SNS COLLEGE OF TECHNOLOGY

(An Autonomous Institutions)

Saravanampatti,Coimbatore-35

DEPARTMENT OF MECHANICAL ENGINEERING

ENGINEERING THERMODYNAMICS (19MET201)

Name of the faculty	: Dr.V.Karthi / Asst. Prof.
Department	: Mechanical Engineering
Academic Year	: 2023 – 2024
Batch	: 2022 Batch
Class Handled	: II- Yr/ B.E (Mechanical Engineering)
Section	: B
Unit	**: III**
Title	**: SECOND LAW**

Second Law of Thermodynamics

Outline:

- Review of The First Law of Thermodynamics
- The Second Law of Thermodynamics
- Types of Processes
- The Carnot Cycle
    - Applications
- Concept of Entropy
    - Reversible processes
    - Irreversible processes
- Combining the First and Second Laws
    - Applications
- Consequences of the Second Law
    - Entropy and Potential Temperature
    - Atmospheric Motions

First Law of Thermodynamics

Statement of Energy Balance / Conservation:

- Energy in = Energy out
- Heat in = Heat out

$$dq = c_v dT + p\,d\alpha$$

Heating
Sensible heating
Latent heating
Evaporational cooling
Radiational heating
Radiational cooling

Change in Internal Energy

Work Done
Expansion
Compression

- **Says nothing about the direction of energy transfer**
- **Says nothing about the efficiency of energy transfer**

Second Law of Thermodynamics

The **Second Law of Thermodynamics** determines whether a given process can naturally occur → Preferred direction of energy transfer
→ Fraction of heat that can be converted into work

Often called the "Supreme Law of Nature"

Application of the second law reveals that there are three types of thermodynamics processes that can occur without external forcing:

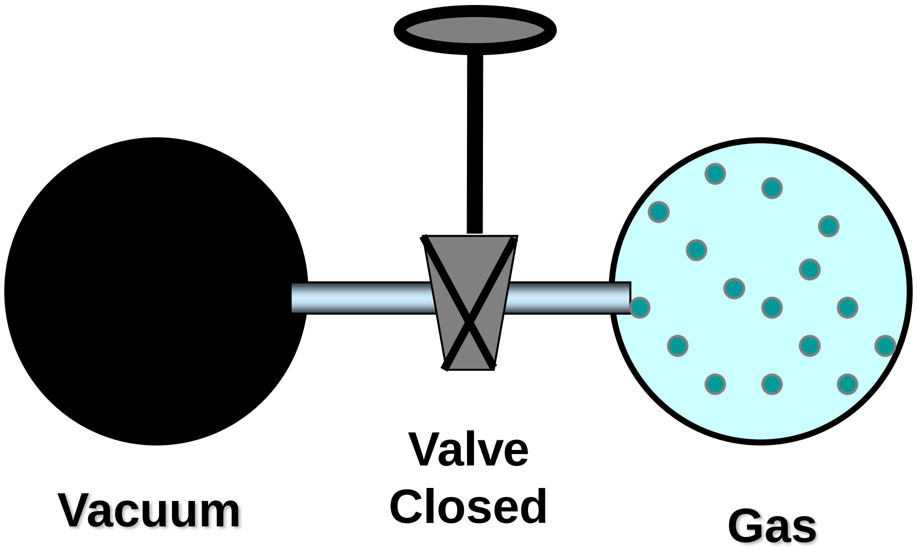
- **Natural (or Irreversible)**
- **Impossible**
- **Reversible**

Types of Processes

Irreversible (or Natural) Processes:

- Physical processes that proceeds in one direction but not the other
- Tend toward an equilibrium at their final state

Example: Free Expansion of Gas



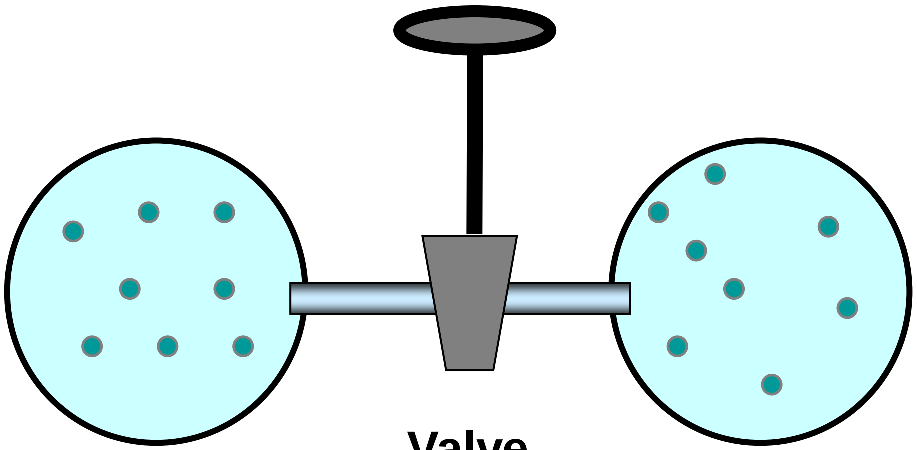
What will happen when we open the valve?

Types of Processes

Irreversible (or Natural) Processes:

- Physical processes that proceeds in one direction but not the other
- Tend toward an equilibrium at their final state

Example: Free Expansion of Gas



Initially, the gas rapidly expands to fill the vacuum

For a period of time, the air "sloshes" back and forth (or oscillates) between the two regions

Eventually, the oscillation ceases and each region contains equal amounts of the gas

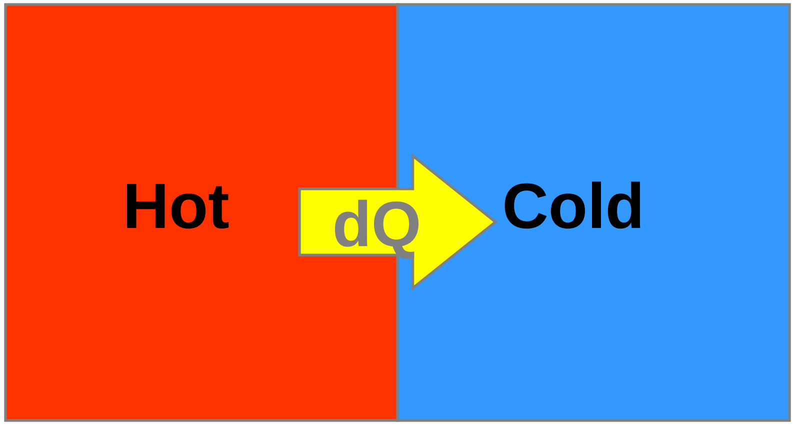
An equilibrium has been reached
The entropy increases

Types of Processes

Irreversible (or Natural) Processes:

- Physical processes that proceeds in one direction but not the other
- Tend toward an equilibrium at their final state

Example: Free Thermal Conduction



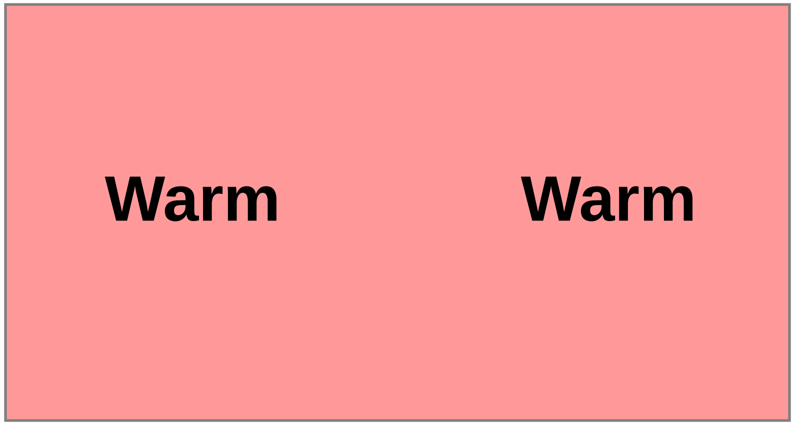
What will happen over time?

