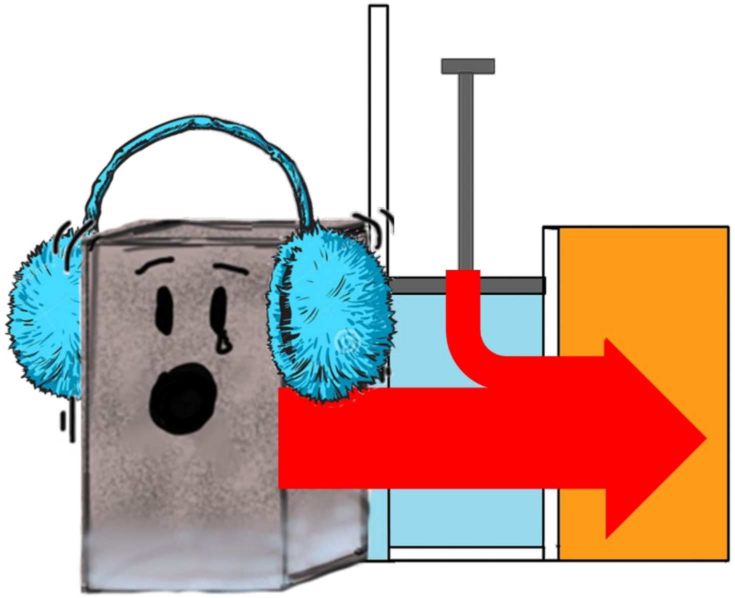
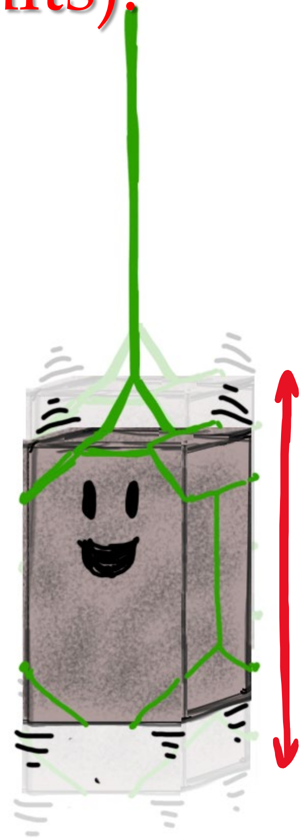
# Lecture 25.

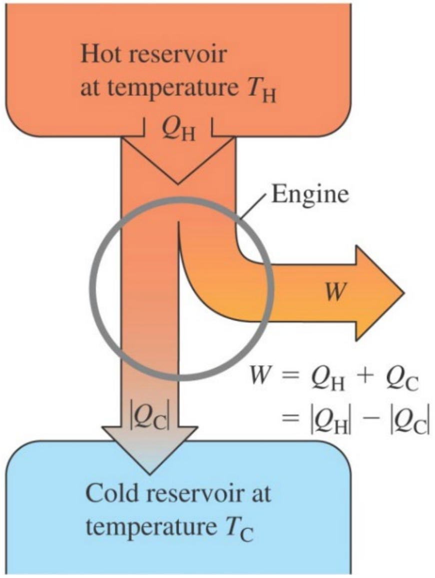
# Carnot vs Stirling. Equilibrium. Restoring force (if time permits).





# Reminder

## Engine

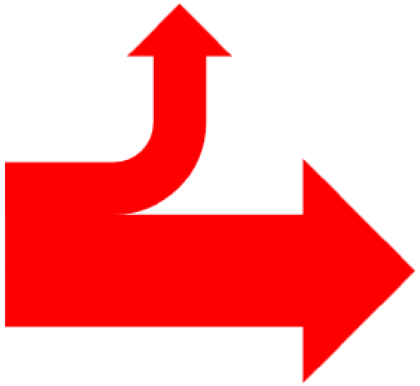



Efficiency:

$$e = \frac{|W_{net}|}{|Q_{in}|}$$

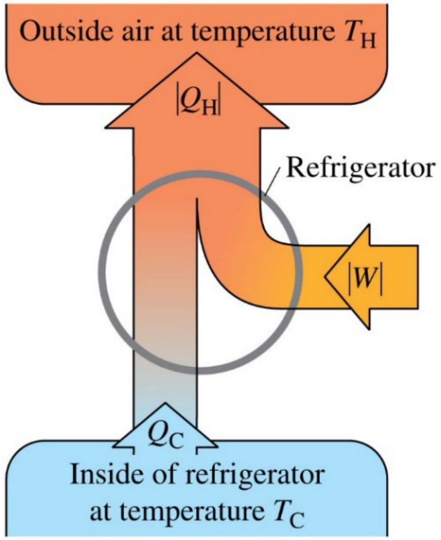
$|W|$

$|Q_{in}|$



$|Q_{out}|$

## Refrigerator

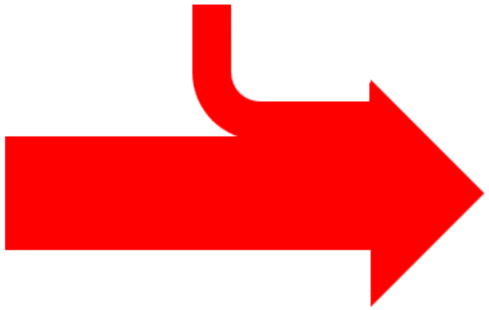



Coefficient of Performance:

