Conversational
Rocket Science

A ConversationalGeek® Book

Learn about:

- What it takes to reach orbit
- Why rockets use multiple stages
- How to calculate the orbit of a spacecraft

2nd Edition

By Brien M. Posey (Microsoft MVP, Commercial Scientist Astronaut Candidate)

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Note from the Author

Greetings, and welcome to Conversational Rocket Science. I'm Brien Posey, a long time tech author and speaker. Even though I'm probably best known for my work in IT, I have also spent the last few years training as a commercial Scientist-Astronaut Candidate. Given my background, I thought that it might be fun to switch things up a bit, and write about something other than information technology.

Rocket science is one of those things that seems to be a total mystery to most people. It also has a reputation for being extraordinarily difficult. It doesn't have to be that way though. My goal in writing this book is to make rocket science accessible. I want to cut through some of the technical jargon and advanced math, and present rocket science in a way that anyone with a basic knowledge of high school algebra will be able to understand. In doing so, I will show you how to calculate an orbit, and I will explain how to determine whether a rocket will be able to reach that orbit. It should be a lot of fun.

Brien Posey

The "Conversational" Method

We have two objectives when we create a "Conversational" book: First, to make sure it's written in a conversational tone so it's fun and easy to read. Second, to make sure you, the reader, can immediately take what you read and include it in your own conversations (personal or business-focused) with confidence.

These books are meant to increase your understanding of the subject. Terminology, conceptual ideas, trends in the market, and even fringe subject matter are brought together to ensure you can engage your customer, team, co-worker, friend and even the know-it-all Best Buy geek on a level playing field.

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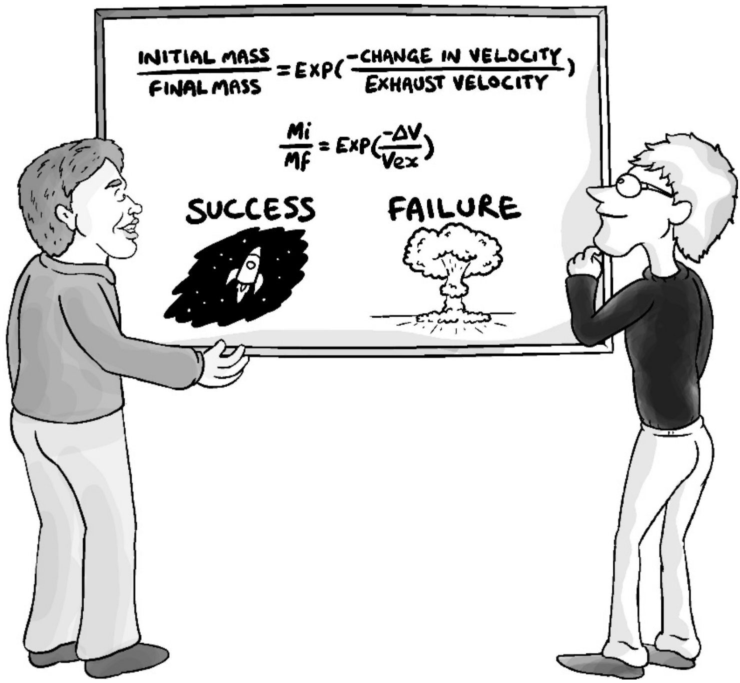
We infuse humor into our books through both cartoons and light banter from the author. When you see one of these boxes, it's the author stepping outside the dialog to speak directly to you. It might be an anecdote, it might be a personal experience or gut reaction and analysis, it might just be a sarcastic quip, but these "geek in the mirror" boxes are not to be skipped.

> Within these boxes I can share just about anything on the subject at hand. Read 'em!

Rocket Science!



The phrase "it's not rocket science" gets used a lot as a way of saying that something is not overly difficult. The flip side to this however, is that the phrase implies that rocket science is pretty much the most difficult thing imaginable. As someone who has spent the last few years studying rocket science, I can tell you from firsthand experience that there is a legitimate reason why rocket science has earned its reputation for being difficult. Even so, my goal for this book is to explain the basics of rocket science in a way that is relatively easy to understand.

Before I get started, I need to take a moment and talk about the elephant in the room. One of the things that makes rocket science so difficult is that it relies heavily on math. Unfortunately, it is impossible to talk about rocket science without using some math. However, I am going to keep the math to a minimum, and I will try to make it as easy as I can.

Don't worry if math isn't your thing. You can always skip right over the math. For those who do want a taste of the math, I am going to keep things simple, and avoid calculus like the plague. You may see some calculus-like symbols later on (such as μ or Δ), but these represent constant values, not some crazy mathematical operation.

