Momentum and Energy

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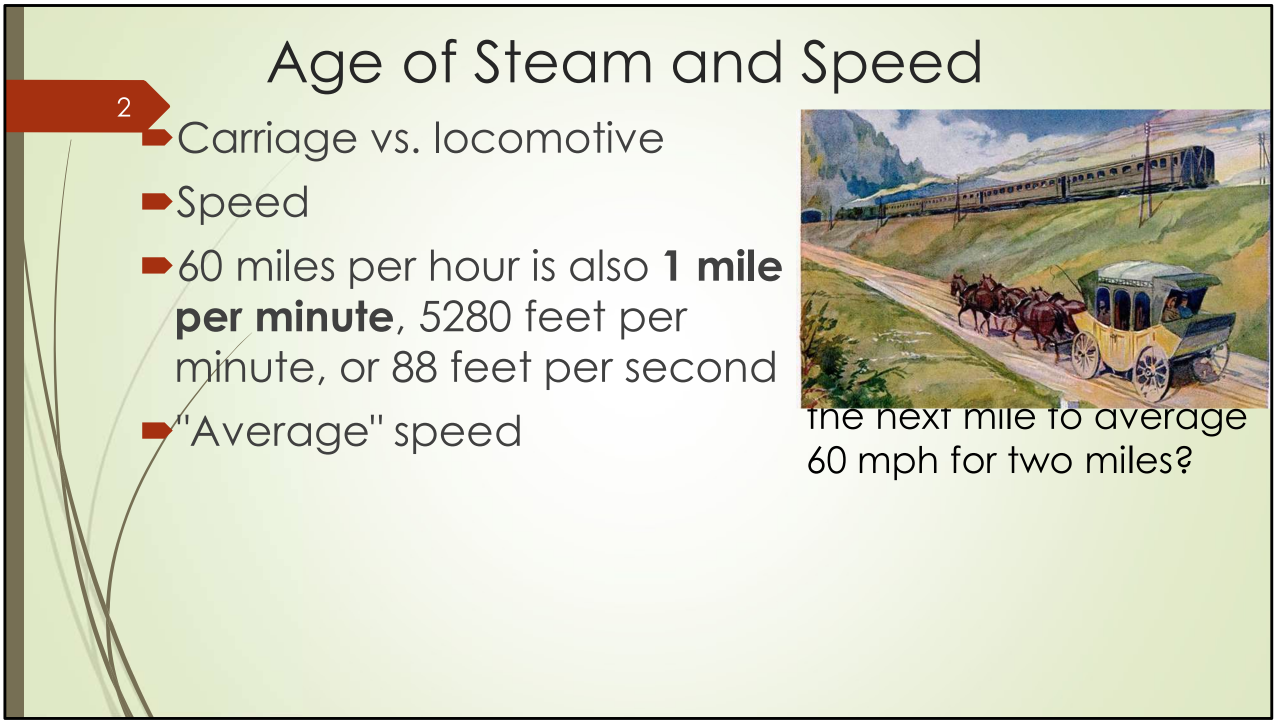
The success of Newton's laws and the scientific method opened the floodgates of discovery in Europe in the seventeen and eighteen hundreds. In this session, we will explore the discoveries about momentum and energy that contributed to the industrial revolution that changed everyone's life in the western world.



*In Newton's day, a horse drawn carriage would travel at about 2 mph and it would take sailing ships a month to cross the Atlantic. By 1850, steam locomotives reached speeds of 70 mph and steamships could cross the Atlantic in 8 days. Speed is an everyday term, but it can be misunderstood.
*Speed is the ratio of distance traveled to time. *The same speed might be given in different units. For example, 60 mph, 1 mile/min, 5280 feet per minute, and 88 ft/second are all the same speed.
*It is sometimes called average speed, but this is misleading. The method used to find an average is to sum several numbers and then divide by the count but that is not the definition of speed.
*Here is a trick question that illustrates the difference (read text box). The answer is not 90 mph. This is an example of how the word "average" is misleading. The answer is that no speed in the second mile would accomplish this goal because traveling two miles at 60 mph would take two minutes, but you already used two minutes to travel the first mile at 30 mph.

Angular Frequency

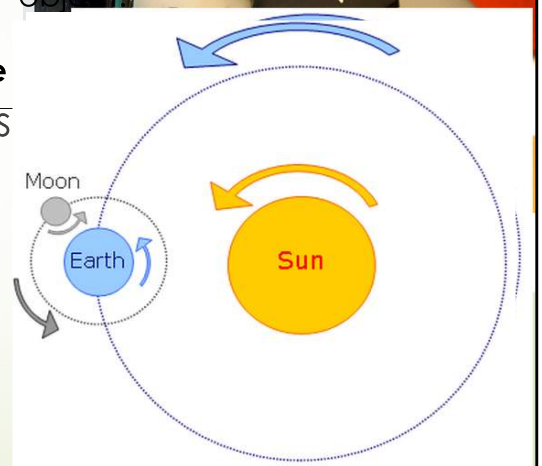
3

- Angular frequency is the ratio of change in angle divided by elapsed time
- **Rotation** vs. **Revolution**
- Often measured in rotations per minute, RPM

$$\textbf{Angular frequency} = \frac{\textbf{Change in angle}}{\textbf{Elapsed time}}$$

Revolution is motion of the entire object about another object or about a point outside the ob