$$K = \frac{|Q_C|}{|W_{net}|}$$

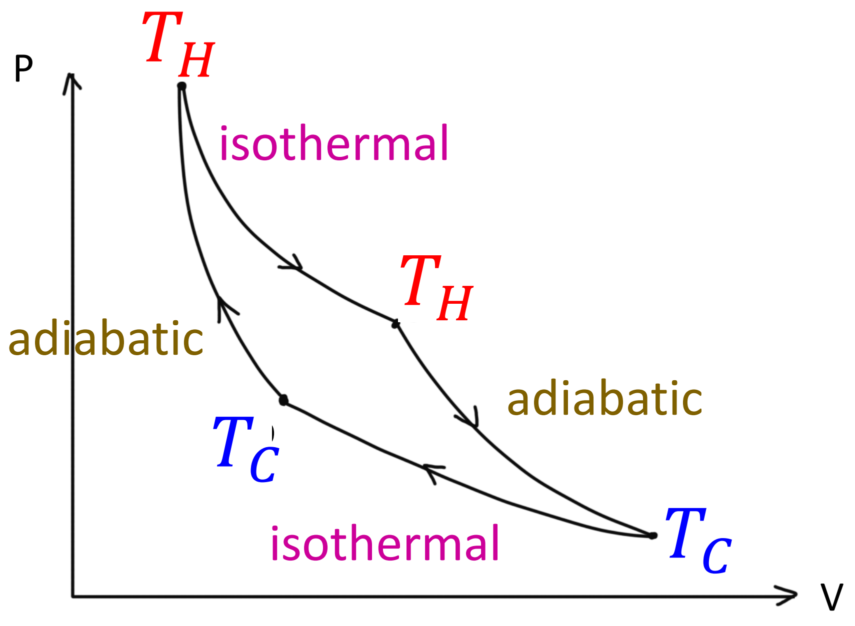
$|W|$

$|Q_C|$

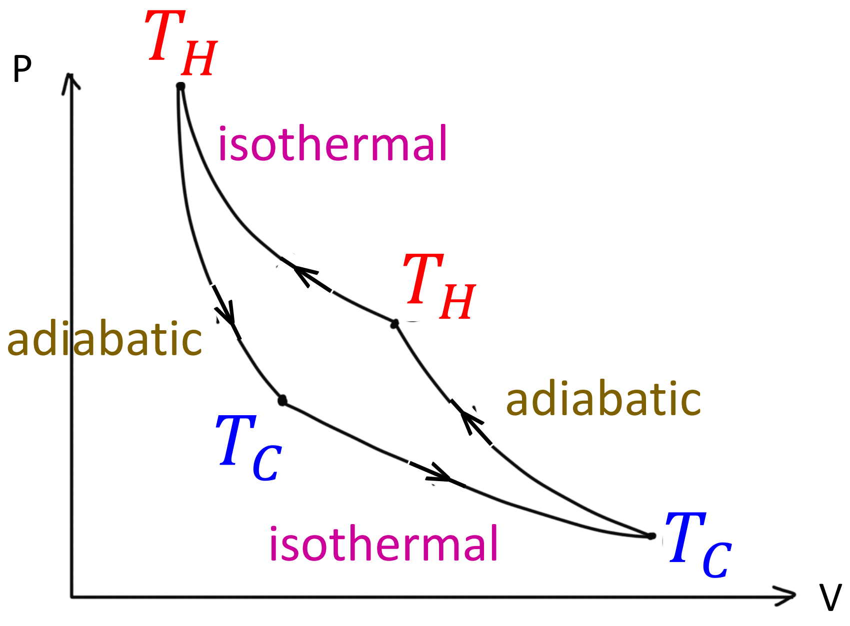


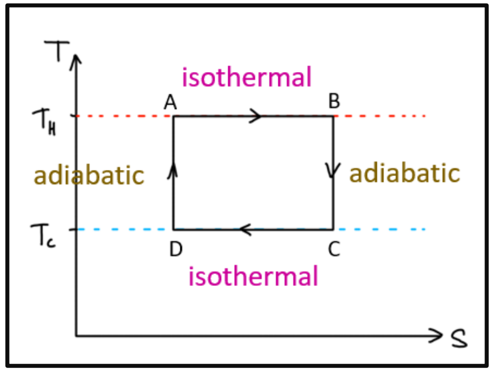
$|Q_H|$

- Carnot Engine




- Carnot Refrigerator




Efficiency: $\boxed{e = e_{max} = 1 - \frac{T_C}{T_H}}$

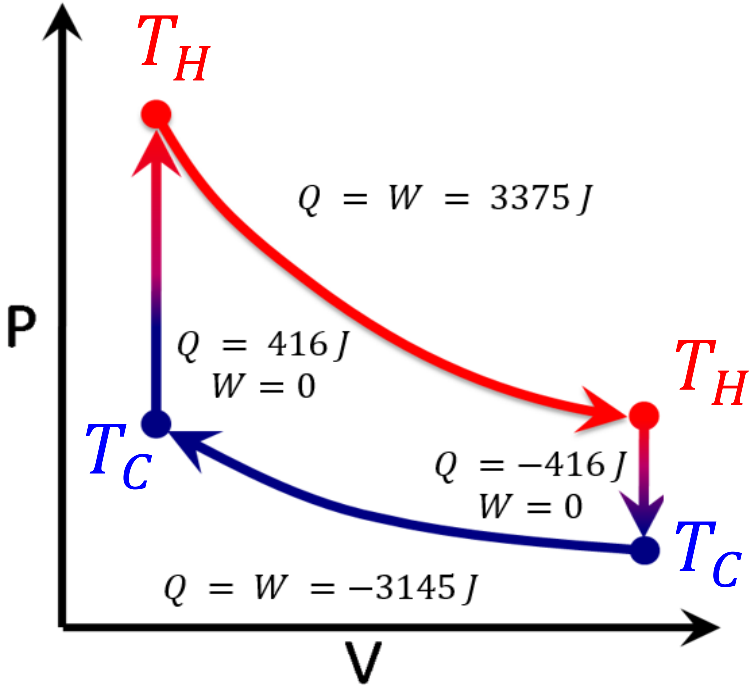
Coef of Performance: $\boxed{K = K_{max} = \frac{T_C}{T_H - T_C}}$

- Larger efficiency or CoP would violate 2nd Law of Thermodynamics
- @ $T_C = 0\,^oC, \quad T_H = 20^oC$:

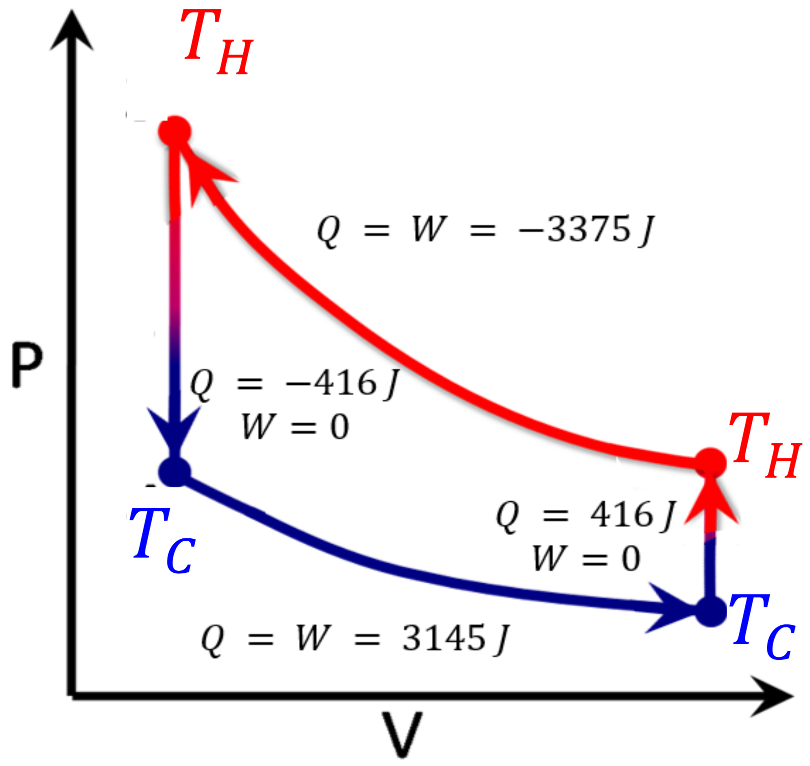
Efficiency: $e =$ 6.8%

Coef of Performance: $K =$ 13.7

- Stirling Engine




- Stirling Refrigerator

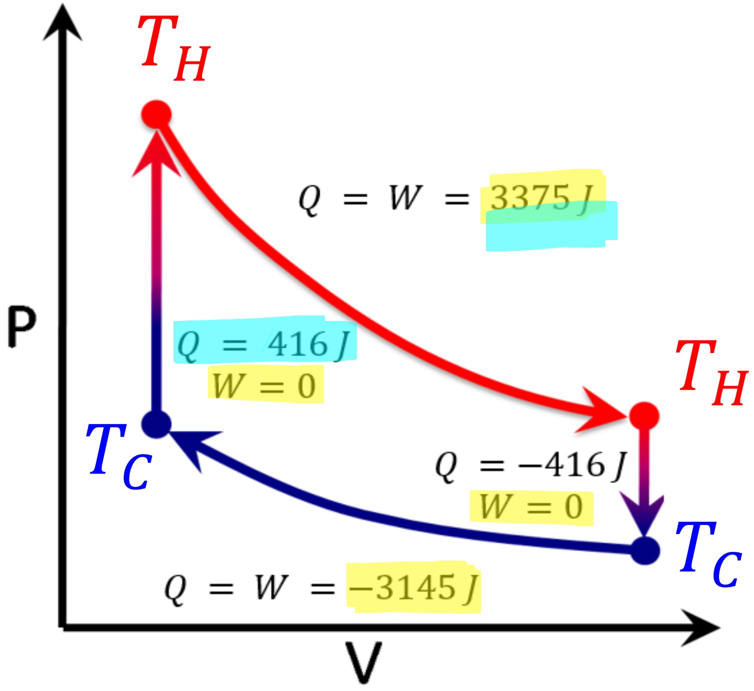



- $@\ T_C = 0\,^oC,\ \ T_H = 20^oC$:

Efficiency: $e =$ 6.1%

Coef of Performance: $K =$ 11.9

- Stirling Engine




$$e = \frac{|W_{net}|}{|Q_{in}|} = $$

$$= \frac{3375 - 3145}{3375 + 416} =$$

$$= \frac{230}{3791} \rightarrow 6.1\%$$

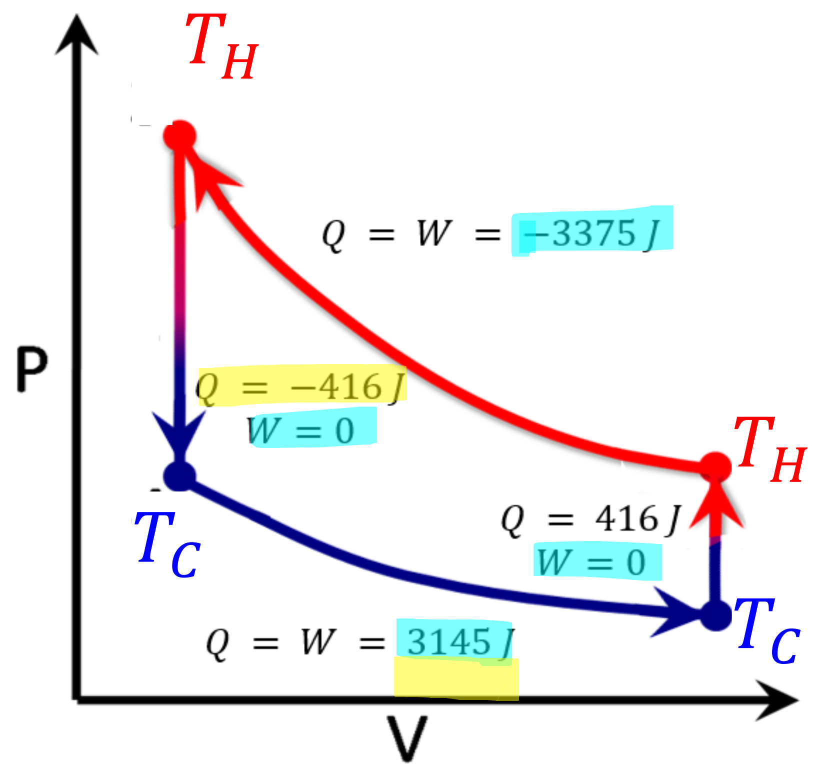
- @ $T_C = 0\,^oC, \;\; T_H = 20^oC$:

$$\text{COP} = \frac{|Q_c|}{|W_{net}|} = $$

$$= \frac{|3145 - 416|}{|-3375 + 3145|} = $$

$$= \frac{2729}{230} = 11.9$$

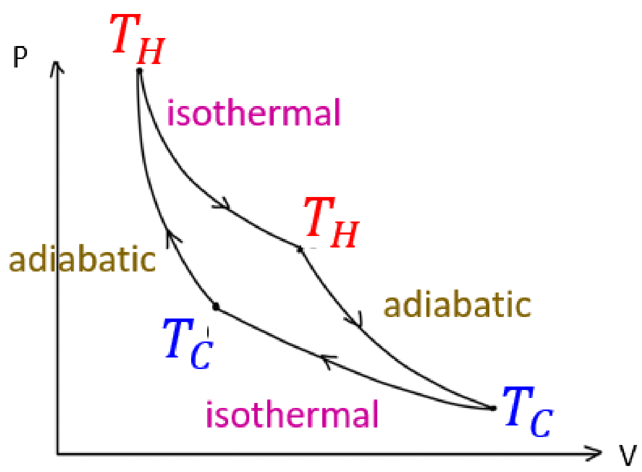
- Stirling Refrigerator




- @ $T_C = 0\,^oC$, $T_H = 20^oC$:

# Summary

- We analyzed Stirling engine / refrigerator and Carnot engine / refrigerator operating between $T_H = 20\,^oC$ and $T_C = 0^oC$.



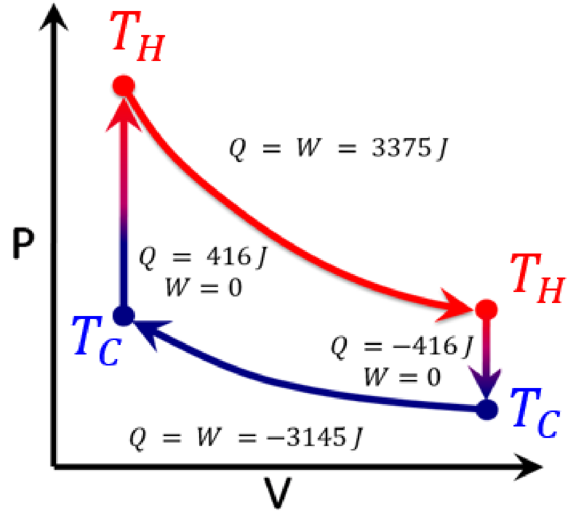

$$e = 1 - T_C/T_H = 6.8\%$$

$$K = T_C/(T_H - T_C) = 13.7$$

benchmark
not practical

$$e = |W_{net}|/|Q_{in}| = 230/3791 = 6.1\%$$

$$K = |Q_C|/|W_{net}| = 2729/230 = 11.9$$



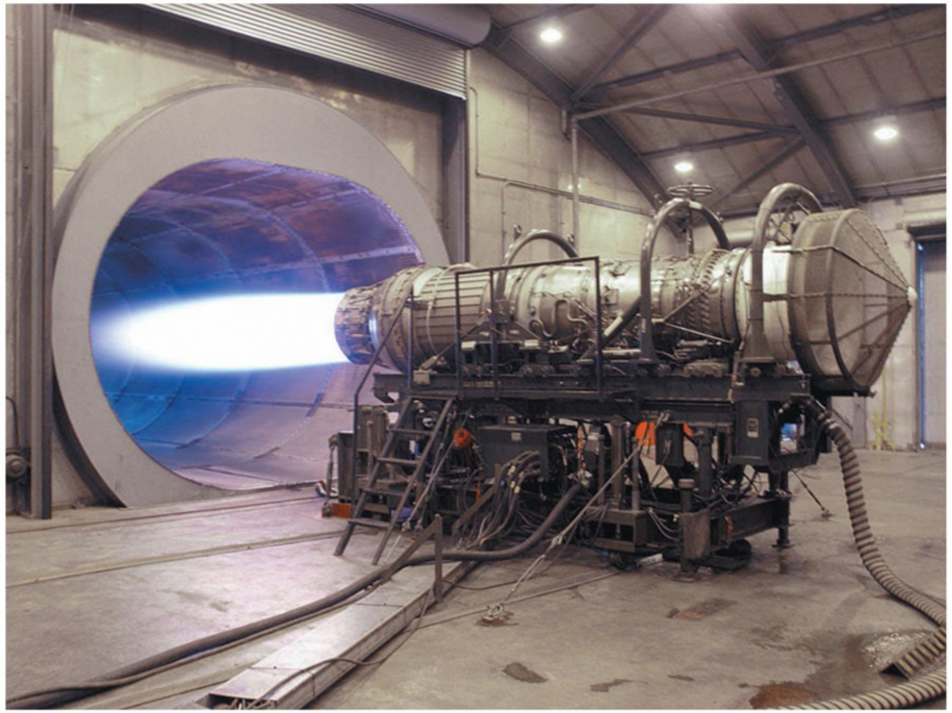

- The Stirling engine $e$ and $K$ are below the Carnot values, as expected!

# Engine Efficiency

- Maximize the efficiency of a real engine by making intake temperature $T_H$ as high as possible, and exhaust temperature $T_C$ as low as possible
- That's why temperatures inside a jet engine are made as high as possible
- Exotic ceramic materials are used that can withstand temperatures in excess of 1000 °C without melting or becoming soft

$$\boxed{e_{max} = 1 - \frac{T_C}{T_H}}$$

- $e_{max} = 1$ only if $T_C = 0$ – impossible!