So with that said, the question I want to answer in this book is, "What does it take to put a rocket into orbit around the Earth?" In some ways however, that is the wrong question to ask. The real goal is to put some sort of payload into orbit. That payload might be a crew of astronauts, it might be a satellite, or perhaps something else. In any case, putting the payload into orbit is the real objective. The rocket is simply the vehicle that gets it there.

Getting into to Orbit

To achieve orbit, a rocket has to carry its payload to the correct altitude, and accelerate it to orbital velocity. Velocity and gravity are the forces that allow the payload to orbit the Earth.

As you no doubt know, an astronaut who is orbiting the Earth in a spacecraft is weightless. One of the big misconceptions about weightlessness is that once a spacecraft is in space, gravity just goes away. However, nothing could be further from the truth. Gravity is just as present in orbit as it is on Earth. The reason why astronauts are weightless while in orbit is because the spacecraft is in freefall toward the Earth.

You don’t have to go to space to be weightless. Weightlessness can be created in an airplane, by flying a parabolic trajectory in which the plane descends at the same rate as gravity. There are actually companies that offer zero gravity flights to the general public, but be warned… The planes used for microgravity research are commonly referred to as “The Vomit Comet” because of their tendency to cause motion sickness.

The reason why a spacecraft can stay in orbit is because the Earth is round. The spacecraft is falling toward the ground, but it is also flying so quickly toward the Earth’s curved horizon, that the ground keeps falling away. In other words, the spacecraft is falling toward the ground, but ground keeps getting further away because of the curvature of the Earth. With the proper altitude and velocity, the forces of velocity and gravity can be kept in equilibrium, and the spacecraft never gets any closer, nor any further from the Earth.

To illustrate this concept, imagine what would happen if you tied a small object to a string and then swung the sting in a circle. The object’s momentum would make the object want to travel in a straight line. However, the string is anchored to an immobile central point (your hand). This causes the object to move in a circle instead of a straight line. In this example, the object has velocity, just like a spacecraft in orbit. The string is like gravity, in that it continuously pulls the object toward a central point. Assuming that the object’s velocity is fast enough to keep the object from falling to the floor, and slow enough to avoid breaking the string, the object will “orbit” around your hand.

How Much Propellant Does a Rocket Need?

Getting a rocket to launch a payload to the required altitude and velocity is surprisingly difficult. One of the main reasons for this is that, even though it is the payload that needs to be placed in orbit, the rocket also has to lift its own weight. This rocket's total mass is made up of structural components, propellant, the rocket motor, and of course the payload.

Newton's third law states *that for every action, there is an equal and opposite reaction*. In the case of a rocket, it burns propellant (which is made up of fuel and an oxidizer), and emits hot gasses out of a nozzle. The exhaust gasses are directed downward (toward the ground). The opposite reaction, cited in Newton's third law, results in the rocket rising toward the sky. The question then becomes a matter of how to burn the propellant in such a way as to generate enough thrust to achieve orbital velocity.

One of the first formulas that first year physics students learn is *F=MA*, or Force equals Mass times Acceleration. In the case of a rocket engine, the amount of force exerted by the engine can be attributed to the mass of the propellant that is being burned, and the propellant's acceleration. The greater the mass of the propellant that is being burned, and the faster the acceleration of the burn, the greater the force. Let me give you a really simple example.

When I was a child, I had a toy air and water rocket, as I am sure many of you also did. For those who aren't familiar with air and water rockets, they are essentially plastic rockets that use water for fuel. To use the rocket, you would add a certain volume of water, and then attach an air pump. The compressed air that is pumped into the rocket forces the water out of the rocket once the pump is released. The spray of water creates enough thrust to make the rocket fly.

So with this in mind, consider the relationship between propellant mass and acceleration. In the case of an air and water rocket, the acceleration is the result of pressurized air. If you don't pump enough air into the rocket, then it won't fly, because the propellant (the water) is not being sufficiently accelerated. On the other hand, if you pump a little bit of extra air to the rocket, then it will fly even higher, because the propellant is being accelerated more quickly.

Of course the propellant mass also plays a role. I once tried filling the rocket with air only, completely omitting the water. When released, the rocket flew about four inches, compared to its usual 50 feet. This happened because the propellant did not have sufficient mass.

The key to putting a rocket into orbit is to determine how much of the rocket's total mass needs to be propellant. Remember, the rocket's mass is made up of the propellant, the payload, and any structural or mechanical components.

A rocket burns propellant at a known rate. This burn rate is referred to as the exhaust velocity, or Vex. This number varies depending on the type of propellant being used, but for engines that burn liquid hydrogen and liquid oxygen, the exhaust velocity is about 4500 meters per second (although this number is greatly affected by the engine's efficiency).

