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Bridges: Inspired by Nature

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Introduction

There exists a sketch of a headless nude male torso that looks alive, caught as if in the act of turning. Even more amazing, accompanying it is a sketch of a tall, slender building that captures the twisting torsion and movement shown in that figure. (1) The building that resulted from the inspiration provided by this figure drawing is "Turning Torso," a breathtaking tower built in Sweden that appears as if a giant hand reached out of the sky and twisted the building on its base. This building, an abstraction of the original idea, twists as if it possesses a spinal column. Santiago Calatrava is the architect, sculptor, artist and engineer who created and connected both the preparatory drawn images and this architectural marvel. It is but one of many of his architectural feats.

It is impossible to view Calatrava's work without some sort of personal response. What better way to interest and engage students in architecture is there than through the study of the graceful elegance of Calatrava's artistic structures? I want them to develop a sense of wonder and curiosity that will make them thirst for more. The particular focus of this unit is Santiago Calatrava's work because of the unique way in which he studies human, vegetative and animal forms in nature and applies his findings to architectural structures in general and bridges in particular. Since I am a high school art teacher and this unit is intended for my three 3-D Design art classes for next year, art will be an integral part of this unit. In this unit, students will develop an understanding of the rationale for creating bridges, study bridges in their historical contexts, and follow the development of new ideas, techniques, processes and materials and other considerations for the building of bridges. The unit will culminate with the students building their own individual bridges, assessing them and then displaying them in an art exhibit. Even though the emphasis of this unit is on art, it can be adapted for use in other disciplines, particularly those of science and math.

In 10 years the students will probably have forgotten details such as which bridge is the longest or tallest in the world. Those memorized facts are not enduring understandings. What is really important is that they remember the idea of bridges as paths of travel. Never again should they cross a bridge without thought or an awareness of that structure in its environment. Perhaps they will occasionally think about the impact that particular bridge has on that community. Students could be part of a community that is planning the building of a future bridge and they can have a more informed voice in its development.

Before taking Professor Emeritus of Architectural Engineering Martin Gehner's seminar at Yale on "Bridges:

The Art and Science for Creating Community Connections," I must confess that I used to traverse bridges without giving them much thought. After studying bridges, I will not be guilty of that again.

Objectives

In this unit, students will develop an understanding of the reasons why people need and create bridges and the impact that these bridges have on the communities and areas that they connect once they are built. They will understand that a bridge solves a problem and that they all cross over obstacles and connect one place to another. The examples that the students will see will help them understand why people throughout history and in different cultures have arrived at their solutions for bridges.

Students will be able to identify and remember the basic types of bridges and understand the principles involved in their construction through a variety of teaching strategies. They will also be able to understand some of the reasons why the different types of bridges are selected for their locations, realizing that a bridge should fill a particular need and fit a specific location. They will become familiar with selected appropriate historical examples of each of these basic types of bridges and understand how bridge construction, technology, materials, needs, environmental concerns, innovations and other factors have impacted bridge construction through the ages. Reasons for bridge failures will be explored. Students will also understand and be able to use the bridge as a metaphor.

An understanding is needed of how Santiago Calatrava has been inspired by nature. Students will analyze how he has incorporated the principles of structure found in nature into the basic design of some of his architectural buildings and bridges and even his sculptures and furniture. The importance of keeping a sketchbook like Calatrava and Leonardo da Vinci will be stressed. Since I am presenting this unit to my 3-D Design art students, I also want my students to see the influence of Calatrava's study of nature on his sculptures. The Fibonacci numbers will be examined in relation to nature (as in a spiral of a seashell) so that the students can build their models using the grace inherent in these natural numbers in their bridge measurements. The students will also understand how the visionary Leonardo da Vinci used his observations from nature in his art and invention ideas. There will be a clear connection between art and the other disciplines, particularly math and science.

Using personal observation and inspiration from a specific example such as a leaf that they have found or adapted from nature, students will be able to apply the principles of bridge construction to the creation of their own individual bridge models. Students will use their skills to first sketch the object(s) from nature. They will learn how to use graph paper and understand the concepts of scale and proportion, applying them to their renderings. After experimentation, research, and utilizing class input, the students will improve and modify their sketches that they have drawn. Then they will actually build their bridges, using their knowledge of structure, functions and materials. They can construct them using a selection of appropriate materials. The students will also learn from their peers and me through collaboration and a sharing of ideas throughout the process of building their bridges.

The students will also be able to analyze, evaluate and assess their own creations and the bridges of their peers using some of the appropriate vocabulary that they have learned during the course of the unit. A reflective thinking sheet that the students fill out should not only include what they perceive their successes and obstacles to be in the planning and building of their bridge, but they should also be able to explain the type of bridge that they have constructed and the forces involved. These objectives easily align with the Delaware State Art Standards which are listed in the appendix.

Strategies

Most art teachers have always used differentiated instruction, even before it had this catchy label. Since I have a wide variety of students who range from the valedictorian at one end to special education and REACH students at the other, I use a variety of strategies and activities for maximum learning. REACH students are those who have exceptional needs beyond those of the mainstreamed special education students. There are certain concepts that all of the students are expected to understand. For example, the forces of compression and tension are two ideas that are integral to the understanding of bridges. It could be on a level of "push" and "pull" which explains compression and tension on their simplest levels or it could be on a much more in-depth level of understanding. For example, I may have AP Physics students and students in AP math classes. Their understandings of the math formulas and the applied technology involved may far exceed mine. They can extend these understandings to further levels (taking these ideas and "running with them") for extra credit and personal satisfaction, if desired. All students can be successful with this unit and all students can be successful building bridges. The different levels of understanding and sophistication are normal and do not detract from the final results.

As an introduction to bridges, I will start with a CRISS (Creating Independence through Student-owned Strategies) Strategy called "Think-Pair-Share." If your classes are larger like some of mine, instead of pairing the students, the students can work in small groups. Large hands-on art classes present multiple challenges so teaching methods can be adapted and supplies stretched or substituted and space utilized as best as possible. Also, I teach in an AB Block schedule setting with 90 minute classes. For our art classes, that is a vast improvement over our previous model that featured 45 minute classes. All of the strategies and activities in this unit can be adapted to any scheduling model. In this beginning activity, each student will individually write down possible purposes of bridges and then share these in small groups at their tables. Then each group will share and discuss these with the whole class. This will hopefully serve as a stimulating "jumping off point" for the rest of our unit. The resulting discussions and sharing of ideas are essential parts of the learning for this unit. The students will list the results from this activity on an 18" x 24" piece of paper that will be hung on our "Bridge Wall." During the unit, we (the students, not just I) can add anything deemed relevant to the wall for sharing and future reference. Further explanation about the display wall appears later.

This "Think-Pair-Share" strategy can also be used as a short student-centered activity to stimulate any introductory thinking for the next part of the unit. It can be used to stimulate student thinking about actual bridges by naming real bridges such as the Delaware Memorial Bridge (a major suspension bridge on which most of my students have traveled) or the small overpass down the road from our high school (a beam bridge). They will also name types of bridges in a separate activity. Even though these introductory activities are separate, their findings are interrelated. Each bridge that they name also represents a basic type or combination of bridge types. The key to the "Think-Pair-Share" strategy is to adhere to the time limits to keep it short and the students focused.

