Skyscraper Structures

How do skyscrapers stand up?

It is recommended that you first complete the Social Sciences lesson for Third Grade before beginning this Science lesson. The Social Sciences lesson will give students a basic understanding of the differences between structures constructed by using a load-bearing method versus a skeleton frame system.

Theme

This lesson investigates the structural systems of skyscrapers by looking at three Chicago favorites: the Willis Tower (originally called the Sears Tower), the John Hancock Building, and the Inland Steel Building. By acting out the structural systems of each building and studying photographs of the buildings under construction, students will be able to apply this knowledge and build their own structures.

Student Objectives

- recognize and name the four structural elements used in these three skyscrapers
- describe how three Chicago skyscrapers stand up
- experiment by building their own structures

Activities

- study the photographs of the three Chicago skyscrapers under construction
- act out the structural systems of three Chicago skyscrapers
- build the structural frame for a skyscraper

Type

- indoor, desktop activities
- outdoor or gym activities

Timeframe

three class sessions of 40 minutes each

Materials

- *optional:* **Tension and Compression Information** - to share with students
- **Handout A** - photographs of a column, beam, cantilever, and truss
- **Handout B** - information and photographs of three Chicago skyscrapers
- **Handout C** - photographs of the Willis Tower
- **Handout D** - photographs of the John Hancock Building
- **Handout E** - photograph of the Inland Steel Building
- **Human Building Experiments** - activities connected to the three skyscrapers (3 pages)
- boxes of toothpicks *(approximately 60 toothpicks per student)*
- bags of stale mini-marshmallows *(approximately 40 marshmallows per student)*; or a cup of raisins or frozen peas *(per student)*
- *optional for demonstrating compression and tension*: a plastic bag with handles filled with heavy items; a heavy book; and a yard stick
- *optional*: blow dryer

Vocabulary

load-bearing method of construction building a structure by stacking one brick or stone on top of another

skeleton frame system of construction building a structure by creating a steel frame and hanging glass, steel, or stone panels on the outside

tension a force that stretches or pulls apart a material

compression a force that squeezes or presses a material together

wind a natural force that pushes on the sides of buildings

floor plan a drawing of a building seen from above with the roof removed

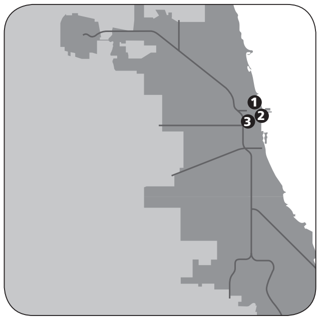
elevation a drawing of a building seen directly from the front, back, or sides

column a vertical structural element that supports a load

beam a horizontal structural element that supports a load

cantilever a beam that projects out and is supported only at one end

truss a rigid frame that is often in the shape of many triangles



Location Information

❶ **The John Hancock Building**
875 North Michigan Avenue
Chicago, Illinois

❷ **The Inland Steel Building**
(renamed the 30 West Monroe building in 2003)
30 West Monroe Street
Chicago, Illinois

❸ **The Willis Tower**
233 South Wacker Drive
Chicago, Illinois

Discussion Points

column

- Why do you think architects might add columns to their building designs? (to support the floors, walls, or roof)
- Look around the room. Do you see any columns at work? Or, do you see any table legs that are acting as small columns to help hold up the table top?
- *If you have explained tension and compression:* How does a column feel when it is working? (it is in compression)

beam

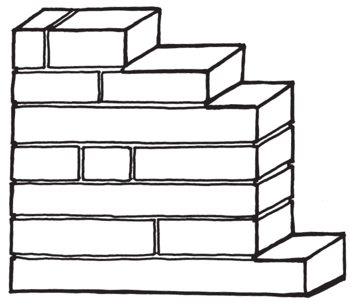
- Where do you think architects might use columns and beams together in their building designs? (doorways, windows, other types of openings)
- Look around the room. Do you see any beams at work? Do you see any columns and beams working together?
- *If you have explained tension and compression:* How does a beam feel when it is working? (the top of the beam is in compression; the bottom is in tension)

