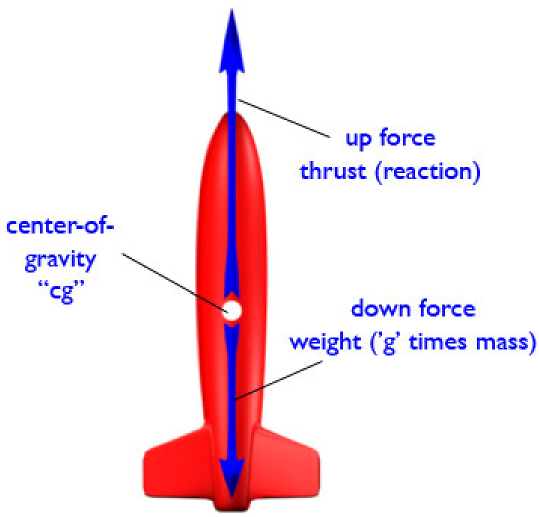
SECOND LECTURE: Thrust, Drag & Lift; Rates of Change—Vectors

In our last meeting we talked about TWO of the FOUR FORCES that govern how your rocket will fly. We mentioned that all matter has MASS—and therefore INERTIA—a property that resists a change in motion in a straight line UNLESS the forces acting on that mass CHANGE.

Today we'll introduce two additional forces that we need to understand, I'll introduce the concept of 'rates of change' and finally we'll see how to put all four forces together, using VECTORS.



Review: Weight (Gravity) and Thrust

WEIGHT: is the Earth's gravitational attraction to the MASS of the rocket.

THRUST: is the reaction to the force of the hot exhaust gases expelled from the rocket NOZZLE. We'll talk about what a 'reaction' force is in a moment.

See the arrows in the picture? I want you to remember that this is how we picture VECTORS. You'll recall that ANY FORCE has a DIRECTION… and a MAGNITUDE.

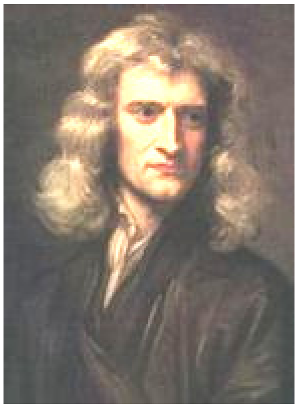
Lastly, recall the see-saw. Remember that our 'cg' is the point at which our ROCKET WILL ROTATE when forces act upon it—just like the see-saw that tilts.

[DEMONSTRATION] Here, in my hand is the rocket you'll be building. Because I'm the teacher, I get one first! Now watch as I balance the rocket from end-to-end. Do you see how —just like the see saw—if I move my hand AWAY from the rocket's cg, the rocket will tilt?

PROBLEM 5: Now just suppose we want to add a more powerful motor, with a larger size, more MASS (rocket propellant) so that the rocket could go higher, faster. What do you think will happen—when we put the heavier motor into the rocket?

YOUR ANSWER ____

Hint: which direction would the cg move—towards the nose cone or closer to the nozzle of the rocket? (Remember the see-saw.)



Isaac Newton's 'Physical Laws'

We've already talked a little about INERTIA.

Newton's Second Law tells us that whenever we observe matter in motion, there must be a FORCE (or more precisely, a combination of forces) at work.

The Third Law explains thrust. Take a minute to review these, and then we'll delve a little bit deeper—don't worry—we'll stay focused on the fun parts!

First LAW (also called INERTIA)
Every body continues in its state of rest, OR in uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.

Second LAW (sometimes called 'F = m • A')
Force is equal to the change in MOMENTUM (MASS times Velocity) of the body for each infinitesmal unit of time. Force equals mass times Acceleration if the mass of the body remains constant. $\mathbf{F = \Delta (m \times V) / \Delta t}$ $F = m \times A$ (if m constant)

Third LAW (also called "action-reaction")
To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

If we fully understand these laws and if we can learn how to CALCULATE with vector forces then we can PREDICT how our rocket will move as a result of the FORCES that act upon it!

