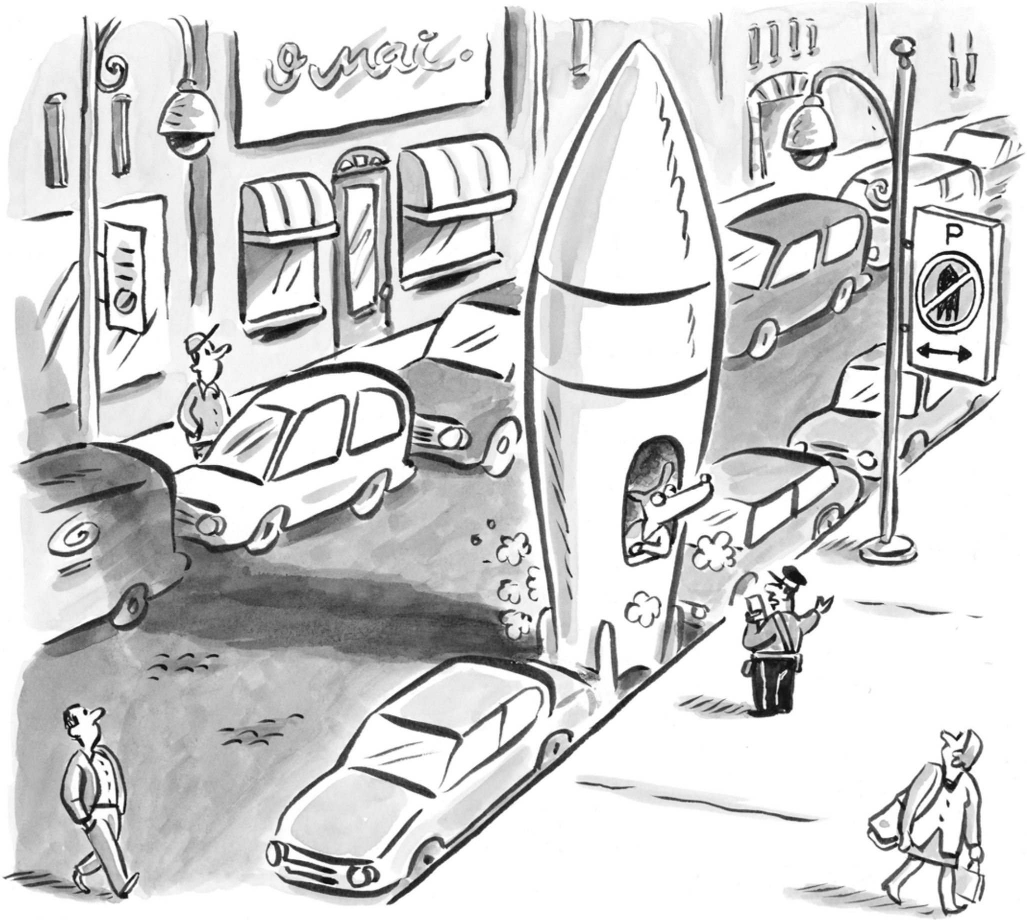


"Nice maneuver, but you can't leave it here."

