Classical Engineering Thermodynamics I

Lecture 1 | Introduction to Thermodynamics

What is "Thermodynamics"?

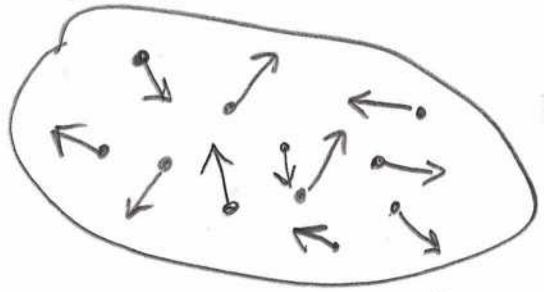
- A science in which the storage, transformation, and the transfer of Energy are studied.
- The word is derived from Greek:
  - **Thermis:** Meaning "Warmth" or "Heat"
  - **Dynamis** The origin of our English word for "Dynamic" (Wikipedia)

    "Dynamic" Pertains to⊛
    (a) Force or Power
    (b) Force related to Motion
- **Thus, "thermodynamics" relates two scientific concepts of "Warmth" & Motion**

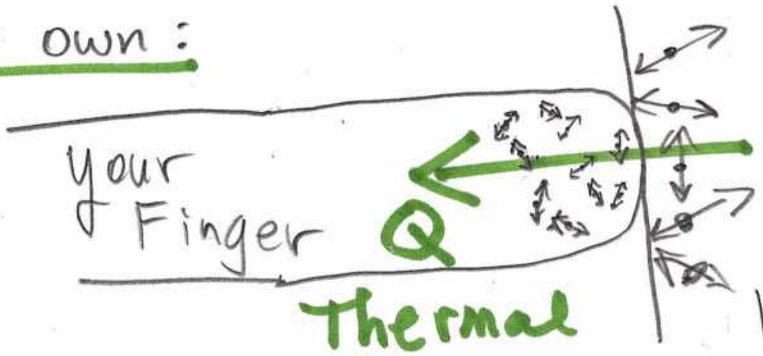
⊛ Random House Webster's College Dictionary, N.Y., 2001

Q: If "Heat" is related to "motion", then what is moving? To <u>where</u> is it moving?

A: Any substance on a <u>microscopic scale</u> is comprised of atoms and/or molecules having some degree of <u>random motion</u>:



- This random motion is "<u>thermal energy</u>"
- <u>What we feel as "Warmth", or "Heat", on a macroscopic scale is the thermal energy of another body being transfered to our own:</u>



Thermal Energy transfer ("Heat") kJ

A "Hot" object's molecules' have greater random motion than your finger

- It is the difference in the magnitude of random thermal motion of each object's molecules/atoms that drives thermal energy transfer, or "Heat" Transfer, Q (kJ) between objects

- An object DOES NOT CONTAIN "HEAT"!

- "Heat" is thermal Energy transfer

- In thermodynamics, we will develop concepts and mathematical expressions that relate the transformations and transfers of Energy (both in the form of thermal Heat and ordered Work) to the inherent macroscopic properties of a body, such as pressure, temperature, entropy, internal energy, etc.

- The subject of thermodynamics is based on

Experimental Observations

that have been organized into Four statements (or "Laws"). They are called "Laws" because there has never been any experimental evidence that they are untrue.

- **Laws of Thermodynamics** (Developed, Historically, without considering atoms or molecules → based on macroscopic observation!)

- **the 0^{th} Law**

  - this law states that if two bodies are in thermal equilibrium with a third body, then they are also in thermal equilibrium with each other.

  - This Law is the fundamental basis for a thermometer

- **The 1^{st} Law**

  - Basically a revised statement of the principle of Energy Conservation

• The 2nd Law (Related to Entropy)

(a) Asserts a "direction" for Energy transformations and transfer processes.

(b) Indicates whether or not a given process can actually occur.

(c) Sets fundamental limits on how much thermal energy can be converted to useful work by a device (or engine)

(d) May have implications on the nature and direction of time itself!

• The 3rd Law

- States that the Entropy (atomic "disorder") of a pure crystalline substance is zero at absolute zero temperature

[Also Known as the "Nerst Heat Theorem" formulated by Walther Nerst, circa 1916]

One extra Law is needed for us to use thermodynamics to analyze a body (or "System") undergoing some process:

- **Law of Mass Conservation [Classical Physics]**
  - States that the mass within a closed box will remain constant over time, regardless of the process occuring inside the box or whatever work and Heat interactions are performed on the box.
  - Philosophically, Epicurus (341–270 B.C.) thought of this, as well as Nasīr al-Dīn al-Tūsī (1201–1274 AD)
  - Postulated by Joseph Black (1728-1799), Henry Cavendish (1731–1810), and Jean Rey (1583–1645)
  - Experimentally Proven by
    - (a) Mikhail Lomonosov in 1748
    - (b) Antoine Lavosier in 1789 [the "Father of Modern chemistry]
  - In 1905, Albert Einstein showed that Energy is proportional to mass:

$$\boxed{E = mc^2}$$

Note: This Mass conservation Law gets tricky in both Relativity and Quantum Mechanics (see Wiki)

"Classical" thermodynamics

- Analyzes the Macroscopic properties of a body (or "System") using the 4 Laws of thermodynamics which were obtained without considering the microscopic nature of matter (atoms, molecules, etc.).

