#4

Learning Activity #4:

Design a Truss Bridge with a Computer

Overview of the Activity

In this learning activity, we will use a specially developed software package called the West Point Bridge Designer to design a truss bridge. We will use the software to create a structural model, then run a simulated load test to evaluate the design. The load test will help us to identify members with inadequate strength. We will strengthen these members by increasing their size. Finally we will optimize the design by minimizing its cost.

Why?

Design is the essence of engineering. To learn about engineering, you must learn about design. And the only way to fully appreciate the challenges and rewards of design is to *do it*. In this learning activity, we will design a bridge, with the aid of a computer and some special software. Then in Learning Activity #5, we will do the same sort of design by hand.

Why use the computer first? The West Point Bridge Designer software allows you to learn about the *design process,* without having to worry about the mathematical calculations that would normally be required in certain phases of the process. All of the quantities you measured or calculated manually in Learning Activities #2 and #3—tensile strength, compressive strength, loads, reactions, and member forces—are computed automatically by the West Point Bridge Designer. By doing all these computations for you, the software allows you to focus on the creative part of the design process—structural modeling—and to explore many more design alternatives than you could do otherwise. Modern computer-aided design software provides essentially the same benefits to practicing engineers. Thus when you use the West Point Bridge Designer you are also learning how engineers use the computer as a design tool.

Learning Objectives

As a result of this learning activity, you will be able to do the following:

- Describe the *problem-solving process.*
- Describe the *engineering design process.*
- Explain how the engineering design process is applied to the design of a highway bridge.
- Explain how engineers use computers to enhance the engineering design process.
- Design a truss bridge, using the West Point Bridge Designer software.

Key Terms

To successfully complete this learning activity, you must understand the following key terms and concepts from previous learning activities:

truss	**deck**	**load**	**Owner**
member	**floor beam**	**internal force**	**Design Professional**
top chord	**foundation**	**tension**	**Constructor**
bottom chord	**abutment**	**compression**	**plans & specifications**
diagonal	**pier**	**strength**	**quality control**
vertical	**joint**	**failure**	**shop drawings**

If you need to refresh your memory on any of these terms, see the Glossary in Appendix D.

Information

Problem-Solving

Engineering design is really just a specialized form of problem-solving. All engineers are problem-solvers, but you certainly don't need to be an engineer to solve problems effectively.

We are all confronted with problems every day. Sometimes they are large and complicated, like deciding which college to attend or figuring out how to program your VCR. Other times they are small and simple, like deciding which movie to watch tonight. But no matter what problem you're facing, you'll solve it more effectively and more efficiently if you use a methodical process to achieve a solution. Consider this example:

A teacher has just received a new set of reference books for his classroom but has no place to put them. He asks Rush, one of his students, to put up some bookshelves as a service project. Rush is in a hurry. He has basketball practice right after class and wants to go to a movie after practice. He decides to do the bookshelf project quickly and with as little effort as possible. He goes to the local hardware store and buys a four-foot length of wooden shelving, two metal shelf brackets, and four small woodscrews. He returns to the classroom,

drills four holes in the wall, attaches the brackets to the wall with the four screws, and places the shelf on top of the bracket. Then he heads off to basketball practice. When the teacher returns to the classroom a few minutes later, he is pleasantly surprised to find that Rush has already finished the job. The teacher is immediately disappointed, however, when he notices that the shelf is too short. The reference books require six feet of shelf space, not four. But Rush never bothered to ask how large the shelf needed to be. Nonetheless, the teacher begins placing the books on the shelf. After only five or six books are in place, the screws suddenly pull out of the wall, and the shelf crashes to the floor.

The next day, the teacher asks Anne to do the job. Anne is also in a hurry, but she realizes that the best way to get a job done quickly is to do it right the first time. Before doing anything, she asks the teacher a series of questions. How many books are there? How much do they weigh? Where is the best place in the classroom for the books to be located? What color would best match the classroom décor? With the answers to these questions, she sits down and sketches three alternative solutions—a single six-foot shelf; two three-foot shelves, one above the other; and a simple three-shelf bookcase that would stand on the floor. She shows the sketches to the teacher and explains the advantages and disadvantages of each alternative. The single six-foot shelf will be least expensive but will use a large amount of wall space. The two-shelf arrangement will use less wall space, but the upper shelf will be harder to reach. The bookcase will be movable, but it will also be most expensive. The teacher decides on the two-shelf arrangement. Anne takes careful measurements and makes a final sketch of her design. She takes the sketch to the hardware store and gets the manager's recommendation on the number and types of brackets and screws required for the job. Then she brings all of the materials back to the classroom, carefully plans how she will assemble the shelves, and starts the job. She ensures that the mounting screws are driven into the wooden wall studs, so they don't pull out. Finally, when the job is complete, she carefully places all of the reference books on the shelves to ensure that they are strong enough. She adds a few extra books, just to be sure. Anne gets an A for the project. More important, she gets the satisfaction of knowing that she did the job well and, in the process, made a positive contribution to her class.

Obviously, Anne's solution to the bookshelf problem is a lot more effective than Rush's. Anne succeeds because she follows a methodical **problem-solving process**, consisting of the following seven steps:

1) **Identify the problem** – The teacher asks Anne to put up a new bookshelf.

2) **Define the problem** – Anne asks questions until she understands exactly what the teacher wants.

3) **Develop alternative solutions** – She sketches three different bookshelf configurations.

4) **Analyze and compare alternative solutions** – She determines the advantages and disadvantages of each configuration.

5) **Select the best alternative** – She presents her three alternatives to the teacher, and the teacher chooses the one that best meets his needs.

6) **Implement the solution** – Anne makes a final sketch, buys the necessary materials, obtains the advice of an expert, plans the job, and puts up the shelves.

7) **Evaluate the results** – Anne loads the bookshelves to ensure that they are strong enough.

Rush's problem-solving process can be summed up in three words: *Just do it!* This approach might work for selling sneakers but usually doesn't work very well for solving problems—especially large, complicated ones. Rush fails because he tries to solve a problem he doesn't really understand; he doesn't consider a range of alternative solutions; he doesn't acquire the necessary technical expertise to do the job; and he doesn't develop a plan before starting to work. In Rush's case, the consequences of the failure aren't too severe—a few holes in the wall and some wasted lumber. But what if Rush had been a structural engineer and the bookshelf had been a bridge? Then the consequences of his haphazard problem-solving process could have been tragic.

If Rush ever has to put up another set of bookshelves, he probably won't make the same mistakes as he did on his first attempt. But what if he needs to change the oil in his dad's car or build a deck or apply to college? Will he make the same sorts of careless errors every time he is confronted with a new and unfamiliar problem? He won't, if he learns that the problem-solving process can be applied to *any kind of problem* and can substantially improve his chances of achieving a successful solution on the *first* try.

The Engineering Design Process

Engineering design is a specialized form of problem-solving—the application of math and science to create something that meets a human need. What are the "human needs" that engineers fulfill? The products of engineering are all around us. Every building, every bridge, every highway, every car, every airplane, every electrical appliance, and every computer you have ever used was designed by a team of engineers. The many forms of technology that form the fabric of modern civilization are all products of engineering.

Yet engineering design is much more than just math, science, and technology. It is also a creative process—one requiring the ability to conceive of problem solutions that no one has previously imagined. Theodore von Kármán, an eminent scientist and engineer, expressed this sentiment perfectly when he said, "The scientist describes what is; the engineer creates what never was." [1]

Some of the finest examples of creative engineering design are the world's great suspension bridges. With their graceful cables, monumental towers, and grand scale, these structures are both beautiful and awe-inspiring. Many have become symbols of the cities in which they reside. Can you even imagine San Francisco's Golden Gate without the Golden Gate Bridge; or New York City's East River without the Brooklyn Bridge? Yet there was, in fact, a time when each of these great bridges existed only in the mind of an engineer. Indeed, the real creativity in the design of the Brooklyn Bridge lies not in its physical appearance, but in the ability of its designer, John Roebling, to envision this spectacular structure, even though nothing like it had ever been attempted before.

How does a great bridge come to be? How is the engineer's dream translated into a steel and concrete structure carrying tens of thousands of vehicles per day? The answer lies in the *engineering design process*—a systematic approach that engineers use to create technological solutions to problems.

THE NEED

Project Planning Stage
1 Needs Analysis
2 Development of Conceptual Alternatives
3 Selection of the Preferred Alternative

Design Stage
4 Preliminary Subsystem Selection
5 Detailed Subsystem Analysis
6 Detailed Subsystem Design

Construction and Operation Stage
7 Procurement
8 Construction
9 Operation and Maintenance

As it is depicted here, the engineering design process consists of nine distinct phases, grouped into three major stages—*project planning, design,* and *construction and operation.* This diagram is intended to illustrate the process in a general way. It applies equally well to the design of a skyscraper, a car, or a stereo system. But to see what actually happens in each phase, let's apply this process to a specific example—the planning, design, and construction of a major highway bridge.
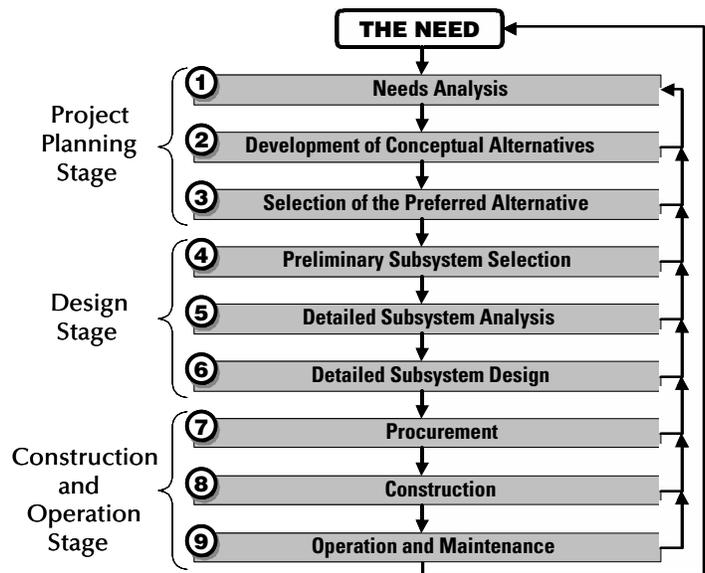
[1] Quoted in A. L. Mackay, Dictionary of Scientific Quotations (London: Adam Hilger), 1991.

Bridge Design

The Project Planning Stage

Let's imagine that a state Department of Transportation (DOT) decides to route a new highway across a major river. The DOT has initiated the engineering design process by identifying a **need** for a new highway bridge. To meet this need, the department hires an engineering firm to design the structure. The DOT is acting as the Owner for the project. The Design Professional is a senior structural engineer from the engineering firm—a woman named Anne, who first became interested in engineering when her high-school teacher asked her to put up a set of bookshelves in the classroom many years ago. Anne assembles the Design Team, whose members include structural, transportation, geotechnical, hydraulic, and environmental engineers from the firm, as well as other technical specialists hired as consultants for this particular project.

The project planning stage begins with a **needs analysis** (Phase 1 on the diagram on the previous page), in which the Design Team and the Owner work together to define the project requirements and constraints as fully as possible. The needs analysis includes a determination of:

- the proposed location of the bridge,

- the amount of vehicle traffic it can be expected to carry,

- the number of traffic lanes required,

- aesthetic requirements for the completed structure,

- the laws and regulations that will affect the design, and

- the project budget.

As part of the needs analysis, the Design Team also conducts a thorough site investigation, aimed at determining such factors as:

- the width and depth of the river,

- the potential for ice buildup in winter,

- the height and slopes of the river banks,

- the type of soil and the depth to good foundation material—like strong rock,

- the conditions at the proposed location of the **approaches**—the roadways leading up to the ends of the bridge,

- the amount of boat traffic in the river,

- the required width and height of the navigation channel in the river, and

- the potential environmental impact of the structure.

Once the **needs analysis** is complete, the **development of conceptual alternatives** (Phase 2) begins. During this phase, the Design Team develops a range of distinctly different alternative bridge types and configurations. These alternatives are analyzed and compared, with the ultimate objective of selecting the bridge type that is best suited to the needs of the Owner and the characteristics of the site.

The development of conceptual alternatives is heavily influenced by the needs analysis. For example:

- If the river is very deep at the crossing point, it will be difficult and expensive to build piers in the water. In this case, a long-span structure with fewer piers is called for.

- Even if it is feasible to put piers in the river, their locations may be dictated by government regulations governing the width of the navigation channel for boats.

- Such constraints on the locations of the piers will often determine the required span length of the bridge. And the required span length often has a major influence on which bridge configuration is most economical. (See the sidebar at right.)

- The height and steepness of the riverbanks can also influence the selection of the bridge type. High, steep banks might favor the use of an arch bridge. Low-lying banks might require the construction of ramps on either end of the bridge, in order to raise the structure to an adequate height over the water. But the feasibility of building long ramps will depend on how much development—buildings, streets, factories, and so forth—exists along the shoreline at the proposed bridge location.

