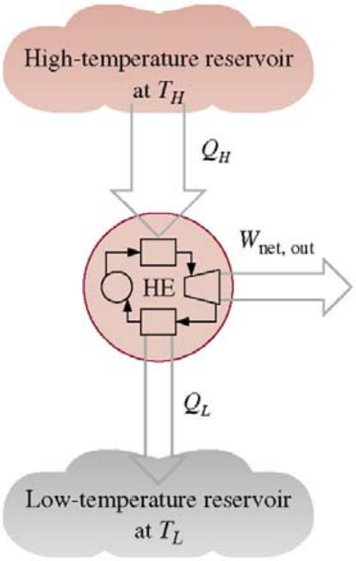
Kelvin Planck Statement of the Second Law

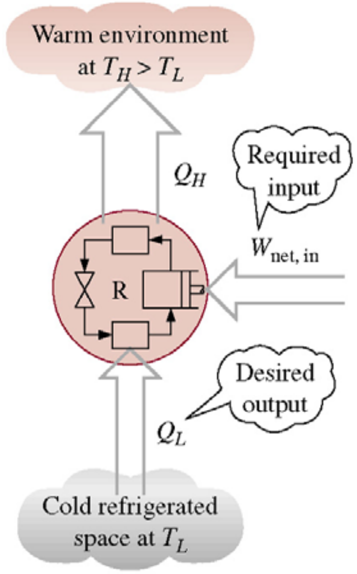
It is impossible to construct an engine which, operating in a cycle, will produce no other effect than the extraction of heat from a single reservoir and the performance of an equivalent amount of work.

Clausius Statement of the Second Law

It is impossible to have a system operating in a cycle which transfers heat from a cooler to a hotter body without work being done on the system by the surroundings