- Historically:

  (a) Developed from ancient musings (Aristotle, etc.)! As early as 1100 A.D. "Heat" (or thermal energy) was postulated to be "some kind of motion" within a body.

  (b) Francis Bacon and Robert Hooke postulated that Heat was some "quivering" or "agitated motion of the parts of a body"

Birth of Classical thermo →

  (c) Count Rumford (Benjamin Thompson) in 1797 showed experimentally that "Heat" is something being excited and agitated within a body, and Heat transfer is the movement of this agitation from one body to another. He did not know what was being "agitated" (we know it's atoms)

(d) Classical thermodynamics continued to develop in "fits and spurts", partially because many chemists and scientists did not believe atoms or molecules existed!

By ~1900, Classical Thermodynamics and the macroscopic Laws were considered to be "Complete"

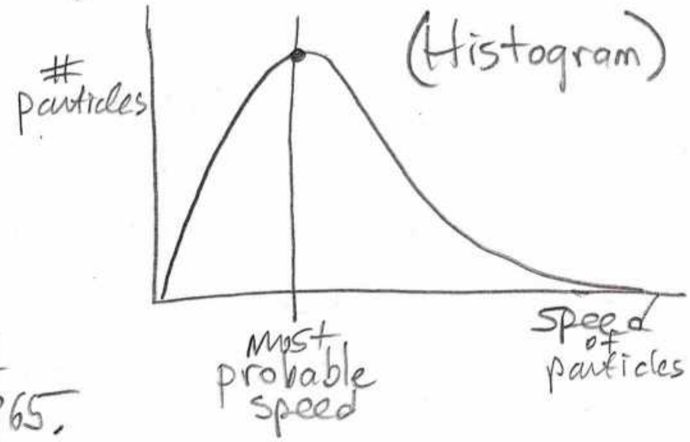
<u>Note</u>: Besides scientific curiosity, <u>the Major reason behind the drive to understand the relationship between thermal energy changes</u> within a body of Matter, and the <u>Work interactions and Heat interactions</u> between the body and the outside world was to <u>increase the efficiency of Steam Engines</u>

"Statistical" Thermodynamics

- Pertains to the analysis of the energies and motions of atoms and molecules on a microscopic level, using statistics, and then relating the statistical averages to what we experience in the macroscopic realm (temperature, pressure, "Heat", Entropy, etc.)

Birth of Statistical → thermo

- James Clerk Maxwell pioneered the use of statistics for molecular motion in gases in 1860 to derive the Maxwellian Velocity Distribution of particles



- Ludwig Boltzmann put Maxwell's theory on solid ground in 1865.

- In 1905, Boltzmann related the organization of microscopic particles in matter to the macroscopic property called "Entropy".

- Boltzmann committed suicide by hanging in Italy in 1905, due to depression and migraines.

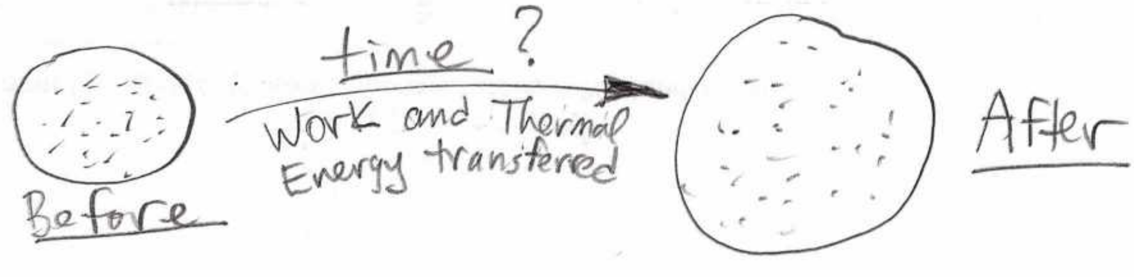
Thermodynamics for the Engineer (Classical in ME 315 & 316)

- The Engineer's objective in studying Thermodynamics is most often the analysis or design of a device such as a refrigerator, a computer, or a nuclear power plant.
- It must be emphasized that the science of thermodynamics is an incomplete set of knowledge for the engineer to perform a complete analysis.
- There is important information that thermodynamics itself cannot provide:

1. **Time Scales of Processes**. *Thermodynamics does not predict any timescale over which a process will occur.* Thermodynamics is only concerned with the "before" and "after" of a process and often ignores the "in-between". The "in-between" part that is not addressed is related to "how fast" a process advances to the end result and is often important to an engineer.

