Cardboard Shuttles

Build and fly model spacecraft to demonstrate the principles of re-entry aerodynamics. See how ungainly vehicles fly gracefully at high speed!

Suggested grade level: 6-8

Activity length: 45-60 minutes

Required materials: Cardstock, poster board

Relevant topics: Aerodynamics, structures

Purdue Space Day, an educational outreach program of Purdue University's Department of Aeronautical and Astronautical Engineering, organizes the largest free STEM advocacy children's event in the Midwest, as well as myriad year-round outreach events throughout the surrounding metropolitan area. These activity write-ups are provided free of charge as an extension of Purdue Space Day's STEM programming.

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Questions? Comments? Contact Purdue Space Day via email at psd@purdue.edu. We'd love to hear your feedback to help us improve our activities and write-ups.

Activity Summary

Students build gliders from cardboard which demonstrate principles of high-speed aircraft design.

Key Concepts: Aerodynamic forces, aerospace structures, engineering design

NGSS Summary: The key concepts of this activity align with NGSS Disciplinary Core Ideas for middle school science education. Specifically, they meet the following Physical Sciences standards:

- MS-PS2.A – Forces & Motion
- MS-PS3.C – Relationship Between Energy and Forces

This activity also connects to the following standards for Engineering, Technology, and Applications of Science:

- ETS1.A – Defining and Delimiting an Engineering Problem
- ETS1.B – Developing Possible Solutions
- ETS1.C – Optimizing the Design Solution

Learning Objectives

Students will be able to understand how aerodynamic forces change with speed, and how high-speed vehicles must be designed with structural integrity and robustness in mind.

Scientific Background

Due to its illustrious 30-year career, the Space Shuttle orbiter is an iconic shape, recognizable the world over. This revolutionary vehicle was the first to reach orbit and then glide back to Earth under its own power, using its long, triangular "delta" wing. However, NASA has also considered a variety of drastically different shapes for orbital re-entry vehicles, both before and after the Shuttle program. One of the most interesting of these concepts is that of the *lifting body*, or what is effectively an aircraft without wings. These vehicles are able to re-enter the atmosphere and glide back to land like airplanes do, despite the fact that they have no wings. A few of NASA's lifting bodies from the 1960s are shown below.

Figure 1: Lifting body designs (left-right) X-24, M2-F3, and HL-10 (photo: NASA)

Typically, an airplane's wings are what allow it to fly – air flowing over the wings produces lift, which pushes the plane up into the sky. Wings have a special shape – known as an airfoil - which creates a difference in pressure between the top and the bottom surface. An airplane's wing is specially designed to create a large pressure difference and thus a large lifting force, but any object will feel a force if the air flowing around it isn't symmetric. For example, look at the two photographs below. They are images recorded in a water tunnel, and they show how water moves around different objects (air should move in a similar fashion0. The object in the left picture is a flat plate and the object in the right picture is a cylinder.