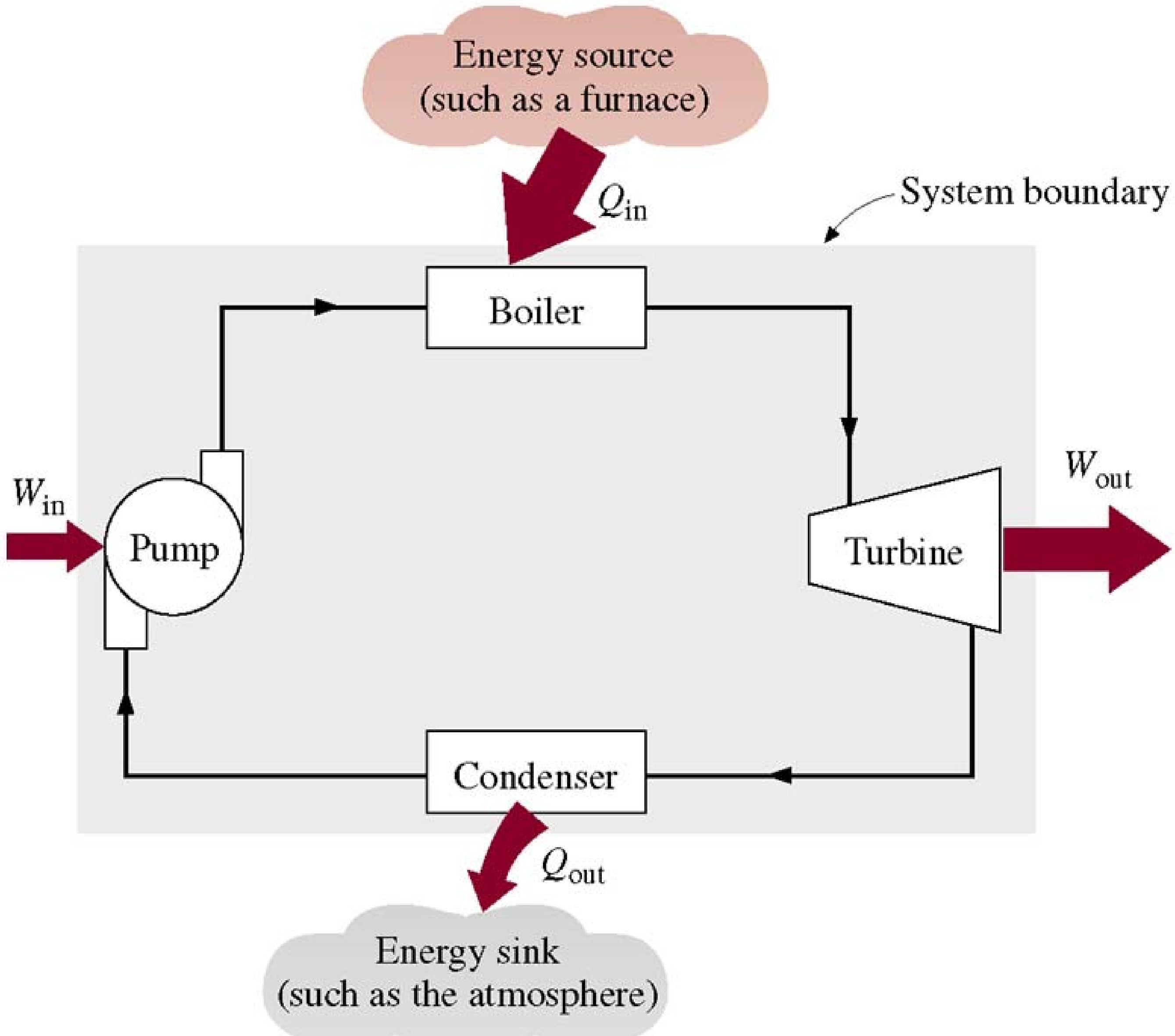


Reversible Heat Engine

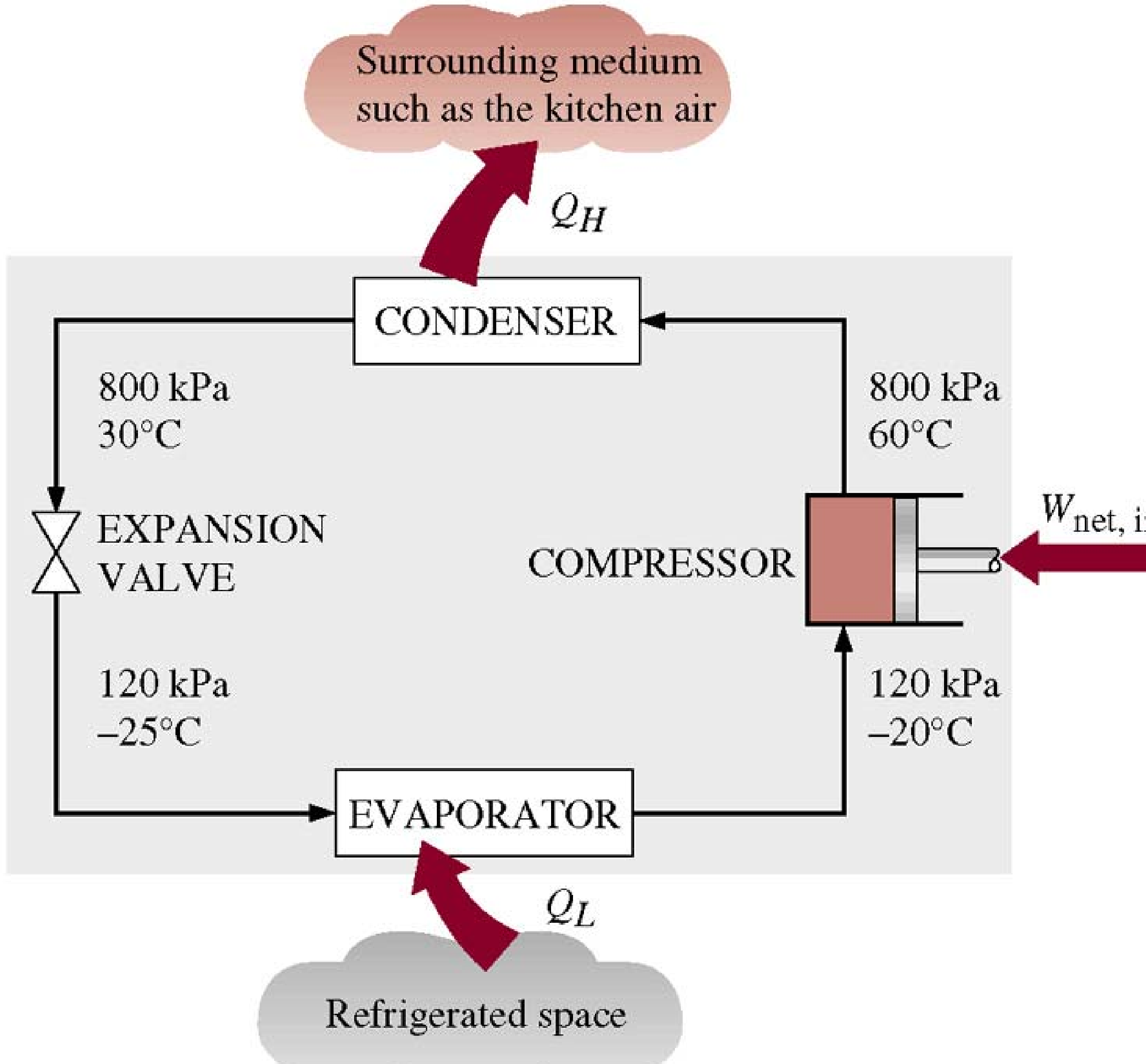


Reversible Refrigerator

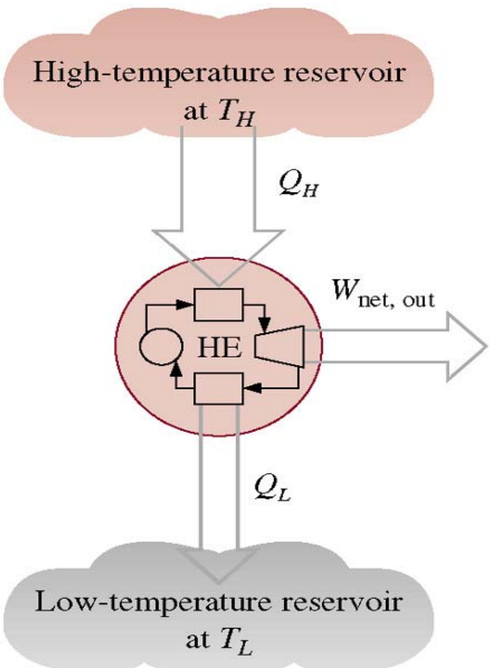
Actual Heat Engine



Actual Refrigeration Machine



Carnot Power Cycle

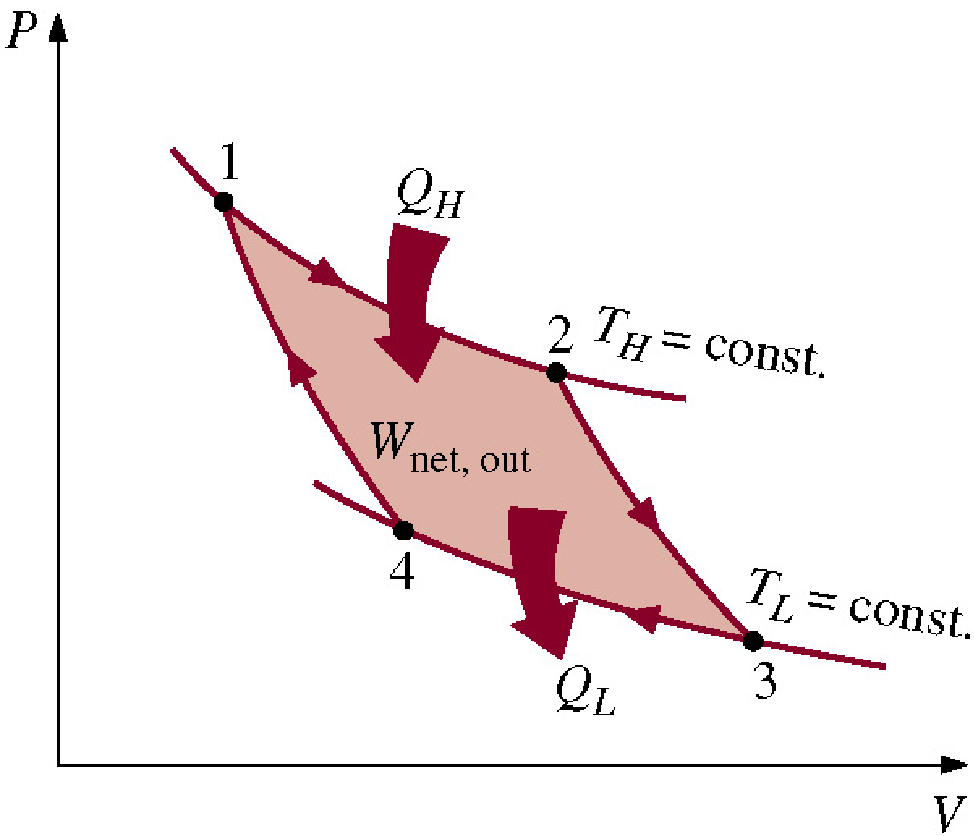


Reversible constant temperature heat transfer,

process $1 \rightarrow 2$, process $3 \rightarrow 4$

Reversible adiabatic expansion,

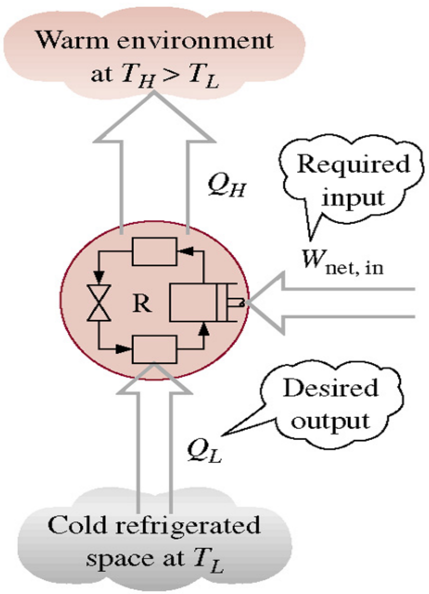
process $2 \rightarrow 3$, process $4 \rightarrow 1$



$$\text{Efficiency} = \frac{\text{Desired Effect}}{\text{Required Input}}$$

$$\eta_{cycle} = \frac{Q_H - Q_L}{Q_H} = \frac{\text{Work}}{Q_{in}}$$

Carnot Refrigeration Cycle



Reversible constant temperature heat transfer,

process $4 \to 1$, process $2 \to 3$

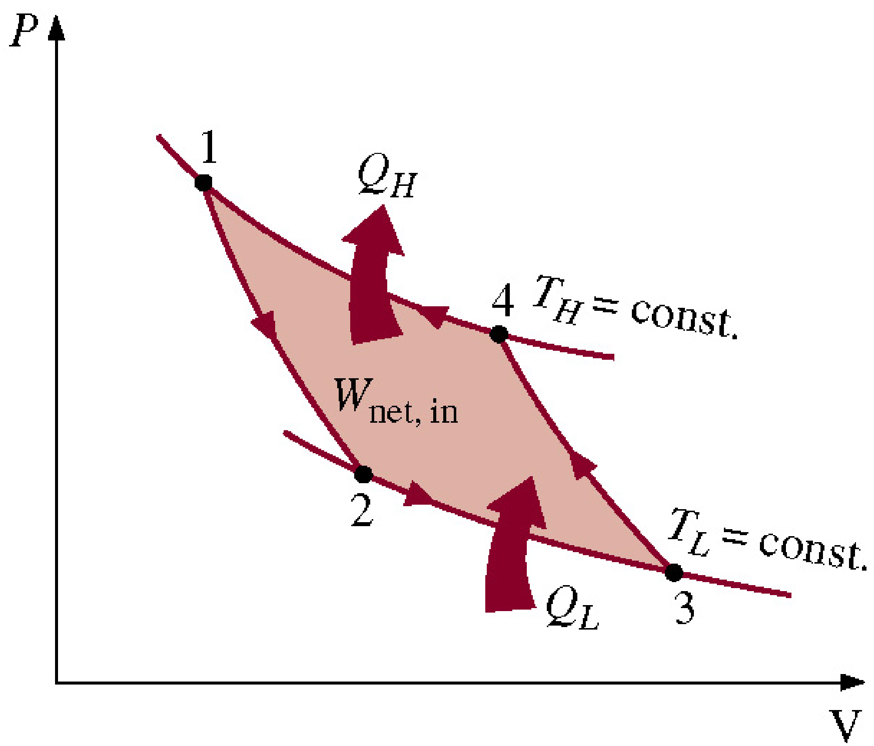
Reversible adiabatic expansion,

process $1 \to 2$process $3 \to 4$

$$\text{Coefficient of Performance} = \frac{\text{Desired Effect}}{\text{Required Input}}$$

