

Translational Motion

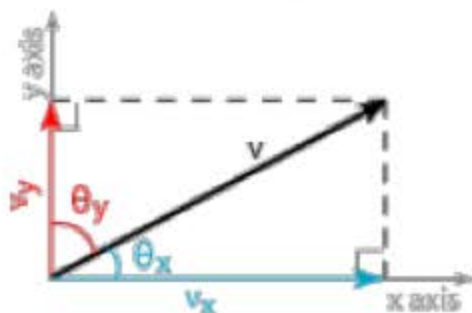
Dimensions (length or distance, time)

- One dimension = magnitude of length or distance only.
- Two dimensions = length or distance on a 2D plane (xy coordinates).
- Three dimensions = length or distance in 3D space (xyz coordinates).
- Four dimensions = length or distance in 3D space at a given time (xyz coordinates).

Vectors, components

- Scalar: without direction. For example, length, time, mass.
- Vector: with direction. For example, displacement, acceleration, force.
- Components: the portion of the vector in a given direction.

Axis-vector components



$$v_x = v \cos \theta_x = v \sin \theta_y$$

$$v_y = v \cos \theta_y = v \sin \theta_x$$

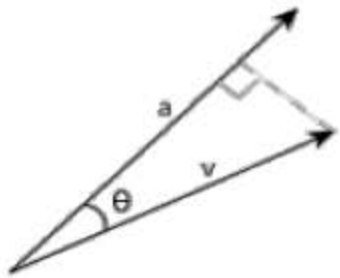
$$v^2 = v_x^2 + v_y^2$$

If there is z axis:

$$v_z = v \cos \theta_z$$

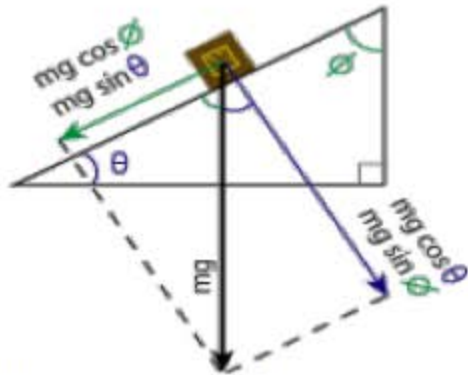
- $v^2 = v_x^2 + v_y^2 + v_z^2$

Vector-vector components



- $v_a = v \cos \theta$

Gravity components on slope



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- Trigonometric rules:
 - SOH CAH TOA = silly old Harry, caught a herring, trolling off Anglesea.
 - SOH: $\sin \theta = \text{opposite} / \text{hypotenuse}$.
 - CAH: $\cos \theta = \text{adjacent} / \text{hypotenuse}$.
 - TOA: $\tan \theta = \text{opposite} / \text{adjacent}$.

Vector addition

- You can only directly add vectors if they are in the same direction.
- To add vectors in different directions, you must add their x, y and z components. The resulting components make up the added vector.
- The vector sum of all components of a vector equal to the vector itself.
- Operation involving a vector and a vector may or may not result in a vector (kinetic energy from the square of vector velocity results in scalar energy).
- Operation involving a vector and a scalar always results in a vector.
- Operation involving a scalar and a scalar always results in a scalar.

Speed, velocity (average and instantaneous)

- Speed: scalar, no direction, rate of change in distance.
- Velocity: vector, has direction, rate of change in displacement.

- Average speed: $speed_{average} = v_{avg} = \frac{l}{t}$

$$velocity_{average} = v_{avg} = \frac{s}{t}$$

- Average velocity:
- Instantaneous speed is the speed at an instant (infinitesimal time interval).
- Instantaneous velocity is the velocity at an instant (infinitesimal time interval).
- Instantaneous speed equals instantaneous velocity in magnitude.
- Instantaneous velocity has a direction, instantaneous speed does not.
- The direction of instantaneous velocity is tangent to the path at that point.

Acceleration

- Acceleration is rate of the change

$$a_{avg} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t}$$

- Average acceleration:
 - Uniformly accelerated motion along a straight line
 - If acceleration is constant and there is no change in direction, all the following applies:
 - The value of speed/velocity, distance/displacement are interchangeable in this case, just keep a mental note of the direction.
 - $s = v_{avg}t$
 - $v_{avg} = \frac{v_f + v_i}{2}$
 - $a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t}$
 - $v_f^2 = v_i^2 + 2as$
 - $s = \frac{1}{2}at^2 + v_it$
 - $l_f = l_i + s$
 - You need to memorize those, be able to rearrange them, combine them, and how to use them.
 - You need to assign one direction as + and the opposite as -, and then keep this scheme for all your calculations.
 - For Cartesian coordinates, take upward and rightward motion as positive; down and left as negative.
 - For free falls, take downward as positive.
 - You can assign in what ever fashion you want, as long as the opposite direction is opposite in sign.

Free falling bodies

Free falling objects move toward the ground at constant acceleration.



- On Earth, the rate of acceleration is g , which is 9.8 m/s^2 .
- Whenever something is in the air, it's in a free fall, even when it is being tossed upwards, downwards or at an angle.
- For things being dropped, it's easier if you take down as positive, since that will make g positive.
- For things being tossed downwards, it's easier if you take down as positive, since that will make both initial velocity and g positive.
- For things being tossed upwards, the initial velocity will have opposite sign as g . You can take either up or down as positive depending on the question and what's convenient, but either way, initial velocity will have opposite signs as g .
- The acceleration due to gravity is constant because the force (weight) and mass of the object is constant.
- The net acceleration is a constant g if you don't take air resistance into consideration. Usually questions ignore air resistance. But if the question gives you air resistance, then the acceleration is no longer constant - it will decrease with time until it gets to zero at terminal velocity.
- When there's air resistance, the acceleration will decrease because the force (weight - resistance) is decreasing due to increasing resistance or friction at higher speeds.
- At terminal velocity, weight = friction, so the net force is 0. Thus, the acceleration is 0. So, the speed stays constant at terminal velocity.

Projectiles

- Projectiles are free falling bodies.
- The vertical component of the projectile velocity is always accelerating toward the Earth at a rate of g .
- The vertical acceleration of g toward the Earth holds true at all times, even when the projectile is traveling up (it's decelerating on its way up, which is the same thing as accelerating down).
- There is no acceleration in the horizontal component. The horizontal component of velocity is constant.
- What is the time the projectile is in the air? Ans: use the vertical component only- calculate the time it takes for the projectile to hit the ground.
- How far did the projectile travel? Ans: first get the time in the air by the vertical component. Then use the horizontal component's speed $\times$ time of flight. (Don't even think about over-analyzing and try to calculate the parabolic path).
- When you toss something straight up and it comes down to where it started, the displacement, s , for the entire trip is 0. Initial velocity and acceleration are opposite in sign.
- When you toss something straight up and it comes down to where it started, there is symmetry. Initial velocity and final velocity are equal and opposite. Time spent going up = time spent coming down.

Orbiting in space

Satellites orbiting the Earth are in free fall.



- Their centripetal acceleration equals the acceleration from the Earth's gravity.
- Even though they are accelerating toward the Earth, they never crash into the Earth's surface because the Earth is round (the surface curves away from the satellite at the same rate as the satellite falls).

Units and dimensions

- A unit is a label for a quantity.
- unit + unit = unit
- unit - unit = unit
- unit x unit = unit²
- unit / unit = no unit
- Dimensions are powers of units.
- unit = one dimension.
- unit² = two dimension.
- unit³ = three dimension.
-

Common SI units

Quantity	SI unit	Name
Length	m	meter
Area	m ²	meter squared
Volume	m ³	meter cubed
Mass	kg	kilogram
Density	kg/m ³	kilogram per meter cubed
Time	s	second
Speed	m/s	meter per second
Acceleration	m/s ²	meter per second squared
Force	N	Newton
Pressure	Pa	Pascal
Temperature	K	Kelvin
Energy	J	Joule
Power	W	Watt
Charge	C	Coulomb
Potential	V	Volt
Current	A	Ampere
Resistance	Ω	Ohm
Magnetic field	T	Tesla

- The product of operations involving all SI units is also in SI units.

- **Prefixes for units**

Prefix Abbreviation Multiplier

exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^9
mega	M	10^6
kilo	k	10^3
hecto	h	10^2
deka	da	10^1
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Force, Motion and Gravitation

Center of mass

The center of mass is the average distance, weighted by mass

$$x_{cm} = \frac{\sum x_i m_i}{\sum m_i} \quad y_{cm} = \frac{\sum y_i m_i}{\sum m_i} \quad z_{cm} = \frac{\sum z_i m_i}{\sum m_i}$$

- In a Cartesian coordinate, the center of mass is the point obtained by doing a weighted average for all the positions by their respective masses.
- The center of mass of the Earth and a chicken in space is going to be almost at the center of the Earth, because the chicken is tiny, and its coordinate is weighted so.
- The center of mass between two chickens in space is going to be right in the middle of the two chickens, because their positions are weighted equally.
- You do not have to obtain the absolute coordinates when calculating the center of mass. You can set the point of reference anywhere and use relative coordinates.
- The center of mass for a sphere is at the center of the sphere.
- The center of mass of a donut is at the center of the donut (the hole).