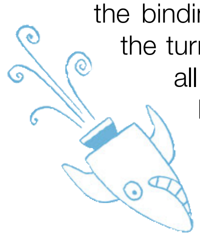
Rocket Maneuvers

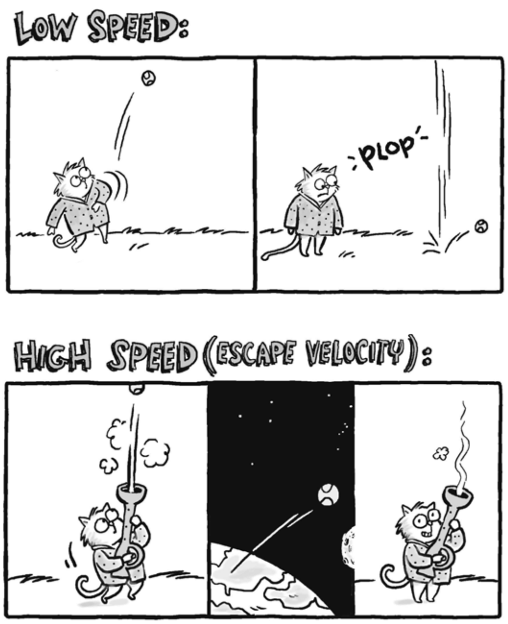
Navigating within Nothing

Satellites are doing a great job. They orbit Earth and help us to establish worldwide communication, bring us TV signals, help us to navigate, look at the weather, produce maps of Earth and many other things. Did you ever think about having your own satellite? To avoid all the complications of developing the satellite itself, let us just think about bringing it up in space. To simplify the problem even further, let us think about getting a tennis ball with our name on it into space. The simple approach: Take one and throw it up in the air. What will you observe?

Too Fast to Stay

Most likely, the ball will fall back down to the ground. But you will also observe that the faster you throw it, the higher it will go. The reason why it comes back is the gravitational force that acts between Earth and the ball. This force is the reason why we are all "attached" to the surface of Earth and can walk on it without getting dragged into space. One can say that gravitation binds us to the earth. This binding can be quantified with a certain energy. If you throw up your tennis ball, it also has a certain amount of kinetic energy. The faster you throw it, the more it gets. This energy cancels some part of the binding energy of the gravitation. At the turning point of the ball, it has lost all its kinetic energy and regains it by being accelerated back to the ground. Doing a bit of calculus allows you to get a solution to the question: "So how fast do I have to throw my tennis ball to give it more energy than it has gravitational energy?" This velocity – called "escape velocity" – is your ticket into outer space. It depends on Earth's mass and its radius. It has a value of 11.2 km/s, 40,000 km/h or 25,000 mph. This is pretty fast. For the sun, the escape velocity is much higher: 617.5 km/s.





This escape velocity is indeed the minimal velocity that you need to have in order to leave Earth and go into outer space – but this applies only in the case that you do not have any further propulsion, as in the example of a thrown ball: once it left your hand, its velocity will decrease. But rockets can

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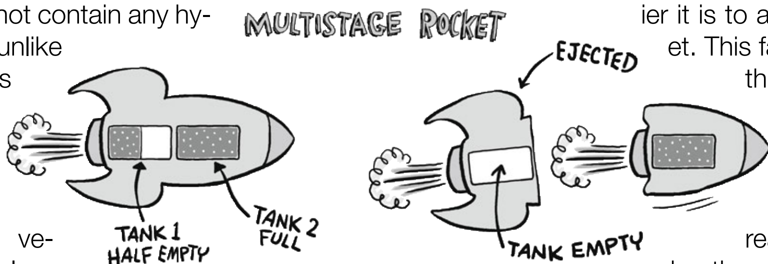
keep accelerating and that's what allows them to start with much lower velocities. An example for an object without propulsion for which the escape velocity is more important are atoms. Hydrogen and helium are pretty light atoms. The temperature of the gases of our atmosphere determine the average kinetic energy of their atoms. For an equal temperature, and hence an equal kinetic energy, light atoms are faster. This is the reason why our atmosphere does not contain any hydrogen or helium: unlike for the heavy atoms like nitrogen and oxygen, the hydrogen's and helium's temperature leads to velocities which are larger than the escape velocity. That's why they leave Earth.



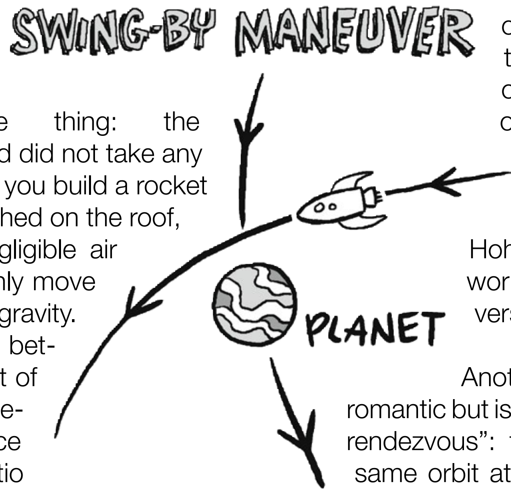
By the way: You can decrease the escape velocity if you make use of the fact that Earth is spinning. Depending on the direction of your start (against or in direction of Earth's rotation) you can increase or decrease the escape velocity by about 10%. As Earth's rotational velocity is largest at the equator, many space launch facilities are located in this region, such as for example the American Cape Canaveral or the European Guiana Space Center.

