The WAY TOYS WORK

The Science Behind the Magic 8 Ball, Etch A Sketch, Boomerang, and More



ED SOBEY ◆ WOODY SOBEY

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To everyone who plays with toys and wonders how they work

CONTENTS

Acknowledgments

Bob Guildig and the staff of Eastside Trains, Inc., in Kirkland, Washington, introduced us to the new era of high-tech electric trains. We're still running the American Flyer train Ed's father bought for him when he was born. Bob demonstrated integrated circuit remote-controlled trains that smoke when you press a button. Thanks, Bob.

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Thank you all.

Introduction

Wow, That's Neat!

Some toys command interest and inspire wonder. They do the unexpected or the seemingly impossible. They make us think about how they work and how they relate to the scientific concepts we've learned. They're just neat.

Fling an Aerobie and watch it fly, and fly and fly some more. Experience tells us we shouldn't be able to fling something so far with so little effort. Launch a boomerang with a hefty throw and it returns. That's crazy; things we throw don't come back. Draw a picture on an Etch A Sketch and erase it with the flip of a wrist so it's ready for the next creative idea. Pull a toy car back eight inches and watch it zoom 20 feet across the kitchen floor. What convoluted laws of physics allow for such seemingly magical experiences?

> *I think we should teach them wonders. . . . The purpose of knowledge is to appreciate wonders even more.*
>
> —Richard Feynman, physicist (1918–1988)

The magic of toys is not shrouded in secrets, but is there for us to see. Take screwdriver in hand and open toys up to enjoy the magic in a new way. While the toys themselves inspire awe, seeing how they're made lets us admire the engineers' creativity and problem-solving abilities. As awesome as the toys are to play with, they are even more awesome to understand.

Toys of technological wonder provide a common ground for learning and fun. This is the type of learning that comes from experiments, discovery, and experience—learning that allows us to apply what we already know to help us understand what we see but can't fathom. This is authentic learning that can be applied to the world around us, and that can inspire more discovery and learning. *The Way Toys Work* is your launching pad for exploring awesome toys and discovering how they work.

Guidelines for Reverse Engineering

Reverse engineering is the process of taking stuff apart to see how it works. Governments and corporations do it all the time to reveal the technologies their competitors have invented. In the same way, you can reverse engineer toys to figure out how they do the awesome things they do. But before you start, let us give you some guidelines to follow.

You'll need some tools. A good Phillips screwdriver is essential. You might want to have several of varying sizes. Amazingly, the Phillips screwdriver on a Swiss Army knife fits more screws than any other screwdriver we've found. A set of jeweler's screwdrivers will let you open up many small devices. You'll want a few flat head screwdrivers, too. These few tools will open up many of the toys. However, other toys will require a hacksaw and needle-nose pliers. For toys encased in plastic, we use a rotary cutting machine.

You'll need stuff to take apart. Thrift stores and garage sales provide a steady source of stuff—and usually the price is right. Let your neighbors or friends know you're looking for formerly working toys, and they'll turn up some gems. In this throwaway culture we live in, there is always a supply of yesterday's technology and toys.

You'll need to take safety precautions. Wear protective glasses or goggles whenever you're taking stuff apart. Parts can fly out when you least expect them to, so always protect your eyes. Resist the temptation to wrestle with a toy that refuses to open up. Rather than getting physical with the inanimate object, outfox it. Look to see what is holding the pieces together; find that last screw you overlooked. Sometimes manufacturers place screws under labels or otherwise out of sight.

If you decide to force a toy apart, be mindful of what is downstream of the screwdriver. Anything that's in the "line of fire," or downstream, of your screwdriver—your hand, a nice table, your friend's face—will become its unintended target when you slip. Aim your force toward a deserted volume of space.

If you're taking apart a toy that plugs into an electrical outlet, cut off its electric plug before you begin your work. Then bend the plug's prongs outward (so that no one can plug it in) and throw it away. We didn't always do this—until the day a fourth grader in one of our programs inserted a discarded plug into a wall outlet. The resulting explosion left him shaken but unharmed, and the electrical outlet destroyed. Now we always bend the prongs outward so they can't be inserted into an outlet.

You'll need to sharpen your sense of awe. Awe sharpening is harder than awl sharpening, because you'll never get it sharp enough. In our haste to get the important stuff done, we too often overlook the stuff that makes life fun. We tell students that the number one rule of science is that when you find something interesting, stop and focus on it.

