Paper Towers

Synopsis

Each student makes a tower using two sheets of newsprint and ten inches of transparent tape. The object is to build the tallest tower that will resist being blown over by the teacher from one arm's length away. In the process, students formulate the basic engineering principles of tower design.

Objectives

This exercise provides students with an opportunity to use model-building as a way to help understand the forces and phenomena at work in the world around them. This process skill is a component of the Science as Inquiry strand of the *NC Standard Course of Study for Middle School Science*: "Mastery of integrated process skills: formulating models." Likewise, this exercise meets the *NSES Content Standard A (Science as Inquiry)* for levels 5-8, "Abilities Necessary to do Scientific Inquiry: develop descriptions, explanations, predictions, and models using evidence."

Through follow-up discussions, specific curricular objectives can be addressed. Depending on the direction of these discussions, students can be expected to be able to do any of the following:

- describe gravity as a universal force that pulls everything toward the center of the earth;
- describe the role of center of mass in the movement of an object;
- analyze the relationships between form and function in both living organisms and man-made structures; and
- describe science and technology as human endeavors, influenced by the prevailing cultures and beliefs of the time.

Introduction

This exercise gets students right into using their hands and having to think and plan. They experience success right away and they get immediate appreciation for their peers' ideas. They will not be intimidated by numbers or equations, yet they should come away with a tangible sense of what is meant by concepts such as center of gravity (center of mass) and wind resistance. When the exercise is over, they get the additional message that much of engineering is common sense. We have taken two class days, as shown here, but one could eliminate the second tower, do the discussion at the end of the first day, and move on. Adding information about the Washington Monument and the Eiffel Tower after they have made their own towers allows them to feel the structures rising out of the history and sociology of real towers.

Procedure

Materials:

- Newsprint the size of a full size newspaper. A hundred sheets for 20 students will be enough for two days with some extra pieces in case of mishaps. This can purchased from a school supply or paper supply store. You might even get a gift from a local newspaper. (Two caveats: Newsprint that comes on pads is often smaller than a full sheet of newspaper and more expensive. That's okay, but the towers will be smaller. Newsprint from actual old newspapers works just fine, but it will already have some creases in it. Again, not a serious problem; just something to consider.)

- Handy rolls of scotch tape, any width.
- Scissors.

Assignment for Day 1: Each student should take 2 sheets of newsprint and 10" of Scotch tape and build a paper tower as tall as she can that will resist being blown over by the teacher from one arm's length away. Do this in 20 to 30 minutes. We do it on the floor. Paper can be cut, torn or folded to taste. Tape can only be used to attach paper to paper. Tape should not be used to attach paper to other objects or the floor.

When setting up this exercise, we think it is important to keep the directions short and sweet. *Do not* belabor these rules. *Do not* talk about the principles of tower design. That discussion will come after the students have had a chance to *discover* some of those principles for themselves.

The extent to which you bend these rules is entirely up to you. Ten inches of tape should be about enough to do the job. But some students will need a bit more. The main issue here is that the tape is just used to connect paper to paper and *does not* become a major structural material. We tell the students they will have 20 minutes, but we often extend this time. Just make sure to leave enough time to test each tower.

The Test: Students watch and note what happens when the teacher decides on direction and gives one big breath blow to each tower. It is important that *all students watch* each test. This is an important step in their learning from each other. Do not discuss what happens; just continue until all towers have been tested. Measure the height of the tallest tower that did not fall. Record this number.

The Science Notebook: After all the towers have been tested, ask the students to write about their experiences. We prefer having each student keep a science notebook. At this stage in the exercise, they might write about some or all of the following:

- Describe what they did to build their tower, including any difficulties they had in getting it to stand up. This description should be clear enough that another person could read it and reproduce a reasonable copy of their tower.
- Describe what happened when their tower was tested. Did it sway and then right itself? If it fell over, exactly what did they see? Did the whole tower fall as one piece? Or did it buckle in the middle?
- Finally, have them answer this question: "What instructions would you give a friend so that he or she could do this exercise successfully? In other words, give the simplest rules of tower design."
- Note that it is entirely proper for students to write about what they saw when other students' towers were tested. Or even to write about good techniques they saw, even if they had not thought of them on their own.

