Phil's Orderly Physics Curriculum Important Concepts List (POPCICL)

[Warning : This list is not intended to be comprehensive, but rather to highlight a few key concepts]

Units

The fundamental units of measurement include : length, mass, time, electric current

Derived units are created from fundamental units by multiplication or division

You cannot add, subtract, or equate physical quantities with different units.

Vectors

Vectors are described by two properties : magnitude and direction.

You can change a vector quantity by changing either magnitude or direction, or both.

You can describe a vector as a single magnitude and direction, or as components along mutually orthogonal axes.

Orthogonal vectors (or vector components) are independent.

Independent variables do not directly affect one another.

Vector addition is done graphically by placing the tail of one vector at the head of another without rotating either.

Vector subtraction is done graphically by inverting the second vector and performing vector addition.

Vector addition is done algebraically by adding the individual orthogonal components.

A vector dot product between two vectors gives you a scalar (number) that represents the component of one of the vectors along the direction of the other vector.

Motion (Kinematics)

Displacement is a vector quantity; distance is a scalar quantity.

If you walk in a complete circle, your displacement is zero, but your distance traveled is non-zero (and equal the circumference of the circle you just walked)

Velocity is the rate of change of position with time; it tells you how quickly your position is changing.

Velocity is a vector quantity; speed is a scalar quantity.

If run completely around the block, your average velocity is zero because your total displacement is zero; but your average speed is a non-zero, positive, scalar quantity.

Acceleration is the rate of change of velocity with time; it tells you how quickly your velocity is changing.

The acceleration due to gravity near the surface of the Earth is g = +9.8m/s directed downwards; but if if the y-axis is directed upwards, then the acceleration due to gravity is given by $a_y = -g$.

Quantities of motion (including velocity, acceleration, and displacement) along one orthogonal axis do not affect the quantities of motion along any other orthogonal axis.

Projectile Motion describes the motion of a object that is in motion and subject only to the influence of gravity.

An object in projectile motion (in which we neglect air resistance), will follow a parabolic trajectory.

Forces

Without a net force applied, objects continue to move with their current velocity, which could be zero. (Newton's First Law)

An object with no net force on it is said to be in equilibrium.

The net force on an object is the vector sum of all the forces acting on it.

A net force on an object acts to accelerate it (Newton's Second Law)

Doubling the net force on an object will double the resulting acceleration.
For the same applied net force, doubling the mass of the object will halve the acceleration.

For every force applied by object A onto object B, there is an equal and opposite force applied by object B onto object A (Newton's Third Law)

The force of gravity acts as an attraction between the centers of any two masses.

Near the surface of the earth, the force of gravity is (nearly) constant and always straight down.

The force of gravity scales linearly with the mass : double the mass, and the force will double.

The acceleration due to gravity is independent of mass. If we ignore air resistance, a feather and a bowling ball will fall at the same rate.

The restoring force of a spring depends linearly on the stiffness (k) of the spring and linearly on how much the spring is compressed (or stretched) from its relaxed length.

An ideal spring is massless and has no internal friction (it doesn't heat up just by stretching or compressing)

The normal force is the force provided by a surface (ground, tabletop) to keep a massive object from breaking through it.

The normal force of a surface always acts perpendicular to that surface.

The normal force is a "just enough" force. Up to the breaking point, the surface always provides just enough of a counter force to counteract the perpendicular (to the surface) component of other forces pulling/pressing an object against the surface.

Tension is the force provided by a flexible connector (rope, string, wire) to keep an object from breaking away from it.

Tension is always directed along the direction of the connector (rope/string/wire)

Tension is a "just enough" force. Up to the breaking point, the connector always provides just enough of a counter force to counteract the component of other forces pulling/pressing the object away from the connector.

An ideal rope/string/wire is massless and does not stretch or compress.

In an ideal rope, the magnitude of the tension is the same throughout the rope.

An ideal pulley changes the direction of the tension force but does not change its magnitude.

The force of friction always acts parallel to the surface (the interface between the two rubbing objects) and in the direction that opposes the motion or attempted motion.

Static friction acts to oppose attempted motion. Kinetic friction acts to opposes actual motion. The coefficient of static friction is generally greater than the coefficient of kinetic friction for the same interface.

Static friction is a "just enough" force. Up to the "slipping point", the surface always provides just enough counter force to counteract the parallel (to the surface) component of other forces attempting to push/pull an object along the surface. Kinetic friction is a fixed/constant force between two objects in motion.