In order to determine how much propellant is required, we also need to know how fast we need to be going in order to achieve orbital velocity. This determination is surprisingly complicated, because you have to factor in for things like atmospheric density, gravitational losses, and even the rotation of the Earth. In the interest of keeping the numbers nice and even, let's just call orbital velocity 8000 meters per second. That works out to 4.97 miles per second. Actual orbital velocity can be faster or slower, depending on a variety of factors.

Now that we have numbers for orbital velocity and we have a burn rate for the propellant, we can calculate the propellant fraction. The propellant fraction is derived from the ideal rocket equation (which I will talk about later), and looks like this:

$$\frac{Initial\ Mass}{Final\ Mass} = Exp(\frac{-Change\ in\ Velocity}{Exhaust\ Velocity})$$

In other words, the rocket's initial mass before it burns any propellant, divided by the rocket's mass after it has used up all of its propellant is equal to the exponential change in negative velocity divided by the exhaust velocity. This formula is often expressed as:

$$\frac{Mi}{Mf} = Exp(\frac{-\Delta V}{Vex})$$

So let's put some numbers into this formula. Delta V is going to represent orbital velocity (more precisely, the change in velocity (from a standstill) required to reach orbital velocity). In this case, Delta V is going to be 8000 meters per second. The exhaust velocity value we are going to use is 4500 meters per second. Hence:

ΔV = 8000 meters per second
V_{ex} = 4500 meters per second
$-\Delta V / V_{ex} = -1.78$

If we plug this into the propellant fraction equation, we find that:

(Final Mass / Initial Mass) = exp(-1.78)
(Final Mass / Initial Mass) =0.168

This final result of 0.168 can be expressed as a percentage, in this case 16.8%. It means that 16.8% of the total mass that is being launched can be something other than propellant. In other words, if this rocket is to reach orbital velocity, then 83.2% of its total mass will have to be propellant.

Why Do Rockets Have Stages?

Although the rocket from the previous example can theoretically achieve orbital velocity, such a rocket may not be practical. Quite frankly, this rocket probably would not be structurally sound because the formula probably does not allow for adequate structural mass. Rocket scientists solve this problem through staging.

Think of staging as one rocket sitting on top of another rocket. When the first rocket burns all of its propellant, the second rocket is ignited. The advantage to this technique is that when staging occurs, much of the rocket's structural mass is eliminated, thereby making it more efficient.

Remember earlier when I said that it isn't actually the rocket that we have to get into orbit, but rather the payload? Throwing away part of the rocket during the staging process is completely acceptable if the goal is to deliver the payload into orbit without regard for what happens to the rocket.

To illustrate just how much of an advantage staging actually gives us, let's work the rocket equation in a different way. So far we have worked the rocket equation using a target value for Delta V in order to find a propellant fraction. Let's instead treat Delta V (the maximum velocity) as an unknown, and solve to determine how much velocity the rocket can achieve.

For this, we will use a small rocket with 20,000 KG of propellant, 4000 KG of structural mass, and a 1000 KG payload. To calculate Delta V, we will multiply Vex (the exhaust velocity) by the natural logarithm of the rocket's initial mass divided by its final mass when all of the propellant has been burned.

We will continue to use 4500 meters per second as the exhaust velocity. The initial mass will be the sum total of the mass of the propellant, structure, and payload. In this case, the initial mass is 25,000 KG. The final mass once all of the propellant has been burned is 5000 KG.

In this example, the math works out like this:

ΔV = Vex ln (Initial Mass / Final Mass)
ΔV = 4500 ln (25,000 / 5000)
ΔV = 7242.471 Meters per second

So now that we have a value for Delta V, let's see how the value changes if we break the rocket into two separate stages. We will assume that each stage contains equal structural mass and equal propellant, and produces equal thrust. Since the payload normally sits at the top of the rocket, its mass will be added to the second stage.

So the first stage contains 10,000 KG or propellant and 2000 KG of structural mass. The second stage contains 10,000 KG of propellant, 2000 KG of structural mass, and a 1000 KG payload.

The way that we have to work this problem is to calculate two separate values for Delta V, one for each stage. Those values are then added together to find the total Delta V, or the total velocity of the rocket.

The tricky thing about the math is that when calculating Delta V for the first stage, the initial and final masses must include the mass of the second stage and the payload. Remember, the first stage is carrying the second stage, so the second stage's mass must be factored in. So here are the numbers that we will use:

First Stage Initial Mass = 25,000 KG
First Stage Final Mass = 15,000 KG (the first stage has burned 10,000 KG of propellant, but the propellant in the second stage remains)
Second Stage Initial Mass = 13,000 KG

Second Stage Final Mass = 3000 KG
Vex = 4500

Here is the math:

First Stage
ΔV = Vex ln (Initial Mass / Final Mass)
ΔV = 4500 ln (25,000 / 15,000)
ΔV = 2298.724

Second Stage
ΔV = Vex ln (Initial Mass / Final Mass)
ΔV = 4500 ln (13,000 / 3000)
ΔV = 6598.513

When we add the Delta V values for the first stage and the second stage together, we get a final total Delta V of about 8897.237 meters per second, which is substantially higher than the Delta V value that was produced by a single stage rocket of exactly the same mass. If we are estimating that orbital velocity is 8000 meters per second, then the single stage rocket fails to achieve orbital velocity, while the two stage rocket exceeds orbital velocity. In fact, the two stage rocket has extra capacity that could be used to add structural materials (in the interest of improving the rocket's structural integrity), or to launch a heavier payload.

