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Learning by Mistakes-Bridge Failures

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Introduction

"Mistakes are portals of discovery," according to James Joyce. The evolution of bridges is attributed to creativity, technology, and mistakes. Prior mistakes have facilitated the incredible bridges of today. This unit of study is intended to lead my students through these portals to discover bridges.

I am a middle school teacher for the gifted and talented students. For the past nine years, I have been fortunate to teach qualifying students in this elective semester program. One of the units I taught is architecture, in which basic bridge types are covered. This unit on bridges is written to challenge my sixth grade students with productive thinking, and creative strategies. Bridges will act as a vehicle to connect math, science, geography, history, and technology using different learning styles. Of special interest are bridges that have encountered some challenges or problems. These challenges might be due to forces within or beyond human control. Specific challenges are when a bridge has failed, collapsed, been neglected, or destroyed.

I hope that my students will not only be inspired by the subject matter and the challenges that are presented, but will also make the connection between bridges and humans. These unusual circumstances, problems, or mistakes are human errors that are a part of life. If an engineer, inspector, ship captain or general takes responsibility for a bridge's demise, then students' errors or failures may be viewed as only miniscule by comparison. Oftentimes, those students who excelled in elementary school lag behind in middle school because they do not enjoy being different. My gifted or talented middle school students struggle with peer-pressure. They are teased and feel threatened by being successful academically. For them, it is often easier or tempting not to be academically competitive. They view themselves as being able to get by with little effort or failing academically, to conform. When challenged or when mistaken, they sometimes simply give up. If I can inspire them to problem solve using bridges, be creative, and arrive at new ideas, maybe they would aspire to be engineers, scientists, humanists, or productive citizens with knowledge of their individual talents and interest.

Rationale

The appeal of bridges is a reflection of our interests in science, mathematics, art and history. The scientist is enthralled with bridges for their convergence of forces. The mathematician calculates and graphs their ability to combine stress and strain with elasticity to balance imposed loads. Bridges appeal to the artist in us by just the shear beauty and magnitude of their presence. Their size, symmetry, form, and function combine to create something significantly more than just an object of beauty. Little wonder that artists use bridges as their subjects for paintings such as Van Gogh's *The Bridge at Langlois*. The ability to build the impossible or reach the unattainable is also part of the allure. The child in each of us wonders what is on the other side of the water, or divide. If one could only cross over to the other side, what unusual things would be seen? Imagine looking down into a Himalayan gorge, while crossing a simple suspension bridge made of twisted cellulose fibers. (I believe I have gephyrophobia.) The historian can only be impressed, for like the pyramids in Egypt, early bridges (Clapper design) were built involving the movement of huge stones, constructing bridges without mortar.

This unit is created for students to capitalize on their subject interest by studying various bridges; culminating in constructing a three dimensional bridge. I hope to spark their curiosity by having them learn the history of bridges, the challenges, and the mistakes.

Objectives

In the Gifted and Talented Program I teach, the primary objective is to problem solve using inductive and deductive reasoning. By researching the history of bridges, students will be able to explain the technological achievements that have made them noteworthy. Once they possess this background knowledge each student will create a hands on project according to subject interest and construct a bridge that in some manner has failed. These activities are inductive reasoning in that each takes something that is known to find an unknown. The final activity is to analyze bridge failures and the causes. This activity is deductive because the student is taking an unknown, like why the bridges collapsed, and concluding with a known.

In lesson one; the students will review basic bridge types. They will independently research data on famous bridges, naming and locating famous bridges throughout the world. In each bridge researched they will identify the compression and tension forces. In lesson two, students will select an activity to do by subject interest. They may construct a cofferdam which is part of the bridge foundation or construct an arch. Another option is for them to make paper bridges, graphing the relationship between span and load. My artist students will paint a famous bridge. Someone who appreciates history might want to explain the role of a bridge in a famous battle. In lesson three, students will draw a two dimensional blueprint and use problem-solving skills and productive thinking to construct a three dimensional bridge. In a presentation of their bridge, they will explain why this type was chosen for a given location, the challenges it presented, and concluding with the cause for the bridge's failure. In lesson 4 students will ascertain which bridges in their area are deficient. By contacting elected officials, they will become advocates for bridge safety.

Strategies

In the *Yale Institute Seminar, Bridges: The Art and Science for Creating CommunityConnections*, our Seminar leader, Professor Emeritus of Architectural Engineering, Martin Gehner, guided a study of bridge building by examining pre-existing conditions, conceptual development, realization, and performance. Pre-existing concerns include the community, resource materials, and the environment. According to Professor Gehner, these pre-existing conditions determine the type of bridge that is built. By researching bridges, students will learn that bridges identify and connect communities. The evolution of materials used in bridges will be examined as students explore the history of bridge building. Selecting three bridges to research, the students will create a time line around the classroom. Making a flip book of one of the researched bridges, each student will examine a structure in more detail. Environmental factors will be examined as bridge failures are explored.

The conceptual development includes the design, the engineering, materials, methods of construction, and cost. As students learn about bridge types, they will learn what type of bridge design is appropriate for a given location. This relationship between location and type, as well as, various methods of construction will be addressed as students complete their flip books.