- Often the Owner will want the bridge to cost as little as possible. Even if minimizing cost is *not* an objective, however, keeping the construction cost within the project budget is essential. Thus the financial constraints identified during the needs analysis are critical to the development of conceptual alternatives.

- Sometimes the Owner places a high value on aesthetics and is willing to pay extra for a visually appealing structure. This might be the case, for example, if the bridge is to be located in a downtown waterfront area, where improving residents' quality of life and promoting tourism would be important design requirements.

- Sometimes aesthetic considerations will *require* the use of a certain bridge type, even if it is not as efficient or economical as other alternatives. For example, sometimes an older bridge becomes functionally inadequate (even if it is still structurally safe) because its roadway does not have enough lanes to handle modern traffic demands. In such cases, a new bridge is often built immediately adjacent to the older one, so that each bridge carries several lanes of traffic. When a new bridge is built adjacent to an older one, the new one is often designed to look identical to the older one—even if a different configuration might be more efficient.

On an Actual Bridge Project

Which bridge type is most economical?

Different types of structures tend to be most economical for different span lengths. For very long spans of 3,000 feet or more, suspension bridges are generally used. For spans of 1,500 to 3,000 feet, cable-stayed bridges are becoming increasingly popular. Various types of arch bridges and cantilever trusses are often most economical for spans in the range of 1,000 to 2,000 feet, while beam bridges and truss bridges are most common for spans under 1,000 feet. For excellent descriptions of these bridge types and how they work, see David Macaulay's beautifully illustrated book Building Big (Houghton Mifflin, 2000).

Suspension Bridge

Cable -Stayed Bridge

Cantilever Truss Bridge

Arch Bridge

Tied Arch Bridge

Truss Bridge

Beam Bridge
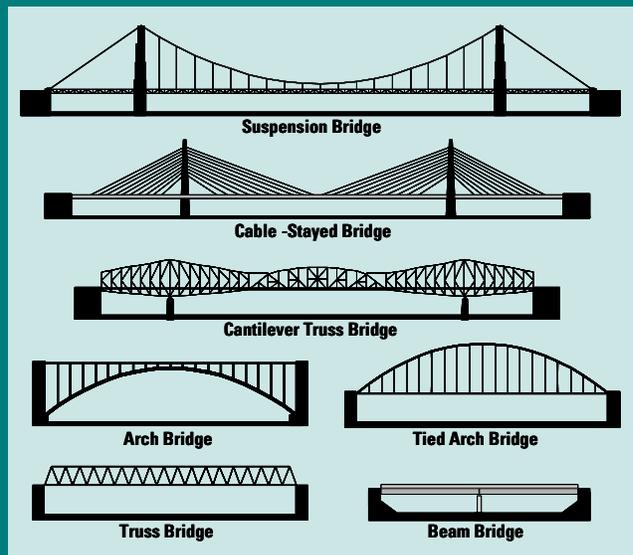
These examples demonstrate that developing conceptual alternatives to meet a particular set of project requirements is not an easy task. During this phase, the Design Team doesn't have the time or resources to do detailed design work. Conceptual alternatives are only developed in enough detail (1) to ensure that the completed structure will meet the Owner's needs and (2) to perform a reasonably accurate cost estimate. In this phase, the designer's experience may be more important than any other factor in determining which project alternatives are feasible and which are not.

At the conclusion of this phase, the Design Team often produces a report called a **type study**. The type study describes the alternative bridge configurations that were considered by the designers. It explains the advantages and disadvantages of each and provides the Design Professional's recommended alternative. This recommendation is based on thorough consideration of many criteria, including:

■ How well the design satisfies the Owner's requirements,

■ construction cost,

■ constructability,

■ expected duration of the construction project,

■ environmental impact,

■ community impact,

■ requirements for obtaining land and legal rights-of-way,

■ traffic safety, and

■ aesthetics.

The type study is presented to the Owner, who may accept the designer's recommendation or opt for one of the other alternative configurations. The Owner's **selection of a preferred alternative** (Phase 3) is the final phase of the Project Planning Stage. The product of this phase—the selected alternative—is called the **conceptual design**.

In our example project, the width of the river at the proposed bridge site is 2000 feet. The river is quite deep, so all piers and abutments must be placed on the shore. The riverbanks are low and flat. Based on these considerations and the Owner's requirements, the Design Team develops three alternative bridge configurations—a truss, a tied arch, and a cable-stayed bridge. Each will have a main span of 2000 feet, and each will carry six lanes of traffic. The Design Team's preliminary cost analysis indicates that the cable-stayed bridge will be least expensive. The Owner has also expressed a preference for the appearance of the cable-stayed structure. In considering the other selection criteria, the designers find that none of the three conceptual alternatives has a clear advantage. Thus the Design Professional's type study recommends the cable-stayed bridge, and the Owner accepts her recommendation.

The Design Stage

With the conceptual design complete, the Design Stage begins. A major highway bridge is an enormously complex system. The Design Team deals with this complexity by breaking the large system into a series of smaller, simpler components or **subsystems**. For our cable-stayed bridge, these subsystems might include the towers, the foundations, the deck, the main beams supporting the deck, the cables, the highway approaches, the electrical lighting system, the toll plaza, and the landscaping of the site—to name only a few. Responsibility for each subsystem is assigned to technical specialists with expertise in that area. For example, structural engineers will work on the towers, deck, beams, and other structural elements; geotechnical engineers will have responsibility for the foundations; transportation engineers will be assigned to handle the highway approaches and the geometric layout of the toll plaza.

The Design Stage begins with the **preliminary selection of subsystems** (Phase 4). Here the technical specialists decide what types of subsystems best meet the needs of the project. For example, the structural engineer decides whether to use steel or reinforced concrete for the towers. The geotechnical engineer decides whether to use **spread footings** or **piles** for the foundations. (See the sidebar at right.) At this point, the subsystem selections are only tentative. They might be changed later, depending on the results of the two succeeding phases.

The remainder of the Design Stage consists of the **analysis** and **design** of these subsystems (Phases 4 and 5). Analysis and design are *not* distinct, sequential phases. Rather, they form a cycle, which usually must be repeated numerous times before a satisfactory design solution is reached. Each repetition of the analysis-design cycle is called an **iteration**.

In our example, Anne, the structural engineer, has decided to use concrete towers, similar to the ones used on the Sunshine Skyway Bridge pictured below. On the first iteration, she models the structure, then she *analyzes* it to determine how much compressive force each tower will be required to carry. Based on these analysis results, she *designs* the tower. She determines the overall dimensions, the type of concrete, and the amount of steel reinforcement required to safely carry the load. Yet part of the load that the tower must carry is its own weight, which can't be calculated accurately until the exact dimensions of the tower have been determined. Since these dimensions weren't known when the initial structural analysis was conducted, the loads Anne used for this first iteration could only have been a rough estimate. Once she completes the first iteration, she determines the dimensions, and then re-calculates the loads with greater accuracy. But since the loads have now changed, a new structural analysis is necessary. The analysis results from this second iteration will be somewhat different from the previous results; thus, in the second design iteration, Anne might need to change the dimensions of the tower again. New dimensions will cause the loads to change again, and yet another analysis will be necessary. If it seems that these cycles of analysis and design will go on endlessly, don't worry! With each new iteration, the differences between the new loads and the previous ones get smaller and smaller. After several cycles, the differences become insignificant, and no further iterations are necessary.

On an Actual Bridge Project

Spread footings or piles?
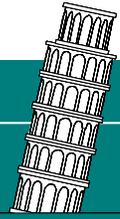
The purpose of a foundation is to distribute the weight of a structure (and all the loads acting on it) to the soil on which the structure rests. Without a well-designed foundation, the structure will settle excessively and might even collapse.

The type of foundation used for a particular structure depends primarily on the quality of the soil below the surface of the ground. If there is good firm soil or solid rock relatively close to the surface, the geotechnical engineer will typically choose a spread footing—a flat slab of concrete placed directly on the firm soil or rock. However, if the soil near the surface is soft, the bridge will probably need to be supported on piles—long steel or concrete shafts that are driven down through the soft soil layers and into firm soil or rock below

Pier or Abutment
Spread Footing
Soft Soil
Firm Soil

Pier or Abutment
Pile Cap
Pile
Soft Soil
Firm Soil
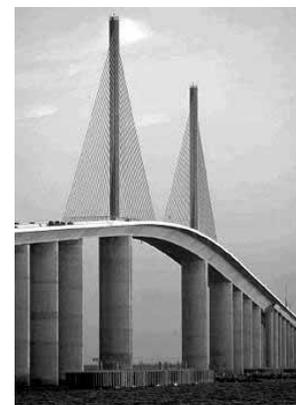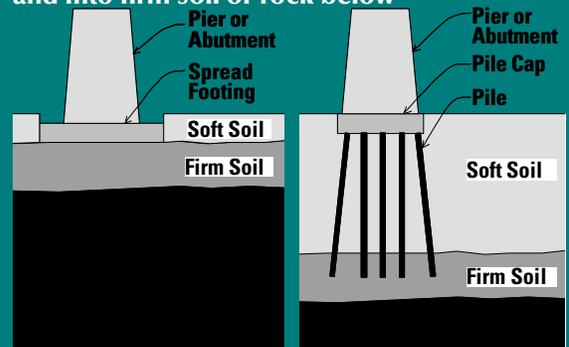
Throughout the Design Stage, analysis-design cycles are conducted for each of the bridge subsystems. Because most of these subsystems are interconnected, changes in one often affect the design of others. For example, as the structural engineer's estimate of the weight of the towers changes, the geotechnical engineer will need to modify the design of the tower foundations accordingly. Even though the Design Team members are all working on different parts of the project, they must work closely together to ensure that their subsystem designs are well integrated.

As the upward arrows on the design process diagram suggest, iterations can occur at *any* phase of the design process, not just between Phases 5 and 6. During the development of conceptual alternatives, the Design Team may identify shortcomings in the needs analysis that must be rectified. When presented with the completed type study, the Owner may decide that none of the conceptual alternatives are acceptable and send the designers back to drawing board to develop new ideas. Sometimes, analysis reveals that a previously selected subsystem won't work or that an alternative subsystem will work more efficiently. In each of these situations, the engineering design process takes one or more steps *backward*, then resumes with a new design requirement, a new alternative, or a new subsystem. But these apparent setbacks should not be regarded as failures. They are inevitable and, indeed, they are desirable, because they often result in a better solution to the problem at hand.

As the Design Stage progresses, the Owner often uses formal **design reviews** to monitor the conduct of the design process. Through this management technique, the Owner ensures that the design is progressing on schedule and the project requirements are being addressed. To conduct a design review, the Owner requires the Design Professional to submit a complete draft of the design—drawings, reports, and draft specifications—at certain specified levels of completion. For example, the Owner might require design submittals when the work is 30%, 60% and 90% complete. The Owner—in this case, the Department of Transportation—reviews each submittal and provides written comments back to the Design Professional. Members of the Design Team are expected to address each of these comments in subsequent design submittals, to ensure that the DOT is 100% satisfied with the completed design. The Design Stage concludes with the delivery of a complete set of **plans and specifications** to the Owner.

The Construction and Operation Stage

During this final stage of the engineering design process, the Owner selects a Constructor, the Constructor builds the bridge, and the completed structure is placed into service. The **procurement** phase (Phase 7) begins with the selection of a Constructor. In the United States, this selection is normally done by competitive bidding—a process called **design-bid-build project delivery**. Design-bid-build project delivery generally works like this:

- The Owner advertises the project through public notices and ads in industry publications.

- Construction contractors obtain copies of the plans, specifications, and other bidding documents from the Owner.

- Construction contractors prepare and submit their bids. A **bid** is the contractor's estimate of how much it will cost to construct the bridge. In submitting a bid, the contractor is saying, "I can build this structure for x dollars." To ensure the fairness of the process, bids are always submitted in sealed envelopes.

- On a designated day, the Owner conducts a **bid opening**. In a public meeting, all bids are opened and read aloud. Each bid is checked to ensure that it includes all required information and that the bid amount is not unreasonably low. A bid that meets these conditions is called *responsive* and *responsible*.

- The Owner awards the construction contract to the lowest responsive, responsible bidder. This contractor becomes the Constructor for the project.

It is important to note that design-bid-build is not the *only* form of project delivery available to Owners. An alternative called **design-build project delivery** is becoming increasingly popular in the U.S. and is, in fact, the norm outside of the U.S. Design-build project delivery is described in Learning Activity #5.

Once the contract is awarded, the Owner issues a **notice to proceed**—an official authorization to start work on the project. But even after the notice is issued, the Constructor has a lot of things to do before construction can actually begin. These include hiring sub-contractors, preparing a construction plan and a project schedule, setting up the construction site, establishing jobsite safety and quality control procedures, ordering materials, and preparing shop drawings.