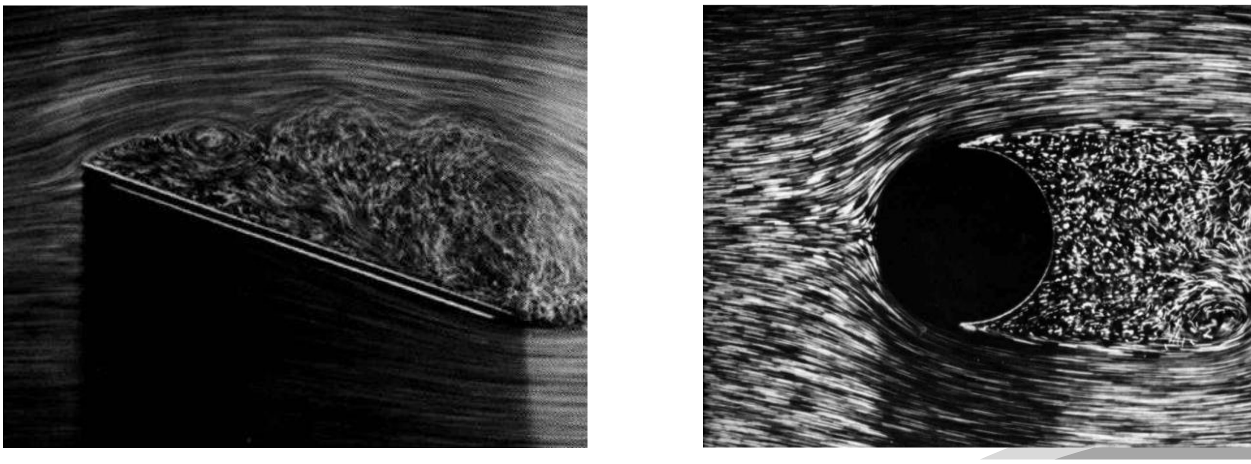

Figure 2: Flow over a flat plate (left) and a cylinder (right)

Although the shadows make it a bit difficult to see, the flow around the cylinder is almost perfectly symmetric – the water splits at the front (on the left edge), flows around the cylinder, and rejoins at the rear. In contrast, the flow around the flat plate is very asymmetric – it is fairly smooth on the bottom, but over the top of the plate the fluid is deflected upwards significantly. This should produce a lift force, as the asymmetric flow will produce different pressures on the top and the bottom.

We can use the same principle to create lifting bodies. As long as the aircraft is designed to create an asymmetric airflow, it should produce some lift. Since lift increases at higher speeds, even a small

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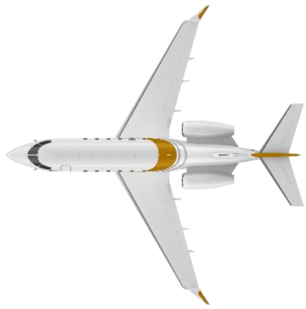
amount of “lifting ability” will allow a lifting body to fly if it travels quickly enough. We can describe the ability of an object to produce lift using a *lift coefficient.* The lift coefficient is a nondimensional (i.e. unitless) number that describes how much lifting force an object generates relative to the amount of force it feels from air hitting it (it’s a ratio, which is why it has no units). We can use the lift coefficient to describe how much lift something produces using the following equation:

$$L = \frac{1}{2} \rho v^2 C_L S$$

In this equation, L is lift, ρ is the air density, S is the area of the lifting surface, C_L is the lift coefficient – a value which describes how effectively the surface creates lift – and v is velocity, or speed.

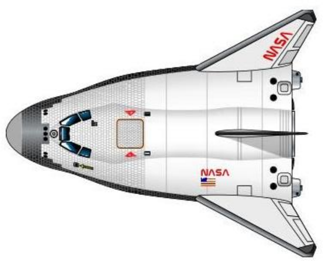
We can use a typical plane – such as a business jet – as an example to see how this works (note: values below are approximate, based on the Learjet 75). We start by assuming that the lift produced by the wings equals the weight of the plane.



Lift: 96,000 N
Air density: 0.5 kg/m^3
Maximum lift coefficient: 1.5
Wing area: 30 m^2
Velocity: 92 m/s

In this example, the plane must fly no slower than 92 m/s (about 200 mph) for its wings to generate enough lift to keep it in the air. Airplane wings are relatively large and quite good at producing lift, but almost any object can produce some amount of lift as the air moves over it (see the above section for a more thorough explanation of this) – just not quite as efficiently as a wing.

Since lifting bodies produce lift much less efficiently than winged aircraft and have much smaller lifting areas, they must fly much, much more quickly to stay airborne. For example, consider the HL-20, a concept developed by NASA in the 1990s. We can apply the lift equation just as we did above:



Lift: 103,500 N
Air density: 0.5 kg/m^3
Maximum lift coefficient: 0.4
“Wing” area: 0.115 m^2
Velocity: 3000 m/s