Newton's first law, inertia

The law of inertia basically states the following: without an external force acting on an object, nothing will change about that object in terms of speed and direction.

In the absence of an external force:

- Something at rest will remain at rest
- Something in motion will remain in motion with the same speed and direction.
- Objects are "inert" to changes in speed and direction.

Newton's second law ($F = ma$)

$$F = ma$$

A net force acting on an object will cause that object to accelerate in the direction of the net force.

- The unit for force is the Newton. $N = \text{kg}\cdot\text{m}/\text{s}^2$
- Both force and acceleration are vectors because they have a direction.
- Many questions omit the direction attribute because it is so obvious. For example, when an apple falls to the ground (or on Newton), we all know that the force of gravity acts downwards, and the apple of course, falls downwards. Questions in this scenario are just simple cases of plugging in the formula
- However, more difficult questions have directional attributes associated with them. For example, when a bar of soap slides down an inclined plane, the force of gravity acts downwards, but the acceleration is not completely downwards, but is "slanted". Therefore, you need to do vector analysis (simple ones only. The exam is too short for complex, time-consuming ones that appear in your physics midterm).

Newton's third law, forces equal and opposite

Every action has an equal and opposite reaction

- for the exam, you need to know that this law applies to propulsion. This is why rockets work even in the vacuum of space.

Concept of a field

- For the purposes of the exam, fields are lines.
- When lines are close together, that shows a strong field.
- When lines are far apart, that shows a weak field.
- Lines / fields have direction too, and that means they are vectors.
- Things travel parallel, perpendicular, or spiral to the field line.

Law of gravitation ($F = Gm_1m_2/r^2$)

$$F = G \frac{m_1 m_2}{r^2}$$

- Gravity decreases with the square of the distance.
- If the distance increases two fold, gravity decreases by a factor of four.
- The "distance" is the distance from the center of mass between the two objects.
- Gravity is the weakest of the four universal forces.
- This weakness is reflected in the universal gravitational constant, G ,

which is orders of magnitude smaller than the Coulomb's constant.

Uniform circular motion

Memorize the equations

- acceleration: $a = \frac{v^2}{r}$
- force: $F = ma = \frac{mv^2}{r}$
- circumference: $c = 2\pi \cdot r$
- arc: $\text{arc} = \frac{\theta}{2\pi} \cdot c = \theta \cdot r$
- area: $A = \pi \cdot r^2$
- sector: $A' = \frac{\theta}{2\pi} \cdot A = \frac{1}{2} \theta \cdot r^2$
- note that theta is always in radians. To convert degrees to radians, use this formula: $2\pi \cdot \text{rad} = 360 \cdot \text{deg}$
- The simple harmonic laws of frequency and period applies here also.

Get the concepts

- Distinguish between velocity and speed: Velocity is displacement over time. Speed is the distance over time.
- Displacement is the shortest, straight-line distance between two points on the perimeter of a circle (technically, this is called the chord). Distance is circumference and arc.
- Some typical cases:
 - For displacements and distances that approach zero, the instantaneous velocity equals the speed.
 - For a quarter around the circle ($\pi/2$ radians or 90 degrees), the displacement is the hypotenuse of a right-angled triangle with the radius as the other two sides. Using Pythagoras, the displacement is square root of $2r^2$. The distance is the arc of 1/4 circumference.
 - For half around the circle, the displacement is the diameter and the distance is the half the circumference.
 - For three quarters around the circle, the displacement is again obtained by Pythagoras. The magnitude of the displacement here is the same as that at a quarter of a circle, but the direction is different. The distance, is 3/4 of the circumference.
 - Complete around the circle, the displacement is zero, which makes the velocity also zero. The distance is the circumference.
- The velocity is always less or equal to the speed.
- The displacement is always less or equal to the distance.
- Displacement and velocity are vectors. Distance and speed are not.
- Moving around a circle at constant speed is also simple harmonic motion.

- frequency = how many times the object goes around the circle in one second.
- period = time it takes to move around the entire circle.

Centripetal Force ($F = -mv^2/r$)

Centripetal force is due to centripetal acceleration. Centripetal acceleration is due to changes in velocity when going around a circle. The change in velocity is due to a constant change in direction.

- Centripetal force: $F = ma = \frac{mv^2}{r}$
 - Sometimes a negative sign is used for centripetal force to indicate that the direction of the force is toward the center of circle.
- Centripetal acceleration: $a = \frac{v^2}{r}$
- The direction of both the acceleration and the force is toward the center of the circle.
- The tension force in the string (attached to the object going in circles) is the same as the centripetal force.
- When the centripetal force is taken away (Such as when the string snaps), the object will fly off in a path tangent to the circle at the point of snap.

Weight

Weight is the force that acts on a mass

- Weight is a force. It has a magnitude and a direction. It is a vector.
- Because it is a force, $F=ma$ holds true.
- Your weight on the surface of the Earth: $F=mg$, where g is the acceleration due to Earth, which is just under 10.
- You weigh more on an elevator accelerating up because $F=mg + ma$, where a is the acceleration of the elevator.
- An elevator accelerating up is the same thing as an elevator decelerating on its way down, in terms of the acceleration in $F=mg + ma$.
- You weigh less on an elevator accelerating down because $F=mg - ma$, where a is the acceleration of the elevator.
- An elevator accelerating down is the same thing as an elevator decelerating on its way up, in terms of the acceleration in $F=mg - ma$.
- You weight less when you are further away from the Earth because the force of gravity decreases with distance.
- However, you are not truly "weightless" when orbiting the Earth in space. You are simply falling toward the Earth at the same rate as your space craft.
- You gain weight as you fall from space to the surface of the earth.

- For a given mass, its weight on Earth is different from its weight on the Moon.
- When something is laying still on a horizontal surface, the normal force is equal and opposite to the weight.
- When something is laying still on an inclined plane, the normal force and friction force adds up in a vector fashion to equal the weight.

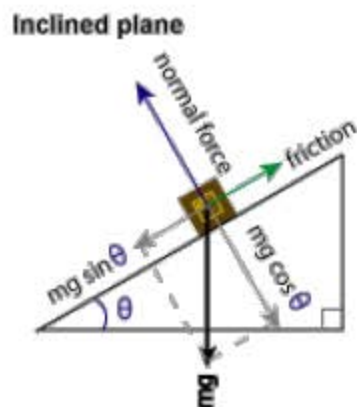
Friction, static and kinetic

Friction is a force that is always in the direction to impede the sliding of surfaces.

Static friction: $F_s = \mu_s N$ Kinetic friction: $F_k = \mu_k N$
 μ is the coefficient of friction and N is the normal force.

- Like any other force, friction is a vector. However, its direction is easy because it's always opposite to the motion of the surface involved.
- Static friction pertains to objects sitting still. An object can sit still on an inclined plane because of static friction.
- Kinetic friction pertains to objects in motion. A key sliding across the table eventually comes to a stop because of kinetic friction.
- Static friction is always larger than kinetic friction.
- The coefficient static friction is always larger than the coefficient of kinetic friction.
- The coefficient of friction is intrinsic to the material properties of the surface and the object, and is determined empirically.
- The normal force at a horizontal surface is equal to the weight
- The normal force at an inclined plane is equal to the weight times the cosine of the incline angle (see inclined planes).
- We can walk and cars can run because of friction.
- Lubricants reduce friction because they change surface properties and reduce the coefficient of friction.
- Every time there is friction, heat is produced as a by-product.

Motion on an inclined plane



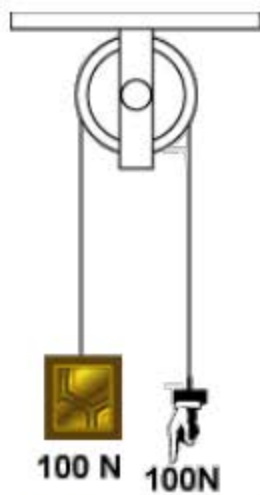
- Gravity is divided into two components on an inclined plane.

- One component is normal (perpendicular) to the plane surface: $F_N = mg \cdot \cos\theta$
 - The other component is parallel to the plane surface: $F_{\parallel} = mg \cdot \sin\theta$
- To prevent the object from crashing through the surface of the inclined plane, the surface provides a normal force that is equal and opposite to the normal component of gravity.
- Friction acts parallel to the plane surface and opposite to the direction of motion.
- In a non-moving object on an inclined plane: normal component of gravity = normal force; parallel component of gravity = static friction.
- Unless the object levitates or crashes through the inclined plane, the normal force always equals the normal component of gravity.
- In an object going down the inclined plane at constant velocity: parallel component of gravity = kinetic friction (yes, they're equal, don't make the mistake of thinking it's larger. Constant velocity = no acceleration = no net force).
- In an object that begins to slip on the inclined plane: parallel component of gravity > static friction.
- In an object that accelerates down the inclined plane: parallel component of gravity > kinetic friction.
- When you push an object up an inclined plane, you need to overcome both the parallel component of gravity and friction.
- When you push or pull an object up an inclined plane, make sure you divide that force into its components. Only the component parallel to the plane contributes to the motion.