Once **construction** (Phase 8) actually gets underway, the contractor builds the bridge—much as you did in Learning Activity #1—along with all associated highways and facilities. The overall objective of the construction phase is to complete the project on time, within the Owner's budget, and to the level of quality required by the plans and specifications. The Design Team typically has only minimal involvement in this phase. The design engineers usually review the Constructor's shop drawings and are often called upon to respond to the Constructor's requests for information, as unforeseen circumstances are encountered on the construction site.

Finally, after many months of design and construction, it is Opening Day for the new bridge. A brass band plays, and the Commissioner of Transportation makes an inspirational speech. The Governor cuts the ribbon, and a wave of traffic surges forward across the span. The crowd cheers. The bridge is complete, and every member of the Project Team takes a moment to revel in their accomplishment. But only a moment! Back at the office, a new project—a new challenge and a new opportunity to serve society—is waiting.

Ideally, the nine-phase engineering design process concludes with many years of conscientious **operation and maintenance** (Phase 9) by the Department of Transportation. Trained technicians carefully inspect the entire structure every two or three years, looking for signs of deterioration and identifying needed repairs. Maintenance crews regularly clean the storm drains and expansion joints, repaint weathered steel, and repair cracked asphalt. As a result of this modest investment in routine maintenance and repair, the bridge might serve its purpose safely and effectively for a century or more. Ultimately, of course, the structure will become obsolete, or the cost of maintaining it will exceed the cost of building a new bridge. At this point, there is a **need** for a replacement bridge, and the design process begins all over again with Phase 1.

Unfortunately, bridges are often not effectively maintained. Sometimes bridges are placed into service then simply forgotten. More often, state and local governments have well-designed inspection and maintenance programs in place but don't receive enough funding to perform needed repairs. But trying to save money by cutting back on bridge maintenance is "penny wise and pound foolish." Bridges that are not maintained deteriorate rapidly, resulting in the need for expensive rehabilitation or replacement projects. Such projects ultimately cost far more than routine maintenance programs, especially considering the hidden costs associated with closing down major highways for months at a time, while bridges are rehabilitated or replaced.

Computer-Aided Design

Few things have revolutionized the engineering design process more that the widespread availability of computers and various forms of computer-aided design (CAD) software. CAD software provides designers with incredibly powerful tools for drawing, modeling, analyzing, and evaluating engineered systems. Specifically, modern computer-aided design programs enhance the design of bridges in the following ways:

- Using CAD software, an engineer can create accurate two-dimensional and three-dimensional drawings of a bridge. As the design evolves, CAD drawings can be easily updated. Hand-drawn plans must be redone from scratch every time the design changes.

- CAD provides the capability to accurately visualize a completed structure, long before the first shovel of soil is turned or the first batch of concrete is poured. Thus CAD can be used effectively in the development of conceptual alternatives (Phase 2) and in the presentation of alternatives to the Owner (Phase 3).

- Some CAD software provides the capability to create a highly accurate structural model, then analyze the structure to determine its internal forces, then automatically select steel or concrete members strong enough to carry these forces. As such, CAD can substantially increase the efficiency of Phases 5 and 6 in the design process. By expediting the analysis-design cycle, CAD makes it possible for the engineer to explore a wider variety of design alternatives and thus achieve greater efficiency and lower cost.

- Because computer-generated designs can be saved in electronic form, CAD gives teams of engineers unprecedented capability to share design information via computer networks and the Internet. This capability allows the members of the Design Team to coordinate their efforts across the office or across the globe.

With their ease of use, realistic graphics, and incredible computational capability, CAD programs sometimes make us think that human engineers have become obsolete. But nothing could be farther from the truth! Like the electronic calculator and the slide rule before it, like the T-square and the draftsman's scale, CAD software is only a tool. Like any tool, it can improve human efficiency, but it can never substitute for human creativity and good judgment. And like any tool, CAD can be misused. Some aspects of structural modeling and design simply cannot be automated. They require in-depth understanding of engineering principles, an appreciation for constructability, and good old-fashioned common sense. Designers who use CAD software as a "black box"—a problem-solving tool whose inner workings they do not fully understand—are toying with disaster, because they have no basis for assessing whether or not the computer's answers make sense. More than one experienced engineer has said, "Never use the computer for a task that you can't already do by hand."

The West Point Bridge Designer

The **West Point Bridge Designer** is a computer-aided design program developed to introduce you to the engineering design process and to demonstrate how engineers use the computer as a problem-solving tool. The software will enable you to create a structural model of a truss, then run a simulated load test to determine if the structure can safely carry its applied loads—its own self-weight and the weight of a standard highway truck loading. In effect, the West Point Bridge Designer does automatically what we did manually in Learning Activity #3. The only difference is that the projects provided in the West Point Bridge Designer are full-sized bridges made of steel, while the project provided in Learning Activity #3 is a model bridge made of cardboard.

The West Point Bridge Designer attempts to mimic the "look and feel" of an industry-standard CAD program, but with a simpler user interface that allows fewer opportunities for errors. Ease of use is achieved primarily by using seven built-in design projects. Once you have selected a project, the software automatically establishes the scale of the drawing, the bridge supports, and the drawing grid. You can begin creating your structural model immediately, using a few simple drawing and editing tools. With a standard CAD program, you would have to define the scale, supports, and grid by yourself, and you would be confronted by an overwhelming array of drawing and editing tools. The very characteristics that make standard CAD software so powerful and flexible also make it seem complex and intimidating to new users.

The Bridge Designer helps prevent errors by allowing you to place joints only at pre-defined grid points, by requiring you to draw members from joint to joint, by allowing member properties to be selected from drop-down lists, and by providing truss templates to guide your creation of a stable structural model.

The most important feature of the West Point Bridge Designer is its simulated load test. Once you have created a complete, stable structural model, you can run the load test with the click of a single button. When you initiate the load test, the software will perform the following actions behind the scenes:

- Create supports at the appropriate locations in your structural model.

- Calculate the weight of all members, and apply these forces to the structure as loads.

- Calculate the weight of the concrete bridge deck, asphalt road surface, and floor beams, then apply the corresponding loads to the structure.

- Apply a standard AASHTO H20-44 truck loading to the structure at multiple positions, representing the movement of the truck across the bridge. AASHTO is the American Association of State Highway and Transportation Officials, an organization that develops design codes and specifications for highway bridges in the United States. The H20-44 truck is a vehicle with two axles spaced 4.0 meters apart. The front axle weighs 35 kilonewtons (kN), and the rear axle weighs 145 kilonewtons (kN). These axle weights are further increased by a *dynamic load allowance* of 33%, to account for the effects of the moving load. This means that a moving truck causes about 33% higher internal forces in the truss members than a stationary truck would cause.

35 kN   **145 kN**
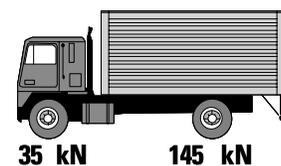
- Check the structural model for stability. If the structural model is unstable, the West Point Bridge Designer will stop the load test, inform you of the problem, and provide some suggestions for fixing it.

- Perform a structural analysis, considering the combined effects of the bridge self-weight and truck loading. For each truck position, the software calculates the displacement of each joint and the member force for each member in the structural model.

- For each member, compare the calculated member forces for all truck positions, and determine the absolute maximum tension force and the absolute maximum compression force. These are the critical forces that determine whether a given member is safe or unsafe.

- Calculate the tensile strength and compressive strength of each member, using standard AASHTO strength equations.

- For each member, compare the absolute maximum tension force with the tensile strength, and compare the absolute maximum compression force with the compressive strength. If the force exceeds the strength in either case, the member is unsafe; if not, the member is safe.

- Display the load test animation.

The results of the load test are provided in a variety of different forms, both numerical and graphical. As you will see in this learning activity, the load test results will help you to strengthen any unsafe members and to optimize your design to minimize its cost.

Q1

What portion of the engineering design process does WPBD address?

When you use the West Point Bridge Designer to design a truss, what phases of the nine-phase engineering design process are you doing?

The Learning Activity

The Problem

The Need

With the success of the Grant Road Bridge project, the Town Engineer of Hauptville has decided to replace several other obsolete bridges in the town. The first of these is an old concrete beam bridge that carries Lee Road over Union Creek, a short distance from the Grant Road Bridge. The old bridge will be demolished and replaced with a more modern structure. The Town Engineer is very satisfied with the work done by Thayer Associates on the Grant Road Bridge, so he hires this firm to design the new Lee Road Bridge as well.

Design Requirements

The Hauptville Town Engineer works closely with civil engineers from Thayer Associates to develop the following design requirements for the bridge:

- The new bridge will be constructed on the abutments from the old structure. These existing supports are 24 meters apart.

- The bridge must carry two lanes of traffic.

- The bridge must meet the structural safety requirements of the AASHTO bridge design code.

- For consistency with the nearby Grant Road Bridge, the new structure should be a truss. It is not necessary for it to be a Pratt Through Truss, however.

- The bridge will be made of steel.

    Because of the limited project budget, it is essential that the new bridge cost as little as possible.

Your Job

You are a structural engineer employed by Thayer Associates. You are assigned to design the main trusses for the Lee Road Bridge. Your responsibility is to design trusses that are safe, that satisfy all of the other design requirements, and that cost as little as possible.

The Solution

The Plan

Our plan to design the Lee Road Bridge is depicted in the flowchart on the following page. Each rectangle in the chart represents one step in the design process. The arrows indicate the order in which the steps should be performed. The diamonds represent decision points. When you reach one of these, your next step will depend on the answer to the question.

Start

**Select a
Design Project**

**Decide on a
Truss Configuration**

Draw Joints

Draw Members

**Load Test
Your Design**

**Are
Any Members
Unsafe
?** — yes → **Strengthen
Unsafe Members**

no

**Are the
Member Selections
Optimum
?** — no → **Optimize Selection
of Members**

yes

**Is the
Shape
Optimum
?** — no → **Optimize the
Shape of the Truss**

yes

**Is the
Configuration
Optimum
?** — no → **Try a New Truss
Configuration**

yes

Choose the Optimum Design

Record Your Design

Start the West Point Bridge Designer

To run the West Point Bridge Designer, click the Windows **Start** button, then select **Programs**, then **West Point Bridge Designer**, and finally **WPBD4.exe**. Read the Tip of the Day, then click the **OK** button to close it. At this point, you'll see the Welcome screen. Ensure that the **Create a New Bridge Design** option is selected, and click **OK**.

Select a Design Project

The Drawing Board Setup Wizard is now displayed, and you are prompted to select a design project. The Lee Road Bridge has a span of 24 meters, so select the **Single Span Truss (24 meters)** option, and click the **Next** button.
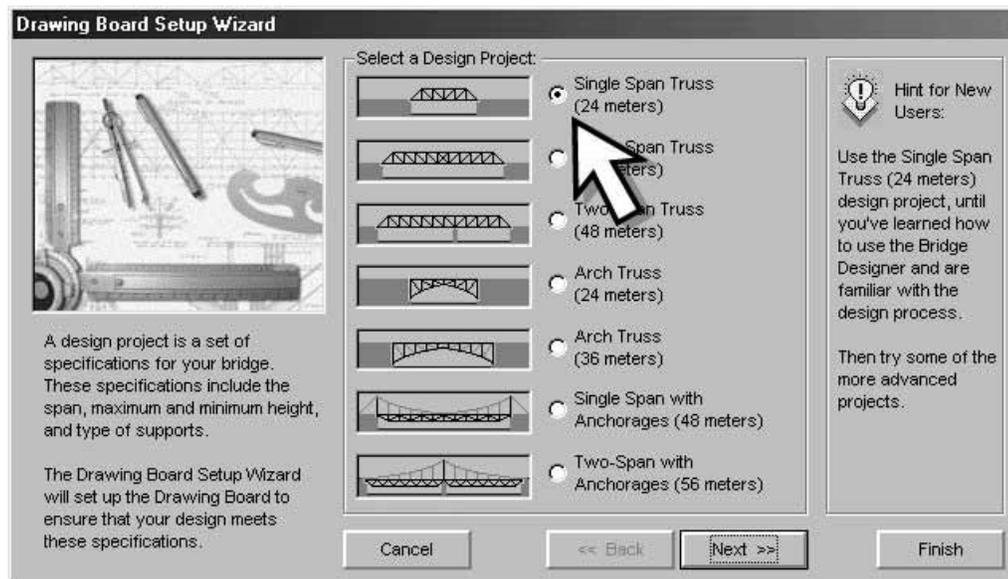
Decide on a Truss Configuration

The West Point Bridge Designer will allow you to create virtually any truss configuration (including statically indeterminate ones), as long as the resulting structural model is stable. But determining whether or not a configuration is stable can sometimes be tricky. Until you've gained some experience, it's best to start with a simple, standard configuration—like the Pratt, Howe, or Warren truss. The West Point Bridge Designer provides *templates* for a variety of different standard truss configurations. If you use a template, the locations of all joints and members for the standard truss you selected will be displayed with light gray lines on the Drawing Board.