Types of Processes

Irreversible (or Natural) Processes:

- Physical processes that proceeds in one direction but not the other
- Tend toward an equilibrium at their final state

Example: Free Thermal Conduction



Heat is gradually transferred from the hot region to the cold region

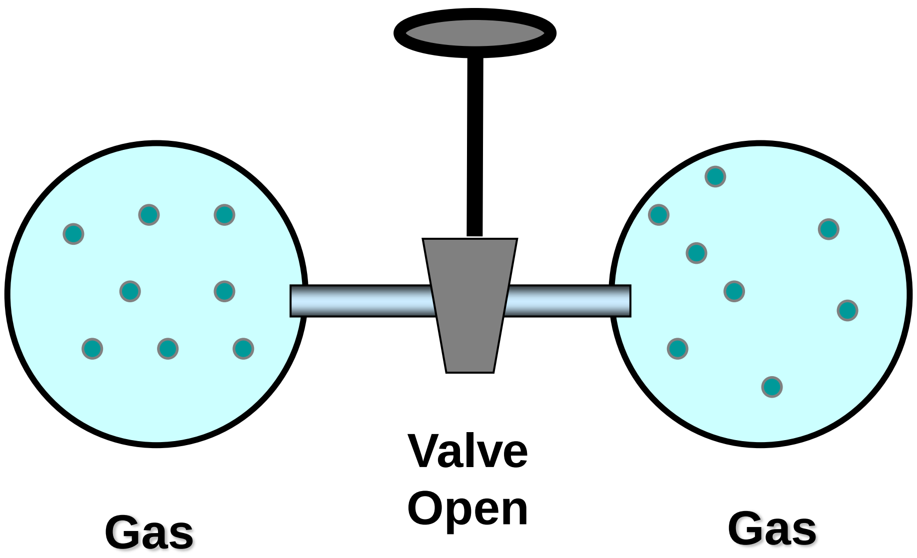
Eventually, the two regions will have the same temperature (heat transfer stops)

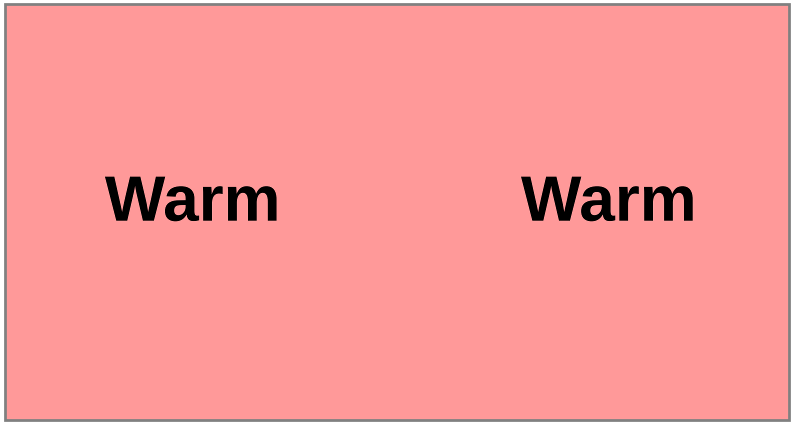
An equilibrium has been reached
The entropy increases

Types of Processes

Equilibrium:

- Physical processes that are time independent
- Properties of the system do not change with time



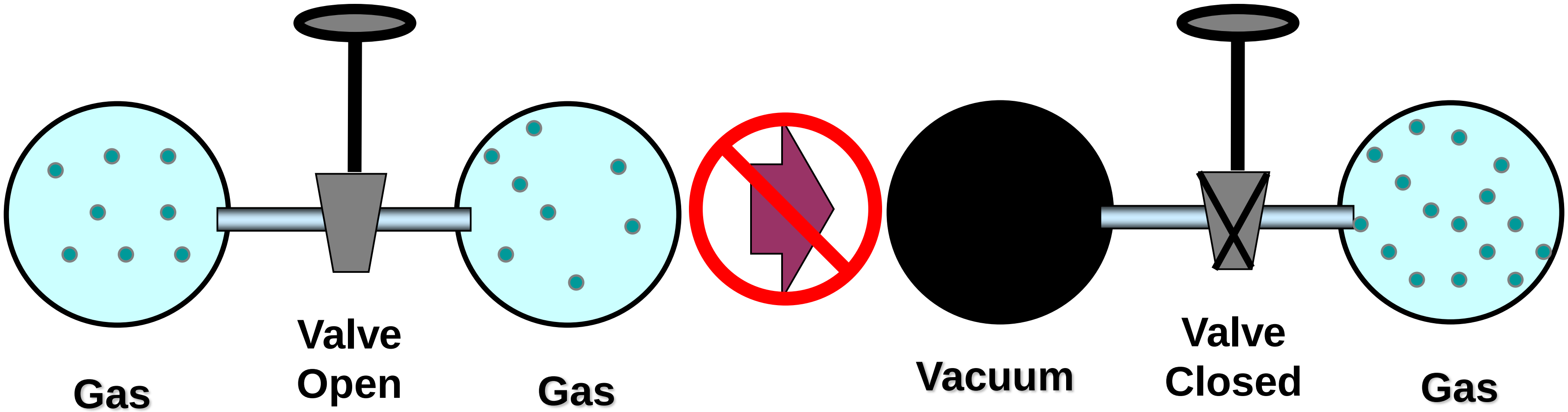


Types of Processes

Impossible Processes:

- Physical processes that do not occur naturally
- Takes a system away from equilibrium

Example: Free Compression of Gas



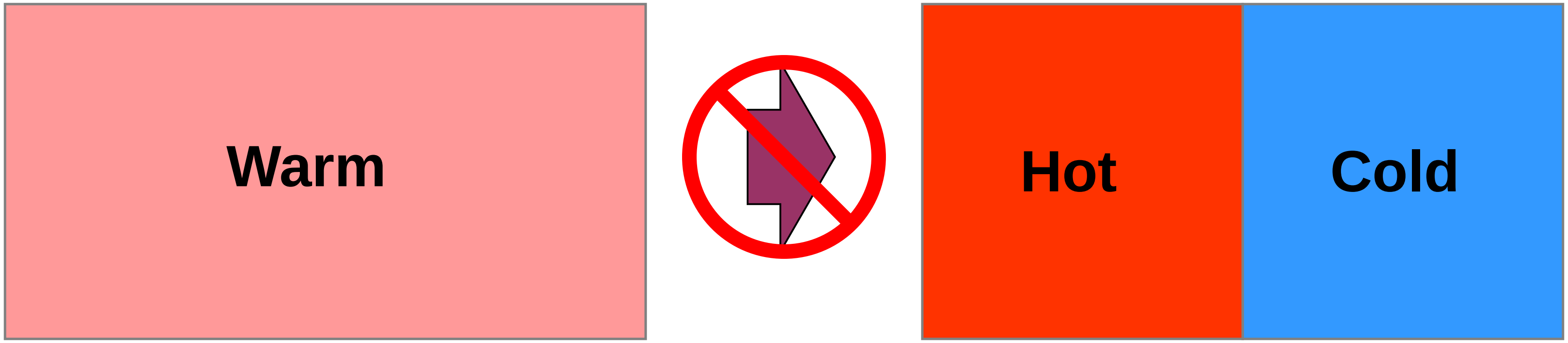
Without external forcing, the gas will never compress itself to create a vacuum

Types of Processes

Impossible Processes:

- Physical processes that do not occur naturally
- Takes a system away from equilibrium

Example: Free Thermal Conduction



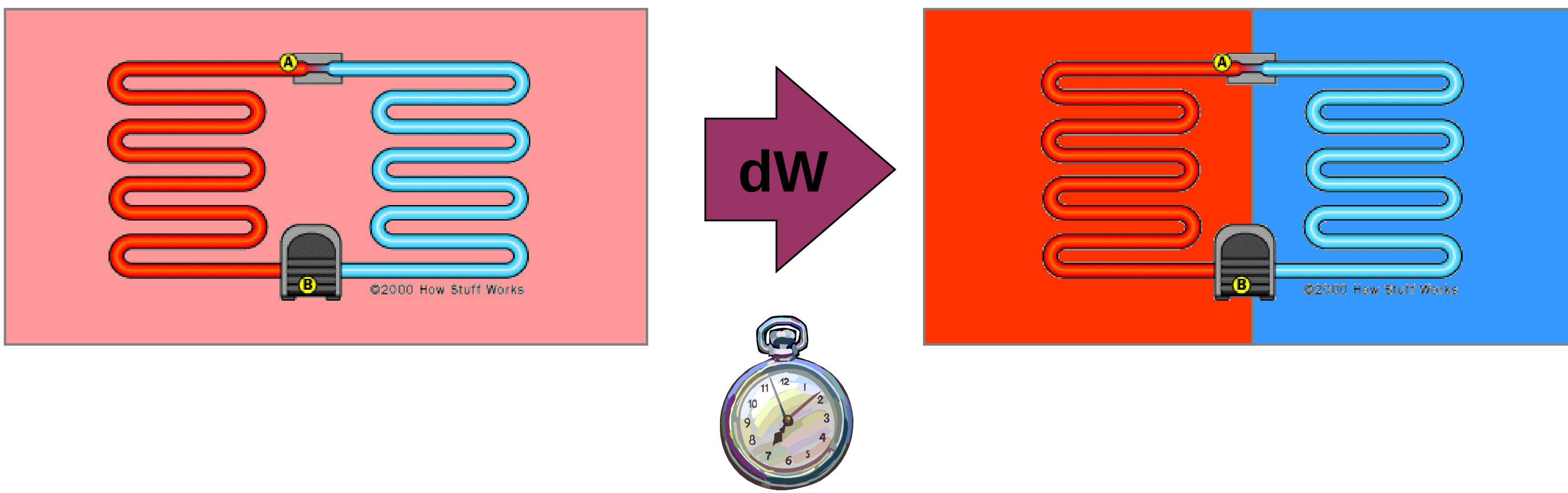
Without external forcing, the heat will not separate itself into a hot region and a cold region