THRUST and "ACTION-REACTION"

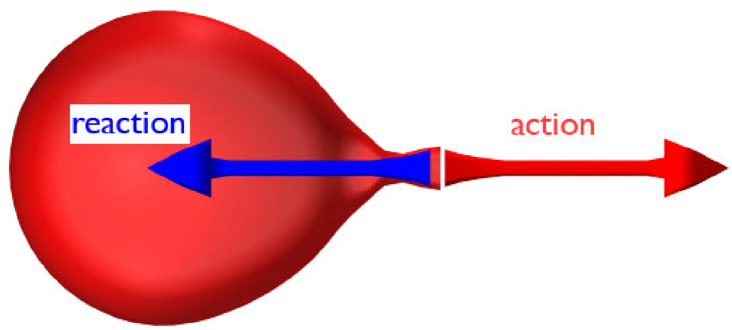
THRUST is a "reaction" force which is explained by Newton's THIRD LAW. Rocket propellant (in the case of your rocket, a solid fuel pretty similar to the solid fuel booster used in the space shuttle) undergoes rapid combustion and super energetic [hot] gas molecules are exhausted out of the rocket's nozzle.

In this CHEMICAL REACTION the compounds of the fuel are combined with oxygen molecules (chemists call this 'rapid oxidation' but you and I call it 'combustion' or 'explosion'!)

Note that in ROCKETS –the "oxygen to combine" is ALWAYS carried along with the other elements of the rocket propellant. That's why rocket engines can work in space, where there is no oxygen. That's also why, since about 8 times as much oxygen mass is carried as the rest of the fuel, "mass-ratios[1]" are so important.

At any rate, these new molecules are expelled at hundreds of times their former velocity. Mass times Velocity "mV" or a MOMENTUM is created. Now, a fundamental law of our science tells us that energy can neither be created, nor destroyed. You may recall discussions about "the conservation of energy" from your science class.

So, in order to conserve the balance of energy, when we create this new MOMENTUM (the mass accelerating away from the nozzle) we must have an equal, OPPOSING MOMENTUM in order to conserve total energy (the mass of the rocket, accelerating in the opposite direction—THRUST).



One way to think of your rocket's thrust is to imagine a balloon in which the trapped air is suddenly allowed to escape, as in the figure above. What is the source of the "energy" of the balloon? The air pressure, caused by the balloon membrane trapping the air inside. Where did that stored (potential) energy come from in the first place? The person's lungs who blew up the balloon! What is the mass? The total mass of the trapped air molecules, that soon expels into the open atmosphere. And what is the result? A thrust is created that pushes the balloon very rapidly across the room until the trapped air is released.

TWO NEW FORCES: 'Aerodynamic' Drag and Lift

So far we've been talking about two basic forces that exist anywhere in the universe—as long as there is a rocket 'propellant' and oxygen (stored in the rocket's tanks) or another source of momentum expelled from the rocket's nozzle.

When we have to 'lift-off' from Earth or any planet with an atmosphere, we will also be concerned with TWO ADDITIONAL forces. Now in the almost perfect vacuum of space, this second set of AERODYNAMIC forces—lift and drag—do not apply, since they are due to the pressure of the molecules of air (or atmosphere, in the case of a planet unlike Earth). That's why when you see many science fiction movies the spaceships

[1] Towards the end of my lectures, we'll look at THRUST and the ROCKET EQUATION in more detail to see what mass-ratios are all about, and why they are so important to rocket engineers.

can look so “un-aerodynamic” –they don’t have to be streamlined, because there is no “drag” or force of any atmosphere!

“VIC” --Very Important Concept

DRAG: A force that opposes the forward motion of the rocket with increasing pressure of air molecules ‘as they pile up’ in front of—or ‘stick along the sides of’—the rocket;

LIFT: A force that occurs when the body, nose cone and fins of the rocket cause an imbalance of air pressure, so that the rocket wants to rotate about its cg until the air pressure on all sides is once again equal.

Now, I want to make a slight distinction here, for those of you who may have studied ‘LIFT’ from the perspective of how an airplane’s wings work. Although the physics (or the math) is the same, LIFT is the greatest force for an airplane—it is NOT for the rocket. While airplane lift keeps the aircraft flying, the rocket depends upon thrust to overcome falling back to Earth.