The Drawing Board Setup Wizard now prompts you to select a template. Choose the **Pratt Through Truss**, and click **Next**.
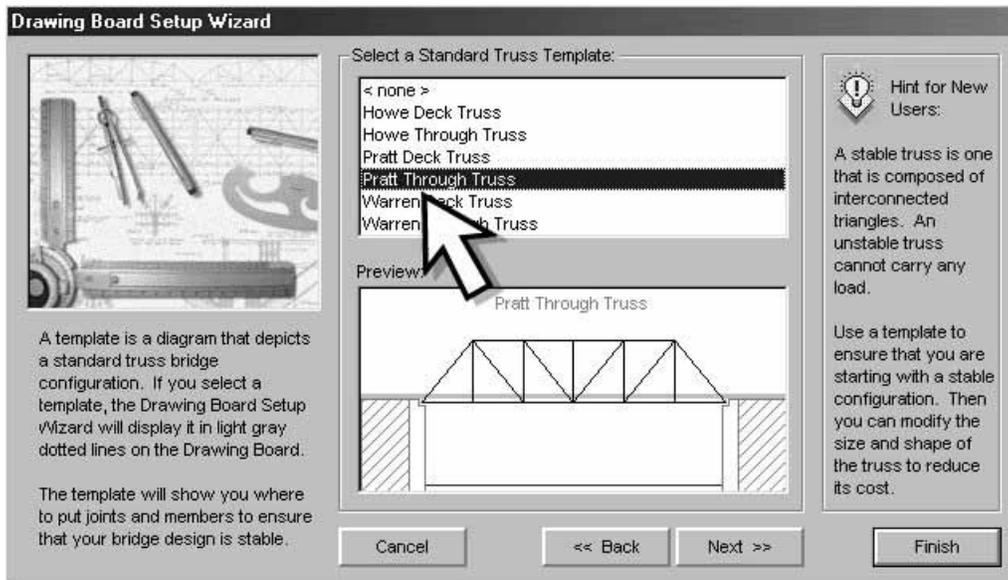
Now enter your name in the **Designed By** box and, if you like, add a **Project ID**. The Project ID is a name or number you assign to your design for future reference. If you are planning to try a variety of different design alternatives, the Project ID is a good way to keep track of them. Both your name and the Project ID will appear in the Title Block on the Drawing Board and are also included on the hard-copy printout of your design.
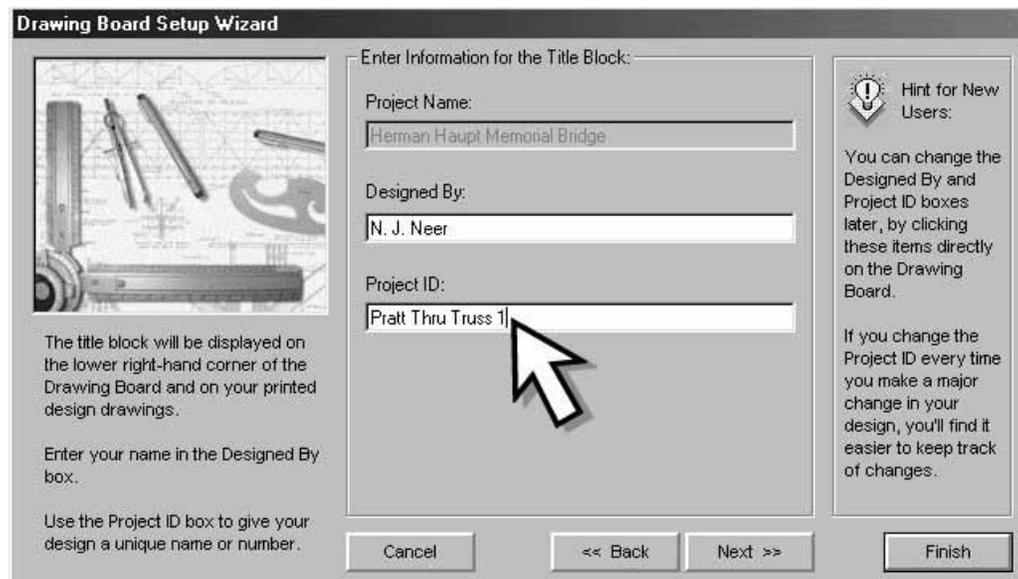
Click **Next**, then **Finish**. The Drawing Board Setup Wizard disappears, revealing the Bridge Design Window—the graphical environment in which you will create, test, and optimize your design. The Bridge Design Window includes the following major elements:

- Menu bar and Toolbars – Commands for creating, modifying, testing, recording, and reporting a bridge design.

- Drawing Board – The portion of the screen on which you will draw joints and members to create a structural model.

- Design Tools palette – Special toolbar containing tools that are used to create and modify a structural model on the Drawing Board.

- Rulers – Guides that show the vertical and horizontal dimensions of the structural model.

- Title Block – Portion of the Drawing Board displaying the designer's name and Project ID.

- Member List – List of all members in the current structural model, normally hidden on the right-hand side of the Drawing Board. (The Member List can be displayed by dragging it to the left with your mouse).
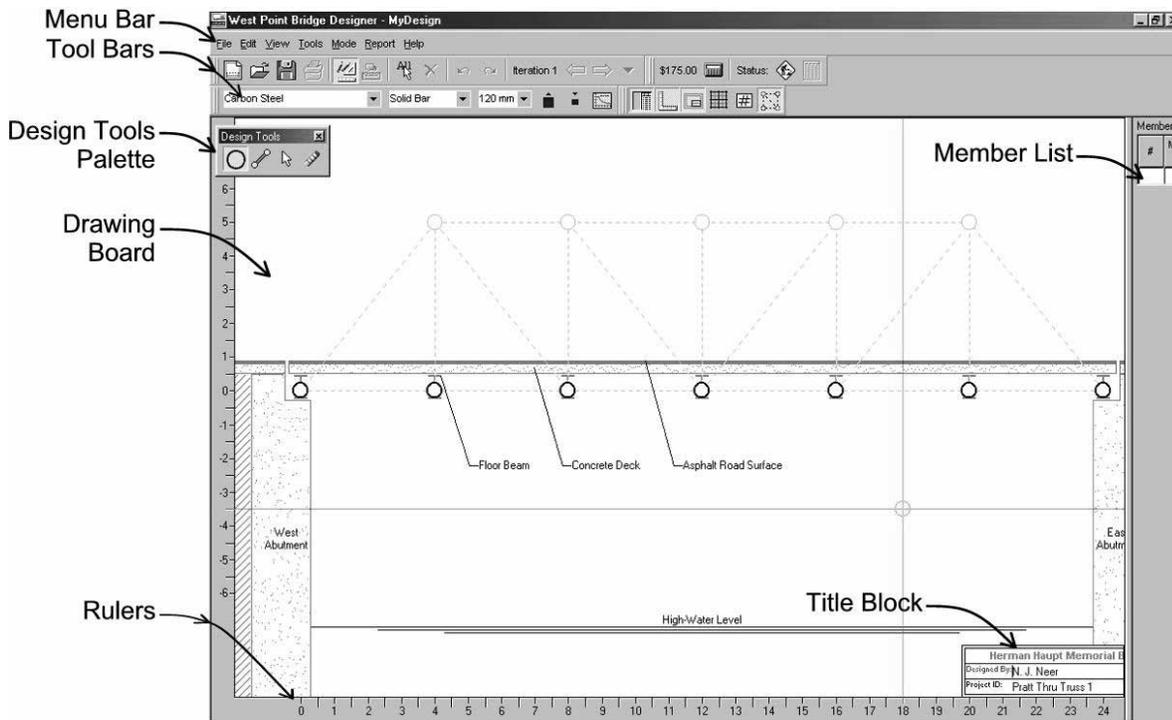
The Drawing Board already shows those portions of the bridge that you *will not* be designing—the abutments, the floor beams, the concrete deck, and the road surface. Note also that the first seven joints in the structural model have been created automatically. They are located at the points where the floor beams are attached to the main truss. Since the positions of the floor beams are fixed, these seven joints cannot be moved or deleted. The Drawing Board also displays the configuration of a Pratt Through Truss, marked with light gray lines. This is the template you selected earlier.

Note that the Design Tools palette has four available tools—the **Joint Tool**, the **Member Tool**, the **Select Tool**, and the **Eraser Tool**. The **Joint Tool** should already be selected.

Draw Joints

With the Drawing Board setup completed, we can begin creating our structural model by drawing **joints** and **members**. We'll begin with the joints. The Drawing Board Setup Wizard has already created the first seven joints automatically. You must create five more—the five joints that lie along the top chord of the truss. The light gray circles in the template show where to put them.

To draw a joint, use your mouse to position the red cross-hairs at the desired location, then click the left mouse button. Repeat this process for all five joints.

TIP

The red cross-hairs allow you to position joints accurately, using the Rulers along the bottom and left side of the Drawing Board.

When you're done, the structural model should look like this:
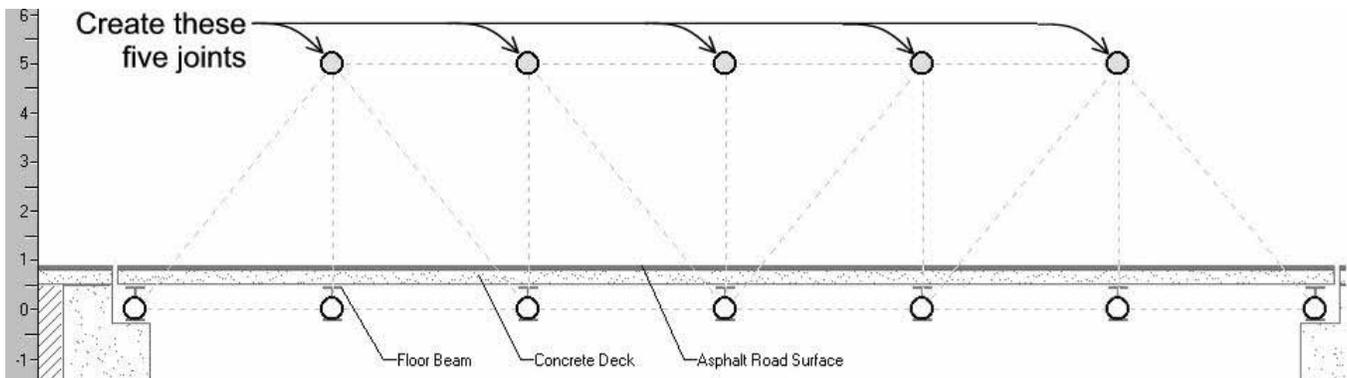
TIP

If you make a mistake while creating or modifying your structural model, just click the **Undo button**.

Draw Members

To draw a member, first select the **Member Tool** on the Design Tools palette. The mouse pointer will change to a pencil.

Members are always drawn from joint to joint. We'll begin by drawing the bottom-chord member on the left end of the truss. Move the mouse pointer close to the first joint—the one immediately above the West Abutment. You'll know when you are close enough, because the joint will "light up"—its color will brighten, and it will take on a three-dimensional appearance **(A)**. Press the left mouse button and hold it down, then drag the mouse pointer toward the second joint **(B)**. As you drag the mouse, you'll see a "rubber band"—a dotted line connecting the first joint and the mouse pointer. When the mouse pointer gets close to the second joint, this joint will also light up, to let you know that you are close enough to complete the member **(C)**. As soon the second joint lights up, you can release the left mouse button. A solid member will be drawn between the two joints **(D)**.
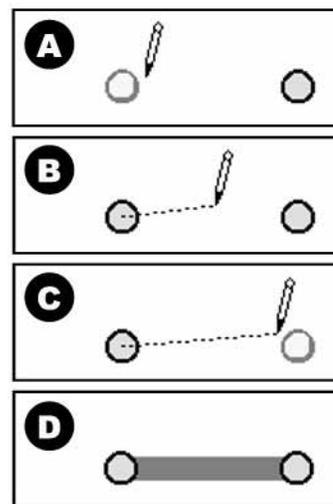
The member you just created is made of carbon steel; it has a solid square cross-section; and its dimensions are 120mm x 120mm. We know this because these three properties are currently displayed in the three Member Properties Lists on the toolbar. These particular properties—carbon steel, solid bar, and 120 mm—are default values. We'll change them later, as we optimize the design.