Many of my students are visual learners. To ensure understanding, I want to use visual representations of the various concepts involved. I can show compression with a very simple but effective demonstration by compressing (pushing or pressing) my palms on either side of a row of approximately 10 books. By compressing the sides of the books, the whole row of books can be picked up. I will draw a simple sketch of a row of books embraced by hands on the board with arrows pointing inward from the sides, labeling them with the words "compression." (See Figure 1.). For visual learners who may be reading this, please refer to the appendix for sketches of these activities. Of course, all types of learners may benefit from viewing these.

To further reinforce the idea of compression, foot-long lengths of a swimming pool noodle can be distributed and shared. Any similar flexible material can be substituted. The students can actually see for themselves the wrinkling or compression of the Styrofoam-type material on the inside of the curve when the length is bent. This demonstration also introduces the force of tension. While the material on the inside of the curve is compressed, conversely, the bottom of the curve is stretched out and is then in tension. (See Figure 2.). Even a single uniform piece of computer paper (or just about any paper, for that matter) will display the properties of compression and tension. When the sheet is in tension (pulled on), it exhibits so much more strength than when it is in compression (the ends are pushed together and it immediately buckles and crumples, rendering it useless unless you are a scavenger like me who saves practically everything). (See Figure 3.). These demonstrations lead the learners into understanding the concepts of tension and compression. These forces can also be demonstrated with the simple bending of other materials such as a ruler, pencil, yarn, wire, a brick, etc. Some are weak when in tension while others are weak in compression. (2) A typical ruler laid flat and supported at each end will bend fairly easily when a force is applied at its center. However, when the same ruler is turned on its edge, it will resist the same force with very little bending at the center. The amount of available material is the same in both positions. (See Figure 4.) (2) However, this example illustrates the strength and concept of a girder as derived by the geometric properties of the cross section in their respective positions. This can also lead naturally into the use of materials and environmental factors. To illustrate the strength of a properly and improperly mixed material like concrete, plaster can be substituted for the cement portion. Students can mix a predetermined amount of dry plaster in a paper cup with varying amounts of water, leaving a stirrer like a craft stick in it. The one with the correct proportions will be the strongest. The mixtures with the least and most amounts of water will be structural disasters.

Visual demonstrations can also be used to demonstrate types of bridges. The idea of a cantilever can be shown using wooden blocks or other materials to represent a teeter totter. (See Figure 5.). The same concept of a cantilever can also be demonstrated using two students facing forward with one arm extended straight out to their sides. If a heavy book is placed on each of their palms, it will be difficult to keep their arms extended. However, if they overlap their hands and place a book in the arms hanging down by their sides for balance or counterweight, then they can support more weight of books on their overlapped hands. Their arms act like cantilevers. (See Figure 6.). This experiment has been demonstrated before with a person sitting on their outstretched hands but that would not be recommended in today's classroom (for safety reasons).

The concept behind a suspension bridge can be illustrated using two classroom chairs

spaced at least three feet apart, back to back. If using a 4" length of board, space them at least 4" apart. Using string or rope, drape two lengths over the ends of the chairs so that it looks like a suspension bridge. Cut three pieces of rope or string at least 30" in length and tie one to each of the two strings in the middle between the chairs (like a swing). Then tie one between the one chair and the middle and the other between the other chair and the middle. Lower a plank or board onto your bridge. Have two students pull the strings or ropes taught on each end as books are added onto the bridge to represent load. Test how much weight it can hold and discuss what happens when the students give the ropes too much slack, representing cables that are not anchored well enough to give the bridge adequate structural support. (See Figure 7.) (3)

All general structures need strength, support, and stability. Students can experiment with all three by placing two even stacks of books 12" apart and then placing a "bridge" consisting of a piece of cardstock or of some other stiff paper across the two stacks. They can count the number of pennies or some similar uniform materials that can be placed one at a time in the middle of the paper bridge until it collapses. Then they can fold a piece of paper like an accordion and place it under the paper bridge, adding pennies until it collapses. An arched piece of paper can then replace the folded piece, with the arch touching the top of the bridge and the ends wedged against the bottoms of both sides of the books. Pennies would again be added until it falls. The experiment can be repeated with differing amounts of taped paper rolls or toilet paper holders under the bridge. These could be repeated using a book on top of each end of the bridge. (See Figure 8.). (4) Students would be encouraged to test out their own theories and supports. The results would be discussed and could be placed on a chart. It will be interesting to see if each group of students, using the same materials, obtains the same results.

A quake table will be demonstrated for the students. A teacher from San Francisco (earthquake country) showed me how easy it is to make one using the detached fronts and backs of 3-ring binders. Cardboard could be used, too. Each cover is separated from the next with a little dollar store bouncy ball at each of the four corners. The first two covers are rubber banded together, entrapping the four balls. Then another binder piece is added with another 4 balls separating it from the last one. It is rubber banded to the existing part. Then another layer is added in the same fashion. Just one table can be used to simulate the earth's movements or two of these quake tables can be set next to each other, leaving a gap so that they could represent two hills separated by a raging river. A bridge made out of blocks can be set on it and the tables can be shaken. (See Figure 9). The destructive California earthquake in 1989 lasted for 15 seconds. Shaking the tables for 15 seconds would simulate the length of that quake. That would lead into discussions about safely building structures for certain parts of the country and what that would entail.

Students have different learning styles. Power Point presentations using both visual images and written explanations should help. A video on bridges and footage on You Tube of the famous Tacoma Narrows bridge disaster will add variety and a change of pace for students. To help students see Calatrava as a real person, a section of a You Tube interview featuring him will also be shown.

On our classroom Bridge Wall, I will add examples of the major ideas as we discuss them. To help students visualize the structural principles involved with each bridge type, I will add a drawn illustration of each with arrows pointing in the directions of force. For example, in a simple beam bridge, loading causes compression at the top of the bridge so the arrows would point horizontally inward. Loading would cause tension along the bottom so the arrows would point horizontally outward. The weight of the beam would also push straight downward onto the end supports that hold it up so the arrows would appropriately point downward. These end supports could be abutments, piers or the land itself. Each poster would be marked with these key terms so that the students can add to their architectural vocabulary with each lesson. Hopefully, they will not feel overwhelmed as each small chunk of knowledge is added. The posters that I have made illustrating each type of bridge such as the arch can go on the wall as can any photos of bridges that the students find in magazines or on the web. Vocabulary words can also go on the wall. After its use is explained to the students, for extra credit they can turn in suggestions on a piece of paper for a better name for the wall. The name could be a metaphor like "Bridge Wall: A Bridge of Ideas."

There will be a bridge resource center in the classroom that will include books from the library plus my personal books. A couple books were purchased at a local bookstore in their bargain section for less than $4.00 each and will be additional resources for the students. One has four small puzzles included and these can be laid out for passing students to do as a community effort.