Here’s a little ‘mind experiment’ so that you can understand these concepts.

[DEMONSTRATION : A ‘Gedanken’ Experiment]

Think about when you are riding in the car with your mom or dad. Have you ever put your hand out of the open window and cupped it, almost like an airplane wing? Depending upon how fast you were traveling and how far you opened your palm to the direction of the wind—you could control the pressure you felt, right?

What you were doing was adjusting the ‘angle-of-attack’ of the air pressure on your hand. If your hand was like a knife-blade towards the wind, you probably felt a slight pressure, but more of a force causing your arm to go up or down—<u>that’s Lift</u>. It is caused when the air pressure above or below your flattened hand is less than on the other side.

If, instead, you opened your palm <u>facing into the wind</u> (or you can make a fist) what you’ll feel is pressure forcing your hand (and your arm because it’s connected) backwards—<u>that’s Drag</u>. The farther you open your palm—THE MORE FRONTAL AREA FACING THE WIND—the greater the pressure.

Now maybe you’ve done this a few times, and at different speeds… say 30 mph, 50 mph, maybe even 65 mph, the ‘legal speed limit’ which I’m sure is never exceeded by your parents while driving on open interstate highways! Now we realize that the force of the wind—the AIR PRESSURE—on our hand seems to be <u>much stronger</u> at 60 mph, than 30 mph, right?

The math tells us that even though our speed goes up by TWICE as much (say from 30 mph to 60 mph), the FORCE of Drag that we feel actually increases to FOUR TIMES as much!

Now what I want you to try and imagine is that your car—instead of traveling maybe fifty miles per hour, is traveling 650 mph instead, which is pretty close to what some of our model rockets will be traveling!

Well, in fact, we can not only imagine it, but we can calculate it! Rather than give you the "Drag equation[2]" right this instant, I think it is more helpful for you to understand the concept mathematically.

Rate of Change, Squares of Numbers and the Math of Exponents

Let's think about our own personal experience—what we've learned about DRAG, and see if we can come up with a formula for it all on our own!

First, we know that the AREA—or 'frontal area'—of our hand was important. The more open the palm (the more area) the more force. Second, the faster we travel, the more air molecules are hitting our open palm, at any one instant. Finally, it would be helpful to know 'just how many air molecules there are' and how much mass they have before they are about to hit us, right?

So here is what the mathematician does: First, she sets up an equation, for a FUNCTION—that is, the relationship between the variable we want to know, and the other variables.

Here it is, from your own experience:

Drag Force {in pounds' force per square foot of area, **or** kg per sq. m per second}

EQUALS …

Some **CONSTANT** {mathematician's place-holder for experimentally observed values}

TIMES

FRONTAL AREA {in square feet, **or** sq. m}

TIMES

MASS OF AIR MOLECULES {the mass of air molecules in pounds/sq. ft. **or** kg/sq. m otherwise called 'density' at a particular altitude, in this case, we'll use 'sea level'}

TIMES

VELOCITY 'SQUARED' {the speed of the air molecules hitting us, from the DIRECTION directly perpendicular to our open palm… measured in either feet per second **or** meters per second—but notice we've SQUARED this amount!}

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[2] If you want to know more, go on to the website, and look up the 'advanced reading' assignment. The math isn't that tough, and you will be able to amaze and delight your friends!

So here's what our equation looks like, to a mathematician or to an engineer:

$$F_d = C_d \bullet A_f \bullet \rho_{sl} \bullet V^2$$ [footnote3]

And we read it as follows: "the force of drag equals the experimentally determined drag constant, times frontal area, times 'rho' (Greek symbol for the density of air at sea-level) times Velocity-squared."

Now one question you may have is "what is this CONSTANT (C_d) thingy?" Well, it comes from science, math and engineering, when we MEASURE some force or some physical entity in the real world. It's called a constant because its value remains the same. Rocket scientists, airplane, submarine, auto and building designers use lots of them, constantly☺.

I bet you're also wondering, "where the heck did this Velocity-squared term come from anyhow?" The shortest answer I can give you is that if you think about it, the mass of the air molecules—as we go faster and faster—increases not just because there are more of them coming at us faster, but also because what they hit—your open palm—is an Area, which we measure by multiplying length times width—or in the case of a perfect square, by the 'square' of the length of the sides!

