Fundamentals of Rocket Stability

This is Rocket Science

Parts of a Model Rocket — Glenn Research Center (NASA)

Labels: Parachute Lines, Launch Lug, Parachute, Solid Rocket Engine (Removable), Fins, Nose Cone Payload (Removable), Body Tube, Shock Cord, Recovery Wadding, Engine Mount (Fixed), B6-4
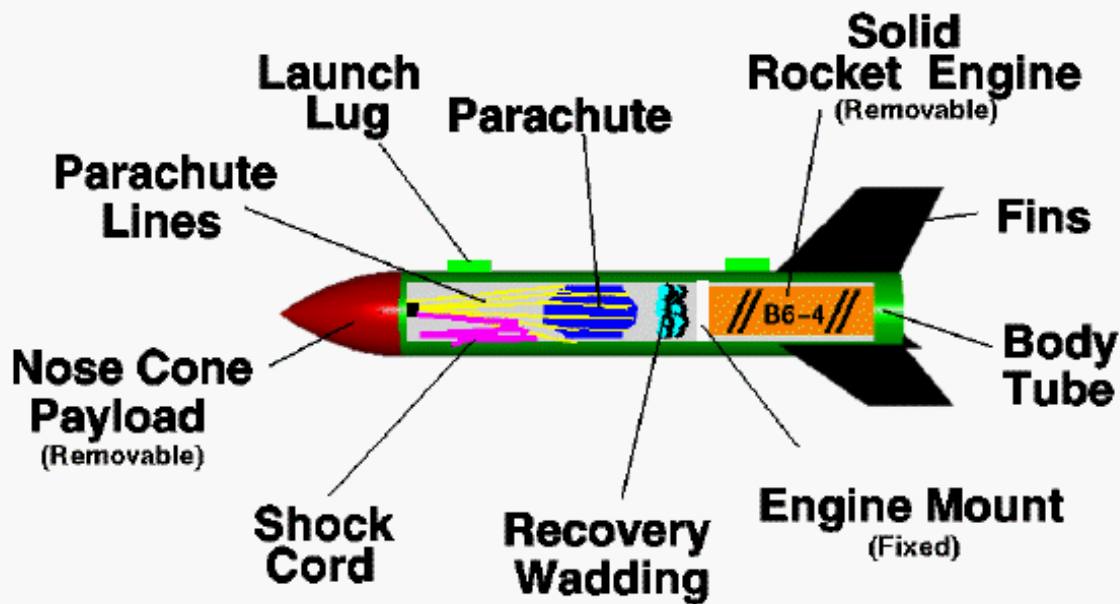
Flying model rockets is a relatively safe and inexpensive way for students to learn the basics of aerodynamic forces and the response of vehicles to external forces. Like an airplane, a model rocket is subjected to the forces of weight, thrust, and aerodynamics during its flight.

