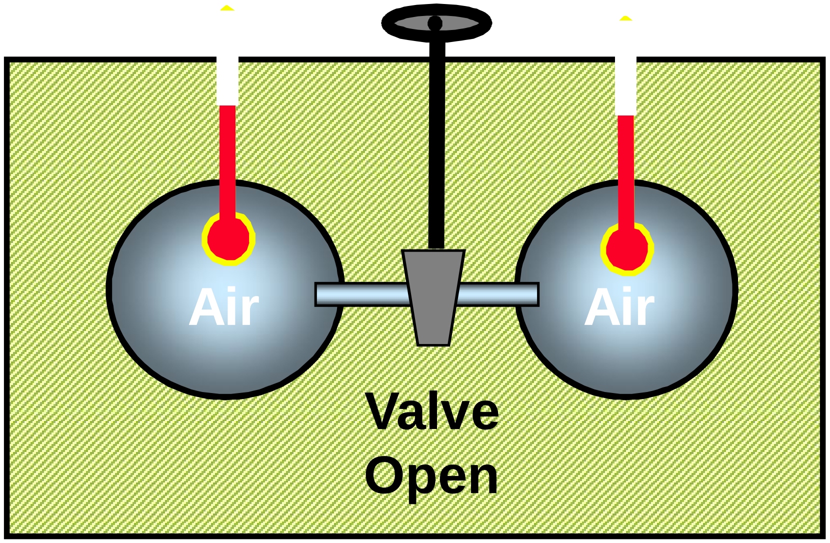
First Law of Thermodynamics



What energy transformations occur as air parcels move around within thunderstorms?

First Law of Thermodynamics

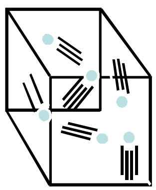
Outline:

- Forms of Energy
- Energy Conservation
- Concept of Work
- PV Diagrams
- Concept of Internal Energy
- Joules Law
- Thermal Capacities (Specific Heats)
- Concept of Enthalpy
- Various Forms of the First Law
- Types of Processes

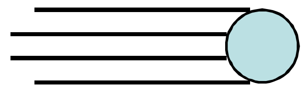
Forms of Energy

Energy comes in a variety of forms…

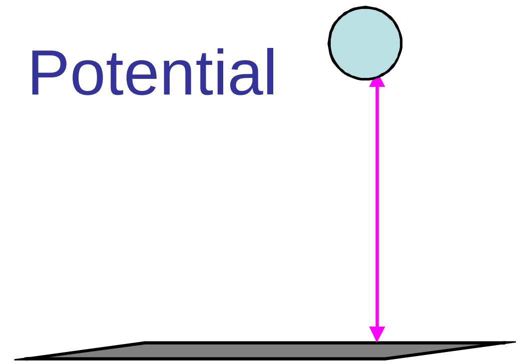
Internal



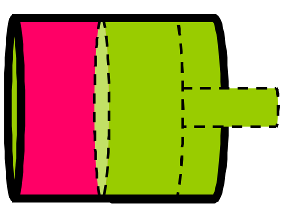
Kinetic



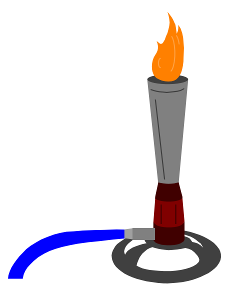
Potential



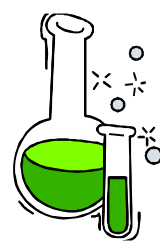
Mechanical



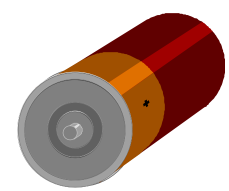
Heat



Chemical



Electrical



Energy Conservation

The **First Law of Thermodynamics** states that total energy is conserved for any thermodynamic system → energy can not be created nor destroyed
→ energy can only change from one form to another

$$Energy(E) = \text{constant}$$

$$E_{\text{internal}} + E_{\text{kinetic}} + E_{\text{potential}} + E_{\text{mechanical}} + E_{\text{heat}} + E_{\text{chemical}} + E_{\text{electrical}} = \text{constant}$$

Our main concern in meteorology…

The Concept of Work

Work is a Mechanical form of Energy:

$$\text{Work} = \text{Force} \times \text{Distance}$$

$$dW = F \times \Delta x$$

The Concept of Work

Work is a Mechanical form of Energy:

$$\text{Work} = \text{Force} \times \text{Distance}$$

$$dW = F \times \Delta x$$

Recall the definition of pressure:

$$p = \frac{\text{Force}}{\text{Area}} = \frac{F}{(\Delta x)^2}$$

We can thus define work as:

$$dW = pdV$$

The Concept of Work

Changes in Volume Cause Work:

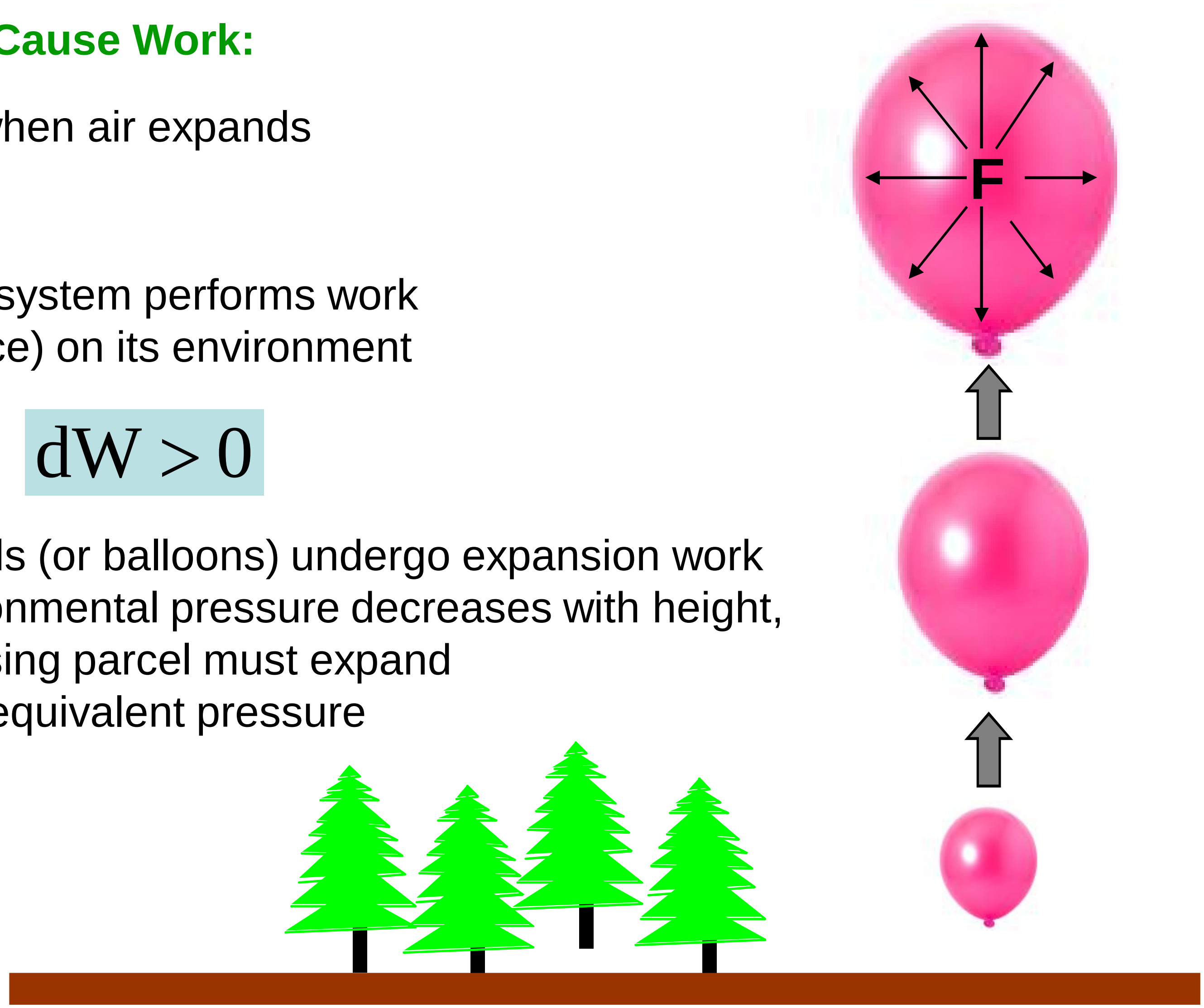
• Work is performed when air expands

Work of Expansion:

- Occurs when a system performs work (or exerts a force) on its environment
- Is positive:

$$dW > 0$$

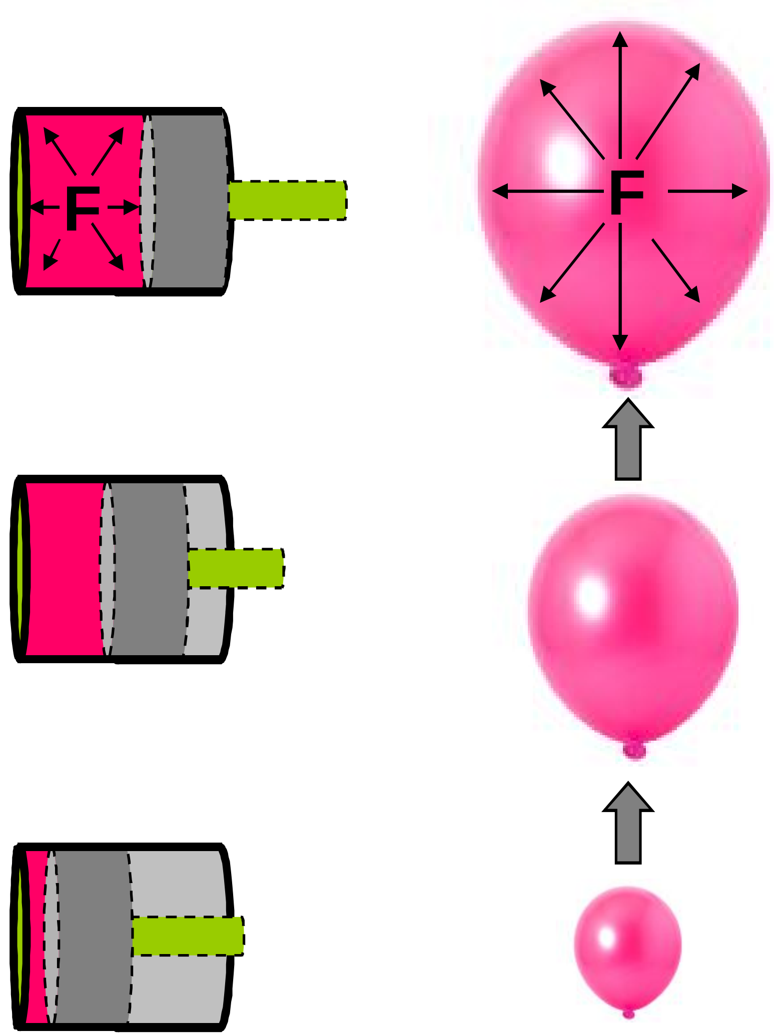
- Rising air parcels (or balloons) undergo expansion work
- Since the environmental pressure decreases with height, with height a rising parcel must expand to maintain an equivalent pressure