The realization includes the plans, technology, and construction. With the creation of the time line, and by culminating our study with a visual display of the bridges, students will see the evolution of the technology that bridges have achieved. They will have a first hand experience in construction by reconstructing a famous bridge.

Some of the performances examined are the functional use, environmental influence, and maintenance. Often flippant remarks are made by student's that they want to be an architect or engineer. Analyzing bridge failures will help them gain an insight into the challenges faced by engineers, and architects. Bridge failures may be caused by environmental factors, such as wind, hurricanes, or earthquakes. Failure may be due to structural or materials defects and maintenance issues. The complex variables that bridge building entails are something for all to hold in awe. Bridge failure is possible, because of the numerous variables. Yet trying to succeed at a challenging task, and sometimes failing, has to be an important life lesson. I hope to spark their curiosity by having them learn the history of bridges, channeling subject interest about bridges, and instilling appreciation of them. Challenges present accomplishments and sometimes failures, in life, as well as, in building bridges.

In summary, the student will: construct a time line to chronologically order the development of bridges and their history, create a flip book of a famous bridge including a sketch, use interdisciplinary methods to have students study one aspect of bridges including construction, science (physics), art, and history. Then they will construct a famous bridge that has had challenges and analyze the cause of failure.

Basic Bridge Information

"In civilized countries bridges are littered about the landscape in generous numbers and in a rich variety...one virtue of bridges is that both the structure and the way it works are clear for all to see" [1] By examining the history of various bridges students can see how this technology and structure has evolved. Students will see the variety of some major bridges as they are reviewed by type and materials used.

Early Bridges

"Basic bridge designs are developed from natural bridges-a tree trunk that has fallen across a stream, vines hanging over a river, or stones that make a stepping-stone path across a shallow stream." [2] From these natural bridges people undoubtedly created his own. One of the earliest types of bridges is the stone "clapper", which means "heap of stones". [3] Before 2000 B.C., it is believed early suspension bridges, floating pontoon bridges and cantilevers could be found in China. [4] These bridges were built to enable man to hunt, gather food, or trade by exploring new lands. Some early bridge achievements are found in Babylon, Egypt, and Persia. In the 7 th to 6 th century B.C. the Babylonian leaders, Nabopolassar and his son, Nebuchadrezzar II, built a bridge that crossed the Euphrates River near the Tower of Babel. It was 120 to 200 meters long with seven brick, stone, and timber piers. "The Greek historian Herodotus (c.485-425 B.C.) described how Persian King Darius I and Xerxes I connected Asia and Europe using pontoon bridges in 513 and 543 B.C. respectively" destroying the Spartans and Athenians. [5] Darius I had a pontoon bridge built across the Danube and the Bosphorus. In 480 B.C. Xerxes I, his son, crossed the Hellespont invading Greece. [6] As impressive as these bridges are, it is the Romans who refined and brought engineering into a new era.

Roman Bridge Builder

As the Roman Empire spread, roads were built to connect the lands, and bridges were built to connect the roads. They brought sophistication and engineering savvy to bridge building. Several major contributions the Romans made to bridge building are the arch cofferdams, cement, and building bridges in sections. The arch is an important contribution because it allowed the Romans to build longer and stronger aesthetically beautiful bridges that did not hinder water traffic. The arch has four essential parts: the abutment, the centering (wooden form), the voussoirs (wedge shaped stones), and the keystone. The keystone is the center stone. Arches are built from the abutments (supported sides) up. The voussoirs are added to each side, building up, and then the keystone is added, in the center, joining the voussoirs. Once the keystone is in place, the centering is removed.

Cofferdams were used as a method to build the piers for the foundation of a bridge. A bridge is only as strong as its foundation, and the cofferdam allowed for a strong foundation to be built. They were made with double walls creating a "water tight box built of piles". [7] It was built around the place to be excavated and water inside was pumped out. Cofferdams were later used in shallower water while caissons were used for deeper water. Although the Romans built some bridges without mortar, for others it was necessary. Using the volcanic ash, pozzalana, from Vesuvius, they created a natural cement by combining it with, water, and lime. This cement being waterproof was ideal for building piers.

One technique that the Romans used was sectional building. This allowed for bridges to be built from the banks out, instead of across the river and up. This process is described in the following quote:

> Roman arches were semicircular, which had important consequences. In a semicircular arch, more of the thrust goes directly downward than in a shallow arch, which in consequence requires strong side-bracing at the abutments. This meant that, if the piers were wide enough (one-third of the span), any two could support a complete arch without further propping from the sides. Thus it was possible for Roman engineers to build bridges out from the shore a span at a time-cofferdam, then foundations, then piers, then arch-rather than having to go through the much more difficult operation of putting the entire bridge substructure in position first. [8]

