Applying Newton's Laws

The next step in becoming a rocket scientist is to apply rocket science and mathematics to the design and construction of actual rockets. There are many tricks of the trade for maximizing thrust and reducing rocket mass. Each of these tricks is an application of one or more of Newton's laws. Although there are many different kinds of rockets, the same laws apply to all.

Rockets are generally classified as either solid or liquid. They produce thrust by burning propellants and expelling the combustion products out of the engine. Propellants are simply a combination of fuel and oxidizer. The oxidizer for solid propellants is a chemical containing oxygen. For example, gunpowder, used in the engines of model rockets, contains potassium nitrate (KNO_3). Potassium nitrate provides the oxygen needed for the other gunpowder chemicals to burn rapidly. The oxidizer for liquid rockets is usually pure oxygen chilled to 90 K (-183^{o}C or -297.3^{o}F) so that it condenses into liquid oxygen (LOX).

The propellants for rockets are held in tanks or within cases. This is both an advantage and a disadvantage. Because they carry their propellants (oxygen onboard), rockets can work in space. No other presently available vehicle can do that. A jet engine cannot function in space because it is an "air-breather." Although jets and rockets both employ Newton's law of action and reaction, the jet needs to draw in air from the atmosphere to burn its fuel. This limits the altitude of a jet plane.

Solid Propellant Rockets

The first true rockets, "fire arrows" invented by the Chinese, employed solid propellants. An early form of gunpowder was packed into a cylinder closed off at one end. On the other end was an opening. When the gunpowder was ignited, it burned very quickly and created great quantities of gas and other combustion products that rushed out of the hole. This produced thrust. Flight control was accomplished by attaching a long stick to the rocket to create drag as the rocket sailed through the air. This wasn't a very accurate

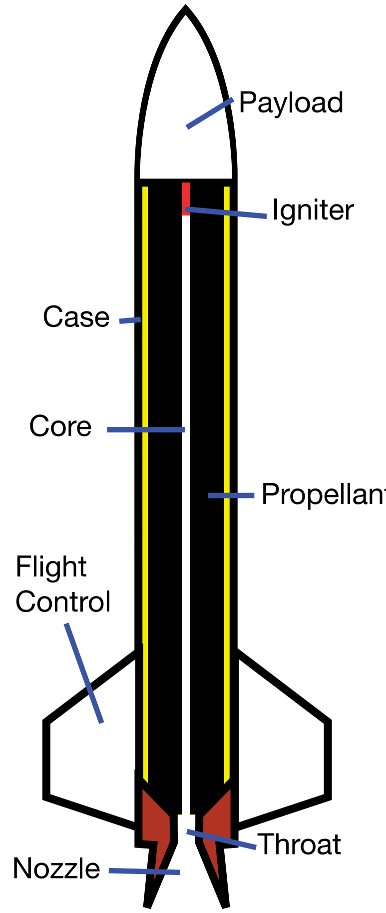
Four-stage, solid propellant Scout rocket.

system, but the rocket usually flew in the intended direction.

More than 1,000 years later, solid propellant rockets are not appreciably different from the Chinese fire arrows. The solid rocket boosters (SRBs) for the space shuttle are very large tubes packed with propellants that are closed off at one end and have a hole at the other. The SRBs do have many other sophisticated innovations, but, in principle, they are no different from their primitive ancestors.

Solid propellant rockets have a simple design. They consist of a case or tube in which the propellants are packed. Early rockets used cases made of paper, leather, and iron. Modern rockets use a thin and lightweight metal such as aluminum. Making the case from thin metal reduces the overall weight of the structure and increases flight performance. However, the heat from the burning propellants could easily melt through the metal. To prevent this, the inner walls of the case have to be insulated.

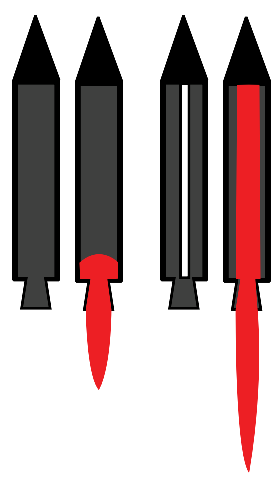
The upper end of the rocket is closed off and capped with a payload section or recovery parachutes. The lower end of the rocket is constricted with a narrow opening called the *throat*, above a larger cone-shaped structure, called the *nozzle*. By constricting the opening, the throat causes the combustion products to accelerate greatly as they race to the outside (second law). The nozzle aims the exhaust straight downward so that the rocket travels straight upward (third law).



