1. BLUNDERSPUDS AND CARROT CANNONS—ARTILLERY AND BOYLE'S LAW

> BLUNDERBUSS: an obsolete muzzle-loading firearm with a bell-shaped muzzle. Its calibre was large so that it could contain many balls or slugs, and it was intended to be fired at a short range, so that some of the charge was sure to take effect. The word is also used by analogy to describe a blundering and random person.
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> *Encyclopedia Britannica*, 1911

The spud gun was a staple weapon of junior soldiers from at least the 1960s onwards. It comprised a tiny piston mounted on the handle of a toy handgun, the trigger of which pulled back a cylinder over the piston. The cylinder had a nozzle that could be jabbed into a potato, removing a pellet. When you squeezed the pistol hard, you compressed air in the cylinder and the pellet of spud was ejected like a small bullet. Later a three-in-one design came out that could do more. It could not only fire pieces of potato, but also squirt water and ignite tiny explosive caps.

I have to admit, however, that I have recently tried out these weapons of my youth, and they are much less impressive than I recall. Perhaps instead of a potato pistol, we should aim for something a little bigger, a potato musket maybe?

In the olden days there was a very large-bore musket rather wonderfully named a "blunderbuss." With the assistance of the kids at our Saturday Science Club in Guildford and a little science, I decided to come up with a vegetable equivalent worthy of the name "Blunderspud." (Though as it turns out, we discovered that carrots actually made the best bullets . . . so I guess we'll have to call it a Carrot Cannon from now on.)

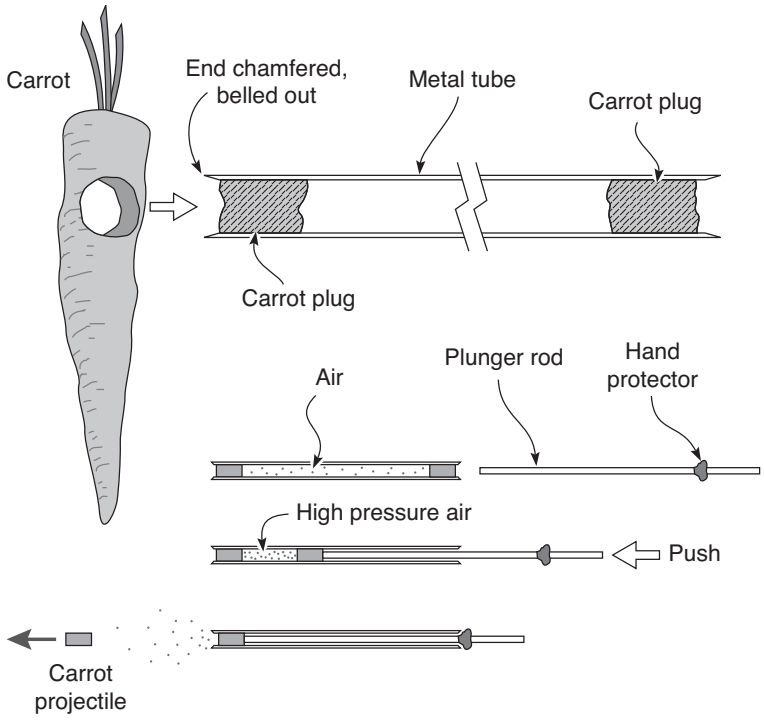
What You Need

A metal tube about 600 mm (24") long, preferably steel, thin-walled, with an internal diameter of 10–20 mm (3/8" to 3/4"), or a plastic tube of the same length, thin-walled (about 1.5 mm), with an internal diameter of about 20 mm (3/4")
A plunger: a strong round wooden rod or bamboo stick that fits inside the tubing
Sponge rubber or plastic, duct tape—to make a hand protector for the plunger
Carrots—large ones—larger in diameter than the outside of the tubing
A rod or tube (of steel or some other strong metal) that fits loosely inside the tube (for widening the tube at the ends)
A hacksaw
A round file, a deburring tool, or a knife

What You Do

You can use plastic, copper, or other metal tubing for the carrot cannon. First cut your barrel to, say, 600 mm (2') long. The longer the barrel, the more compressed air there will be to store energy, so long is good. However, there is an ergonomic limit to how long you can make the barrel, because the plunger needs to be longer than the barrel, and you need to be able to push the plunger with a high degree of force into the barrel. So, unless you have arms like a gorilla, the plunger shouldn't be much longer than 900 mm (3'), including 150 mm (6") for a handgrip.