The Romans are also known for using stone for their bridges, but in truth, they also created wooded bridges. These wooden bridges have not survived. The oldest Roman bridge, identifiable by name, is the *Pons Sublicius* which crossed the Tiber River. Built in the 6 th century B.C., Horatius Cocles defended it against the Etruscans. "Sublica" means "pile or stack" It probably was made of wood. [9] Another wooden bridge, built in 55B.C. for military purposes, was one that Julius Caesar wrote of in *Gallic War.* It is described as a quarter mile long timber trestle bridge built in *ten days* to cross the Rhine. One stone bridge still standing is the Ponte Fabricio in Rome built in 62 B.C. This bridge connected the bank of the Tiber River with an island in the middle of the river. The distance was 200 ft. The bridge was not to impede river traffic, but to allow the infirmed access to the hospital on the island. The bridge was built with two stone arches. It allowed for ships to pass underneath and the sick to be moved across it. What made this bridge unusual were the three smaller arches in the spandrels above the center pier and the abutments, "designed to reduce weight and provide additional channels for floodwaters".[10]

Stone bridges built without mortar like the Pont du Gard in Nimes, France were built by the Romans. It is described as "the most famous surviving section of a Roman masonry aqueduct-and the highest bridge the Romans ever built-it is an extraordinary piece of engineering that combines functionality and mathematical precision with great beauty." [11] One of the largest bridges built in the Roman Empire, and still standing, is the Alcantara Bridge in Spain built by the engineer, Caius Julius Lacer (cAD100). It is a granite arch bridge crossing the Tayus River, 57 meters high, and 194 meters long, with 6 semicircular arches. It too was built without mortar. The aforementioned bridges, built in Rome, France, and Spain are prime examples of Roman contributions to bridge building. Roman beliefs in gods were so strong that before any crossing could be built the priest must be called. "The Latin *pontifex*, priest, originally meant 'builder of bridges". [12] This fact foretells the relationship between the clergy and bridges in the Middle Ages.

Chinese Bridge Builders

China has a diverse topography that necessitates different types of bridges. The Chinese were innovative in several of these designs. One such innovation came about because of a dilemma. Li Chun brilliantly solved how to build a bridge over the Xiao River in the 6 th century. A Roman semi-circular arch would not have worked. In order for it to be long enough, it would have been too high, and too heavy. He needed a new plan. More than one arch wouldn't work because the river was too fast to build a pier. So, Li Chun designed a shallow low arch 7 meters in height, with more advanced spandrels, smaller arches on either side, than those that the Roman were using. This design of a segmented arch was not seen in Europe until the 19 th century, 800 years later. [13] It received, in 1989, the International Historic Civil Engineering Landmark award by the American Society of Engineers. [14] Not only did the Chinese build improved arch bridges, they also diversified the types of bridges being built. In the book, Rivers, LiDao Yan (472-527) describes a wooden cantilever bridge in the Gansu Province built in 405-418 that is 13 meters long. [15] This design allowed for bridges to be built across wider spans. Suspension bridges that crossed gorges like the Anlan Bridge at Guan Xian in Sichuan

Province was first constructed in the 3 rd century B.C. It has been rebuilt many times, most recently in 1975 with steel cables. [16]

Middle Ages

The church built bridges, as well as, cathedrals. Some of these bridges had chapels constructed on them, such as the bridge d'Avignon which became famous as a children's song. Special monastic groups, the "Fratres Pontifices", were used to maintain and protect these bridges from thieves and robbers. These monks saw the building of bridges as symbolic for crossing over into the afterlife. People donated money to the churches for bridge construction and were promised rewards in the afterlife. The possibility is that the church began overseeing bridge building and bridge maintenance because there is evidence of human sacrifices incorporated into the foundations of early bridges! "At least one child's skeleton has been discovered immured in the foundation of a bridge." [17] Another reason the church was involved in bridge building is that it promoted trading which in turn made towns and cities wealthier. The church would benefit directly from this prosperity. Bridges also aided in communication between the church and the people, and among the clergy.

The Railroad and the Industrial Revolution

"Leonardo da Vinci and Galileo developed theories about the strength of building materials" [18] . Sadly, these and other theories were not understood until much later in history. How materials react to forces was not understood until after the Industrial Revolution. During the railroad's race to connect the east and west by rail, many types of rail bridges were built, and the loads greatly increased. Stronger and more bridges were needed quickly. After several railroad bridges collapsed the strength of materials began being studied.

The railroad was essential for the Industrial Revolution. Industry depended on the railroad to bring it materials for manufacturing and to transport the finished product to markets. Trains also accelerated the transportation of goods and people and thus helped to create this economic boom. The railroad obviously needed bridges to connect the rails. The first type of bridge the railroad used was the brick arch. In this semi-circular Roman and Medieval arch bridge, "the rise of the arch must be about half its span". [19] This formula presented several problems. From the flat ground to the bridge, the arch aspect of the bridge would force the train to rise at an incline thus the bridge would have to be "humped-back" or had to be built with a long and sloping approach. [20] Railroads could not traverse the hump. In 1837, Isambard Kingdom Bruel built a bridge with two brick arches, each arch being a 128 ft. span with a 24ft. rise across the Thames at Maidenhead. Skeptics doubted its design, but the bridge held. It is still there carrying even greater loads today. These flatter, or multiple arch bridges solved this problem and were used very successfully.