How Many Gs Will Be Produced at Liftoff?

One more thing that I want to talk about before I move on is the G force exerted by the rocket. Humans can only withstand a certain number of Gs. Excessive G forces can also cause structural damage to the rocket.

When I took aerobatic flying lessons, my instructor cautioned me not to pull too many Gs because it is possible to cause severe damage to the airframe if you exceed the plane's G load rating.

So before we put a payload into our imaginary rocket, we need to know how many Gs it will be subjected to. In other words, we want to find out if the rocket is going to leave the launch pad ascending gently like a hot air balloon, or violently like something fired out of a cannon.

As part of my spaceflight training, I have spent a lot of time in the centrifuge, learning to cope with G forces. Depending on their direction, G forces can make you pass out, or they can make it feel as though someone has parked their car on your chest.

In order to find out, we need to know two things – the rocket's mass and the amount of thrust that is being produced by the engines. As you may recall, our example rocket had a mass of 25,000 KG. We don't know the amount of thrust produced by the rocket aside from the fact that the thrust is greater than 25,000 KG. If the thrust were less than this number, the rocket would not be able to leave the ground. Rather than working out the thrust mathematically based on the previous example, let's just pretend that this rocket is producing 30,000 KG of thrust.

If we want to determine the number of G forces that are exerted at lift off, we first have to subtract the vehicle's mass from the total thrust to find the excess thrust. In this case, 30,000 KG of thrust minus 25,000 KG of mass, leaves us with 5000 KG of excess thrust. Now we divide the excess thrust by the vehicle's total mass. In this case, 5000 KG of excess thrust divided by the 25,000 KG vehicle mass gives us 0.2. This value reflects the G forces exerted by the rocket at liftoff. Since we are always under a load of 1 G here on Earth, we must add a value of 1 to this number, giving us a total of 1.2 Gs at launch. This would make for a very smooth, comfortable, and slow initial acceleration.

One thing to keep in mind is that this calculation only gives us the initial G force that is created at launch. As the rocket flies, it burns propellant. This causes the rocket's mass to be reduced, resulting in an increased velocity. Furthermore, the Earth's atmosphere becomes less dense as the rocket climbs, which allows for an even greater acceleration. As such, the peak G load is likely to be far higher than the G force that is initially experienced at liftoff.

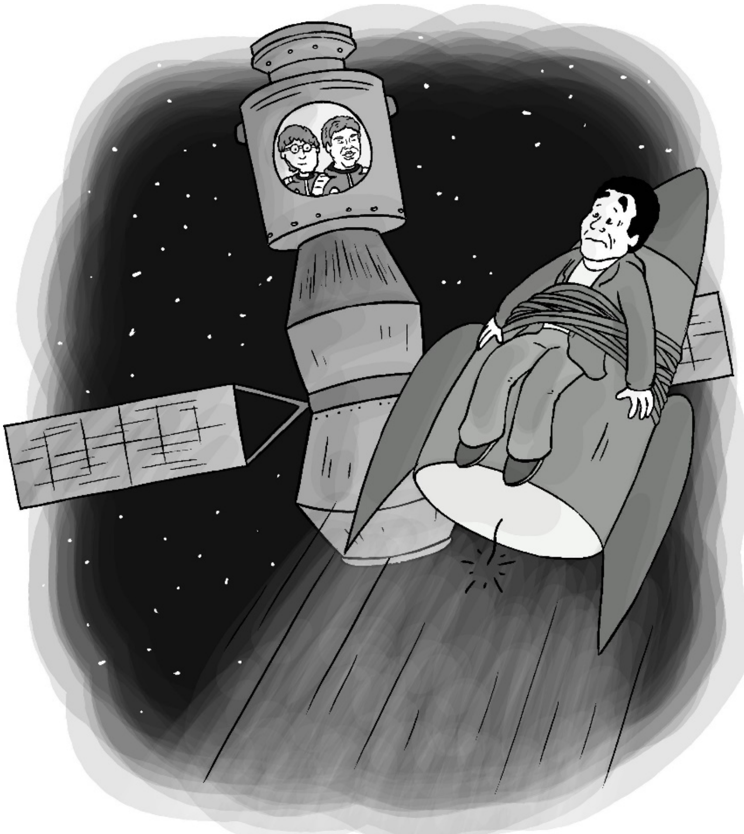
So would it be possible to use this same formula to determine the G load at a specific point in the flight? Not quite. There are a few problems with doing that.