The Concept of Work

Changes in Volume Cause Work:

- Similar to a piston in a car engine



The Concept of Work

Changes in Volume Cause Work:

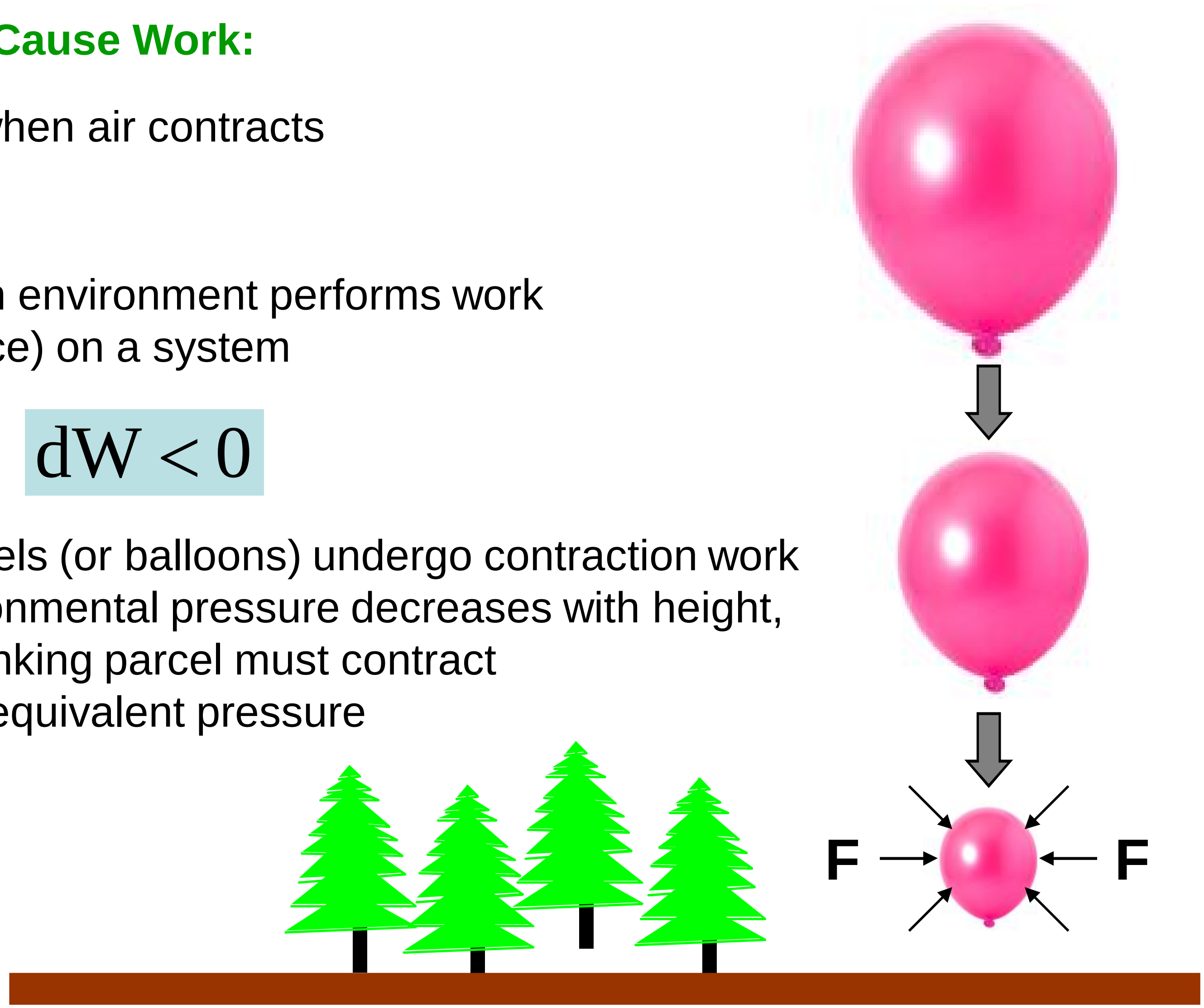
• Work is performed when air contracts

Work of Contraction:

- Occurs when an environment performs work (or exerts a force) on a system
- Is negative:

$$dW < 0$$

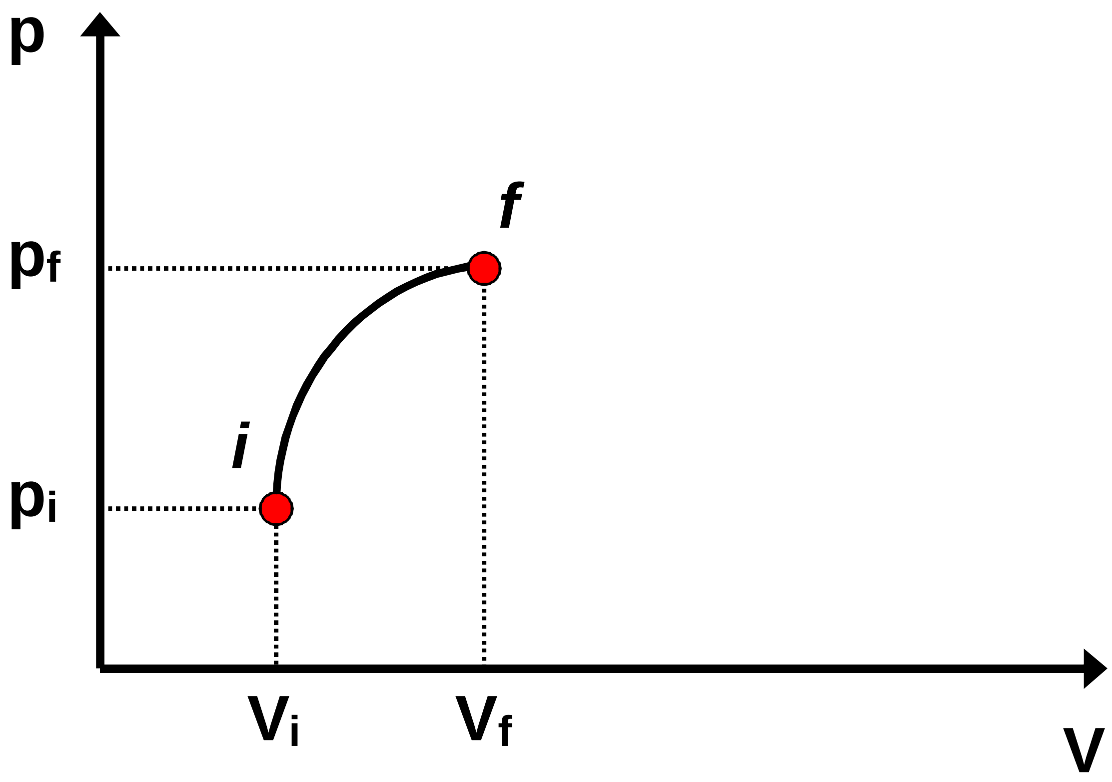
- Sinking air parcels (or balloons) undergo contraction work
- Since the environmental pressure decreases with height, with height a sinking parcel must contract to maintain an equivalent pressure



PV Diagrams

Another Way of Depicting Thermodynamic Processes:

- Consider the transformation: $i \longrightarrow f$

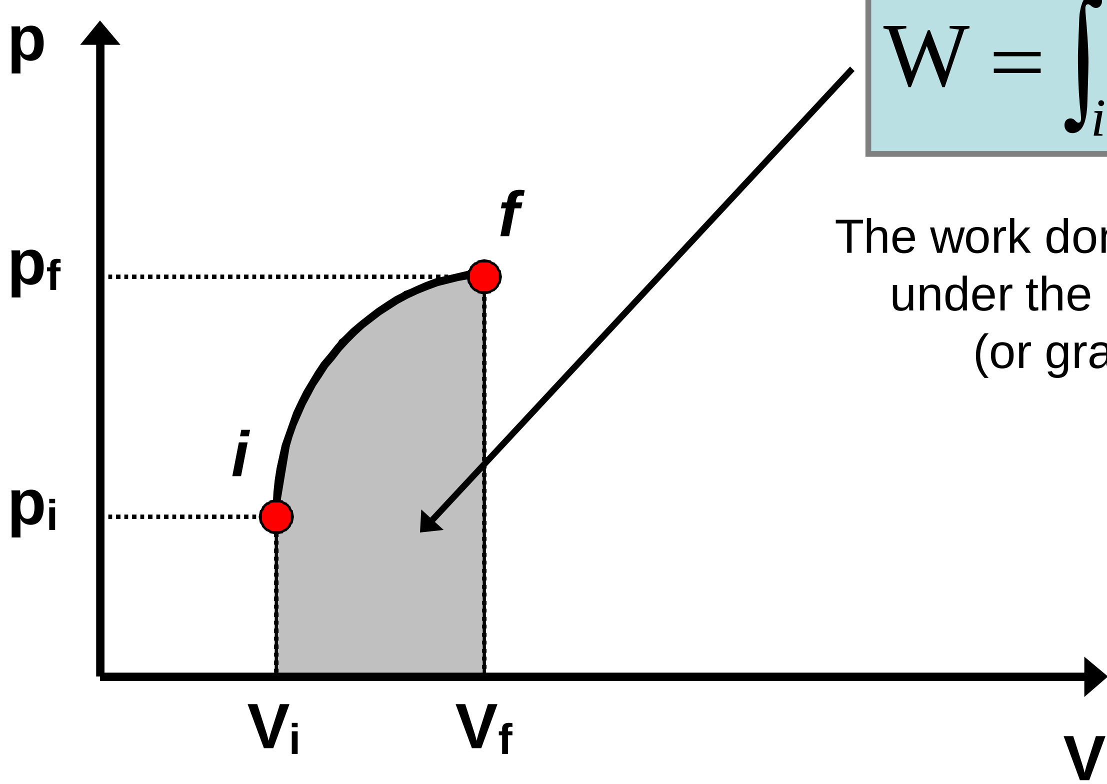


PV Diagrams

Another Way of Depicting Work:

- Consider the transformation: $i \longrightarrow f$

$$dW = pdV$$

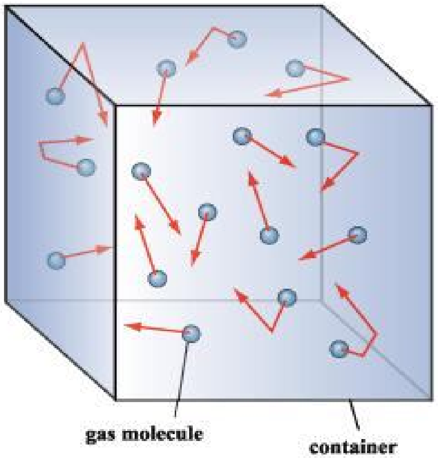


$$W = \int_i^f pdV$$

The work done is the area under the i → f curve (or gray area)

First Law of Thermodynamics

Internal Energy = Kinetic Energy + Potential Energy
(of the molecules in the system)



- Depends **only** on the current system state (p,V,T)
- Does **not** depend on past states
- Does **not** depend on how state changes occur

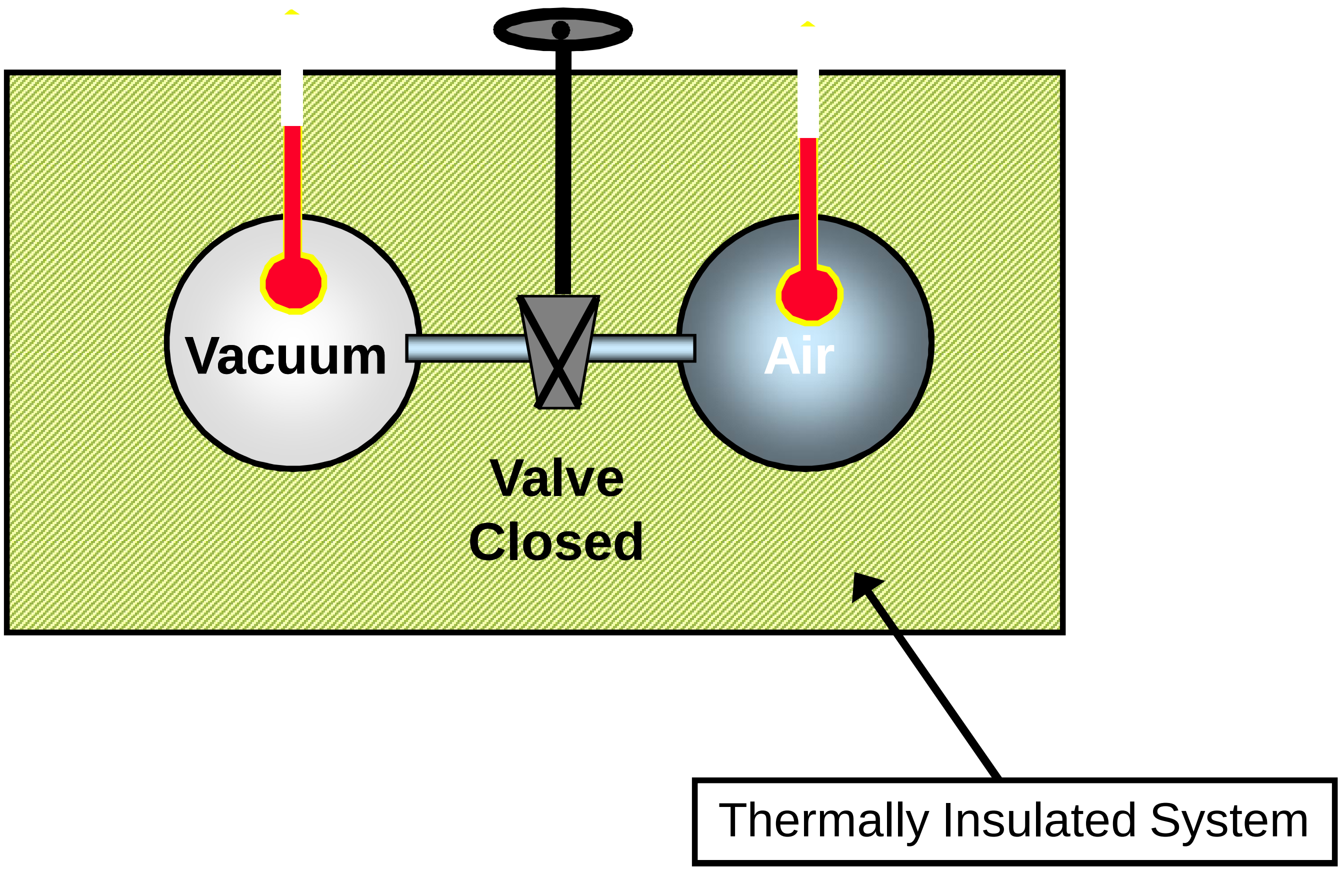
- Changes are the result of external forcing on the system (in the form of **work** or **heat**)

$$\Delta E_{\mathrm{internal}} = \mathrm{Work}_{\mathrm{environment}} + \mathrm{Heat}_{\mathrm{environment}}$$