So our plea, as much to ourselves as to you, is to never let the awe get dull. Be on the lookout for those things that might prompt you to think, "Wow, that's neat. I wonder how that works." Then go find out.

Patents

Isn't the Internet great? You can find out so much information while sitting in your pajamas at your computer. For instance, if you can find a patent number on a toy, you can see a copy of the patent online. It used to be an expensive task to find patents. Now there are several services that can retrieve them. We prefer www.google.com/patents. A patent describes, sometimes in painful detail, how the toy or other gizmo works. It contains drawings showing the parts, and it lists who filed the patent and when it was filed and granted. If you have a favorite toy, you might find it fun and informative to look for the patent number and go on a search.

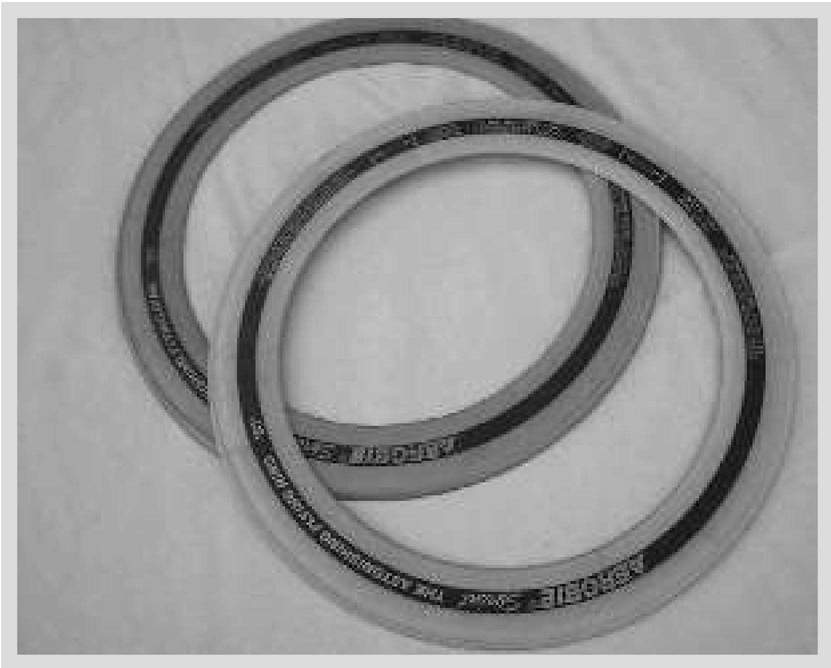
Build Your Own

We are big believers in the idea of learning by making stuff. We also advocate innovating new products by creating prototypes. Making new stuff or improving existing stuff isn't a case of perfecting the design on paper, then going to the shop to build the final product. Before you build something you have to have *some* idea of how to make it work, but the development process will continue as you start to assemble the components. You'll learn so much that you didn't know you needed to know—you'll learn stuff that you would never have thought of just by looking at a two-dimensional design. Only when you start to put the pieces together do you find out if they fit and if your innovation will work.

Building inherently invites collaboration. People get interested, even excited, when they see what you're working on. You won't inspire that much excitement by just talking about a design or showing sketches. Prototypes beg people to get involved and to contribute. And each person's contribution can improve the final product.

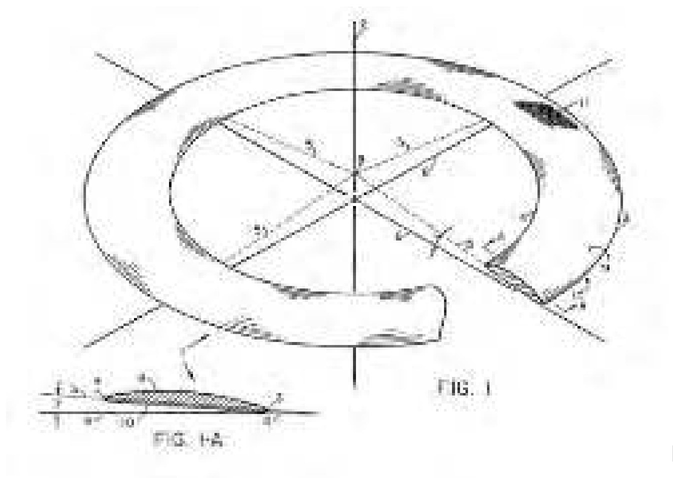
So try building your own versions of these toys. Building and testing them is as much fun as playing with the ones you buy at the store, and you'll learn so much more.