Next you need to bevel the edge of the ends of the tube on the *inside* of the tube to sharpen it. You will then be able to cut into the vegetable with a reasonably low force. More subtly, that bevel should be on the *inside* so that the piece of vegetable cut off will be slightly larger than the inner diameter of the tube; that way it will form a gas-tight seal. I find that a simple craft knife will do a reasonable job of this on plastic, but you may find it easier to use a file, and a file is certainly indicated for metal. I also have a slightly unusual workshop tool called a "deburring tool." A deburring tool consists of a tiny curved blade made of hardened steel that is mounted so that it rotates freely in its handle. It is easy to use and does a neater job. The edge of the tube doesn't need to be razor sharp—cutting the edge down from its normal 1.5 mm to, say, 0.7 mm or 0.5 mm will be fine.



Now, if you are using copper tubing, it may help to widen both ends of the tube further by bellying the tubing out slightly as follows: insert the steel rod 1/2" to 1" into the tube and roll it around, so that it bellies out the ends of the tubing slightly. Copper tends to be surprisingly malleable and can be worked in this way quite easily. Repeat this process until you have a tube end 1 mm (1/32") or more wider than the body of the tube.

Then you must tape a hand protector securely to the plunger, leaving a large enough portion of the plunger-rod projecting out to ensure that your hand can get a firm grip. The protector prevents you from cutting your hand on the sharp end of the tube when you shoot. You could also incorporate a handgrip near the breech end of the tube to allow you to put more force on the carrot cannon when firing. Now place a large carrot on a flat surface, use one hand to guide the tube into the *side* of the carrot, and the other to push it downwards, thus cutting a piece of carrot and pushing it up the tube. Do the same again at the other end, so that you have carrot in both ends. Now place the plunger on the ground or on a tabletop and, guiding it with one hand, force the tube down onto the plunger, pushing in one

piece of carrot (the bullet carrot) 25 mm (1"). Do the same at the other end with the piston carrot, pushing it in perhaps 50 mm (2") or more. You are now ready to fi

Push the plunger hard and reasonably fast, while aiming the muzzle of the tube at the target. With luck, the piston carrot should slide down smoothly toward the bullet carrot until the bullet carrot suddenly shoots out at high speed.

Trouble can arise if the piston or projectile leaks. If this happens, just eject them and try again, or simply put another carrot plug in the piston end and try again; you then will probably fire two plugs of vegetable instead of one.

The cannon we have constructed here works by compressing air, with the breech carrot plug acting as a piston inside the cylindrical tube. As the air is compressed, force builds up on the other piece of carrot until the static friction between the latter and the tube wall is insufficient to keep it in place, and it shoots out of the tube at very high speed. The piston carrot should just fall to the ground in front of the weapon.

You will find that carrots work well. They are best loaded transversely, but obviously you need good large carrots, large enough so that when the tube cuts into them the tube is entirely filled. Vegetables that are hard and fresh are best, although aged carrots can be restored somewhat by soaking them in cold water for a while.

Try other vegetables: carrots are very good, but is there something better?

- Potatoes work pretty well—but they're not as good as carrots.
- Try a larger-bore cannon, a veritable blunderspud ("blundercarrot" just doesn't have the same ring to it . . .)—but beware!—it may need a lot of force from your arms to make it work well.

You can now try out various ways to improve your weapon. One neat feature might be the ability to use the piston of one shot as the projectile for the next shot, but you'll have to get the length of the plunger just right. (Thanks to Geoff Th son for this excellent refinement.) How well does this work? Does a pellet of potato that has been used as a piston actually work properly as a projectile after it has been pushed down the barrel and perhaps lost some of its frictional properties? Could you deal with this by actually *narrowing* the muzzle end of a carrot cannon? And what about extending a widened barrel to act as a low-friction expansion chamber, to ensure that as much of the energy in the compressed air as possible becomes available when the pellet starts to move. A related question: Is it worth packing the projectile further down inside the barrel? Does this give it longer to accelerate under the compressed air pressure?