On this slide we show the parts of a single stage model rocket. We have laid the rocket on its side and cut a hole in the body tube so that we can see what is inside. Beginning at the far right, the **body** of the rocket is a green cardboard tube with black **fins** attached at the rear. The fins can be made of either plastic or balsa wood and are used to provide stability during flight. Model rockets use small, pre-packaged, solid fuel engines The engine is used only once, and then is replaced with a new engine for the next flight. Engines come in a variety of sizes and can be purchased at hobby stores and at some toy stores. The thrust of the engine is transmitted to the body of the rocket through the **engine mount**. This part is fixed to the rocket and can be made of heavy cardboard or wood. There is a hole through the engine mount to allow the **ejection charge** of the engine to pressurize the body tube at the end of the coasting phase and eject the nose cone and the recovery system. **Recovery wadding** is inserted between the engine mount and the recovery system to prevent the hot gas of the ejection charge from damaging the recovery system. The recovery wadding is sold with the engine. The recovery system consists of a **parachute** (or a **streamer**) and some **lines** to connect the parachute to the nose cone. Parachutes and streamers are made of thin sheets of plastic. The **nose cone** can be made of balsa wood, or plastic, and may be either solid or hollow. The nose cone is inserted into the body tube before flight. An elastic **shock cord** is connected to both the body tube and the nose cone and is used to keep all the parts of the rocket together during recovery. The **launch lugs** are small tubes (straws) which are attached to the body tube. The launch rail is inserted through these tubes to provide stability to the rocket during launch.
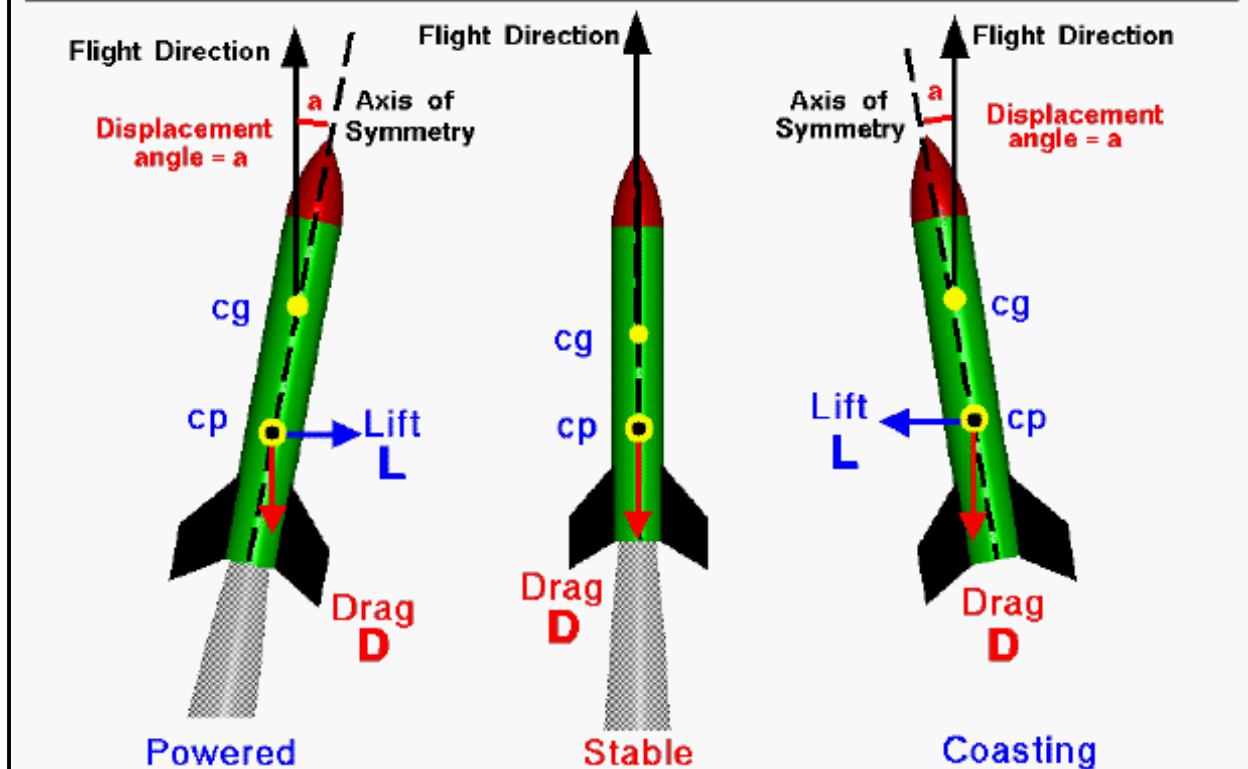
During the flight flight of a model rocket small gusts of wind, or thrust instabilities can cause the rocket to "wobble", or change its attitude in flight. Like any object in flight, a model rocket rotates about its center of gravity (cg), shown as a yellow dot in the figure. The rotation causes the axis of the rocket to be inclined at some angle "a" to the flight path. Whenever the rocket is inclined to the flight path, a lift force is generated by the rocket body and fins, while the aerodynamic drag remains fairly constant for small inclinations. Lift and drag both act through the center of pressure (cp) of the rocket, which is shown as the black and yellow dot in the figure.

On this slide we show three cases for which the flight direction is exactly vertical. In the center of the figure, the rocket is undisturbed and the axis is aligned with the flight direction. The drag of the rocket is along the axis and there is no lift generated. On the left of the figure, a powered rocket has had the nose of the rocket perturbed to the right. On the right of the figure, a coasting rocket has had the nose of the rocket perturbed to the left. We denote the angle in both cases by the symbol "a". Considering the powered rocket case, we see that a lift force is generated and directed towards the right or downwind side of the rocket. On the coasting rocket case, the lift is directed towards the left, also the downwind side of the rocket.

For the powered case, both the lift and the drag produce counter-clockwise torques (or twists) about the center of gravity; the tail of the rocket will swing to the right under the action of both forces and the nose will move to left. For the coasting case, both lift and drag produce clockwise torques about the center of gravity; the tail of the rocket will swing to the left under the action of both forces and the nose will move to the right. In both cases, the lift and the drag