This unit will culminate with an art show displaying the individual bridges that each of my students will have designed and built and then evaluated through discussion and a written reflective thinking piece. Their ideas for the bridges must be inspired by nature somehow. We will go on a field trip to the grounds of the school with sketch paper to get ideas from the environment. The students will be encouraged to be attuned to nature and quietly use their skills of observation, looking up for things like the symmetry of the trees with their branches or at birds in flight. They will need to look eye level with those structures that are on the ground and at everything in-between. Sketching their discoveries that catch their fancy as possibilities will be required because they will need to make the connection to a possible design for a bridge. They need to think abstractly and be willing to stretch creatively, discarding ideas that do not work. At the top of the pyramid of Bloom's Revised Taxonomy is *Creating*. That is what the students will do with the hands-on activity of creating their own bridges.

Bridges

A variety of representative images of bridges will be shown as examples of certain types of bridges through history and as a timeline of sorts as improvements and advancements have been made. The Power Point presentation will be of images that I have collected. As they are shown, a variety of issues will be discussed such as community needs, location, materials, maintenance, environmental factors, load, etc. The members of the bridges that are under compression and those under tension will be discussed with several of these examples to reinforce those concepts with the students. Examples of the four main types of bridges will be shown. They are beam, arch, cantilever (which is really an extension or improvement of the beam) and suspension bridges. Different types may be combined in one structure. The length of the area to be spanned helps determine the type of bridge used. Beam bridges should have a maximum length of 70 to 100 feet before the structures become too inefficient. Truss bridges have a greater strength and the maximum that they can span efficiently is 150 to 200 feet. Arch or trussed arches can span spaces of up to 1,000 feet before the structures become inefficient and the maximum for suspension bridges is approximately 2 miles.

A plank over a creek is a simple beam bridge. Beam bridges can be strengthened by creating a system of trusses or girders. The first bridges were probably fallen trees over a space, making them beam bridges. The following bridges are a sampling for this Power Point presentation. Among the first slides to be shown will be a short primitive beam bridge covered with dead vegetation and flat stones in Afghanistan. A loaded donkey is being led across. In contrast, the complex Forth Railway Bridge in Scotland was one of the first bridges made in steel and is an impressive but strange looking cantilever bridge.

In tropical and other locations, simple suspension bridges are often made of rope woven out of creepers, vines, grasses, and other natural materials. Handmade suspension bridges will include the one that crosses the Trisula River in Nepal and it will be compared to the new one in Kakum National Park in Ghana. Modern suspension bridges have evolved into such structures as the famous Golden Gate Bridge in San Francisco, the Verrazano Narrows Bridge in New York, the Brooklyn Bridge in New York City, and the Humber Bridge in England.

Arch bridges will be introduced with discussions about the Romans and images of impressive aqueducts that have survived such as the Pont du Gard in France and the slender Segovia aqueduct in Spain. China was independently developing bridge technology from the rest of the world and a slide of the graceful Anji or Zhaozhou Bridge from the 6th century AD will be included along with explanations of why it was so innovative. The Ponte Vecchio in Florence with its buildings, the Pont Neuf in Paris, London Bridge, the Rialto Bridge in Venice with its shops, the Mostar Bridge that was destroyed in Bosnia and the ancient Persian Allahverdi Khan Bridge will be among those that will be included. The Iron Bridge at Coalbrookdale in England, built in 1779, was the first iron bridge and was all cast and put together with pins and no bolts.

Examples of unusual bridges will be shown. Bridges have been made of lined-up floating boats and there were the temporary Bailey bridges from the war. The zigzag bridge for the Shanghais Yu Yuan Bazaar is reputed to ward off evil spirits because the spirits supposedly can only travel in straight lines. Some very modern bridges will include the three-armed Ribbie Way Footbridge in Lancashire and the wild BUGA Bridge in Germany. Included will also be images of some local bridges whose locations students will be encouraged to guess.

There is an interactive PBS site that correlates with the *Building Big Bridges* video at http://www.pbs.org/wgbh/buildingbig/bridge/challenge/multi/meeting.html (accessed July 14, 2008). (5) Even though it is simplistic for high school students, it actually contains a fair amount of material and can act as a review to reinforce the basic concepts. It has images of some famous bridges and other information but my favorite part is the glossary. Under *Forces* it lists *squeezing (compression), stretching (tension), bending, sliding (shear),* and *twisting (torsion).* The students can drag the glide to apply force to the shape in each to see the results. In each, they can click to see an example of an existing bridge. For *twisting*, the site shows a photo of the Tacoma Narrows Bridge with curved red arrows showing the oscillation. Under *Loads*, they have listed *weight of structure, weight of object, soft soil, temperature, earthquake, wind,* and *vibration*. To illustrate the weight of an object, cartoon elephants are added until the bridge breaks. It comes complete with sound effects like the wind howling and earthquake noises. Under *Materials* they list *wood, plastic, aluminum, concrete*, *reinforced concrete, cast iron*, and *steel*. After *cast iron* is clicked, the students can select *Properties of Each* to see that the type is cast iron, the ingredients are iron with lots of carbon, and a simple cost and weight chart. When the *Pros and Cons* icon is selected, the weaknesses shown for cast iron are being weaker than steel in tension and that it breaks without warning. For A*pplication* it includes arch bridges and historic domes. The example that it shows is Iron Bridge in England.

Santiago Calatrava's Structures: Inspired by Nature

The next Power Point presentation that I will show my students has powerful images of Calatrava's sketches and the buildings that were inspired by them. Calatrava often sketches his ideas in notebooks for future use. Photos of all the structures can be found in a multitude of resources but the sketches that have inspired the structures are not always found with them. Remember the old saying about a picture being worth a thousand words? To fully grasp the leap from sketch to completed structure, seeing the images is really helpful. Philip Jodidio has written at least two outstanding books on Calatrava brimming with exquisite color images that are well worth finding. So has Alexander Tzonis. Both have written books on his complete works. I have included a source for each of the images below.

The first image that will be shown will be the sketch of the headless male torso mentioned in my introduction. I will ask my students to guess what kind of structure might have resulted from this drawing. Possibly at least one student may say that no architectural structure could possibly result from such a drawing. Hopefully that will lead to lively discussion, especially after I show them the sketch for the building, "Turning Torso." Then I will show them a photo of the actual building that was inspired by it. Jodidio writes of it, "Calatrava's sketch shows the relationship of the tower both to his own sculpture and to the headless male figure-the history of art meets engineering." (6)

The next image will be of a watercolor sketch of a dome-shaped building with what appears to be two triangular wings on top. Overlapping it is a bird with wings outstretched plus an image with the wing-like extensions open and one with them closed along with two computer renderings of the completed structure. (7) These are for the new World Trade Center Transportation Hub in New York City by Ground Zero. Calatrava won the competition to design this project and he had the image of a bird released from a child's hand in mind. Tzonis writes, "… given the context of the September 11 tragedy, the bird figure becomes a unique symbol most appropriate for the site and occasion." (8) Jodidio writes of it, "The architect has understood that light must shine into the very heart of one of the darkest events in recent American history, and that he has touched the sensitivity of New Yorkers even before the wings of his new station rise up out of the ground." (9) I want my students to be aware of the imagery and also remind them of how a structure must fit a particular location and fill a certain need. Calatrava certainly achieves that goal here. Also, Calatrava is known for working well with the community and the various stakeholders, modifying his designs as he collaborates with them. I have read or heard about what a pleasure it is to work with him from and in so many sources that I realize that he must be the exception for architects, not the norm.