Aerobie



History of the Aerobie

Lots of toys are invented by someone stumbling onto a design or idea. Not so with the Aerobie. Inventor Alan Adler worked for years to perfect the design and find the right materials to create this flying ring, which can be thrown several times farther than a flying disc such as a Frisbee. Adler, an engineering professor at Stanford University, used his knowledge of aerodynamics to design the Aerobie. Before he invented the Aerobie he invented the Skyro, which set a Guinness World Record in 1980 when it was thrown 857 feet. The Aerobie beat that record when Scott Zimmerman chucked one 1,257 feet in 1986. Scott's throw set the world record for the longest throw of an inert, heavier-than-air object. Although the record was bested a few years later, it remains the world record for an "object without any velocity-aiding feature."



Patent no. 4,456,265

How Aerobies Work

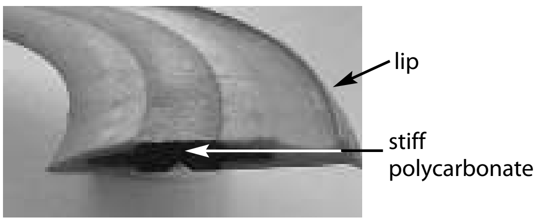
To understand how a flying disc or ring flies, read about the Frisbee (page 52). Aerobies are different from Frisbees in several ways. Whereas a Frisbee has a blunt edge to create turbulence and reduce lift at the leading edge, the Aerobie has a unique lip, or spoiler, on its outer edge to create stability. Its slender profile presents much less drag surface than a flying disc. Less drag allows it to travel farther.

The Aerobie also differs from the Frisbee in that, as a ring instead of a disc, it has an opening in the center. In flight, air moves through the opening so that the inside edge is also a leading edge, which generates more lift.

You can make your own version of the Aerobie and determine how much of a spoiler is needed to get a good flight.

Inside the Aerobie

By looking at a cross section of the Aerobie, you can see features that may have otherwise eluded you. Cut through one side of the Aerobie, as shown here. A coping saw or another saw with a slender blade works well.



Check out the shape. It looks like a wing, which it is. The odd part of the design is the lip, or spoiler, on the outside edge. That spoiler was the breakthrough design feature.

Another problem Professor Adler had to overcome was making the outer edge soft enough that it wouldn't hurt someone who might be hit by it, yet keeping the toy rigid enough to fling. That's why you'll find a dark polycarbonate backbone in the middle of the softer and lighter outer material.

If you want to put your Aerobie back together, glue the cut edges back together with plastic glue. Reinforce the weld by gluing a craft stick to the underside, across the glued edge. It looks a bit odd, but it will fly fine.

Build Your Own

Cut out the centers of several thick paper dinner plates. Fling your "rings" to see how they fly. A few brands of paper plates are made of heavier material; they make for rings that fly well without modifications. Most paper plate rings, however, require some help.

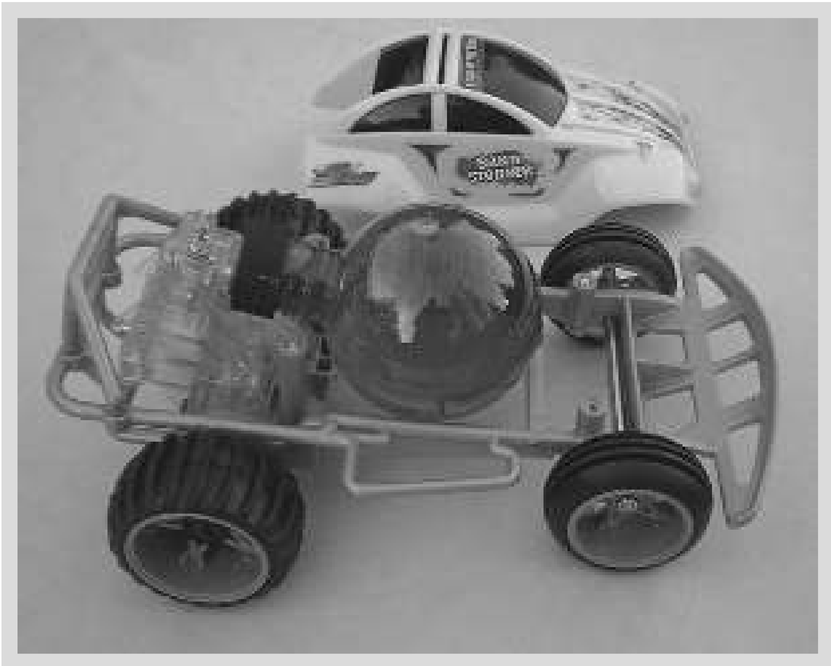
Mount two plates upside down on top of a third, right-side-up plate to form a flying saucer–like toy, and tape them together. Check how this flies. To improve the flying characteristics, try affixing four metal washers or pennies at even intervals along the outer edge. Now try out your creation. Next, try bending up the edges of the plates to make a lip like that of the Aerobie. Adjust the position of the lip until your ring flies level. Then try adding more evenly spaced weights to your ring. The goal is to create a ring flyer that travels far. It should fly level, without either side rising.