Rotation is motion of an object about a line through its cent called an **axis**

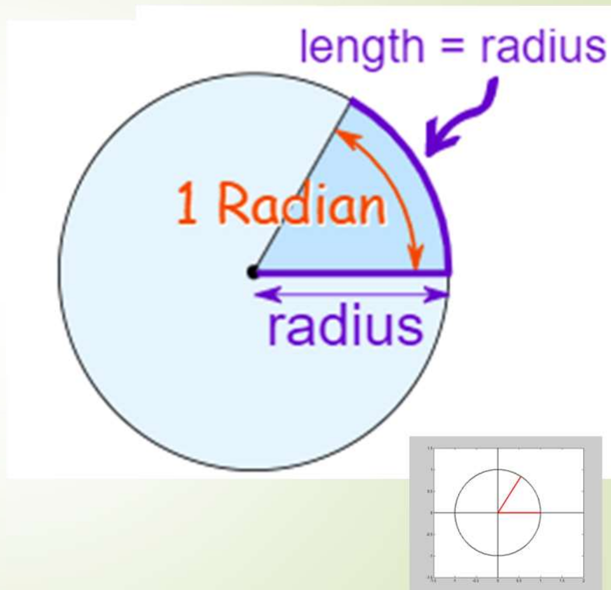


*Angular frequency describes how fast an object is rotating or revolving. These words are commonly used interchangeably but they are different. It is most important to use them correctly when describing the motions of objects in space such as planets, moons, meteors, and comets.
*Rotation is motion of an object about a line through its center called an **axis** *while **revolution** is motion of the entire object about another object or about a point outside the object. *For example, the earth rotates around its axis once in 24 hrs. and revolves around the sun once in 365 1/4 days. The moon rotates on its axis once while it revolves once around the earth, which is why one side is always facing the earth.
*Angular frequency is often measured in rotations per minute or rpm. Examples are *33 1/3 rpm for a vinyl record player and, *5000 rpm maximum engine rotation. These are often called revolutions per minute. It only matters if the object might have both types of motion.

Angle Measurement

4

- Radius; length, center to the edge
- Radians: angle
- 2π radians in a circle (about 6.28…)
- 1 rotation (or revolution) = 2π radians



*Engineers and scientists who work with rotating or spinning objects like motors or wind turbines use another method of measuring angles that is based on the natural law of circles where the unit of angular measure is related to part of the circle called the ***radius** which is the distance from the center to the edge.
*This unit of angle measurement is the **radian** which is the angle at the center that cuts a length of one radius on the edge.
*Because a diameter is twice as long as a radius, the natural law of circles might be that the circumference is 2π times longer than the radius.
*This implies that there are 2π radians (6.28..) in a circle
*The advantage of this unit of measure isn't readily apparent.

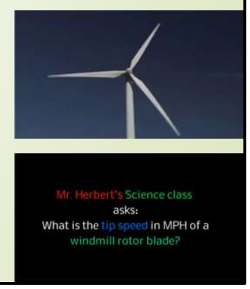
Speed in a Circle

5

- Linear speed is proportional to both the angular frequency and the distance from the axis of rotation

  Linear speed = angular frequency x radius

- 1 rotation = 2π radians (6.28…)
- Wind turbine, 20 rpm, 125.6 radians per minute
- Length of turbine blade ~100 feet
- Linear speed is 12,560 feet/min or about 142 miles per hour
- 140,000 to 679,000 bird deaths /yr

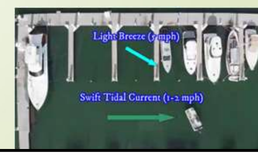


*The linear speed of a spot on a rotating object depends on the angular frequency and the distance from the axis if rotation.
*Recall that one rotation is 2π radians so we can convert RPM into radians per minute by multiplying by 2π (about 6.28).
A typical large wind turbine rotates at 20 rpm or about 125.6 radians per minute
*If the blades are about 100 feet long, *the linear speed at the tip would be 125.6 x 100 or 12,560 ft/min or about 142 mph
*In 2020, a study of 44 wind facilities in the Northeast US, reported 2,039 bird deaths and 22 facilities reported 418 bat deaths. National estimates range from 140,000 to 679,000 bird deaths per year from US wind turbines.

Speed with Direction: Velocity

6

- **Velocity** is speed with direction
- Wind velocity
- Can be represented by a vector



*Velocity is speed with direction and may be represented by a vector.
*For example, a pilot wants to know the wind speed and direction which is the wind velocity
*The velocity of an object like a plane or car is often the sum of two velocity vectors. Here are some examples:
*When a plane lands with a cross wind, the plane's velocity needs to line up with the runway so the pilot points the plane into the wind so the sum of the velocity from the plane's engines and the velocity of the wind is in line with the runway
*The driver of this bus does not adjust for the water velocity. The bus' velocity is straight ahead and the velocity of the water is sideways, so the sum is off to the right
*The boat's velocity is the sum of the velocity produced by the motor, the wind, and the water current

Momentum and Impulse

7

- Newton's concept of impetus
- Momentum is proportional to both the mass and the velocity
- Momentum is a vector
- Greek letter Delta*, stand for the phrase "*the change in*"
- Newton's 2nd law; Impulse equals change in momentum

$$F\Delta t = m\Delta V$$

Δ

*Aristotle had a concept called **Impetus** that combined speed and air friction. When a moving object like a cannon ball used up its impetus, it fell straight down. Even though Galileo refuted this concept, it survives in an odd way. *Newton defined momentum is the product (multiple) of mass and velocity. *The letter used for momentum is P which is an homage to Aristotle's concept of impetus, so momentum is described by this formula using a p for momentum.

*Momentum is a vector in the same direction as the velocity. Boldface is used to indicate vectors in this equation.

*Recall that the root symbol stood for a phrase. Similarly, the Greek letter, capital delta, stands for the phrase *the change in*.

Newton's second law may be described as "Impulse equals change in momentum.