Stability of a Model Rocket — Glenn Research Center
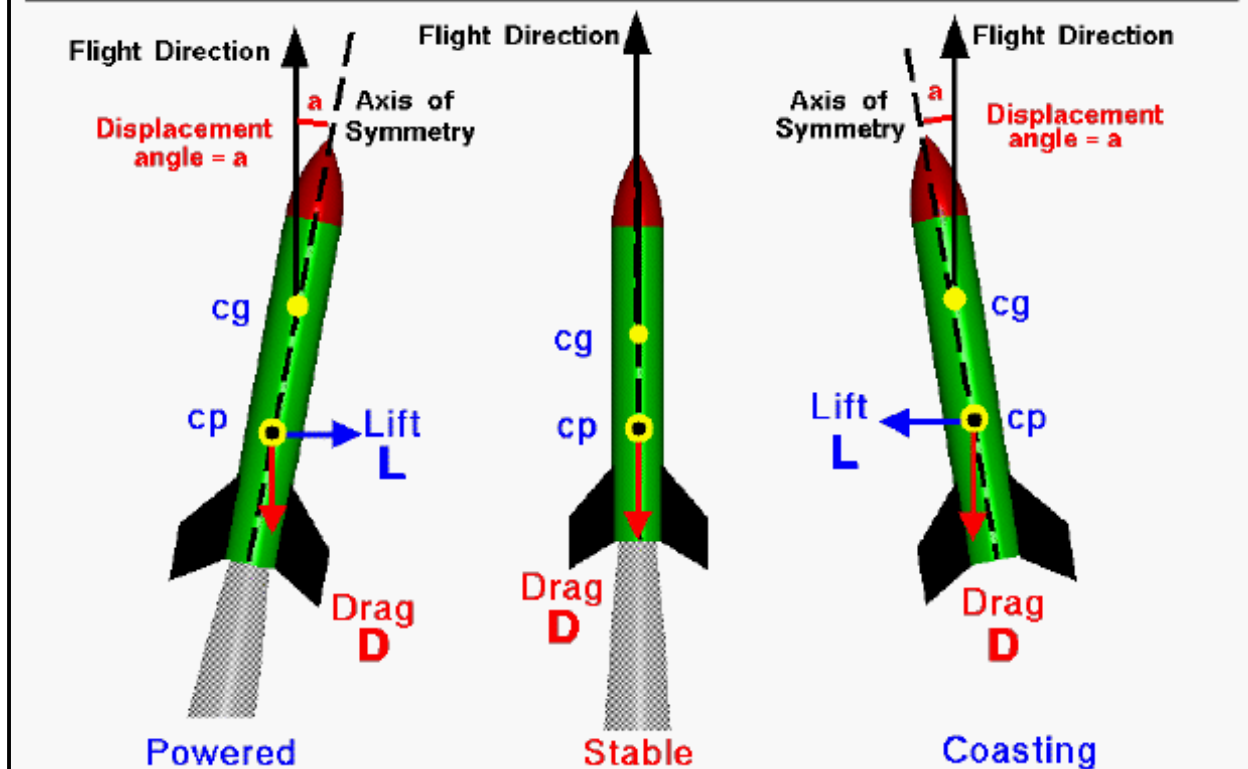
forces move the nose back towards the flight direction. Engineers call this a **restoring force** because the forces "restore" the vehicle to its initial condition.

A restoring force exists for this model rocket because the center of pressure is below the center of gravity. If the center of pressure is above the center of gravity, the lift and drag forces maintain their directions but the direction of the torque generated by these forces is reversed. This is called a **de-stabilizing force**. Any small displacement of the nose will generate forces that cause the displacement to increase. **For a stable model rocket, the center of pressure must be located below the center of gravity.**

There is a relatively simple test that you can use on a model rocket to determine the stability. Tie a string around the body tube at the location of the center of gravity. (Be sure to have the parachute and the engine installed.) Then swing the rocket in a circle around you while holding the other end of the string. After a few revolutions, if the nose points in the direction of the rotation, the rocket is stable and the center of pressure is below the center of gravity. If the rocket wobbles, or the tail points in the direction of rotation, the rocket is unstable. You can increase the stability by lowering the center of pressure (increase the fin area) or by raising the center of gravity (add weight to the nose.)

Determining Center of Gravity – cg — Glenn Research Center (NASA)
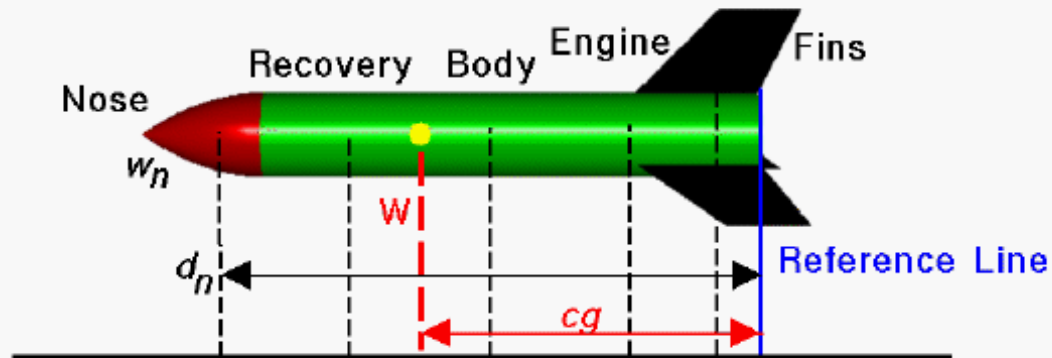
Each component has some weight w_i located some distance d_i from reference line.

Distance cg times the weight W equals the sum of the component distance times component weight.

$$cg\, W = d_n w_n + d_r w_r + d_b w_b + d_e w_e + d_f w_f$$

As a model rocket flies through the air, it rotates about a point called the **center of gravity**. The center of gravity is the average location of the weight of the rocket. The mass (and weight) is actually distributed throughout the rocket. And for some problems, it is important to know the distribution. But for rocket trajectory and maneuvering, we need to be concerned with only the total weight and the location of the center of gravity. How would you determine the location of the center of gravity?