One problem is that the formula does not take atmospheric density into account. As the rocket climbs, the air gets thinner and the rocket is going to accelerate more quickly as a result. This formula would not account for that acceleration. Similarly, the rocket's mass is reduced as it burns its fuel, which also results in a faster acceleration.

Another problem is that this formula assumes that the rocket's thrust remains constant. In reality, liquid fuel engines can be throttled in flight to increase or decrease thrust.

The space shuttle throttled down its main engines just prior to passing through Max Q (the point of maximum dynamic pressure) in an effort to reduce the stress on the vehicle. Once the shuttle passed this point, the engines were throttled back up.

Orbital Mechanics



Now that I have talked about what it takes for a rocket to reach orbital velocity, I want to shift gears a bit and talk about orbital mechanics. Given the short length of Conversational Geek books, and the fact that I promised to stay away from advanced math, I am only going to be able to cover some really basic concepts. Even so, it should still be enough to give you an idea of how a spacecraft orbits the Earth.

The Orbital Inclination

One of the big misconceptions about space launches is that rockets travel straight up. Although rockets do of course go up, they also follow a down range ground track. This ground track varies based on the desired orbital inclination.

The orbital inclination essentially describes the tilt of the orbital plane with relation to Earth's equator. An orbit that circles the Earth at the equator has an orbital inclination of zero, because the orbit is fixed to zero degrees of latitude.

Conversely, the International Space Station has an orbital inclination of 51.6 degrees. This means that the space station's ground track takes it between 51.6 degrees north latitude and 51.6 degrees south latitude.

When a spacecraft is launching into orbit, the minimum orbital inclination that it can achieve is equal to the latitude of the launch site. For example, the launch facility at the Kennedy Space Center in Florida is located at 28.6083 degrees north latitude. Hence, it would be impossible to launch into an equatorial orbit from the Kennedy Space Center, because an equatorial orbit has an orbital inclination of zero, and zero is smaller than 28.6083.

It is possible to launch to the International Space Station from the Kennedy Space Center, because the space station is at a 51.6 degree orbital inclination, which is higher than the Kennedy Space Center's 28.6083 degree latitude. When launching to the International Space Station from the Kennedy Space Center, launch vehicles follow a ground track that roughly follows the eastern coast line of the United States and Canada.

Calculating a Circular Orbit

Orbital inclination is not the only factor that is important with regard to an orbit. There are other variables that must be considered, such as the orbital velocity and the altitude of the orbit. In just a moment, I will show you a simple formula for calculating a circular orbit. Before I do, there are two basic facts to keep in mind.

First, orbital velocity decreases as the orbital radius increases. In the case of a spacecraft that is orbiting the Earth, this means that a spacecraft in high Earth orbit (such as a geostationary orbit) will have a lower orbital velocity than a spacecraft in low Earth orbit.

The second point to keep in mind is that as the orbital radius increases, so too does the orbital period. The orbital period is the length of time it takes to complete an orbit. Let me give you an example. When the space shuttle was flying, it orbited the Earth in roughly about 90 minutes. As such, the orbital period was about 90 minutes (keep in mind that this is an estimate).

Some shuttle missions, especially those related to servicing Hubble, had a higher orbital radius, and therefore had a longer orbital period.

In contrast, geostationary satellites are satellites that remain in the same position in the sky. These satellites are not “parked” at a particular spot in space as it might seem. If the satellite was not moving, it would fall back to Earth. Instead, the satellite is orbiting so far above the Earth that its orbital period (24 hours) exactly matches the Earth’s rotation, giving the illusion that the satellite is in a fixed location in space.

As you have probably already guessed, there is a mathematical relationship between orbital velocity and the altitude or radius of the orbit. The formula used to express this relationship varies depending on whether the orbit is circular or elliptical.

For the purposes of this book, I am going to focus primarily on circular orbits. I will talk a little bit about elliptical orbits later on, but I won't use any math when I do.

Although elliptical orbits tend to be more commonly used, I am going to focus on circular orbits because it makes the math a lot easier. If you want to gain a greater understanding of elliptical orbits, you might look up Kepler's laws of planetary motion.

There are four values that are used when calculating a circular orbit. The first of these values is Vcir. This value reflects the velocity of the circular orbit. Earlier I expressed orbital velocity as Delta V. The reason why I am using Vcir here is because the orbital velocity will be constant. To be technically precise, Delta V indicates the change in velocity needed to reach orbit. If a rocket is sitting on the ground not moving, then its Delta V, the change in velocity required to reach orbit, will be the same as its orbital velocity.