Solid Propellant Rocket

To appreciate how the throat of the rocket accelerates the combustion products, turn on the water for a garden hose. Open the nozzle to the widest setting. Water slowly flows out. Next, reduce the opening of the nozzle. Water quickly shoots out in a long stream (second law) and the hose pushes back on you (third law).

The propellant in solid rockets is packed inside the insulated case. It can be packed as a solid mass or it may have a hollow core. When packed as a solid mass, the propellant burns from the lower end to the upper end. Depending upon the size of the rocket, this could take a while. With a hollow core, the propellants burn much more rapidly because the entire face of the core is ignited at one time. Rather than burning from one end to the other, the propellant burns from the core outward,



End-burning and hollow core rockets.

towards the case. The advantage of a hollow core is that the propellant mass burns faster, increasing thrust (second law).

To make solid rockets even more powerful, the core doesn't have to be round. It can have other shapes that increase the surface area available for burning. The upper ends of the space shuttle SRBs had star-shaped cores. When ignited, the large surface area of the star points boosted liftoff thrust. In about one minute, however, the points burned off, and the thrust diminished somewhat. This was done on purpose because the space shuttle begins accelerating through the sound barrier. Passing through causes vibrations that are diminished by the temporary thrust reduction of the SRBs (second law).

Solid propellant rockets have two other major systems at work. One is the control system, which will be discussed later. The other is the igniter.

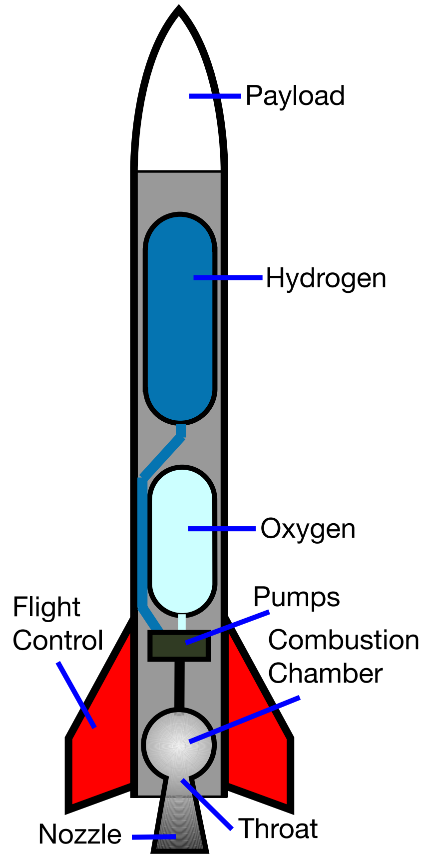
The Chinese fire arrows were ignited with fuses. This was a dangerous practice because the fuse could burn too quickly and not give the rocketeer time to get out of the way. Fuses were used for centuries until they were replaced by electric ignition. With an electric system, a wire with high resistance heats and ignites the propellant.

The space shuttle's SRBs and the SRBs that will be used for the new SLS rockets have a more dynamic ignition system. A small rocket motor is mounted inside the upper end of the core. When it ignites, it shoots a long tongue of flame down the core to ignite the entire surface at once. This cause the SRBs to reach full thrust in less than one second.

Liquid Propellant Rockets

Liquid propellant rockets are an invention of the twentieth century. They are far more complex than solid rockets. Generally, a liquid rocket has two large tanks within its body. One tank contains a fuel, such as kerosene or liquid hydrogen. The other tank contains liquid oxygen.

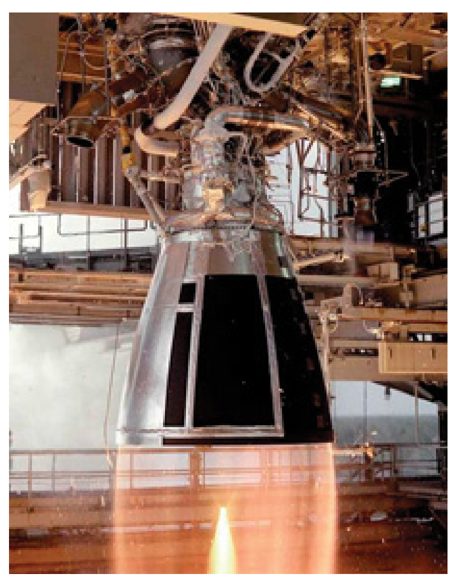
When the liquid rocket engine is fired, high-speed pumps force the propellants into a cylindrical or spherical combustion chamber. The fuel and oxidizer mix as they are sprayed into the chamber. There they ignite, creating huge quantities of combustion products that shoot through the throat and are focused downward by the nozzle. (Remember how the laws control this!)