Direct Stress or Solid Pressure

Solid pressure (a.k.a. Direct Stress) is the applied force per unit area on a material when the force (or a component of the force) is applied perpendicular to the surface.

The same force applied across a smaller area will result in a larger solid pressure.

When solid pressure exceeds the "ultimate compressive strength" of a material, the material will fracture.

Energy

Total Energy is always conserved. Energy cannot be created or destroyed; only converted from one form to another, or transferred from one object/system to another.

There are many forms of energy. Quantitative accounting of some of these forms of energy is difficult (for the beginning physics student), but Mechanical Energy is straight-forward to calculate.

The Mechanical Energy of an object/system is the sum of the Potential Energies and Kinetic Energies of that object/system.

Kinetic Energy is the energy of motion. Kinetic energy scales linearly with mass but quadratically with velocity of the moving object. *Technically, Kinetic Energy is the energy of [coordinated directional] motion; as opposed to the random motion of molecules that make up heat (thermal energy).*

Potential Energy is the energy of relative position, shape or configuration of multiple objects (as in the case for gravity) or a complex deformable object (as in the case of a spring).

A particle or singular object can only have kinetic energy. Potential energy requires having two or more interacting objects.

Spring Potential Energy scales linearly with the stiffness of the spring (k), but quadratically with how far the spring is compressed (or stretched) from its relaxed length.

Gravitational Potential Energy near the surface of the Earth scales linearly with the mass of the object and also linearly with the height of the object.

Work is the transfer of energy. It has the same units as energy.

Once we have defined what to consider as being in our system, internal work is a result of forces acting between two objects that are both inside the system; external work is a result of a force acting between an object in the system and an object outside the system.

Internal work can be due to [mechanically] conservative forces or [mechanically] non-conservative forces.

Positive work done by conservative internal forces associates with a negative change in potential energy.

[Mechanically] Conservative Forces (force of gravity, elastic restoring force, *and electric [electrostatic] force*) conserve mechanical energy. [mechanically] Conservative forces only act to convert one form of mechanical energy to another (PE to KE, or KE to PE)

[Mechanically] Non-conservative forces, convert mechanical energy to non-mechanical forms of energy

Non-mechanical energy includes heat, light, chemical energy, and nuclear energy.

The force of friction converts mechanical energy into heat. We can calculate the amount of heat generated by calculating the work done by the force of friction over a certain displacement.

External work can cause a change in the kinetic energy of a system, the potential energy of a system, or a change in the internal energy of the system (if, for example, there is friction between two objects that are both inside the system)

An increase in internal energy corresponds to a rise in temperature.

Power is the rate of change of energy with time.

Momentum and Collisions

Linear Momentum is defined as mass times velocity and it is a vector quantity (it has magnitude and direction)

Total Linear Momentum is always conserved for an isolated system.

A system is an isolated system if there is no transfer of momentum between objects inside the system and anything outside the system.

Impulse is the name given to a change in momentum and has the same units as momentum (kg m/s)

Impulse is a measure of the transfer of momentum from one object to another.

(this is similar to how "work" was the name given to a change or transfer of energy"

Impulse is the integral of an applied force , integrated over time.

(this is similar to how "work" was the integral of an applied force, integrated over distance)

Newton's second law can be more generally written as : the net force on an object is equal to the change in that object's momentum divided by the duration of the impact.

Momentum is distinct from Kinetic Energy. Two objects can have the same momentum but have different kinetic energies. Or two objects can have the same kinetic energies but have different momenta.

A collision with a high kinetic energy object is more likely to cause penetration or fracture of the target while a collision with a high momentum object is more likely to cause acceleration of the target.

A collision is any interaction between two objects in which forces are applied over a relative short time.

In a perfect elastic collision, the colliding objects separate after the collision with their shape undeformed.

In a perfect elastic collision, both total momentum and kinetic energy are conserved.

In a perfect inelastic collision, the colliding objects stick together after the collision.

In a perfect inelastic collision, total momentum is conserved, but kinetic energy is not conserved.

Two colliding object separating, but ending up deformed after a collision, is an example of an [non-perfect] inelastic collision.

For an elastic collision between two objects in one dimension, the relative velocity between the two objects is the same before and after the collision, but with a sign change to indicate a change in relative direction.