Teacher Prep

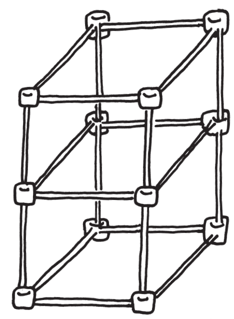
- photocopy or scan **Handouts A–E** for display or projection
- prepare the marshmallows by allowing them to sit out on a tray for a day (stale marshmallows make sturdier building materials, and students are less likely to eat them)

Background Information for Teacher

There are two completely different ways to construct a building: the ***load-bearing method*** and the ***skeleton frame system***. Both methods can be found in Chicago buildings, but all new skyscrapers use the skeleton frame system.



load-bearing method



skeleton frame system

The ***load-bearing method*** of construction involves stacking one block of stone or brick on top of another. Examples of this construction method include the Monadnock Building at Dearborn and Jackson Streets in Chicago and the Pyramids in Egypt. The blocks on the bottom support and carry the load of the blocks on the top. As the building gets taller, the walls at the bottom must be made thicker in order to carry the full weight of the building. The north end of the 16-story Monadnock Building has walls that are 6 feet thick at the bottom. Today, skyscrapers are no longer constructed using this method.

By the mid 1880s, a stronger building material called steel had been perfected. Steel dramatically increased how high buildings could be built. Steel was used as a skeleton for the building. Imagine lots of toothpicks and mini-marshmallows connected together to form a 3-dimensional frame. Then imagine covering this frame with aluminum foil to act as a 'skin' or outside covering. Such a method of construction is called the ***skeleton frame system***. Skyscrapers have a skeleton and a skin (which doesn't support any weight), just as people do.

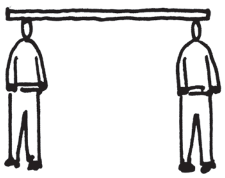
The Chicago architecture firm of Skidmore, Owings & Merrill (SOM) designed all three Chicago skyscrapers in this lesson. Their architects and engineers worked together to invent new ways to solve structural problems. Each of these skyscrapers used revolutionary new methods not seen on this scale before.

SOM is one of the most well-known architecture firms in the world. Since the firm began in Chicago in 1936, they have designed more than 10,000 buildings, interiors, and urban planning projects. Their Chicago offices are located at 224 South Michigan Avenue in the same building as the Chicago Architecture Foundation. Their 850 employees work in offices in New York, San Francisco, Washington DC, Los Angeles, London, and Hong Kong.

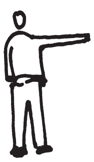
Four structural elements

column - a vertical structural element that supports a load
Demonstrate by placing a book on the head of a standing student.

beam - a horizontal structural element that supports a load
Demonstrate by placing a yard stick across the heads of two standing students.



cantilever - a beam that projects out and is supported only at one end
Demonstrate by having students extend one of their arms out from the shoulder.



truss - a rigid frame, often in the shape of many triangles
Demonstrate by having students stand side-by-side in a row with arms and legs extended so their bodies form Xs. The hand and foot of one student should be in contact with the hand and foot of the next student, and so on.

Columns, beams, cantilevers, and trusses can be combined in various ways to support a building. The simplest form is the straightforward skeleton frame system shown above. A very tall building such as the Willis Tower or the John Hancock Building often requires a special frame. The three buildings presented in this lesson show the more complex ways in which a building with a skeleton frame system can be constructed. **Handout B** summarizes the three methods which can be seen in detail in **Handouts C and D**. The **Human Building Experiments** explain the principles of each framing method.