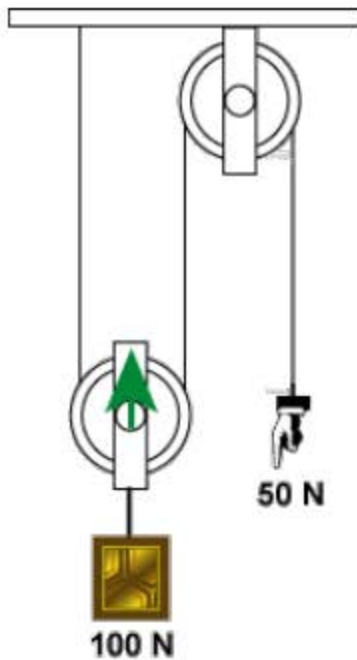
Analysis of pulley systems

Pulleys reduce the force you need to lift an object. The catch - it increases the required pulling distance.

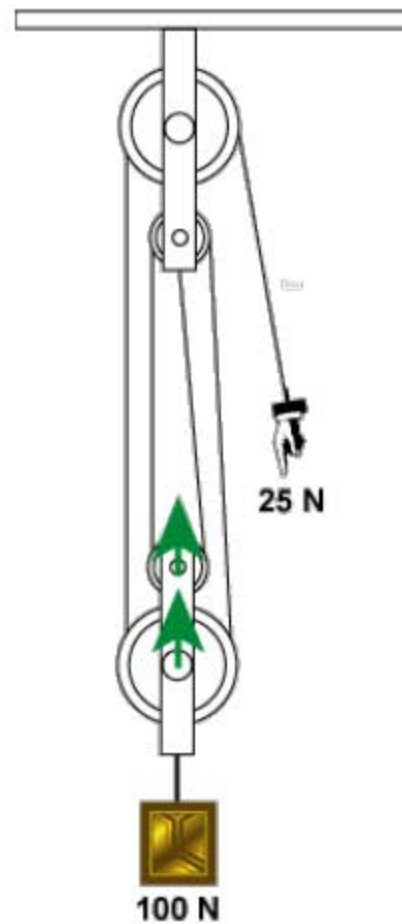
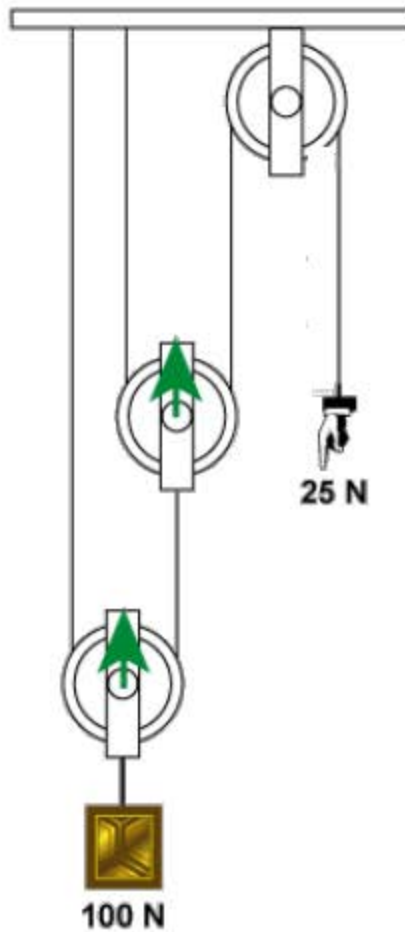
- For the purpose of the exam, just memorize the simple pulley systems below.
- Rule of thumb: The ropes on either side of a moving pulley contributes to pulling the load.
- The exam will most probably give you simple pulleys where only the above rule is applicable.
- Complex pulleys will have additional ropes that contribute to the pulling of the load (most likely not tested on the exam).
- The distance of pulling increases by the same factor that the effort decreases.



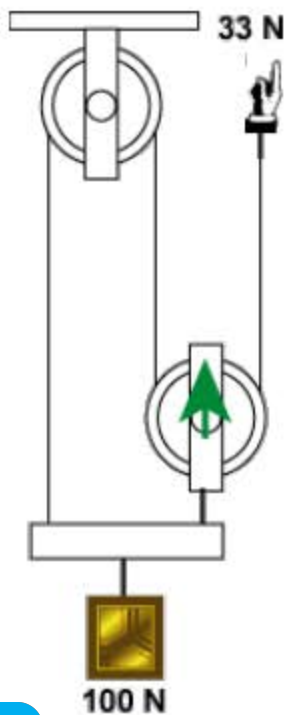
There are no moving pulleys here. If the weight of the box is 100 N, you have to pull with a force of 100 N. For every 1 meter you pull, the box goes up 1 meter.



When there is one moving pulley, the force needed to pull is halved because strings on both side of the pulley contribute equally. You supply 50 N (which is transmitted to the right-hand rope) while the left-hand rope contributes the other 50 N. Because effort here is halved, the distance required to pull the box is doubled.



There are two moving pulleys here. Counting the ropes reveal that when we tug on one rope, it gets transmitted to a system where 4 ropes pull on the load. Thus, you can pull the 100 N box with only 25 N. However, for every 4 m you pull, the box only goes up 1 m.



This is a complex pulley. Just like the simple pulleys, the ropes on both sides of the moving pulley contribute. Here, the left-most rope contributes also. This makes 3 contributing ropes, which makes the effort required to be reduced by a factor of 3. The distance you need to pull here is 3 times the distance the box will travel.

Force

- There are 4 universal forces... get it?
- Universal forces are also called fundamental forces.
- The four forces are:
 - The strong force: also called the nuclear force. It is the strongest of all four forces, but it only acts at subatomic distances. It binds nucleons together.
 - Electromagnetic force: about one order of magnitude weaker than the strong force, but it can act at observable distances. Binds atoms together. Allows magnets to stick to your refrigerators. It is responsible for the fact that you are not falling through your chair right now (I should love to throw you quirky examples like this one).
 - Weak force: roughly 10 orders of magnitude weaker than the strong force. Responsible for radioactive decay.
 - Gravity: roughly 50 orders of magnitude weaker than the strong force. Responsible for weight (not mass!). Also, responsible for planet orbits.

Equilibrium and Momentum

Equilibrium

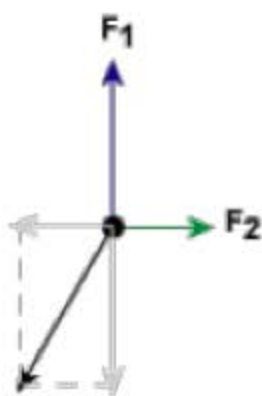
- When something is in equilibrium, the vector sum of all forces acting on it $= 0$.
- Another way to put it: when something is in equilibrium, it is either at rest or moving at constant velocity.
- Yet another way to put it: when something is in equilibrium, there is no overall acceleration.

Concept of force, units

- Force makes things accelerate, change velocity or change direction.
- In the exam, a force is indicated by an arrow.
- The direction of the arrow is the direction of the force.
- The magnitude of the force is often labeled beside the arrow.
- $F=ma$, so the unit for the force is $\text{kg}\cdot\text{m}/\text{s}^2$

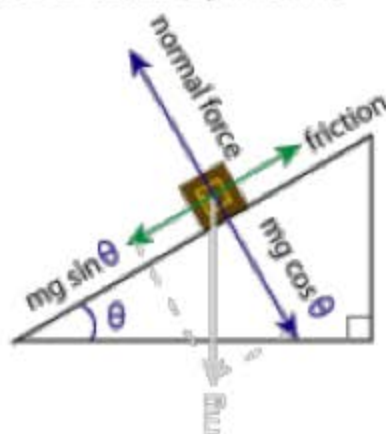
Translational equilibrium (Sum of $F_i = 0$)

Translational equilibrium



- $F_1 + F_2 + F_3 = 0$
- When things are at translational equilibrium, the vector sum of all forces $= 0$.
- Things at translational equilibrium either don't move, or is moving at a

Translational equilibrium



$$mg \cos \theta = \text{normal force}$$

$$mg \sin \theta = \text{friction}$$

- constant velocity.
- If an object is accelerating, it's not in equilibrium.
- Deceleration is acceleration in the opposite direction.
- At translational equilibrium:
 - An apple sitting still.
 - A car moving at constant velocity.
 - A skydiver at falling at terminal velocity.
- NOT at translational equilibrium:
 - An apple falling toward the Earth with an acceleration of g .
 - A car either accelerating or decelerating.
 - A skydiver before he or she reaches terminal velocity.

Rotational equilibrium (Sum of Torque = 0)

- When things are at rotational equilibrium, there the sum of all torques = 0.
- Conventionally, positive torques act counterclockwise, negative torques act clockwise.
- When things are at rotational equilibrium, they either don't rotate or they rotate at a constant rate (angular velocity, frequency).
- You cannot have rotational equilibrium if there is angular acceleration.
- Deceleration is acceleration in the opposite direction.
- At rotational equilibrium:
 - Equal weights on a balance.
 - Propeller spinning at a fixed frequency.
 - Asteroid rotating at a constant pace as it drifts in space.
- NOT at rotational equilibrium:
 - Unequal weights in a balance such that the balance is begins to tilt.
 - Propeller spinning faster and faster.
 - Propeller slowing down.