(this is called the relative velocity equation)

For 2D or 3D collisions, the momentum along each orthogonal axis is conserved independently.

Center of Mass

The center of mass of an 1D or 2D object is the location for which the object will be balanced if supported from underneath at that point.

A 3D object will be balanced if the center of mass is directly above or below the pivot/suspension point.

The center of mass of a system or object is found by taking a mass-weighted average of the locations of the particle that make up that system or object.

We may treat an extended object as having all its mass concentrated at its center of mass for the purpose of linear (non-rotational) motion and forces.

For an isolated system, the momentum of the center of mass of the system does not change, regardless of any internal forces or collision that occur within the isolated system.

Circular Motion

Acceleration can be decomposed (broken up) into a “tangential” component that is along the direction of motion (direction of the instantaneous velocity vector at any moment) and a “centripetal” component that is perpendicular to the direction of motion.

Purely tangential acceleration (along the line of motion) only changes the speed (magnitude of the velocity) of an object but not its direction

Purely centripetal acceleration (perpendicular to the line of motion) only changes the direction of an object, but not its speed.

Tangential and centripetal forces are not new additional forces on a system; they are a re-labeling of the existing forces (pushing, pulling, gravity, normal, tension, spring, etc) – decomposing the existing force vectors into “along the motion” and “perpendicular to the motion” components instead of the typical x- and y-components.

Rotational Motion

When a force is directed in-line with an object's center-of-mass, it will cause linear acceleration of the object (translational motion) but no rotational motion.

If a force is directed off-center compared to the object's center-of-mass, it can cause rotation of the object.

Rotation is described relative to some axis of rotation, such as a fixed pivot point like a hinge.

If an object does not have a fixed pivot point, rotation occurs about its center of mass.

Analogous to the four quantities of motion for linear motion (displacement, velocity, acceleration, duration), rotation motion is described by four quantities of rotational motion : angular displacement, angular velocity, angular acceleration, and duration)

Angle (θ) and angular displacement ($\Delta\theta$) is measured in radians (1 radian = 57.3° , 2π radians = 360°)

Angular velocity (ω) is measured in radians per second.

Angular acceleration (α) is measured in radians per second-squared.

The (curved) linear distance traveled by a particle undergoing rotation is called the arc-length (symbol, s) and is given by the product of the angular displacement ($\Delta\theta$) and the radius from the axis of rotation (r)

Moment of inertia is the rotational analog to mass. It is a distance(squared)-weighted total mass of an object.

A moving extended (non-point-particle) object can have both translational and rotational kinetic energy.

Analogous to translational kinetic energy, rotational kinetic energy is proportional to the object's moment of inertia and the square of its angular velocity. [$KE_{rot} = (1/2)I\omega^2$].

Torque & Angular Momentum

Torque is the rotational analog to force. Torque is a distance-weighted-force, and like force is a vector quantity.

Torque is the cross product between the radius vector and the applied force vector.

A vector cross product between two vectors gives you a vector that represents the how perpendicular the two vectors are to each other. The cross-product's direction is determined by the right-hand-rule.

For an extended object to be in static equilibrium, two conditions for equilibrium must be met. The sum of the forces must be zero, and the sum of the torques must be zero.

For an object in static equilibrium, you are free to choose the “axis rotation” to be at any point. Choosing the axis at a point of force application reduces the number of terms in the zero net torque equation.

Newton's three laws of motion also apply for rotational motion.

An object that is not rotating will remain at non-rotating, and an object rotating with constant rotational velocity will maintain that constant rotational velocity unless acted upon by an external torque.

The net torque on an object is proportional to the its moment of inertia and its angular acceleration.
Doubling the net torque on an object will double the resulting angular acceleration.
For the same applied net torque, doubling the moment of inertia will halve the angular acceleration.

For every torque applied by object A onto object B, there is an equal and opposite torque applied by B onto A.

Angular momentum is the rotational analog to linear momentum.

The angular momentum for a particle is equal to the cross product between the radius vector and the linear momentum vector. It's direction is determined by the right-hand-rule.

The angular momentum for an extended object is the product of the its moment of inertia and angular velocity.

Angular momentum is always conserved for an isolated system. If the moment of inertia of an isolated system is doubled, its angular velocity will be halved.

Analogous to the alternative formulation of Newton's second law for linear motion; torque can be defined as the time derivative of the angular momentum.