   Timescales of processes are addressed in your other courses such as Heat Transfer, Fluid Mechanics, Chemical Kinetics, and Mass Transfer.

   A true "real-world" engineering analysis usually requires some or all of these subjects.



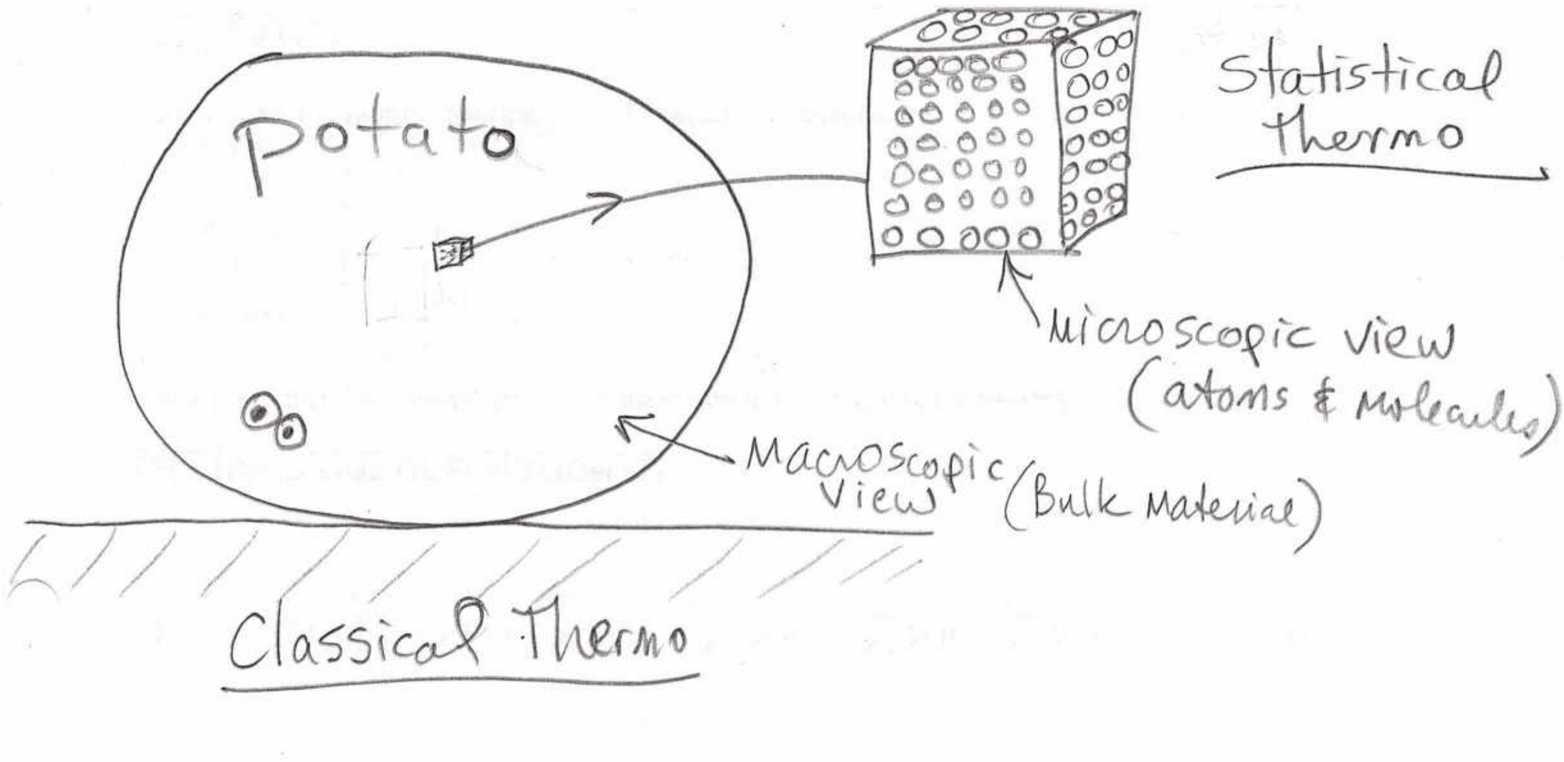
2. **The Microscopic Structure of Matter**. Classical Thermodynamics ignores the fact that matter is composed of elementary particles (*e.g.*, electrons, protons, neutrons, atoms, and molecules). The spatial distance over which these particles interact is known as the ***Microscopic Scale***.

   When Classical Thermodynamics was being developed, the discrete nature of matter was disputed or not fully understood. Later, it *was* understood that the large-scale (or *macroscopic*) phenomena that we perceive is a fundamental consequence of the statistical nature of elementary particle interactions on the microscopic scale. This field of study called *Statistical* Thermodynamics is beyond the scope of this class.

   However, we will sometimes be referring back to a simple picture of the microscopic nature of matter in order to gain a proper understanding of observed macroscopic phenomena.

   It is my opinion that to ignore the microscopic nature of matter in Classical Thermodynamics classes is equivalent to ignoring 150 years of revolutionary research that has been used by engineers to construct our present society.