# Entropy Changes for Stirling Refrigerator

$\Sigma\, dQ = Q$

$n$ = 1 mole

$C_v$ = (5/2) $R$

$$dS = \frac{dQ}{T}$$

- Entropy changes for the gas alone:

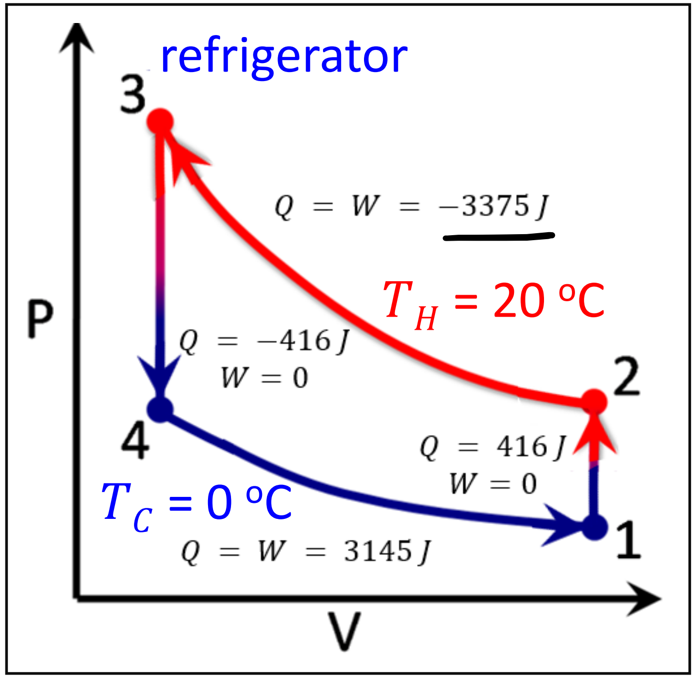
$$2\rightarrow3: \Delta S_g = \frac{Q_{2\to3}}{T_H} = \frac{-3375}{293} = -11.51\ \frac{J}{K}$$ ✓

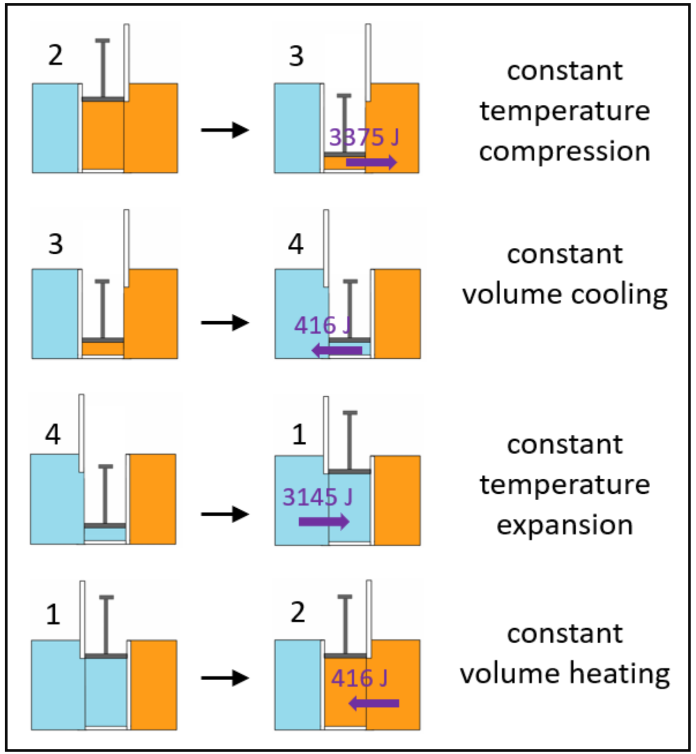
$$3\rightarrow4: \Delta S_g = n\, c_v \ln \frac{273}{293} = -1.47\ \frac{J}{K}$$ ✓

$$4\rightarrow1: \Delta S_g = \frac{Q_{4\to1}}{T_C} = \frac{3145}{273} = +11.51\ \frac{J}{K}$$ ✓

$$1\rightarrow2: \Delta S_g = n\, c_v \ln \frac{293}{273} = +1.47\ \frac{J}{K}$$ ✓

- $\Delta S_g$ = 0 !



$$\boxed{dS = \frac{dQ}{T}}$$

- $T = \text{const}$
  - $dS = \dfrac{dQ}{T} \quad \Rightarrow \quad \boxed{\Delta S_T = \dfrac{Q}{T}}$

- $V = \text{const}$ → T changes!
  - $dS = \dfrac{dQ}{T}, \quad dQ = nC_v dT \quad \Rightarrow \quad \Delta S = \int dS = nC_v \int_{T_i}^{T_f} \dfrac{dT}{T}$
  - $\Delta S = nC_v \int_{T_i}^{T_f} \left(\dfrac{dT}{T}\right) = \boxed{nC_v \ln\left(\dfrac{T_f}{T_i}\right) = \Delta S_v}$

- $P = \text{const}$ → T changes!
  - $dS = \dfrac{dQ}{T}, \quad dQ = nC_p dT \quad \Rightarrow \quad \Delta S = \int dS = nC_p \int_{T_i}^{T_f} \dfrac{dT}{T}$
  - $\Delta S = nC_p \int_{T_i}^{T_f} \left(\dfrac{dT}{T}\right) = \boxed{nC_p \ln\left(\dfrac{T_f}{T_i}\right) = \Delta S_p}$