"VIC" --Very Important Concept

RATES OF CHANGE—MANY PHYSICAL VARIABLES in science and mathematics depend upon an <u>exponential variable</u>: that is, a term that is squared (a power of 2) or an 'exponent' (other powers).

In the case of our rockets, we find 'squares' (powers of 2) in the equations for the following parameters:

The force of Gravity (weight) varies with the SQUARE of the distance between two attracting masses. If our rocket is 2 times further from the center of the Earth (a very long way away) it weighs ONE-FOURTH what it weighs on the ground.

The forces of Lift and Drag vary with the SQUARE of the Velocity of the air or atmosphere molecules. As we just saw, if our speed in the direction opposing the atmosphere goes up by ten times, the Drag is 100 times as much!

[3] The equation used by engineers actually has a "1/2" term, but I've incorporated that into the constant for simplicity. See the 'advanced readings' on the Delta V website for more.

[Class Exercise: SQUARES and Rate of Change on the SLIDE RULE]

I want you to take out your SLIDE RULE and look first, at the "D" scale. Choose a number, let's say "2". OK, now move the cursor above the 2 on D, and then, I want you to look at the top of your rule, at the "A" scale. Do you see that the cursor is on the "4"? That makes sense, because "2 times 2" (or 2-squared) is equal to 4.

So a number "squared" is just that number, TIMES ITSELF. Well OK, so what's the big deal? The big deal is this: the square of a number (like all "exponents") INCREASES VERY RAPIDLY as the original number grows larger. Let's see if we can create a TABLE of examples:

2 squared… is "4"   6 squared… is "36"   12 squared… is "144"

All right, now remember I asked you to imagine that instead of sticking your hand out of the car window at 50 mph—to think about what would happen if you stuck your hand outside of the "window" of your model rocket, if it were moving at 650 mph?

Let's see if we can work this out: the force on your hand (from the drag equation) at 50 mph is about 1 pound of pressure (for an average sixth-grader's hand size, at sea-level). Now, if our speed (velocity) goes from 50 to 650— VELOCITY HAS INCREASED BY 13 TIMES.

So, if we "square" 13, we can find out how much the FORCE of Drag will increase—that is, how much pressure we would feel on our hand if we were able to put it outside of our rocket's "window." OK, so look at your slide rule, find "13" on the D scale. Got it? Look above it now at the A scale, and read the SQUARE of 13 is 169.

So, the force we would feel, if we could put our hand outside of the model rocket, is not 1 pound of air pressure, but 169 TIMES 1 pound… or, an astounding (do the multiplication in your head) 169 POUNDS OF PRESSURE! That's about eighty percent of your teacher's body weight! You could say, you have me 'in the palm of your hand'☺.

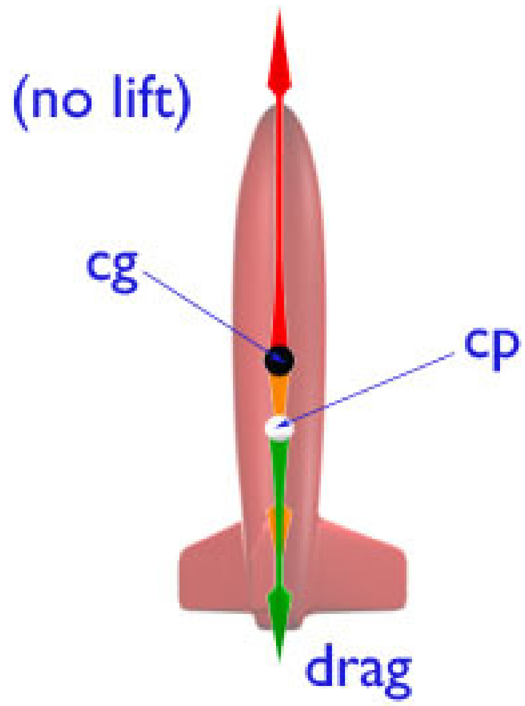
Now I hope you can see why car designers, airplane designers, ship designers and rocket designers spend so much time trying to make their designs aerodynamic. Did you ever wonder why the front and rear 'air foils' of a NASCAR or Formula 1 race car are so important? Now you do!