Analysis of forces acting on an object

- Draw force diagram (force vectors).
- Split the forces into x, y and z components (normal and parallel components for inclined planes).
- Add up all the force components.
- The resulting x, y and z components make up the net force acting on the object.
- Use Pythagoras theorem to get the magnitude of the net force from its components.
- Use trigonometry to get the angles.
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Newton's first law, inertia

- The significance of Newton's first law on equilibrium is: things in equilibrium will remain in equilibrium unless acted on by an external

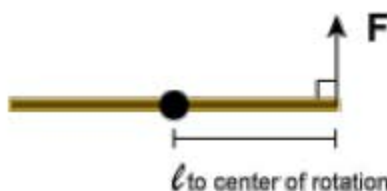
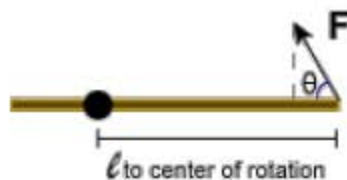
force.

- The significance of Newton's first law on momentum is: things resist change in momentum because of inertia (try stopping a truck. It's not easy because it resists changes to its huge momentum).
-

Torques, lever arms

- Torque

Torque



◦ $\text{Torque} = F l \sin \theta$

$\text{Torque} = F l \sin 90^\circ = F l$

- Torque is the angular equivalent of a force - it makes things rotate, have angular acceleration, change angular velocity and direction.
- The convention is that positive torque makes things rotate anticlockwise and negative torque makes things rotate clockwise.
- Lever
 - The lever arm consists of a lever (rigid rod) and a fulcrum (where the center of rotation occurs).
 - The torque is the same at all positions of the lever arm (both on the same side and on the other side of the fulcrum).
 - $F_1 l_1 = F_2 l_2$
 - If you apply a force at a long distance from the fulcrum, you exert a greater force on a position closer to the fulcrum.
 - The catch: you need to move the lever arm through a longer distance.

Weightlessness

- There are two kind of weightlessness - real and apparent.
 - Real weightlessness: when there is no net gravitational force acting on you. Either you are so far out in space that there's no objects around you for light-years away, or you are between two objects with equal gravitational forces that cancel each other out.
 - Apparent weightlessness: this is what we "weightlessness" really means when we see astronauts orbiting in space. The astronauts are falling toward the earth due to gravitational forces (weight), but they are falling at the same rate as their shuttle, so it appears that they are "weightless" inside the shuttle.

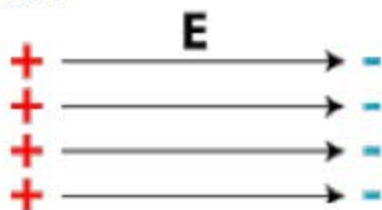
Momentum

- Momentum = mv , where m is mass, v is velocity and the symbol for momentum is p .
- Impulse = Ft , where F is force and t is the time interval that the force acts.
- Impulse = change in momentum: $Ft = m\Delta v$
- Conservation of linear momentum
 - Total momentum before = total momentum after.
 - Momentum is a vector, so be sure to assign one direction as positive and another as negative when adding individual momenta in calculating the total momentum.
 - The momentum of a bomb at rest = the vector sum of the momenta of all the shrapnel from the explosion.
 - Total momentum of 2 objects before a collision = total momentum of 2 objects after a collision.
- Elastic collisions
 - Perfectly elastic collisions: conservation of both momentum and kinetic energy.
 - Conservation of kinetic energy: total kinetic energy before = total kinetic energy after.
 - Kinetic energy is scalar, so there are no positive / negative signs to worry about.
 - If you drop a ball and the ball bounces back to its original height - that's a perfectly elastic collision.
 - If you throw a ball at a wall and your ball bounces back with exactly the same speed as it was before it hit the wall - that's a perfectly elastic collision.
- Inelastic collisions
 - Conservation of momentum only.
 - Kinetic energy is lost during an inelastic collision.
 - Collisions in everyday life are inelastic to varying extents.
 - When things stick together after a collision, it is said to be a totally inelastic collision.

Electrostatics and Electromagnetism

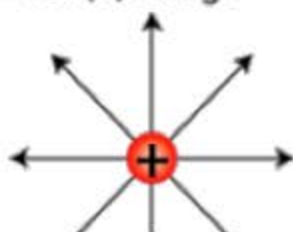
Electrostatics

- Charge, conductors, charge conservation
 - Charges are either positive or negative. Zero charge is neutral.
 - Like charges repel, unlike charges attract.
 - Charge is quantized, and the unit of charge is the Coulomb.
 - Conductors are materials in which charges can move freely. Metals are good conductors.
 - Charge is always conserved. You can't create or destroy charge, you can only transfer charge from one source to another.
- Insulators
 - Insulators are materials in which charges can not move freely. Nonmetals are good insulators.
- Coulomb's law ($F = kq_1q_2/r^2$, sign conventions)
 - $F = kq_1q_2/r^2$
 - $k = 9E9 \text{ Nm}^2/\text{C}^2$
 - q is positive for positive charges and negative for negative charges.
 - Positive F = repelling force.
 - Negative F = attractive force.
- Electric field
 - field lines

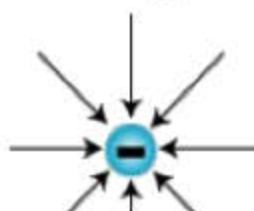


- Electric field is denoted by the vector E .
- Lines that are closer together denote stronger fields than lines that are farther apart.

E for (+) charge

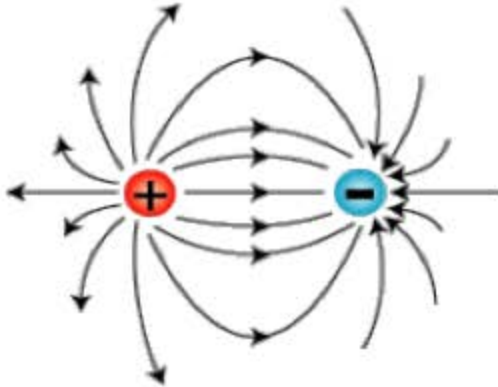


E for lone (-) charge



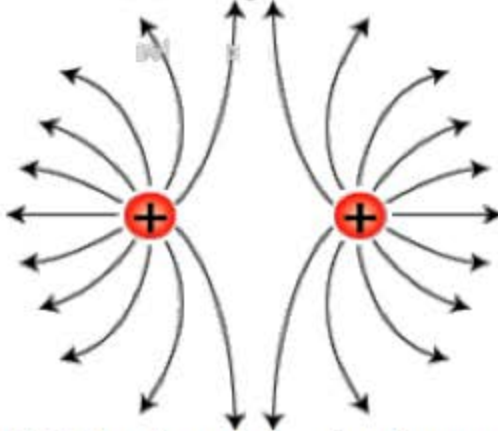
- Electric fields come out of positive charges, and goes into negative charges.
- The unit for electric field is N/C , or Newtons per Coulomb.
- field due to charge distribution

E for dipole



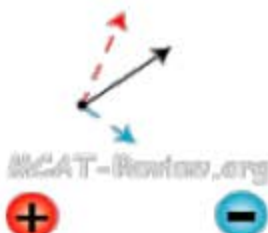
-
- Field lines come out of the positive end and goes into the negative end of a dipole.

E for 2 (+) charges



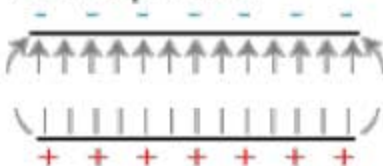
-
- Field lines for two negative charges are the same as those for two positive charges except that the direction of the field lines would be reversed.

E as vector sum



-
- The direction and magnitude of the field at any point in space can be calculated as the vector sum of all the field components there.

E for capacitors



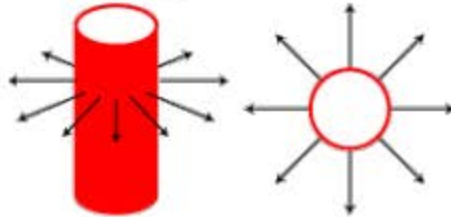
- Electric field in between a capacitor is uniform until it reaches the ends of the capacitor.

E for (+) wire



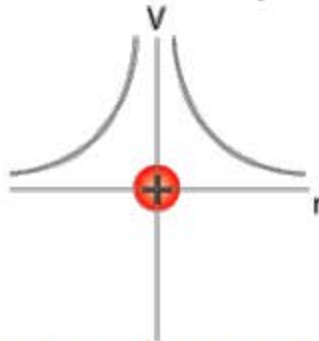
-
- Electric field for wires runs radially perpendicular to the wire.