   A simple conceptual microscopic perspective actually aids in your understanding of the macroscopic phenomena that we will be dealing with……and to not include it is a disservice to an engineering student's quality of education and their eventual proficiency within the engineering profession.



Engineering Application Areas of thermodynamics

- Steam Power Plants (Nuclear, Coal, Natural gas)
- Refrigeration Systems
- Air separation and liquification plants
- Chemical Rocket Engines
- Environmental Issues
- Cars (gasoline)
- Trucks (diesel)
- Air Conditioning
- Heat Pumps
- Fuel Cells
- Computers
- Supersonic, Hypersonic gas flows
- Electrically conducting gases (plasmas)
- Human Body
- Furnaces
- Weather
- Geothermal Energy Conversion
- Many, many more!

Dimensions, Units, and Unit Conversion

A SI (International System)

- Simple because it is a base-10 system
- Logical in it's convention of usage

Base Dimensions

Dimension	Unit	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
temperature	kelvin	K (not °K !!)
electric current	ampere	amp
amount of substance	mole	mol
luminous intensity	candela	cd

Supplementary Dimensions

plane angle	radian	rad
solid angle	steradian	sr

Derived Dimensions

force	newton	$N=kg\ m/s^2$
pressure	pascal	$Pa=N/m^2= kg/m\ s^2$
energy	joules	$J=N\ m = kg\ m^2/s^2$
power	watts	$W= J/s = kg\ m^2/s^3$

Be careful with "calories"! see back of book

- SI standard prefixes (memorize!)

prefix	meaning
pico	10^{-12}
nano	10^{-9}
micro	10^{-6}
milli	10^{-3}
base	10^{0}
kilo	10^{3}
mega	10^{6}
giga	10^{9}
tera	10^{12}

B English System (United States Customary System)

- No apparent systematic numerical base
- Units evolved over time from Medieval usage, maybe even before that
- Relationships between units seem arbitrary (although I have read books that do show some consistency in some units)
- The U.S. uses it in engineering, so I am forced to use it in Thermo I & II (Sorry!)

Dimension	Unit	Symbol
length	foot	ft
time	second	s
temperature	degree Fahrenheit	^oF
mass	pound mass	lb_m
force	pound force	lb_f

Note: (a) Horsepower $\Rightarrow \frac{\text{Work}}{\text{time}}$ interactions

(b) British Thermal Unit (Btu) $\Rightarrow$ Thermal Energy ("Heat") interactions

$$\frac{\text{Thermal Energy}}{\text{time}} = \frac{\text{Btu}}{\text{time}}$$

The nice thing about SI is that there is a single unit for energy and power: Joule and Watt, respectively: $1\,\text{Btu} = 778.169\,\text{ft-lb}_f = 3.9\times10^{-4}\,\text{hp-h} = 1055.056\,\text{J}$

Lecture 2 : Classical Mechanics Review

- A physical quantity that is described by a single number is called a "scalar" quantity.

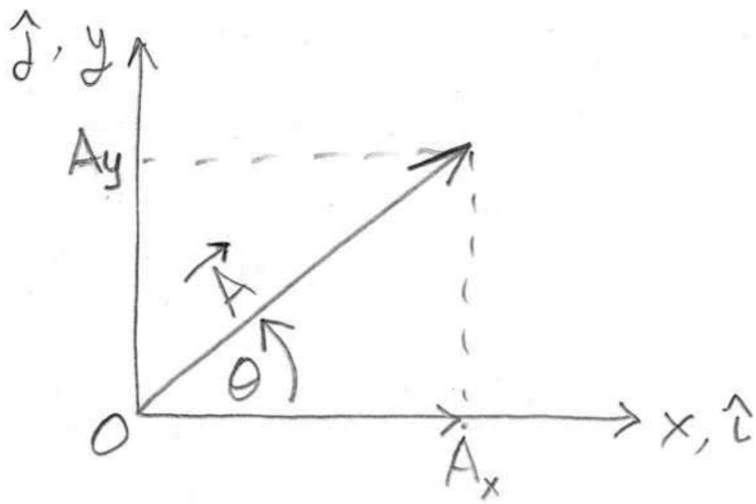
  Examples: temperature T, mass m, time t, Energy E, speed $|\vec{v}|$

- A quantity having both magnitude and direction in space is called a vector quantity.