Conservation of Momentum

8

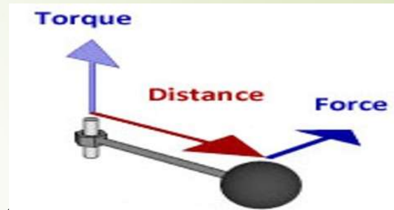
- Conservation: Total before equals the total afterwards
- Momentum vectors can be summed using graphical methods

*Conservation means that the sum of the elements is the same before and after an event.
*Because momentum is in the direction of the velocity, the momenta from several objects can be added using vector addition and the sum of momenta is the same before and after an event.

Newton's Laws and Circular Motion

9

- Torque: perpendicular force multiplied by its distance to the axis of rotation
- Angular momentum: angular inertia multiplied by angular speed

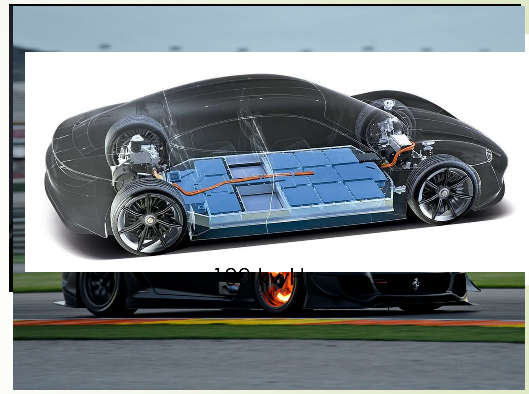


*Newton's laws apply to rotational motion. **Torque** is related to force. It is proportional to both the amount of perpendicular force and the distance of the force from the axis of rotation. It is commonly used to describe how to tighten nuts and bolts on cars.*
Angular momentum is like linear momentum except in a circle. Like momentum, it is proportional to the angular speed and the mass but shape and distribution of the mass matters. Increasing the distance of the mass from the axis of rotation increases the angular inertia and reduces the angular frequency and vice versa.

Types of Energy

10

- Energy is conserved
- Kinetic energy
- Sound waves
- Potential energy
  - Height (gravity)
  - springs
  - chemical
- Heat



*Energy is more illusive than momentum because it can take several forms and you have to account for all of them before the sums are equal before and after an event
*Energy of motion is called **kinetic** energy. It is proportional to the mass and the square of the speed.
*Motion of speakers can transform energy of motion into waves of sound energy
*Energy can be transformed into **potential energy** using *gravity and *springs and then transformed back into kinetic energy.*
*****Energy can be stored in bonds between molecules where we call it **chemical** energy like the battery in an electric vehicle
*Energy of motion ultimately ends up as **heat**. In this example the kinetic energy of the car is transformed into heat in the brakes.

Transfer of Energy

11

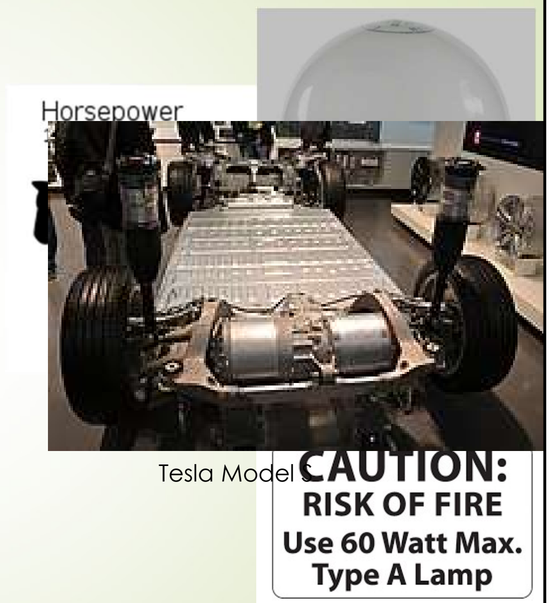
- Heat Energy
  - Conduction
  - Convection
  - Radiance
- Work
- Friction

Just as there are many forms of energy, there are several ways that energy can be transferred from one form into another or between objects.
*If an object has more heat energy than nearby objects, there are three main ways that energy is transferred to the cooler objects.
*Conduction is direct contact between the objects
*Convection is an indirect method that uses air currents between objects to transfer heat
*Radiance is transfer of heat by rays of light (more later)
*Work is defined as the product of force in the direction of motion and distance moved. Even though force has direction, work does not. Pushing on an immoveable object might be difficult but it doesn't transfer energy to the object and is not considered work by this definition.
*Most forms of motion energy are transferred to an object's surroundings by friction that ends up as heat