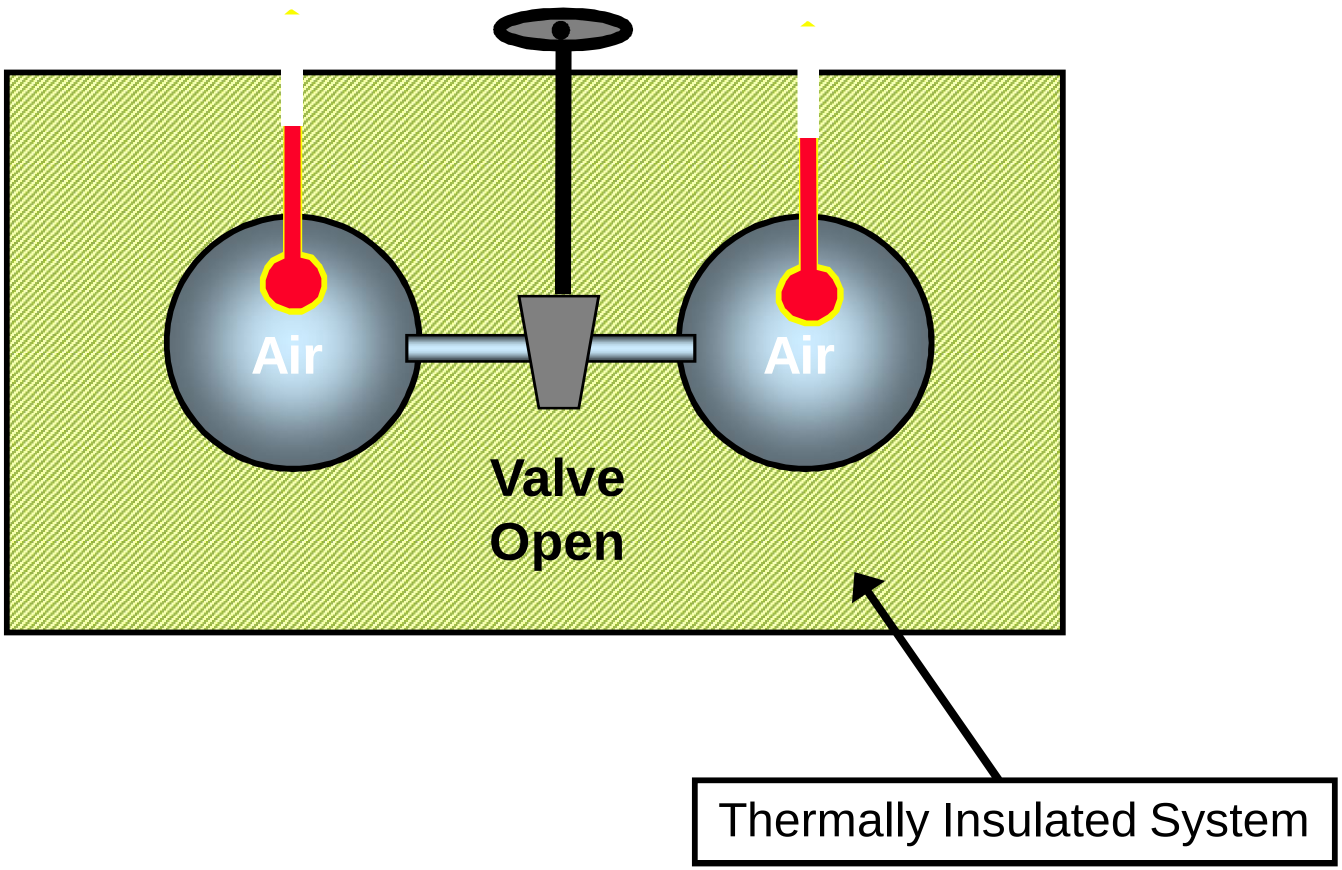
$$dU = -dW + dQ$$

$$dU = -pdV + dQ$$

Joules Law

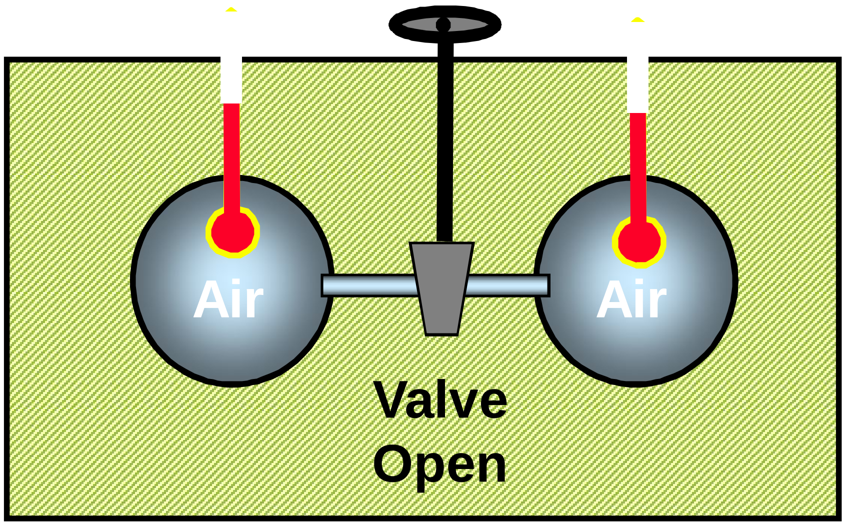


Joules Law



Joules Law

- **Air expanded to fill the container**
  - Change in volume
  - Change in pressure
- **No <u>external</u> work was done**
  - Air expanded into a vacuum within the system
- **No heat was added or subtract**
  - Thermally insulated system
- **No change in internal energy**
- **No change in temperature**



$$dU = -pdV + dQ$$

$$dU = 0$$

What does this mean?

Joules Law

- **Air expanded to fill the container**
  - Change in volume
  - Change in pressure
- **No <u>external</u> work was done**
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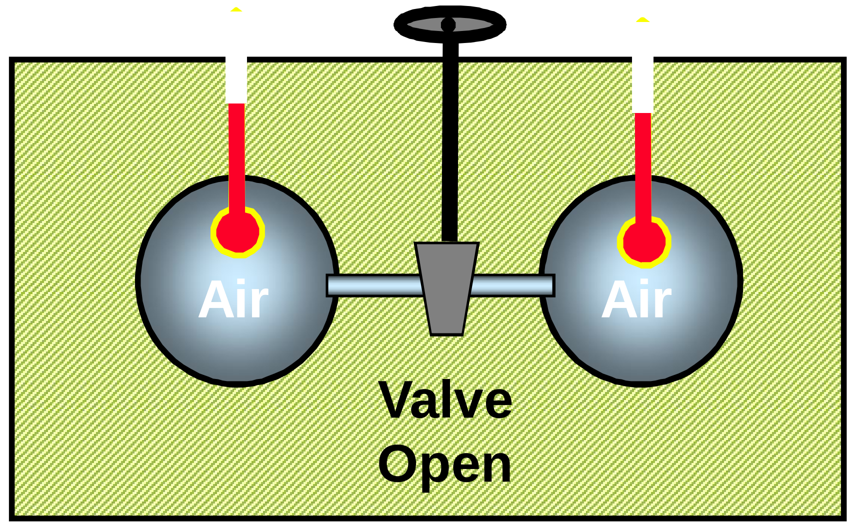


Internal Energy is <u>only</u> a function of temperature

$$U = U(T)$$

$$dU = -pdV + dQ$$

$$dU = 0$$

Thermal Capacities (Specific Heats)

Assume: A small quantity of heat (dQ) is given to a parcel
The parcel responds by experiencing a small temperature increase (dT)

Specific Heat (c):

$$c = \frac{dQ}{dT}$$

Two Types of Specific Heats:

- Depends on how the material changes as it receives the heat

Constant Volume:

$$c_v = \left(\frac{dQ}{dT}\right)_{\text{constant volume}}$$

Parcel experiences no change in volume

Constant Pressure:

$$c_p = \left(\frac{dQ}{dT}\right)_{\text{constant pressure}}$$

Parcel experiences no change in pressure

Thermal Capacities (Specific Heats)

Specific Heat at Constant Volume:

- Starting with:

$$c_v = \left(\frac{dQ}{dT}\right)_{\text{constant volume}}$$

- If the volume is constant (dV = 0), we can re-write the first law as:

$$dU = -pdV + dQ \rightarrow dU = dQ$$

- And substitute this into our specific heat equation as