E for (+) cylinder

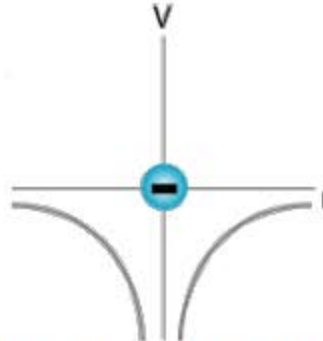


- - Electric field for a cylinder runs radially perpendicular to the cylinder, and is zero inside the cylinder.
- o Potential difference, absolute potential at point in space

Potential for (+) charge



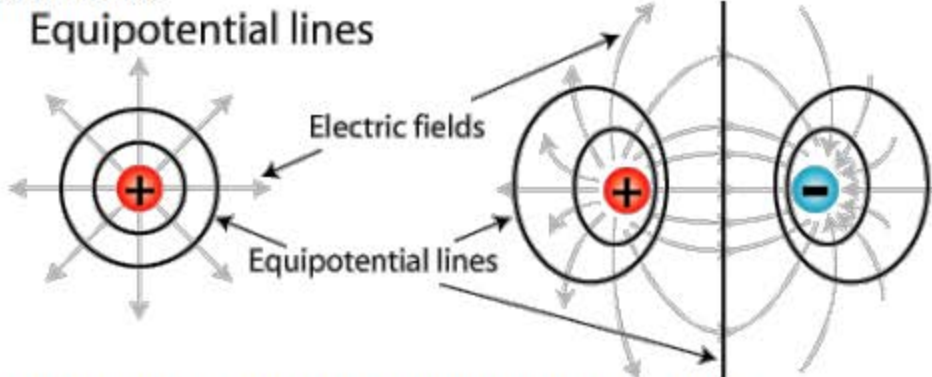
Potential for (-) charge



-
- Absolute potential (V) is the amount of energy per charge that something possesses.
 - $V = \frac{U}{q_0} = kq/r$
 - V is the electric potential (absolute potential) caused by q, which is experienced by q_0 .
 - q is the charge that is causing the potential, not the charge that's experiencing the potential.
 - Traditionally, q_0 is the charge experiencing the potential. The magnitude of q_0 is very small.
 - U is the electrical potential energy possessed by q_0 .

- r is the distance between the potential-causing charge and the charge that's experiencing the potential (r is always positive).
- if there are multiple charges contributing to the potential, then calculate the potentials each of them causes (positive charges cause positive potentials, and negative charges cause negative potentials), and sum them together.
- The unit for potential is Volts (V) or Joules per Coulomb (J/C).
- Potential difference (ΔV) is the difference between two potentials.
 - $\Delta V = V_B - V_A$
 - Potential difference is used in scenarios such as the difference in potential between the two plates of a capacitor, or the positive and negative terminals of a battery.

◦ Equipotential lines

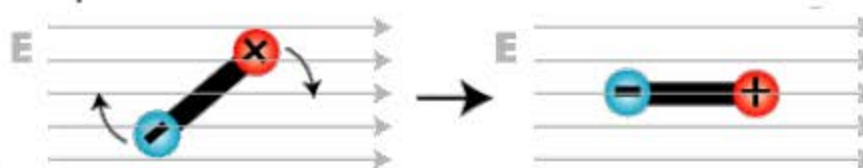


- Equipotential lines are places where the potential is the same.
- Equipotential lines are always perpendicular to electric field lines.

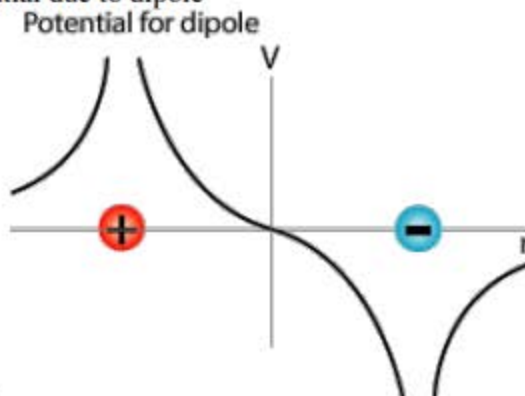
◦ Electric dipole

- definition of dipole
 - dipole = a positive charge and a negative charge separated by some distance.
- behavior in electric field

Dipole in an electric field

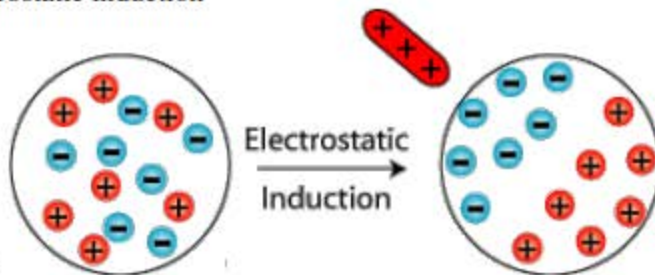


- A dipole in an electric field will want to align itself with the electric field, such that the positive end of the dipole is in the direction of the electric field.
- potential due to dipole



- To calculate the exact potential at a given point, just calculate the individual potential due to the positive charge and the negative charge, then add them together.

◦ Electrostatic Induction

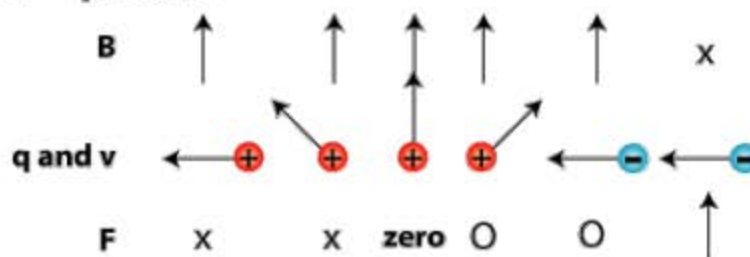


- Induction does not involve any type of conduction.
 - Electrostatic induction is where a charged object induces the movement / redistribution of charges in another object.
 - The classical example of electrostatic induction is picking up pieces of paper using a comb rubbed against fur.
 - It's called electrostatic induction because it's static - the charged species polarizes non-charged species by simply being there. This is not the same as electromagnetic induction, which is how electric generators work. Luckily electromagnetic induction is not listed as an official AAMC topic.
- Gauss' law
- $\Phi_E = EA \cos\theta$
 - Φ_E is electric flux.
 - E is electric field, A is area that the field goes through, and θ is the angle between the field and the normal of the area.
 - $\Phi_E = q/\epsilon_0$
 - For an enclosed surface, the electric flux is equal to q , the charge inside the enclosure, over the permittivity of free space.
 - The net electric flux through any enclosed surface is totally dependent on the charge inside. If there's no charge inside, then the net electric flux through the enclosure is zero.
 - An important application of Gauss's law is the Faraday cage. Basically, the electric field inside a closed conducting cage is zero. This is because the charges on the conducting cage will rearrange to cancel out any external field

Magnetism

- Definition of the magnetic field **B**
- Magnetic field **B** exists in a region of space if a moving charge experiences a force due to its motion in that region.
 - The unit for magnetic field is the Tesla (T) or $N \cdot s / m \cdot C$
- Existence and direction of force on charge moving in magnetic field

$$\mathbf{F} = q\mathbf{vB} \sin\theta$$

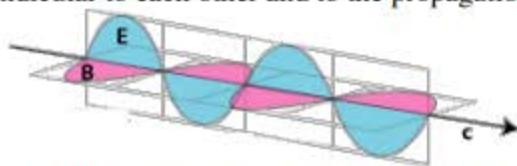


- $X = \text{into the page}, O = \text{out of the page}$
- $F = qvB \sin\theta$
- θ is the angle between the charge velocity and the magnetic field. Sometimes the $\sin\theta$ is omitted as θ is assumed to be 90° .
- The force is always perpendicular to both the magnetic field and to the velocity of the charge.

- You can use the right hand rule to predict the direction of the force. The thumb is the direction of a positive charge, the middle finger is the direction of the magnetic field, and the palm faces the direction of the force.
- Special scenarios / cases
 - Charge moving in a circle
 - $F = qvB = mv^2/r$
 - You are setting the electromagnetic force equal to the centripetal force, which maintains the orbit. Using this equation, you can solve for whatever the question asks you.
 - Current carrying wires
 - $F = qvB \sin\theta = (it)vB \sin\theta = (it)(L/t)B \sin\theta = iLB \sin\theta$
 - i is current, L is length of wire.
 - Consider the current in the wire as moving positive charges (by tradition, the direction of the current is defined as the direction of moving positive charges).
 - You can calculate the direction of the force on the wire in the same way using the right hand rule. Just treat the direction of the current the same as the direction of velocity of a positive charge.
 - Two wires will attract each other if the current is in the same direction.
 - Two wires will repel each other if the current is in opposite directions.