Types of Processes

Impossible Processes:

- Physical processes that do not occur naturally
- Can only occur with an input of work from the environment

Example: Forced Thermal Conduction



Types of Processes

Reversible Processes:

- Reversal in direction returns the system and the environment to its original state
- A conceptual process
- Idealized version of how things should be
- No process is truly reversible

Conditions that allow processes to be almost reversible

- Process occurs at a very slow rate
- Each intermediate state of the system is an equilibrium state
- State variables are at equilibrium

Types of Processes

Distinction between Reversible and Irreversible Processes:

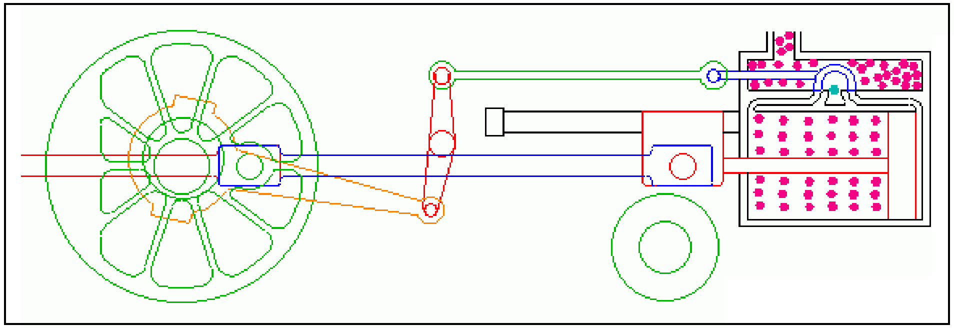
Reversible: One can reverse the process and both the system and the environment will return to its original states

Irreversible: One can reverse the process and return the system to its original state, but the environment will have suffered a permanent change from its original state.

Carnot Cycle

Nicolas Leonard Sadi Carnot:

- French engineer and physicist
- Worked on early engines
- Tried to improve their efficiency
- Studied idealized heat engines, cyclic processes, and reversible processes
- Wrote his now famous paper, "A Reflection on the Motive Power of Fire" in 1824
- Introduced the "Carnot Cycle" for an idealized, cyclic and reversible process



http://en.wikipedia.org/wiki/Nicolas_L%C3%A9onard_Sadi_Carnot

Carnot Cycle

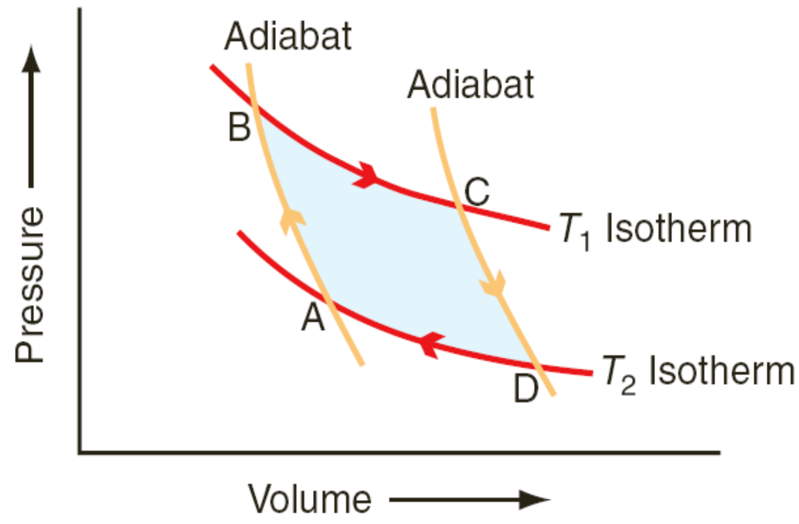
Basic Concepts:

Cyclic process:

- A series of transformations by which the state of a system undergoes changes but the system is eventually returned to its original state
- Changes in volume during the process may result in external work
- The **net** heat absorbed by the system during the cyclic process is equivalent to the **total** external work done

Reversible process:

- Each transformation in the cyclic process achieves an equilibrium state



Transformations along A-B-C-D-A represents a cyclic process

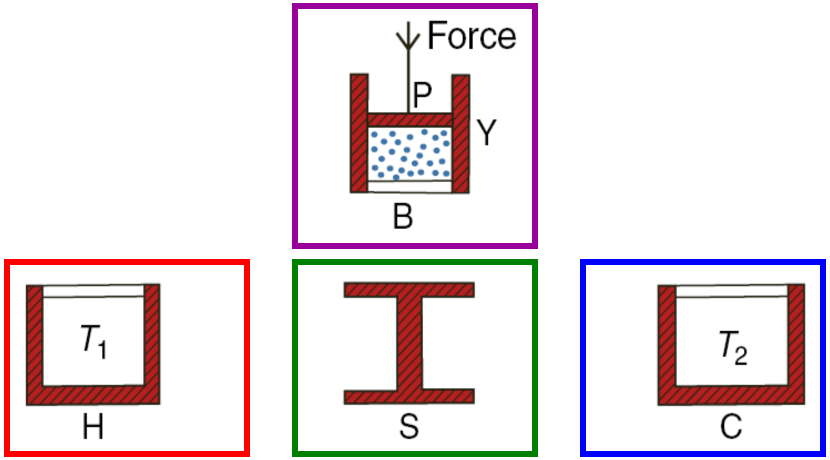
The entire process is reversible since equilibirum is achieved for each state (A, B, C, and D)

Carnot Cycle

Carnot's Idealized Heat Engine:

<u>The Components</u>

- A "working substance" (blue dots) is in a **cylinder (Y)** with insulated walls and a conducting base (B) fitted with an insulated, frictionless piston (P) to which a variable force can be applied
- A **non-conducting stand (S)** upon which the cylinder may be placed to insulate the conducting base
- An infinite **warm reservoir of heat (H)** at constant temperature T_1
- An infinite **cold reservoir for heat (C)** at constant temperature T_2 (where $T_1 > T_2$)



Carnot Cycle

Carnot's Idealized Heat Engine:

The Four Processes:

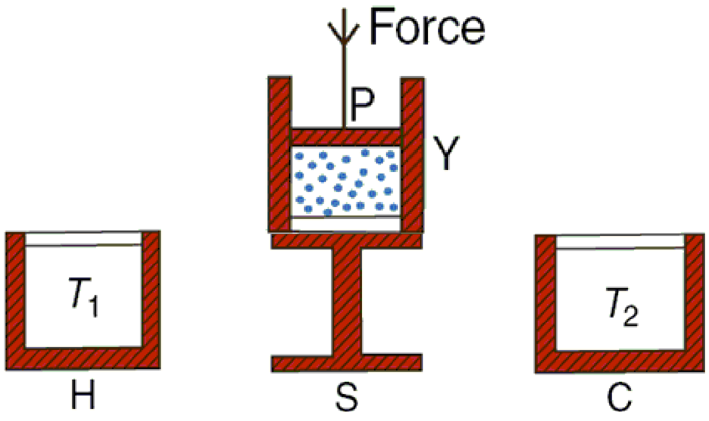
(1) Adiabatic Compression

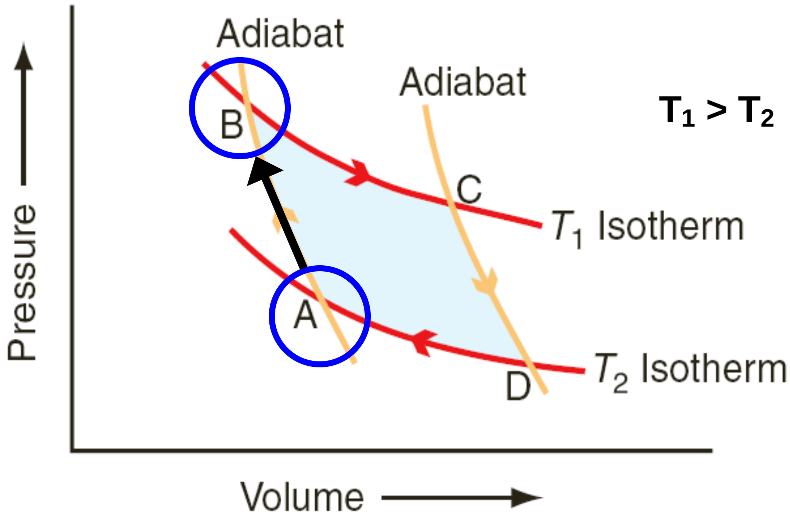
The substance begins at location A with a temperature of T_2

The cylinder is placed on the stand and the substance is compressed by increasing the downward force on the piston

Since the cylinder is insulated, no heat can enter or leave the substance contained inside

Thus, the substance undergoes adiabatic compression and its temperature increases to T_1 (location B)