What is the best angle at which to aim the tube for maximum range? And what happens when you use bigger or smaller tubes?

Hazard Warning

Don't fire a carrot cannon directly at anyone unless they are wearing high-quality protective goggles, such as those sold for use in paintball games, and do not fire at anyone who is close at hand. Although carrot bullets are pretty harmless, they can cause a big bruise at close range, and a direct hit on someone's eye could cause blindness, which would be appalling.

Less dramatically, watch out that you don't cut your hand while loading the carrot cannon. Leather gloves may be helpful at first. And don't forget to include the hand protector and to position your hand behind it so that it protects you.

How much does the rate at which the potato musket is driven affect the final muzzle velocity?

And what about the accuracy of the device? Does the short ride up the barrel mean that the weapon's aim is necessarily inaccurate?

The amount by which the barrel and breech ends are bellied out is important. The first affects the frictional grip of the muzzle end, and the second the gas seal of the piston. How tight does its fit have to be to give a good seal?

How It Works: The Science behind the Carrot Cannon

Boyle's Law tells you how much pressure increases when you compress a gas. It says that the pressure increases in proportion to the reciprocal of the volume. So when the volume goes down, the pressure goes up. In math, we might put this as:

$$P = k / V,$$

where P is the pressure, k is a constant, and V is the volume of the gas. The pressure we talk about here is the absolute pressure, not the pressure relative to atmospheric pressure or gauge pressure. The air in the cannon starts off at 0 barg (0 psig), which is 1 bara (15 psia).

So if we start with a volume of, say, 60 cm^3, and finish with 6 cm^3, then the pressure will have gone from 1 bar absolute (15 psia) to 10 bara, which is 9 bar gauge (130 psi).

Another way to consider the carrot cannon is to estimate the energy (E) stored in the compressed gas as being proportional to the logarithm of the pressure

reached and to the volume of the tube. Using this formula, we can estimate the energy as roughly 10 Joules.

If all of this energy were delivered to the projectile, then the projectile would have a speed proportional to the square root of the energy divided by its mass. In fact, 10 Joules would be enough, theoretically, to take a 5 g (1/5 oz.) projectile up to a speed of 60 m s^{-1}, or 120 mph. If we do only half as well as this, then the carrot bullet will fly out at 30 m s^{-1} or 60 mph, which explains why you need to take care where you aim!

And Finally . . .

What about non-vegetable materials? With other materials you will probably need to include some juice to act as a lubricant (although this could be added later), but whatever you try must also grip the inside of the tube tight enough to seal it, and, in the case of the projectile plug, tight enough to allow a good build up of pressure. The bellying out of the tube is clearly very critical. Can ring indentations around the inside of the tube help the projectile to grip and hence allow the weapon to reach a higher pressure?

You could of course replace the piston-end plug with a permanent piston, using industrial O-ring seals perhaps, or a cup-shaped seal as seen on bicycle air pumps. This is the sort of thing discussed in patents on toy guns, such as GB143548, dating from 1921. The author of that patent, Heinrich Beck, describes how you can make a quick-firing revolver using pellets punched in quick succession from a disk of spud. But perhaps this is getting too far away from the elegant rustic simplicity of our basic blunderspud or carrot cannon.

Patents

Buerk, Carl. Improvements in or relating to toy fire-arms. UK Patent 329,233, filed November 23, 1928, and issued May 15, 1930.

More or less the modern toy spud gun.

Beck, Heinrick. Toy guns. UK Patent 143,548, filed November 11, 1917, and issued April 21, 1921.

An altogether more sophisticated toy gun capable of firing successive shots quickly. It works by moving a large slice of potato around in the breech of the gun. As you pump the piston to and fro, it automatically loads and then fires a piece of potato at each stroke.