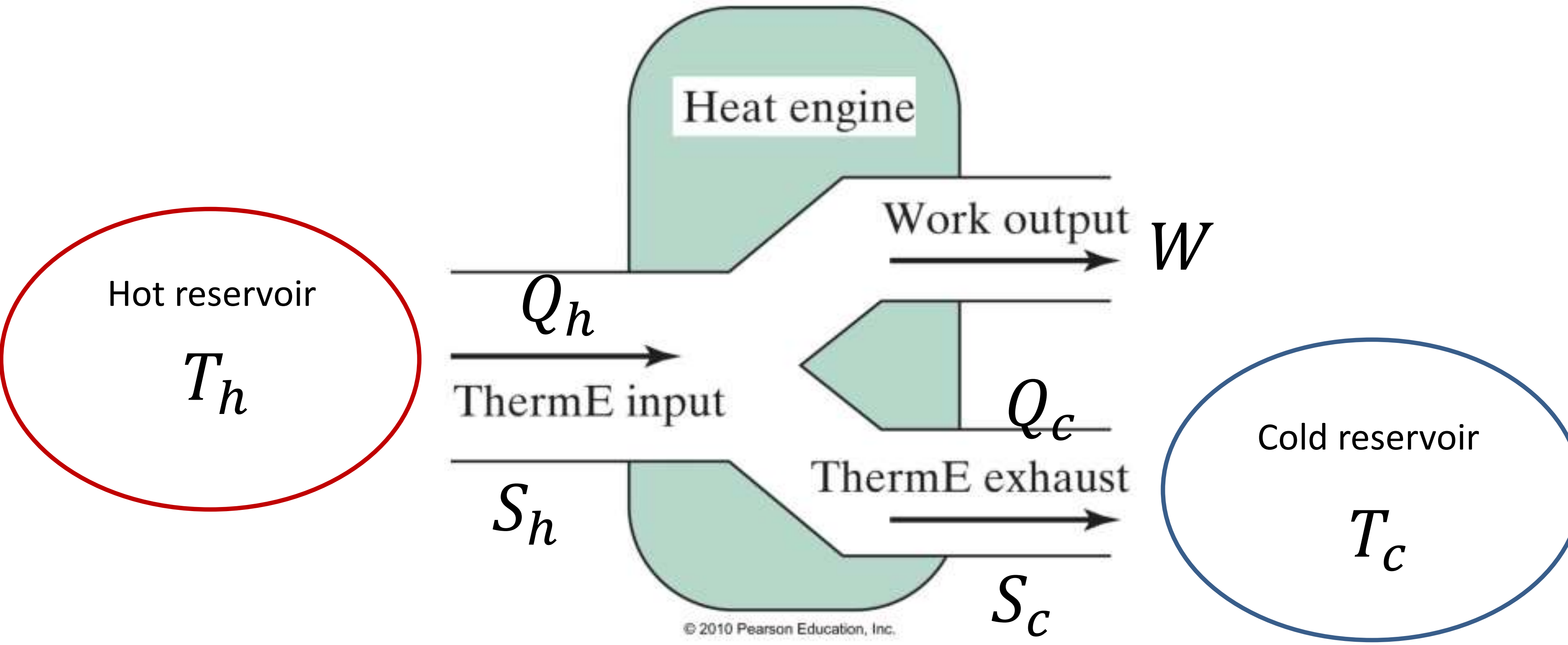
Heat Engine Efficiency



Another way of stating the 2nd Law of Thermodynamics:

$$\boxed{\eta \leq 1 - \frac{T_c}{T_h}}$$

Heat Engine Efficiency

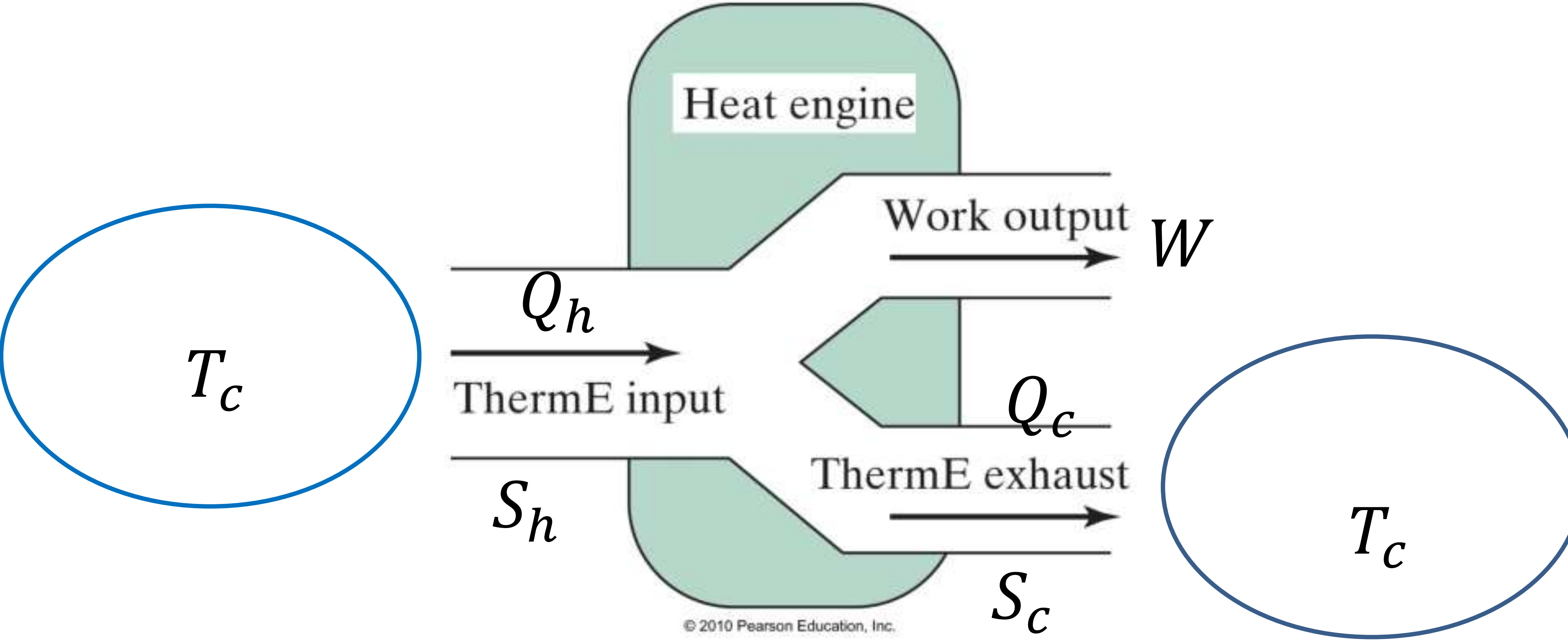


The equal sign holds of the entropy does not change:

$$S_{out} = S_{in} \qquad S_c = S_h \qquad \eta = 1 - \frac{T_c\, S_c}{T_h S_h} = 1 - \frac{T_c}{T_h}$$

A process in which the entropy does not change is ***reversible***.
This would be ***an ideal heat engine*** (no friction, heat losses, etc.)

Heat Engine Efficiency



What happens if the two reservoirs are at the same temperature?

$$W = 0$$

$$\eta = 1 - \frac{T_c}{T_c} = 0$$

Summarize:

- No heat engine can be 100% efficient
- Some of the thermal energy always goes into exhaust heat
- The efficiency can never exceed the maximum theoretical efficiency given by

$$\text{Max Efficiency} = \frac{T_h - T_c}{T_h}$$

(Temperature measured in K)

- A (theoretical) heat engine operating at max efficiency is reversible, i.e., no entropy is generated.

Example:

- Input = boiling water (100 C = 373 K)
- Output = ice (0 C = 273 K)

$$\text{Max Efficiency} = \frac{T_{in} - T_{out}}{T_{in}}$$

(Temperatures measured in K)

- Max Efficiency = (373K-273K)/373K = 100K/373K = 27%

Clicker Question

If a heat engine were to operate at the maximum theoretical efficiency, the entropy in this process would

A. increase.
B. stay the same.
C. decrease.
D. increase or stay the same.
E. decrease or stay the same.

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Clicker Question

An inventor claims to have invented a ship that draws in seawater, extracts heat from the water, and expels the cooled water. The extracted heat is converted to work to propel the ship. This invention would

A. violate the first law of thermodynamics.
B. violate the second law of thermodynamics.
C. violate the principle of conservation of energy.
D. violate the principle of conservation of entropy.
E. violate Newton's laws.
F. not violate any laws of physics.

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Clicker Question

A heat engine draws in heat from a hot reservoir at a temperature of 900 K. It expels waste heat into the environment at a temperature of 300 K. The efficiency of this heat engine

A. is not limited.
B. could be anywhere between 0 and 1.
C. is greater than 2/3.
D. must be less than 1/3.
E. is less than or equal to 2/3.

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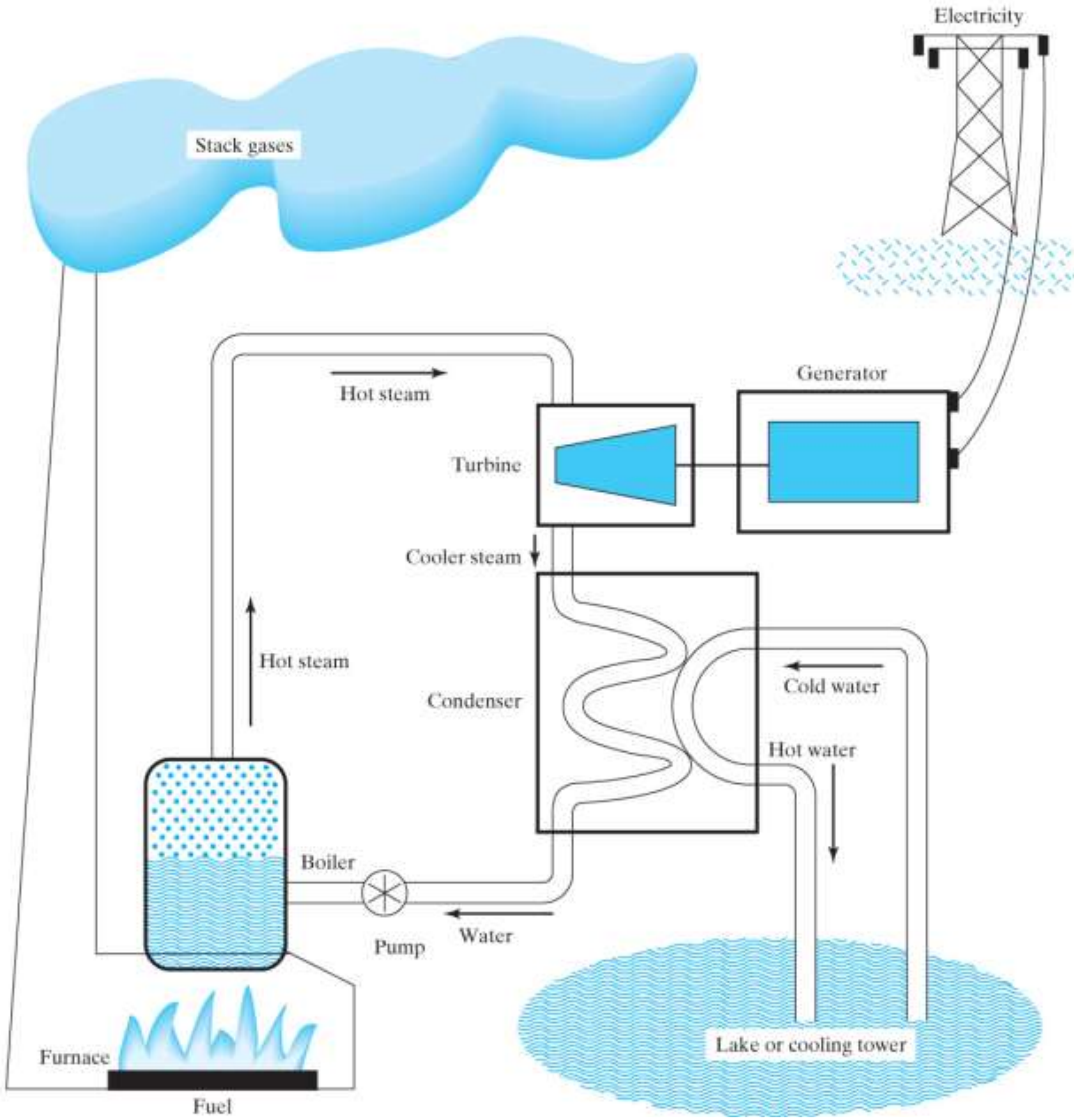
“Maximum efficiency” is without friction or other losses! The second law says you cannot do better!