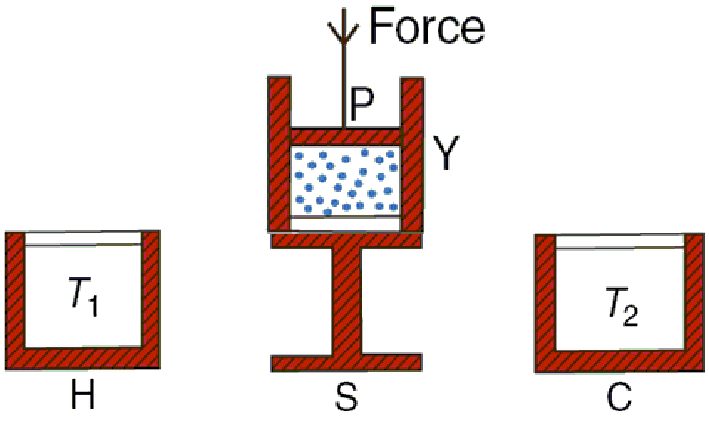


Carnot Cycle

Carnot's Idealized Heat Engine:

<u>The Four Processes</u>:

(1) Adiabatic Compression



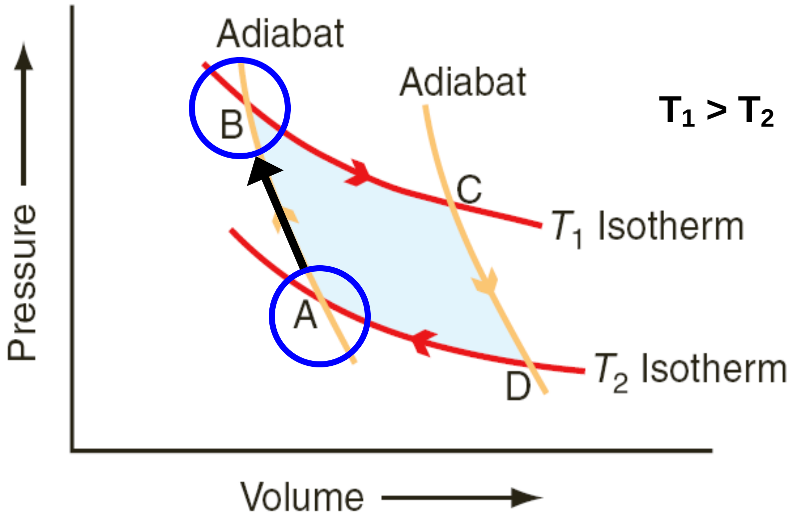
$$Q = \Delta U + W$$

$$Q_{AB} = 0$$

$$\Delta U_{AB} = c_v(T_1 - T_2)$$

$$W_{AB} = -\Delta U_{AB}$$

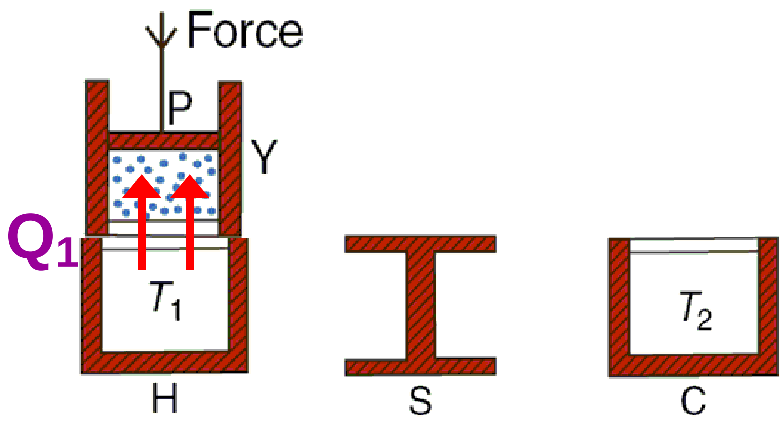
$$W_{AB} = -c_v(T_1 - T_2)$$



$T_1 > T_2$

Carnot Cycle

Carnot's Idealized Heat Engine:



The Four Processes:

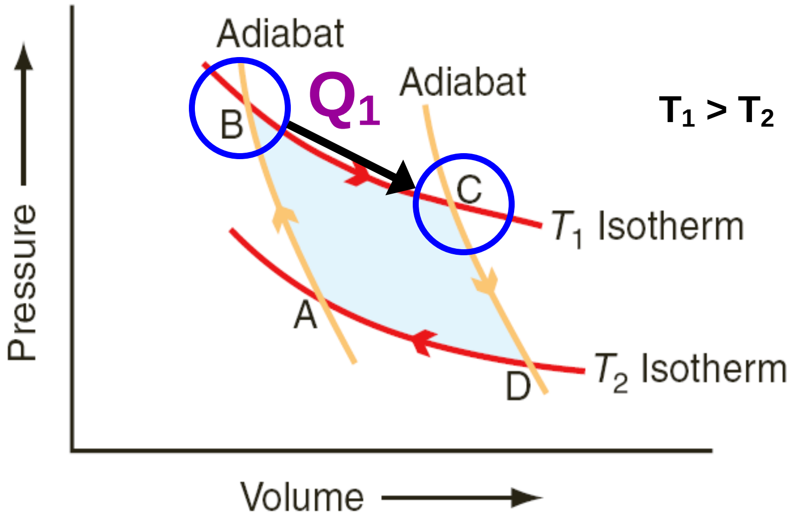
(2) Isothermal Expansion

The cylinder is now placed on the warm reservoir

A quantity of heat Q_1 is extracted from the warm reservoir and thus absorbed by the substance

During this process the substance expands isothermally at T_1 to location C

During this process the substance does work by expanding against the force applied to the piston.



Carnot Cycle

Carnot's Idealized Heat Engine:

<u>The Four Processes</u>:

(2) Isothermal Expansion

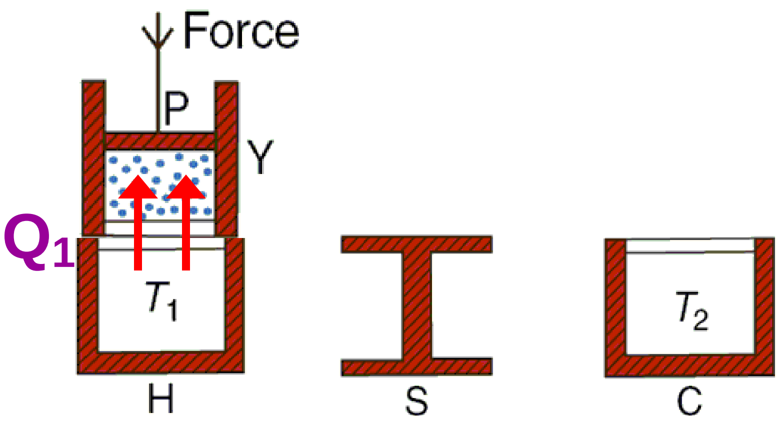
$$Q = \Delta U + W$$

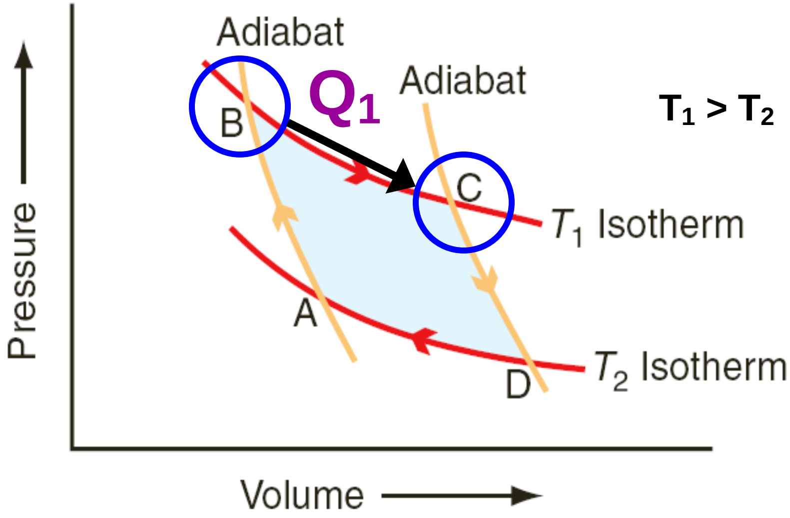
$$\Delta T = 0 \qquad Q_{BC} = Q_1$$

$$\Delta U_{BC} = 0$$

$$W_{BC} = Q_{BC}$$

$$W_{BC} = R_d T_1 \ln\left(\frac{V_C}{V_B}\right)$$





Carnot Cycle

Carnot's Idealized Heat Engine:

The Four Processes:

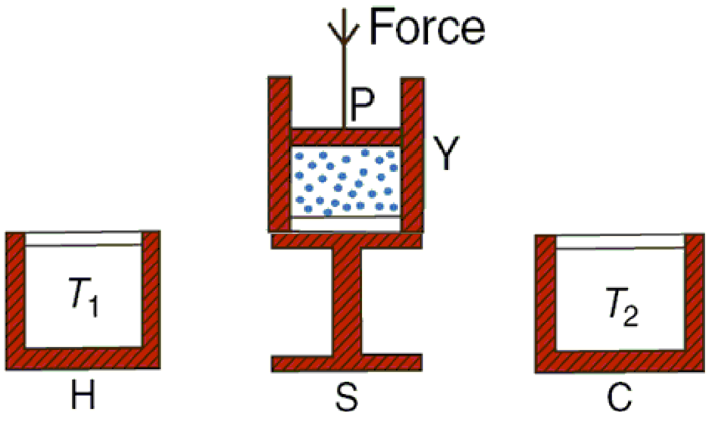
(3) Adiabatic Expansion

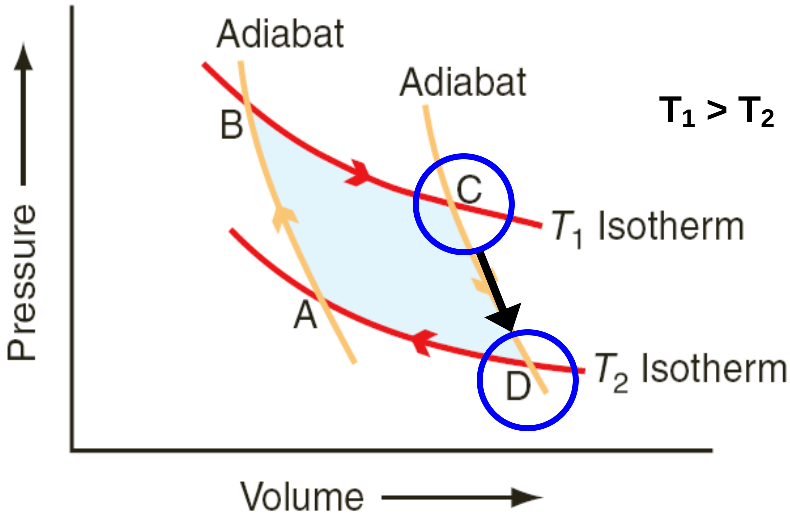
The cylinder is returned to the stand

Since the cylinder is now insulated, no heat can enter or leave the substance contained inside

Thus, the cylinder undergoes adiabatic expansion until its temperature returns to T_2 (location D)

Again, the cylinder does work against the force applied to the piston





Carnot Cycle

Carnot's Idealized Heat Engine:

The Four Processes:

(3) Adiabatic Expansion

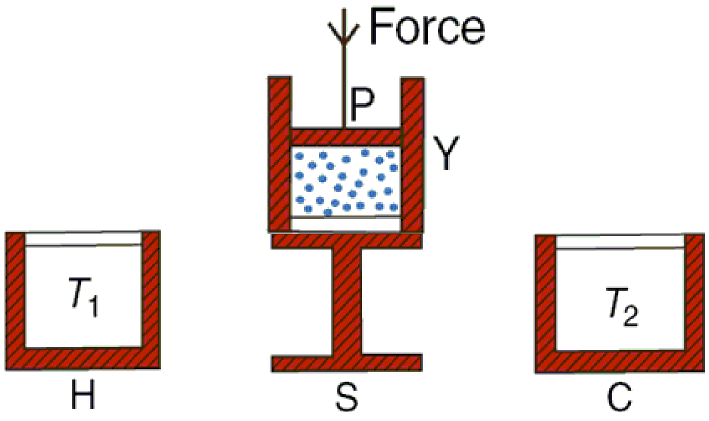
$$Q = \Delta U + W$$

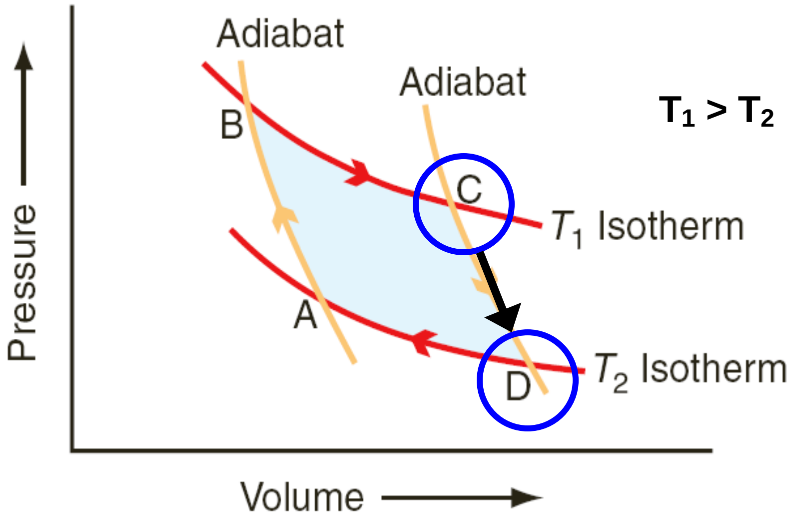
$$Q_{CD} = 0$$

$$\Delta U_{CD} = c_v(T_2 - T_1)$$

$$W_{CD} = -\Delta U_{CD}$$

$$W_{CD} = -c_v(T_2 - T_1)$$





$T_1 > T_2$

Carnot Cycle

Carnot's Idealized Heat Engine:

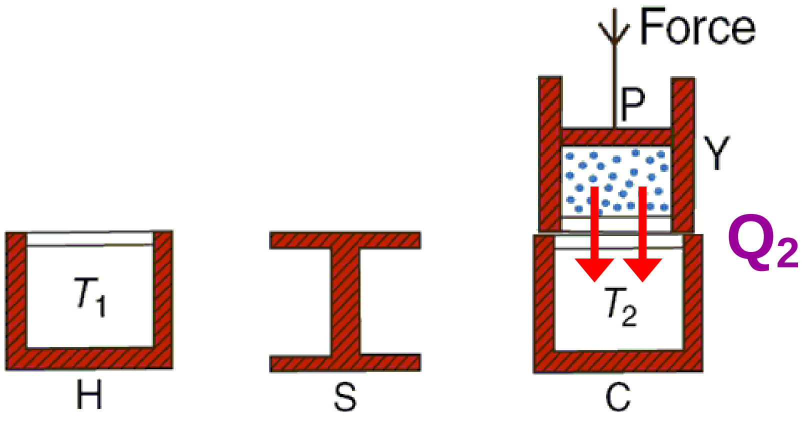
The Four Processes:

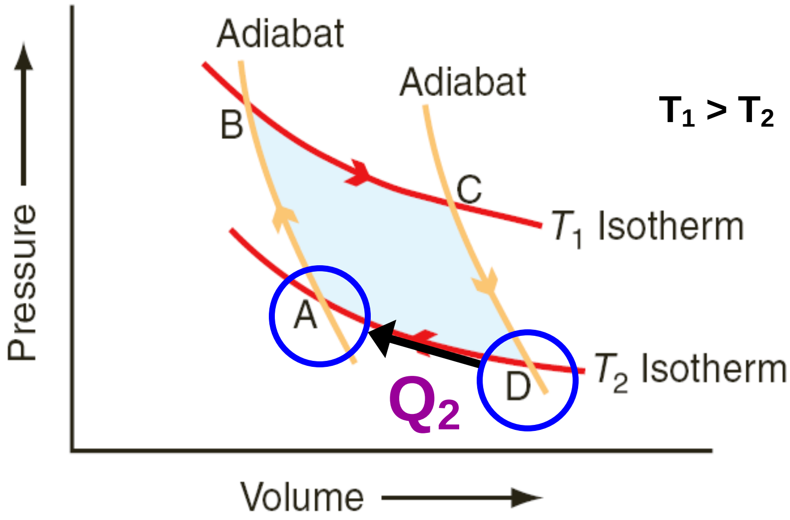
(4) Isothermal Compression

The cylinder is now placed on the cold reservoir

A force is applied to the piston and the substance undergoes isothermal compression to its original state (location A)

During this process the substance gives up the resulting compression heating Q_2 to the cold reservoir, allowing the process to occur isothermally





Carnot Cycle

Carnot's Idealized Heat Engine:

The Four Processes:

(4) Isothermal Compression

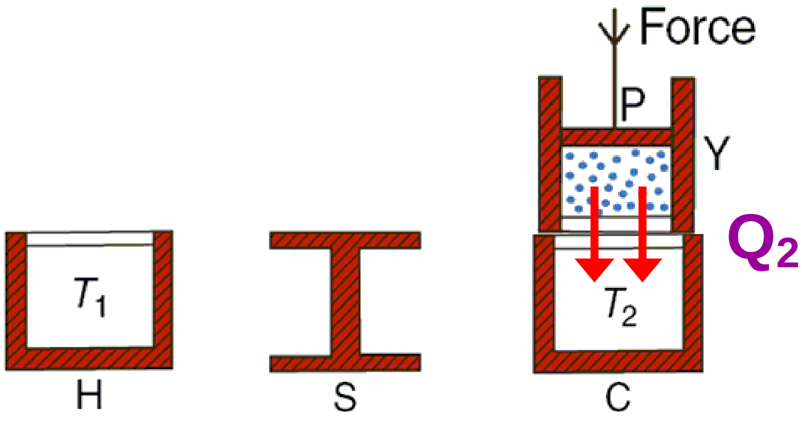
$$Q = \Delta U + W$$

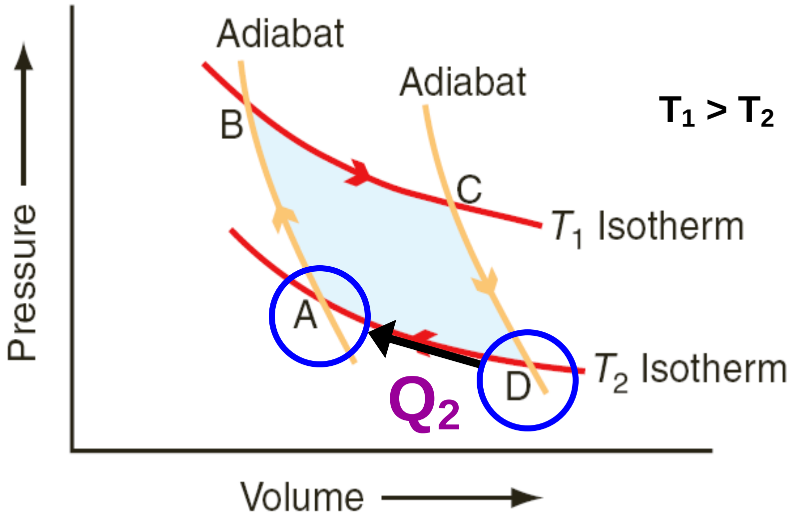
$$\Delta T = 0 \qquad Q_{DA} = Q_2$$

$$\Delta U_{DA} = 0$$

$$W_{DA} = Q_{DA}$$

$$W_{DA} = R_d T_2 \ln\left(\frac{V_A}{V_D}\right)$$





Carnot Cycle

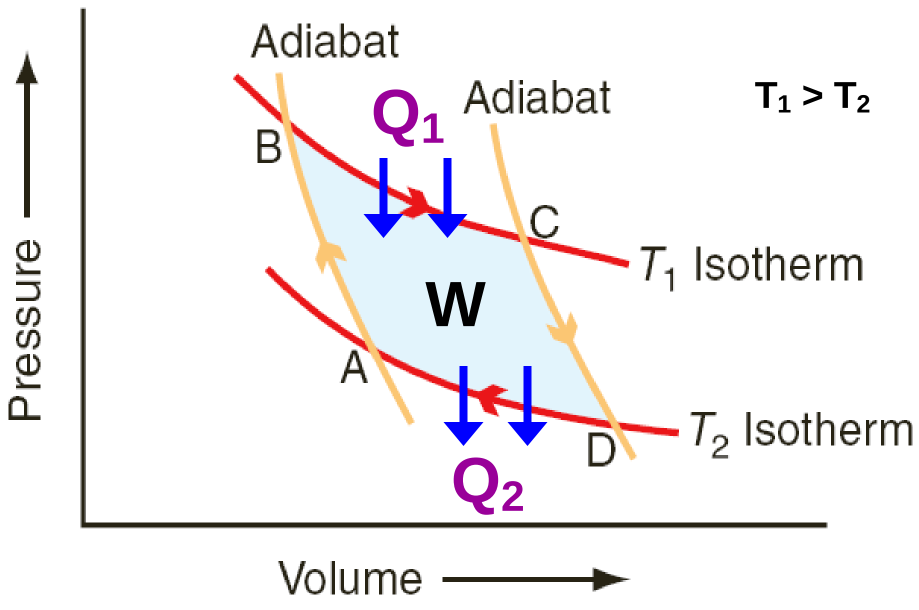
Carnot's Idealized Heat Engine:

Net Effect:

The **net** work done by the substance during the cyclic process is equal to the area enclosed within ABCDA

Since the process is cyclic, the **net** work done is also equal to Q_1+Q_2

The work is performed by transferring a fraction of the total heat absorbed from the warm reservoir to the cold reservoir



$$W_{NET} = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$

$$W_{NET} = Q_1 + Q_2$$

where: $Q_1 > 0$ and $Q_2 < 0$

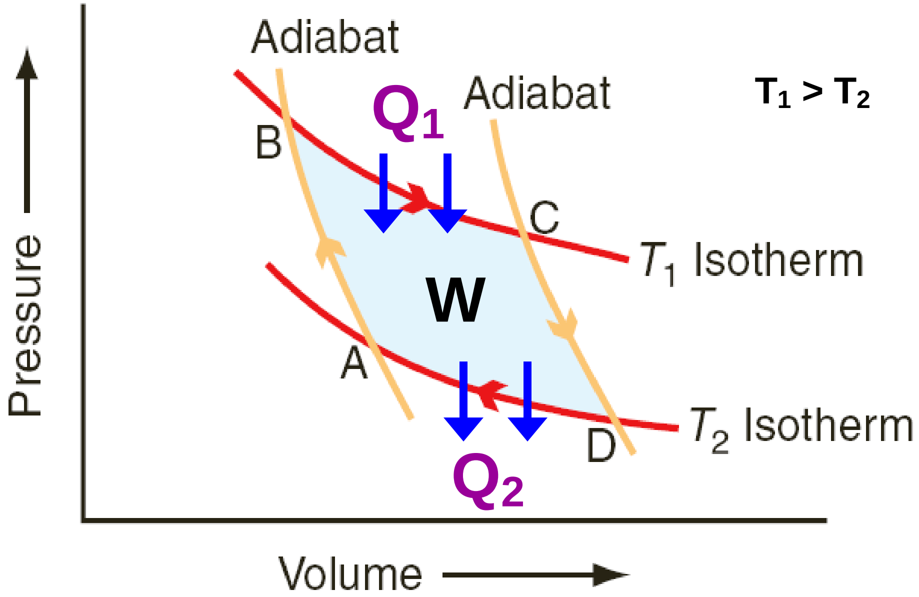
Carnot Cycle

Carnot's Idealized Heat Engine:

Efficiency:

We can define the efficiency of the heat engine (η) as the ratio between the net work done (W_{NET}) and the total heat absorbed (Q_1), or:

$$\eta = \frac{W_{NET}}{Q_1} = \frac{Q_1 + Q_2}{Q_1}$$



By considering the relations valid during each process, it can be shown that:

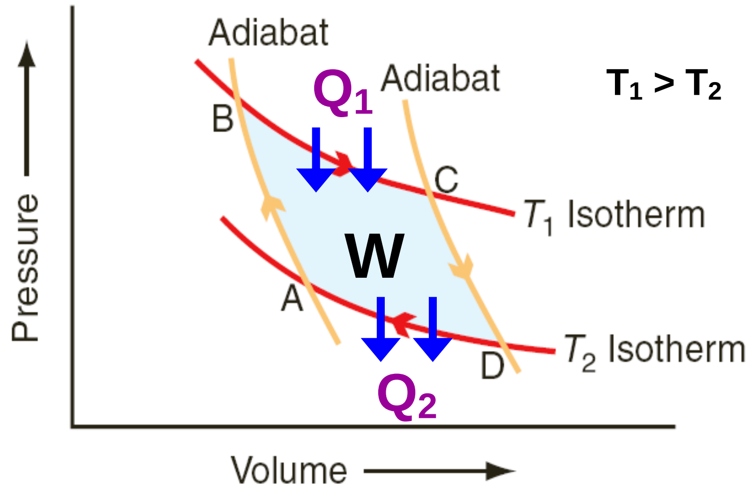
$$\eta = 1 - \frac{T_2}{T_1}$$

Carnot Cycle

Carnot's Idealized Heat Engine:

Important Lesson:

- It is impossible to construct a cyclic engine that transforms heat into work without surrendering some heat to a reservoir at a lower temperature