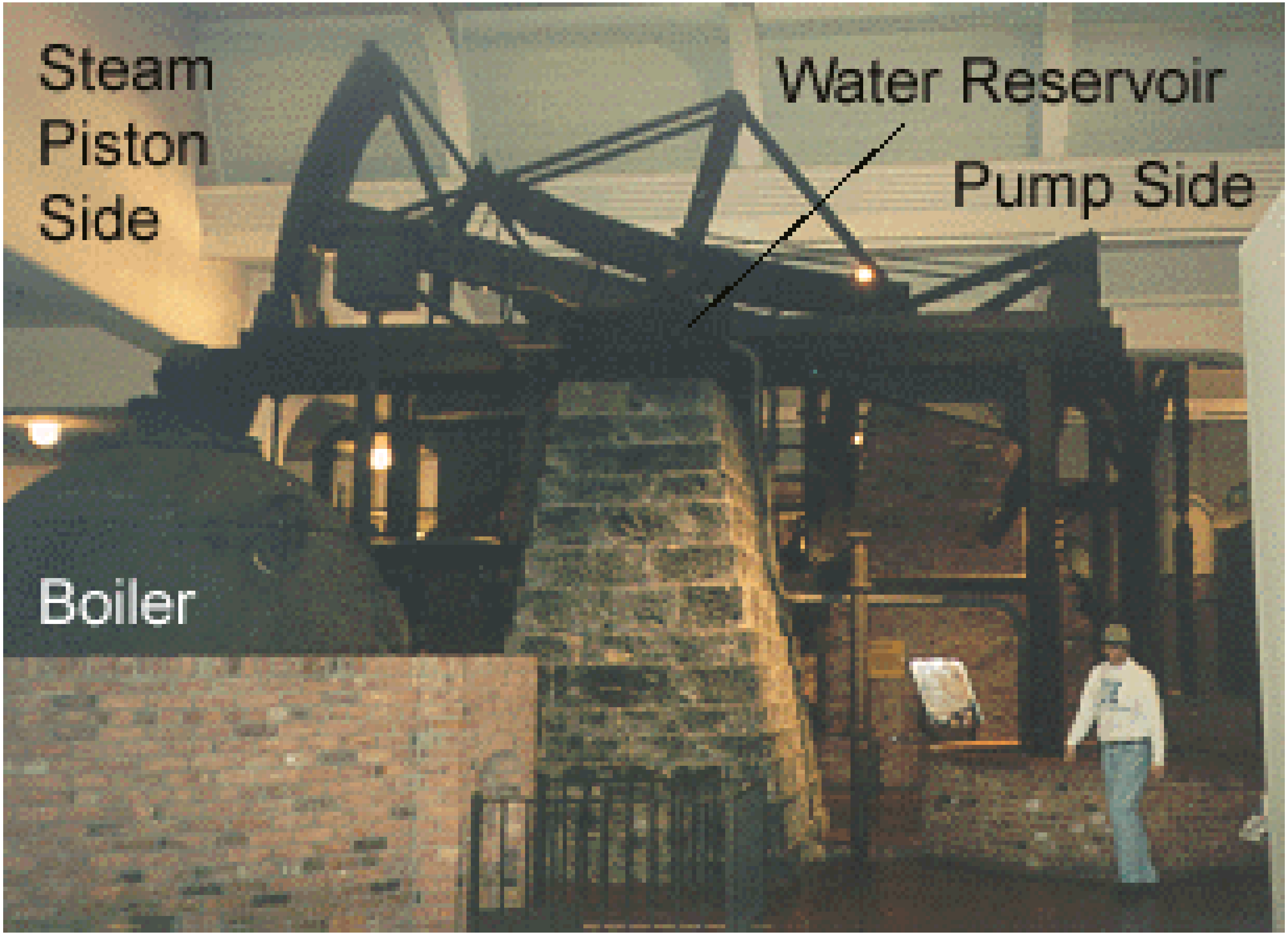
$$COP_{refrigerator} = \frac{Q_L}{Q_L - Q_H} = \frac{Q_{in}}{Work}$$

$$COP_{heat\ pump} = \frac{Q_H}{Q_L - Q_H} = \frac{Q_{out}}{Work}$$



<u>NEWCOMEN ATMOSPHERIC ENGINE</u>

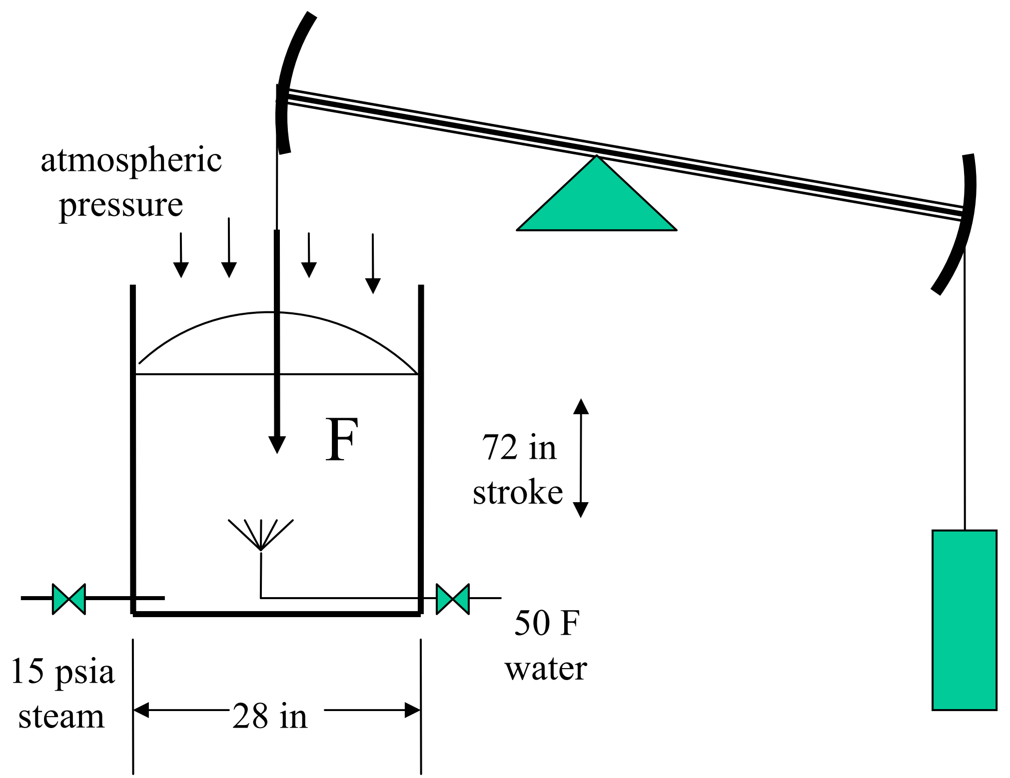
Ford Museum,Detroit, 1760, 14 strokes/min