Railroad bridges in America were often made from a wood truss design. Wood was plentiful and inexpensive, with little or no transportation cost. As trains became larger, they became heavier, and a moving train would shake a wooden bridge apart, thus a stronger type was necessary. "In 1841, Squire Whipple built his first iron bridge, The *Erie Canal* Bridge in New York State, using two kinds of iron, cast iron and wrought iron." [21] Whipple became the "Father of Iron Bridges" in America. He used math to calculate the forces of tension and compression leading the way to test bridge design before construction.

The cast iron arch bridge was a great success. The cast iron beam bridge was not. Cast iron has similar properties to stone in that it has strong compression strength, but is weak in tension. It weighed less than stone, was less expensive to transport, and created less force on the abutments. Some cast iron beam bridges were built in the 19 th century, but they had to be replaced. The beam relies on tension in which the cast iron is weak. It was confused with the compression strength of the arch, in which cast iron is strong when in compression. Cast iron went out of vogue when a more economical material was found. Today steel plate girders are used for short railroad spans, and box girders made with steel plates may be used for longer beam bridges. [22]

James Finlay of Pennsylvania invented the modern suspension bridge of today in 1796. Wrought iron chains began being used after 1790. Suspension bridges were cheaper and more practical to build. The foundation required less construction, comparatively two towers to several arches or piers. Thomas Telford completed the Menai Strait Bridge in 1825. The 550 ft bridge used wrought iron chains. This type of bridge building was suspended for about 100 years because of the railroad. In England during the "Railway Mania" from 1835-1845, it is estimated that between 30,000- 60,000 bridges were built to accommodate the railroad. In other words, about 3,000-6,000 were built a year! Most of these were masonry arches. Samuel Brown constructed a rigid suspension bridge over the River Tees. It was destroyed in months because the weight of the locomotive exceeded the tensile strength of the bridge. [23] Suspension bridges were not thought to be able to carry the loads. Several hundred high tensile steel wires are now woven to make steel cables. These cables **c**onnect the roadway to the towers.

Bridges of Today

The material that most bridges today are made of is pre-stressed concrete and steel. Remember, the Romans developed concrete from volcanic ash. It began being used again in the 18 th century. [24] The advantages of reinforced concrete are that it is fire resistant, inexpensive, can be molded into desired shapes, and resists compression and tension. [25] The newest type of bridge is the cable stayed. These bridges were used to rebuild Germany after World War II because they could be inexpensively built on existing piers.

The type of bridge used for a specific site is often predetermined by the location and other environmental factors. Some of these other factors will be discussed in the later sections. A beam bridge's single span is usually 30 feet, an arch bridge spans 800-1000 ft. and a suspension bridge spans more than a mile. The New River Gorge Bridge in West Virginia is a 1700 ft. steel and concrete arch. The world's longest suspension bridge is on schedule to be completed in 2011 connecting Sicily and Italy. New bridges are often pushing the limits of physics, materials and technology.

Famous Bridges

Each of the following bridges is famous in its own right. A bridge may receive acclaim because of its longevity, or perhaps simply for its beauty. It may have been a pivotal point in a battle. It also could have set the standard in a new type of design. Most bridges, by their function, allow for economic growth, improved communication among people, and aid in travel. Whichever of the previous reasons applies to the bridges noted below, these famous bridges tell who we are. Many have become the hallmark, identifying a given location. They are our structural art. The following bridges are discussed in chronological order.

*Tarr Steps- The first is the Tarr Steps, the age of which is unknown. These types of bridges "were built by pre-historic man in both the Bronze Age and Iron Age." [26] Located in Somerset, England this bridge is known as a stone clapper. The word clapper has origins in French, Latin, or Anglo-Saxon meaning "pile of stones". [27] The piers had cutwaters to redirect the water. It is believed the devil made it because the stones were not indigenous to Exmoor. People were not to cross it, "Romans avoided it". [28] Superstition surrounded it. It is made of granite, 55 meters in length, with 17 blocks for beams.

*Xeres I- In 480 BC, Xerxes' I**,** a Persian ruler, had his army build a pontoon bridge at Hellespont. This bridge was constructed from using more than six hundred ships. Two rows of ships were configured, 360 on the Black Sea side and 314 on the other. They were tied slantwise on one side, and at right angles on the other, to create less strain. The ships were tied together with cables of flax and papyrus, and then planks were added, followed by brush, then soil. [29] The army took seven days and nights to cross it!

* The Anji Bridge- This bridge was built from 605-617. It means "Safe Crossing" and spans the Xiache River in China. It was built by architect Li Chun. Built with open spandrels, this design preceded similar European designs by 700 years. Another engineering innovation was that Li Chun "used x dove tails in vertical joints" [30] During the cold winters of construction the builders formed an ice path by pouring water and letting it freeze. Then they would be able to slide the stones from the quarry to the construction site. [31]

*The An Ping Bridge- This bridge is in the Fujian Province of China and is the world's longest stone slab clapper, bridge. It is comprised of "331 boat-shaped piers, supporting innumerable parallel stones slabs" [32] The largest of these slabs weighs 25 tons. Built from1138-1152, it was1.25 miles long. It was the longest bridge in China until 1905.