Discussion Points
(continued)

cantilever

- When you are swimming at pool, where might you see a fun kind of cantilever? (The diving board)
- If you were an architect, why might you use a cantilever in your design? (to shelter a building entrance from sun or rain)
- *If you have explained tension and compression:* How does a cantilever feel when it is working? (The top side of the cantilever is in tension; the bottom side is in compression)

truss

- Give one example of where you have seen a truss? (holding up the Elevated train tracks; a truss bridge; a truss in a roof)
- Why do you think architects might create designs with trusses? (when they need a very strong structure, but don't want to add a lot of extra weight)
- *If you have explained tension and compression:* How does one triangle within a truss feel when it is working? (the top two sides of a triangle are in compression; the bottom horizontal side is in tension)

Interdisciplinary Connection

Fine Arts
Have students imagine what their own home, school, or another famous Chicago building looked like when it was under construction. Look carefully at the photographs of the Willis Tower, the John Hancock Building,and the Inland Steel Building under construction for inspiration. Illustrate their own ideas on paper.

Resources

The Art of Construction: Projects and Principles for Beginning Architects and Engineers, 3rd ed., Mario Salvadori. Chicago: Chicago Review Press, 1990.

Building Big, David Macaulay. Boston: Houghton Mifflin, 2000.

The Hows, Whats, and Wows of the Sears Tower, A Guide for Teachers, Kelley Fead. n.p. Contact the Sears Tower at 312.875.9447 for information about obtaining a copy or visiting the building.

The Sears Tower, Craig A. Doherty and Katherine M. Doherty. Woodbridge, CT: Blackbirch Press, Inc., 1995.

The Sears Tower: A Building Book from the Chicago Architecture Foundation, Jay Pridmore. San Francisco: Pomegranate, 2002.

Unbuilding, David Macaulay. Boston: Houghton Mifflin, 1980.

What it Feels Like to be a Building, Forrest Wilson. Washington, DC: The Preservation Press. 1988.

www.pbs.org/wgbh/buildingbig
A website about skyscrapers, domes, bridges, dams, and tunnels produced by PBS in conjunction with the television series. It also includes information for teaching tension and compression.

www.skyscrapercenter.com
A global tall building database compiled by the authority on the subject, The Council for Tall Buildings and Urban Habitat.

Activity Procedures

DAY ONE

Introduction to four structural elements and three Chicago skyscrapers

1 Introduce the four structural elements—column, beam, cantilever, and truss – using the Background Information and the photographs on **Handout A**. ***Optional:*** Share more details on the structural aspects of these buildings by discussing how tension and compression are at work in each structural element. Use the **Tension and Compression Information** provided on the handout.

2 Show the three skyscrapers on **Handouts B–E**. Point out the structural elements on both the construction photographs and the finished buildings.

DAY TWO

Human building experiments

3 Experiment by using students to demonstrate structural elements of the three skyscrapers. (See the **Human Building Experiments** handouts in this lesson. The experiments may work best in the gym or outdoors.) Frequently refer to the three skyscrapers and make connections between the human structures and the real structures.

4 Review the photographs of the three skyscrapers and discuss.

DAY THREE

Students make their own structures

5 This is the day when students apply what they've learned about how skyscrapers stand up. In designing and building their own structures from toothpicks and marshmallows, students should be able to explain the decisions they made. Display the photographs of the Willis Tower, John Hancock Building, and Inland Steel Building under construction for inspiration.

6 Distribute approximately 60 toothpicks and either 40 mini-marshmallows or a cup of raisins or frozen peas to each student. (Refer to the Teacher Prep list for specifics on marshmallow preparation.) Have students build their own skeleton frame structures. The goal for the students is to build a structure that is both tall and structurally stable. Will they use bundled tubes, cross-bracing, or clear span construction methods? Which shape is more stable: a square or a triangle? Students should discover that the triangle (the shape which makes a truss) is more stable than a square. What could your students do to make their structures more stable? Did everyone in the class use the same building method? Did some work better than others?