  Examples: Velocity $\vec{v}$, acceleration $\vec{a}$, displacement $\vec{x}$, Force $\vec{F}$

A vector is represented with an arrow and is resolved into components with respect to a coordinate system:

Example:



Note: You must have a coordinate system in order to resolve components

The vector is expressed, in a Cartesian coordinate system (shown above) as

$$\boxed{\vec{A} = A_x \hat{i} + A_y \hat{j}}$$ ($\hat{i}$ & $\hat{j}$ are unit vectors)

Since θ is the angle between the vector $\vec{A}$ and the x-axis, the components can be expressed trigonometrically as

$$A_x = A \cos\theta \quad , \quad A_y = A \sin\theta$$

Applying Pythagorean's Theorem, the Magnitude of the vector is

$$|\vec{A}|^2 = A_x^2 + A_y^2$$

or

$$\boxed{|\vec{A}| = \sqrt{A_x^2 + A_y^2}}$$

the angle θ is also found using trigonometry:

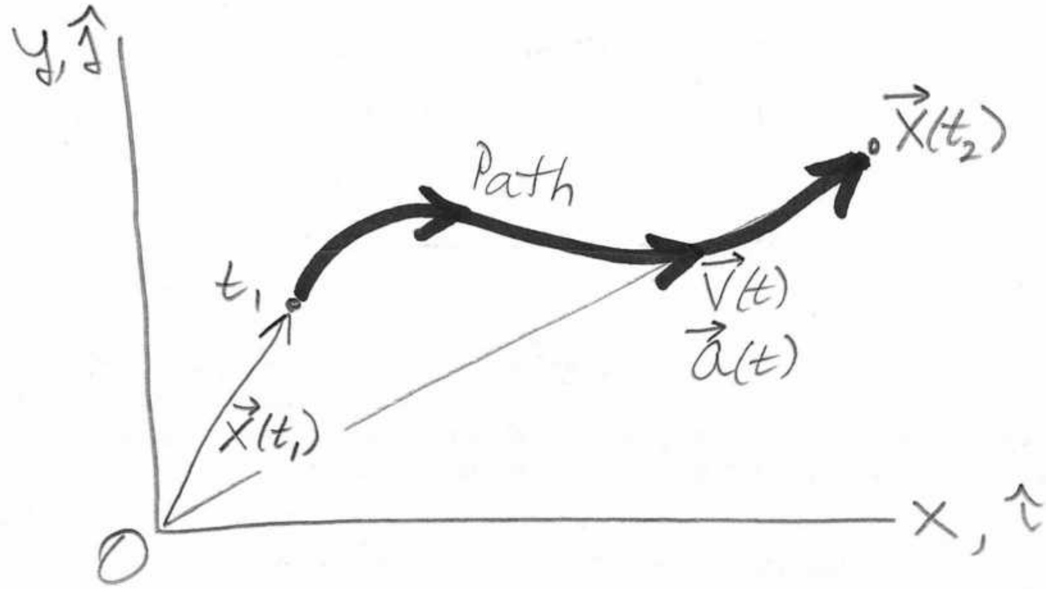
$$\tan\theta = \frac{A_y}{A_x}$$

so

$$\boxed{\theta = \arctan(A_y/A_x)}$$

A) <u>Kinematics</u>: The part of mechanics that describes motion of bodies (not forces!)

- <u>Coordinate system Oxy (fixed, not moving)</u>



(1) <u>Instantaneous Displacement</u>

As measured along the trajectory path from the origin, O,

$$\boxed{\vec{X}(t) = x(t)\hat{\imath} + y(t)\hat{\jmath}}$$

(2) <u>Instantaneous Velocity</u>

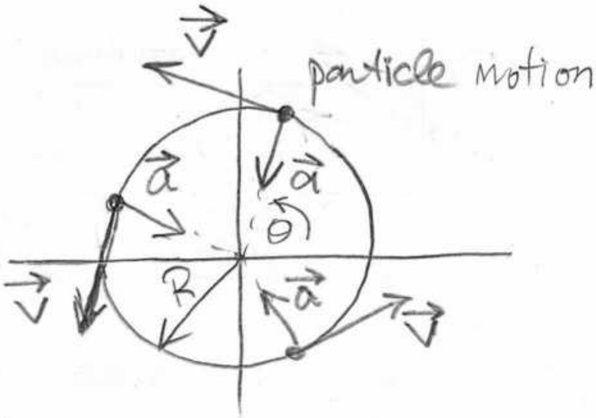
$$\vec{V}(t) = \frac{d\vec{X}}{dt}$$

$$\vec{V}(t) = \frac{dx}{dt}\hat{\imath} + \frac{dy}{dt}\hat{\jmath}$$

(3) <u>Instantaneous acceleration</u>

$$\vec{a}(t) = \frac{d\vec{V}}{dt} = \frac{d^2x}{dt^2}\hat{\imath} + \frac{d^2y}{dy^2}\hat{\jmath}$$

- Uniform Circular Motion (Constant speed)
  - Note that the acceleration vector is not constant $\Rightarrow$ it is continuously changing direction (but not magnitude)



- $\vec{V} = \cancelto{0}{V_\perp}\,\hat{r} + V_\parallel \hat{\theta}$, $v \equiv |\vec{V}| = V_\parallel$ (tangential speed)