Liquid propellant rocket

Liquid propellant engines have a number of advantages over solid propellant engines. A wider array of propellant combinations are available for different applications. Some of these require an ignition system and others simply ignite on contact. Monomylmethylhydrozene (fuel) and nitrogen tetroxide (oxidizer) ignite spontaneously. These are called *hypergolic* propellants. With hypergolic propellants, a rocket engine does not need an ignition system. Hypergolic propellants are great for attitude control rockets like those that will be arrayed around the *Orion* service module.

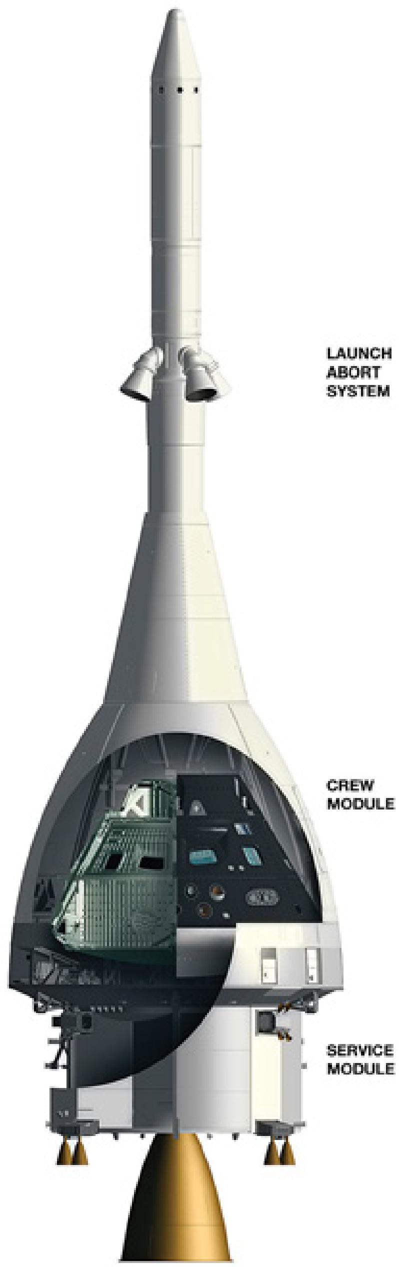
Another advantage of liquid propellants is that they can be controlled. Adjusting their flow into the



RS-68 Liquid propellant engine test firing.

combustion chamber adjusts the amount of thrust produced. Furthermore, liquid engines can be stopped and restarted later. It is very difficult to stop a solid propellant rocket once it is started, and thrust control is limited.

Naturally, with any technology, there is a price to pay. The engine of a liquid propellant rocket is very complex and subject to failure. It also has more structural mass than comparable solid propellant rockets. One method for mass reduction is to use thin, lightweight metal for the nozzle. Normally, the nozzle is very thick and heavy, to prevent it from eroding away in the high-temperature streams of exhaust gases. A thin-wall nozzle needs a cooling system. Small tubes lace the walls and carry liquid hydrogen. Hydrogen becomes a liquid at 20.27 K (-252.87°C or -423.17°F). The super cold hydrogen absorbs the heat from the gas stream and protects the walls of the nozzle. The hydrogen, now heated, is then injected into the combustion chamber. With this system, the engine has less mass and produces greater thrust (second law again!).



The full stack of the Orion spacecraft is shown. An aeroshell surrounds the capsule for liftoff. On top is the escape rocket system. Several of Orion's attitude control rockets are seen around the service module.