Power

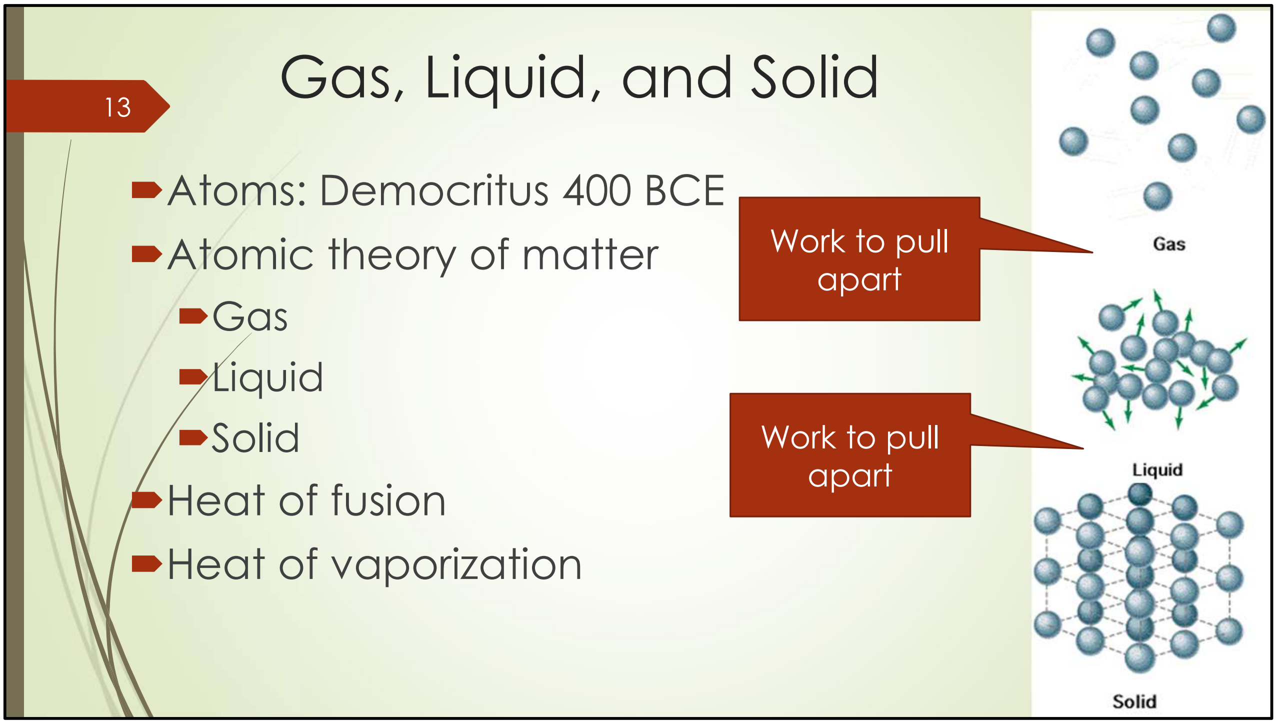
12

- Energy transferred per amount of time
- Horsepower
- Watt steam engine, 200 hp
- Electric power in watts or Kilowatts
- EV car; Tesla 815 KW



Tesla Model

*Power is the rate at which energy is transferred. Recall that one method of transferring energy is a force acting through a distance.
*In order to market his steam engines to miners, James Watt invented a measure of power named the horsepower. *He found that a strong horse could raise 550 lbs. of coal out of a mine at a rate of 1 foot per second. It would be doing 550 ft-lbs of work each second so it would have a power of 550 ft-lbs/second. He used this measurement unit to compare the cost of using horses to buying one of his engines. One of his
*Ironically, the international standard unit of power is named for him, the watt. It is used to describe the rate that electrical energy is converted into light and heat.
*The Kilowatt is close to a horsepower. A Tesla EV can accelerate from zero to 60 in about 3 seconds.



*Democritus proposed that you couldn't continue to divide matter into smaller pieces indefinitely but instead you would arrive at tiny, hard, indivisible particles that he called atoms that means uncuttable
*We can think of matter as composed of these very hard atoms that have a small attraction for each other like tiny steel ball bearings that are slightly magnetized.
*If the atoms have a lot of kinetic energy, they move too fast to stick together. In this form they move independently of each other, and this state is called a gas
*If they have less kinetic energy, their attraction causes a loose association that still allows for some independent motion. This is the liquid state
*If they have even less kinetic energy and move even slower, they associate themselves in more rigid arrangements, but they still vibrate next to each other. This is the solid state.
*If you start with a solid and add heat energy, work has to be done to pull them apart so they can move relative to each other. The heat it takes to transform the solid into a liquid is called its **heat of fusion**.
*If you heat a liquid, more work is needed to pull them completely apart, so they move independently as a gas. The heat it takes is called the **heat of vaporization**

Gas Pressure

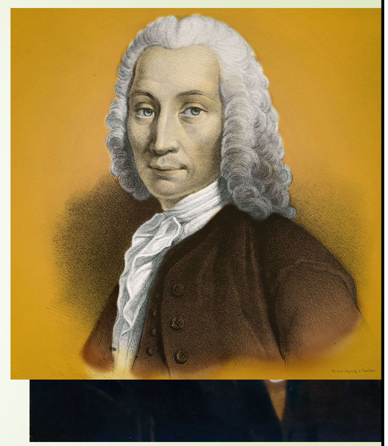
- Particles rebounding from walls is a change in their momentum
- Change in momentum is caused by an impulse
- The force on the gas particles equals their force on the wall
- Gas pressure is measured in units of force per area, psi

*When a particle of gas hits the stationary wall of its container, it rebounds like a billiard ball and changes direction but not speed. This implies that it changed momentum. *From Newton's second law, we know this required an impulse and *from his third law we know that the force on the particle that changed its momentum is matched with an equal but opposite force on the wall of the container.
*Pressure is the average force of these collisions divided by a unit of area, e.g. pounds per square inch or psi. A typical tire pressure is 38 psi.

Heat and Temperature

15

- Fahrenheit; Mercury thermometer, 1714
- Salted ice water: zero, melting ice 32, boiling water 212
- Celsius 1742; Boiling 100, freezing 0
- Not useful for comparisons

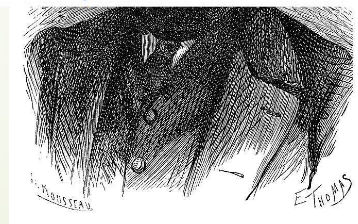


*Fahrenheit was familiar with using a column of mercury to measure air pressure in a barometer. He observed that the volume of mercury changed when it was hotter or cooler and he devised a sealed glass tube containing mercury that would vary in height with different amounts of heat and invented the thermometer.
*He wanted to avoid negative numbers on his scale when measuring outdoor temperatures, so he used salted ice-water as zero. On this scale, ice melts at 32 degrees and boils at 212.
*Anders Celsius, proposed a different scale that marked the melting point of ice as zero and the boiling point of water as 100. It is often called the centigrade scale due to its division into 100 degrees.
*The problem with both scales is that comparing two temperatures based on an arbitrary zero was meaningless. For example, if the temperature today is 20 and yesterday it was 2, does that mean it is ten times hotter today?