Calculating cg

You can calculate the center of gravity. But in general, this is a complicated procedure requiring the use of calculus. This figure shows a simplified version of the center of gravity calculation that you can use. We assume that we already know the weight and location, relative to some reference location, of each of the major parts of the rocket: the nose, recovery system, body tube, fins, and engine. The **total weight** (W) of the rocket is simply the sum of all the individual weights of the components. Since the **center of gravity** (cg) is an average location of the weight, we can say that the weight of the whole rocket times the location of the center of gravity is equal to the sum of the weight of each component times the distance of that component from the reference location. (This is equivalent to saying the center of gravity is the mass-weighted average of the component locations.)
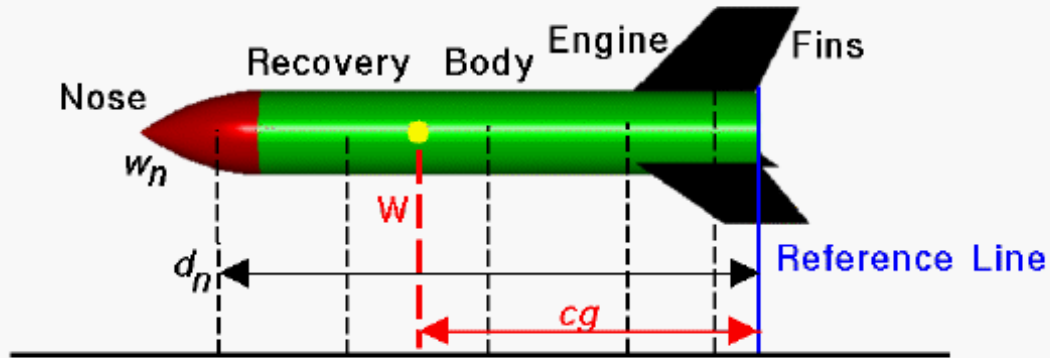
Components' Location

On the slide, we show the weight and distance of the nose relative to the reference line. The location of the reference line is arbitrary (it could be measured from the tip of the nose instead of from the base of the rocket as shown in the figure) but we have to remember where it is.

Determining Center of Gravity – cg Glenn Research Center

Each component has some weight w_i located some distance d_i from reference line.

Distance cg times the weight W equals the sum of the component distance times component weight.

$$cg\ W = d_n w_n + d_r w_r + d_b w_b + d_e w_e + d_f w_f$$

The cg is a distance measured from the reference line as well. The "distance" of the nose (dn) is the distance of the center of gravity of the nose relative to the reference line. So we have to be able to calculate or determine the center of gravity of the nose and each of the other rocket components. For some simple shapes, finding the cg, or average location of the weight, is quite simple. For example, when viewed perpendicular to the axis, the body tube is rectangular. The center of gravity is on the axis, halfway between the end planes. There is a technique for determining the center of gravity of any general shape, and the details of this technique is given on another page.

Determining cg Mechanically

For a model rocket, there is a simple mechanical way to determine the center of gravity for each component or for the entire rocket:

- If we just balance the component (or the entire rocket) using a string or an edge, the point at which the component (or rocket) is balanced is the center of gravity. (Just like balancing a pencil on your finger!) Obviously, we could not use this procedure for a large rocket like the Space Shuttle, but it works quite well for a model.

- Another, more complicated way, is to hang the model from some point (the corner of a fin, for example) and drop a weighted string from the same point. Draw a line on the rocket along the string. Repeat the procedure from another point on the rocket (the nose, for example). You now have two lines drawn on the rocket. The center of gravity is the point where the lines intersect. This procedure works well for irregularly shaped objects that are hard to balance.

Determining Center of Pressure – cp
(simplified)
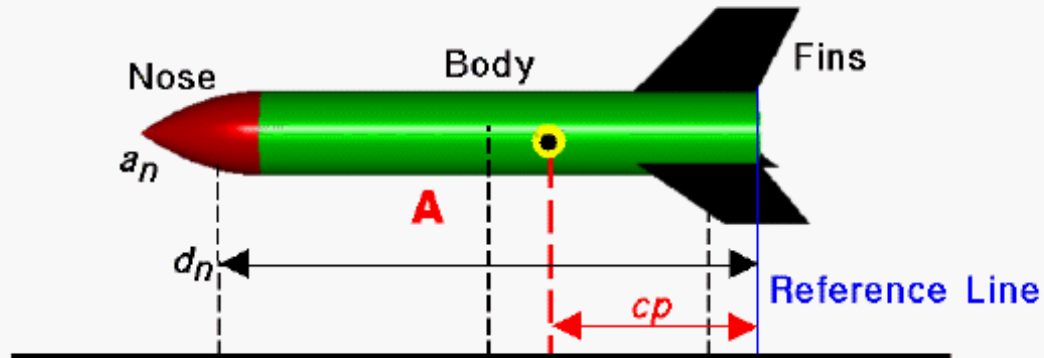
NASA — Glenn Research Center

Each component has some area a_i located some distance d_i from reference line.