$$c_v = \left(\frac{dU}{dT}\right) \quad \text{or} \quad dU = c_v dT$$

Thermal Capacities (Specific Heats)

Specific Heat at Constant Volume:

• Since the internal energy is a state variable and does not depend on past states or how state changes occur, we can define changes in internal energy as:

$$\Delta U = \int_{T_2}^{T_2} c_v dT$$

• Also, if we substitute our specific heat equation into the first law:

$$dU = c_v dT \quad \longrightarrow \quad dU = -pdV + dQ$$

We can obtain an **alternative form** of the **First Law of Thermodynamics**:

$$dQ = c_v dT - pdV$$

Thermal Capacities (Specific Heats)

Specific Heat at Constant Pressure:

- Starting with

$$c_p = \left(\frac{dQ}{dT}\right)_{constant\ pressure}$$

$$dQ = c_v dT - pdV$$

$$pV = nR^* T$$

and recognizing that,

$$d(pV) = pdV + Vdp$$

we can obtain another **<u>alternative form</u>** of the **First Law of Thermodynamics**:

$$dQ = c_p dT - Vdp$$

Also,

$$c_p = c_v + nR^*$$

Concept of Enthalpy

Assume: Heat (dQ) is added to a system at constant pressure

Impact: **1)** The system's volume increases ($V_1 \rightarrow V_2$) and work is done

$$dW = p(V_2 - V_1)$$

2) The system's internal energy increases ($U_1 \rightarrow U_2$)

$$dU = U_2 - U_1$$

Using the First Law:

$$dQ = (U_2 - U_1) + p(V_2 - V_1)$$

We can then define Enthalpy (H) as:

$$H = U + pV$$

Concept of Enthalpy

Enthalpy:

$$dQ = (U_2 - U_1) + p(V_2 - V_1)$$

$$H = U + pV$$

If we differentiate the definition of enthalpy and use prior relationships, we can obtain the following relation:

$$dQ = dH = c_p dT$$

We shall see that Enthalpy will be a useful concept since most sources and sinks of heating in the atmosphere occur at roughly constant pressure