*The Bridge d' Avignon- The d' Avignon bridge was built in France from 1177 thru 1187. In 1177, Benoit, a shepherd boy, had a vision that God told him to build a bridge. When questioned by the bishop, Benoit lifted a huge stone and carried it to the river where the bridge was to be. He was told by the Bishop to build the bridge. He built it in a V shape to accommodate the spring flooding. Its elliptical arches allowed for narrower piers. The tall arches allowed for a higher narrow roadway. The height accommodated flooding. The narrow roadway made it easier to defend against enemies. It has a chapel, to St. Nicholas, that is located in the 2 nd pier. In this chapel, Saint Benoit (later canonized) is buried. The chapel was used for meeting of the clergy, as well as prayer. It was built in 10 years time and without mortar. In 1226, Louis VIII ordered it destroyed. The town rebuilt the bridge but did not do as good of a job as the original builders. Flooding in the 17 th Century partially destroyed it. Today only four arches remain.

*The Rialto Bridge- This bridge located in Venice, Italy was built from 1588 until 1591. In the 16 th century, Renaissance artists such as Michelangelo and Palladio competed to design the bridge in Venice's Grand Canal at Rialto. Antonio da Ponte's design won with a single arch bridge. The bridge has shops on each side with a road in the center. Having survived natural disasters, it still stands today as a symbol of Venice. It is a very famous landmark in Italy.

*The Coalbrookdale Iron Bridge- This bridge is located in Coalbrookdale England and was built from 1776-1779. It was the first large bridge made completely of cast iron. This bridge symbolizes the beginning of the Industrial Revolution. The 100 ft. span used screws as in wooden bridges, not bolts. When it was the only bridge to survive the flood of 1795, this new material was appreciated even more. It is still standing, but closed to traffic.

*The Britannia Bridge-Built in 1850, this bridge is in Wales. The bridge was made of two rectangular wrought iron side by side tubes. One of the biggest obstacles was putting the tubes in place. This was accomplished by floating them on pontoons during a high tide and then hoisting them up. [33] This type of bridge is a prerequisite to tube section bridges of today.

*The Brooklyn Bridge- This famous bridge crosses the East River in New York City. Bridge designer, John Roebling, a German immigrant, died of tetanus a few weeks after his foot was injured while surveying the construction site. His son, Washington Roebling, completed the job. One of the biggest obstacles was building the two towers. Another obstacle was that it took three years to build the caissons. From inspecting the foundation, W. Roebling got caisson disease (the bends or decompression illness) in 1872, which left him incapacitated. He supervised the construction from his apartment window which overlooked the site. His wife, Emily, acted as his messenger to see the job completed. Roebling "perfected the process of spinning cable wires". [34] In 1883 when completed, it was the world's longest span. It was a huge achievement and still stands as a symbol of New York, connecting Manhattan and Brooklyn.

*The Forth Bridge- This steel bridge is in Scotland. Sir Benjamin Baker and Sir John Fowler designed this bridge to withstand wind pressure five times that of the Tay Bridge (see Bridge Failures). Completed in 1890, and still in use today, this was Europe's first all steel rail bridge. It is the second longest cantilever in the world. Painted *International Orange,* it is always being repainted and checked for corrosion.

*The Tower Bridge- Completed in 1894, and located in London, its steel frame construction is covered with ornate Victorian masonry. This double lift bridge, the only movable one on the Thames, rises in 1.5 minutes. When it was first built it was criticized as "a monstrous and preposterous architectural sham". [35] Now as Eric de Mare said, that the British "have grown fond of the old fraud". It has two steel walkways on top that were closed in 1909 when anti-aircraft cannons were placed there. The walkway was reopened in 1982. [36]

*The George Washington Bridge- This bridge is in New York City was built from 1927 to 1931. A suspension bridge designed by Othmar Ammann in 1931; its span of 3500 ft. doubled the previous record. [37] The towers were supposed to be covered in masonry, but because of the Great Depression, it was left showing the metal structure of the towers. Another cost saving measure was to use the cable suspension method, instead of chain suspension. Designed with two decks, the top was to have eight lanes and two walkways the bottom was to be for local trains. In 1962 six bottom lanes where added.

*The Sydney Harbor Bridge- This bridge is in Australia. Nicknamed "the old coat hanger", it opened in 1932. Influenced by Lindenthal's Hell Gate Bridge in New York, this arch bridge was built by cantilevering out from the banks, then joined in the center. Steel cables support the deck. It is the widest bridge in the world with 4 rail, 8 traffic lanes, and a pedestrian walkway. [38]

*The Golden Gate Bridge- This famous landmark is located in San Francisco, California. It was designed by Joseph Strauss and opened in 1937. With 4200 ft. between the towers, it was the longest span in the world when it opened. Although the setting of the bridge is beautiful, the environmental challenges were harsh. The southern pier was to be built in water that was cold and deep. Caissons could not be built because the trestle roadway kept being destroyed. After several attempts were abandoned, a cofferdam was built. Architect Irving Morrow chose to paint it red.

*The New River Gorge Bridge- This bridge is in West Virginia and was completed in 1977. It is the longest arch bridge in the world. [39] It is a 1700 ft. steel deck arch. It has four lanes of traffic, 876 ft above the river.