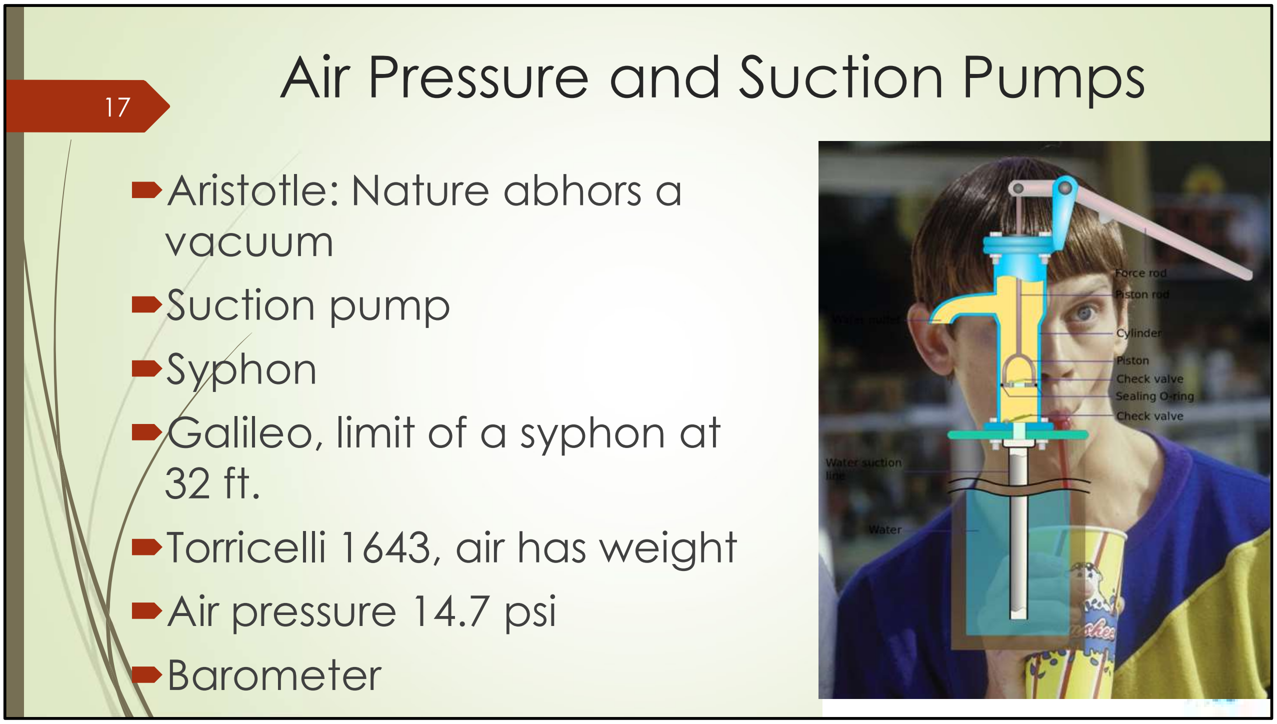
Heat and Temperature

16

- Lord Kelvin; 1848, absolute zero, no motion
- Melting ice, 373° K, Boiling water 473° K
- **Entropy**: randomness, 3rd Law of Thermodynamics
- Heat is the total energy content of the sample
- Temperature is the average energy



*Lord Kelvin proposed that since temperature was related to kinetic energy of motion, zero degrees should be zero motion. His scale places zero at zero motion. It uses the same size intervals as the Celsius scale.
*On the Kelvin scale, ice melts at 373° K and water boils at 473° K
*Entropy may be thought of as the amount of randomness to a sample's motion. At absolute zero, all motion of an object's particles stops so its entropy is zero.
*Heat content of a gas is the total kinetic energy of the particles plus the heats of fusion and evaporation.
*Temperature is the average kinetic energy of the particles that touch the thermometer. It does not measure the heat of fusion or evaporation.

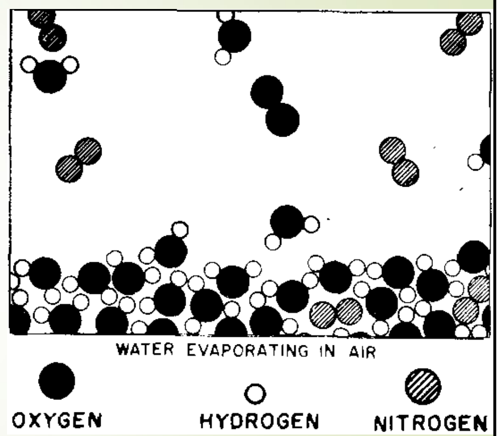


*Aristotle taught that nature abhors a vacuum and if you try to create one, a force of nature will oppose your efforts. For example, if you suck on a straw to create a vacuum, a force of nature will try to fill that vacuum and drive a liquid up the straw to your mouth.
*A lift pump is a mechanical version of sucking a straw. It tries to create a vacuum at the top of a pipe filled with water.
*A syphon is similar, but it uses the weight of a longer column of water below the surface to lift a shorter column over the edge of a container.
*Galileo noticed that a syphon wouldn't lift water more than 32 feet, but he didn't know why.
*Evangelista Torricelli, who was mentored by Galileo, discovered that air had weight. Air has mass and, according to Newton's law of gravity, it also has weight. A column of air 1 square inch wide and a hundred miles tall is attracted by the earth's mass and weighs 14.7 lbs. This weight is called atmospheric pressure. A column of water that is 1 inch square and 32 feet high, also weighs about 14.7 lbs. Suction pumps are limited to 32 feet of water because that is all the atmosphere will support.
*A column of mercury about 3/4 of a meter high also weighs about 14.7 lbs. This is short enough to fit in a room and can be used to measure atmospheric pressure in mm of Hg.