Forms of the First Law of Thermodynamics

For a gas of mass *m*	For unit mass
$dQ = dU + dW$	$dq = du + dw$
$dQ = dU + pdV$	$dq = du + pd\alpha$
$dQ = c_v dT + pdV$	$dq = c_v dT + pd\alpha$
$dQ = c_p dT - Vdp$	$dq = c_p dT - \alpha dp$
$c_p = c_v + nR^*$	$c_p = c_v + R_d$

where:

p = pressure
V = volume
T = temperature
α = specific volume

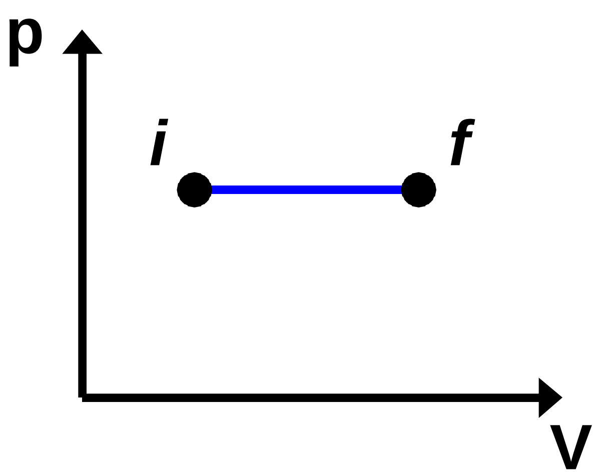
U = internal energy
W = work
Q = heat energy
n = number of moles

c_v = specific heat at constant volume (717 J kg^{-1} K^{-1})
c_p = specific heat at constant pressure (1004 J kg^{-1} K^{-1})
R_d = gas constant for dry air (287 J kg^{-1} K^{-1})
R* = universal gas constant (8.3143 J K^{-1} mol^{-1})

Types of Processes

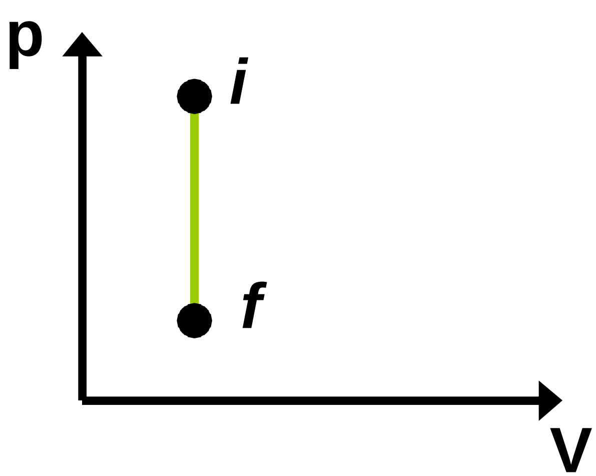
Isobaric Processes:

- Transformations at constant pressure
- dp = 0



Isochoric Processes:

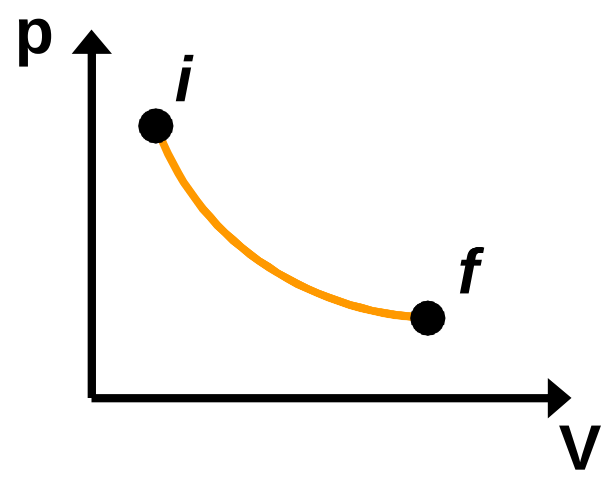
- Transformations at constant volume
- dV = 0
- dα = 0



Types of Processes

Isothermal Processes:

- Transformations at constant temperature
- $dT = 0$



Adiabatic Processes:

- Transformations without the exchange of heat between the environment and the system
- $dQ = 0$
- More on this next lecture…

First Law of Thermodynamics

Summary:

- Forms of Energy (know the seven types)
- Energy Conservation (know the basic concept)
- Concept of Work (expansion and contraction in the atmosphere)
- PV Diagrams (origins of an equation for Work)
- Concept of Internal Energy (know the basic concept)
- Joules Law (know what it implies to internal energy)
- Thermal Capacities (Specific Heats)
- Concept of Enthalpy (know the basic concept)
- Various Forms of the First Law
- Types of Processes (isobaric, isothermal, isochoric, adiabatic)