Go Rocket, Go!

We know now that each journey into outer space starts with escaping the gravitational field of Earth. The question is: how can we reach that speed? Typically we use rockets. They follow the principle of ejecting high-speed jets of rocket propellant. According to Newton's laws this leads to a thrust of the rocket.

You can keep accelerating a rocket as long as there is still some propellant left. The interesting point about rocket propulsion: it has to accelerate not only the mass of the rocket, but also its own mass (at least before it leaves the rocket). So the more propellant is used, and expelled, the easier it is to accelerate the rocket. This fact is considered in the famous "rocket equation". It tells us that the maximum velocity that a rocket can reach is determined by the velocity with which the propellant leaves the rocket multiplied with the logarithm of the ratio of the masses of a full and an empty rocket.

So for maximum rocket speed you can either try to maximize the exhaust velocity of the propellant or the ratio of a full to an empty rocket. The rocket equation also tells you that it is more efficient to use a multistage rocket instead of a single large rocket. Multistage rockets have several stages, each equipped with engines and propellant. After each one is empty, it is detached from the rest of the rocket. Next to the optimization of the mass ratios and the usage of multistage rockets you can also increase the rocket's final velocity by increasing the exhaust velocity of the propellant. Classical rocket propellants exist in solid and liquid form and are used in combustion engines. The good thing about that: they even work in a vacuum, as in



outer space. There, a classical airplane's turbines could not work without any surrounding air. Oh, one thing: the rocket equation that we quoted did not take any external forces into account. If you build a rocket car (a car with the rocket attached on the roof, making it really fast) with negligible air resistance, that's fine. It will only move horizontally and can ignore gravity. But for a rocket, you should better take into account the effect of gravity. Nevertheless, the statements about the dependence on the full to empty mass ratio and the exhaust velocity remain valid. For rocket movements out in space, gravity can be neglected.

Maneuvers in Outer Space

Once you made it into outer space you can perform several maneuvers, next to a simple "staying in an orbit" or "flying in a direction". Imagine you are surrounding Earth, but want to change your distance to Earth by changing the orbit. An interesting one is, for example, the geostationary orbit at about 36,000 km above Earth's equator. Remember that on each orbit you need a specific time to circle the Earth (or any other object in outer space, ➚[1]). In a geostationary orbit this time corresponds to the time that earth needs to rotate. This means that a satellite in a geostationary orbit will have a fixed position from Earth's point of view. A maneuver that is used to change the orbit is called "Hohmann transfer". If you want to do a Hohmann transfer to move further away, you need two little impulses, each in the direction of flight and tangential to the orbit. The first one will bring you into an elliptic path, the actual Hohmann orbit. The second impulse of the same type as the first moves our spacecraft out of the Hohmann orbit into a second, circular path. Hohmann transfers of course also work the other way around by reversing the impulses.

Another maneuver which sounds romantic but is quite complicated, is a "space rendezvous": two spacecrafts meet in the same orbit at the same place. One of it is passive and waits; the other one is active and approaches the passive one. It sounds quite easy: first you do a Hohmann transfer and get into the right orbit. Then you just have to get closer to the passive craft. This you can do by applying a little thrust. But wait! This will change your velocity which will lead to a change of orbit. So it involves a little more thinking, orbit changing and impulses.

Last but not least let us introduce the "swing-by maneuvers". If you plan a space mission to an object far away, let's say to Mars, you want to save every bit of propellant that you can. Swing-by maneuvers accelerate your spacecraft via the gravitational force of other planets which are met on the way and fly in the same direction. You can even use multiple swing-by maneuvers as it was done for the Rosetta space probe launched in 2004 (➚[2]). On its way to the comet 67P/Churyumov–Gerasimenko it performed three swing-bys of Earth and one of Mars. Such a sophisticated journey requires perfect timing! "Oops, we missed Mars" would have meant the end of the mission.

➚[1]: *"Kepler's Laws" on page 47*
➚[2]: *"The Voyager Probes" on page 55*