Using the procedure described above and following the dotted lines on the template, draw all 21 members in the structural model. In general, you can create members in any order you like; however, for this learning activity, you should create them in the following sequence (also shown in the picture below):

- Members 1 through 6 – bottom chord, from left to right

- Members 7 through 10 – top chord from left to right

- Members 11 and 12 – left and right end posts

- Members 13 through 17 – verticals from left to right

- Members 18 through 21 – diagonals from left to right

As we test and optimize the design, we will refer to individual members by their member numbers. If you create your members in a different sequence than the one shown here, your member numbers will be different, and you won't be able to follow along.
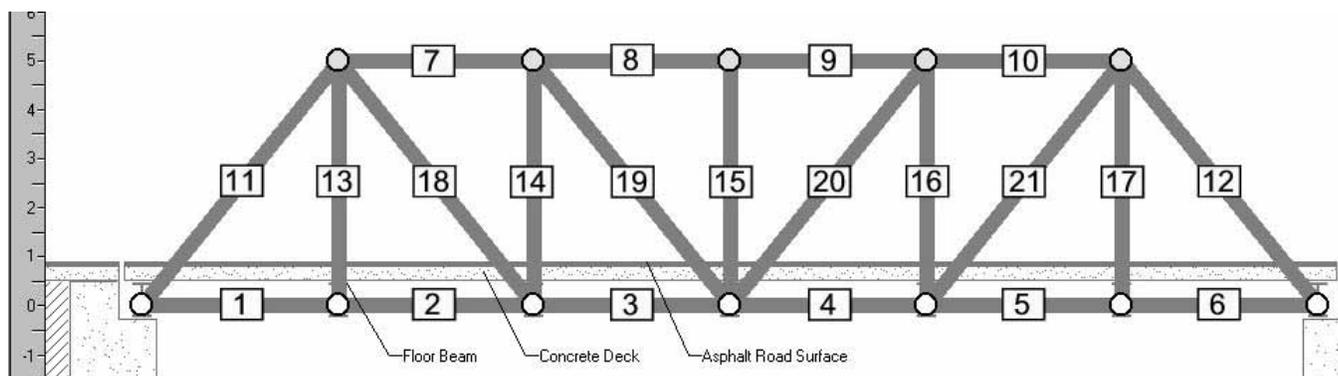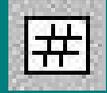
Load Test Your Design

The structural model is now complete. Of course, we won't know if the truss is strong enough to carry its specified loads until we perform a structural analysis and evaluate the safety of each member. We could do this by hand, just as we did in Learning Activity #3. But that would take a lot of time, leaving us with much less time to optimize our design and explore alternative design concepts. So, instead, let's use the computer to perform our structural analysis and evaluation for us.

To evaluate your design, click the **Load Test Mode button** on the main toolbar. After a few seconds, the Drawing Board disappears, and in its place, a full-color three-dimensional rendering of your bridge (with the town of Hauptville in the background) appears. Your bridge is first subjected to its own weight and the weight of the concrete deck and asphalt road surface. Then a standard AASHTO H20-44 truck crosses the bridge to validate the structure's ability to carry a vehicular load safely. If the truck crosses the bridge, your design is successful—it is strong enough to carry the specified loads safely.

But our design is definitely not successful. It does carry its own weight, but as soon as the truck moves onto the bridge, the structure collapses.
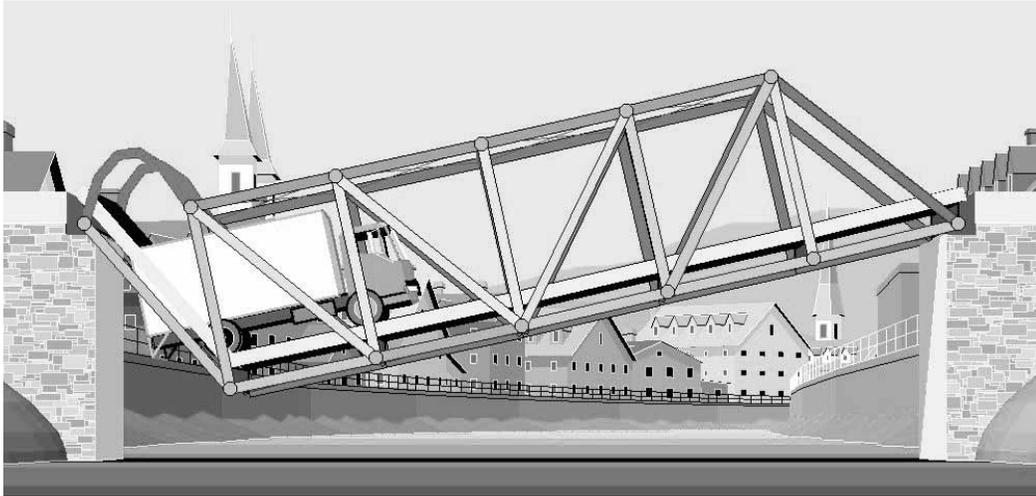
There's an old expression that engineers use when an idea doesn't work out exactly as intended: "Back to the drawing board!" In many ways, this expression captures the optimistic spirit of engineering. If one idea doesn't work, then the engineer keeps trying until he or she finds one that does. No design is ever accomplished on the first attempt. The design process is inherently iterative, and most successful designs are the result of many trials and many alternative design concepts. And so we, too, must go back to the drawing board—to find out why the bridge collapsed and to correct the problem.

Strengthen Unsafe Members

Click the **Drawing Board Mode button** to go back to the Drawing Board. When the Drawing Board display is restored, you will notice that the two end posts, Members 11 and 12, are both highlighted in bright red. The red highlighting indicates that these two members are unsafe in compression. The internal force in each member is greater than the corresponding compressive strength. Both of these members will need to be strengthened before the design can be judged successful.

There are several possible ways to strengthen a member. We can use a stronger material; we can use a larger member size; or, if the member is in compression, we can make it shorter. Of these three, it is generally best to begin by increasing the member size. We will experiment with changing materials and member length later in the design process.

Before you can make any changes to member properties, you must select the member you want to change. Note that the **Select Tool** has automatically been chosen from the Design Tools palette. Move the mouse pointer over Member 11, and click the left button. The member will turn light blue, indicating that it has been selected.

Now click the drop-down button next to the Member Size list on the toolbar. From the list of available member sizes, choose the next larger size—**130mm**. The size of Member 11 is now increased to a 130mm by 130mm square bar. To de-select the selected member, just click anywhere on the Drawing Board other than on a joint or member.
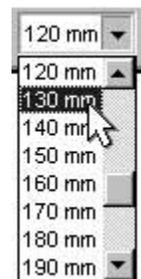
Repeat this process for Member 12.

The two unsafe members have now been strengthened. But are they strong enough to carry load safely? The only way to tell is to run the load test again. Click the **Load Test Mode button**, and observe the load test animation. The bridge still collapses! Upon returning to the Drawing Board this time, however, note that only Member 11 is highlighted in red. Increasing the member size to 130mm was good enough for Member 12, but not for Member 11.

Select Member 11, and increase its size to 140mm.

Now run he load test once more. This time, the truck crosses the bridge safely.
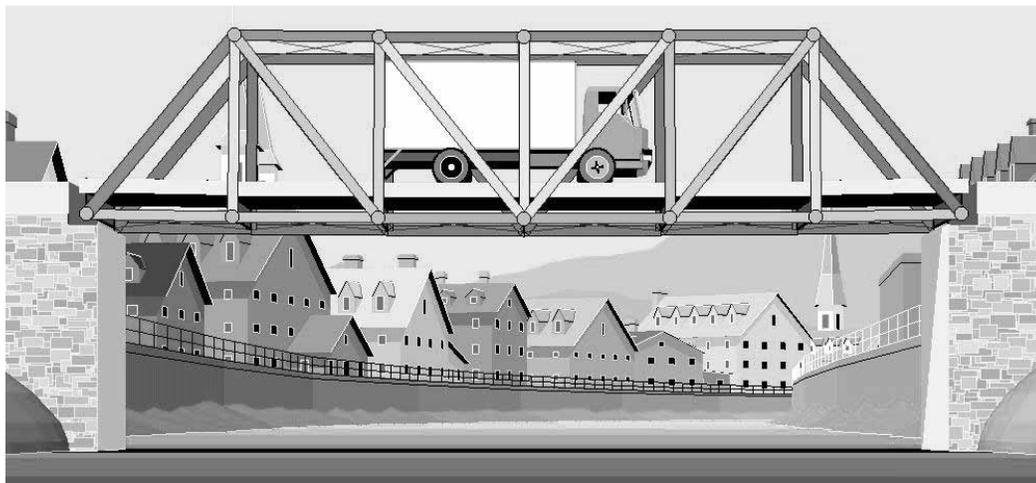
Optimizing the Design

Congratulations! You now have a successful design for the Lee Road Bridge. The design is successful because it spans the required distance and carries all of the specified loads safely. But don't relax yet! Recall that our design objective is to minimize the cost of the bridge. We don't yet know if we have met this objective.

The cost of one main truss is displayed on the main toolbar and automatically updated as you create and modify your structural model. The current cost is **$5672.55**. Our challenge is to determine if this cost can be reduced, without compromising the safety of the structure. This process is called **optimizing the design**.
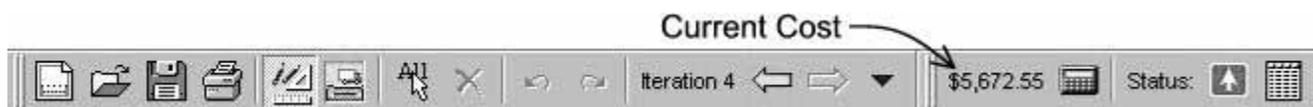
We will optimize our design for the Lee Road Bridge in three distinct phases. First, we will optimize the selection of member properties—material, cross-section, and size—for our Pratt Through Truss. Then we will optimize the shape of the truss—by exploring a range of different shapes and selecting the one that costs the least. Finally we will optimize the configuration itself—by exploring a range of alternative configurations and picking the least expensive one.

There are many millions of possible alternative designs for the Lee Road Bridge. We haven't the space to explore even a tiny fraction of them in this book. Rather we will look at a few representative examples, as a means of illustrating the *optimization process.* Once you have mastered this process, your ability to consider alternatives—and ultimately to develop a truly optimal design—will be limited only by your own time and motivation.

Optimize Member Properties

To optimize the member properties for our design, we must select a material, cross-section, and size for each member, such that the total cost of the truss is minimized.

While the load test animation is still running, take a careful look at the colors of the members. Recall that the *intensity of color* is proportional to the *internal force-to-strength ratio*. If the force-to-strength ratio of a member is greater than one, the member is unsafe. An optimally designed member should have a force-to-strength ratio slightly less than one. Such a member would be strong enough to safely carry its internal force, yet would use no more material than absolutely necessary. In the load test animation, such a member would be bright blue or bright red, depending on whether it is in tension or compression.

The load test animation shows us that few, if any, of the members in our current design are optimally designed. The pale blue bottom chords and diagonals are clearly much stronger than they really need to be. The light pink verticals are similarly over-designed. The top chords and end posts are bright red, but they aren't optimally designed either! Remember the important observation we made in Learning Activity #2—that hollow tubes are considerably more efficient than solid bars for carrying compression. The top chords and end posts in our current structural model are solid bars, so we should be able to reduce their cost substantially by changing them to hollow tubes.

It's time to go "back to the drawing board" once more—this time to optimize our design.

Let's begin the optimization process by changing the two end posts and the four top chord members from bars to tubes. To save time, let's make this change on all six members simultaneously.

> ### TIP
> **You can change the properties of two or more members simultaneously by using multiple selection. Hold down the Ctrl key on your keyboard, then click on each member you want to select. Any changes you make to member properties will affect all of the selected members.**
>
> Ctrl
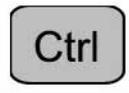
Use multiple selection to choose Members 7, 8, 9, 10, 11, and 12 simultaneously. Now click the drop-down button next to the **Cross-Section list** on the toolbar, and choose **Hollow Tube**. Members 7 through 12 have now been changed from solid bars to hollow tubes, though their sizes remain unchanged.

Anytime we make a change to the design, we must validate it by running the load test. In this case, you will find that all of the members we just changed to tubes are now unsafe. We must work through a methodical process to determine *the smallest possible member size that passes the load test* for each of these six members. Here's how to do it:

- Select Members 7 through 12, then click the **Increase Member Size button** one time. This will change each member to the next larger available size. Members 7, 8, 9, and 10 will all be 130mm; Member 11 will be 150mm; and Member 12 will be 140mm.

- Run the load test. Again all six members fail, so all six need to be strengthened again.

- You will need to repeat this process—increase all six members to the next available size, and run the load test—four more times before any of the members are strong enough to pass the load test. On this design iteration, the size of Members 7, 8, 9, and 10 is 170mm. Member 11 is 190mm, and Member 12 is 180mm. On this iteration, Members 8 and 9 still fail the load test, but the other four pass.

- On the next iteration, increase only Members 8 and 9 to 180mm, and run the load test once more. At this point all members are found to be safe, and the design is again successful.

The cost of the truss is now **$5092.30**—a reduction of about 10% from our original cost. Clearly changing compression members from solid bars to hollow tubes does produce a cost saving. Thus we ought to do the same for any other members that carry load in compression. But how can we be sure that we have identified all compression members in the structural model? The load test animation is helpful, but in cases where the compressive member force is small, the color change in the animation may not be noticeable. The best way to identify compression members with certainty is to use the Member List.