Following this will be slides of the breathtaking addition to the Milwaukee Art Museum that was finished in 2001, starting with the preliminary sketch of the top with a bird and then following up with images of the completed structure that illustrate the wings open and closed. (10) The graceful design of the wings is brilliant and the photos included in the books by both of these authors show the building's elegant artistic sculptural qualities. Calatrava's finished addition soars with steel and glass and features a movable sunscreen called the Brise Soleil. Calatrava also added a bridge that effectively connects the museum to the city.

The slides of the Orient Station in Portugal and sketches for it yield two different sections that have been inspired by structures in nature. Jodidio writes that Calatrava's sketches show "the extent to which he has simplified and rendered more abstract the original forest inspiration." (11) The train station's glass and steel canopy roof resembles a rain forest of abstract repeating forms. The other parts of the building that have been inspired by nature relate to that of the human figure. A man has been drawn leaning left with arms extended in two sides of a triangle. That is translated into the shape of triangular supports used throughout the station. (12)

Most architects create structures that are immobile. In Calatrava's dissertation, he explored frames that could fold and unfold (not unlike an umbrella but much more sophisticated and thoughtful) and was intrigued by movement. This has been reflected in some of the previous slides and also in the ones of Ernsting's Warehouse, a plain warehouse made exemplary in part by Calatrava's doors that open and shut horizontally like the lids of a human eye. (13)

Regarding the Montjuic Communications Tower built in Barcelona that is linked with the 1992 Olympic Games, Tzonis writes, "As is often the case, the architect's sketches reveal many of the ideas that are the origin of his projects. A kneeling figure, who might be imagined to hold an Olympic flame, or an athlete balanced in motion like the *Discobolus* by Myron are the sublimated references here." (14). This structure soars with grace and elegance and an abstract figure holding a torch can be imagined.

The next slides will show drawings of a nude male figure with arms clasped and stretched skyward metamorphosed into a sleek needle form. These are the inspiration for the torch for the 2004 Athens Olympics. (15)

Calatrava's gift for incorporating movement is also shown in the tree-like structures in the sketches and in the eloquent model that shows the folding roof mechanism of the Bauschanzli Restaurant in Zurich, Switzerland. (16) The model could be mistaken for a beautiful abstract sculpture of trees. In fact, Jodidio writes that Calatrava in 1997 wrote,

> "Architecture and sculpture are two rivers in which the same water flows. Imagine that sculpture is unfettered plasticity, while architecture is plasticity that must submit to function, and to the obvious notion of human scale (through function). Where sculpture ignores function, unbowed by mundane questions of use, it is superior to architecture as pure expression."(17)

Since my students are 3-D design students, a good homework assignment for them would be to explain what they think that quote means. Then we could discuss their thoughts after they turn them in.

I will show a photo of an early sculpture that resembles an abstract figure (a head on a tall cone) that illustrates the "finger" principle and then a photo of Calatrava's "Shadow Machine," a sculpture with feather-shaft type fingers that move using the same principle. (18) This graceful sculpture is on the grounds of the Museum of Modern Art in New York City.

Calatrava also has designed a lot of furniture and has a vast collection of sketches, particularly of the human figure. He painted a blue human figure on its hands and knees that looks like it could be a beam bridge or the base of a table. He also elongated human figures and they influenced the designs of his abstract tables. The glass tops are held up by very abstract forms that resemble thin angled reclining figures. (19)

I will also show the yellow watercolor studies of a leaf with the drawn veins radiating out from the center, accompanied by a yellow fish with head and ribs radiating from its spine. Below these are the abstractions of these combined images painted in brown to resemble wood. The resulting table has a glass top through which can be viewed a rib-like sculpture. (20)

Calatrava has drawn a whimsical gesture of a person sitting cross-legged with arms outstretched and what looks like a red ball on its head. Next to this drawing is a very abstract rendering of it. The slide that follows will be of The Boy with a Slinky, also known as Suspended Object or Discerning Eye, an abstract sculpture that embodies the preceding images. (21)

An interesting juxtaposition of styles is shown in Calatrava's sketch of an elegant abstract bioshelter or sort of ethereal greenhouse inspired by trees for the medieval-looking Cathedral of St. John the Divine in New York City. (22) A similar idea involving two trees forming an arch becomes the basis for complex arches of the BCE Place Gallery and Heritage Square in Toronto, Canada. (23)

A musical instrument provided the inspiration for the Community Centre Barenmatte Suhr Aargau in Switzerland. The graceful bridge with strings of a violin can be seen in the equally graceful ceiling supports. The elements are repeated in arcs across the spaces. (24)

Through Calatrava's sketches, we see the curved top of a bull's head transformed into startling similarly curved experimental roof supports. The steel constructions can be seen in the Jakem Warehouse in Switzerland. (25) These images can be followed with the whimsical but striking sketch of a dragon with opened mouth against a wall and wing extended along the ceiling. It precedes an image of the ceiling that it inspired in the remodeled Tabouretti Theatre in Switzerland. (26)

The side view sketches of a horse show the thinner front legs and the stronger angled hind legs. The leap from those images to the structures of the 9 d'Octubre Bridge in Valencia, Spain, is amazing. The beam part of the bridge looks like the body of the horse. The bridge's thin supports on the left side are fortified with cement blocks, paralleling the thin front legs of the horse, complete with hooves (the cement blocks). The graceful cement supports on the right flair out in shape, echoing the shapes of the hind legs of the horse. (27)

The last image that I will show of Calatrava's will be a watercolor of an outstretched nude woman who appears to be reaching for the sky. Her left arm is shown in two positions, one being lightly drawn in pencil, giving it a gestural feeling of movement. The image of this reaching woman will be shown so that my students will realize that "The figure studies of Calatrava are not necessarily related directly to specific works. This watercolor, however, does show the spirit that inhabits much of his architecture."(28)

Calatrava's bridges

Calatrava has built over 50 bridges. Because of time constraints, only selected bridges of his will be shown. The Alameda Bridge in Valencia, Spain, is an arch bridge for road traffic, as are the James Joyce Bridge in Dublin, Ireland, and the Observatory Bridge in Liege, Belgium. The Alamillo Bridge in Seville, Spain, the Toolenburg Roundabout Bridge in Haarlemmermeer, Netherlands, and the Turtle Bay Sundail Bridge in Redding, California, are all cable-stayed bridges for road traffic. The Campo Volantin Footbridge in Bilbao, Spain, is an amazing pedestrian arch bridge with a suspended transparent lighted deck. The Katehaki Bridge in Athens, Greece, the Trinity Footbridge in England and the Milwaukee Art Museum Pedestrian Bridge in Wisconsin are all for pedestrian traffic but are examples of cable-stayed bridges.

Activities

In this unit, there will be a wide variety of strategies, presentations of material and activities. The first activity will be the "Think-Pair-Share" activity described earlier in which students will brainstorm and then share all of the possible purposes of bridges that they can. Their lists can go on the classroom "Bridge Wall. Following will be discussions of the forces involved with bridge building along with several hands-on demonstrations illustrating these forces along with examples of bridges. A diverse collection of bridges through history will be discussed using a Power Point presentation, stressing the rationale for creating bridges and the myriad factors that are considered in the planning and building of bridges. These will include but not be limited to community needs, locations, materials, climate, weather, cost, and other considerations that will be explored in more depth.