You can also create a ring flyer by cutting out the center of an empty pie pan. Adjust its flight by bending the outer edge up or down.

Resources

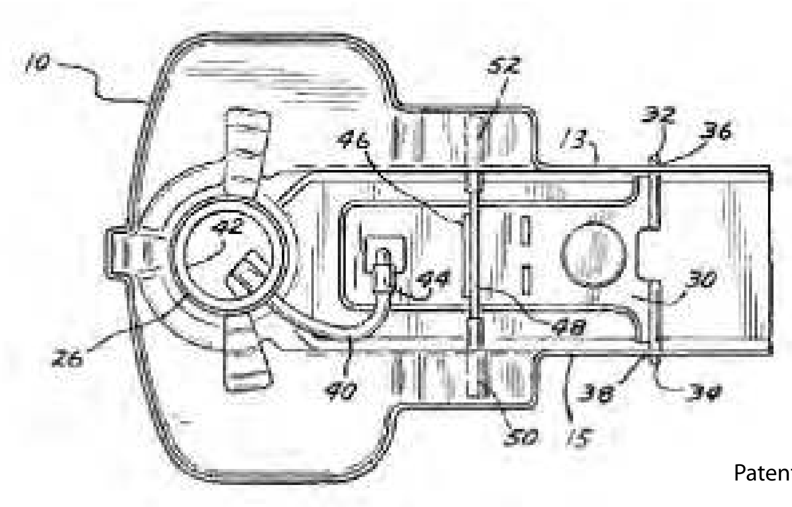
Teachers wanting to incorporate Aerobies and Frisbees into classroom learning opportunities should look at Ed's book *Loco-Motion: Physics Models for the Classroom* (Zephyr Press, 2005).

Air Hog



History of the Air Hog

The idea of a toy plane that's driven by air pressure and a piston came from inventors in England. The inventors were unable to sell their idea to big toy companies—they hadn't yet made a flying prototype—but they found interest in a young Canadian company, Spin Master. Following the success of two previous toys, Spin Master invested a half-million dollars to develop the idea into a product. Beginning in 1998, sales—like the planes themselves—took off.



Patent no. 3,789,540

How Air Hogs Work

Like all Air Hogs toys, an Air Hogs car has a pneumatic motor. Air pressure—you provide the energy by pumping air into a pressurized reservoir—pushes on a piston. The piston is attached to a crankshaft that converts the linear motion of the piston into the rotary motion of the wheels. Add some gearing and a flywheel to keep the spin going through angular momentum, and the car is ready to go. To control air flow to the piston's cylinder, there are intake and exhaust valves. Each has a tiny black ball that you can see (and easily lose if you take the car apart!).

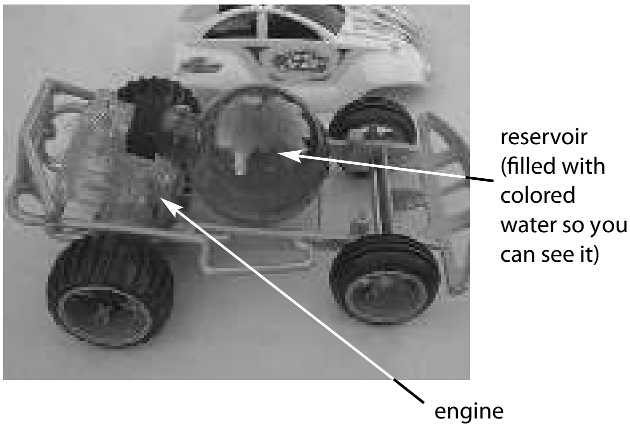
The car comes with a pump to fill the reservoir. Air enters the reservoir through a ball valve, supported by a spring, that lets air into the reservoir, but not out. When the reservoir is filled and you're ready to play, you spin the left rear wheel (or the propeller, if you have a plane or helicopter). As it rotates, it turns the crankshaft (attached through the gears). The crankshaft pushes up on the piston, which is connected to a spring. The spring lifts the bottom of the second valve to let air into the chamber, driving the piston down.