The second value you will need is the Universal Gravitational Constant. This value is $6.673*10^{-11}$ m^3 KG^{-1} S^{-2}, and is commonly expressed as G.

The third value you will need to know is the combined mass of the central body and the orbiting body. Although this one might sound a little bit intimidating, it's actually easy to come up with the value, at least in the case of a spacecraft that is orbiting the Earth.

The central body in this case is the Earth. The orbiting body is the spacecraft. However, because the Earth has a far greater mass than the spacecraft, the spacecraft's mass is insignificant, and can be disregarded. The mass of the Earth is $5.972*10^{24}$ KG

The last value you need to know is the radius of the orbit, which can be expressed as R. This one is a little bit tricky, but is not difficult to come up with. The reason why this one tends to require just a little bit of extra thought is because orbits are often expressed in terms of altitude. The International Space Station for example, orbits the Earth at an altitude of about 400 KM above the surface of the Earth.

When calculating an orbit, the orbital radius is the distance from the orbiting body, in this case the space station, to the center of the Earth (not the distance from the space station to the ground). Hence, we need to know both the Earth's radius and the altitude of the orbit. The Earth's radius varies because of an equatorial bulge, but the mean radius of the Earth is 6371 KM. Hence, the orbital radius of the International Space Station would be roughly about 6771 KM. That's the Earth's radius (6371 KM) added to the orbital altitude (400 KM).

It is worth noting that in order for the formula I am about to show you to work correctly, the orbital radius must be expressed in meters, not KM. Hence, we would express the radius of the International Space Station's orbit as 6,771,000 meters.

So now that you know the four values used to calculate a circular orbit, here is what the formula looks like:

$$Vcir = \sqrt{\frac{GM}{R}}$$

In the case of a circular orbit around the Earth, this formula can be simplified a little bit. Because the universal gravitational constant (G) and the mass of the Earth (M) are constant values, they can be multiplied together with the result treated as a constant. This constant, known as the Standard Gravitational Parameter, is usually expressed as Mu (μ). For our purposes, μ=GM, or $3.986004418*10^{14}$. The simplified formula therefore becomes:

$$Vcir = \sqrt{\frac{\mu}{R}}$$

So now that you know the formula, let's calculate the approximate orbital velocity (Vcir) of the International Space Station. Our answer won't be exact, because I rounded some of the values, and because the space station's velocity occasionally changes. However, our estimate will be close. We know the value of μ and we know the orbital radius, so we need only to plug in the numbers. Here is how it works out:

$$Vcir = \sqrt{\frac{3.986004418 * 10^{14}}{6771000}}$$

The value we get for Vcir is 7672.59 meters per second, or 4.77 miles per second.

Around the World in 90 Minutes

Since we have calculated the orbital velocity, let's take things one step further and estimate the orbital period. As you may recall, the orbital period is the amount of time it takes to complete an orbit. The orbital period is often expressed as a value T, which reflects the number of seconds required to complete an orbit. Here is the formula:

$$T = 2\pi\sqrt{\frac{R^3}{\mu}}$$

If we plug in some numbers, the equation looks like this:

$$T = 2\pi\sqrt{\frac{6771000^3}{3.986004418 * 10^{14}}}$$

$$T = 2 * 3.14159 \sqrt{\frac{3.10426252011 * 10^{20}}{3.986004418 * 10^{14}}}$$

The answer works out to 5544.85 seconds. If we divide this by 60, we get an orbital period of 92.41 minutes. In other words, in this orbit, the International Space Station would complete an orbit in about an hour and a half.

Elliptical Orbits

Although the space station is in a circular orbit around the Earth, elliptical orbits are very common. All of the planets in the solar system for example, are in an elliptical orbit around the sun.

There are a few things that make an elliptical orbit different from a circular orbit (aside from the fact that the math gets a lot harder). For starters, an elliptical orbit has a different eccentricity than a circular orbit. I haven't talked about eccentricity yet, but it's not as complicated as it sounds.

Picture a circular ring made out of rubber. Because the ring is a perfect circle, it has an eccentricity of 0. If you were to squeeze the ring a little bit, then the circular ring becomes slightly elliptical, and its eccentricity becomes slightly greater than 0. If you squeeze the ring even harder, then the elliptical shape becomes far more pronounced, and the eccentricity value increases a little bit more. Hence, the eccentricity of the orbit describes the shape of the ellipse. A circular orbit will always have an eccentricity of 0, while an elliptical orbit will have an eccentricity that is greater than 0, but less than 1.

Circular and elliptical are not the only types of orbits. An orbit with an eccentricity of 1 is said to be a parabolic orbit. If the eccentricity exceeds 1, then the orbit becomes hyperbolic.