The students will watch the 60 minute PBS *Building Big Bridges* video that features David Macaulay, author of *The Way Things Work,* in the classroom. (29) Since our class periods are 90 minutes, there will adequate time for discussion of the film's highlights afterwards. The following day I will take the students to one of our computer labs where I will first show them the 1940s footage of the Tacoma Narrows Bridge disaster on the YouTube website (30). Then the students will visit and experiment with one of the interactive websites that goes along with video. (5)

The structures inspired by objects in nature created by Santiago Calatrava will be explored through a Power Point presentation. The elegant and creative bridges of Santiago Calatrava will also be viewed. The nature studies and ideas for inventions of Leonardo da Vinci will also be studied. Included will be the system of proportion and measurement used in Leonardo's *Vitruvian Man.* I will pass around some Euros (European coins) that I have that feature Leonardo's *Vitruvian Man* represented on one side, leading the discussion into the enduring power of symbols. That can further lead into a discussion of the mathematical Fibonacci numbers and their use in architecture. The beautiful spiral of a seashell can be used as an example for the application of these numbers.

For homework, students should bring a list of every bridge that they encounter on the way to school. On another day, they will write a reaction to the quote by Calatrava concerning sculpture and architecture that they will copy off of the board. (17)

Students will study the natural structure found in leaves and apply their findings to the structures of possible bridge designs, using Calatrava for inspiration. They will also use their peers and themselves to apply the structure of the human body in the same way. The classroom skeleton will also be available for inspiration. The students will walk outside for a short field trip to study and sketch things in nature as the inspiration or link to their own bridge designs. They will experiment with a series of sketches, transforming their objects into bridge structures, selecting one that they can actually transition successfully. The use of scaling and graph paper will be explained and demonstrated. Students will draw their designs on graph paper and plan the execution of the building of their bridge models. Then the students will actually build their bridges, assessing their progress during the building process and then applying those evaluative skills to their final results.

The unit will culminate with an art exhibit of the students' sketches and their bridge models, complete with invitations to the opening night reception for students, their families, the school staff and community members.

Optional or possible additional activities can include inviting an architect or city planner to talk with the class, examining string instruments for their relationship to cable-stayed and suspension bridges, and having the students paint a dramatic watercolor wash background with a silhouette of their own bridge. The similarities between the deceptively simple sculptures of Brancusi and Calatrava can also be explored, resulting in a smooth abstracted sculpture inspired by nature that is carved or modeled by each student.

The following are three lesson plans that give more detail than those of the preceding activities.

Lesson Plan 1: The Examination of the Structure of Leaves and Humans

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The background for this lesson was laid in the one that precedes it. The objective of that lesson was for students to see and then understand how the architect and artist Calatrava draws upon objects found in nature as inspiration for some of the structures that he designs. A description of some of those images shown in the Calatrava Power point is included earlier in this unit. For example, among the images is a watercolor sketch of a leaf with veins radiating out from the center. Accompanying it is a sketch of a fish with ribs flaring out from its spine, resembling the structure of the leaf. The shared concept becomes the structure for a table base. (19) The discussion is very important because students need to understand the bridge between Calatrava's ideas in sketches to his finished structures so that they can apply those understandings to their own designs. That will have been followed by the viewing of images of nature drawings by Leonardo da Vinci and the correlation of his discoveries to his invention ideas.

The objective of this one-day lesson is the student examination of leaves and human figures to see a correlation on their own (gently guided by me) between particular objects in nature (the leaves or humans) and possible architectural structures.

Calatrava's images with the leaf and fish sketches will lead into the examination of the structure and beauty of tree leaves. Each table or group of students will be given a packet of leaves to examine. Each will contain examples of the two basic types of trees which are conifers (those with needle-like leaves like those of pines, firs, junipers and spruces) and the flat leaves or blades of broadleaf trees like maples. Both types are found on our school grounds.

Also included in the packet will be simple leaves that are identified by the single individual leaf on a stem and compound leaves which are those that have three or more leaflets on a shared stem. Broadleaf trees are further classified by the types of edges that the leaves possess. Examples of simple leaves with smooth edges are dogwoods, willows and redbuds. Willow, holly, beech, cherry, plum, aspen and birch trees all have leaves with saw-toothed edges. Trees that bear acorn as a fruit and have leaves that are lobed include a wide variety of oak trees. Trees that have lobed leaves but bear non-acorn fruit include sassafras and sweetgum trees, maples, tulip trees and sycamores.

There are two types of trees with compound leaves. Those with leaves arranged like feathers include hickory, walnut, ash, and locust trees. Those with leaves arranged like fingers on a hand include the horse chestnut. Any examples that you might collect will reflect the area of the country in which you live since you will need to find readily available specimens. The leaves should probably be gathered relatively close to the time that they will be used and can be pressed under weights such as books. If they are collected too soon, they will become too dry, crumbling away quickly from the handling of many hands. If they will be used over and over, they can be preserved in close to their natural state by soaking them for a week or two in a mixture of water and glycerin.

The amount of time that you spend on leaf examination is up to you. After discussion about classification, each group of students can first classify their leaves as conifers or broadleaf specimens. Then they can divide the broadleaf examples into simple and compound categories. They can further be broken down into saw-toothed versus smooth-edged versus lobed.

An example of opposite-leaf plants and alternate-leafed plants will be shown to the entire class since branches will not fit in the leaf bags well. This involves how the leaves are arranged on the branch. If the leaves on the branch grow directly opposite from each other and match up, then they are considered to be opposite. In alternate-leaf plants, the leaves never are opposite of each other. Instead, there is a leaf on the left of the branch and then, on the right, there is a leaf a lower down so that a staggered affect is created.

A main focus of this lesson is actually on the variety and beauty of the structures of leaves rather than on their scientific classification. The students should develop their observational skills. Through thoughtful reflection and discussion, students will need to make the leap from looking at leaves to thinking of how these structures can become the supports and structures of bridges. Students will sketch at least one leaf with veins and experiment with forms that it might suggest.

After examining leaves, the students will be asked to recall some of Calatrava's figure studies and their inspiration to certain structures. Then they will create simple quick sketches of classmates at their tables in different poses that could possibly be used along with structures that each pose suggests. The students are in charge of this section of the lesson. Each group should have at least a couple of students willing to experiment with poses. At the end of the period, the signed drawings will be collected for credit and then some of them that are more on target will be hung in the classroom the following day for display.

Among the materials needed for this lesson are a packet that includes a variety of leaves for examination for each table or small group of students and just one example each of a branch of opposite-leaf plants and alternative-leaf plants. Each group of students will use each other as models for figure drawing. They will also need drawing paper, pencils, erasers and possibly drawing boards or the equivalent. If a school skeleton is available, that can also be examined and posed in the classroom. I made a bridge in preparation for the teaching of this unit and used the class skeleton's ribcage for inspiration for my cable-stayed bridge. I will share the steps of my thinking process for my bridge with my students.