  $\vec{a} = a_\perp \hat{r} + a_\parallel \hat{\theta}$

- acceleration components

  $\perp$ to motion: $\boxed{a_\perp = \frac{v^2}{R}}$

  in terms of the period of rotation
  (1 cycle = 2π radians)

$$\boxed{v = \frac{\text{Circumference traveled}}{\text{time } \Delta t} = \frac{2\pi R}{\Delta t}}$$

so
$$a_\perp = \frac{4\pi^2 R^2}{R(\Delta t)^2}$$

$$\boxed{a_\perp = \frac{4\pi^2 R}{(\Delta t)^2}}$$

Example 1 A 5 inch diameter turbine shaft rotates at 500 rpm. What is the radial acceleration at the outer shaft surface

(a) in units of ft/s^2

(b) in units of m/s^2

(c) in terms of earth's surface gravity ("g's")

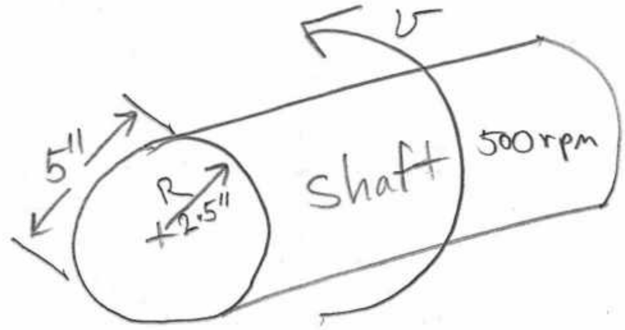
Assumptions

(1) turbine shaft rotates at constant tangential speed $V_{\parallel}$

(2) the acceleration of gravity at the earth's surface is $9.81\ m/s^2 = 32.2\ ft/s^2$

Solution

Draw a picture!



The circumference of the turbine shaft is $C = 2\pi R = \cancel{2}\pi \frac{D}{\cancel{2}} = \pi D$

$$C = \pi \times 5\,\cancel{inch} \times \frac{1\,ft}{12\,\cancel{inch}}$$

$$\boxed{C = 1.309\ ft}$$

The rotation frequency of the shaft is

$$\omega = 500\,\frac{rev}{\cancel{min}} \times \frac{1\,\cancel{min}}{60\,sec} = 8.3\bar{3}/sec$$

The tangential speed of the outer circumference is

$$v_{\parallel} = C\omega$$

$$v_{\parallel} = 1.309\,ft \times 8.333/sec$$

$$\boxed{v_{\parallel} \approx 10.91\,ft/sec}$$

(a) The radial acceleration (inward) in ft/s² is

$$a_{\perp} = \frac{v_{\parallel}^2}{R} = \frac{(10.91\,ft/s)^2}{2.5\,\cancel{inch} \times \frac{1ft}{12\,\cancel{inch}}}$$

$$\boxed{a_{\perp} = 571.2\,ft/s^2}$$

(b) The radial acceleration in m/s² is
(see back cover of textbook for unit conversion factors)

$$a_{\perp} = 571.3\,\frac{ft}{s^2} \times \frac{0.3048\,m}{ft}$$

$$\boxed{a_{\perp} = 174.1\,m/s^2}$$

(c) The outer shaft surface acceleration in Earth Surface g's:

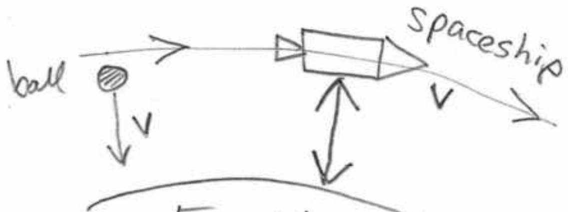
$$a_{\perp} = \frac{174.1\,m/s^2}{9.81\,m/s^2}$$

$$\boxed{a_{\perp} \approx 17.7\,g's}$$

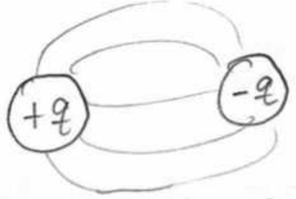
B) Dynamics

- Relates motion (Kinematics) to its causes (Forces)
- "Force" is a vector quantity, $\vec{F}$
- "Force" is a measure of the <u>interaction</u> of one body with another body.
- <u>Contact Force</u>: when a force involves direct contact between two bodies:

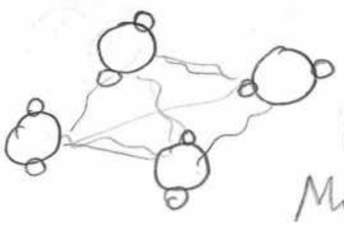
<u>Long Range Forces</u>: These forces act even when the two bodies are separated by empty space:



Earth
(gravity)



Charged Objects
(Electric Field)



Intermolecular Forces Between Molecules/Atoms

Newton's Laws of Motion

- Clearly stated by Sir Isaac Newton in 1686
- These laws must be deduced from <u>experiments</u>
  - ⇒ they cannot be derived from anything more fundamental (Classically)
- Valid only when velocity ≪ speed of light and gravity is "weak" (non-relativistic).