Putting The Forces All Together –Vectors

Remember during our first lecture I told you that finding the cg of your rocket was very important, because as the rocket flies, it will ROTATE about this point, when all of the forces act upon it?

Now that we have mentioned the other two, aerodynamic forces, let's see if we can use our 'arrows' –VECTORS—to see what goes on.

Take a look at the picture below: what I've done is show the rocket in straight flight, moving directly perpendicular to the ground. Everything's fine—that's the way we want things to go.



Notice the NEW imaginary 'dot' on the rocket. We call it the 'center-of-pressure.' This is the point on the longitudinal axis of your rocket is where the forces of LIFT and DRAG accumulate.

(You can also see the cg and the Thrust and Weight forces from before.)

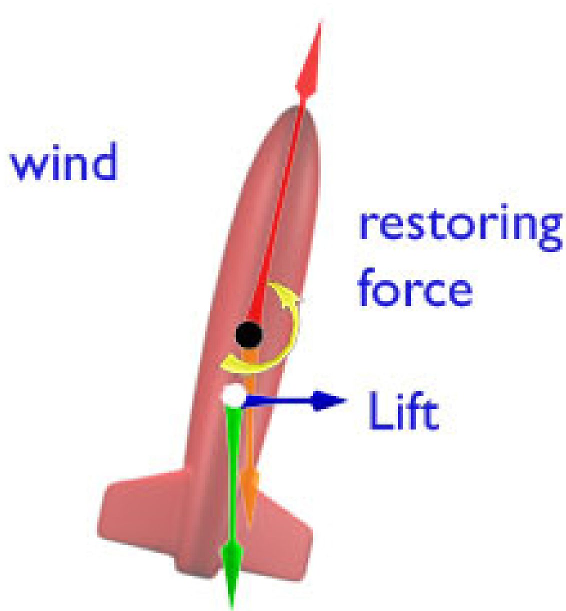
Notice please, a couple of other things:

1) The Drag Vector (at this point, because of the high Velocity of the rocket) is actually longer (greater) than the force of Gravity!

2) There is NO LIFT. So the air pressure on each side of our rocket is 'in balance'.

3) The center-of-pressure 'cp' is BELOW the cg. You'll see why this is so important in our next example.

Now, in the picture below, our rocket is still in 'powered flight,' but this time, there is a WIND, coming at a right angle, from the rocket's **Left Side**:



Notice this time, that even though the overall motion of the rocket is still "straight up" –that the ANGLE of the rocket's nose has been MOMENTARILY knocked out of alignment with the rocket's flight direction!

VECTORS can help us PREDICT how the forces acting on the rocket will cause its MOTION to change.

First, we now have a LIFT force, which is caused by the uneven air pressure on one side of the rocket—the wind coming from the left side. Second, the LIFT force is at right-angles to the cp, causing a 'torque' or turning force, just like our see-saw, which makes the rocket want to rotate around its cg.

Remember I said it was important for the cp to be BELOW the cg? That is what causes the rocket's nose to want to rotate, back TOWARDS the wind.

Also, you can see that now DRAG is not quite acing along the rocket's length, but at a slight ANGLE. This also causes a slight torque, because you can see that in this picture, the drag force is acting slightly to the left of the rocket's cg.

Since our cp is about the length of the rocket's diameter BELOW the cg, our rocket will have what engineers call a "RESTORING FORCE" –that is, the nose of the rocket will tend to go back in the direction we want it to! [See the circular arrow about the rocket's cg, in the picture above.]

I know you're thinking, "why doesn't the wind, coming from the LEFT, make the rocket go towards the RIGHT? After all, it's <u>pushing</u> the rocket!" Well, remember Newton's SECOND LAW? You can't just look at any <u>one</u> force (vector) in isolation from all of the others. You have to look at the SUM of the VECTORS (forces)—in order to understand what ultimately will happen.

OK. That's our lecture for now. Next time, we'll examine the four VECTORS more closely, we'll take a look at several basic flight equations and we'll see how the flight trajectory of our rocket can be predetermined with some degree of accuracy by using the concepts we've learned.