Controlling Flight

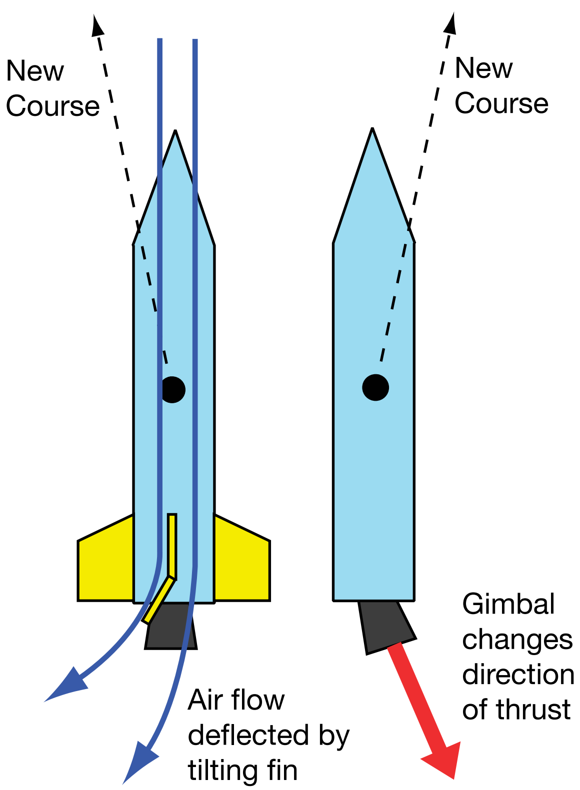
Newton's third law gets a workout in the control systems for rockets. Launch rods for old rockets were ineffective. Military rockets were launched by the thousands so that at least a few would hit their targets. Accuracy improved when small vanes were added to the exhaust stream. The vanes imparted stability by causing the rockets to spiral like bullets.

Another technique was to add fins, like the feathers on an arrow, to the lower end of the rocket case. As long as a rocket flies "straight as an arrow," the fins provide little drag or friction with the air. However, if the engine end of the rocket begins "fishtailing," drag increases greatly. The air stream strikes the fin, and the fin directs the stream to the side. The lower end of the rocket moves the opposite way and corrects the fishtailing (Newton's third law). Fins are used extensively with model rockets and small missiles.

Rocket fins on model rockets are a passive system for flight control. They remain fixed and do their job if the rocket starts going astray. Robert Goddard took fins a giant step forward by turning them into an active system. Goddard's fins could be made smaller (and lighter!) because they were not fixed. Even a slight straying from the planned course would cause the fins to react and tilt slightly in the appropriate direction.

The heart of Goddard's control system, later used in the V2 and other advanced rockets, was a gyroscope. Gyroscopes, which are a kind of top, spin at high speeds and become stable due to their inertia (first law). In other words, the axis of the gyroscope points in one direction. If the rocket veers from course, the movement acts on the alignment of the gyroscope, and a linkage or an electrical system connected to the gyroscope transmits the appropriate corrections to the movable rocket fins.

You can get an idea of the effectiveness of movable fins with a simple demonstration. Balance the end of a long stick on the palm of your hand. If the stick starts tilting to the right, you automatically move your hand to the right to straighten up the stick. Movable fins do the same thing. The rocket starts tilting to the



right. The leading edge of the fins bend to the right. This causes the air stream to be deflected to the left. The lower end of the rocket moves to the right, and the rocket is back on course.

Naturally, some fins are more complicated than just described. Depending upon the rocket design, the entire fin may not move. Instead, a lower flap might be the controllable part of the fin (kind of like a rudder). Very small movable fins might also be placed towards the nose of the rocket. These are called *canards,* and they permit rapid and extreme control maneuvers for air-to-air military missiles. Small fins, called *vanes*, may be placed within the exhaust stream of the engine. When a vane tilts, it directs part of the exhaust to one side or another. The lower end of the rocket responds by moving the other way. All of these fin styles are examples of Newton's third law in action.

Another way the third law is applied for controlling flight is through gimballed engine nozzles. *Gimballed* means the nozzle can tilt in different directions. Movements of the nozzle can steer the rocket on a new course or make course corrections. The solid rocket boosters that will be used for the SLS rockets will use gimballing for control.

Controlling Mass

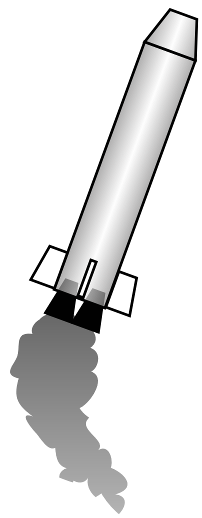
The total mass of a rocket has a major influence on its performance. If the rocket has a greater mass than the engines are capable of lifting, the rocket remains stuck on Earth (first law). The lighter the rocket, the better. However, since the rocket must carry all of its propellants (there aren't any filling stations in space —YET!), a big part of the rocket's mass has to be its propellants. The mass of the propellants burned is a big part of thrust (second law). Mass savings have to come from elsewhere — the rocket structure.