Table 7.1

Heat engine efficiencies. Typical temperatures, best possible efficiencies, and actual efficiencies.

Engine type	T_{in}(°C)	T_{ex}(°C)	Efficiency (%)	
			Best possible	Actual
Transportation				
Gasoline automobile/truck	700	340	37	20
Diesel auto/truck/locomotive	900	340	48	30
Steam locomotive	180	100	20	10
Steam-electric power plants				
Fossil fuel	550	40	60	40
Nuclear fuel	350	40	50	35
Solar powered	225	40	40	30
Ocean-thermal (solar)	25	5	7	???

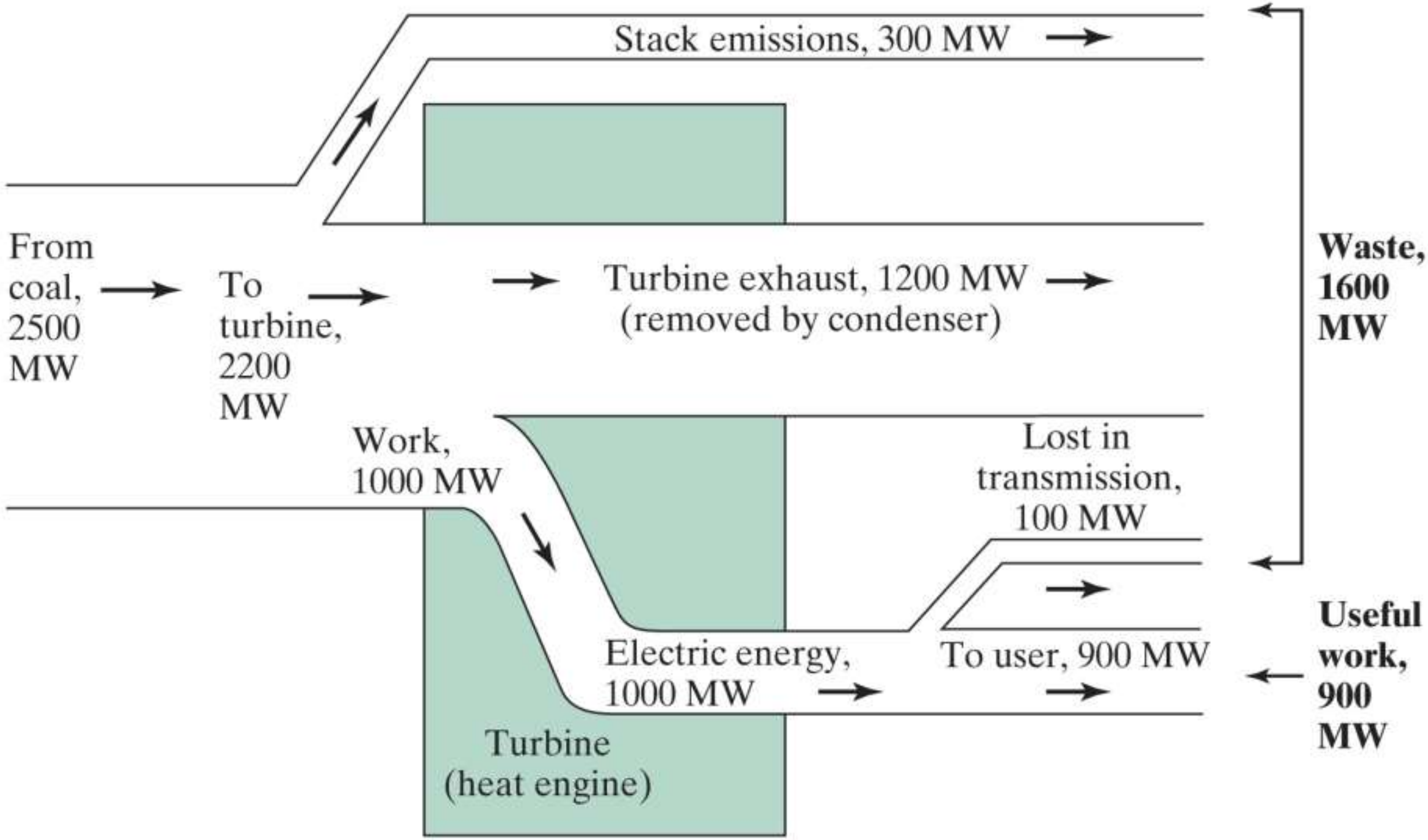
The Steam-Electric Power Plant



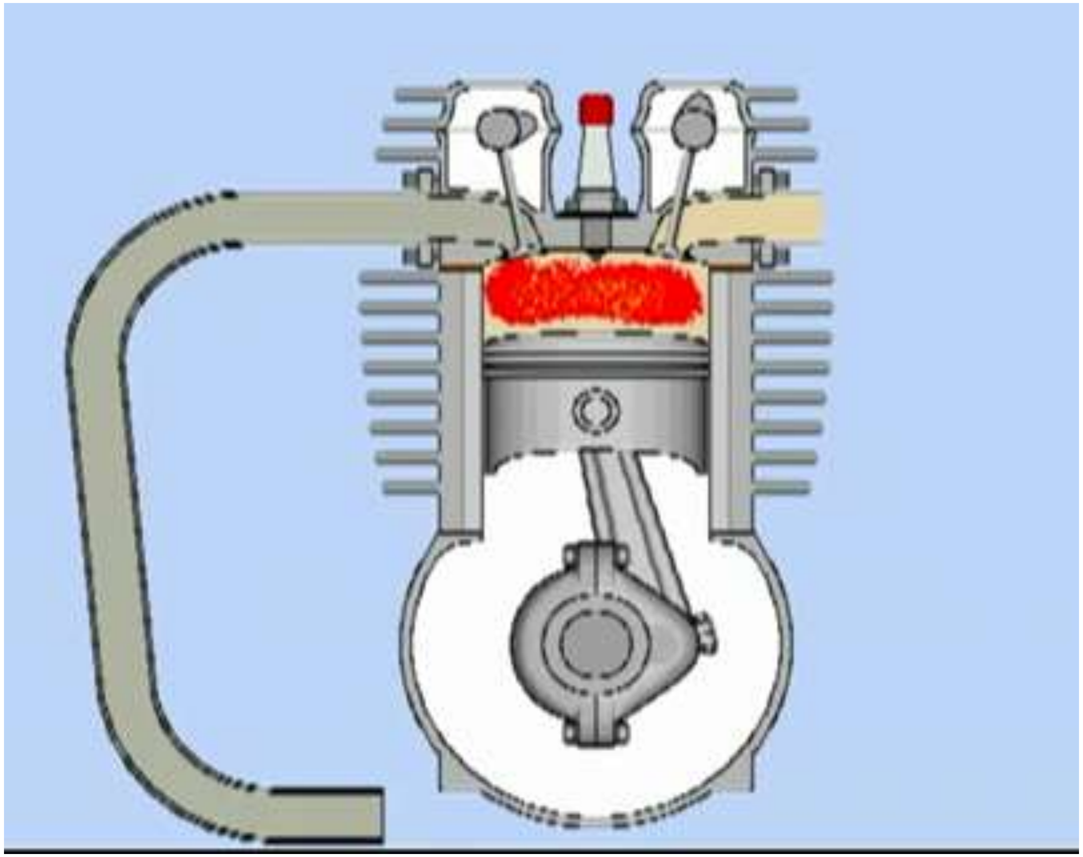
Electric power out

Coal in

Steam-Electric Power Plant