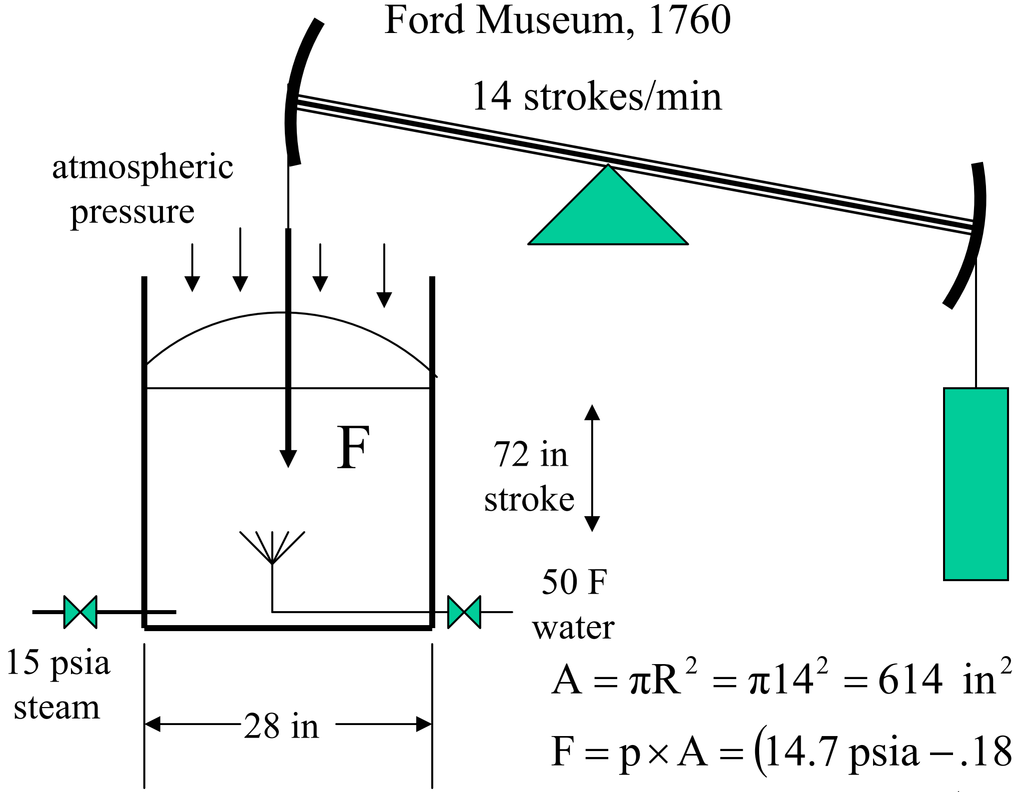
NEWCOMEN ATMOSPHERIC ENGINE

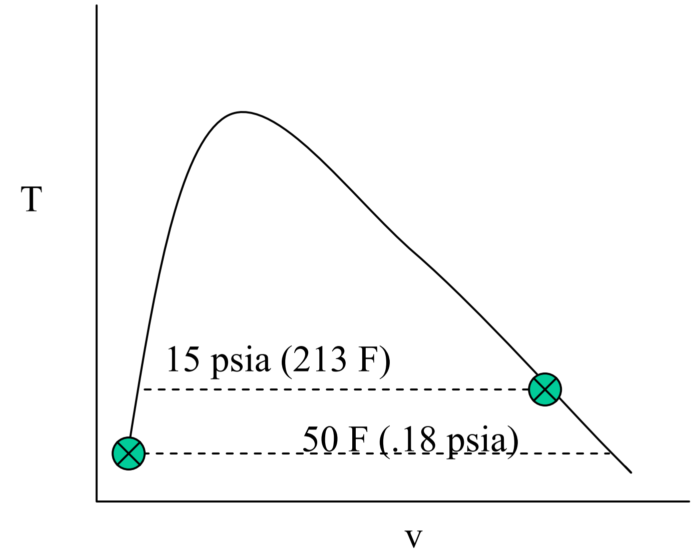
Ford Museum, 1760

14 strokes/min



NEWCOMEN ATMOSPHERIC ENGINE





$$A = \pi R^2 = \pi 14^2 = 614 \ \text{in}^2$$

$$F = p \times A = (14.7 \text{ psia} - .18 \text{ psia}) 614 \text{ in}^2 = 9114 \text{ lbs}$$

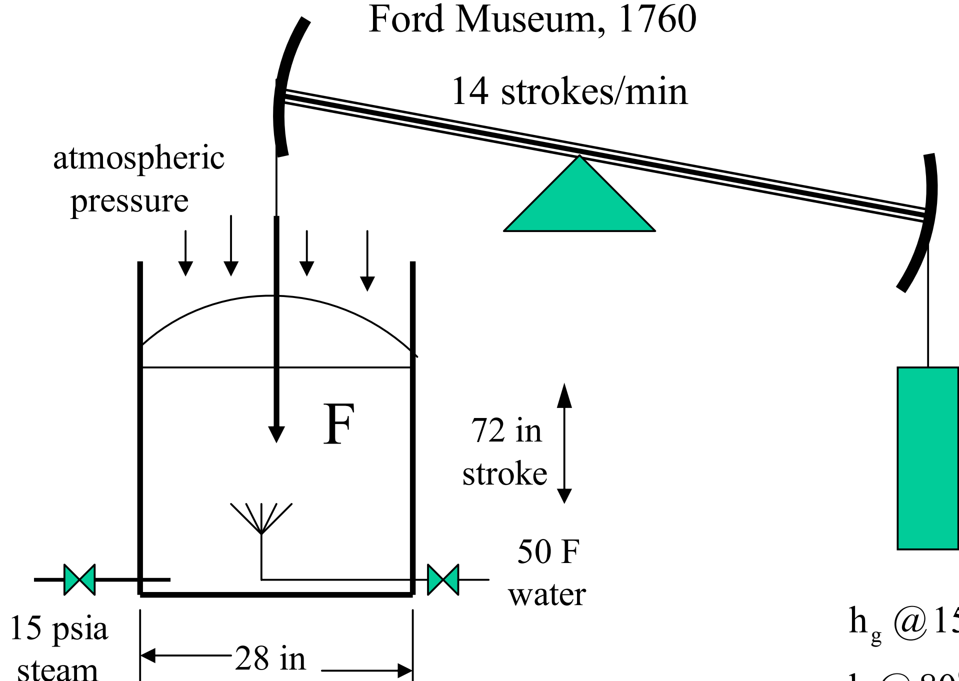
$$W = F \times d = 9114 \text{ lbs} \times (72/12) \text{ ft} = 54{,}684 \text{ ft lb/ stroke}$$

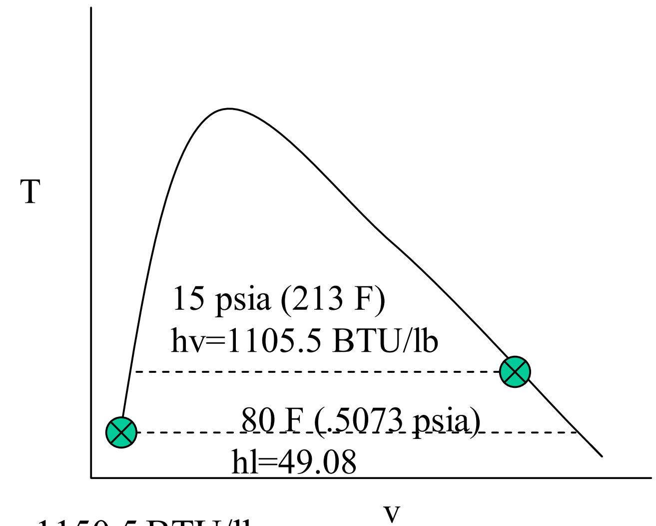
$$\text{Power} = 54{,}684 \frac{\text{ft lb}}{\text{stroke}} \times 14 \frac{\text{strokes}}{\text{min}} = 765{,}000 \frac{\text{ft lb}}{\text{min}}$$

$$\text{Power} = \frac{765{,}000 \text{ ft lb/min}}{33{,}000 \text{ hp/ft lb/min}} = 23 \text{ HP or } 17.5 \text{ kw}$$

$$m = \frac{V}{v} \times \text{strokes} = \left(\frac{614 \text{ in}^2\text{/stroke}}{144 \text{ ft}^2\text{/in}^2} \right) \times 14 \frac{\text{strokes}}{\text{min}} / 26.6 \frac{\text{ft}^3}{\text{lb}} = 13.4 \text{ lb/min}$$

NEWCOMEN ATMOSPHERIC ENGINE





$$A = \pi R^2 = \pi 14^2 = 614 in^2$$

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$$\mathrm{Power = \frac{765{,}000\ ft\ lb/min}{33{,}000\ hp/ft\ lb/min} = 23\ HP\ or\ 17.5\ kw}$$

$$\mathrm{m = \frac{V}{v} \times strokes = \left(\frac{614\ in^2/stroke}{144\ ft^2/in^2}\right) \times 14\,\frac{strokes}{min} / 26.6\,\frac{ft^3}{lb} = 13.4\ lb/min}$$