Distance *cp* times the area **A** equals the sum of the component distance times area.

$$cp\ \mathbf{A} = d_n a_n + d_b a_b + d_f a_f$$

As a model rocket flies through the air, aerodynamic forces act on all parts of the rocket. In the same way that the weight of all the rocket components acts through the center of gravity (cg), the aerodynamic forces act through a single point called the **center of pressure (cp)**. How do you determine the location of the center of pressure?

Calculating cp

You can calculate the center of pressure. But, in general, this is a complicated procedure requiring the use of calculus. The aerodynamic forces are the result of pressure variations around the surface of the rocket. In general, you would have to determine the integral of the pressure times the unit normal, times the area, times the distance from a reference line. Then divide by the integral of the pressure times the unit normal, times the area. (Lot's of work!) For a model rocket, there are some simplifying assumptions that we can use to make this task much easier. Model rockets are fairly symmetric about the axis of the rocket. This allows us to reduce the full three dimensional problem to a simple, two dimensional cut through the axis of the rocket. For model rockets, the magnitude of the pressure variation is quite small. If we assume that the pressure is nearly constant, finding the average location of the pressure times the area distribution reduces to finding just the average location of the projected area distribution.

Simplified Calculation of cp

This figure shows a simplified version of the calculation procedure that you can use. We assume that we already know the projected area and location, relative to some reference location, of each of the major parts of the rocket: the nose, body tube, and fins. The projected area of the

Determining Center of Pressure – cp
(simplified)

Glenn Research Center
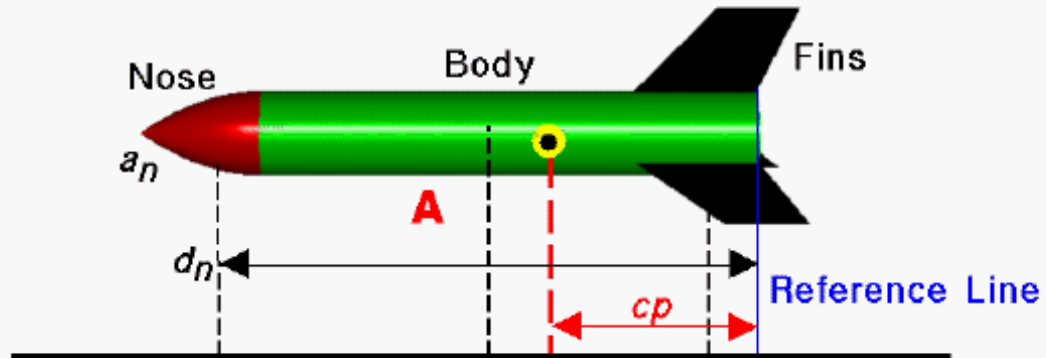
Each component has some area a_i located some distance d_i from reference line.

Distance cp times the area A equals the sum of the component distance times area.

$$cp\ A = d_n a_n + d_b a_b + d_f a_f$$

rocket is the sum of the projected area of the components. Since the center of pressure (cp) is an average location of the projected area, we can say that the area of the whole rocket times the location of the center of pressure is equal to the sum of the projected area of each component times the distance of that component from the reference location. The "location" of each component is the distance of each component's center of pressure from the reference line. So you have to be able to calculate or determine the center of pressure of each of the components. For example, the projected area of the body tube is a rectangle. The center of pressure is on the axis, half way between the end planes.

Mechanically determining cp
For a model rocket, there is a simple mechanical way to determine the center of pressure for each component or for the entire rocket. Make a two dimensional tracing of the shape of the component (or rocket) on a piece of cardboard and cut out the shape. Hang the cut out shape by a string, and determine the point at which it balances. (Just like balancing a pencil with a string!) The point at which the component (or rocket) is balanced is the center of pressure. You obviously could not use this procedure for a very large rocket like the Space Shuttle. But it works quite well for a model.
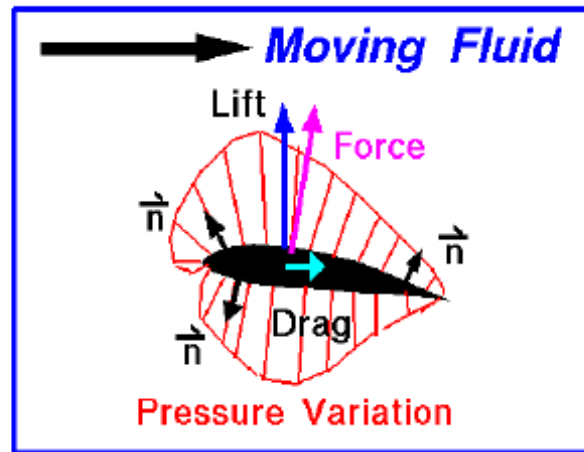
Moving Fluid

Lift

Force

$\vec{n}$ $\vec{n}$

$\vec{n}$

Drag

$\vec{n}$

Pressure Variation

Pressure forces act normal (perpendicular) to surface.
Force on the body is the vector sum of the pressure x area
around the entire solid body.