1st Law

> A body acted upon by no <u>net</u> forces moves with constant velocity (which may be zero) and zero acceleration

- This Law defines "inertia", the tendency for a body at rest to "want to" remain at rest ⟶ to resist changes in motion.
- Defines what an <u>inertial reference frame</u> is
  - ⇒ A frame of reference in which the 1st Law is valid

2^{nd} Law

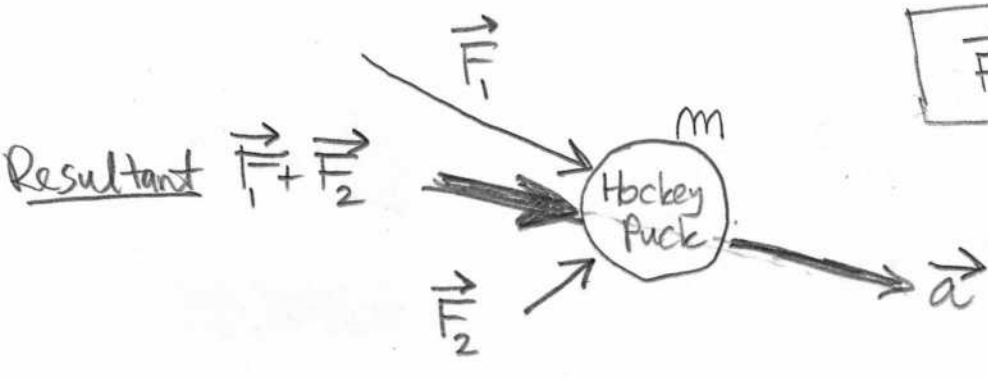
$$\boxed{\sum \vec{F} = m\vec{a}}$$

- If a <u>net</u> external force acts on a body, then the body accelerates.
- The direction of acceleration is the same as the direction of the <u>net</u> Force.
- The Magnitude of the <u>net</u> force vector is proportional to the magnitude of the acceleration vector.

$\Rightarrow$ This is the Classical <u>definition of "mass"</u>:

$$\boxed{m \equiv \frac{|\sum \vec{F}|}{|\vec{a}|}}$$

$$\boxed{\vec{F}_1 + \vec{F}_2 = m\vec{a}}$$



(Note that the 2^{nd} Law connects Kinematics with Dynamics)

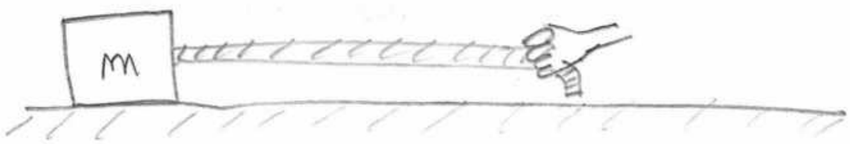
3rd Law

$$\boxed{\vec{F}_{A\,\text{on}\,B} = -\vec{F}_{B\,\text{on}\,A}}$$

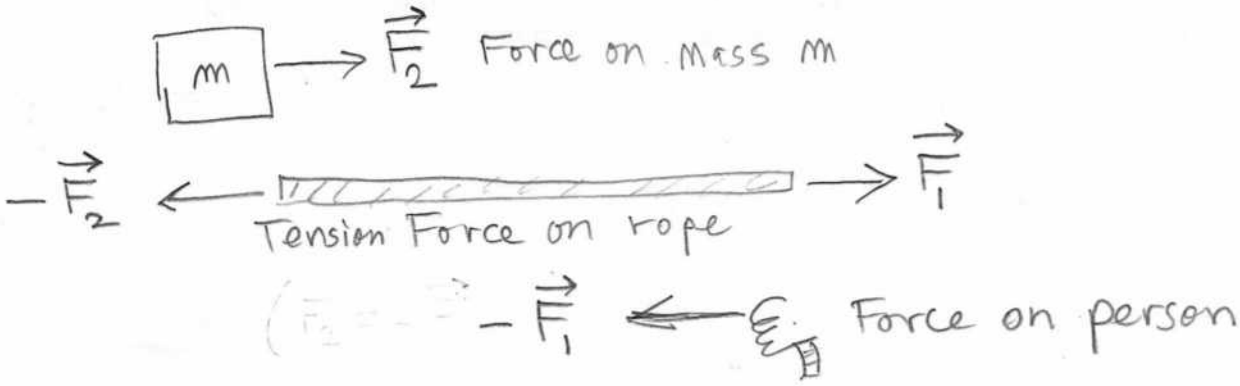
If body A exerts a force on body B (an "action"), then body B exerts an equal and opposite force on body A (a "reaction").

- This is called an "action-reaction pair"

Pulling on a rope:



Action-reaction pair:



Example 2 A Flowerpot having a mass of 10 kg is suspended by a chain from the ceiling. What is its weight? What force (magnitude and direction) does the chain exert on it? What is the tension in the chain?