Discussion: : After the students have finished writing in their notebooks, begin the class discussion asking this question again: "What instructions would you give a friend so that he or she could do this exercise successfully? In other words, give the simplest rules of tower design." As students offer statements, write their responses on the board. Try to capture those responses in the students' own words. They will probably generate a list something like this (though they will almost certainly not use words like *tensile* and *center of gravity*):

- The center of gravity must stay over the base.
- Make the tower stiff enough to achieve this.
- Keep the weight low.
- Make the base wide.
- Minimize the surface area and thus the wind resistance.
- Use a tubular triangular support at the base. This is the most rigid structure for the weight.
- Use tape and/or paper as *tensile* materials to attach the legs to the base. (These might be struts between tripod legs and the base of the tower that will keep the legs from splaying out.)

When these, or at least the first 4 or 5 rules, stated in the students' own words, are written for all to see, draw a line over them and above that write in block letters: ENGINEERING PRINCIPLES OF TOWER DESIGN. This is the evidence that engineering is common sense. These principles are applied by every engineer in designing every tower that is ever built to last. Students make these statements from their knowledge and experience in life, which defines common sense.

This class-generated list could be added to the students' notebooks.

We have seen classes in which all the students tried to build tall towers, but very few considered the nature of the base. And we have seen classes in which none of the students paid any attention to wind resistance. The result in each case might be that the students didn't really have much to learn from each other. The discussion, then, might reveal some of the important concepts. *However, do not just give away the tricks of the trade*. Try to *guide* the discussion so that students articulate the basic concepts *in their own words*. Once armed with some information generated by their peers, the students are ready to hear the assignment for Day 2.

Assignment for Day 2: Give this assignment at the close of Day 1. Suggest that students practice making towers at home. They may try as many techniques as they like, as many times as they like. Tell them that in the next class they will be given fresh materials, and they will get to build another tower. As a *homework assignment*, ask students to write a paragraph about what they will try to do to build a better tower on Day 2. This could include a diagram.

On Day 2, you might be more rigid about the time limit, since the exploration stage should have been accomplished at home. Test the new towers and measure the tallest. Compare these results with the Day 1 results. Typically, the Day 2 best is twice as tall as the Day 1 best. One year, one of our students made a tower that touched an eleven-foot ceiling! We have also observed that *many more* students build successful towers on the second day.

Further discussion: Here are some other possible questions and answers.

- "What design aspects made so many Day 2 towers so much taller than Day 1 towers?"
  (Craftsmanship and care with folding and rolling!)
- What is craftsmanship? How does one do it well? How can one tell by looking at something the level of excellence of the craftsmanship?
- "How many ways can a tower fail?"
  (They can fall over or bend over.)
- "What about one that leans or bends a bit but does not fall? Is that failure?"
  (It is for a building because humans like horizontal floors. But pine trees get along quite nicely when they bend a bit.)
- "What does this say about a major difference between nature's engineering and human engineering?"
  (Plants and animals can survive a great deal of posture-damaging wounds by means of healing and regeneration, which humans have yet to engineer.)
  (Humans must have horizontal floors to walk on, so walls must stay vertical.)

Extensions

The sociology of tower design. The following information is from:

David P. Billington, 1978. *Structures and the Urban Environment*. Lecture Notes 1980 CE 262. Princeton University Dept. of Civil Engineering.