# Entropy Changes for Stirling Refrigerator

$$dS = \frac{dQ}{T}$$

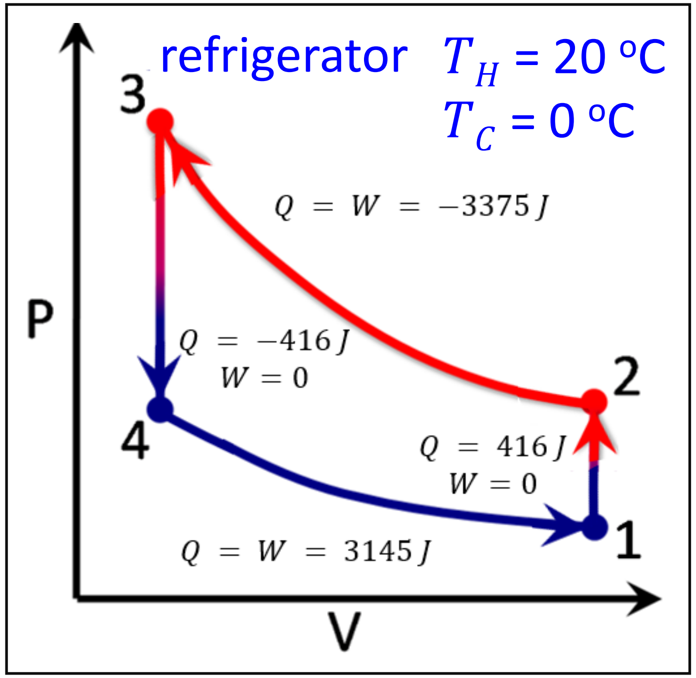
- Entropy changes for reservoirs:

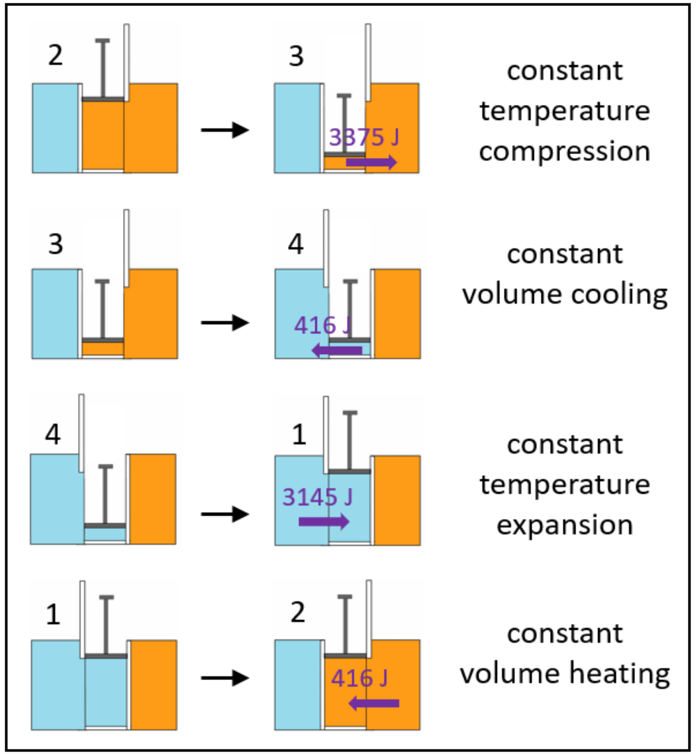
$2\rightarrow3$: $\Delta S_{HR} = \dfrac{3375\,J}{T_H = 293\,k} = +11.51\ \dfrac{J}{k}$

$3\rightarrow4$: $\Delta S_{CR} = \dfrac{+416\,J}{T_c = 273\,k} = 1.52\ \dfrac{J}{k}$

$4\rightarrow1$: $\Delta S_{CR} = \dfrac{-3145\,J}{T_c = 273\,k} = -11.51\ J/k$

$1\rightarrow2$: $\Delta S_{HR} = \dfrac{-416\,J}{T_H = 293\,k} = -1.43\ \dfrac{J}{k}$



# Entropy Changes for Stirling Refrigerator

- Entropy changes for the gas alone:

$n$ = 1 mole
$C_v$= (5/2) $R$

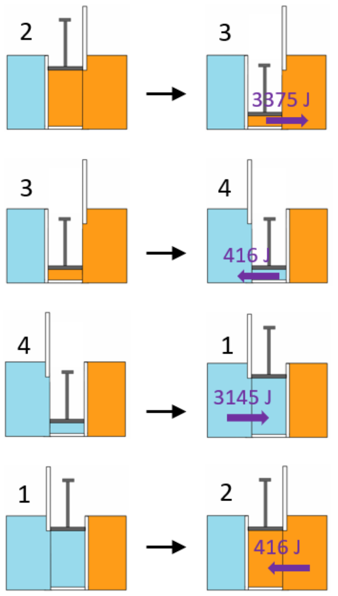
$$2\to3: \Delta S_g = Q/T_H = -11.51\ J/K$$

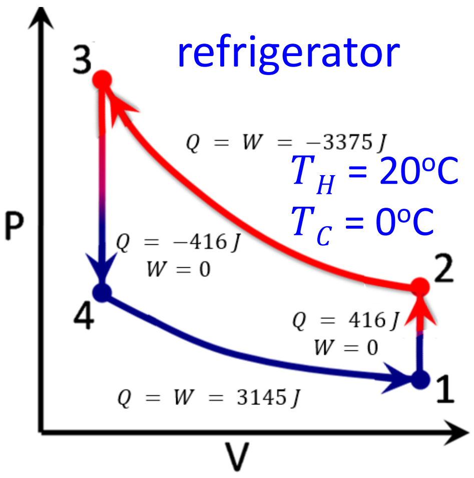
$$3\to4: \Delta S_g = nC_v \int_{T_H}^{T_C} \frac{dT}{T} = nC_v \ln\left(\frac{T_C}{T_H}\right) = -1.47\ J/K$$

$$4\to1: \Delta S_g = Q/T_C = +11.51\ J/K$$

$$1\to2: \Delta S_g = nC_v \int_{T_C}^{T_H} \frac{dT}{T} = nC_v \ln\left(\frac{T_H}{T_C}\right) = +1.47\ J/K$$

- $\Delta S_g = 0$ for complete cycle




- Net $Q$ out of cold system: 2729 J
- Net $W$ input: 230 J
- Net $Q$ into hot system: 2959 J