Assumptions

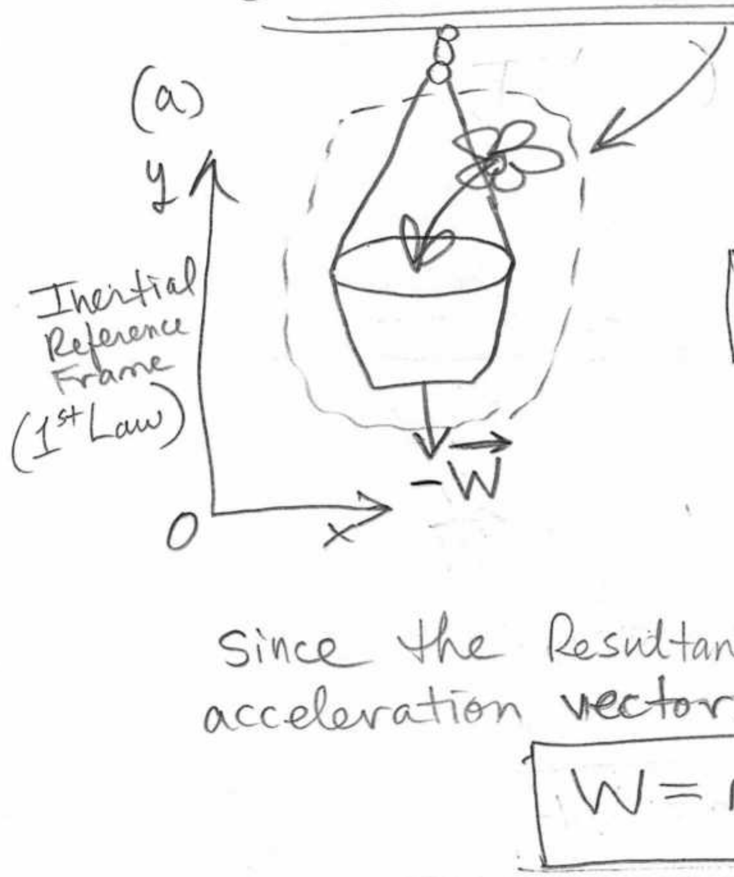
(1) Assume that the weight of the chain is negligable

(2) Assume that the local gravitational constant is $g = 9.81\ m/s^2$

(3) Assume an inertial frame of reference

Solution

Draw A Free-Body Diagram!



$$\boxed{\sum \vec{F} = m\vec{a}}$$ Newton's 2nd Law

$$\sum \vec{F}_{Pot} = -\vec{W} = -m\vec{g}$$

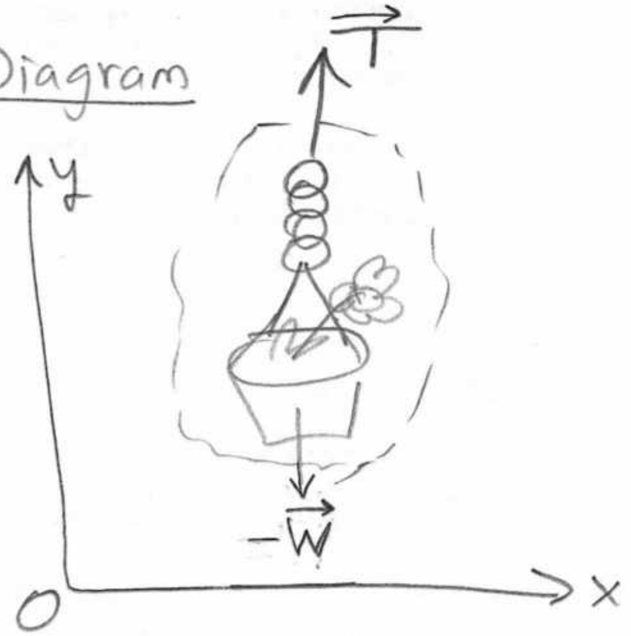
Since the Resultant Force (Weight) vector and acceleration vectors are co-linear, then

$$\boxed{W = mg}$$ (downward)

$$\boxed{W = (10 kg)(9.81\ m/s^2) = 98 \frac{kg\,m}{s^2} = 98\ N}$$

(b) What force does the the chain exert on the flower pot?

Draw a Free-Body-Diagram



$\vec{\Sigma F}_{Flower} = 0$

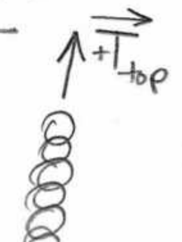
since the flower pot is in mechanical equilibrium, the vector sum of forces must be zero:

$$\Sigma \vec{F} = 0 = \vec{T} + (-\vec{W})$$

or $\boxed{T = W}$ The chain must pull up with force $T = 98\ N$

(c) What is the tension in the chain?

Because the chain is in mechanical equilibrium,



$$\Sigma \vec{F}_{chain} \equiv 0$$

$$\vec{T}_{Top} + (-\vec{T}_{Bottom}) = 0$$

or $\boxed{T_{top} = T_{Bottom} = 98\ N}$