Lesson Plan 2: Finding and Developing Ideas from Nature as Inspiration for Bridge Designs

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The objective of this lesson is for students to find and draw objects in nature outside on school grounds that will be their inspirations for their bridge designs. This one-period lesson will directly follow Lesson Plan 1. To introduce this exercise, the Calatrava images of some of his structures that have been inspired by nature will be briefly reviewed. A discussion will follow about the successes and obstacles from the examination and resulting drawings of leaves and the human forms from the previous lesson. We will also constructively comment on to the student drawings that are on display from that lesson.

Students will then pack up all necessary supplies for the mini-field trip outside to explore objects from nature on the school grounds. The class must stay together in the same general area outside. Each student must have paper, a drawing board or similar backing, a pencil and an eraser before leaving the classroom. Chairs may be carried out if students do not want to sit on the grass. I will take a sharpener and extra pencils and paper with me, leaving a note on the door informing visitors about the change in our location. The office will already have been notified about our plans.

Once outside, students will be encouraged to be very observant and look on different levels around them. They can examine the structures of the tree branches up high and the worms, acorns and grass down low. They should sketch any objects that might hold future inspirational possibilities for their bridge designs. All are required to make sketches during this provided opportunity, but they are also free to explore on paper other natural objects that may not be found outside, such as sea shells or giraffes. They should start to work out their bridge designs, using a series of sketches to transform their objects into their desired bridges. If students are satisfied with their leaf and figure drawing exercises from the previous class period, then they can explore them further, also. The students will return to the classroom with sufficient time to put everything away.

Lesson Plan 3: The Building of the Bridge Models

The objective of this lesson is for the students to each build their own individual bridges, using their drawings that have been inspired from nature and developed into feasible designs. Each student will have received a handout explaining the criteria for the building of their bridges at the beginning of the unit. This will give them time to thoughtfully develop their bridge designs as they are exposed to information throughout the unit. Students need to understand what is expected of them so that they can plan in advance. The handout will include size restrictions and bridge considerations. For example, the finished bridges may not exceed 36" in length, 8" in width and 24" in height because of room storage constraints. The actual building of the model will be a summation of all that they will have learned up to this point. This activity that entails the actual construction of their bridge models will be by far the longest activity in duration during this unit. It will take between two and three weeks and students will be encouraged to work on them during any free time that they have.

Students may choose the basic constructions of a beam bridge, an arch, a cantilever or a suspension bridge or any combination including the addition of trusses for support. It will be stressed that it is better to keep the concept and design simple. However, students must be able to explain the principles behind their design, exhibiting their understanding of how forces affect the strength of their bridge. Students should know if their bridges rely primarily on compression, tension or trusses to carry forces from the deck of the bridges to the bridges' supports.

The available materials in the classroom will be shown to the students with the strengths and weaknesses of some of the materials described. The safest, most sensible methods of cutting pieces will be demonstrated, including using mat board scraps under the pieces to be cut so that the table surfaces will be protected. Even though students will be working individually on their own bridges, they will be encouraged to brainstorm and share ideas, creating an environment of creativity and collegiality. Using the scaled drawings on graph paper that they have done during a previous lesson, they will make informed decisions on the appropriate materials to use for their bridge designs.

Materials will include mat board and foam board for the bridges and their bases. Scraps of these can be obtained free from most framing stores. Most frame stores usually have mat board scraps in quantity, but do not have as many foam board scraps on hand so you can call around and ask places to save them for you. Balsa wood is an excellent material for bridges. Clay can also be used. Most art teachers are scavengers and collect and save wire, string, drinking straws, wood, etc. X-acto knives, drills, a jigsaw and hand saw and pliers will also be available. Students can be creative and use a variety of materials and they can be encouraged to bring in their own materials if they desire. The bridge pieces can even be made out of rolled pieces of newspapers. It should be stressed, however, that the materials used should simulate the actual materials that would be used in their bridges if they were real. The students should try to use joints and connections similar to what their bridges would actually specify. The students will have a deadline for the completion of their bridges.

End Notes

1. Philip Jodidio. *Santiago Calatava* (Koln, Germany: Taschen, 2007), 74-76.
2. Andrew Dunn. *Structures: Bridges* (New York: Thompson Learning, 1993), 8.
3. Andrew Dunn, *Structures: Bridges* (New York: Thompson Learning, 1993), 14.
4. Andrew Dunn, *Structures: Bridges* (New York: Thompson Learning, 1993), 17.
5. WGBH Boston /PBS website for Building Big Bridges with David Macaulay http://www.pbs.org/wgbh/buildingbig/bridge/challenge/multi/meeting.html (accessed July 14, 2008).
6. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen, 2007), 74-76.
7. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 385, 386, 387, 381, 382.
8. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 384.
9. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen 2007), 17.
10. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York, Rizzolo, 2004), 294, 291, 295.
11. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen, 2007), 54-56, 59.
12. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen, 2007), 56.
13. Philip Jodidio. *Santiago Calatrava: Complete Works 1979-2007* (Koln, Germany: Taschen, 2007), 52, 53, 58, 59.
14. Philip Jodidio*. Santiago Calatrava: Complete Works 1979-2007* (Koln, Germany: Taschen, 2007), 116,117.
15. Alexander Tzonis. *SantiagoCalatrava: The Athens Olympics* (New York: Rizzoli 2005) 88, 89.
16. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 162, 163.
17. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen, 2007), 8, 9.
18. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 272, 273.
19. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rozzoli, 2004), 360-367, 358.
20. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 368, 369.
21. Alexander Tzonis. *SantiagoCalatrava: The Complete Works* (New York: Rizzoli, 2004), 280, 281.
22. Alexander Tzonis. *Santiago Calatrava: The Complete Works* (New York: Rizzoli, 2004), 233, 231.
23. Werner Blazer, editor. *Santiago Calatrava: Engineering Architecture* (Basel: Birkhal-Verlag, 1989), 62, 63.
24. Werner Blazer, editor. *Santiago Calatrava: Engineering Architecture* (Basel: Birkhal-Verlag, 1989), 41, 42, 45.
25. Werner Blazer, editor. *Santiago Calatrava: Engineering Architecture* (Basel: Birkhal-Verlag, 1989), 71, 74, 69.
26. Werner Blazer, editor*. Santiago Calatrava: Engineering Architecture* (Basel: Birkhal-Verlag, 1989), 97, 101.
27. Werner Blazer, editor. *Santiago Calatrava: Engineering Architecture* (Basel: Birkhal-Verlag, 1989), 129, 132, 133.
28. Philip Jodidio. *Santiago Calatrava* (Koln, Germany: Taschen, 2007), 21.
29. WBGH/Boston PBS Video *Building Big Bridges with David Macaulay.*
30. Tacoma Narrows Bridge Collapse "Galloping Gertie" (YouTube). www.youtube.com.watch?v=3mclp9QmCGs

Bibliography for Teachers

Blazer, Werner, editor. *Santiago Calatrava: Engineering Architecture.* Basel: Birkhauser Verlag, 1989. This volume has some of Calatrava's sketches that have inspired his structures that aren't readily found in other sources.