- Entropy changes for reservoirs

$$2\to3: \Delta S_{HR} = Q/T_H = +11.51\ J/K$$

$$3\to4: \Delta S_{CR} = Q/T_C = +1.52\ J/K$$

$$4\to1: \Delta S_{CR} = Q/T_C = -11.51\ J/K$$

$$1\to2: \Delta S_{HR} = Q/T_H = -1.42\ J/K$$

- Entropy changes for gas + reservoirs:

$\Delta S_g + \Delta S_{HR} = 0$ ←reversible

$\Delta S_g + \Delta S_{CR} = +0.05\ J/K$ ←irreversible

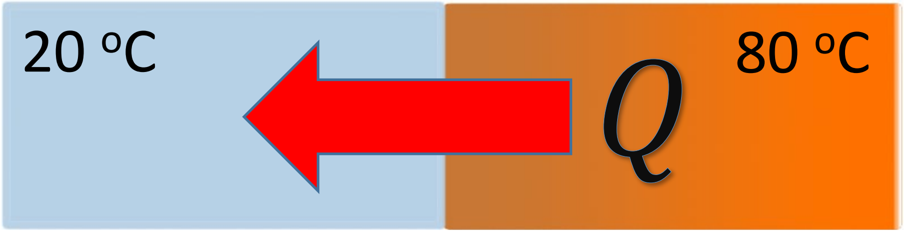
$\Delta S_g + \Delta S_{CR} = 0$ ←reversible

$\Delta S_g + \Delta S_{HR} = +0.05\ J/K$ ←irreversible

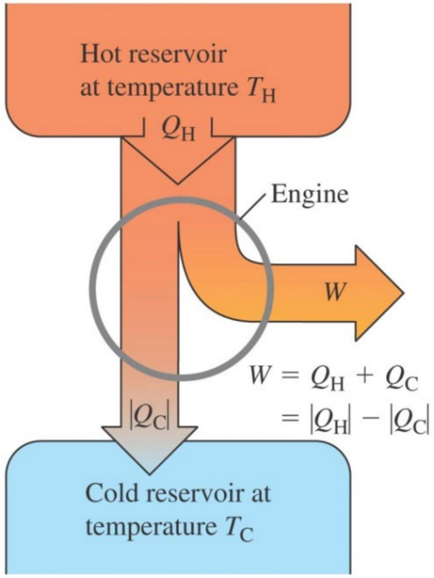
- Total entropy change of system (gas) plus environment (reservoirs) for full cycle is positive ($+0.10\ J/K$) – cycle is irreversible

# Directions of thermodynamic processes

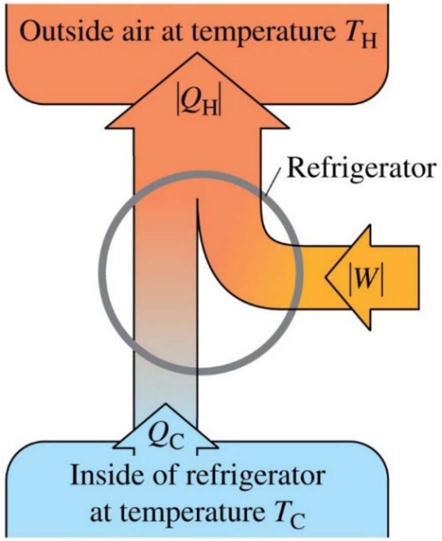
- Why does heat always flow from hot objects to colder objects?




- Why can't we make an engine that converts heat completely into work?

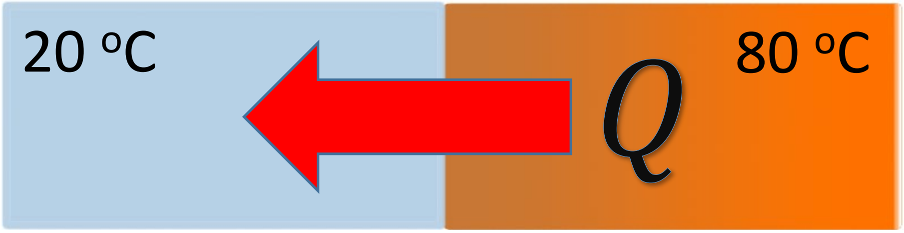



- Why can't we make a refrigerator that requires no work done?



# Directions of thermodynamic processes

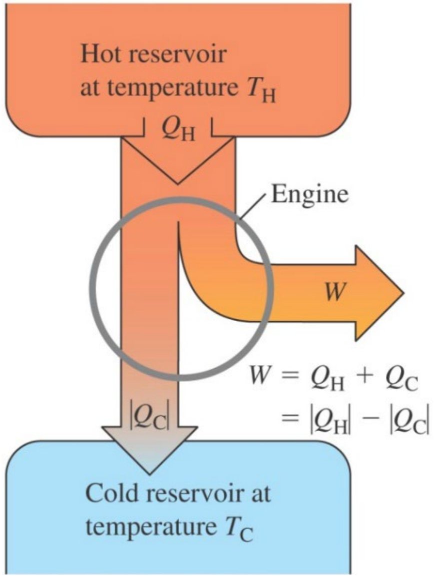
- Why does heat always flow from hot objects to colder objects?



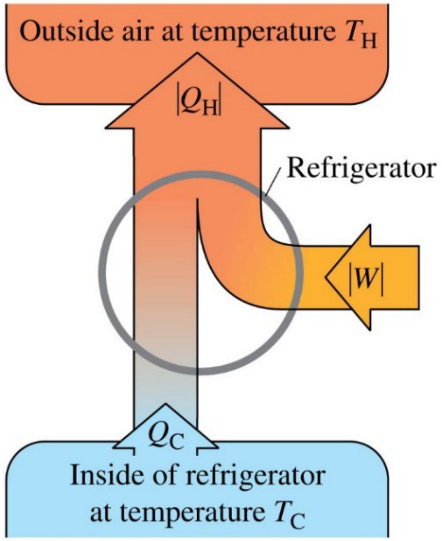

- *Much more microscopic states with evenly distributed heat => system evolves in this direction*

- Why can’t we make an engine that converts heat completely into work?