*The Akashi Kaikyo Bridge- Located in Japan, it was completed in 1998. This bridge was built to withstand severe environmental factors. Supposedly, it can withstand gale winds, earthquakes, and tidal waves. It is built with truss supports under the roadway to decrease wind resistance. It also has dampening units in the towers that swings the bridge in the opposite direction from the wind. It is built to withstand winds up to 180 M.P.H. and earthquakes.

*The Puente del Alamillo Bridge- Designed by Santiago Calatrava, for the Expo "92 in Seville, this bridge is considered an outstanding accomplishment, in that Calatrava

combines the beauty of architecture with the necessities of design. It is 200m. long with a 58 degree backwards angular steel tower. The span is suspended with 13 twin cables.

*The Confederation Bridge- This bridge, in Canada, was built in 1997. The world's longest continuous span, made up of 44 spans, it connects the Northumberland Strait between Prince Edward Island and New Brunswick. According to Federal, criteria it must stand for 100 years as is. This bridge has to overcome the obstacle of ice to the bridge, and not "impede ice" during the spring thaws. [40] Lifestyles of the people have been changed by this bridge because they now are no longer so isolated.

The aforementioned bridges will be used to introduce students to the evolution of bridge building. Through researching these bridges, they will gain an understanding of how materials, the environment, and technology have made them possible.

Failed Bridges

The engineer, Theodore Cooper (1839-1919), wrote paper on American Railroad bridges concerning the load trains carried and discussing bridge failure. He called for" calculation of stresses material testing, and for inspection, but added that a bridge's stability was more reliant on engineers instinct than 'merely upon a theory of stresses". [41] Some estimates say that as many as 25% of bridges collapsed at the end of the 19 th century. Although there is no documentation for this statement, it shows how many bridges were failing at this time. "Many collapses were attributable to causes other than structural inadequacies, including train derailment, fires, flooding". [42] Whatever the correct number may be, it appears to be no coincidence that with the increased load of the railroads more bridges did falter. Bridge failures may be caused by flawed designs, material failure, or environmental forces. As Professor Gehner said in seminar, "The reason for failures is often in the details". Prior to construction of a failed bridge students will be given the list of bridges below and categorize them. The information below should serve as a guide.

A wonderful story about the failure of a bridge concerns The Starimost Bridge, built from 1557 to 1566. Emperor Suleyman the Magnificent had the Ottoman architect, Mimar Hajrudin, build a stone bridge across the Neretva's, "ice cold, emerald green highland river." [43] It was to replace a wooden bridge. The first attempt failed when the scaffolding was removed. After the second attempt, Hajrudin ran away from the village for fear of being beheaded if his bridge failed a second time. He hid in a cemetery, crying, and dug his own grave. Luckily, the bridge held. He was handsomely paid. It was nicknamed the "Stone Crescent". The bridge lasted until November 1993 during the Bosnia Civil War, when it was destroyed. The first attempt to build the bridge was a structural failure. The second bridge which stood, also "failed" not through any design problems but because of environmental failure due to war.

The Dee Bridge in England was the longest metal bridge of it's time. This collapse occurred because engineer, Robert Stephenson, increased the span length miscalculating the load, and thus killing 5 in 1847. This is also an example of a design failure.

The Ashtabula Bridge in Ohio was the worst railroad disaster to date. This bridge was a Howe truss made out of wrought iron. During a blizzard on December 29, 1876 the two locomotive train with eleven cars derailed. The first locomotive made it across, but the other one along with the cars fell. This collapse was blamed on the joints and the wrought iron material failing. This accident is an example of structural failure and material failure. Two of the bridge designers ultimately committed suicide.

Thomas Bouch was knighted when his Tay Bridge was completed. His achievement collapsed on Dec. 28,1879 during a storm. He based his design on old data. He miscalculated the force of the wind. This failure would be caused by environmental forces, wind, but the primary reason was a design inadequacy. The Tay Bridge in Scotland collapsed killing 75 people.

The Quebec Bridge was completed on August 29, 1907 in Canada. It crossed the St. Lawrence River. Engineer, Theodore Cooper, expanded the arms of the cantilevers from 1600 to 1800 ft. causing the southern one to bend. A telegram halting work to investigate this bending was never heeded. It collapsed killing 75 workers. Its replacement collapsed in 1916 killing 11 people. This bridge was a design failure.

Tacoma Narrows Bridge, "Galloping Gertie" was completed in 1940. Its existence lasted only about four months when vibrations caused by 42m/hr winds caused her to fall. Its failure was due to its design. The sides were solid not allowing the wind to travel through it. The sides acted as a barrier. Its deck alone was too thin, caused it to twist uncontrollably. It was replaced with a deeper bridge with truss sides. There are video images of this phenomenon which are truly amazing to watch.

The Ludendorff Bridge at Remagen, Germany was built during World War I for German troops and goods. This truss arch had two towers at either end in which guns and other goods were stored. Hitler ordered it destroyed when the Allies appeared on the other side. Germans planned to blow it up, but when detonated, it didn't blow. Allies captured bridge and within days 25,000 Allied troops crossed into Germany. On March 17, 1945 the bridge collapsed due to damages incurred during multiple attempts to blow it up.