Extensions

- Test the students' toothpick-and-marshmallow structures under windy conditions. Hold a blow dryer at the same distance from each structure and blast them each with a three-second "wind gust." Did their structure tip over or stand strong? What methods did students use to help their structures stand up? Which structural systems were more successful in withstanding the wind gust?

- Architects and engineers typically use seven structural elements to help buildings to stand up: the column, beam, cantilever, and truss used in the skyscrapers of this lesson, plus the arch, vault, and dome. As an extension activity, students can study how and where these other three structural elements are used.

- Take a walk around the block with your class and hunt for some of the seven structural elements. Bring along paper, pencils, and clipboards to document where they were found. Once back in the classroom, discuss the findings. Have students draw or write about the elements that help buildings stand up.

- Bring in (or borrow from another class, if necessary) a set of wooden unit blocks for your students to use to build structures with columns, beams and cantilevers.

- Build truss, bundled tube, and clear span structures on a very large scale using newspaper logs. To make the logs, you will need a large quantity of full-page newspapers, several rolls of masking tape, and a large workspace. For each log, stack four full newspaper sheets neatly on top of each other. Beginning at one corner, roll the sheets into a tight roll. (This takes some practice. Use a pencil as a guide to start the roll; then slide the pencil out after two or three turns.) Secure each log well with masking tape. Trim about one inch off the ends of each log.

- Visit a nearby construction site with your class. Can students recognize any of the structures from this lesson in the building being constructed? After returning to the classroom, have students draw pictures of what they observed.

- The Chicago Architecture Foundation offers a field trip called, "Structure: The Secret of Skyscrapers" for 3rd and 4th Grade students. It includes a 45-minute interactive workshop session about the seven structural elements, followed by a 45-minute walking tour to identify the elements in buildings. Contact the Education Department at 312.922.3432 or education@architecture.org for more information. **www.architecture.org**

Illinois Learning Standards and Benchmarks

11B Know and apply the concepts, principles, and processes of technological design.

11.B.2a Identify a design problem and propose possible solutions.

11.B.2b Develop a plan, design and procedure to address the problems identifying constraints.

11.B.2c Build a prototype of the design using available tools and materials.

11.B.2d Test the prototype using suitable instruments, techniques, and quantitative measurements to record data.

11.B.2e Assess test results and the effectiveness of the design using given criteria and noting possible sources of error.

11.B.2f Report test design, test process and test results.

12D Know and apply concepts that describe force and motion and the principles that explain them.

12.D.2b Demonstrate and explain ways that forces cause actions and reactions.

Optional Tension and Compression Information To Share With Students

There are four big ideas in understanding how buildings stand up:

- Gravity pulls all objects, including buildings, towards the earth.
- Buildings are designed with structures that counteract the pull or force of gravity.
- A force is any action that maintains or changes the position of a structure.
- Tension and compression are opposite forces at work in buildings. Just like you cannot see the force of wind, you cannot see tension and compression. But you can see the effects of these forces.

The structural elements of a building and the materials used for those elements are subjected to two primary forces: **tension** and **compression**. Tension and compression are opposite forces, but one is not stronger than the other. Some parts of a building are designed to work in compression; other parts are designed with materials and elements that work in tension. In many aspects of the building, however, both tension and compression are at work.

Tension When something is "in tension" or tensed, it is being pulled and stretched, and it is getting longer. Consider a rubber band: It does what it is supposed to do only when it is stretched. When you try to compress it, nothing happens. Building materials that work well in tension include steel cables, steel, plastic, and aluminum.