The crankshaft is attached to a metal gear with eight teeth. It drives a plastic gear with 22 teeth, and that gear drives a third gear with 52 teeth that is attached to the wheel. When a small gear drives a larger gear, which in turn drives an even larger gear, these gears in series slow down the rotation speed (from small to large) but increase the torque, or turning force, that powers the wheels.

Once we took apart the car we were able to estimate that for every turn of the big wheel, the piston completed six or seven cycles. This estimation was validated when we calculated the gear ratio, which is $^{52}/_{8}$, or 6.5. (The biggest gear has 52 teeth, and the smallest has eight. Therefore, for every revolution of the wheel, the piston moves up and down 6.5 times.)

Inside an Air Hog

The Air Hogs car is a great toy to take apart. Turn it over to see the transmission. Pushing the lever to the “Power Sprint” side engages both rear wheels to the power train, making the car go straight ahead. Sliding the lever to the “Spin Out” side disengages the right rear wheel so that the car, powered only by the left rear wheel, turns in circles.

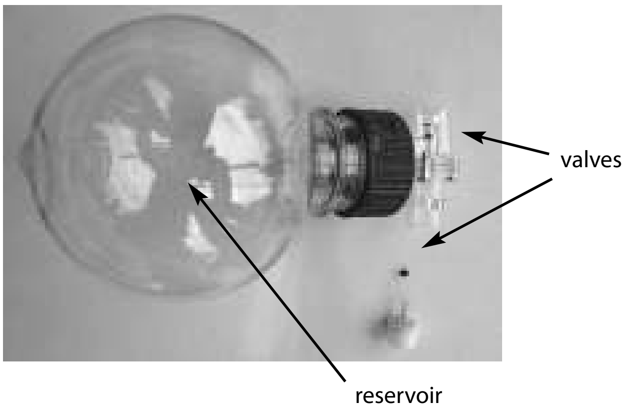


Using a Phillips screwdriver, you can loosen and remove the four screws that secure the body to the chassis. Next, disconnect the air reservoir. WARNING: Although you may be tempted to just twist off the air reservoir (clear plastic ball), ***don’t.*** The reservoir has weak walls that you might damage by squeezing too hard. Instead, use pliers to twist the black collar in order to remove the reservoir.

Turn the car over to remove the four screws that hold the rear wheels and motor in place. With the air reservoir disconnected, you can pull the rear wheel assembly down from the chassis.

Look, from the side, at the valve that lets air in. You’ll see a tiny ball supported by a spring. Air from the pump depresses the ball slightly, which allows air to flow into the reservoir. During the pump’s recovery stroke, the spring pushes the ball up in place to prevent air from leaking back out. Once the spring has pushed the ball up, air pressure from the reservoir (in addition to the spring) holds it in place.

Slowly spin the left rear wheel. You’ll see a white plastic piece—a piston—rise and fall six or seven times with each revolution of the wheel. Air can’t escape the reservoir until the piston rises. To get the car to move, you turn the wheel, which moves the piston, which releases air. As the wheel turns, it moves the white piston up to push on another tiny ball that’s attached to the large spring. When this ball moves, air escapes from the reservoir and pushes the piston down. When the piston moves down, the spring pushes the ball



back in place to block the flow of air. So once you start the wheel spinning, the reservoir delivers a blast of air to the piston six to seven times per wheel revolution. You can hear the "puff, puff" of air escaping when the car operates.

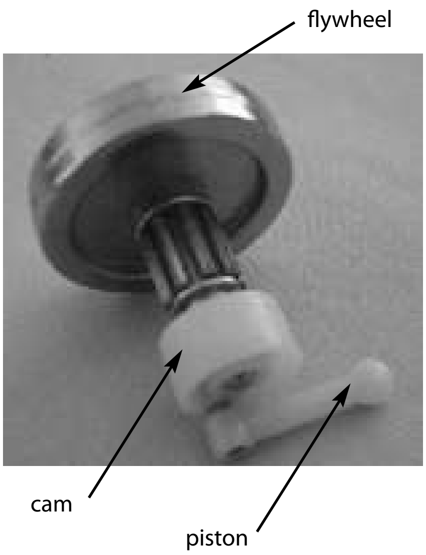
Lightly screw the reservoir back onto the valve assembly; this will hold the two parts of the assembly together. Two tiny screws hold the valve assembly onto the motor. Remove these with a jeweler's screwdriver. Now ask yourself: "Do I feel lucky?" If your answer is no, don't take apart the valve assembly. If your answer is yes, spread a white towel on your workbench to catch the two tiny balls that will soon come bounding out.