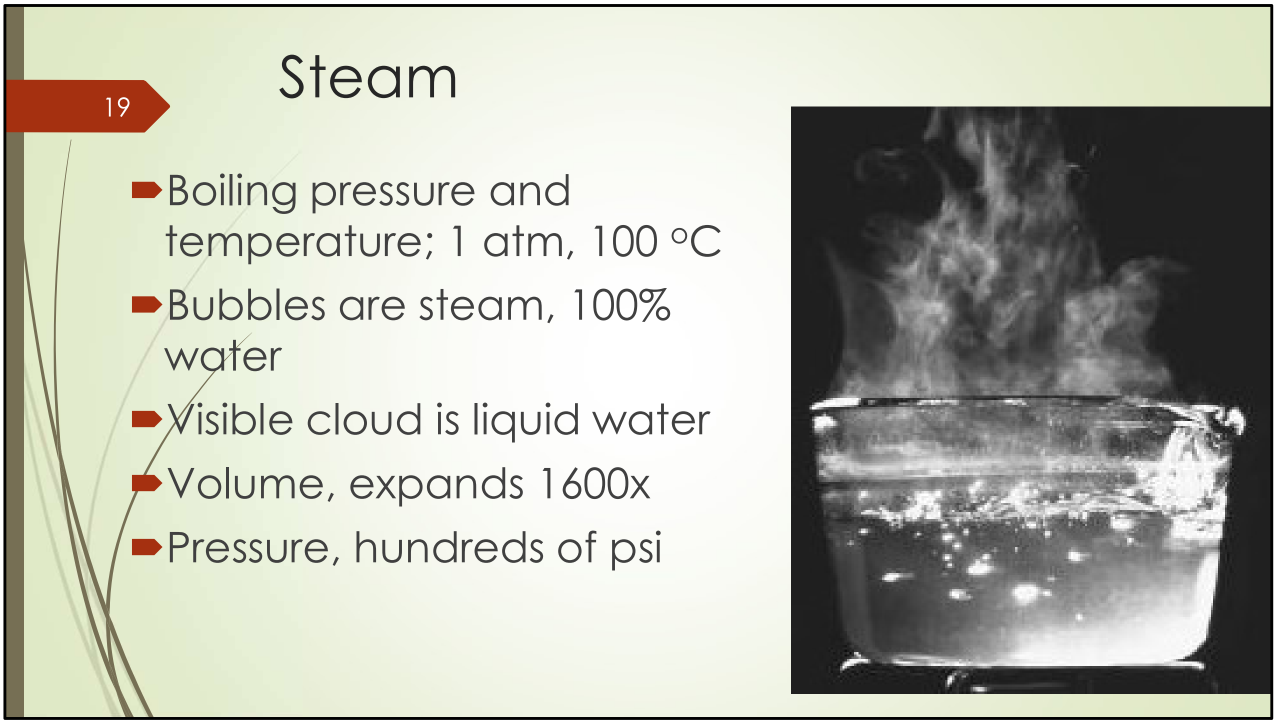
Evaporation

18

- Evaporation into the air
- Evaporation rate is proportional to temperature and air pressure



*At the interface between liquid water and air, some of the water particles will have enough speed to break free of their attraction to other water molecules but when they do, they collide with the air molecules.
*The rate at which water particles can escape a liquid into the air depends on the temperature of the liquid and the air pressure above the liquid.

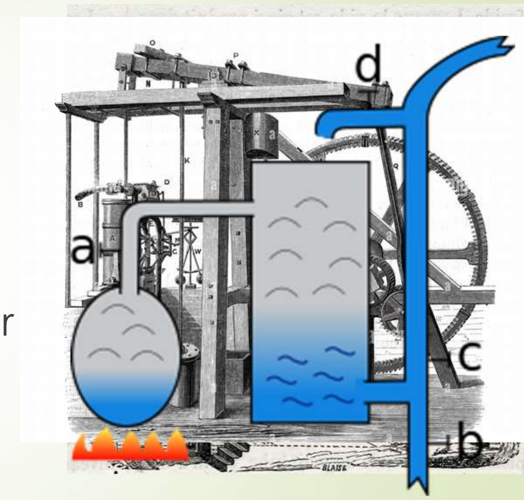


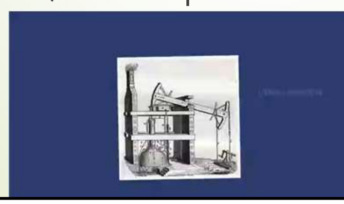
*Boiling occurs when the water particles are moving fast enough to separate from each other within the liquid water, in spite of the water's weight and the air pressure above it. This occurs at one atmosphere of air pressure and temperature of 100 deg. Celsius, 373 degrees Kelvin or 212 degrees Fahrenheit.
*The bubbles in the water are 100% water in its gaseous state. This is steam. It is transparent. Just above the surface of the water, the steam mixes with water particles that have evaporated from the surface
*As the water vapor rises, some of it cools and condenses into tiny droplets of liquid water that we can see. This is often called steam, but it is liquid water floating in the air.
*Steam, the gaseous form of water, takes up 1600x more volume than when its in its liquid state.
*If the boiling water is contained in a metal shell that restricts its expansion, the steam can cause pressures of hundreds of pounds per square inch.