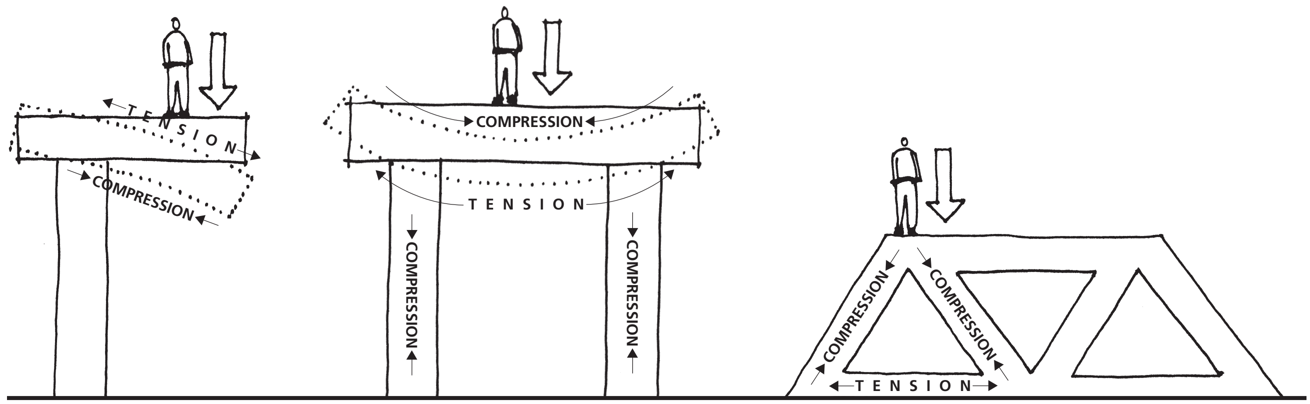
Test with students Fill a plastic shopping bag with a few heavy items. Have a student pick the bag up by its handles and hold it for 30 seconds. Does it feel like their arm is getting longer or shorter? Longer, of course! Their muscles are stretching, so their arm is in tension.

Structural elements that work in tension are the bottom of a beam, the top of a cantilever, and a truss. A column is the only one of the four structural elements that does not work in tension; it works only in compression.

Compression is the opposite of tension. When something is being compressed or is "in compression," it is being squeezed together, and it is getting shorter. (A mnemonic clue is the word "press" in the middle of "compression.") A thick sponge is useful for illustrating how compression works in structural elements. Stand a sponge up on a short end and press down. It's easy to see the sponge getting shorter as it compresses. Structural elements and building materials that work well in compression include a leg of a table, brick, concrete, cast iron, and steel. Steel works very well in both tension and compression, which is why skyscrapers are constructed using this material.

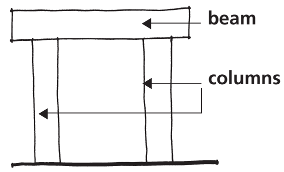
Test with students Place a heavy book on the head of a student. Does it feel like their body is getting longer or shorter? Shorter, of course! Their body is in compression.

Structural elements that work in compression are a column, the top of a beam, the bottom of a cantilever, and a truss.



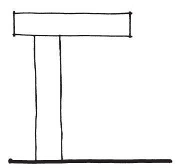
Cantilever **Columns and Beam** **Truss**

Handout A

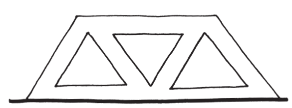


column
a vertical structural element that supports a load

beam
a horizontal structural element that supports a load



cantilever
a beam that projects out and is supported only at one end



truss
a rigid frame, often in the shape of many triangles

TOP Columns and beams on a building under construction, Chicago. (CAF COLLECTION)

MIDDLE A cantilever at the entrance to a building, Chicago. (CAF, 2002)

BOTTOM Trusses under the Elevated train tracks, Chicago. (CAF, 2002)

Handout B

Willis Tower, 1974

(originally named the Sears Tower)
33 South Wacker Drive
architect: Bruce Graham and engineer Fazlur Kahn of Skidmore, Owings & Merrill

method of standing up	- a “bundled tube” structural system - the first skyscraper in the world with this system
structural elements seen	- columns, beams
everyday objects similar to the Sears Tower structure	- 9 plastic straws, 9 paper-towel tubes, or 9 pencils tied together

LEFT Willis Tower. (© TRIZEC PROPERTIES, 2002. USED WITH PERMISSION.)