Three screws hold the two halves of the valve assembly together. Remove them, then unscrew the reservoir. That will allow the two halves to come apart. Watch one of the balls bounce away as you separate the halves. It'd be tough to find a replacement for one of these, so don't lose it.

Notice the O-ring in the upper half of the valve assembly. O-rings are used in high-pressure devices such as scuba tank valves and space shuttle tanks. Higher pressures squeeze the O-ring, causing it to make a better seal.

Now, before someone bumps the table and those tiny balls are lost forever, put the valve assembly back together.

To access the motor, unscrew the four screws holding the top piece. Lift out the crankshaft (the white plastic piece attached, off center, to the wheel), the metal gear, and the flywheel assembly.



When assembled, the crankshaft fits under the piston. When it pushes up on the piston, the piston lifts the lower ball, which admits air that drives the piston down and shuts off the supply of air. To start the engine you have to spin the wheels to initiate the cycle.

The flywheel (the metal disc at the end of the shaft) keeps the shaft spinning. Once it has started to spin, its momentum will keep it rotating, allowing the crankshaft to release more air. (See Friction Car, page 49, for a discussion of another application of a flywheel.)

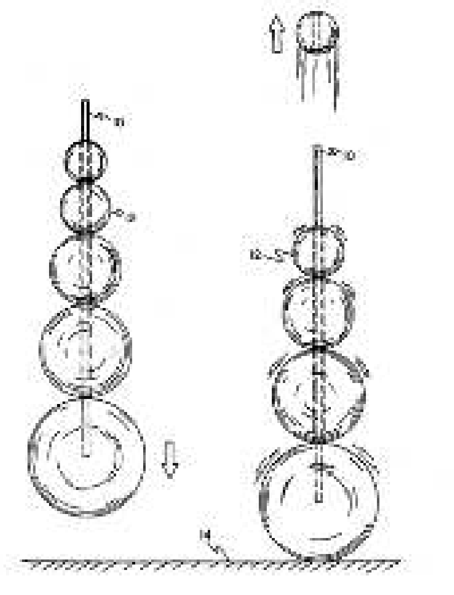
Finally, you can remove the several screws holding the two halves of the transmission housing together. While the housing is open, count the number of teeth in each of the gears. Now, before you misplace one of the parts, get the transmission back together.

The pump looks well constructed, but is otherwise unremarkable. We recommend leaving it intact.

AstroBlaster

History of the AstroBlaster

A conversation among physicists at a cocktail party was the genesis for the AstroBlaster, a stack of bouncing balls capable of rebounding to five times its drop height. Bill Hones, his father Edward, and Stirling Colgate share the patent (patent number 5,256,071).



Patent no. 5,256,071

How AstroBlasters Work

According to the patent, the AstroBlaster demonstrates "an unobvious consequence of fundamental laws of physics—the acceleration of an object to high speed by multiple collisions among a series of heavier objects moving at slower speed."

We ran some experiments to understand what's going on. We pulled the shaft out of the bottom ball so we could bounce test it. We dropped each ball to determine its rebound. We estimate that each of the three bottom balls rebounds to about 75 percent of its drop height. Then we tried the top ball. *Kerplot*. It went almost nowhere, exhibiting about a 20 percent rebound. It seemed that the top ball was made out of a different material than the other three—but we would later find out that this wasn't the case.

When you drop the AstroBlaster, its collision with the ground causes some loss of energy, but not much. Physicists say this is an elastic collision—the total kinetic (moving) energy is the same before and after the collision. Of course, it's not exactly the same. Based on our rebound testing of a single ball, we estimate that it's about 75 percent; the other 25 percent of the kinetic energy is transformed, most into heat energy and a bit into sound.

When the stack of balls hits, the bottom (most massive) ball transfers its considerable momentum to the ball just above it. The second ball now has its own momentum plus the momentum of the bottom ball. When it hits the third ball, it transfers its enhanced momentum to it. The small ball on top is on the receiving end of this substantial transfer of momentum. Since momentum equals mass times velocity, and the top ball is much less massive than the ones below, the transferred momentum manifests as a much higher upward velocity—several times the ball's downward velocity, in fact.