When you started up the West Point Bridge Designer, you probably noticed the Member List on the right-hand side of the Drawing Board. The list is not particularly useful for creating a structural model, so it is hidden from view at startup. When you begin editing your model, however, you'll find the Member List to be a very powerful tool. To view the entire Member List, place the mouse pointer over the left edge of the list. When the pointer changes to a double arrow, press the left mouse button and drag to the left.

The Member List shows the properties of each member—material, cross-section, size, and length—as well as the results of the most recent load test. Load test results are shown as a ratio of force to strength, for both tension and compression.
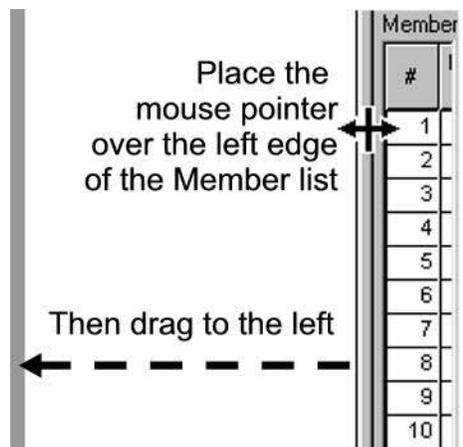
TIP

 You can sort the Member List by clicking any one of the column headings. For example, clicking the Size heading will sort the list from the largest member size to the smallest. Clicking the same heading a second time will sort the list from smallest to largest.

Using the Member List, we can easily identify the members that carry load in compression. Any member for which the number in the "Compression Force/Strength" column is *not zero* carries some compressive force. If you click the **Compression Force/Strength** column heading, all of the non-zero entries in this column will be grouped at the top of the list. In our current structural model, these members include the top chords and end posts (which we have already changed to tubes), the three interior verticals (Members 14, 15, and 16), and the two interior diagonals (Members 19 and 20). All of these members should be designed as hollow tubes.

Note that three of these members—16, 19, and 20—carry *both* compression and tension. This condition occurs because of the moving load. As the AASHTO H20-44 truck crosses the bridge, certain load positions cause these members to be in tension, and certain positions cause them to be in compression. In most cases, you'll find that a member with *any compression force whatsoever* will be more economical when it is designed as a hollow tube.

When we change Members 14, 15, 16, 19, and 20 to hollow tubes (but leave their size unchanged at 120mm), the structure still passes the load test. Thus, in this case, we must find the optimum by systematically *reducing* the size of these members until they fail the load test. Here's how:

- Reduce the size of all five members from 120mm to 110mm—the next lower available size. Now both Members 14 and 16 fail the load test, which tells us that 120mm is the optimum size for these two members.

- On the next iteration, change Members 14 and 16 back to 120mm, and reduce the other three to 100mm. All three still pass the load test.

- On the next iteration, reduce Members 15, 19, and 20 to 90mm. Here Members 19 and 20 fail; thus their optimum size is 100mm.

- Change Members 19 and 20 back to 100mm, and continue reducing the size of Member 15 until it finally fails at 30mm. Its optimum size is 35mm.

The cost of the truss is now $4334.32—another substantial cost reduction.

Now we can optimize the members that carry only tension—Members 1 through 6, 13, 17, 18, and 21. Again, we can systematically reduce the size of these members, running the load test after every change. When a member fails, we know that the next larger size is the optimum. At the conclusion of this process, our design costs **$2838.83**, and the member sizes are as indicated below:

#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)
1	Carbon Steel	Bar	50	8	Carbon Steel	Tube	180	15	Carbon Steel	Tube	35
2	Carbon Steel	Bar	50	9	Carbon Steel	Tube	180	16	Carbon Steel	Tube	120
3	Carbon Steel	Bar	65	10	Carbon Steel	Tube	170	17	Carbon Steel	Bar	45
4	Carbon Steel	Bar	65	11	Carbon Steel	Tube	190	18	Carbon Steel	Bar	55
5	Carbon Steel	Bar	50	12	Carbon Steel	Tube	180	19	Carbon Steel	Tube	100
6	Carbon Steel	Bar	50	13	Carbon Steel	Bar	45	20	Carbon Steel	Tube	100
7	Carbon Steel	Tube	170	14	Carbon Steel	Tube	120	21	Carbon Steel	Bar	50

Q₂

Why are these member selections not symmetrical?

Given that the shape of this truss is perfectly symmetrical, we might expect that the optimal member selections would be symmetrical as well. Yet they are not. The two end posts—Members 11 and 12—are different sizes, as are the diagonals 18 and 21. Why are the optimum member selections not symmetrical, even though the truss itself is symmetrical?

For a truss made entirely of carbon steel, these members are as small as they can possibly be without failing. (Try running the load test now; you'll see that all of the members are either bright blue or bright red.) Thus our truss is as light as it can be and, since steel is priced by weight, we have effectively minimized the *material cost* of this carbon steel truss.

Note, however, that this 21-member structure is composed of ten *different* member sizes. From a practical perspective, this would be a very difficult truss to build. Ordering, fabricating, and assembling all of these different sized members (and their connections) would be both challenging and expensive for the Constructor. Thus, if we minimize the material cost of this truss, we cause its fabrication and construction costs to be quite high. Clearly there is an economic benefit in *standardization*. Using fewer member sizes results in lower fabrication and construction costs. Yet standardization also causes material costs to increase, so too much standardization might be just as uneconomical as too little. In structural design, there is a clear tradeoff between light weight and standardization. The two are almost always competing interests. The engineer's challenge is to find the right balance between them.

The West Point Bridge Designer accounts for this tradeoff when it calculates the cost of your design. Click the **Report Cost Calculations button** on the toolbar to see how the calculation is done. Note that the *total cost* of the truss is broken down into three components—*material cost*, *connection cost*, and *product cost*:

- The **Material cost** is calculated by (1) determining the total mass of the three available materials—carbon steel, high-strength steel, and quenched and tempered steel—in your structural model, (2) multiplying the mass of each material type by the corresponding unit cost, in dollars per kilogram, and (3) adding these together to get the total material cost. Each of the three different types of steel has a different unit cost. Carbon steel is least expensive; quenched and tempered steel is most expensive.

- The **connection cost** is calculated as $25 per joint in your structural model.

- The **product cost** is $100 for each product in your structural model. A *product* is defined as any unique combination of material, cross-section, and size. For example, a 120mm carbon steel bar, a 120mm high-strength steel bar, a 130mm carbon steel bar, and a 120mm carbon steel tube are four different products.

Cost Calculations Report (Design Iteration #3)

Type of Cost	Product	Cost Calculation	Cost
Material Cost	Carbon Steel Bars	(1016.0 kg) x ($0.42 per kg) =	$426.72
	Carbon Steel Tubes	(1765.2 kg) x ($0.63 per kg) =	$1,112.11
	High Strength Steel Bars	(0.0 kg) x ($0.48 per kg) =	$0.00
	High Strength Steel Tubes	(0.0 kg) x ($0.72 per kg) =	$0.00
	Quenched & Tempered Steel Bars	(0.0 kg) x ($0.70 per kg) =	$0.00
	Quenched & Tempered Steel Tubes	(0.0 kg) x ($1.06 per kg) =	$0.00
Connection Cost		(12 Joints) x ($25.00 per Joint) =	$300.00
Product Cost	5 - 50 x 50 Carbon Steel Bars	($100.00 per Product) =	$100.00
	2 - 65 x 65 Carbon Steel Bars	($100.00 per Product) =	$100.00
	2 - 170 x 170 x 8 Carbon Steel Tubes	($100.00 per Product) =	$100.00
	3 - 180 x 180 x 9 Carbon Steel Tubes	($100.00 per Product) =	$100.00
	1 - 190 x 190 x 9 Carbon Steel Tube	($100.00 per Product) =	$100.00
	2 - 45 x 45 Carbon Steel Bars	($100.00 per Product) =	$100.00
	2 - 120 x 120 x 6 Carbon Steel Tubes	($100.00 per Product) =	$100.00
	1 - 35 x 35 x 2 Carbon Steel Tube	($100.00 per Product) =	$100.00
	1 - 55 x 55 Carbon Steel Bar	($100.00 per Product) =	$100.00
	2 - 100 x 100 x 5 Carbon Steel Tubes	($100.00 per Product) =	$100.00
Total Cost			$2,838.83

Close

Note that the $2838.83 total cost of our truss includes $1538.83 in material cost, $300.00 in connection cost, and $1000.00 in product cost. The material cost is already minimized (for carbon steel), and we can't change the connection cost without changing the configuration of the truss. Thus the only way we might reduce the total cost of the design is to reduce the product cost. We know that each reduction in product cost will cause a corresponding increase in material cost, so we must be careful to make only those changes that cause the total cost to go down. The following sequence of modifications to the structural model illustrates how to optimize the product cost of the design:

- In the current design, there are two 45mm bars and five 50mm bars. If we increase the two 45mm bars to 50mm, we eliminate the $100 product cost associated with the 45mm bars, and we only increase the material cost slightly. This change reduces the total cost to **$2754.49**.

- Similarly, changing the single 55mm bar to 65mm eliminates another product and reduces the total cost to **$2679.82**.

- Change the single 35mm tube to a 50mm bar, and the total cost is further reduced to **$2614.51**.

- Change the two 100mm tubes to 120mm tubes. The cost is now **$2567.45**.

- Change the two 170mm tubes to 180mm, to reduce the cost to **$2505.91**.

- We have now successfully reduced the number of products to five. Can we go further? One possibility might be to increase the nine 50mm bars to 65 mm, but this change causes the total cost to rise. Making nine members substantially larger causes the material cost to increase much more than $100; thus the cost of eliminating this product is greater than the benefit. We certainly don't want to incorporate this change into our design, so use the **Undo button** to eliminate it.

- Changing four 120mm tubes to 180mm produces the same result. The total cost increases, so the change is not justified.

By now, you should be able to see the logic behind this phase of the optimization process. In every case, we achieve greater standardization by making members *larger*. Because larger members are also *stronger*, there is little risk that the changes will cause the design to become structurally unsafe. A given change proves to be worthwhile if the increased material cost is less than the $100 saving we gain by eliminating a product.

Now, however, we will make one more change that seems illogical. Our current structural model has a single 190mm tube—Member 11, the end post on the left side. If we reduce the size of that member to a 180mm tube, we can eliminate a product *and* reduce the material cost, resulting in a total cost of **$2394.51**. Since we made Member 11 smaller, we would logically expect it to fail the load test. But when we run the load test, the structure carries its load successfully!

Q3

Why does Member 11 pass the load test?

When we first began the process of optimizing the design, Member 11 required a 190mm tube to pass the load test. At that time, reducing the member size to 180mm caused the structure to fail. Yet now the 180mm tube passes the load test. What happened?

We have come a long way since our $5672.55 truss passed the load test for the first time. By methodically optimizing first the material cost, then the product cost, we have reduced the total cost of the design by more than half. Yet there may be room for even more improvement. So far, we have used only carbon steel. We won't know if our design is truly optimal until we try the other two types of steel. Again, the way to do this successfully is to do it methodically—changing one particular group of members and carefully observing the result; then using that result to guide subsequent changes.

- Let's try changing the eight 50mm carbon steel bars to high-strength low-alloy (HSLA) steel. Note that, by changing all eight bars, we won't add to the total number of products in the structural model. We just substitute a new HSLA steel product for an old carbon steel one. Of course, HSLA steel is more expensive than carbon steel, so the immediate effect of the change is to cause the total cost to rise. But HSLA steel is stronger than carbon steel, so we should be able to make these members smaller without compromising the safety of the structure. In fact, a bit of trial and error will show that these eight bars can be reduced to 45mm and still pass the load test. The total cost drops to **$2371.61** as a result.

- Since changing to HSLA steel provided some cost benefit, let's try changing these same eight members to the strongest of the three materials—quenched and tempered steel. In this case, the substantial increase in material strength allows us to safely reduce the size of these members to 35mm, and the total cost is further reduced to **$2337.99**.

- Since quenched and tempered steel worked well for our first batch of tension members, let's try it for the second as well. If we change the three 65mm bars to quenched and tempered steel, we can reduce their size to 45mm, and the cost of the truss drops to **$2297.62**.

- Clearly the higher strength steels reduced the cost of tension members in our design. Will they do the same for the compression members? Let's try changing the six 180mm tubes from carbon steel to HSLA steel. Unfortunately, in this case, using the stronger steel does not allow us to use a smaller member size. When we change these members to 170mm tubes, the structure fails the load test. Using quenched and tempered steel for these members produces exactly the same result.

- Similarly, using the higher strength steels for the four 120mm tubes produces no benefit.

Q4

Why did high-strength steel produce no benefit for compression members?

For tension members, using high-strength low-alloy steel and quenched and tempered steel produced significant cost benefits. For compression members, using these steels produced no benefit at all. Why not?