To produce enough lift to fly, the lifting body must fly at 3000 m/s – that’s well over 6 *thousand* miles per hour, or roughly ten times the speed of sound. If nothing else, this exercise makes it obvious why we design commercial aircraft with wings; however, at the high speeds which re-entry vehicles experience as they return from space, the lifting body concept starts to become more appealing. Any re-entry vehicle will be travelling at high speed anyway, and the lack of wings makes the structure easier to design – keeping wings stiff and cool enough not to melt becomes very challenging at high speeds. Even winged vehicles like the Space Shuttle orbiter benefit from having smaller, thicker wings and generating some of their lift from the body (in addition to the wings). Other good examples are the North American X-15, an experimental research plane developed in the late 1950s, and the Sierra Nevada Corporation Dream Chaser, an uncrewed cargo vehicle designed for flights to the International Space Station and back. The X-15 has short, straight wings that are well-suited to high-speed flight, and the Dream Chaser is a lifting body like the HL-20 shown above.

Suggested Activity Practices

- Look at images of re-entry vehicle designs such as the Space Shuttle, Dream Chaser, Dyna-Soar, HL-20, etc. and compare some of the unique qualitative characteristics (short wings, stubbiness, etc.).
- Explain some of the reasoning behind these design choices (shorter wings and stubbier geometries offer easier mechanical and thermal design for very high flight velocities).
- Have students to construct their own gliders in groups; encourage them to make their own design choices, as long as they build something robust enough to fly at high speeds.
- Demonstrate the differing performances of each glider by launching it twice – once at low speed (with a gentle toss) and once at high speed (with a rubber band or a hard throw).
- Discuss characteristics of the gliders that led to success or failure, and relate them back to the real-world examples provided at the beginning.

Assessment Techniques

Volunteers can observe participants for the following signs of comprehension or learning. For each, volunteers should assign a percentage to indicate how many of the students display an understanding of the concept.

- Students indicate an understanding of the extreme forces created by high-speed flight by designing a robust structure.
- Students are able to explain their rationale for their design choices.
- Students demonstrate comprehension of basic design principles by building symmetrical gliders with components (fins, body, wings, etc.) which they can easily identify explain.
- Students are able to evaluate one or more trade-offs that they have made in their designs.

Participant learning can also be assessed using the following pre-activity and post-activity questionnaires.

Pre-Activity Questionnaire

What allows an aircraft to fly?

What is the best shape for a spacecraft – slender and pointy or thick and bulbous?

What are three adjectives you might use to describe engineering?

Post-Activity Questionnaire

How is lift produced?

What makes certain shapes more desirable for spacecraft design than others?

What are three adjectives you might use to describe engineering?

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Construction Directions

Note: These directions are provided as a guide; they are intentionally vague. Students should be encouraged to design their own gliders according to what they have learned about high-speed flight; this encourages them to embrace the engineering design process and apply the scientific principles they have learned.

Materials Required:

- Thick cardstock
- Clear packing tape
- Foam-core poster board
- Hot glue gun
- Rubber band
- Paper clips and small binder clips

Directions:

1. Sketch a vehicle design on a piece of paper, based on the examples provided and on what you have learned about high-speed vehicle design. Keep in mind that you will have to build this vehicle out of cardstock, so make your design choices accordingly.
2. Fabricate your design, taking care to create a robust structure which can survive high-speed flight as well as a symmetric vehicle that will be able to slice/punch neatly through the air.
3. Attach a launching lug (a rectangular piece of foam-core board approximately 1 cm x 3 cm) to the bottom of your glider using a hot glue gun. Note that the glue is unlikely to adhere well to taped surfaces.
4. Add weights to the front or back of the glider as necessary to get it to balance approximately halfway back from the nose. You can check the balance point by trying to balance the glider on your finger, a ruler, or any straight edge. The balance can be checked with a gentle test flight – give the glider a toss; if it noses into the ground it needs more weight on the tail; if the tail hangs low as it flies, it needs more nose weight.

Launch:

Give the glider a gentle toss to check its balance and to demonstrate its low-speed flight characteristics (which should be lackluster). Then launch it at speed, either by hand or using a rubber band, and compare the performance.

Post-Launch

Discuss any observations which students were able to make about the gliders. Which gliders performed the best, and why? In addition to overall distance and speed, what other factors made for good gliders? Were any more or less stable? Why? How did the low-speed and high-speed tests differ, and why?