Steam Engines

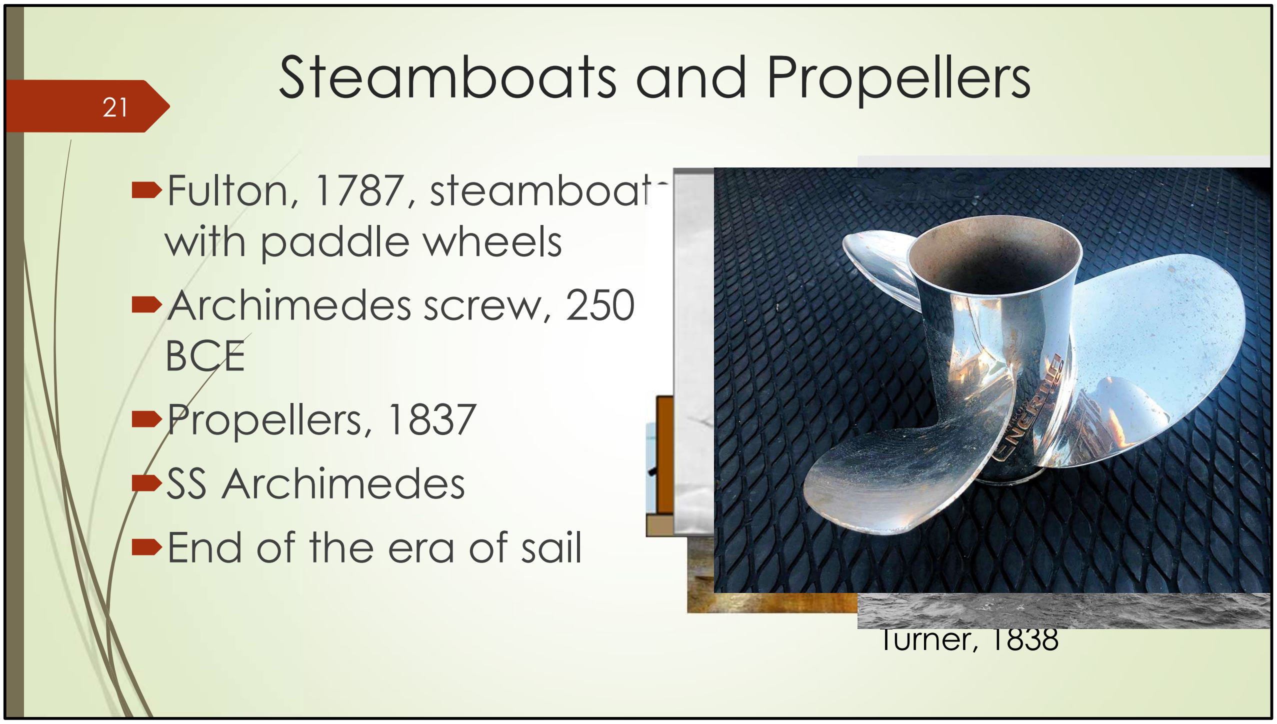
20

- Savery pump
- Newcomen, 0.5% efficient
- James Watt, 10% efficient
- Locomotives, 6% efficient
  - Range; 150 miles with tender
  - Top speed; 126 mph





*An early use for steam power was to pump water out of mines. The Savery pump filled a container with steam and then condensed it to create a vacuum. The vacuum was used to suck water up a pipe. It was limited to 32 feet.
*The Newcomen steam engine used a vacuum to pull a lever. It was inefficient, large, and very slow but it could use its rope to lift more than 32 feet down in the mine.
*James Watt built a steam engine that used the steam pressure directly on the piston and then transferred the steam to a separate chamber where it was cooled and condensed. It turned a large wheel that could turn gears attached to ropes wrapped around drums. It was faster and 20x more efficient than the Newcomen engine.
*Steam locomotives use the steam from boiling water to drive a piston back-and-forth in a cylinder and do not have a condensing chamber. Rather than wait for the steam to condense in a separate chamber, it is discarded with the smoke from the fire. This system is less efficient but faster and lighter weight.
*
*A locomotive that carried extra water and fuel in a separate car had a range of about 150 miles, and *could reach speeds of more than 100 mph.

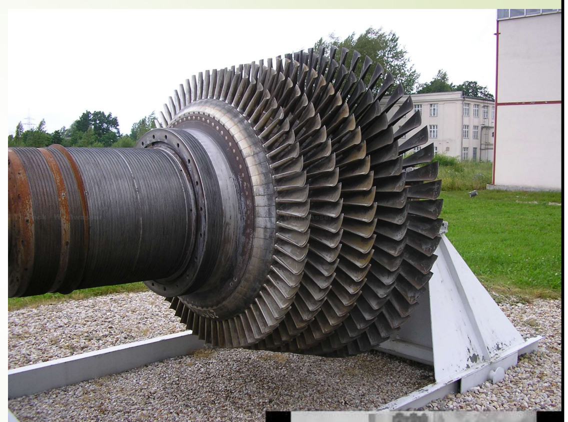


*Robert Fulton put together ideas from other inventors to design a commercially successful steam powered boat in 1787. Early steam powered boats used steam to push pistons that were connected by shafts to paddle wheels on the sides or at the rear of the boat.
*Archimedes invented a pump based on a helical blade rotating inside a tube. *His idea inspired later inventors to use helical shaped blades to propel a ship.
*A sailing ship was equipped with a boiler and an underwater propeller and named the SS Archimedes.
*Steam power connected to propellers marked the end of sailing ships. This was an emotional event that was captured in a famous painting by Turner in 1838 showing a British warship that fought the French at the battle of Trafalgar being towed to the breakers yard by a steam powered tugboat.