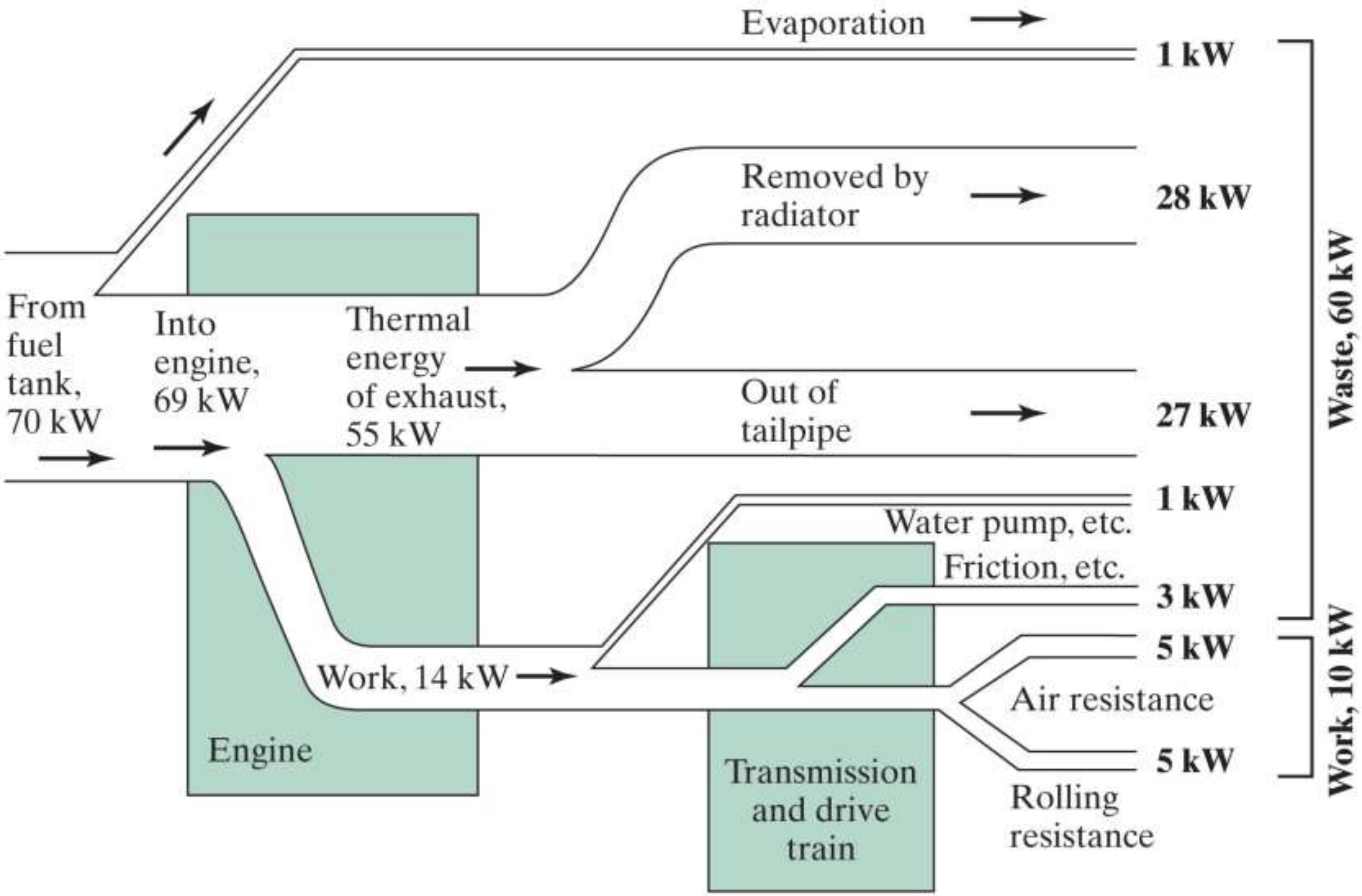


Gas Fueled Automobile



Internal combustion

Gas Fueled Automobile



Transportation efficiency

Table 7.4

U.S. passenger-moving efficiencies of several human transportation modes

	passenger-km per liter	passenger-mi per gal	passenger-km per MJ
Human on bicycle	642*	1530*	18.0
Human walking	178*	425*	5.0
Intercity rail	60	144	1.7
Carpool auto (occupancy = 4)	36	88	1.0
Urban bus	33	80	0.9
Commercial airline	21	50	0.6
Commuting auto (occupancy = 1.15)	11	25	0.3

*For walking and bicycling, the table uses the "gasoline equivalent" of the required number of food calories.