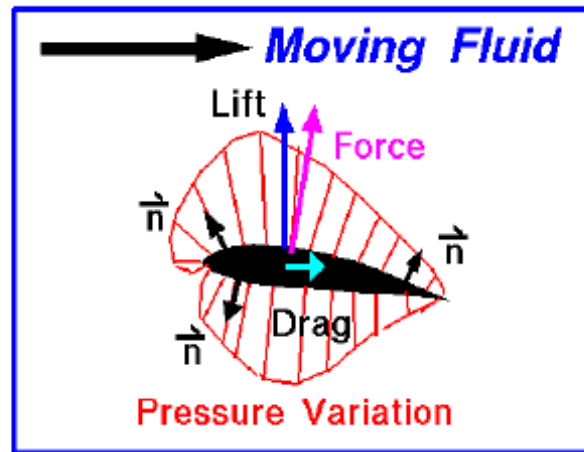$$\vec{F} = \sum_{surface} p\,\vec{n}\,\Delta A = \oint p\vec{n}\,dA$$

Lift = F_{normal}

Drag = F_{stream}

When two solid objects interact in a mechanical process, forces are transmitted, or applied, at the point of contact. But when a solid object interacts with a fluid, things are more difficult to describe because the fluid can change its shape. For a solid body immersed in a fluid, the "point of contact" is every point on the surface of the body. The fluid can flow around the body and maintain physical contact at all points. The transmission, or application, of mechanical forces between a solid body and a fluid occurs at every point on the surface of the body. And the transmission occurs through the fluid pressure.

Variation in Pressure

The magnitude of the force acting over a small section of an object equals the pressure times the area of the section. A quick units check shows that pressure (force/area) times area produces a force. As discussed on the fluid pressure slide, **pressure** is a scalar quantity related to the momentum of the molecules of a fluid. Since a force is a vector quantity, having both magnitude and direction, we must determine the direction of the force. Pressure acts perpendicular (or normal) to the solid surface of an object. So the direction of the force on the small section of the object is along the normal to the surface. We denote this direction by the letter **n**.

The normal direction changes from the front of the airfoil to the rear and from the top to the bottom. To obtain the net mechanical force over the entire solid object, we must sum the contributions from all the small sections. Mathematically, the summation is indicated by the Greek letter **sigma** (   ) In the limit of infinitely small sections, this gives the integral of the

Aerodynamic Forces

Pressure forces act normal (perpendicular) to surface.
Force on the body is the vector sum of the pressure x area around the entire solid body.

$$\vec{F} = \sum_{\text{surface}} p\,\vec{n}\,\Delta A = \oint p\vec{n}\,dA$$

Lift = F_{normal} Drag = F_{stream}

(Continued from page 9)

pressure times the area around the closed surface. If the pressure on a closed surface is a constant, there is no net force produced because the summation of the directions of the normal adds up to zero. (For every small section there is another small section whose normal points in exactly the opposite direction.)

Definitions of Lift and Drag

For a fluid in motion, the velocity will have different values at different locations around the body. The local pressure is related to the local velocity, so the pressure will also vary around the closed surface and a net force is produced. **Summing** (or integrating) the pressure perpendicular to the surface times the area around the body produces a **net force**. Since the fluid is in motion, we can define a flow direction along the motion. The component of the net force perpendicular (or normal) to the flow direction is called the lift; the component of the net force along the flow direction is called the drag. These are definitions. In reality, there is a single, net, integrated force caused by the pressure variations along a body.

Velocity Distribution

For an ideal fluid with no boundary layers, the surface of an object is a streamline. If the velocity is low, and no energy is added to the flow, we can use Bernoulli's equation along a streamline to determine the pressure distribution for a known velocity distribution. If boundary layers are present, things are a little more confusing, since the external flow responds to the edge of the boundary layer and the pressure on the surface is imposed from the edge of the boundary layer. If the boundary layer separates from the surface, it gets even more confusing. How do we determine the velocity distribution around a body? Specifying the velocity is the source of error in two of the more popular incorrect theories of lift. To correctly determine the velocity distribution, we have to solve equations expressing a conservation of mass, momentum, and energy.
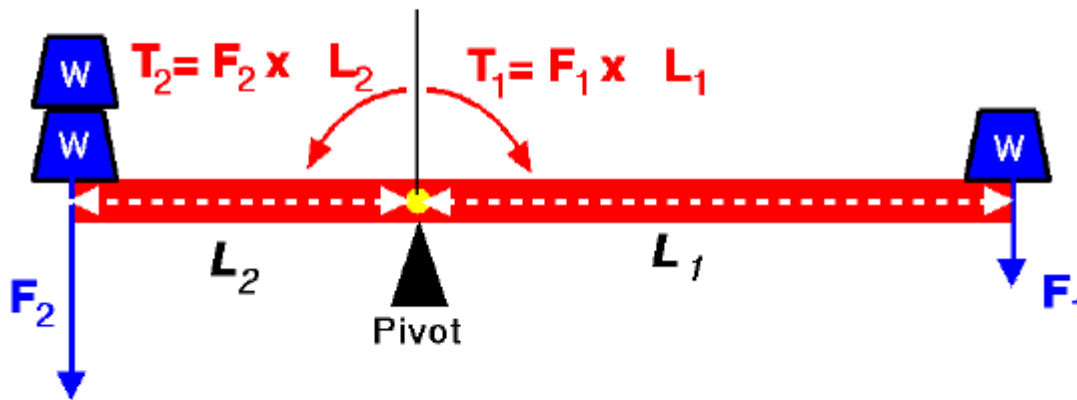
Torque (Moment)