$$\mathrm{h_g\ @\,15,\ psia = 1150.5\ BTU/lbm}$$

$$\mathrm{h_l @\ 80^O F = 49.08\ BTU/lbm}$$

$$\mathrm{Q_{in} = m\Delta h}$$

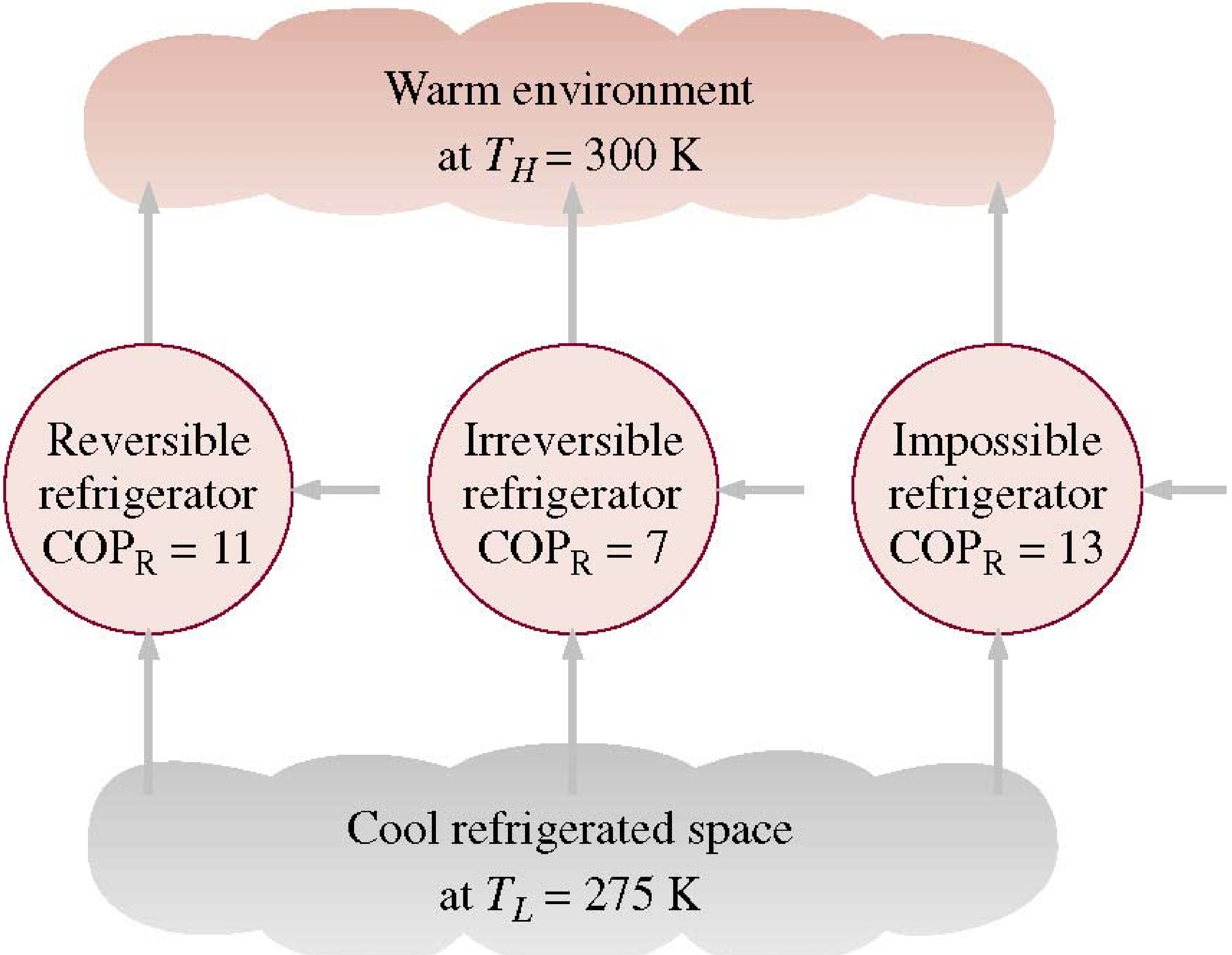
$$\mathrm{Q_{in} = 13.4\ lb/min(1150.5\ BTU/lb - 49.008\ BTU/lb)}$$

$$\mathrm{Q_{in} = 14{,}759.\ BTU/lbm}$$

$$\mathrm{W = \frac{765{,}000\ ftlb/min}{778\ ftlb/BTU} = 932.3\ BTU/min}$$

$$\eta_{\mathrm{CYCLE}} = \frac{\mathrm{W}}{\mathrm{Q_{in}}} = \frac{\mathrm{932.3BTU/min}}{\mathrm{14{,}759.\ BTU/lbm}} = 6.3\%$$

$$\eta_{\substack{\mathrm{CYCLE}\\ \mathrm{CARNOT}}} = \frac{\mathrm{T_h - T_l}}{\mathrm{T_h}} = \frac{213 - 80}{460 + 213} = 20.\%$$


Warm environment
at $T_H = 300$ K
Reversible
refrigerator
$COP_R = 11$
Irreversible
refrigerator
$COP_R = 7$
Impossible
refrigerator
$COP_R = 13$
Cool refrigerated space
at $T_L = 275$ K

Carnot Principles

1. No engine operating between two heat reservoirs, each having a fixed temperature, can be more efficient than a reversible engine operating between the same reservoirs.

$$\eta_{actual} \leq \eta_{Carnot}$$

2. All reversible engines operating between two heat reservoirs, each having its own fixed temperature, have the same efficiency.

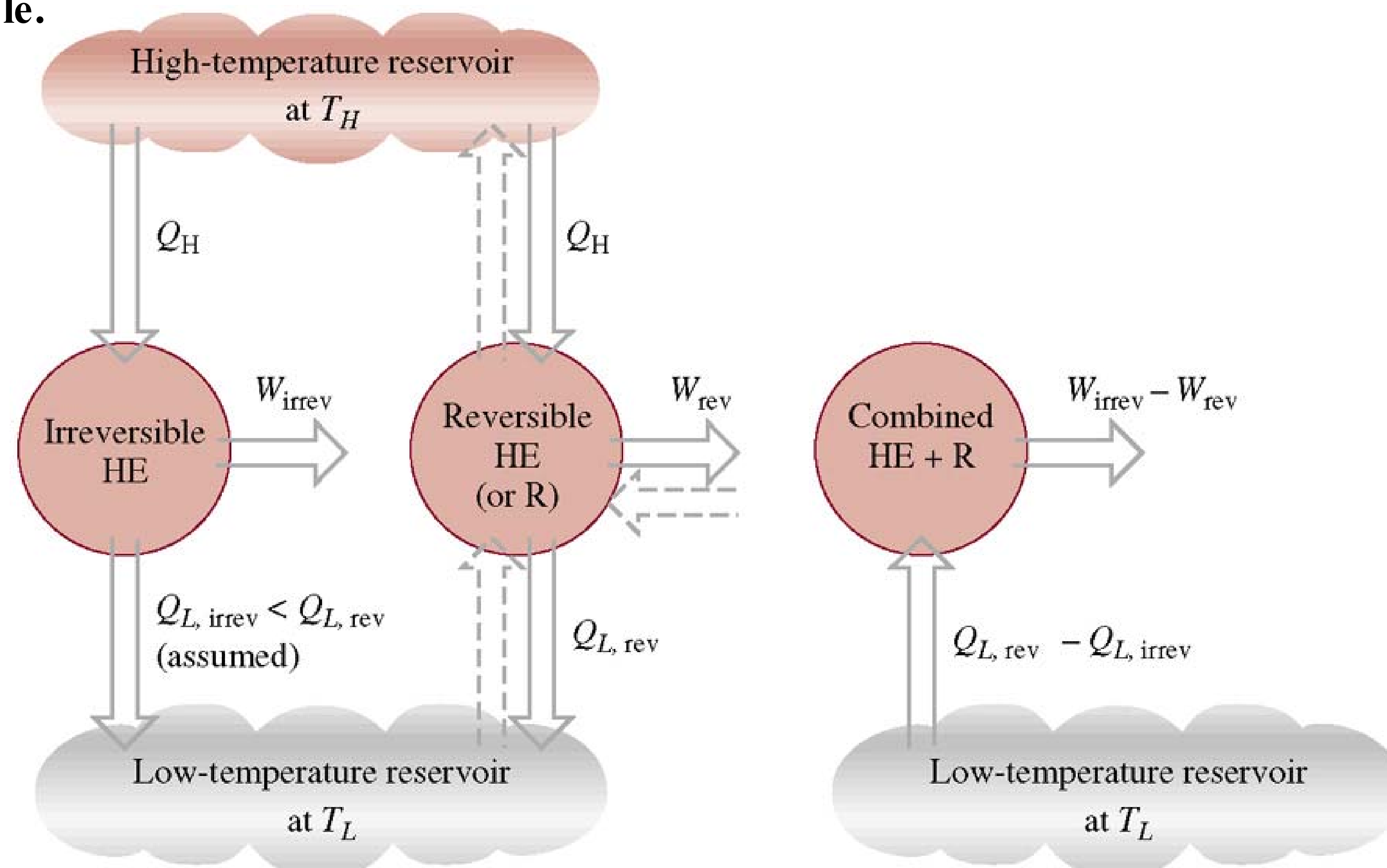
3. The efficiency of any reversible engine operating between two reservoirs is independent of the nature of the working fluid and depends only on the temperature of the reservoirs.