Brown, David J. *Bridges:Three Thousand Years of Defying Nature.* Buffalo: Firefly Books, 2005. This well-laid out book provides a nice overview of bridges.

Dunn, Andrew. *Structures: Bridges*. New York: Thompson Learning, 1993. This book is a gem for younger students. Dunn's wonderful illustrations were the basis for my sketches in Figure 7, Figure 8, and the top half of Figure 4,

Dupres, Judith*. Bridges.* New York: Black Dog & Leventhal Publishers, 1997. Bridge basics are covered using a variety of bridges as examples in this "long" (7 7/8" x 18 ½") volume.

Gordon, J.E. *Structures: or Why Things Don't Fall Down*. London: Plenum Press, 1978. Told with humor, the author explains in simple terms the theories of structures.

Graf, Bernard. *Bridges that Changed the World.* Munich: Prestel, 2002. This contains a great variety of types of bridges along with an explanation of why each bridge has earned a place in the book. They are the stars of this volume.

Jodidio, Philip. *Santiango Calatrava*. Koln, Germany: Taschen, 2007. Published at $9.99, this book is a must for your own personal library if you can afford it.

Jodidio, Philip. *Santiago Calatrava: Complete Works 1979-2007*. Germany: Taschen, 2007. This is a coffee table-type book that you may have trouble putting down. It is that good! Not only are the images gorgeous, but it also contains numerous sketches by Calatrava that have inspired his works along with illuminating quotes.

Kent, Cheryl. *Santiago Calatrava: Milwaukee Art Museum.* New York: Rizzoli, 2005. After perusing this volume, the wonder and use of movement in this museum addition is understood.

Rose, Charlie. YouTube Charlie Rose interview with Santiago Calatrava. www.youtube.com/watch?v=3YOsph6r8sk (accessed July 14, 2008).

Tacoma Narrows Bridge Collapse-"Galloping Gertie" (YouTube). www.youtube.com/watch?v=3mclp9QmCGs (accessed July 28, 2008). This is amazing footage of the actual collapse in the 1940s.

Tzoni, Alexander. *Santiago Calatrava: The Complete Works.* New York: Rizzoli, 2004. A sumptuous book that contains a wealth of images and information, it also includes reproductions of some of Calatrava's sketches from nature that have inspired some of his structures plus a concise catalogue with photos of over 100 of his works in the back.

Tzonis, Alexander. *Santiago Calatrava: Structures in Movement.* Dallas, Texas: Meadows Museum, Southern Methodist University, 2001. This volume contains minimal text but noteworthy structures, sculptures and sketches with a timeline in the back.

WGBH Boston/PBS Video. *Building Big Bridges with David Macaulay.* This video featuring David Macaulay, the award-winning author and illustrator of the best-selling The Way Things Work is worth watching and can be ordered from www.wgbh.org. or a PBS site or checked out from some libraries.

WGBH Boston/PBS website for *Building Bridges with David Macaulay*. http://www.pbs.org/wgbh/buildingbig/bridge/challange/multi/meeting.html (last accessed July 14, 2008). This is a wonderful interactive site for students that reinforces ideas from the video.

Reading List for Students

WGBH Boston/PBS website for Building Bridges with David Macaulay.

http://www.pbs.org/wgbh/buildingbig/bridge/challenge/multi/meeting.html (last accessed July 12, 2008).

Materials for Classroom Use

A variety of appropriate art supplies, materials and tools will be available for student use.

These will include balsa wood, mat board, foam board, drawing paper, graph paper, cardboard, drawing boards, wood scraps, clay, string, wire, nylon, pliers, a drill, X-acto knives, a jigsaw, a hand saw, paints, inks, various glues, glue guns, rulers, triangles, T-squares, pencils, erasers, pencil sharpeners, and various fasteners.

These books will be in the classroom for student use at any time:

Bridges of the World. The Five Mile Press Pty Ltd: San Francisco, CA, 2007. Found in some bookstores for under $4.00, this book features information on Prague's Charles Bridge, the Rialto Bridge in Venice, the Sydney Harbour Bridge, San Francisco's Golden Gate Bridge and New York's Brooklyn Bridge plus it has puzzles of the first four bridges.

Dunn, Chris. *Structures: Bridges*. New York: Thompson Learning, 1993. An excellent book for children, it should still be helpful for high school students because of its simple but clear explanations.

Cowan, Henry J., Ruth Greenstein, Bronwyn Hannah, John Haskell, Trevor Howells, Deborah Malor, John Philips, Thomas A. Ranieri, Mark Stiles and Bronwyn Sweeney. *A Guide to the World's Greatest Buildings: Masterpieces of Architecture & Engineering*. San Francisco, CA: Fog City Press, 2007. Not only does this contain a variety of bridges, it also contains some other great gems through history and it was on the sale racks at bookstores for under $4.00.

Jodidio, Philip. Santiago Calatrava. Koln, Germany: Taschen, 2007. Published at $9.99, this is a must-have for the classroom.

Oxlade, Chris. *Technology Craft Topics: Bridges and Tunnels.* New York: Franklin Watts, 1994. This book is for students and not only does it explain bridge basics, but it has some simple illustrations for students to follow for making their own bridges.

Weiner, Vicki. *The Brooklyn Bridge: New York's Graceful Connection.* USA: Children's Press, a Division of Scholastic Inc., 2004. This tells the riveting story of engineer John Roebling and his son Washington and the building of the Brooklyn Bridge. The concept of caissons, dangerous underwater construction work chambers for men, is clearly explained in words, photos and illustrations.

Implementing District Standards

Delaware State Art Standards:

Standard 1: Understanding and applying media, techniques and processes.

Applying what they have learned in this unit, students will be able to select the appropriate materials and use the proper techniques and processes necessary to turn their bridge designs into three-dimensional bridge models.

Standard 2: Using knowledge of structures and functions.

Students will apply their knowledge of the basic principles and functions of structures to the designing and building of their own bridges. They will effectively use the elements and principles of design in this process.

Standard 3: Choosing and evaluating a range of subject matter, symbols and ideas.

Students will chose, after careful exploration and evaluation, ideas inspired by nature for their bridge designs.