NASA

Torque equals Force times Distance
$T = F \times L$

$$T_2 = F_2 \times L_2 \qquad T_1 = F_1 \times L_1$$

W

W

W

F_2

L_2

L_1

F_1

Pivot

In Equilibrium (balance) $T_1 = T_2$
$F_1 \times L_1 = F_2 \times L_2$

When NOT in balance, system rotates in direction of higher torque

A force may be thought of as a push or pull in a specific direction. When a force is applied to an object, the object accelerates in the direction of the force according to Newton's laws of motion. The object may also experience a rotation depending on how the object is confined and where the force is applied. A hanging door is an excellent example of this type of motion. When you push on a door it can not freely translate because it is confined (or pinned) by the hinges. It does, however, rotate on the hinges. The rotation itself depends on where you apply the force. As you get closer to the hinge, you must apply a larger force to make the door swing. As you get farther from the hinge, you can apply a smaller force to make the door swing.

The product of the force and the distance from a pivot (or hinge) is called the **torque** or the **moment**. Torques produce rotations in the same way that forces produce translations. Namely, an object at rest, or rotating at a constant angular velocity, will continue to do so until it is subject to an external torque. A torque produces an angular acceleration or change in angular velocity. If an object is not pinned, it rotates about its center of gravity when acted upon by an external force. The distance used in the calculation of the torque is then the distance from the center of gravity to the applied force.

As with forces, an object may be acted upon by multiple torques. The motion of the system then depends on the net torque on the system. In the figure we have a beam on which some weights are sitting. The beam itself sits on a pivot. To the right a single weight (W) produces a force (F1) acting at a distance (L1) from the pivot. This creates a torque (T1) equal to the product of the force and the distance.
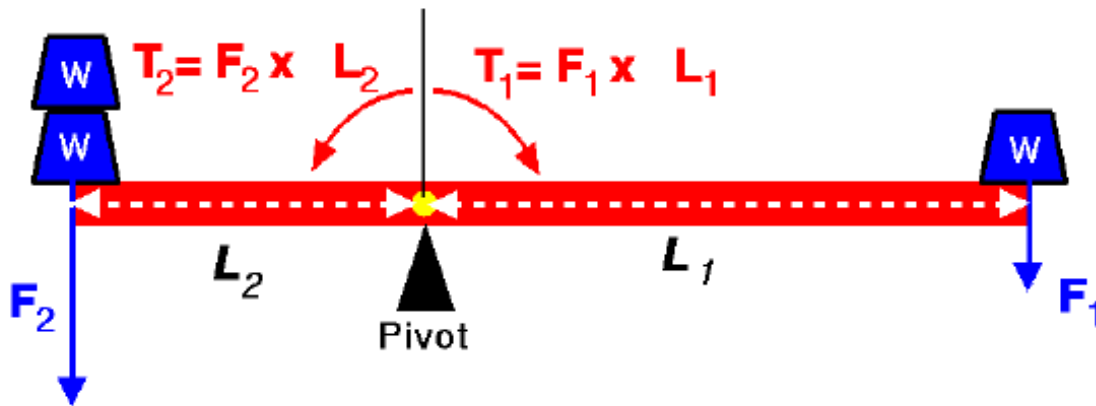
$$T1 = F1 * L1$$

Torque (Moment)

Torque equals Force times Distance

$$T = F \times L$$

$$T_2 = F_2 \times L_2 \qquad T_1 = F_1 \times L_1$$

W
W

W

F_2

L_2

L_1

F_1

Pivot

In Equilibrium (balance) $\quad T_1 = T_2$

$$F_1 \times L_1 = F_2 \times L_2$$

When NOT in balance, system rotates in direction of higher torque

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(Continued from page 11)

To the left of the pivot two weights (W) produce a force (F2) at a distance (L2). This produces a torque (T2) in a direction opposite from T1 because the distance is in the opposite direction.

$$T2 = F2 * L2$$

If the system were in **equilibrium**, or balanced, the torques would be equal and no net torque would act on the system.

$$T1 = T2 \text{ or } T1 - T2 = 0$$

$$F1 * L1 = F2 * L2$$

If F2 = 2 * F1, what is the relation between L1 and L2 to balance the system? If F2 = 2 * F1, and L1 = L2, in which direction would the system rotate?