Electromagnetic Radiation (Light)

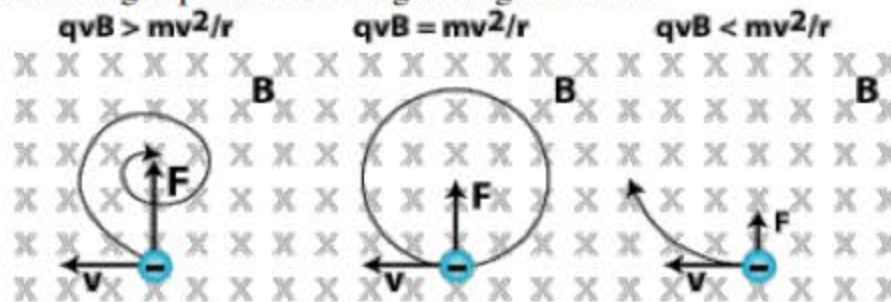
- Properties of electromagnetic radiation (general properties only)
 - radiation velocity equals constant c , in vacuo
 - Electromagnetic radiation travels fastest in a vacuum, at a velocity equals c , or $3 \times 10^8 \text{ m/s}$
 - Light slows down when it travels in a medium other than in vacuo.
 - $n = c/v$, where n is the index of refraction for the medium, and v is the speed of light travelling in that medium.
 - radiation consists of oscillating electric and magnetic fields that are mutually perpendicular to each other and to the propagation direction



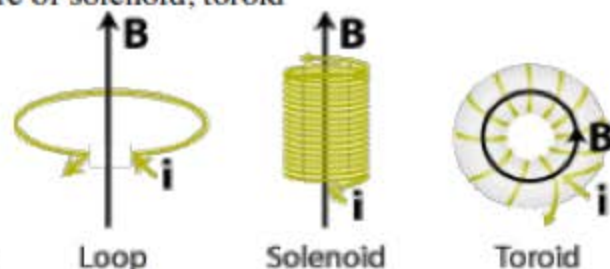
- - Classification of electromagnetic spectrum (radio, infrared, UV, X-rays, etc.)
 - Lower frequency, longer wavelength, less energy
 - Radio Causes electronic oscillations in the antenna
 - Microwave Causes molecular rotation
 - Infrared Causes molecular vibration
 - Visible Can excite electrons to orbits of higher energy. Visible light ranges from 400-700 nm. 400ish being violet, 700ish being red.
 - Ultraviolet Can break bonds and excite electrons so much as to eject them, which is why UV is considered ionizing radiation.
 - X-rays Ionizing radiation, photoelectric effect
 - Gamma rays Even more energetic than X-rays
 - Higher frequency, shorter wavelength, more energy

Magnetism

- Orbits of charged particles moving in magnetic field



- Perfect orbit occurs when $qvB = mv^2/r$
 - When $qvB < mv^2/r$, there isn't enough centripetal force, and the charged particle flies out of orbit.
 - When $qvB > mv^2/r$, there's too much centripetal force, and the charged particle spirals inward.
- General concepts of sources of the magnetic field
 - Anything that involves a moving charge creates a magnetic field
 - Moving charges.
 - Current carrying wire.
 - Solenoids and toroids.
 - The Earth (electric current in the liquid core).
 - Atoms with unpaired electrons is the other source of magnetic fields. This is basically the same deal as moving charges, since the unpaired electrons orbiting the nuclei is the same thing as moving charges.
 - Magnets.
 - Individual atoms of Ferromagnetic and Paramagnetic create magnetic fields because they have unpaired electrons. Ferromagnetic materials have domains of aligned atoms that make them even more susceptible to be magnetized. Both Ferro and paramagnetic material are attracted to magnetic fields.
 - Diamagnetic atoms don't create magnetic fields because the electrons are paired, so their individual fields cancel out. Diamagnetic fields actually is repelled by an external magnetic field.
- Nature of solenoid, toroid



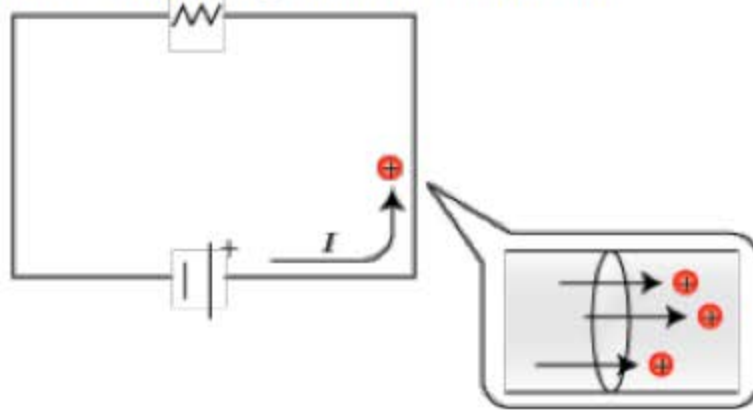
- Loop
 - Solenoid
 - The solenoid is just a coil of current-carrying wire.
 - $B = \mu_0 nI$.
 - n is the number of loops per meter. I is current.
 - The magnetic field produced by a solenoid is directly proportional to the number of coils, and to the current.
 - Toroid

- Toroid
 - Toroid is just a solenoid in a circle.
 - $B = \mu_0 NI / \text{circumference}$
 - N is the total number of loops, I is the current.
 - More loops, smaller circle $\rightarrow$ greater magnetic field.
- Ampere's law for magnetic field induced by current in straight wire and other simple configurations
 - Ampere's law lets you calculate the magnetic field at a radius r from a current-carrying wire: $B = \mu_0 I / 2\pi r$
- Comparison of E and B relations
 - force of B on a current
 - $F = qvB \sin\theta = (it)vB \sin\theta = (it)(L/t)B \sin\theta = iLB \sin\theta$
 - i is current, L is length of wire.
 - Consider the current in the wire as moving positive charges (by tradition, the direction of the current is defined as the direction of moving positive charges).
 - You can calculate the direction of the force on the wire in the same way using the right hand rule. Just treat the direction of the current the same as the direction of velocity of a positive charge.
 - Two wires will attract each other if the current is in the same direction.
 - Two wires will repel each other if the current is in opposite directions.
 - energy
 - Oscillations of electric and magnetic fields (electromagnetic radiation) has energy.
 - $E = h\nu$
 - E is energy per photon, h is Planck's constant, and ν is the frequency of the electromagnetic wave.

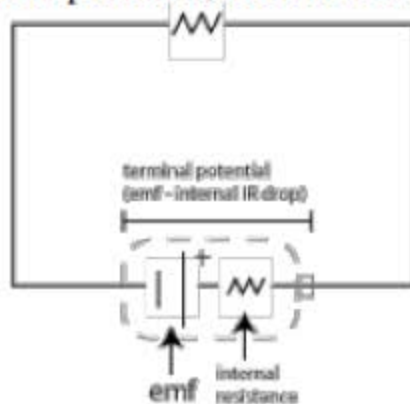
Electronic Circuit Elements

Circuit elements

- Current ($I = \Delta Q / \Delta t$, sign conventions, units)



-
- Current is the rate of charge flow through the cross-section of a conductor (wire).
- Traditionally, the direction of current is taken as the flow of positive charges.
- The unit for current is Coulombs per second, C/s.
- Battery, electromotive force, voltage
 - Electromotive force (emf) is really not a force, but a potential difference, with the unit voltage.
 - A battery is a source of emf.
 - If the battery has no internal resistance, then potential difference across the battery = EMF.
 - If the battery has internal resistance, then potential difference across battery = EMF - voltage drop due to internal resistance.
- Terminal potential, internal resistance of battery



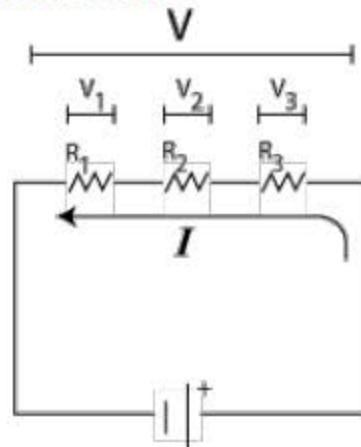
-
- Terminal potential is the voltage across the terminals of a battery.

- Internal resistance of a battery is like a resistor right next to the battery connected in series.
- Terminal potential = $EMF - IR_{\text{internal}}$

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- Resistance

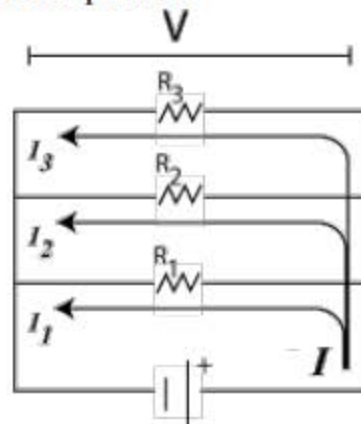
- Ohm's law ($I = V/R$)
- resistors in series



- $I_{\text{series}} = I_1 = I_2 = I_3$
- All resistors in series share the same current.
- $V_{\text{series}} = V_1 + V_2 + V_3$
- Voltage drop among resistors in series is split according to the resistance - greater resistance, greater voltage drop ($V = IR$).

t according to
tage drop ($V =$

- resistors in parallel



- $V_{\text{parallel}} = V_1 = V_2 = V_3$
- All resistors in parallel share the same voltage.
- $I_{\text{parallel}} = I_1 + I_2 + I_3$
- Current among resistors in parallel is split according to the resistance - greater resistance, less current ($I = V/R$).

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= V/R).

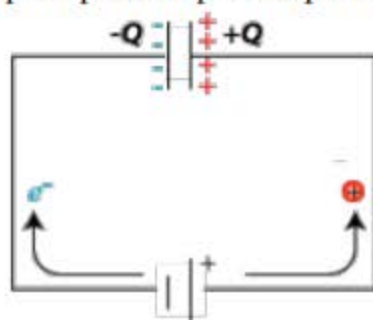
- resistivity ($\rho = RA/L$)

- Resistivity is the inverse of conductivity.
- Greater resistivity, greater resistance of the material.
- Rearranging the above equation to get $R = \rho L/A$. To make a wire of low resistance, select a material that has low resistivity, keep the wire short, and keep the diameter of the wire large.
- Extension cords are made really thick to keep the resistance down, so it doesn't heat up and cause a fire.