Engineering rocket tanks out of lightweight materials strengthened by ribs is a great way of saving mass. Chilling hydrogen and oxygen propellants until they liquefy reduces their total volume. That means smaller, less massive tanks can be used. Gimbaling engines for control means that heavy fins can be eliminated.

When designing new rockets, rocket scientists (and engineers) concern themselves with mass fraction. Mass fraction is a simple inverse mathematical relationship between the mass of the propellants of the rocket and the total mass of the rocket. Although there is

$$MF = \frac{mass\text{ (propellant)}}{mass\text{ (total rocket)}}$$

wiggle room in this equation, the most efficient rockets have mass fractions of about 0.91. That means that of the total rocket, propellant accounts for 91% of its mass. The rocket structure and payload comprises the other 9%. Since you need the mass of the propellants, efforts on saving mass are primarily focused on structure and payload.

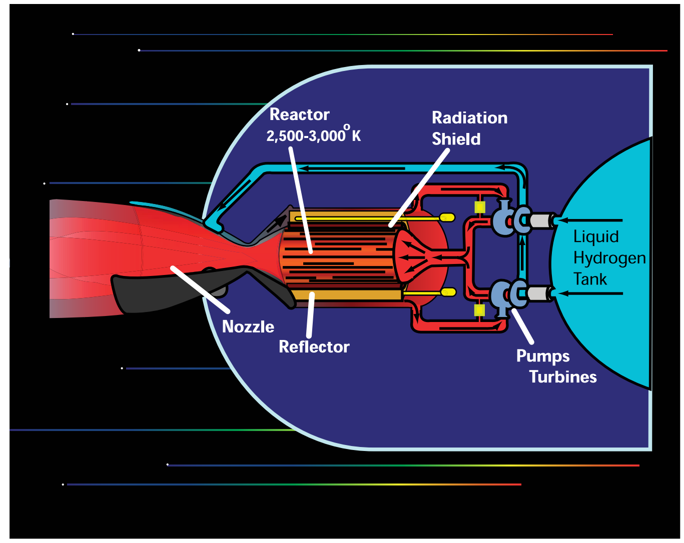


One simple but old trick is staging. Begin with a large rocket, stack a smaller one on top of it, stack a still smaller rocket on top of the second one, and then the payload on top of the third rocket. The large rocket lifts its own mass and the mass of the other two. When the large rocket (first stage) is empty, it drops off. The second rocket (second stage) fires and accelerates itself and the third stage with its payload to higher speeds and altitudes. When it is empty, the second stage is dropped, and the third stage finishes the job of delivering the payload. By staging, the mass of the rocket is reduced in flight, making the upper stages more efficient in doing their jobs.

Future Rockets

Part of the fun of rocket science is that there are always new ideas and new ways of doing things. Solid and liquid rockets are not the only way to go. Other kinds of rockets are "on the drawing board," going through prototype testing, or churning about in the imaginations of dreamers.

Electric rockets have been around since the 1960s. Rather than burning propellants, ions — electrically charged atoms — are driven out of the rocket engine using magnetic forces. In doing so, a very small thrust is imparted to the rocket. (Newton's laws are still at work in this rocket.) Electric rockets, sometimes referred to as "ion drive," are very efficient in converting electrical energy into thrust, but since the mass of ions is very low, the thrust is



Proposed nuclear thermal rocket engine

small, about the force needed to push a walnut across a table. One would think, "Why bother?" The answer is that ion drive can function continuously for months or years on end. It may start off slow, but after months and months of thrusting a vehicle could achieve velocities higher than a chemical rocket that burns all its propellants in a few minutes. Another thing — the electricity for ion drives can come from sunlight captured by solar panels on the spacecraft.

Nuclear power is also under consideration for rocket propulsion. An onboard nuclear reactor would generate lots of heat through nuclear fission (breaking down of radioactive atoms). A supply of hydrogen gas would be heated by the reactor, causing the gas molecules to expand rapidly and stream out of the engine nozzle. No burning would be involved. Think of this kind of rocket as a nuclear-powered balloon.

Still another concept is beaming a powerful laser from Earth towards collectors on a spacecraft. The energy received would be used to heat a supply of gas for propulsion. In this way, the nuclear reactor could be eliminated.

Still further in the future, matter/antimatter drives, such as those proposed in *Star Trek,* might actually be possible.

Where we go and how we will get there all comes down to the rocket scientists of the future, who are sitting in classrooms today.