Tesla Model 3: 134 mpge

Transportation efficiency

Table 7.5

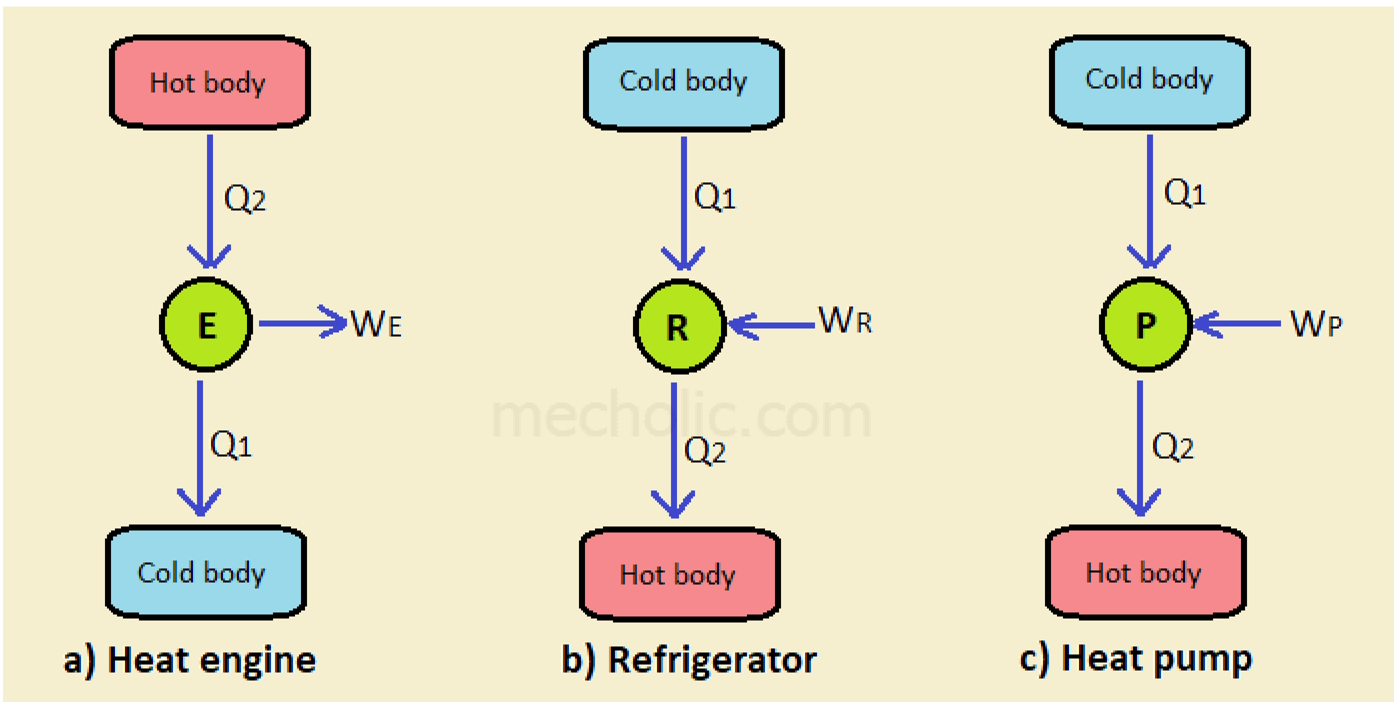
Freight-moving efficiencies of three transportation modes

	kg-km per MJ	tonne-km per liter
Rail (freight train)	2900	100
Truck (heavy)	720	25
Air (freight)	145	5

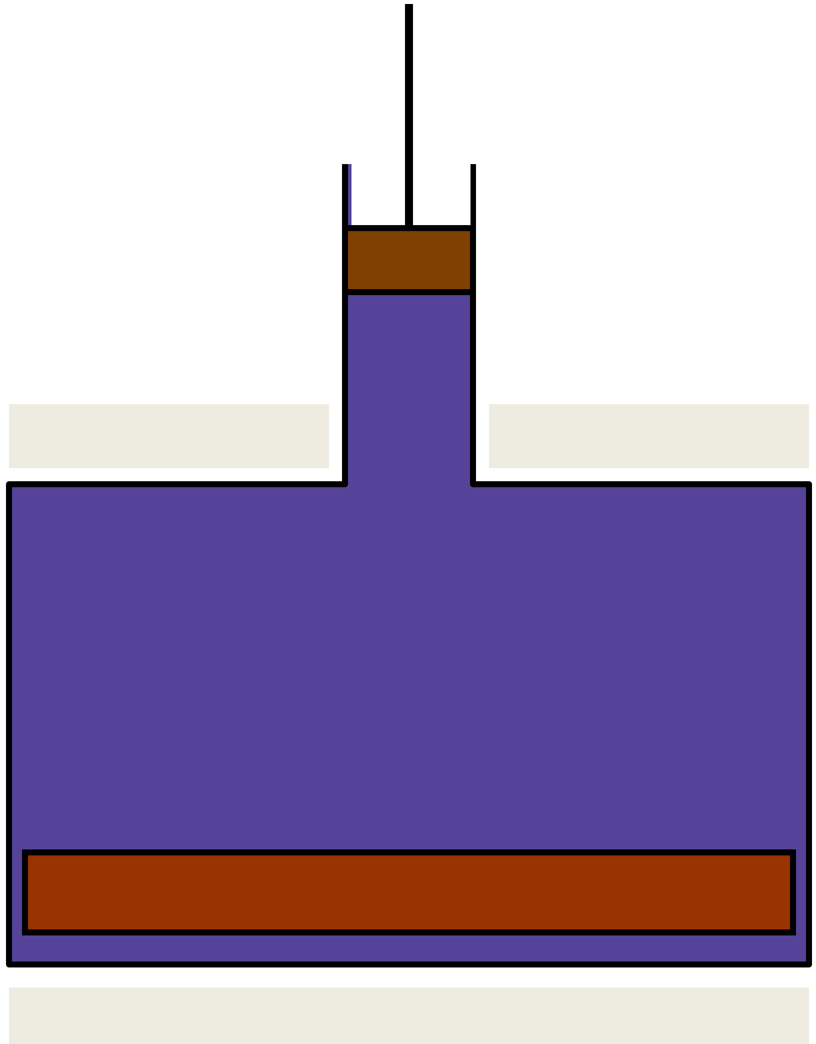
Rail is the most efficient, due to its favorable aerodynamics and the relatively small energy loss of steel wheels on steel track.