4. An absolute temperature scale can be defined in a manner independent of the thermometric material.

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

FIGURE 5-47

Proof of the first Carnot principle.



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

Thermodynamic Temperature Scale

$\eta = \text{function}(T_1, T_3)$

$\eta = 1 - \dfrac{Q_3}{Q_1}$

$\dfrac{Q_1}{Q_3} = \text{function}(T_1, T_3)$

from engine schematics

$\dfrac{Q_1}{Q_2} = f(T_1, T_2) \quad \dfrac{Q_2}{Q_3} = f(T_2, T_3) \quad \dfrac{Q_1}{Q_3} = f(T_1, T_3)$

by identity,

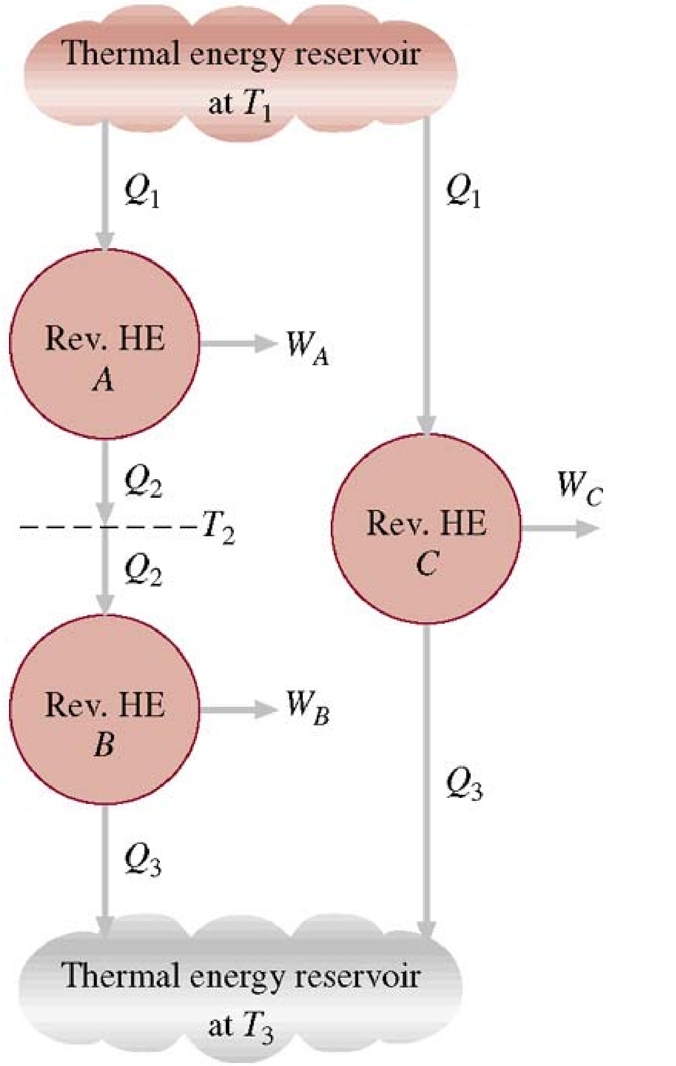
$\dfrac{Q_1}{Q_3} = \dfrac{Q_1}{Q_2}\dfrac{Q_2}{Q_3}$

substituting,

$f(T_1, T_2) = f(T_2, T_3) \times f(T_1, T_3)$

this equation can be satisfied only if,

$\left(\dfrac{Q_h}{Q_l}\right) = \dfrac{T_h}{T_l} \quad \text{and} \quad Q_l = Q_h \dfrac{T_l}{T_h}$



A reversible engine (or a real engine corrected to reversibe) can be used to measure temperature difference.

Second Law $\Rightarrow$ Heat Engine $\Rightarrow$ Thermodynamic Temperature Scale

SECOND LAW $\mathbf{\dfrac{Q_1}{Q_2} = \dfrac{T_1}{T_2}, \quad T_2 = T_1\left(\dfrac{Q_2}{Q_1}\right)}$

T_1 and T_2 - absolute temperatures.

When a reversible engine (or a real engine correctable to reversible) is run between ice and steam temperatures with a constant heat input and Q_{out} is meaasured,

$$\frac{Q_s}{Q_i} = 1.3661 = \left(\frac{T_s}{T_i}\right)$$

$$T_s = 1.3361T_i$$

Temperature scales can be setup for any arbitrarily sleected scale 0 point and Scale Range of degrees between ice and steam.

$$T_s - T_i = \text{Scale Range}$$

substituting for T_s,

$$1.3661T_i - T_i = \text{ScaleRange}$$

$$\mathbf{T_i = \frac{Scale\ Range}{.3661}}$$

For : Celsius Scale

100^O Scale Range

ice as Scale 0

$$T_i = \frac{100}{.3661} = 273.15^O K$$

Celsius $0 = 273.15^O$ K

For : Farenheight Scale

180^O Scale Range

32^O less than ice as Scale 0

$$T_i = \frac{180}{.3661} = 491.68^O \text{K}$$

Farenheight $0 = 491.68 - 32$

Farenheight $0 = 459.68^O$ R

Carnot Cycle Performance

Using the absolute thermodynamic temperature scale,

$$\left(\frac{Q_H}{Q_L}\right) = \frac{T_H}{T_L}$$

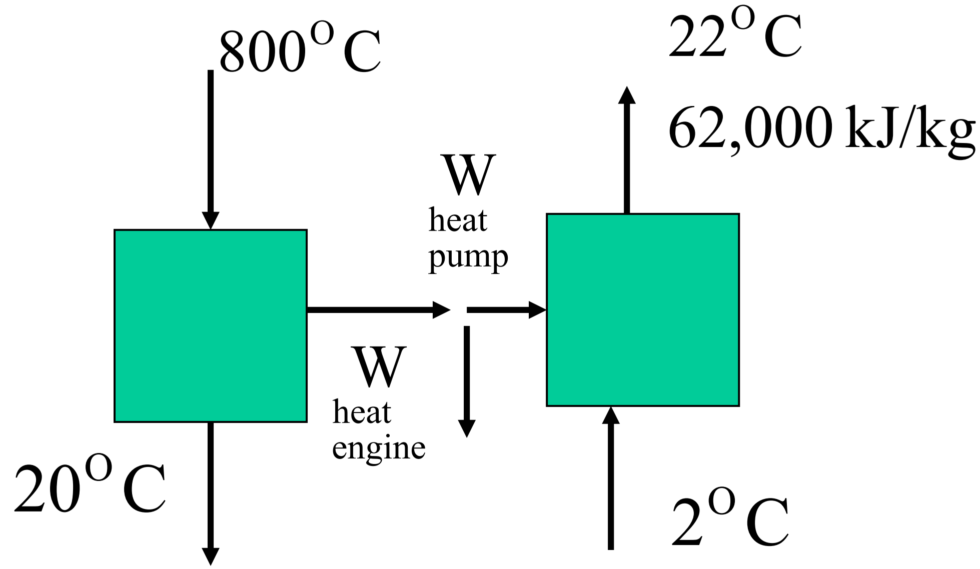
The Carnot efficiency and COP are,

$$\eta_{\substack{\text{ENGINE}\\ \text{CARNOT}\\ \text{REVERSIBLE}\\ \text{CYCLE}}} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} = \frac{T_H - T_L}{T_H} = \frac{\text{Work}}{Q_{in}}$$

$$COP_{\substack{\text{REFRIGERATOR}\\ \text{CARNOT}\\ \text{REVERSIBLE}\\ \text{CYCLE}}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L} = \frac{Q_{in}}{\text{Work}}$$

$$COP_{\substack{\text{HEAT PUMP}\\ \text{CARNOT}\\ \text{REVERSIBLE}\\ \text{CYCLE}}} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L} = \frac{Q_{out}}{\text{Work}}$$

Half the work of an engine operating between 800 C and 20 C is used to power a refrigeration machine absorbing heat at 2 C and rejecting 62,000 kJ/hr at 22 C How much heat is supplied to the engine?