The San Francisco-Oakland Bridge was completed in 1936. It had two spans, 230 ft. each. On October 1989, the Loma Prieta earthquake measuring 7.1 on the Richter scale occurred, lasting 20 seconds. Sixty-two people were killed when the bridge collapsed. The bolts gave way on the upper truss deck section causing it to fall onto the lower deck. This bridge collapse was due to the environmental force of the earthquake and material issues.

Built in 1967, the I-35W Minneapolis Bridge, a steel truss arch, collapsed on August 1, 2007 during rush hour. This eight lane bridge fell into the Mississippi River killing thirteen people, and injuring approximately one hundred people. As of July, 2008, the NTSB has not determined the cause of the collapse. An error in design may have been a factor. Noted for black ice forming on the bridge, concerns have been raised that potassium acetate might have played a role in the collapse.

The Sunshine Skyway Bridge crossing Tampa Bay was comprised of two steel trusses

bridges built in 1954 and 1971. It was struck by the ship, *Summit Venture*, in May 1980. The ship knocked out a 1300 ft. section of the bridge, killing 35 people. The new bridge has concrete barriers to protect it against ships. The new version is painted yellow, and was completed in 1987. It is the worlds longest cable stay bridge. It has concrete spans with cables in the middle of the roadway. It rises 190 ft. above the water to allow for water traffic.

Some bridge failures have been a result of increasing the span or load overestimating the material's strength. Underestimating environmental factors such as wind, water, or corrosion has accounted for other disasters. Outside influences, such as ship traffic and war, have also been the cause of some failures. What will be the cause of bridge failures in the future?

"According to the U.S. Department of Transportation ("DOT"), one of every eight bridges in the nation is structurally deficient. Of the 597,340 bridges in the United States, 154,101 bridges are deficient, including 73,784 structurally deficient bridges, and 80,317 functionally obsolete bridges." [44] Structurally deficient means that the bridge is in poor condition or can not handle the traffic. It might need repair or weight restrictions. If a bridge is functionally obsolete, it does not meet traffic standards. It may not have enough clearance, or the lanes may be too narrow. "Washington D.C. has the countries least safe bridges with 63% of the district's 245 bridges being either structurally deficient or functionally obsolete". [45] According to an ABC News article, 13% of U.S. bridges have the same structural defect rating as the Minneapolis Bridge that collapsed in 2007. [46] The federal government requires bridge inspection once every two years. This inspection comprises of inspection of the substructure (underwater), the superstructure (above water), and the deck or roadway. Each state with the help of the federal government is responsible for maintaining bridges. The problem will be a daunting task in the future. Interstate highways were built in the 1960's, including their bridges. With bridges at least forty years old, the problem of replacement or repairs becomes apparent. "According to DOT, more than $65 billion could be invested immediately in a cost-beneficial way, by all level of government, to replace or otherwise address existing bridge deficiencies". [47] With the current economy, it is a real challenge. The primary means of inspection has been visual observation. As a means to detect problems, it has not been found that reliable. Ultra-sound, x-ray, and impact echo technologies are a few of the resources available. Hopefully, as states improve bridge inspection, and data is collected, funds will be found.

Today the biggest challenge the United States faces is not the fear of a poorly designed bridge, but one that is deficient, old. With computer technology and the resources available, the design of a new bridge should be a safe one. What we have to fear is the old ones. Bridges are a beautiful landmark, but they also connect communities, and make our economy thrive. The challenge is to keep them safe from failure. Hopefully, our country will not have to learn from our mistakes.

Lesson Plans

Lesson 1

In the first lesson, students will learn some background knowledge about bridges. Each student will be given a copy of the Basic Bridge Information and the Famous Bridge sections of this paper. Then they will select three famous bridge names. (No two students will have the same bridge) They will be assigned to do the following: sketch the bridge, give the date constructed, the location, the type, the forces of tension and compression, and the materials used. Students will present each bridge on a 12"x 18" poster. A time line from 2000 B.C. to the present will surround the classroom. Students will order chronologically these posters on the time line.

Conclusions will be drawn as to when types and materials became available by discussing the time line. Students will then be asked to create a flip book for a specific bridge (see appendix). These books will be an explanation of some of the bridges found on the poster time line.

Lesson 2

In the second lesson students will expand their knowledge of bridges by selecting a favorite subject activity. The scientific student will study foundations and simulate how cofferdams were first constructed by the Romans. That student might prefer to demonstrate how keystones in arches work. The mathematics student may wish to graph the loads various paper beam bridges will carry. The artistic student will enjoy selecting a famous bridge to paint. The history enthusiast will enjoy studying which bridges played a significant role in a battle. The finished products will be shared with the class. Each student will describe what they have done and their results. The following is an individual description of each project.

The cofferdam will be constructed by placing a donut ring of clay into a pan with one inch of water. Then six inch dowel rods will be pressed into the clay adjacent to one another forming a circle. Next, a second ring of dowel rods or pop cycle sticks will surround the first ring. Wedge a plastic bag(s) in between the two rings. For added stability, taping the two circles might be necessary. Using a turkey baster, pump the water out of the inner circle. This was the technique the Romans used to build piers for their bridges. [48]

To demonstrate how a keystone works have the student take a swimming noodle and bend it to form an arch. Tie the ends together to maintain this shape. Looking closely, the compression on the interior and, the tension of the outer part of the arch are visible. The student will first mark and then cut the pieces of the noodle into an arch. (With teacher or parent supervision using a knife). Now for the challenge! Try to put the pieces back together on a flat surface. When the keystone is in place, lift the arch.