Turbines

22

- **Turbine**: Steam pushes blades to turn a shaft
- Multi-stage turbines
- The Turbinia; 1894



*A more effective way to convert steam pressure into rotary motion is for the steam to push against blades attached to a shaft. This device is a **turbine**.
*As the steam pushes a blade, it transfers some of its energy to the blade and the steam loses some pressure. To compensate, the next set of blades is longer which produces the same torque on the shaft with less force from the steam.
The first steam powered boat to use a turbine connected to underwater propellers was the Turbinia. The speed record for ships at that time was about 24 mph. It could reach speeds of 39 mph.

Absorption Refrigeration

23

- Absorption causes low pressure
- Water boils at low pressure and chills its surroundings
- Heat is used to dry out the absorber material to repeat the cycle
- Ferdinand Carre patents the absorption chiller, 1859
- Propane refrigerator

Steam can even be used to make ice and keep food cold
*Some chemicals like silica gel, ammonia, and lithium bromide attract water very strongly. They can pull water particles from the gas phase and cause very low gas pressure.
*That low pressure can be used to boil liquid water at a low temperature and cause it to draw so much heat from its surroundings that it can freeze ice, fish, or meat.
*Heat from steam, a flame, or electricity can force the water out of the absorber chemicals so the cycle can be repeated.
*Ferdinand Carre' developed a practical method of using absorption to chill food and make ice in 1859
*Absorption refrigerators are in use today when electricity isn't readily available. They use heat from burning propane to dry out the absorber material.

24

Steam Refrigeration

- Steamships could use steam for refrigeration
- *Paraguay* refrigerated meat from Argentina to France, 1877
- SS Strathleven, Melbourne to London 1880

*Steam powered ships were a natural partner for absorption chillers that could use the ship's steam to keep cargos cold.
*In 1877, Carre equipped the SS Paraguay with his refrigeration machine and it successfully transported frozen meat from Argentina to France.
*Refrigerated ships opened the trade in mutton and beef from Australia to England.

Laws of Thermodynamics

25

- Nature of heat: **thermodynamics**
- #1: Energy is conserved (You can't get something for nothing)
- #3: Absolute zero has zero entropy. Entropy increases with temperature
- #2: You can't break even, randomness always increases if you consider everything

During the age of steam, engineers and scientists sought to understand heat and how use it most efficiently.
*This field of study is called **thermodynamics**. There are three laws of thermodynamics, two of which you already know.
*The first law is that energy is conserved. You might have to search for its many different forms, but they will add up to the same amount before and after an event. This law also means that you cannot get free energy.
*The third law is that entropy is zero at zero degrees Kelvin and increases with temperature.
*The second law is that the entropy (randomness) increases with time if you consider the entropy of the total system, including an object's environment.

Arrow of Time

26

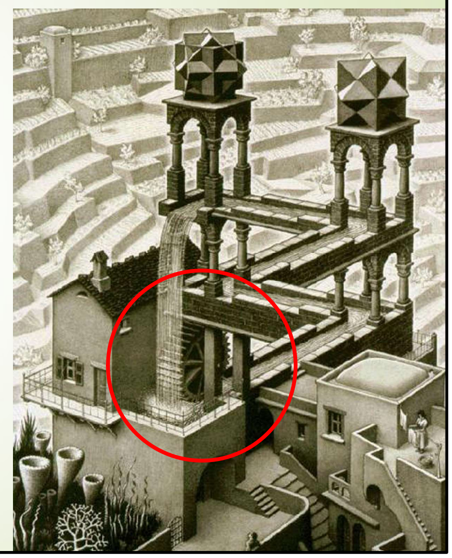
- Conservation of momentum and energy do not specify a direction of time
- However, we can always tell if a video is running backwards
- 2nd Law of Thermodynamics

*The laws of conservation of momentum and energy do not specify a sequence in time.
*However, we can always tell if a video is playing backwards.
*The second law of thermodynamics explains the arrow of time.

Perpetual Motion Machines

27

- Is anything possible?
- Perpetual motion machines
- Renewable or free energy?



*The ability to create ice using steam was so counterintuitive that it seemed that anything was possible. This led to numerous inventions in the 1800s that promised to provide energy for free.
*These types of ideas are called perpetual motion machines. Their designs violate one of the laws of thermodynamics and no one has every made a working model. In 1918, the U.S. Patent office stopped accepting applications that claimed to violate the laws of thermodynamics unless the application was accompanied by a working model.
*This idea is depicted in a famous painting by C.M. Escher.
*Notice the water wheel that provides free work to the mill next door.
* (video)
*Recent attempts to find alternatives to traditional sources of power have spawned new ideas for perpetual motion machines. The difference between an actual alternative and a perpetual motion machine is real alternatives have working prototypes.

Summary

28

- Momentum (m**v**) is conserved
- Energy has several forms: motion, potential, chemical, heat
- Temperature: average kinetic energy
- Transfer of energy: work, heat flow
- Phases of matter; gas, liquid, solid
- Heat of fusion and vaporization
- Steam expands 1600x and can do work
- Thermodynamics: 3 laws

29

What experiences and insights can you share with us?

30

References

- Wind turbines kill birds and bats: Link
- Patents: Link
- Locomotive efficiency: Link
- Thermal efficiency: Link
- Paraguay, refrigerated ship: Link

$$L = mvr$$