$$\mathrm{COP}_{\text{heat pump}} = \frac{Q_{out}}{Q_{out} - Q_{in}} = \frac{Q_{out}}{W_{\text{heat pump}}} = \frac{T_h}{T_h - T_l} = \frac{273.15 + 22}{20} = 14.8$$

$$W_{\text{heat pump}} = \frac{Q_{out}}{\mathrm{COP}_{\text{hea tpump}}} = \frac{62{,}000 \text{ kJ/hr}}{14.8} = 4189.2 \text{ kJ/kg}$$

$$\eta_{\text{heat engine}} = \frac{T_h - T_l}{T_h} = \frac{780^{O} K}{800 + 273.15} = .725 = \frac{W_{\text{heat engine}}}{Q_{in}} = \frac{2 \times W_{\text{heat pump}}}{Q_{in}}$$

$$Q_{in} = \frac{2 \times W_{\text{hea tpump}}}{\eta} = \frac{2 \times 4189.2}{.725}$$

$$Q_{in} = 11{,}556 \text{ kJ/hr}$$

.0103 kg steam executes the following cycle. The absolute high temperature is twice the absolute low temperature and the net work output is 25 kJ. Heat is rejected during a phase change from a vapor to a liquid. What is the rejection temperature?

$$\eta = \frac{T_h - T_l}{T_h} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{W}{Q_{in}}$$

$$T_h = 2 \times T_l$$

$$\eta = \frac{2T_l - T_l}{2T_l} = \frac{W}{Q_{in}} = \frac{25\text{ kJ}}{Q_{in}} = .5$$

$$Q_{in} = \frac{25\text{ kJ}}{.5} = 50\text{ kJ}$$

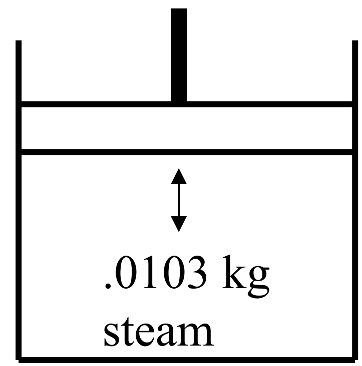
$$Q_{out} = m\Delta H = Q_{in} - W = 25\text{ kJ}$$

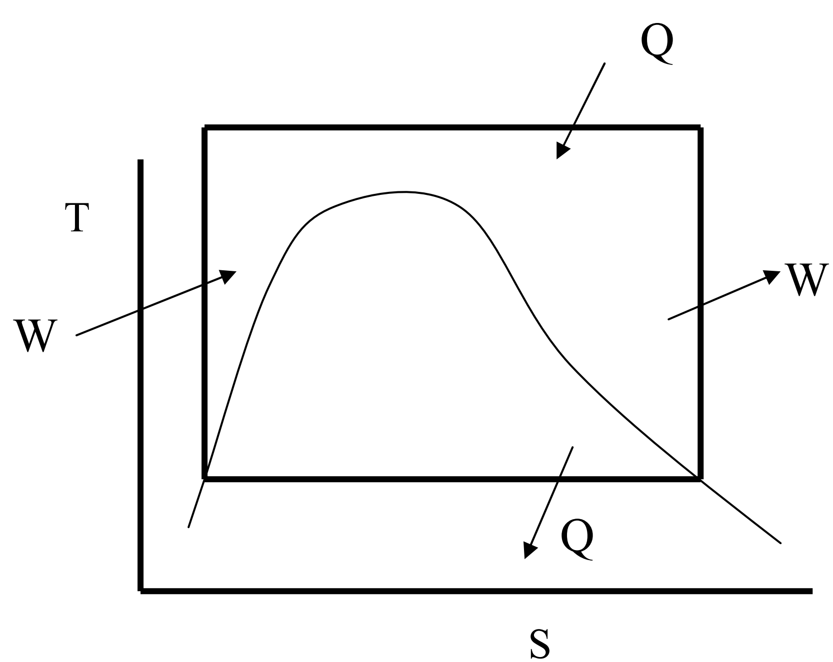
$$\Delta H = \frac{Q_{out}}{m} = \frac{25\text{ kJ}}{.0103\text{ kg}} = 2427.2\text{ kJ/kg} = h_{fg}$$

$$T\ @\ h_{fg} = 2427.2$$

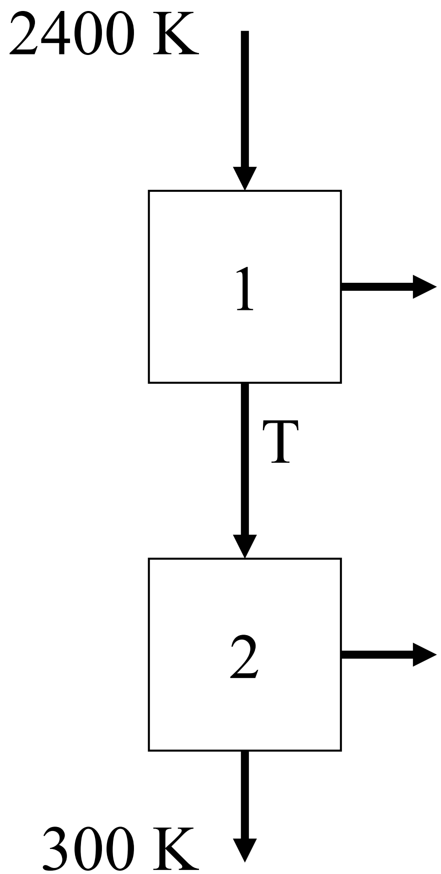
T	h_{fg}
35	2418.6
31.1	2427.2
40	2430.5

$$T = 35 - \frac{(2427.2 - 2418.6)}{(2430.5 - 2427.2)} \times 5 = 31.2^{o}C$$





Two Carnot engines operate in series at the same efficiency. The high temperature engine receives heat at 2400 K and the low temperature engine rejects heat at 300. What is the temperature between the engines?



$$\eta_1 = \eta_2$$

$$\eta = \frac{T_h - T_l}{T_h}$$

$$\frac{2400 - T}{2400} = \frac{T - 300}{T}$$

$$T(2400 - T) = 2400T - 300 \times 2400$$

$$2400T - T^2 = 2400T - 300 \times 2400$$

$$T = (300 \times 400)^{.5}$$

$$T = 848.5^{O}\,K$$

Since

$$\left(\frac{Q_H}{Q_L}\right) = \frac{T_H}{T_L}$$

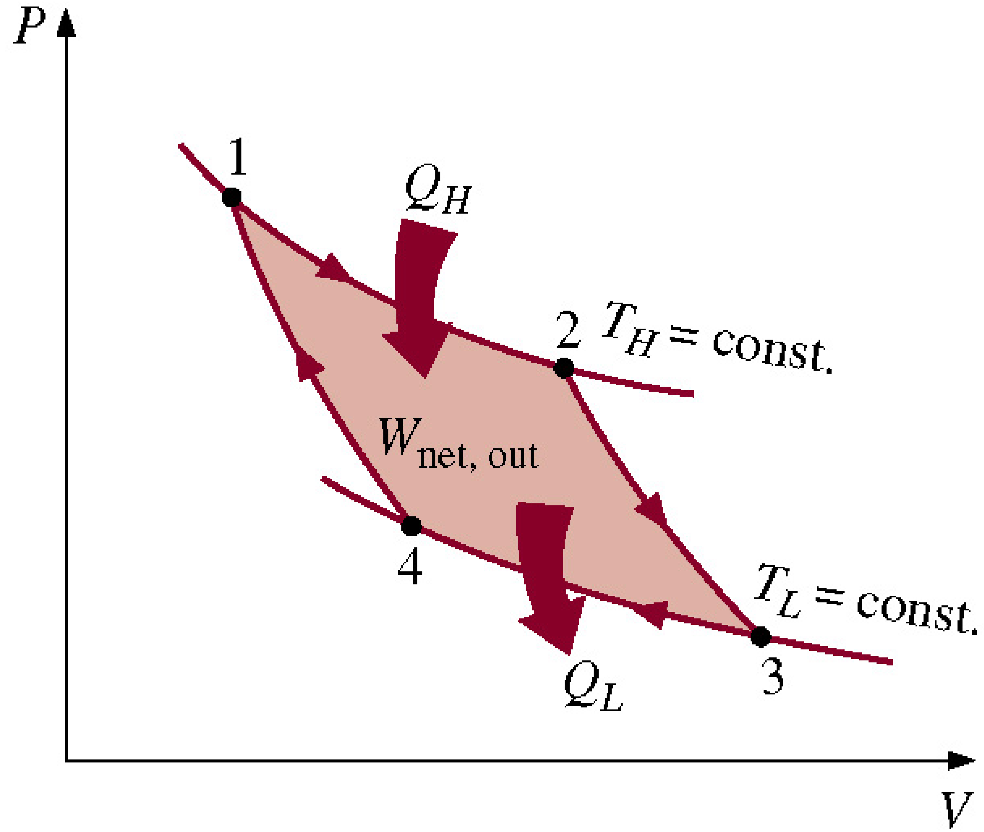
$$\frac{Q_h}{T_h} = \frac{Q_l}{T_l}$$

$$\sum_{cycle} \frac{Q}{T} = \frac{Q_h}{T_h} - \frac{Q_l}{T_l} = 0$$

$\frac{Q}{T}$ may be independent of path,

one of the characteristics

of a thermodynamoc property.