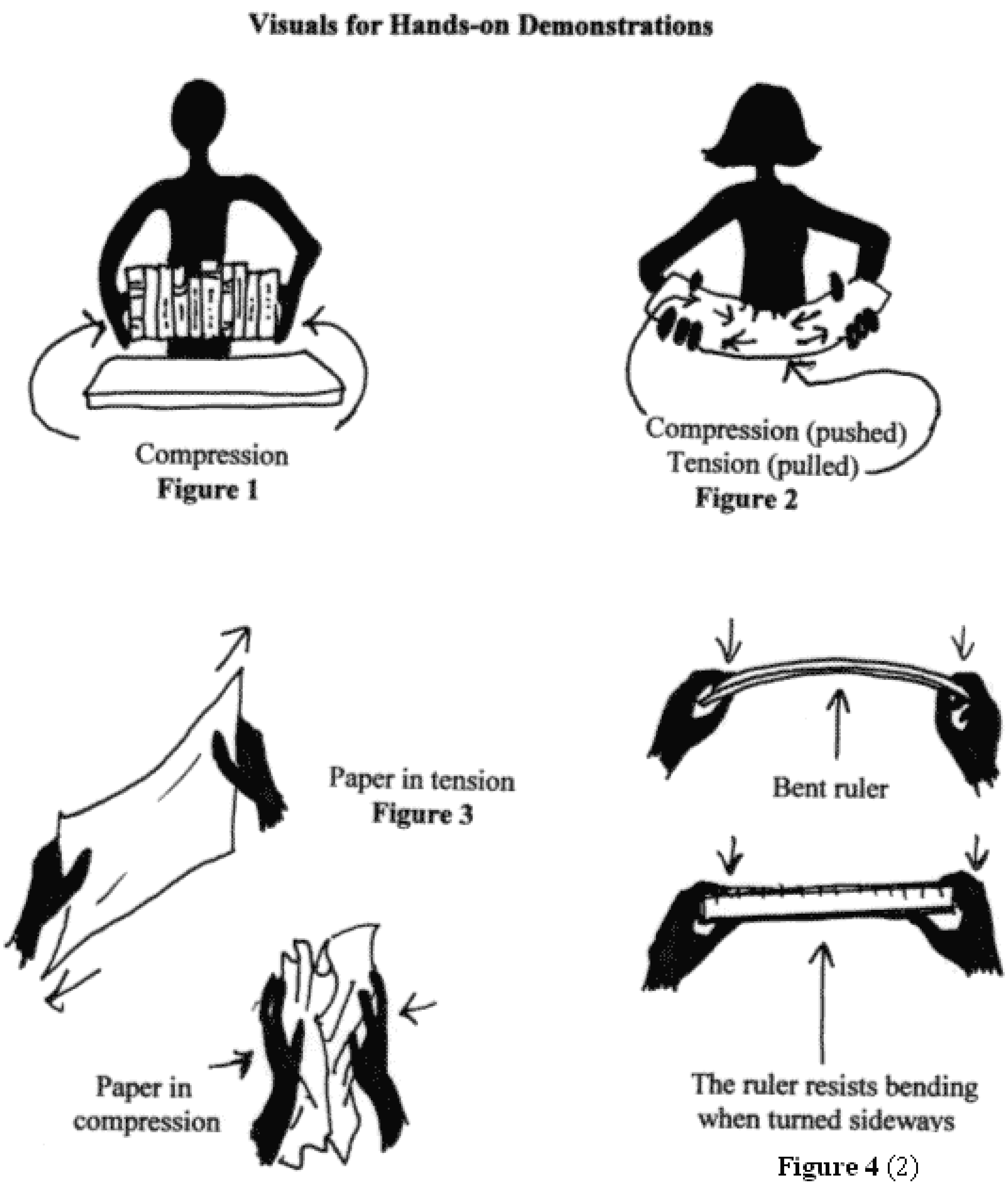
Standard 4: Understanding the visual arts in relation to history and culture.

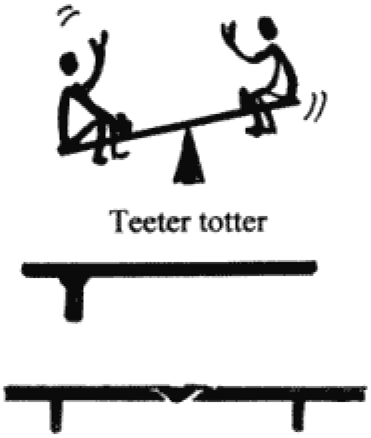
After studying the various bridges throughout history and the roles that they play in their different communities, students will better understand architecture in general and bridges in particular.

Standard 5: Reflecting upon and assessing the characteristics and merits of their work and the work of others.

The students will reflect upon, analyze, assess and evaluate their own progress and that of their peers both during the bridge building process and upon completion.

Appendix





Cantilever principle
Figure 5

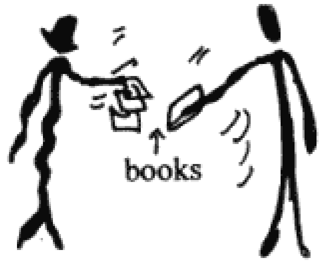
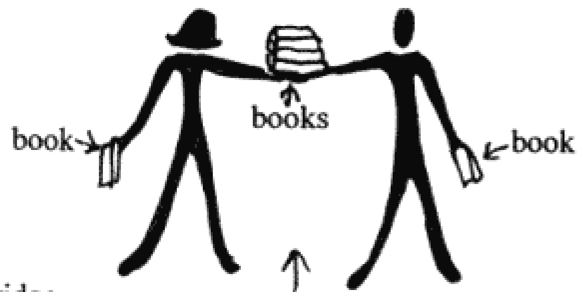
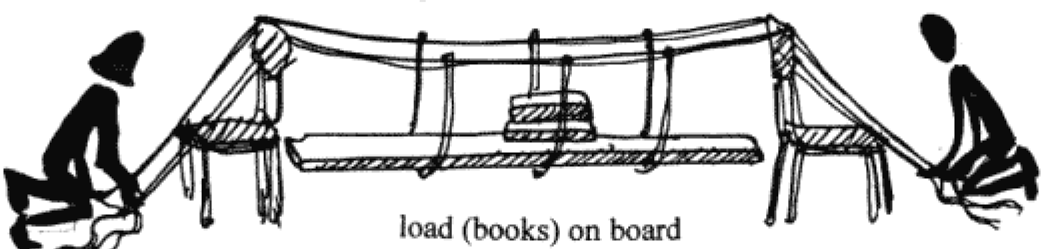


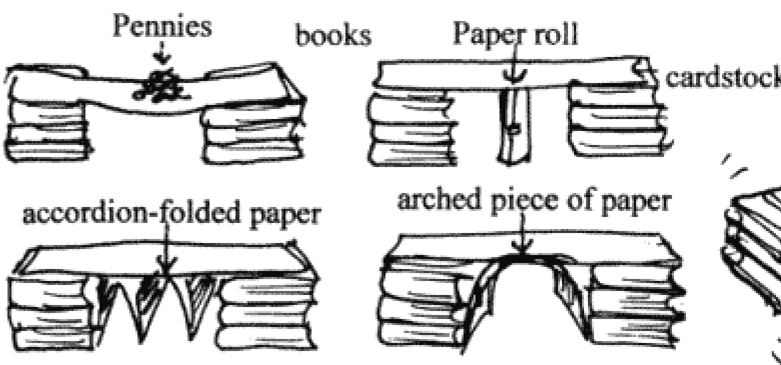
Figure 6



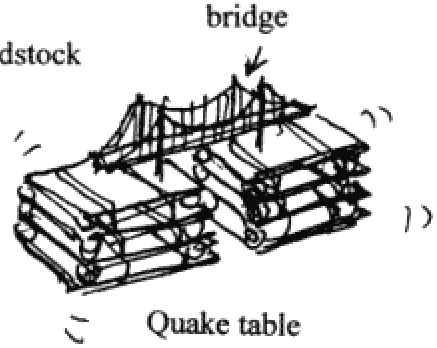
Cantilever principle

A classroom suspension bridge
Figure 7





Bridge supports **Figure 8**



Quake table
Figure 9