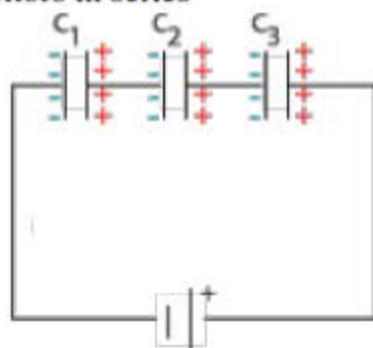
aterial.
 L/A . To make a
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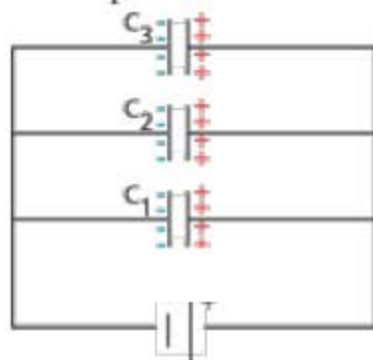
- Capacitance
 - concept of parallel-plate capacitor



- $C = Q/V = \epsilon A/d$
- Greater capacitance is created by a greater charge on plates (Q) for a given voltage (V), greater plate area (A), or smaller distance between plates (d).
- $V = Ed$, where V is voltage across capacitor, E is electric field between capacitor, and d is the distance between capacitor plates.
- energy of charged capacitor
 - $U = Q^2/2C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$
 - U is the potential energy of the charged capacitor, Q is charge stored (magnitude of either +Q or -Q on one of the plates), C is capacitance.
- capacitors in series



- $1/C_{eq} = 1/C_1 + 1/C_2 + 1/C_3$
- capacitors in parallel



- $C_{eq} = C_1 + C_2 + C_3$
- dielectric
 - Dielectric = nonconducting material.
 - Inserting a dielectric between the plates of a capacitor increases the capacitance by either increasing Q (if V is

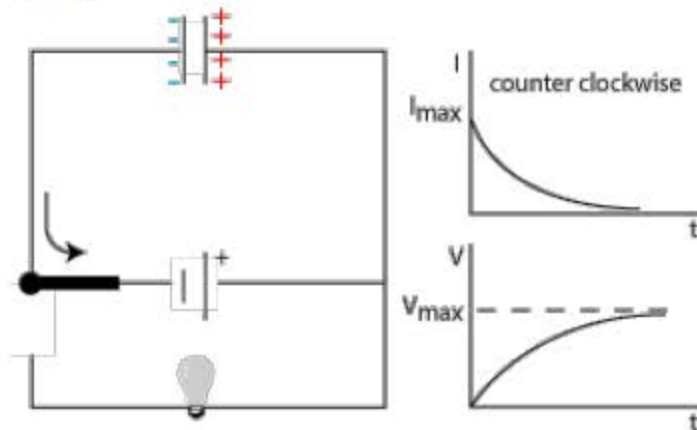
constant) or decreasing V (if Q is constant).

- $V = V_0/\kappa$

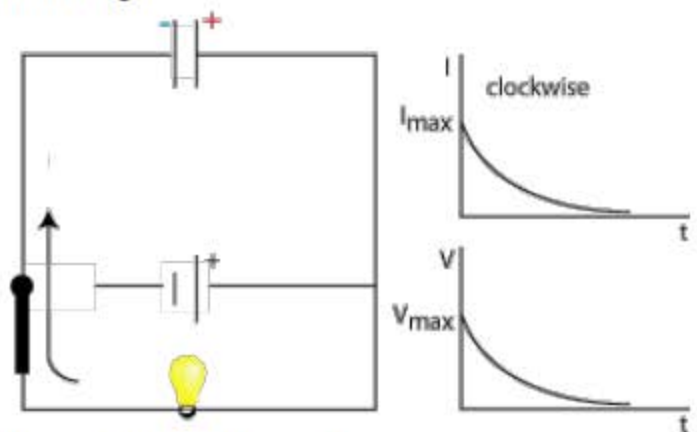
- $C = \kappa C_0$

- Discharge of a capacitor through a resistor

- Charge



- Discharge



- During the discharge of a capacitor, the capacitor acts as a battery and drives current flow, which decreases with time as the capacitor discharges.

- Conductivity theory

- Conductivity is affected by electrolyte concentration:

- No electrolyte, no ionization, no conductivity.
 - Optimal concentration of electrolyte, greatest conductivity due to greatest mobility of ions.
 - Too much electrolyte, ions are too crowded, less ion mobility, less conductivity.

- Conductivity is affected by temperature:

- In metals, conductivity decreases as temperature increases.
 - In semiconductors, conductivity increases as temperature increases.
 - At extremely low temperatures (below a certain critical temperature typically a few degrees above absolute zero), some materials have superconductivity - virtually no resistance to current flow, a current will loop almost forever under such conditions.

- Conductivity (σ) is the inverse of resistivity (ρ).

- Place a capacitor inside a solution, the solution will conduct a

current between the plates of the capacitor, thus you can measure the conductivity of a solution using a capacitor.

Circuits

- Power in circuits ($P = VI$, $P = I^2R$)
 - $P = IV = I^2R$
 - P is power, I is current, V is voltage, R is resistance.
 - Power companies try to save the amount of copper needed for power lines by using thinner wires, which makes R quite high.
 - To minimize P dissipated by the wires, they minimize I by maximizing V . This is why power lines transfer electricity at high voltage.

Alternating Currents and Reactive Circuits

- Root-mean-square current
 - $I_{\text{rms}} = I_{\text{max}}/\sqrt{2} = 0.7 I_{\text{max}}$
- Root-mean-square voltage
 - $V_{\text{rms}} = V_{\text{max}}/\sqrt{2} = 0.7 V_{\text{max}}$
- $V_{\text{rms}} = I_{\text{rms}}R$
- $P_{\text{avg}} = I_{\text{rms}}V_{\text{rms}} = I_{\text{rms}}^2R$

Atomic and Nuclear Structure

Atomic Structure and Spectra

Emission spectrum of hydrogen (Bohr model)

- Bohr model:
 - An electron orbits the positively charged nucleus in the same way that the earth orbits the Sun.
 - Electrostatic attraction pulls the electron toward the nucleus.
 - The electron orbits a high speed to prevent it from crashing into the nucleus.
 - The electron can orbit at different energy levels: $n=1$, $n=2$, $n=3$...etc.
 - The higher the energy level, the larger the radius from the nucleus.
- Emission spectrum of hydrogen:
 - When an electron transitions from a higher energy level to a lower energy level, it emits electromagnetic radiation.
 - The emission spectrum of hydrogen consists of sharp, distinct lines.

Atomic energy levels

- quantized energy levels for electrons
 - The distinct lines of the emission spectrum prove that electron energy is quantized into energy levels.
 - If electron energy is not quantized, then a continuous spectrum would be observed.
- The energy of the energy levels is governed by: $E = -\frac{13.6eV}{n^2}$,
where E is energy and n is the energy level.
 - The equation is negative, so all energies are negative.
 - Negative energies mean that it is energy that contributes to the "stability" of the system - the electron binding energy.
 - The more negative (lower) the energy, the more stable the orbit, the harder it is to knock out the electron.
 - The less negative (higher) the energy, the less stable the orbit, the easier it is to knock out the electron.

- At the highest energy, 0 eV, there is no binding energy, so the electron dissociates.
- For atoms other than hydrogen, the shape of the energy level curve stays the same. However, the numerator is a constant other than 13.6 eV.
- The precise relationship for atoms other than hydrogen is:

$$E = -\frac{Z^2 R_H}{n^2}$$
, where Z is the atomic number.
- Higher Z values give more negative binding energy (more stable) because the more charge, the more electrostatic attraction.
- calculation of energy emitted or absorbed when an electron changes energy levels
 - The wavelength of the emitted or absorbed radiation is governed by the Rydberg formula:

$$\frac{1}{\lambda} = R \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$
, where lambda is the wavelength, nf is the final energy level, ni is the initial energy level, and R is the rydberg constant.
 - The energy of the emitted or absorbed radiation is:

$$E = hf = h\nu = h\frac{c}{\lambda}$$
, where E is energy, f and v both mean frequency and c is the speed of light.
 - Energy is emitted for transitions to lower energy levels (nf < ni).
 - Energy is absorbed for transitions to higher energy levels (nf > ni).

Atomic Nucleus

Atomic number, atomic weight

- Atomic number = the number of protons.
 - The atomic number is what defines an element.
 - When two things have the same number of protons, they are the same element.
- Atomic weight = the weighted average of atomic mass for all isotopes of a given atom.
 - Atomic mass = number of protons + neutrons.
 - The atomic mass is used for an isotope.
 - The atomic weight is used for an element.
- In standard notation the atomic number is always at the bottom, and the weight is always on top: ${}_{\text{number}}^{\text{weight}}\text{Symbol} = {}_2^4\text{He}$
- An easy way to remember this is that the atomic number is "fundamental" to the identity of the element, so it is located at the foundation.