John Hancock Building, 1969

875 North Michigan Avenue
architect: Bruce Graham and engineer Fazlur Kahn of Skidmore, Owings & Merrill

method of standing up	- a cross-bracing system forming triangles and a tapered design - the first skyscraper in the world with this system
structural elements seen	- columns, beams, trusses
everyday objects similar to the John Hancock structure	- a truss bridge - the structure holding up the Elevated train tracks

LEFT The John Hancock Building. (CAF COLLECTION)

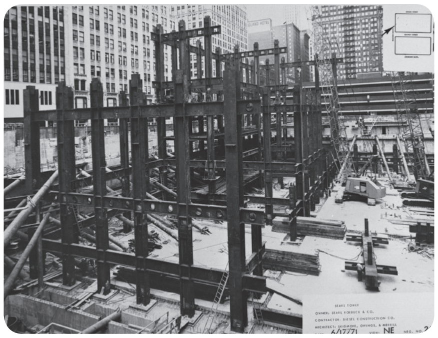
Inland Steel Building, 1958

30 West Monroe Street
architects: Walter Netsch and Bruce Graham of Skidmore, Owings & Merrill

method of standing up	- clear span steel frame construction - the first skyscraper in the world with this system
structural elements seen	- columns, beams, cantilevers
everyday objects similar to the Inland Steel structure	- library bookshelves - a stack of large tables

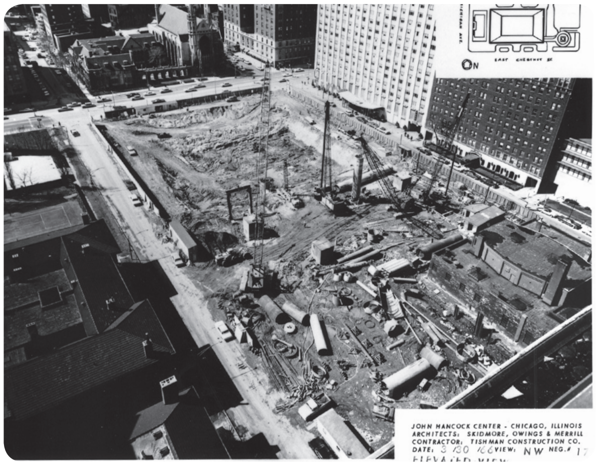
LEFT The Inland Steel Building. (CAF, 2002)