The optimization of member properties for our Pratt Through Truss is complete. The total cost is **$2297.62**, and further cost reductions are not possible without changing the configuration of the structural model or compromising the safety of the design. The final selections for materials, cross-sections, and member sizes are as follows:

#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)
1	Q&T Steel	Bar	35	8	Carbon Steel	Tube	180	15	Carbon Steel	Tube	35
2	Q&T Steel	Bar	35	9	Carbon Steel	Tube	180	16	Carbon Steel	Tube	120
3	Q&T Steel	Bar	45	10	Carbon Steel	Tube	180	17	Q&T Steel	Bar	35
4	Q&T Steel	Bar	45	11	Carbon Steel	Tube	180	18	Q&T Steel	Bar	45
5	Q&T Steel	Bar	35	12	Carbon Steel	Tube	180	19	Carbon Steel	Tube	120
6	Q&T Steel	Bar	35	13	Q&T Steel	Bar	35	20	Carbon Steel	Tube	120
7	Carbon Steel	Tube	180	14	Carbon Steel	Tube	120	21	Q&T Steel	Bar	45

Optimize the Shape of the Truss

Our current design for the Lee Road Bridge is both safe and reasonably efficient. We could easily end the design process here and be entirely satisfied with our product. However, at this point in the process, we have only considered a single design alternative—a standard Pratt Through Truss configuration with a height of 5 meters. We have no way of knowing whether or not this configuration is most economical without considering other alternatives. To achieve a truly optimal design, we must fully consider a broad range of alternative configurations, then select the best one.

Before trying a totally new truss configuration, we should first optimize the shape of the current structural model. The West Point Bridge Designer allows you to change the shape of the truss by moving joints—a simple modification that can produce significant reductions in the cost of your design.

One way to optimize the shape of the structural model is to vary its *height*. The existing truss **(A)** has a height of 5 meters. We might try increasing the height, say to 6 or 7 meters **(B)**, or we might reduce the height to 3 or 4 meters **(C)**. In either case, you can make the change simply by dragging the five top-chord joints up or down. The basic Pratt truss configuration is not changed.

Once you have adjusted the height of the truss, you'll need to evaluate and optimize the new configuration—run the load test; identify and strengthen all unsafe members; and optimize the member properties. Only then can you determine whether or not the change was effective in reducing the cost of your design.
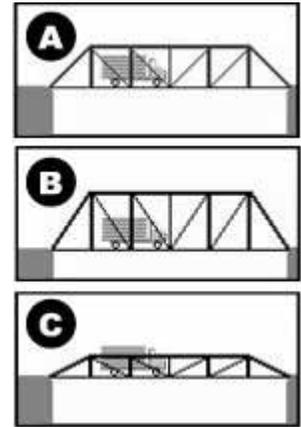
Q5

How would the cost of the design change if we change the height of the truss?

If we increase the height of the truss, do you think the cost of the design will increase or decrease? What if we decrease the height? Explain your answer.

Another way to optimize the structural model is to change its overall shape. For example, we might change the basic Pratt Through Truss **(A)** to a Parker Truss **(B)**, by giving the top chord a more rounded shape. Once again, you can make this change simply by dragging the top-chord joints up or down. Often this minor adjustment can reduce the cost of a design significantly. The Gallery of Truss Bridges (Appendix A) shows a number of actual truss bridges that use this rounded configuration—an indication that it might provide some added structural efficiency.
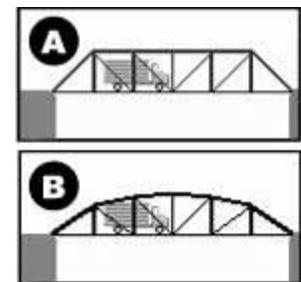
Let's give it a try. Starting with the current $2297.62 Pratt Through Truss design, change it to a Parker Through Truss by (1) moving the center top-chord joint up 1.5 meters and (2) moving the two adjacent joints up 1.0 meter. The resulting truss is 6.5 meters high, as shown below:
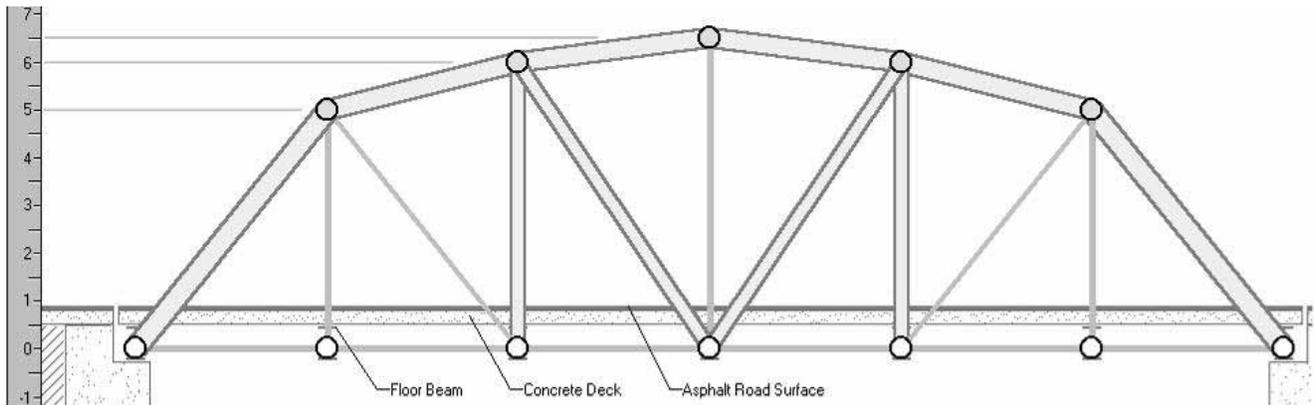
This structure still passes the load test, but the increased member lengths cause the cost to increase to $2366.04. Increasing the height of a truss generally causes the member forces in the top and bottom chords to decrease. Thus we would expect to be able to reduce the sizes of these members. And indeed we can. The top chord—Members 7 through 10—can be reduced from 180mm to 160mm. The bottom chord members 3 and 4 can be reduced from 45mm solid bars to 40mm, and the diagonals 18 and 21 can be reduced to 35mm. Unfortunately, these changes only bring the total cost down to $2315.00—higher than the basic Pratt Through Truss we started with.

One problem with our Parker Truss is that the two end posts—Members 11 and 12—still require the use of 180mm tubes. When we reduced the size of the top chord members from 180mm to 160mm tubes, we added an additional product to the design. The added $100 product cost was greater than the material cost reduction we gained from using smaller members. We could make a substantial reduction in the total cost, if we could figure out a way to use 160mm tubes for the end posts. And we can! Recall that the strength of a member in compression is strongly influenced by its length. Compressive strength decreases sharply with increasing length. Thus if we can make the end posts shorter, we can use a smaller tube size to carry the same internal force. We can make the end posts shorter by breaking them in half—by adding a new joint in the middle of each one—then adding a new member to preserve the stability of the structural model. The result is shown below.
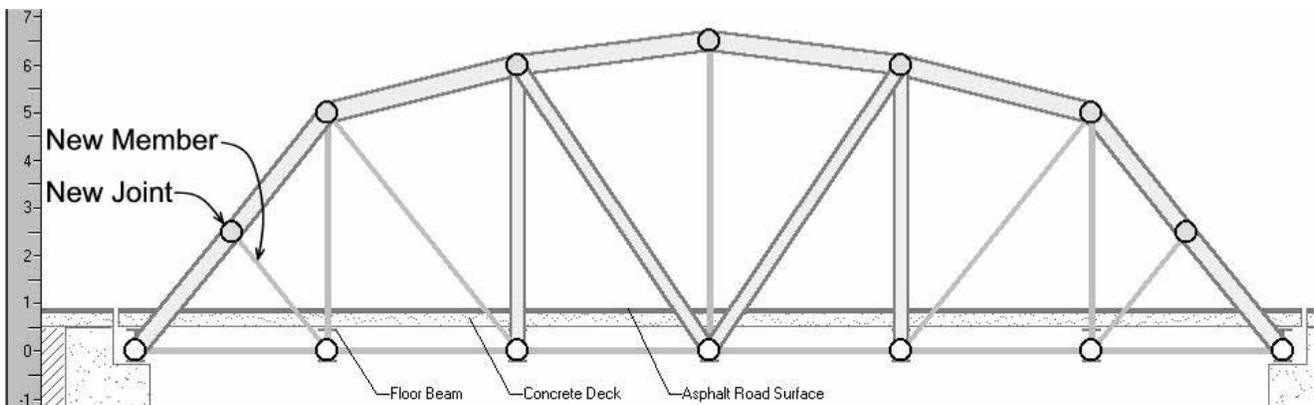
To achieve this new configuration, you'll need to:

Delete Members 11 and 12. To do this, select the two members, then click the **Delete button** on the toolbar.

Select the **Joint Too**l from the Design Tools palette, and draw the two new joints—at a vertical position of 2.5 meters and horizontal positions of 2.0 meters and 22.0 meters.

Select the **Member Tool** from the Design Tools palette. Change the default values in the Member Properties Lists to **Carbon Steel**, **Hollow Tube**, and **160mm**. Then draw the four new end post members. Finally, change the default values in the Member Properties Lists to **Quenched & Tempered Steel**, **Solid Bar**, and **35mm**, and draw the two new diagonals.

This optimized Parker Through Truss has a total cost of **$2226.28**.

Try a New Configuration

Recognizing that we were able to make a modest improvement in the cost of our structural model just by changing its shape, it is clear that we might do even better by starting with an entirely different truss configuration. The more configurations we explore, the more likely we will find one that is even more efficient than our current design.

Let's try the standard Warren Deck Truss configuration. If you follow the template provided by the West Point Bridge Designer, your initial structural model will look like this:
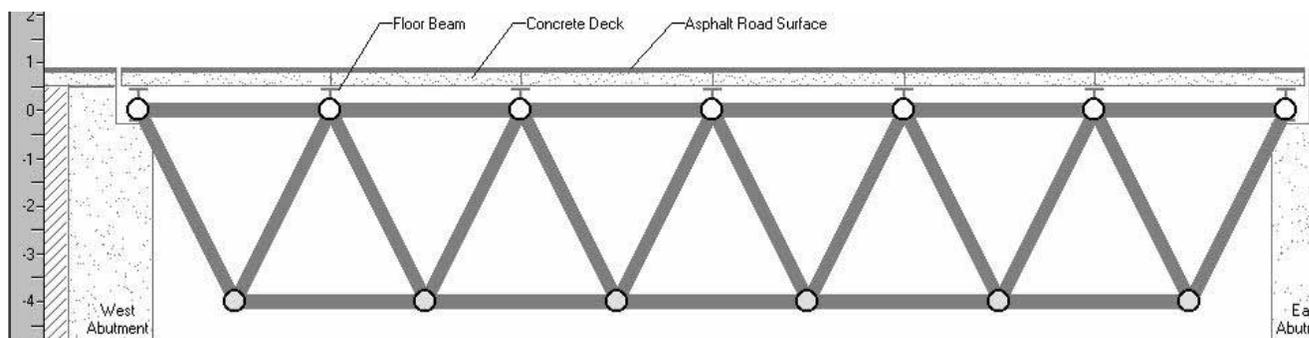
If you optimize the member properties for this truss (following the same procedure we used for the Pratt Through Truss above), the lowest total cost you will be able to achieve is about **$2460**.

Q6

Can you optimize member properties for a truss?

Starting with the standard Warren Deck Truss configuration shown above, optimize the member properties—material, cross-section, and size—such that the total cost of the design is less than $2500. Do not change the shape of the truss.

At $2460, the standard Warren Deck Truss is significantly more expensive than the Parker Through Truss we designed earlier. However, if we change its shape, it is possible to get the cost of the truss under $2180.

Q7

Can you optimize the shape of a truss?

Starting with the standard Warren Deck Truss configuration, can you modify the shape, such that the total cost of the optimized design is less than $2200?

Choose the Optimum Design

In this learning activity, we have developed the following four major design alternatives:

Type	Cost
Standard Pratt Through Truss	$2297.62
Parker Through Truss	$2226.28
Standard Warren Deck Truss	$2457.67
Modified Warren Deck Truss	$2179.78

Of these four alternatives, the modified Warren Deck Truss is clearly the optimum. Nonetheless, we could certainly reduce the cost further, by considering a larger number of alternative configurations. (Indeed, a number of users of the West Point Bridge Designer have created successful designs costing under $1600 for this project.)

On an actual bridge project, however, this degree of optimization would probably be adequate. It wouldn't make much sense for the structural engineer to spend many additional hours refining the design, just to trim a few more dollars off the project cost. (Don't forget that the engineer's time costs money too!) The engineer's professional responsibility is to consider a sufficient number of alternatives to ensure that the final project cost is reasonable. Pursuit of the absolute lowest possible cost is seldom justified.

It is also important to note that selecting a "best" alternative is usually far more complicated than simply picking the design that costs the least. Cost is certainly important, but other factors like aesthetics, ease of construction, availability of materials and labor, type of traffic, soil conditions, environmental impact, and safety might be equally important in determining which design alternative actually gets built. For example, if Union Creek were a navigable waterway, a deck truss might not provide enough overhead clearance for vessels traveling under the bridge; thus a through truss might be required even if it is not the most economical configuration.