In First Law,

$$\oint_{cycle} (dQ - W) = 0$$

lead to the definition of energy as a

thermodynamic property

$$Q = \Delta E + W$$

Ideal Gas Carnot Cycle

$$Q_{1\to2} = W_{1\to2} = RT_1 \ln\left(\frac{p_2}{p_1}\right) = Q_H$$

$$Q_{3\to4} = W_{3\to4} = RT_3 \ln\left(\frac{P_3}{p_4}\right) = Q_L$$

$$\oint W = \oint Q = RT_1 \ln\left(\frac{p_2}{p_1}\right) - RT_3 \ln\left(\frac{P_3}{p_4}\right) = W_{net}$$

for $pv^n = \text{constant}$

$$\left(\frac{p_2}{p_3}\right) = \left(\frac{T_2}{T_3}\right)^{\frac{n}{n-1}} \qquad \left(\frac{p_1}{p_4}\right) \Rightarrow \left(\frac{T_1}{T_4}\right)^{\frac{n}{n-1}}$$

$$\left(\frac{P_2}{p_3}\right) = \left(\frac{P_1}{p_4}\right) \quad \text{or} \left(\frac{P_2}{p_1}\right) = \left(\frac{P_3}{p_4}\right)$$

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{RT_1 \ln\left(\frac{p_2}{p_1}\right) - RT_3 \ln\left(\frac{P_3}{p_4}\right)}{RT_1 \ln\left(\frac{p_2}{p_1}\right)} = \frac{T_h - T_l}{T_h}$$

Note $\sum \frac{dQ}{T} = \frac{RT_1 n}{T_1} \ln\left(\frac{p_2}{p_1}\right) - \frac{RT_3}{T_3} \ln\left(\frac{P_3}{p_4}\right) = 0$

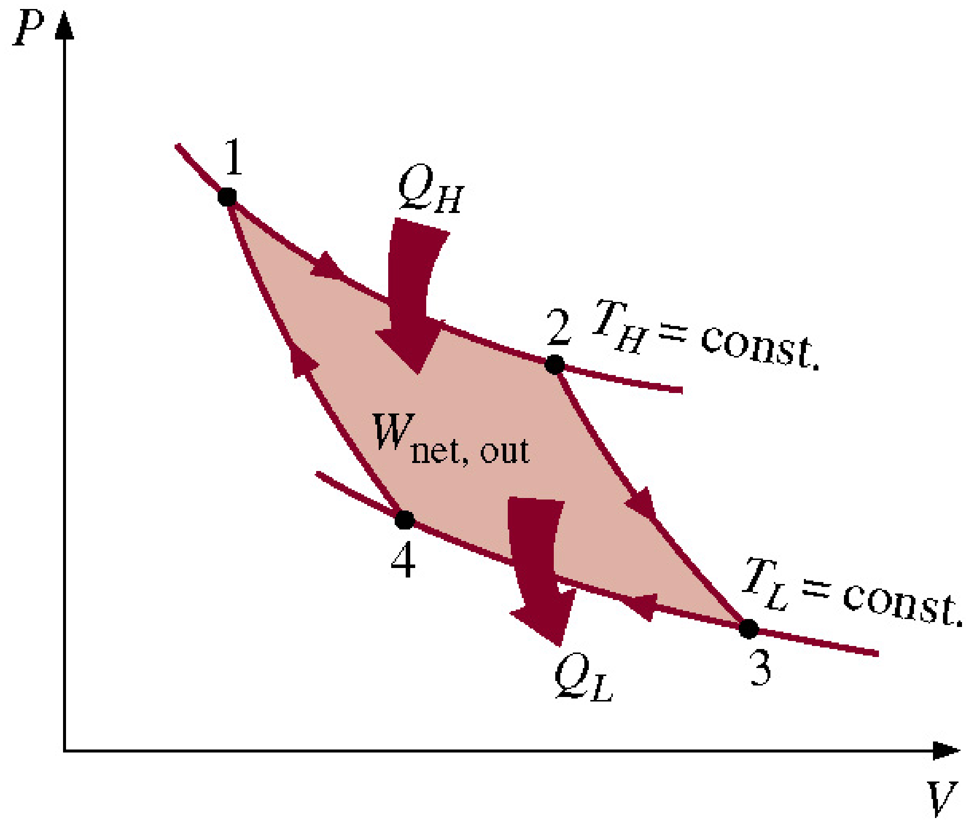
$\sum \frac{dQ}{T}$ behaves in this reversible cycle like a property

Reversible constant temperature heat transfer,

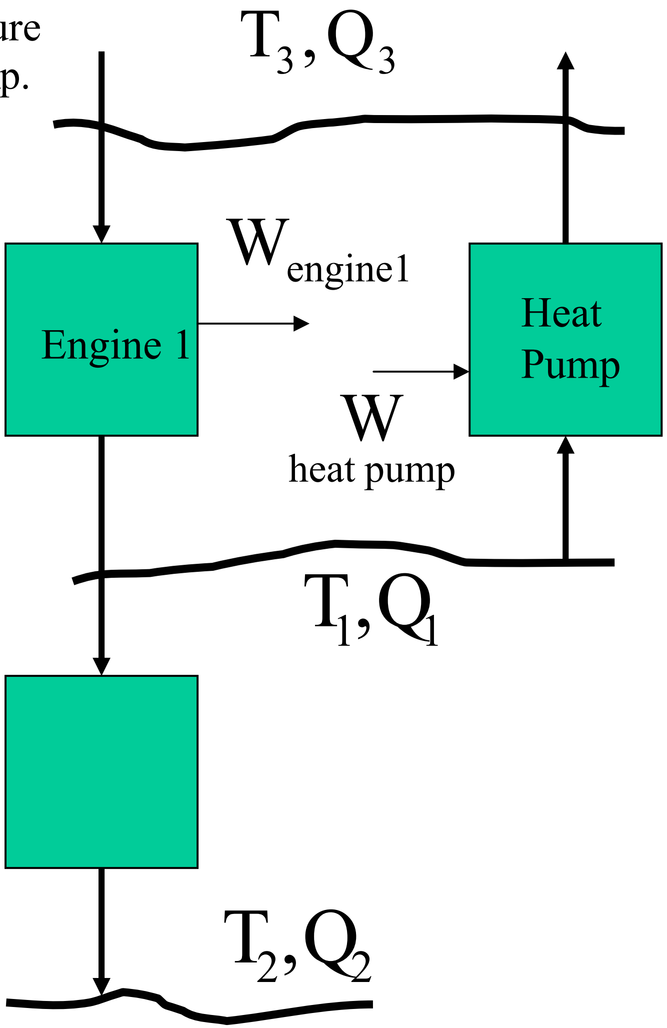
process $1 \to 2$, process $3 \to 4$

Reversible adiabatic expansion,

process $2 \to 3$, process $4 \to 1$



An engineer proposed an attempted to improve the efficiency of a power cycle by transferring heat from the available high temperature source to am alternate higher temperature source using a heat pump. What do you think of this suggestion?



$$\eta_{\text{engine 1}} = \frac{Q_3 - Q_1}{Q_3} = \frac{T_3 - T_1}{T_3} = \frac{W_{\text{engine 1}}}{Q_3}$$

$$Q_3 = W_{\text{engine1}}\left(\frac{T_3}{T_3 - T_1}\right)$$

$$COP_{\text{heat[pump}} = \frac{Q_3}{Q_3 - Q_1} = \frac{T_3}{T_3 - T_1} = \frac{Q_3}{W_{\text{heatpump}}}$$

$$Q_3 = W_{\text{heat pump}}\left(\frac{T_3}{T_3 - T_1}\right)$$

where Q_3 engine1 $= Q_3$ heat pump

$$W_{\text{engine1}} = W_{\text{heat pump}}$$

there is no net work gain with reversible machines

and there would be a net loss with real machines.