Another concept that you should be aware of is that of the semi-major access. The major access refers to the longest line that can be drawn through the ellipse, and the semi major access is the shortest line that can be drawn. Think of the semi-major axis as being the ellipse’s center line.

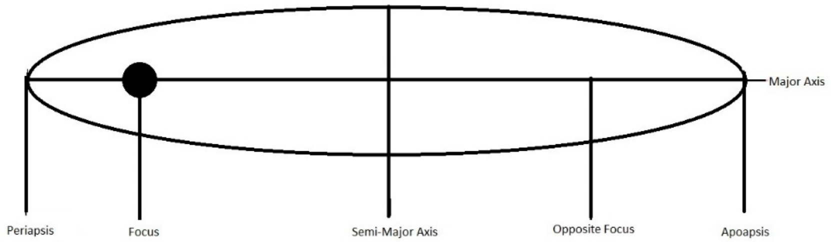
Yet another basic concept used in elliptical orbits is something called the periapsis. The periapsis describes the closest point to the body that is being orbited. For example, if a spacecraft were in an elliptical orbit around the Earth, then the periapsis would be the point at which the spacecraft is closest to the Earth.

This brings up an important point. The furthest point from the body that is being orbited is called the apoapsis. The body that is being orbited (the Earth in this example) is referred to as the focus of the orbit.

Now here is where things get interesting. Just as the apoapsis is the opposite of the periapsis, there is an opposite to the orbital point of focus. This opposite focal point is an imaginary point in space, and is located the same distance from the apoapsis that the true focal point is located from the periapsis. The two focal points are collectively referred to as the foci of the orbit.

Periapsis and apoapsis are generic terms. More specific terms are usually used to describe the body that is being orbited. For Earth orbit for example, the terms perigee and apogee are used. In the case of solar orbits, the terms are perihelion and aphelion.

The diagram below illustrates some of the basic components to an elliptical orbit.



Keep in mind that I am greatly simplifying things. There are actually six different elements used to describe an elliptical orbit. These elements include eccentricity, the semi-major access, the argument of periapsis, the time of periapsis passage, the longitude of the ascending node, and the orbital inclination.

Orbital Rendezvous

Now that you understand the basics of how Earth orbit works, let's suppose a rocket is on the launch pad at the Kennedy Space Center in Florida, and needs to dock with the International Space Station. How can this be accomplished?

A big part of the solution is launching at the correct orbital inclination (51.6 degrees) and within a launch window that will put the space station within relatively close proximity to the spacecraft once it reaches orbit. Even so, there is more to it than that. The spacecraft cannot just target the space station like a ballistic missile might. That approach would likely result in a high speed impact. Instead, the spacecraft launches into an orbit similar to that of the space station, but behind the space station’s orbital track. The spacecraft then adjusts its velocity so that it is able to catch up to the space station.

This change in the spacecraft’s velocity is completely counterintuitive. Imagine two cars traveling on a highway, headed in the same direction, but a couple of miles apart from one another. If the driver of the trailing car wants to catch up to the lead car, he or she would increase the car’s speed to the point that it is traveling at a higher velocity than the lead car. With the trailing car now moving faster than the lead car, it is only a matter of time before the trailing car catches up.

This approach does not work in orbit. If a trailing spacecraft wants to catch up to the space station, it must slow down. Yes, you read that correctly. The spacecraft has to go slower if it is to catch up to the space station.

The reason why the spacecraft cannot speed up in order to catch up to the space station is that increasing the spacecraft’s velocity adds energy to the orbit, thereby increasing the orbital radius. This means that with each orbit, the spacecraft would have to cover a greater distance than the space station, which is in a lower orbit. The end result would be the spacecraft falling further and further behind the space station. This goes back to the two rules I mentioned earlier. As a spacecraft’s orbital radius increases, so does its orbital period, but its orbital velocity decreases.

Conversely, if the spacecraft slows down, then it will drop into a lower orbit than the space station, thereby reducing the distance the spacecraft must cover with each orbit. One way of thinking about this is to imagine two runners racing around an elliptical track. The runner in the inside lane would cover slightly less distance than the runner on the outside lane. In fact, these types of racetracks have offset finish lines that are designed to make up for this difference, so that all runners cover an equal distance. If the finish lines were not offset, and the runners ran at equal speeds, then the runner in the outside lane would soon fall behind because that runner is running a greater distance.

Of course the trailing spacecraft cannot slow down to the point that it is no longer traveling at orbital velocity. Slowing down decreases the energy of the orbit and shrinks the orbital radius. If the spacecraft keeps decelerating, the orbital radius will shrink to the point that it falls within the Earth's atmosphere, resulting in reentry.

The reason why a returning spacecraft gets so hot during reentry is because it slams into the upper atmosphere at a speed that is only slightly slower than orbital velocity. The resulting friction with the air causes the spacecraft to heat to thousands of degrees.