- Why can’t we make a refrigerator that requires no work done?



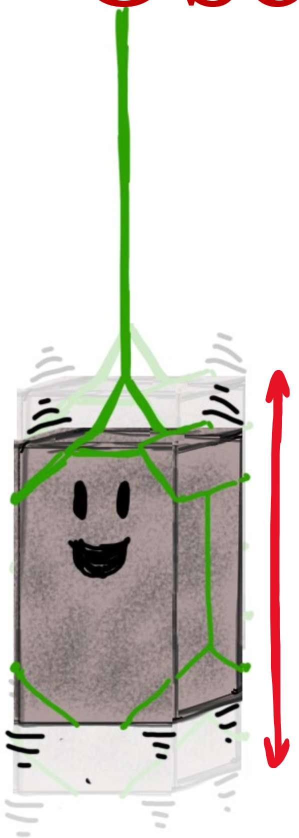

- *Work = “useful” energy, heat = random uncontrollable energy. Can convert all work to heat (easy!). Can convert some heat to work. The net entropy (system + environment) will increase as a result of this process.*



# Bonus: Entropy and the direction of time


https://www.youtube.com/watch?v=uQSoaiubuA0

# PHYSICS 157 PART II
# Oscillations & Waves

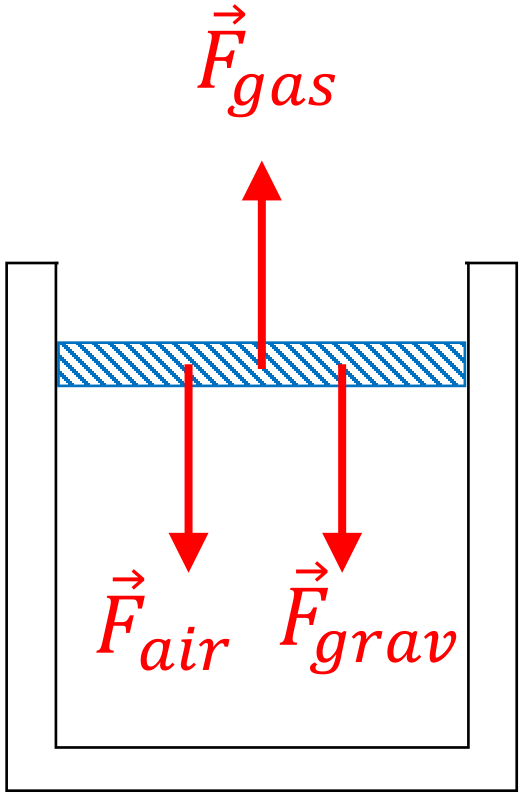


Oscillations And the Tacoma Narrows Bridge Collapse

Details: https://www.youtube.com/watch?v=mXTSnZgrfxM

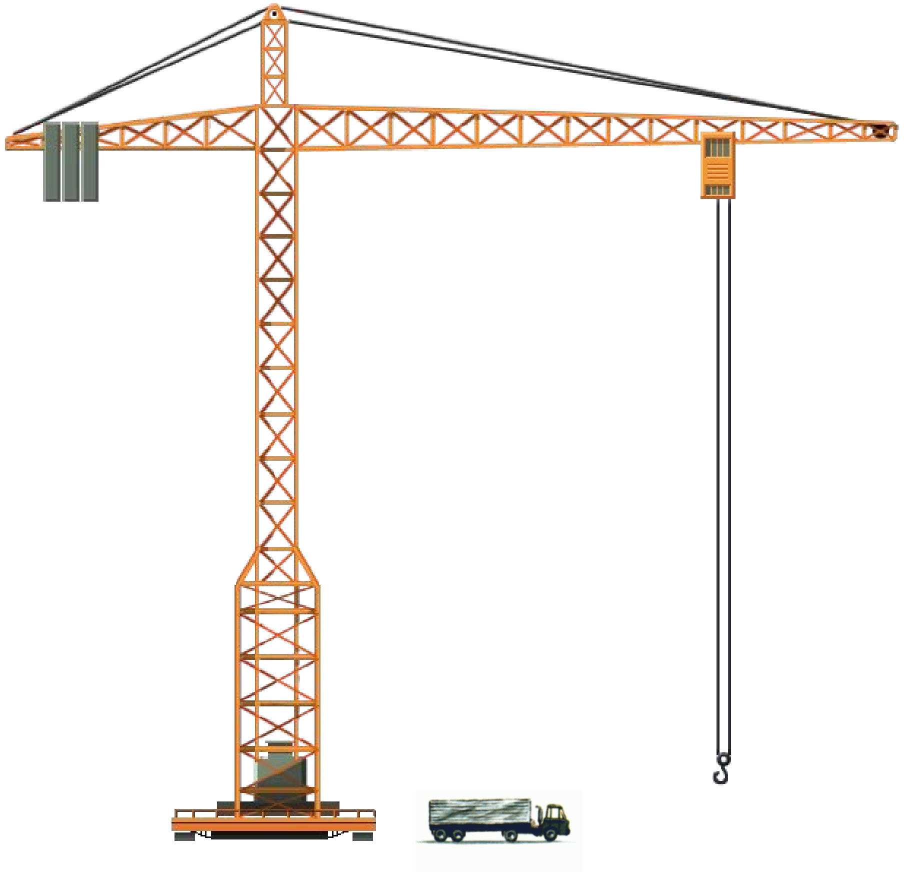
## Mechanical Equilibrium

- occurs when forces (and torques) on each part of the system add to zero




- Example: $\vec{F}_{gas} + \vec{F}_{gravity} + \vec{F}_{air} = 0$
- Piston is in equilibrium

# How do tower cranes work?



# Equilibrium! ☺

# What happens if the forces aren't balanced?

- If a displacement in one direction leads to a net force in the SAME direction, then…


# Unstable Equilibrium! ☹