Even more efficient: container ships/tanker ships

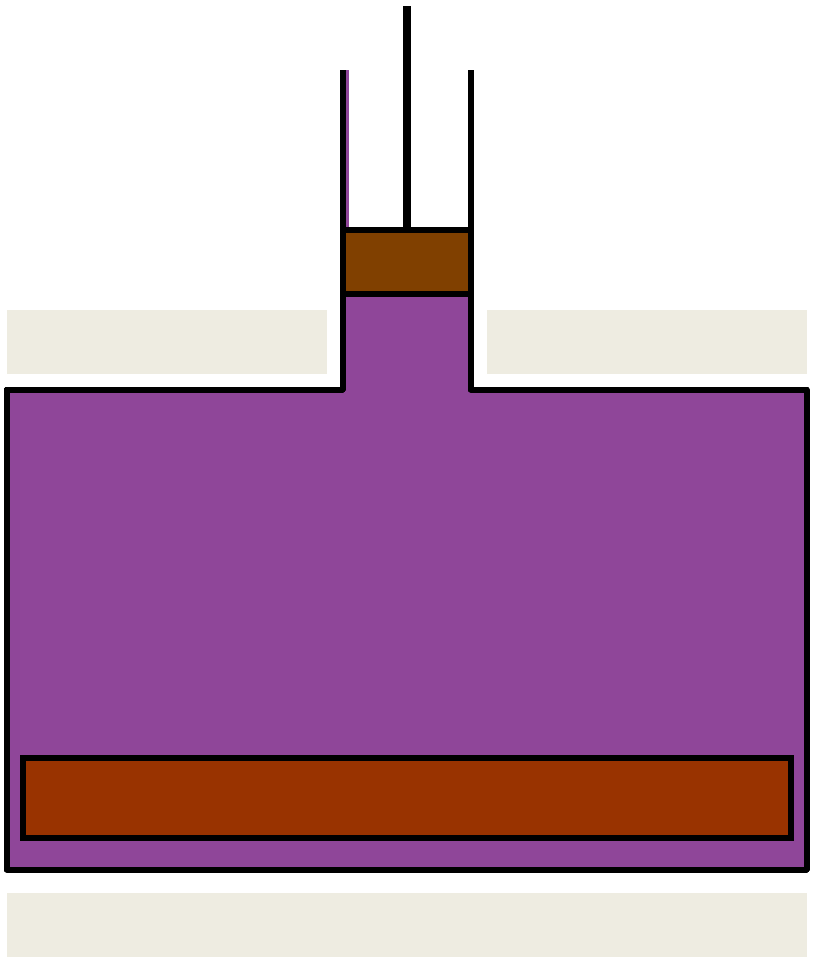
A heat pump is a heat engine run in reverse:



Sterling heat pump



Sterling heat pump

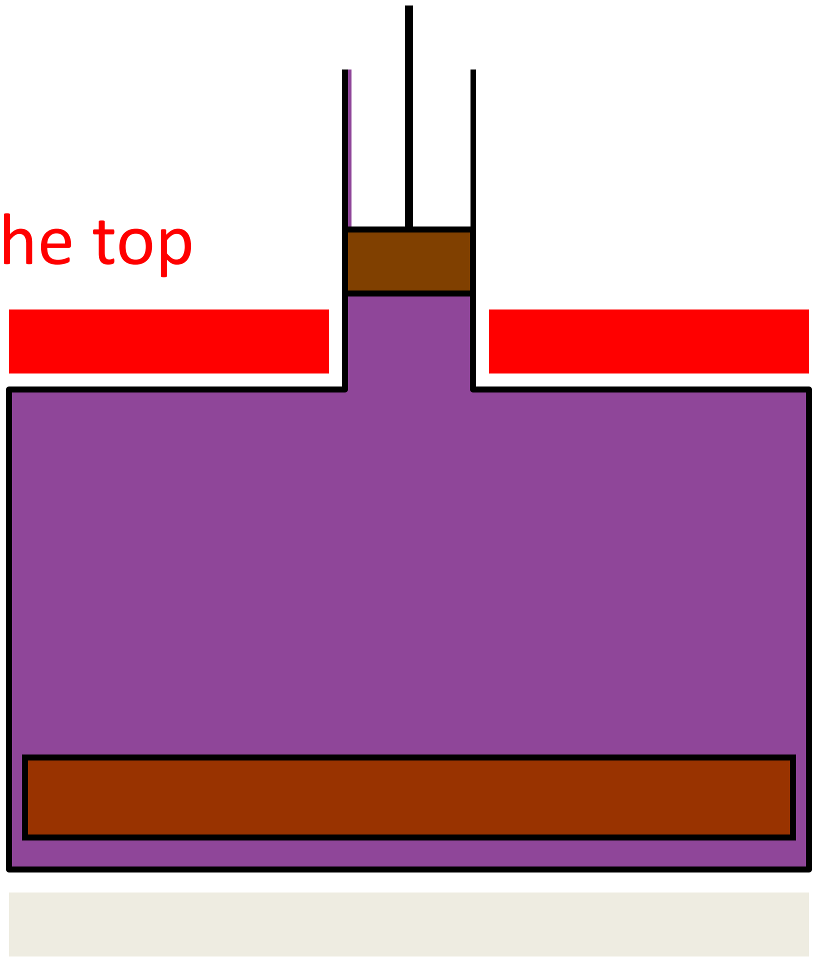


Step 1

Sterling heat pump

Step 1

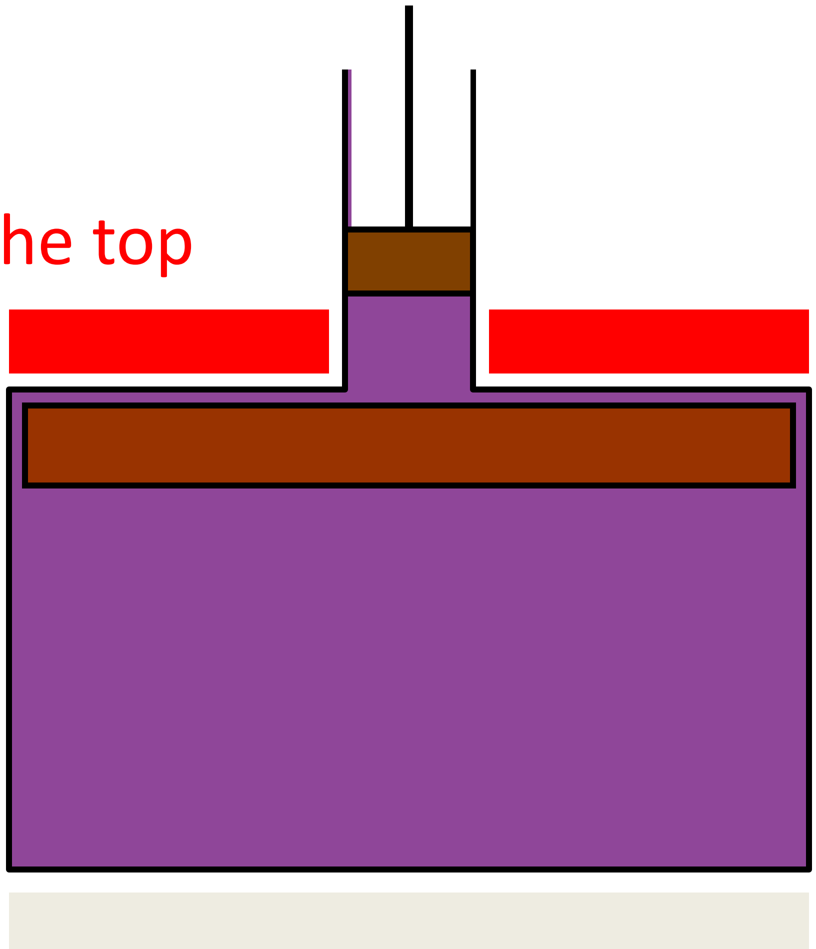
Heat out the top



Sterling heat pump

Step 2

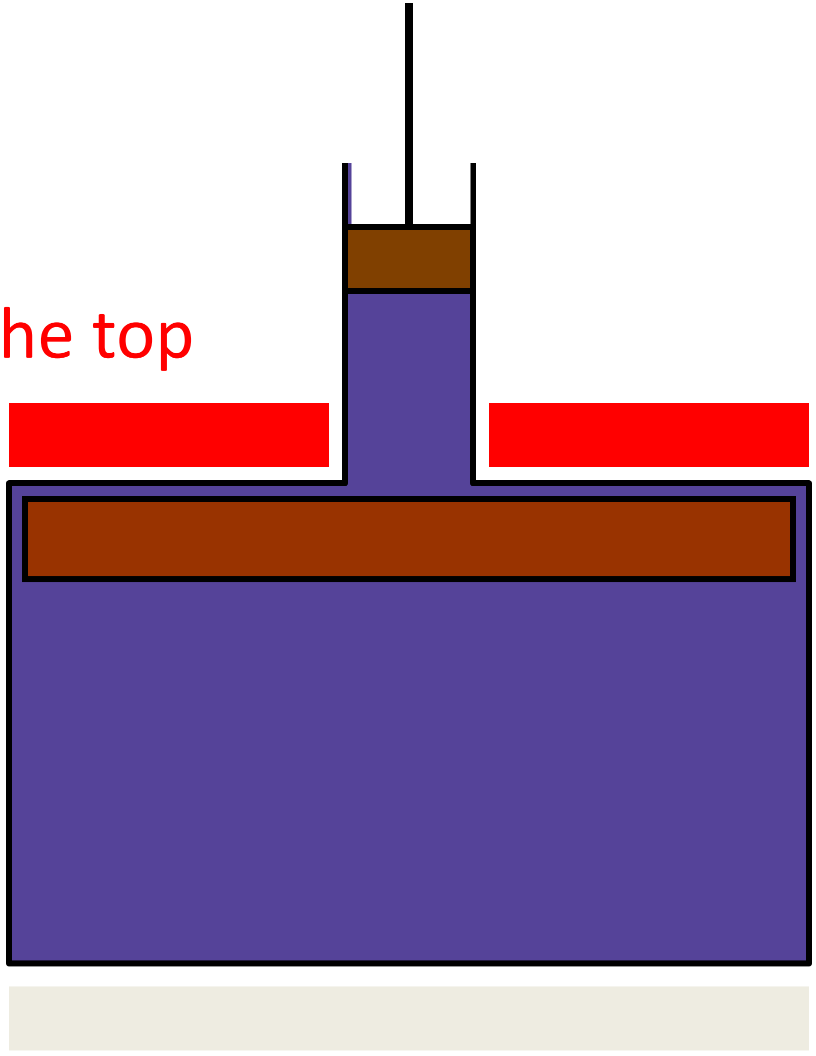
Heat out the top



Sterling heat pump

Step 3

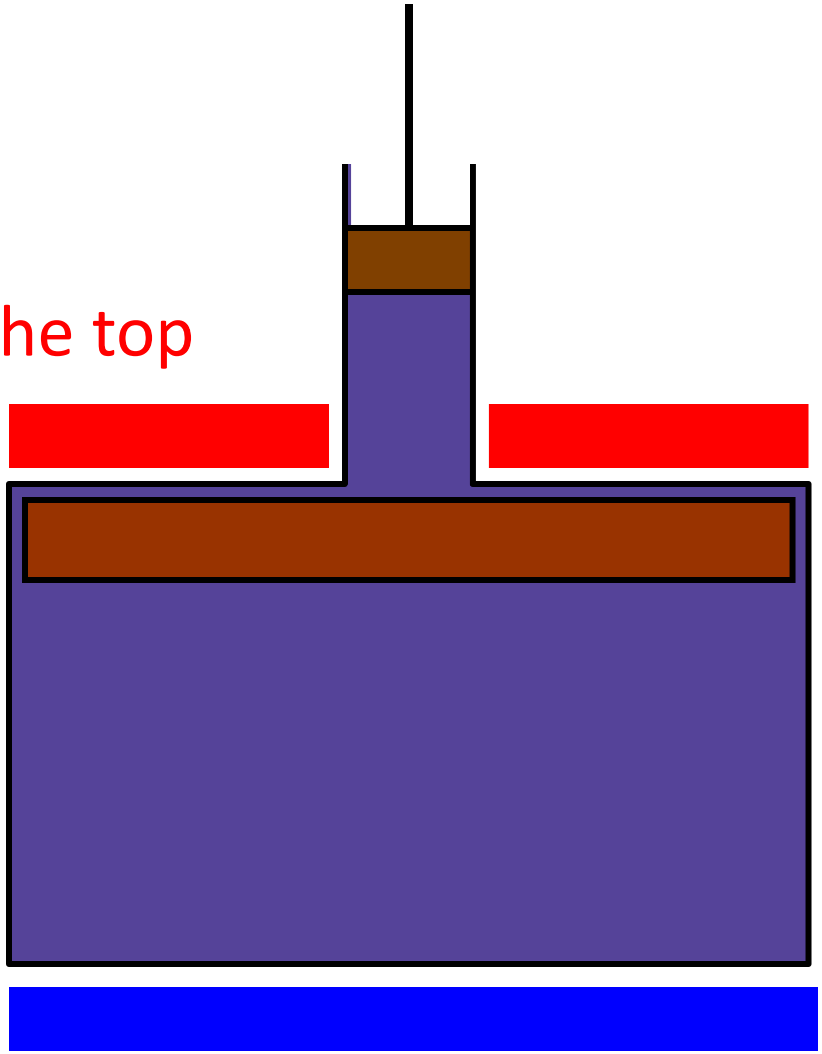
Heat out the top



Sterling heat pump

Step 3

Heat out the top

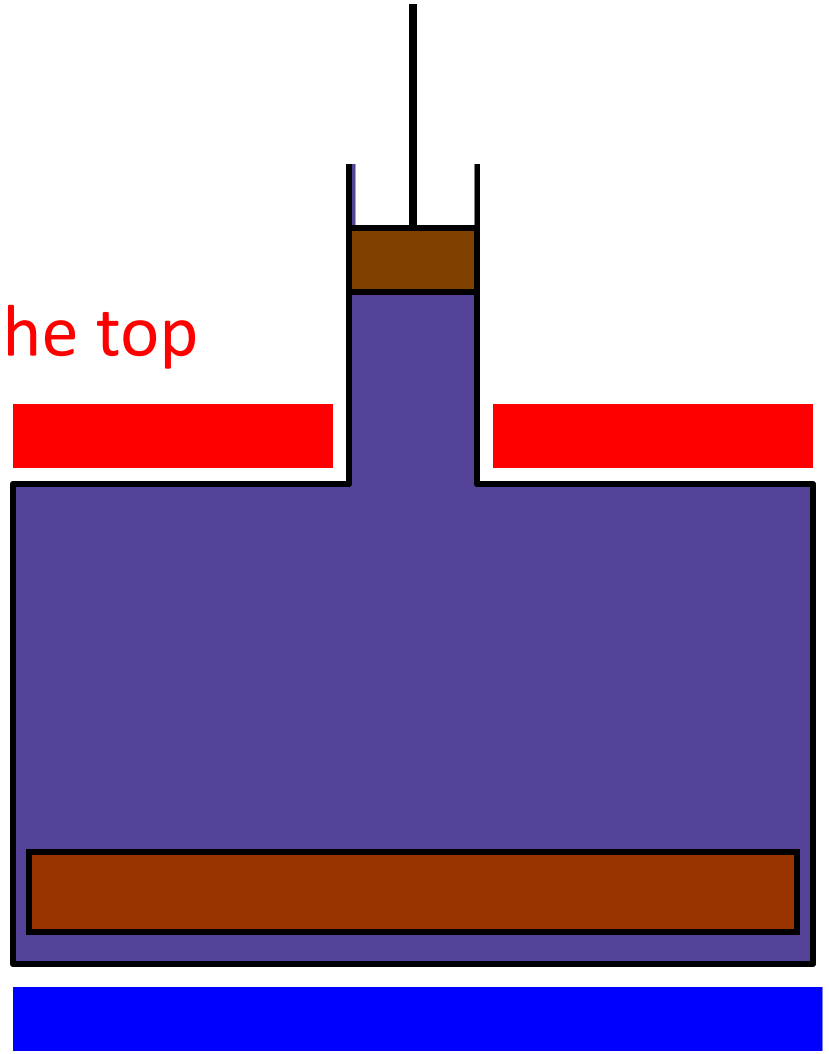


Cold out the bottom

Sterling heat pump

Step 4

Heat out the top



Cold out the bottom

Clicker Question

How can you improve the design of a heat engine so that it is more efficient?

A) Increase the temperature of the hot reservoir.
B) Decrease the temperature of the cold reservoir.
C) Reduce frictional losses.
D) All of the above.
E) None of the above.

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