Examples of Carnot Cycles in Practice

- Steam Engine → has a radiator
- Power Plant → has cooling towers

Examples of Carnot Cycles in Nature

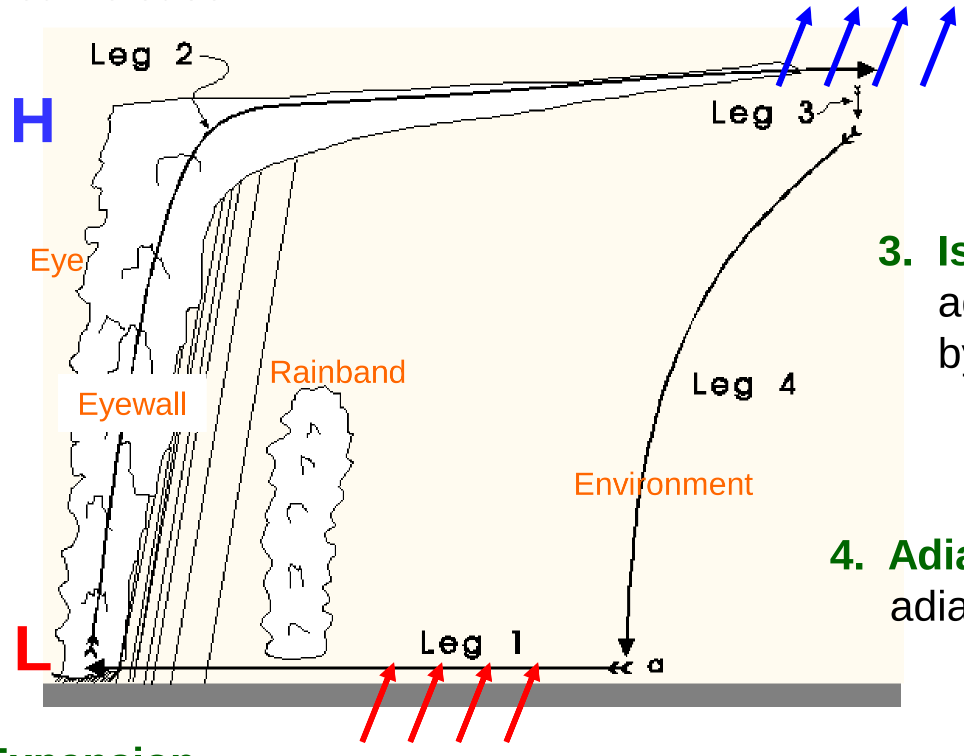
- Hadley Cell (??)
- Hurricane (??)**
- Thunderstorm (??)

Carnot Cycle

Example: A Hurricane

2. **Adiabatic Expansion**
   cooling partially offset
   by latent heat release

Heat Release (Q_2)
(Radiational Cooling)



3. **Isothermal Compression**
   adiabatic warming offset
   by radiational cooling

4. **Adiabatic Compression**
   adiabatic warming

1. **Isothermal Expansion**
   adiabatic cooling offset
   by surface fluxes

Heat Absorbed (Q_1)
(Surface fluxes)
(from warm ocean)

Carnot Cycle

Example: A Hurricane

The National Hurricane Center closely monitors all hurricanes with a wide range of sensors, including buoys and satellites. On 27 August 2005, as Hurricane Katrina was approaching New Orleans, a buoy beneath the storm recorded a sea surface temperature of 29ºC. At the same time a satellite measured cloud top temperatures of -74ºC. Assuming Katrina was behaving like a Carnot cycle, how efficient was Katrina as a heat engine?

Warm reservoir → Ocean
Cold reservoir → Upper atmosphere

$$\eta = 1 - \frac{T_2}{T_1}$$

T_1 = 29ºC = 302 K
T_2 = -74ºC = 199 K

η = 0.34

Carnot Cycle

Example: A Thunderstorm

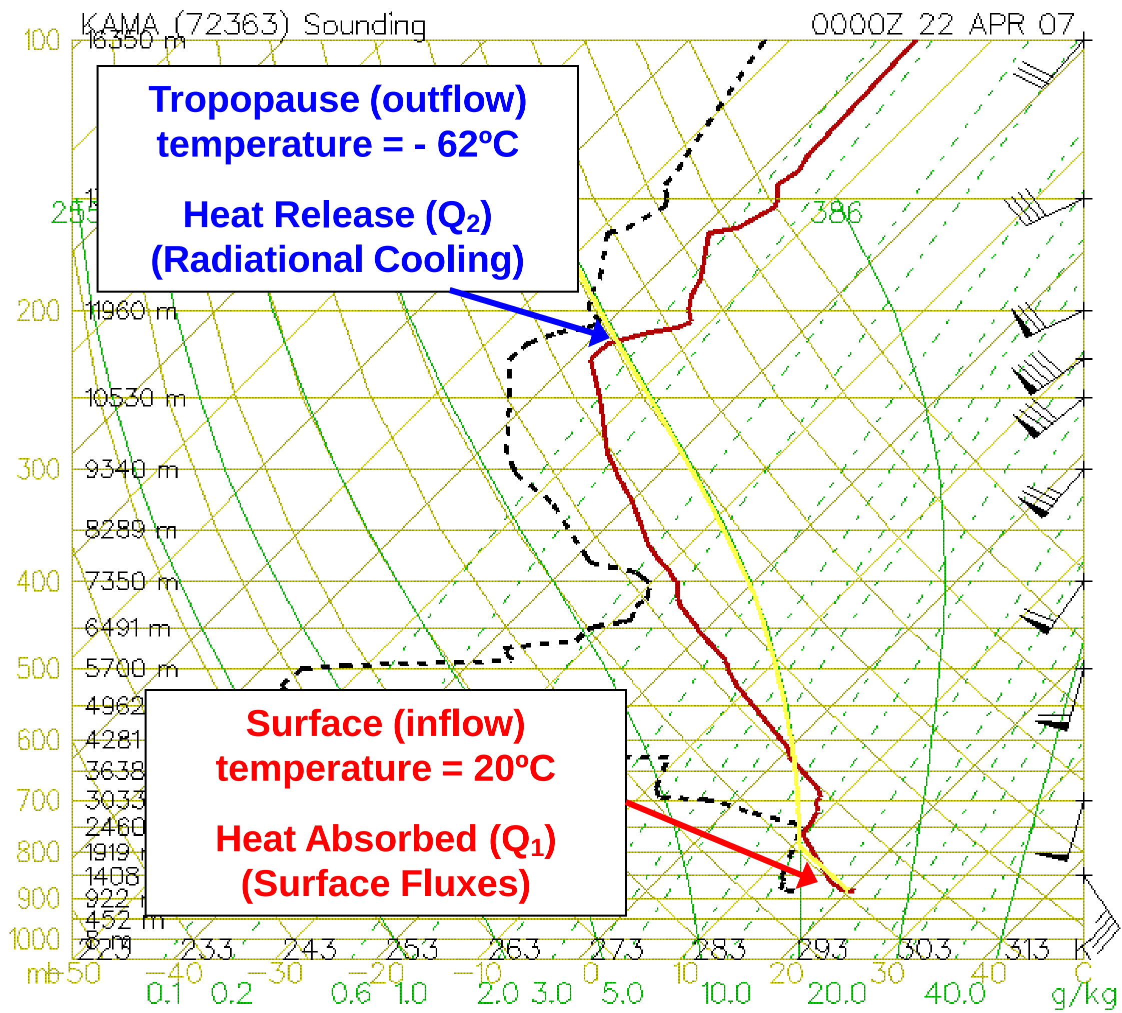
How efficient are typical thunderstorms assuming they behave like a Carnot cycle?

$$\eta = 1 - \frac{T_2}{T_1}$$

This sounding was very near some strong thunderstorms

T_1 = 20ºC = 293 K
T_2 = -62ºC = 211 K

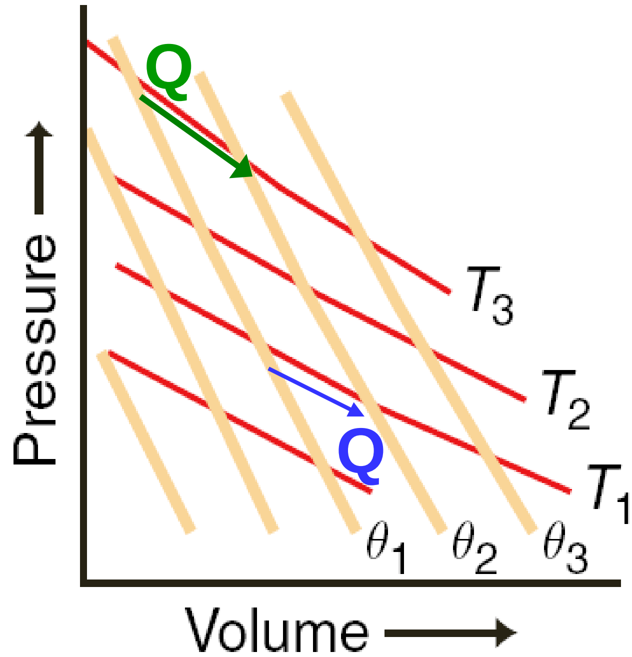
η = 0.28



The Concept of Entropy

Basic Idea and Definition:

- In passing <u>reversibly</u> from one adiabat to another ($\theta_1 \rightarrow \theta_2$) along an isotherm, heat is either absorbed or released
- The amount of heat (*Q*) depends on the temperature (*T*) of the isotherm
- The ratio *Q*/*T* is the same no matter which isotherm is chosen in passing from one adiabat to another.
- Therefore, the ratio *Q*/*T* is a measure of the difference between the two adiabats
- This difference is called **entropy (S).**



Note: θ_1, θ_2, θ_3 are **isentropes** or lines of constant entropy

They are also lines of constant potential temperature (i.e. dry adiabats)

The Concept of Entropy

Basic Idea and Definition:

- Entropy (S) is a thermodynamic state function (describes the state of system like p, T, and V) and is independent of path

$$dS = \frac{dQ_{rev}}{T} \qquad ds = \frac{dq_{rev}}{T}$$

- mass dependent (S) → units: $J\ K^{-1}$
- mass independent (s) → units: $J\ kg^{-1}\ K^{-1}$

Note: Again, entropy is defined only for reversible processes…

Recall:

- Reversible processes are an idealized concept
- Reversible processes do not occur in nature

The Concept of Entropy

Irreversible Processes:

- There is **no** simple definition for the entropy of an irreversible process between a system and its environment

- We do know that the entropy of the universe is always increasing due to irreversible transformations

$$\Delta S_{universe} = \Delta S_{system} + \Delta S_{environment}$$

$$\Delta S_{universe} = 0$$ **Reversible (equilibrium) transformations**

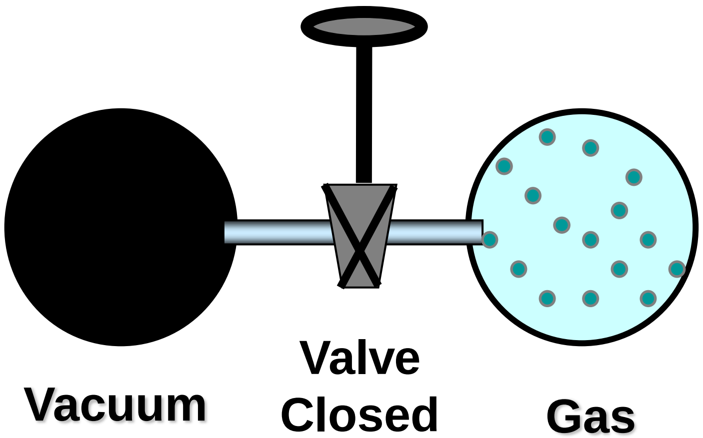
$$\Delta S_{universe} > 0$$ **Irreversible (natural) transformations**

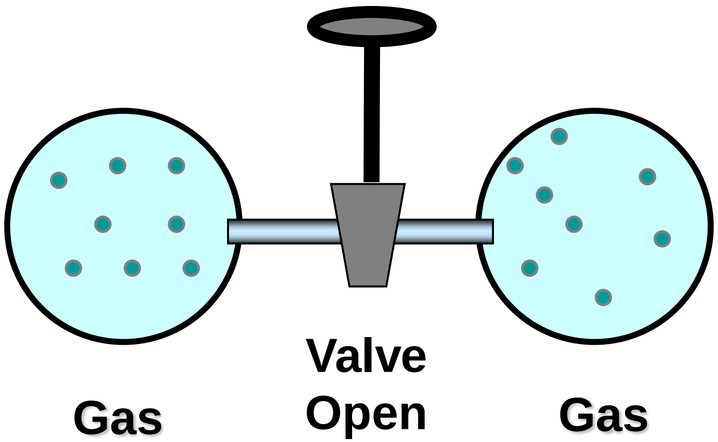
$$dS \geq \frac{dQ_{rev}}{T}$$

The Concept of Entropy

Irreversible Processes:

- Entropy (S) is a measure of the microscopic disorder of a system





Molecules compressed to part of total area

Lots of "Order"
Low Entropy

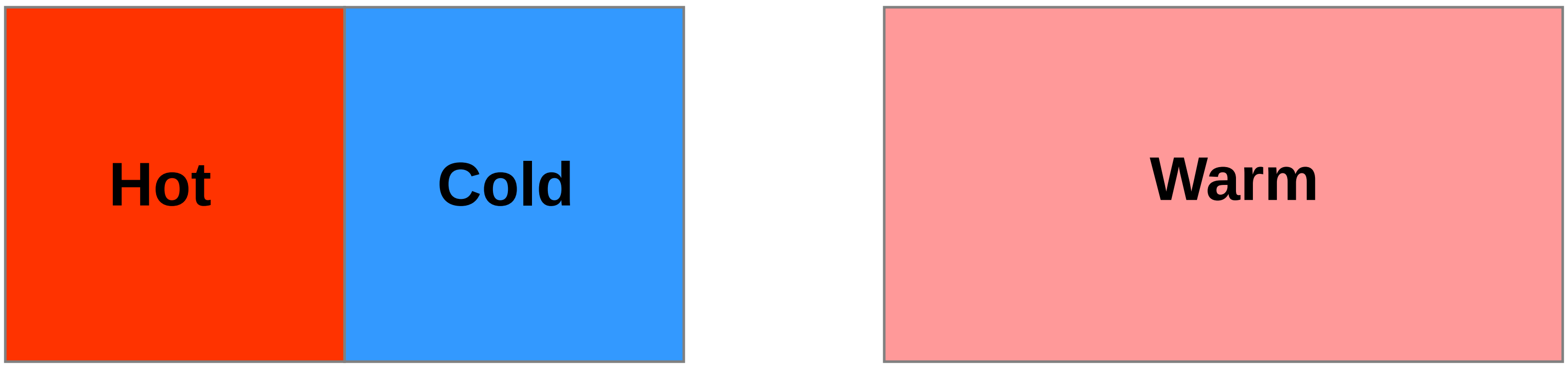
Molecules expand to fill total area

Lots of "Disorder"
Maximum Entropy

The Concept of Entropy

Irreversible Processes:

- Entropy (S) is a measure of energy that is no longer available to do work



Free Thermal Conduction Possible

Lots of Available Energy to do Work
Low Entropy

No Thermal Conduction Possible

No Available Energy to do work
Maximum Entropy

Combining the First and Second Laws

First Law of Thermodynamics

$$dQ = c_v dT + p dV$$

Second Law of Thermodynamics

$$dS \geq \frac{dQ_{rev}}{T}$$

$$TdS \geq c_v dT + p dV$$

There are many other forms since the First Law takes many forms

$$TdS \geq c_p dT - Vdp$$

$$TdS \geq dU + dW$$

$$TdS \geq dH - dW$$

Combining the First and Second Laws

Special Processes:

$$TdS \geq c_v dT + pdV$$

Isothermal transformations

- Constant temperature
- Any irreversible (natural) work increases the entropy of a system

$$\Delta S \geq \frac{W}{T}$$

Adiabatic transformations

- No exchange of heat with the environment
- Entropy is constant

$$\Delta S = 0$$

Isentropic transformations

- Constant entropy
- Adiabatic and isentropic transformations are the exact same thing
- This is why “isentropes” and “dry adiabats” are the same on thermodynamic diagrams

$$\Delta S = 0$$

Combining the First and Second Laws

Special Processes:

$$TdS \geq c_v dT + pdV$$

Isochoric transformations

- Constant volume
- No work is done
- Entropy changes are a function of the initial and final temperatures

$$\Delta S \geq c_v \ln \frac{T_f}{T_i}$$

Isobaric transformations

$$TdS \geq c_p dT - Vdp$$

- Constant pressure
- Entropy changes are a function of the initial and final temperatures

$$\Delta S \geq c_p \ln \frac{T_f}{T_i}$$

Combining the First and Second Laws

Example: Air parcels rising through a cloud

- Most air parcels moving through the atmosphere experience an increase in entropy due to irreversible processes (condensation, radiational cooling, etc.)

- Assume an air parcel rising through a thunderstorm from 800 mb to 700 mb while its temperature remains constant. Calculate the change in entropy of the rising parcel.

p_1 = 800 mb
p_2 = 700 mb
$dT = 0$ (constant T)

$$TdS \geq c_p dT - Vdp$$

After some simplifications, using ideal gas law, and integrating from p_1 to p_2

$$\Delta S \geq -R_d \ln\left(\frac{p_2}{p_1}\right)$$

R_d = 287 J/kgK

ΔS = 38.3 J/kg K

Consequences of the Second Law

Entropy and Potential Temperature:

- Recall the definition of potential temperature:
  - Valid for adiabatic processes

$$\theta = T\left(\frac{p_0}{p}\right)^{R_d/c_p}$$

- By combining the first and second laws with potential temperature, it can easily be shown (see you text) that:

$$dS = c_p d\ln\theta$$

or:

$$\Delta S = c_p \ln\left(\frac{\theta_2}{\theta_1}\right)$$

- Therefore, **any reversible adiabatic process is also isentropic**

Consequences of the Second Law

Atmospheric Motions:

Recall:

- Reversible transformations do not occur naturally
- However, very slow transformations are almost reversible if a parcel is allowed to continually reach equilibrium with its environment at each successive "step" along it path.
- In the atmosphere, **vertical motions** are primarily responsible for **heat transfer** between the surface (a warm reservoir) and the top of the atmosphere, or outer space (a cold reservoir)

Therefore:

Synoptic vertical motions	Very slow (~0.01 m/s) Occur over large scale High and Low pressure systems	Minimal (or no) net heat transfer
Convective vertical motions	Very fast (~1-50 m/s) Occur over small scales Thunderstorms	Large heat transfer

References

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