Washington Monument

1783	Congress ordered equestrian statue of George Washington.
1799	Congress ordered marble monument to George Washington.
1801	$200,000 appropriated by the House, but Senate did nothing.
1833	Private citizens organized Washington National Monument Society and started raising funds.
1836	$28,000 raised. Invited designs to cost less than $1,000,000. Won by Robert Mills for a 500' tall obelisk resting on a 100' tall by 250' radius Greek temple.
1848	Congress & President Polk broke ground.
1854	No temple. Shaft was 152' up for $230,000. Anti-foreign, anti-Catholic group, the American Party, was angered because the Society had accepted a block of marble from the Pope. They destroyed the marble block, occupied the offices of the Society, seized its records, and voted their own members as officers, thereby outraging Congress, which stopped the flow of money and halted construction. Eventually, the American Party collapsed. Still no more money from Congress. The tower stood 21 years unattended.
1876	Centennial year. Congress appropriated $200,000 and ordered the Corps of Engineers to complete construction. The tower was leaning, so foundation work lasted till 1880.
1884	December 6, the final 3300 pound capstone was set in place.

The Washington Monument is still the tallest masonry tower ever built. Since stones cannot carry tension between them, wind resistance is entirely due to dead weight in compression alone. It tapers: the base is 55' square with 15' thick walls; the top is 34' square with 18" thick walls. The Monument is 1000 sq ft at top. Thirty people can go up per elevator. There are 33 sq ft of window for a super view of Washington, DC. No facilities for anything else.

The Monument is the dominant element in the DC landscape. It is a great central sign as an immense structure in a broad park. It is decoration to be admired from afar. Scientifically, it is an efficient masonry column. Socially it is a closed trip to a fine view. Symbolically, it is an elegant example of pure form that orients every sightseer from a distant perspective.

Eiffel Tower

1886	Competition for a tower as the center for a world's fair exposition. Other designs submitted included a huge tower-pump that would humidify Paris in the dry season, a 300 m tall guillotine to evoke the revolution, and a cylinder of lights that would allow every Parisian to read his newspaper at midnight anywhere in the city.
1887	Eiffel signed a pact with the city of Paris: He must complete the tower in less than 2 years for 1.5M francs, and he could charge admission (and keep it all) for 20 years when it would revert to Paris.
1887	Broke ground January 28. By June 30, the foundation was done and the tower started. First platform at 60 m by April 1. Second platform at 75 m by July 5. In the fall, there was worry that 228m was the theoretical maximum height of an iron structure (theory by a professor of mathematics in the Academie Francaise).
1889	Tower completed 1 month ahead of schedule on March 30.

The tower is entirely of iron: Eiffel did not trust steel! It is extremely light for its height, so the vertical load is light (150 lbs/sq in), but the wind load is high due to its great surface area. Therefore, it has a parabolic shape instead of a straight taper. Stresses in wind are nearly constant top to bottom.

The tower's openness allows visitors to see out all the way up. It has three platforms with restaurants, shops, and toilets. It accommodates 10,000 people at once.

It is scientifically an efficient metal cantilever, socially a popular and open trip to a great view, and symbolically an elegant example of pure form, engaging sightseers both from a distance and from a close-up, intimate view of its structure.

Both towers have meanings that go to the hearts of the cultures in which they arise. The monument, closed and classical, reminds one of other times and places and permits much less of an expanding personal vision than does the open, original structure of the tower.

	Washington Monument	**Eiffel Tower**
Height	170 meters 555 feet (56% of Tower)	300 meters 984 feet
Weight	81,000 tons	9,700 tons (12% of Monument)
Weight/Height ratio	1,600/1	9/1
Number of visitors at one time	30	10,000
Cost	$1,300,000 ($300,000 from government)	$1,560,000 ($1,100,000 recovered in first 6 months. Now self-supporting.)
Time from idea to completion	more than 100 years	less than 5 years

Deflection	0.02% of height	0.04% of height
Eco-vulnerability	little	rust--needs paint often
Cost of renovations	$9,000,000 (1999-2000)	$30,000,000 (1980s)

Revised: April 26, 2001