Neutrons, protons, isotopes

- Neutrons = neutral particles that reside in the nucleus.
- Protons = positive particles that reside in the nucleus.
- Isotopes = things with the same number of protons, but different number of neutrons.

Atomic particles

Name	Mass (amu)	Charge	Location
Proton	1	+1	In the nucleus
Neutron	1	0	In the nucleus
Electron	0	-1	Surrounding the nucleus

- Nucleons = protons or neutrons.

Isotopes

- When two things have the same number of protons but different number of neutrons, they are isotopes of the same element.
- Isotopes often have similar chemical properties, but different stabilities (some decay and give off radiation, some don't).

Nuclear forces

- Two forces are at work in the nucleus: the strong force and the electromagnetic force.
- The strong force binds the nucleons together, and is therefore contributes to the binding energy.
- The electromagnetic force is due to electrostatic repulsion between the positively charged protons in the nucleus.
- The nucleus stays together because the strong force is much stronger than the electromagnetic repulsion.
- The strong force is also called the "nuclear force".

Radioactive decay: alpha, beta, gamma, half-life, exponential decay, semi-log plots

- Alpha decay: ${}^{216}_{84}\text{Po} \rightarrow {}^{212}_{82}\text{Pb} + {}^4_2\alpha$. Ejection of a helium nucleus at relatively low speed.
- Beta decay: ${}^{32}_{15}\text{P} \rightarrow {}^{32}_{16}\text{S} + {}^0_{-1}\beta$. Ejection of a high speed electron.
- Gamma decay: ${}^{222}_{86}\text{Rn} \rightarrow {}^{222}_{86}\text{Rn} + {}^0_0\gamma$. Release of high energy electromagnetic wave.

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Name	Notation	Information
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Alpha		
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	Weakest form of radiation. Can be stopped by a sheet
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particle ${}^4_2\alpha$ of paper. It is essentially a relatively low speed helium nucleus.

Beta particle ${}^0_{-1}\beta$ More energy than an alpha particle. Can be stopped by aluminum foil. It is a high speed electron.

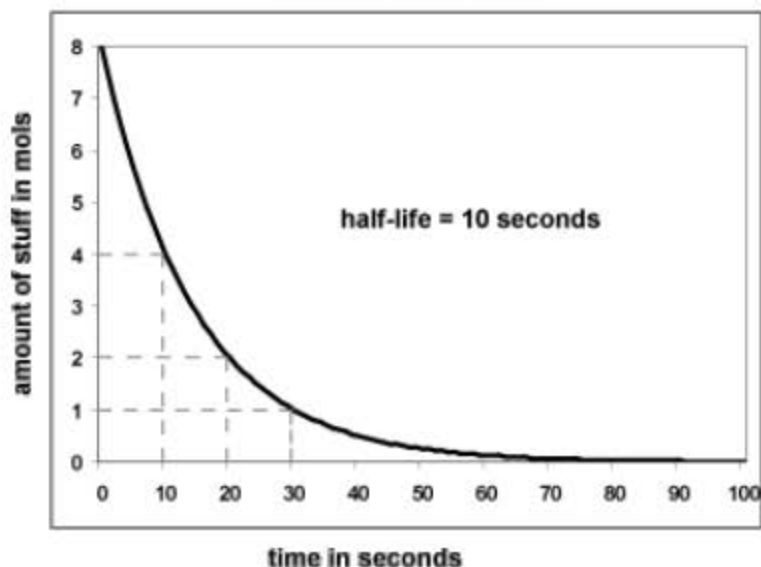
Gamma ray ${}^0_0\gamma$ Strongest form of radiation. It is a high energy electromagnetic wave. Can be stopped by a thick layer of lead or concrete.

- Some notes on α , β , and γ decay
 - Conservation of mass dictates that total atomic weight before the decay equal the total atomic weight after.
 - Conservation of charge dictates that the total atomic number before the decay equal the total atomic number after.
 - Don't get thrown off by particles you do not recognize. As long as they have a weight and a charge, just incorporate these numbers in your calculations.
 - Exam problems on identifying decay products are just math work.
 - Remember: the atomic number (the bottom number) determines what element it is.
- half-life is the time it takes for the amount of something to half due to decay.
 - After 1 half-life, the amount of the original stuff decreases by half.
 - After 2 half-lives, the amount of the original stuff decreases by a factor of 4.
 - After 3 half-lives, the amount of the original stuff decreases by a factor of 8.
 - The mathematical expression for this is:

$$N_t = N_{t=0} \cdot \left(\frac{1}{2}\right)^{\text{Half-lives}} = N_{t=0} \cdot \left(\frac{1}{2}\right)^{\frac{t}{\text{half-life}}}$$
 , where $N_{t=0}$ is the amount the original starting material. N_t is the amount of the original material that is still left. Lastly, t is time.
 - Although the above is the official half-life equation, people like to multiply rather than to divide. Therefore, a more user friendly equation is:

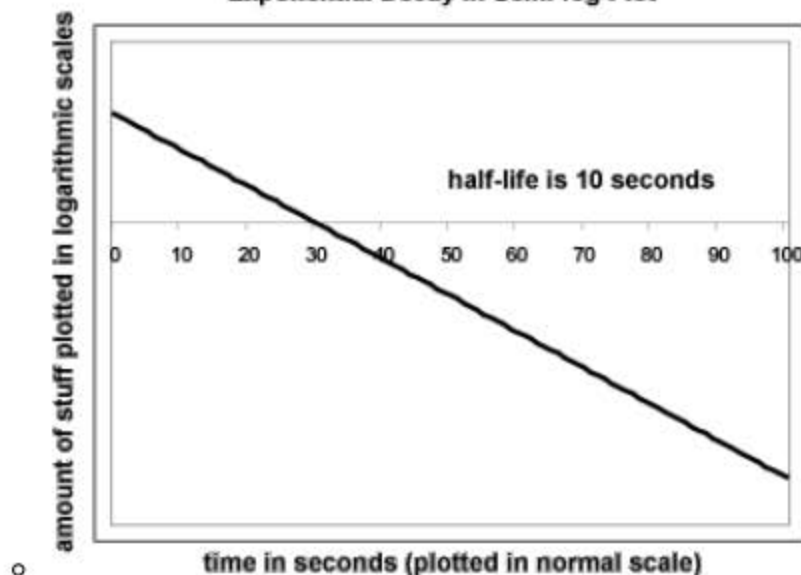
$$N_{t=0} = N_t \cdot 2^{\text{Half-lives}} = N_t \cdot 2^{\frac{t}{\text{half-life}}}$$
- Stability
 - When something is stable, it doesn't decay.
 - When something is unstable, it decays.
 - The more unstable something is, the shorter the half-life.
- Exponential decay:

Exponential Decay



- Semi-log plots: for the purposes of the exam, semi-log plots convert exponential curves into straight lines.
 - Something that curves up becomes a straight line with a positive slope.
 - Something that curves down becomes a straight line with a negative slope.
 - For exponential decay, a semi-log plot graphs the log of amount vs. time.
 - For exponential decay, a semi-log plot is a straight line with a negative slope.
 - The semi-log plot intercepts the x axis where the original y value is 1.

Exponential Decay in Semi-log Plot



General nature of fission

- Fission = one nuclei splitting apart.
 - Uranium undergoes fission when struck by a free neutron.
- The fission of uranium generates more neutrons, which goes on to split

other Uranium nuclei. This is called a chain reaction.

General nature of fusion

- Fusion = two nuclei coming together.
- The Sun works by fusion.
- Hydrogen in the Sun fuses to form helium.

Mass deficit, energy liberated, binding energy

- $M_{\text{nucleons}} = M_{\text{atom}} + \text{binding energy}/c^2$
- $M_{\text{nucleons}} > M_{\text{atom}}$ because some of the M_{nucleons} is converted to binding energy that holds the nucleons together.
 - M_{nucleons} = mass of all the nucleons that make up the atom in their free, unbound state.
 - M_{atom} = mass of the atom.
 - $M_{\text{nucleons}} - M_{\text{atom}}$ = mass deficit (also called mass defect) = ΔM .
 - Binding energy = converting ΔM into its equivalent in energy = $\Delta M c^2$.
 - Energy liberated = binding energy.
- The conservation of mass and energy: the total mass and energy before a reaction is always the same as the total mass and energy after the reaction.
- If the total mass before the reaction is different from the total mass after the reaction, then the difference in mass is made up for by energy.
- The difference in mass before and after a reaction is called the mass deficit or mass defect.
- The energy that makes up for the mass deficit is calculated by: $E = mc^2$
- Energy is liberated when mass is lost during a reaction.
- Energy is absorbed with mass is gained during a reaction.
- More notes on binding energy:
 - Binding energy most commonly refers to nuclear binding energy (the energy that binds the nucleons together).
 - Binding energy is due to the strong force.
 - Binding energy per nucleon is strongest for Iron (Fe 56).
 - Binding energy per nucleon is the weakest for Deuterium (the 2 - nucleon isotope of hydrogen).
 - Less commonly used is the electron binding energy. This is because electron binding energy is more commonly referred to as the ionization energy.