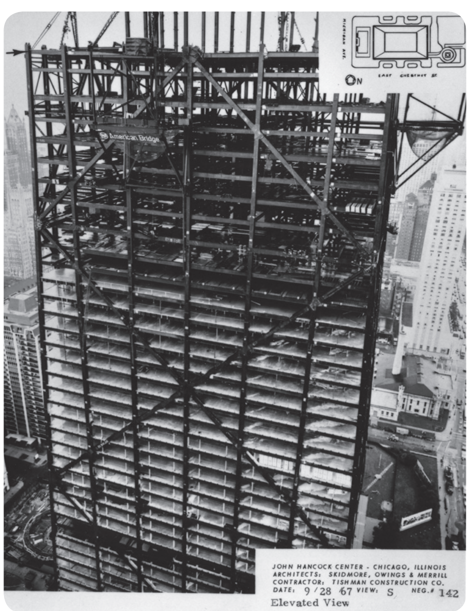
Handout C

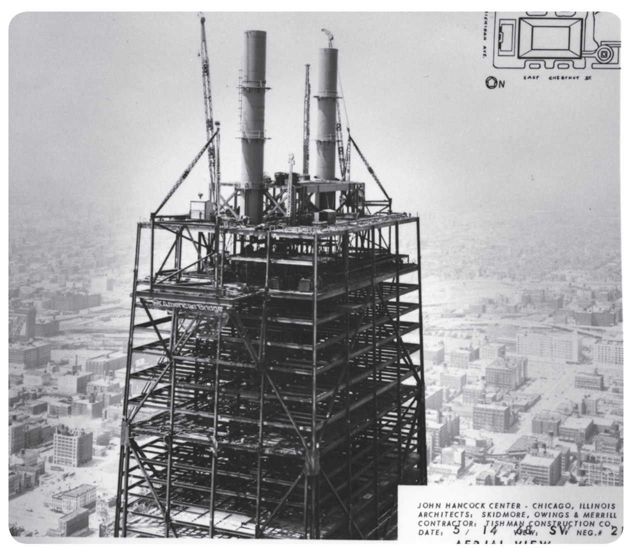


Willis Tower (originally named the Sears Tower) under construction in 1971–1973, Chicago. (© MCSHANE-FLEMING STUDIOS. USED WITH PERMISSION.)

Handout D







The John Hancock Building under construction in 1966–1968, Chicago. (© MC-SHANE-FLEMING STUDIOS. USED WITH PERMISSION.)

Handout E

The Inland Steel Building under construction in 1954–1958, Chicago. (HEDRICH BLESSING, CHICAGO HISTORICAL SOCIETY, HB-20177-A)

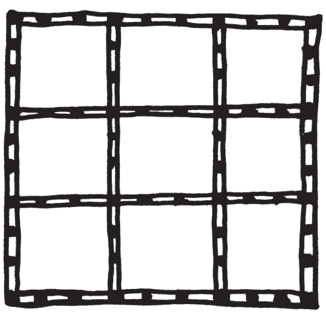
Human Building Experiments - The Willis Tower

Problem
When the wind blows hard in Chicago, buildings sway back and forth. How can a very tall building be strengthened to withstand the wind?

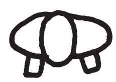
Solution
A bundled tube method. Instead of constructing one single tall tower or tube, nine tubes are bundled together. Also, some of the tubes do not extend to the full height of the building so that the air can move around and break up the force of the wind.

Experiment with students
A. Have one student stand in front of the class with their arms down at their sides, pretending they are the Sears Tower. While the student is standing with their feet staying in one place, imitate the wind by gently pushing and pulling on the student's shoulders. The class should be able to see that it is rather easy to move the "tower" back and forth.

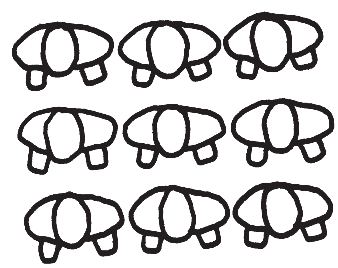
B. Then have 8 more students join this first student in front of the class. The 9 students should stand close to each other in a 3 x 3 square grid. (You may choose to wrap the 9 students with a piece of masking tape to bundle them together.) Again, while their feet stay in one place, carefully push and pull on the students' shoulders to imitate the wind. Students should feel that it has become much harder to move the entire structure. The bundled tubes stiffen the tower.



Plan of the Willis Tower



A. Plan of 1 student



B. Plan of 9 students as bundled tubes

Willis Tower. (© TRIZEC PROPERTIES, 2002. USED WITH PERMISSION.)

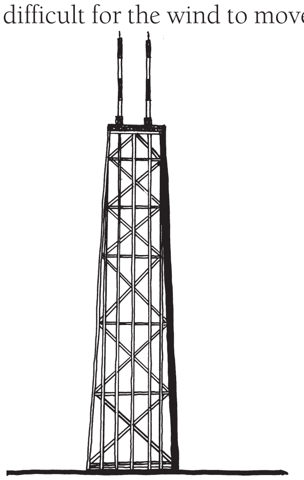
Human Building Experiments - The John Hancock Building

Problem
When the wind blows hard in Chicago, the buildings sway back and forth. How can a very tall building be strengthened to withstand the wind?