In aircraft, the control surfaces produce aerodynamic forces. These forces are applied at some distance from the aircraft cg and therefore cause the aircraft to rotate. The elevators produce a pitching moment, the rudder produce a yawing moment, and the ailerons produce a rolling moment. The ability to vary the amount of the force and the moment allows the pilot to maneuver or to trim the aircraft.
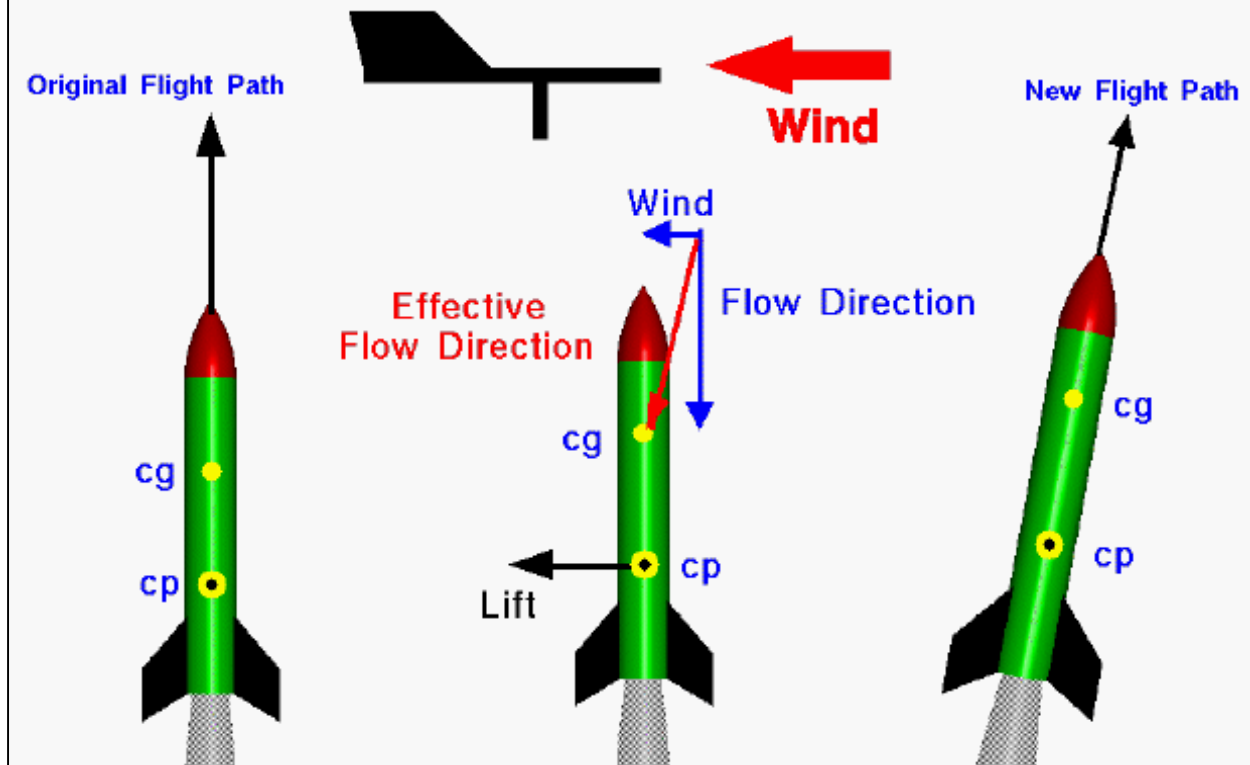
Following the liftoff of a model rocket, the rocket often turns into the wind. This maneuver is called **weather cocking** and it is caused by aerodynamic forces on the rocket. The term, weather cocking, is derived from the action of a weather vane, shown in black on the figure, which are often found on the roof of a barn. The weather vane acts like the vertical stabilizer on an aircraft. It pivots about the vertical bar and always points into the wind. Older, more artistic weather vanes used the figure of a rooster with large flaring tail feathers instead of the wing shown on the figure. This type of weather vane was called a weather cock.

As the rocket accelerates away from the launch pad, the velocity increases and the aerodynamic forces on the rocket increase. Aerodynamic forces depend on the square of the velocity of the air passing the vehicle. If no wind were present, the flight path would be vertical as shown at the left of the figure, and the relative air velocity would also be vertical and in a direction opposite to the flight path. If you were on the rocket, the air would appear to move past you toward the rear of the rocket. Regardless of wind direction, the wind introduces an additional velocity component perpendicular to the flight path. The addition of this component produces an **effective flow direction** at an angle to the flight path that depends on the relative magnitude of the wind and the rocket velocity. Since the effective flow is inclined to the rocket axis, an aerodynamic lift force is generated by the rocket body and fins. The lift force acts through the center of pressure, as shown in the middle of the figure. The lift force causes the rocket to rotate about the center of gravity, producing a new flight path into the wind, as shown on the right of the figure. Because the new flight path is aligned with the effective flow direction, there is no longer any lift force and the rocket will continue to fly in the new flight direction.