This is actually the technique used by orbiting space craft when it is time to come back to Earth. The space shuttle for example, would rotate 180 degrees so that it was flying tail first. With its engines now facing opposite the normal direction, a retrograde deorbit burn would be performed. This would slow the shuttle down to the point that reentry became eminent. The shuttle would then be rotated back into a forward facing orientation, so it could correctly reenter the Earth's atmosphere.

So the key to performing an orbital rendezvous is to position the spacecraft into a lower orbit than the vehicle that it is going to rendezvous with. Assuming that both vehicles are in a circular orbit, you can use the orbital period calculation to determine the amount of time required for the trailing spacecraft to catch up.

Let's look at a simple example. Let's assume that the International Space Station is orbiting at 400 KM above the Earth. Let's also pretend that a supply vehicle launches from the Kennedy Space Center into the same orbital inclination as the space station (51.6 degrees), but that it is trailing the space station by 15 minutes. Since the supply ship will need to be in a lower orbit if it is to catch up to the space station, let's pretend that its orbit is 25 KM lower than that of the space station at 375 KM above the Earth.

In the last section, we used the Orbital Period calculation to determine that the International Space Station has an orbital period of 5544.85 seconds, or 92.41 minutes. By using the same formula, we can also find the orbital period for the supply ship. Here is the math:

$$T = 2\pi \sqrt{\frac{R^3}{\mu}}$$

$$T = 2\pi \sqrt{\frac{6746000^3}{3.986004418 * 10^{14}}}$$

T=5514.16 Seconds or 91.90 minutes.

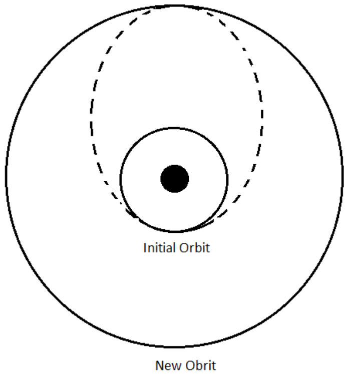
After working the math, we have determined that the International Space Station orbits the Earth in 5544.85 seconds, and the resupply ship is completing an orbit every 5514.16 seconds. Hence, the resupply ship gains 30.69 seconds with each orbit. Since the resupply ship started out 15 minutes (900 seconds) behind the space station, it will take 29.33 orbits to catch up. Since each orbit takes 5514.16 seconds to complete, the total time required for the resupply ship to catch up to the space station will be 161,730.31 seconds, or 44.93 hours.

Of course, there is one small problem with this type of orbital rendezvous. When the resupply ship does eventually catch up to the space station, it won't actually be able to rendezvous with the station because it is in a lower orbit than the space station. Therefore, it is necessary to raise the resupply ship's orbit to match that of the space station. This can be accomplished by using a Hohmann transfer.

A Hohmann transfer is the most efficient way of going from one orbital radius to another. You can think of a Hohmann Transfer as consisting of one half of an elliptical orbit.

Consider the previously mentioned situation in which a spacecraft has just about caught up to the International Space Station and now needs to be placed into a higher orbit that matches that of the space station. The spacecraft would perform a burn to elongate its orbit (thereby making the orbit elliptical). This elliptical orbit has a periapsis that matches the original circular orbit, and an apoapsis that matches the space station's orbit. Once the spacecraft reaches its point of apoapsis, it performs another burn to circularize the orbit. The newly circularized orbit matches the orbital radius of the space station.

You can see a diagram of a Hohmann Transfer below. In the diagram, the dotted line represents the elliptical orbit associated with the Hohmann Transfer. Although the entire ellipse is shown for the sake of illustration, a Hohmann Transfer only uses half of the elliptical orbit before the spacecraft is returned to a circular orbit.



The Big Takeaways

Although rocket science has a reputation for being really complicated, the basic principles of rocketry are actually quite simple. Fireworks after all, are a type of rocket. The thing that makes rocket science complicated is fact that a space rocket must be precisely controlled if it is to reach its intended orbit.

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Easily converse about rocket science.

Have you ever wanted to be an astronaut? It's not just about strapping yourself in and trying not to vomit. There is a lot more to it, including understanding the way rockets work. This book will help you understand what it takes to get a rocket off the ground and into an orbit. Brien writes it so that anyone with a basic knowledge of high school algebra will be able to understand. Often it's said "it's not rocket science" but in this case it actually IS rocket science!

About Brien M. Posey

Brien Posey is currently in his third year of training as a commercial Scientist-Astronaut Candidate, and is preparing for a mission to study polar mesospheric clouds from space. In addition, Posey is a 15 time Microsoft MVP and an internationally published author and conference speaker, with over two decades of information technology experience. You can learn more about Posey's spaceflight training by visiting his Website at www.BrienPosey.com/space.