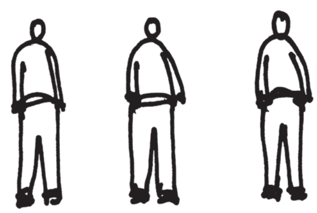
Solution
A cross-bracing system of triangles. The tower is made stronger by adding enormous cross braces on the outside. These diagonal braces tie the horizontal beams and vertical columns together. The braces form triangles because the triangle is the strongest shape. Also, the building's wider base and narrower top make the structure more stable.

Experiment with students
A. Bring three students to the front of the class and have them stand side-by-side, arm's length apart to act as the building's columns. While students are standing with their feet together, imitate the wind by gently pushing and pulling on the student's shoulders.

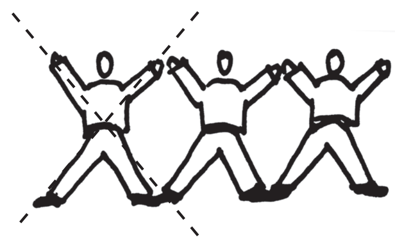
B. Then have the same students stretch their arms above their head and clasp hands with each other. Spread their feet apart so their feet also touch. Point out the triangle shapes that their arms and legs have created. Have observing students turn their heads 90 degrees to see the similarities between the human structure and the John Hancock Building. Then, imitate the wind again, pushing on their shoulders while their feet stay in one place. Students should feel that it has become much more difficult for the wind to move their human structure because the shape of the triangles ties them together.



Elevation of the John Hancock Building



A. 3 students standing side-by-side



B. 3 students connected by cross-bracing

The John Hancock Building. (CAF COLLECTION)

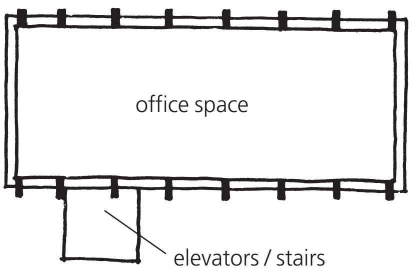
Human Building Experiments - The Inland Steel Building

Problem
Tall office buildings are designed with many columns to hold up the floors and roof. These columns interrupt the space inside and make it hard to arrange the furniture. Also, a tall building must have stairs and elevators so people and supplies can move inside the building. Columns, stairs, and elevators use up limited office space. How can a tall building be constructed so that it has no columns or elevators on the inside of the building?

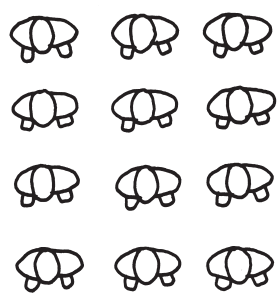
Solution
Clear span construction. Use very strong steel and put columns only along the outside edges of the building. Also, build a separate tower connected to the main building for the stairs and elevators.

Experiment with students
A. Bring 12 students to the front of the class to be the building's columns. Have them stand in a 3 x 4 rectangular grid, about arm's length apart. To demonstrate the problem of an office filled with columns, walk in, out, and around the student columns. Talk about how it is difficult to place furniture in a room like this.

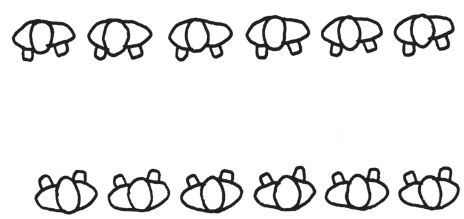
B. Then, rearrange these student columns into two rows. Six students standing shoulder to shoulder should face the opposite row. Demonstrate the open area now created between the students by walking through the middle of the two rows. Talk about how much easier it will be to place furniture in a room like this. Explain how the stairs and elevators in the Inland Steel Building have been moved into an adjoining tower.



Plan of the Inland Steel Building



A. Plan of students/columns in a typical office building



B. Plan of students/columns showing clear-span construction in the Inland Steel Building

LEFT AND RIGHT The Inland Steel Building. (CAF, 2002.)