For the mathematics student to demonstrate the relationship between span and load, have them complete the activity for lesson 2, Paper Bridges in the appendix. Once they complete the worksheet have them graph the results. The artist student may paint any bridge of their choice. The same information presented in the poster activity in lesson one should accompany this project. The history student may construct a diorama of a famous battle. An oral presentation should include the basic facts of the bridge as well as the circumstances of the battle.

Lesson 3

In the third lesson students will construct a bridge. They will choose one from the failed bridge section of this unit. Prior to construction they will find the location using a map and "google earth". The type, length of span, body of water crossed, environmental factors, and history will be required in a report that will be presented at the conclusion of the project. Not only will each student select a bridge to study, but also they will recreate or diagram its impairment. In this part of the lesson the student will learn to appreciate the technological difficulties that have been overcome by giving them an inkling of the difficulties faced. Materials such as: balsa wood, pop cycle sticks, dowel rods, tag board, wire, fishing line, and glue guns will be provided. Additional materials may be brought from home. Each student will draw a blueprint of their bridge to scale. Using this as a pattern, they will then cut out the blueprint and trace the components to construct their bridge.

Lesson 4

In this lesson students will research bridges in their state or area. Students will make a list of which bridges are classified as structurally deficient or structurally obsolete. Have the students write the local department of transportation to inquire when bridges will be repaired or replaced. Teachers might even wish to have their student write local government leaders in support of bridge maintenance or replacement. Students will be asked to keep a log of all contacts and responses. Also included in this list will be a first hand observation of students who have witnessed bridges being repaired or constructed.

Many students today have never constructed a project that is not a kit, or model. By using everyday materials, students will learn how to solve problems while learning about bridges. After the students have completed this unit they will display their bridges and their parents will be invited for a culminating activity. Each student will describe the bridge they have built, and tell how it was constructed and the facts described in lesson three. By chronologically ordering their projects, the technological development of bridges will be reiterated as with the lesson one time line. Additionally, the activities in lesson 2, and logs from lesson 4 will be on display.

With this unit students will gain an understanding of the challenges that bridges have presented in the past as well as in the future. Through research and reasoning they will perceive that bridges in the past may have failed because of lack of knowledge. Today that knowledge is available. The obstacles today are environmental issues and the state of our aged bridges. By researching famous bridges and bridges that have failed and by pursuing hands-on activities about bridges, they will gain insight into the evolution of technology that bridges have endured. Students will learn that bridges are not only the art and science of connecting communities; they will see that they tell the history of our achievements, not failures. We will discover how to build bridges from our mistakes.

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Appendix

Activity I

Each student will research and design a flip book of a famous bridge.

Name of Bridge
Your Name
Sketch

Description of Bridge-Statistics: type, year built, history, length.

Explain why it was built. What does it connect? Predict what would happen of this bridge closed. Explain why the architect chose this type of bridge as opposed to another type.

What weather and environmental factors had to be considered before deciding on what type of bridge to build.

Interesting factsInteresting facts

Activity II Paper Bridges

This activity is designed for students to analyze the relationship between span and load in bridges.

1. Each student should measure and cut out a 2 inch by 4 inch, a 2 inch by 5 inch, and a

2 inch by 6 inch strip of tag board.

2. Using four dictionaries, stacked two each, leave a gap between the books. The distance will be determined by the edge of the tag board resting on the book's binding.

3. Using pennies as weights, count the number of pennies each span will hold. Place the pennies on the span one at a time. Repeat three times. Find the mean. Complete the chart below.

Bridge type_________

4 inch 5 inch 6 inch

Trial 1
Trial 2
Trial 3
Trial 4

4. How does the length of the span affect the load?

5. Using the tag board strips create another type of bridge span. Repeat the chart above.

6. Which bridge holds the most pennies?

Construction Project
Bridge Rubric
Name:

Assignment	Excellent(4)	Good (3)	Satisfactory (2)	Needs Improvement (1)	Incomplete (0)
Blueprint (20 pts.)					
Authenticity (20 pts.)					
Construction (30 pts.)					
Creativity (10 pts.)					
Craftsmanship (20 pts.)					

Virginia Standards of Learning

Reading

7. The student will apply knowledge of appropriate reference materials.

a. Use print and electronic sources to locate information in books and articles.
b. Use graphic organizers to organize information.
c. Synthesize information from multiple sources.
d. Credit primary and secondary sources.

Gifted and Talented Objectives for Richmond Public Schools

Investigating Skills Grades 6-8

Students will be able to collect data through observation and research, hypothesize about outcomes, uncover findings independently and draw conclusions and add design experiments to support a theory.

Reading for High Level Thinking Grades 6-8

Students will be able to select appropriate research material to support and refute their hypothesis and in preparation for effective defense of their theories.

Analysis Grades 6-8

Students will apply logical operations such as deductive reasoning, drawing inferences, comparing/contrasting and predicting outcomes and apply the appropriate terminology.

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