Record Your Design

At the conclusion of the design process, the Design Team prepares a detailed set of plans and specifications—drawings and documents that describe every aspect of the project. These documents are the principal means of communicating the design to the Constructor who will actually build the facility. Designers also maintain copies of all the engineering calculations on which the design is based. All of these documents serve as a permanent record of the design, as well as a valuable reference for future projects of a similar nature.

You should document the products of your design work in a similar manner. The West Point Bridge Designer provides three different ways to record your design:

To save your design in a specially formatted file, click the Save button on the main tool bar, enter a file name, and click OK. This bridge design file can be opened and modified later.

To print a drawing of your design, click the Print button on the main toolbar. A drawing showing the configuration and dimensions of the truss and a table listing the assigned member properties will be printed to your default printer.

To print a detailed report of your most recent load test results, click the Report Load Test Results button on the main toolbar, then click the Print button at the top of the report window.

Conclusion

In this activity, we learned about engineering design by doing it—by designing an actual truss bridge. Using a specially developed software package, we created a structural model, tested it to ensure that it was strong enough to carry its prescribed loading, then optimized it to minimize its cost. As we used the software, we observed that design is always iterative and that design always involves tradeoffs. We also saw how the computer can be used to enhance the effectiveness and efficiency of the design process. What we *didn't* do was to actually build and test the bridge we designed. We're getting pretty good at engineering and construction, but building a 24-meter steel truss bridge is probably still a bit beyond our capability. In Learning Activity #5, however, we'll work through a complete design of a *model* truss bridge, and we will build and test it.

Answers to the Questions

1) **What portion of the engineering design process does WPBD address?** When you use the West Point Bridge Designer, you begin with Phase 4 of the engineering design process. You select one particular subsystem—a main truss—for a highway bridge. Then you proceed with multiple cycles of analysis and design—Phases 5 and 6—until an optimal design for that particular subsystem is achieved. It is important to recognize that, on an actual bridge project, many other subsystems would have to be designed before the final plans and specifications could be produced.

2) **Why are these member selections not symmetrical?** Even though the shape of this truss is perfectly symmetrical, the loading is not. The highway load used in the West Point Bridge Designer load test is a standard AASHTO H20-44 truck loading. The H20-44 has a heavy rear axle and a lighter front axle. Because the loading is not symmetrical, the maximum internal member forces are unequal in symmetrical members, like the two end posts. Since the internal member forces are not symmetrical, the member sizes are not either. Is this realistic? Well, no. The bridge will only carry load safely when the truck crosses from left to right. If the truck reversed direction (with the light axle on the left and the heavy axle on the right), the structure would fail the load test. This is an inaccuracy in the West Point Bridge Designer and one of many reasons why the software should be used for educational purposes only!

3) **Why does Member 11 pass the load test as a 180mm tube?** Early in the optimization process, a 190mm tube was required for Member 11. But at that time, all of the compression members had not yet been changed to tubes, and none of the tension members had been optimized. The optimization of these members caused a significant reduction in the weight of the truss itself. And even though the weight of the truss is quite small in comparison with the other loads applied to this structure, the lighter weight of the optimized truss was just enough to reduce the internal force in Member 11 slightly below the compressive strength of a 180mm tube.

4) **Why did high-strength steel produce no benefit for compression members?** This graph shows the compressive strength vs. length curves for two bars that have identical dimensions but are made of two different types of steel. Note that using a stronger material only improves the compressive strength of relatively short members. The strength of the steel has no effect at all on the compressive strength of longer members.
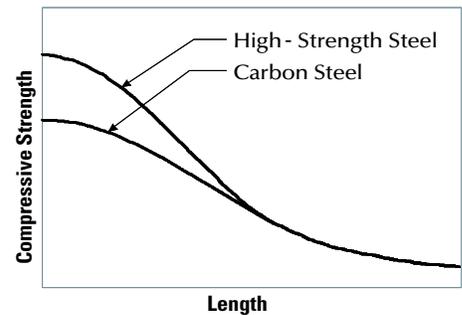

To verify this observation yourself, start up the West Point Bridge Designer, and click the **Report Member Properties button** on the toolbar. You will see a graph of strength vs. length for the member size, cross-section, and material currently displayed in the Member Properties lists. Now select a new material from the drop-down list, and watch how the graph changes.

In our design project, changing the compression members to higher strength steels produced no cost reduction because these members are all relatively long. If the change to stronger steel produced any increase in member strength, that increase was not enough to offset the increased cost of the stronger steel.

5) **How would the cost of the design change if we change the height of the truss?** This is a trick question. There's no way to answer it without actually changing the height of the truss, optimizing member selections for the new configuration, and comparing the new cost with the old one. At first glance, you might guess that reducing the height will cause the cost to decrease. Reducing the height causes the verticals and diagonals to get shorter, and shorter members cost less. But reducing the height also causes the internal member forces in the top and bottom chords to increase. (See Trusses 1 through 4 in the Gallery of Structural Analysis Results, Appendix B.) To pass the load test, you'll need to increase the size of these members, which will add to the total cost. So decreasing the height of the truss causes two competing effects—one that tends to decrease the cost and one that tends to increase it. You'll see these same competing effects in reverse, if you *increase* the height of the truss. As the truss gets higher, the internal member forces in the top and bottom chords get smaller, and you can reduce their cost by using smaller members. But increasing the height also makes the verticals and diagonals longer, which makes them more expensive. Clearly there is a trade-off between (1) the member force in the top and bottom chords and (2) the length of the verticals and diagonals. Every truss has an optimum height, which represents the best compromise between these two competing effects. The best way to find the optimum height for your design is through trial and error.

Design almost always involves these sorts of tradeoffs. It is a rare case indeed when a design change has only positive consequences. More often than not, design changes result in some positive and some negative consequences. The engineer's challenge is to figure our when the positives outweigh the negatives.

6) **Can you optimize member properties for a truss?** By following a methodical procedure to optimize the selection of members for the standard Warren deck truss, you should be able to achieve the following result.
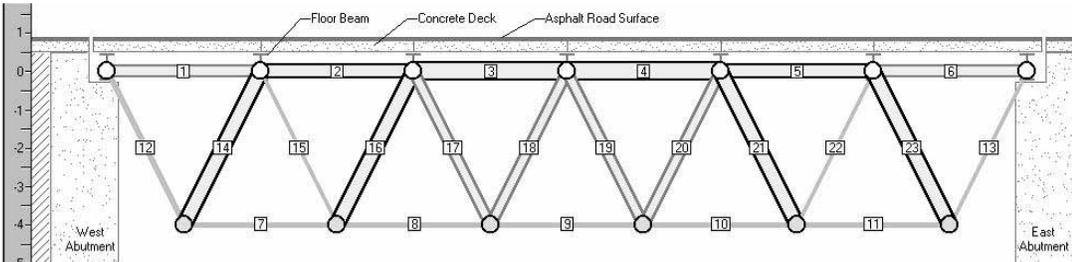
#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)
1	Carbon Steel	Tube	120	9	Q&T Steel	Bar	55	17	Carbon Steel	Tube	120
2	HS Steel	Tube	150	10	Q&T Steel	Bar	55	18	Carbon Steel	Tube	120
3	HS Steel	Tube	170	11	Q&T Steel	Bar	40	19	Carbon Steel	Tube	120
4	HS Steel	Tube	170	12	Q&T Steel	Bar	55	20	Carbon Steel	Tube	120
5	HS Steel	Tube	150	13	Q&T Steel	Bar	40	21	HS Steel	Tube	150
6	Carbon Steel	Tube	120	14	HS Steel	Tube	150	22	Q&T Steel	Bar	40
7	Q&T Steel	Bar	40	15	Q&T Steel	Bar	40	23	HS Steel	Tube	150
8	Q&T Steel	Bar	55	16	HS Steel	Tube	150				

The total cost of this truss is $2,457.67.

7) **Can you optimize the shape of a truss?** The picture below shows one of many possible ways to reduce the cost of the design by changing its shape. The six bottom-chord joints have been moved vertically to increase the height of the truss and to give the bottom chord a more rounded shape. By methodically optimizing the member properties for this new configuration, the total cost can be reduced to $2179.78.
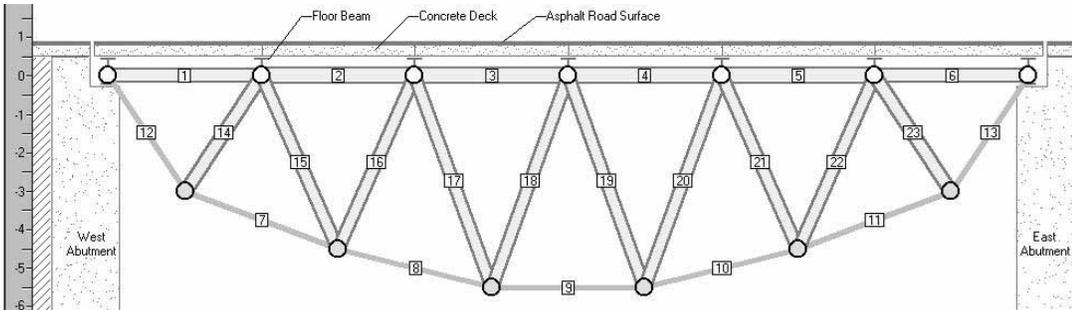
#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)	#	Material	Sec.	Size (mm)
1	Carbon Steel	Tube	130	9	Q&T Steel	Bar	45	17	Carbon Steel	Tube	130
2	Carbon Steel	Tube	160	10	Q&T Steel	Bar	45	18	Carbon Steel	Tube	130
3	Carbon Steel	Tube	160	11	Q&T Steel	Bar	45	19	Carbon Steel	Tube	130
4	Carbon Steel	Tube	160	12	Q&T Steel	Bar	45	20	Carbon Steel	Tube	130
5	Carbon Steel	Tube	160	13	Q&T Steel	Bar	45	21	Carbon Steel	Tube	130
6	Carbon Steel	Tube	130	14	Carbon Steel	Tube	130	22	Carbon Steel	Tube	130
7	Q&T Steel	Bar	45	15	Carbon Steel	Tube	130	23	Carbon Steel	Tube	130
8	Q&T Steel	Bar	45	16	Carbon Steel	Tube	130				

Some Ideas for Enhancing This Learning Activity

The West Point Bridge Designer has proved to be very popular with students, no doubt because it resembles a video game in some ways. Graphical creation of the structural model, the load test animation, and the use of a single easily understood measure of performance all contribute to this resemblance. Like a video game, the Bridge Designer lends itself well to competition. Students generally enjoy competing against each other and against the "best scores" posted the West Point Bridge Designer web page (http://bridgecontest.usma.edu).

This resemblance to a video game has both positive and negative implications. Students who get engaged in "playing the game" often discover important principles of structural engineering in the process. It is virtually impossible to develop a highly optimal design purely by chance. The student must work through many design iterations, and each new iteration must be informed by careful observations of cause and effect. *When I made the member shorter, how did its compressive strength change? When I changed the height of the truss, how did the internal member forces change?* The answers to these sorts of questions will inevitably lead to important insights about structural engineering. *Shorter members are stronger in compression. Increasing the height of the truss causes the internal forces to decrease in the top and bottom chords*.

Nonetheless, using the West Point Bridge Designer as a video game has some obvious dangers. Students who get totally absorbed in "the game" may lose sight of the all-important connection between the simulation and the real-world structure it represents. Students might also develop mistaken impressions of how the engineering design process works on a real project. Design is usually not performed in a competitive mode, and a practicing structural engineer would almost certainly not do hundreds of design iterations just for the sake of shaving a few dollars off of the construction cost.

With these positives and negatives in mind, the teacher might enhance the use of the West Point Bridge Designer as a classroom activity in the following ways:

- Select one of the seven projects in the West Point Bridge Designer, and use it as the basis for a design competition. Offer a prize or bonus points for the design with the lowest cost. Organize the class into teams of two or three students, with *only one computer per team*. This organization will encourage students to interact with each other and to decide among themselves how each new design iteration should proceed. This interaction will make them more aware of their own decision-making process and will enhance their opportunities to discover important insights about structural engineering from each other.

- You can eliminate some of the unhealthy aspects of competition by setting absolute standards of performance, instead of a relative one. For example, instead of giving a reward to the best design in the class (a relative standard), you might offer a 5% bonus to all designs under $2500, a 10% bonus to all designs under $2250, and a 20% bonus to all designs under $2000. This format is still competitive, but students compete against a fixed set of standards, rather than against each other. This format tends to be particularly effective for less gifted students, who might give up more readily when in direct competition with their peers. In a sense, this format is also more realistic, because most actual projects have a fixed project budget—an absolute standard—that the designer must satisfy.

- Rather than holding a competition, have students explore the relative efficiency of various different truss configurations. Divide the class into teams, and assign a *different* truss configuration to each team. The easiest way to do this is to have each team use one of the standard truss templates provided by the West Point Bridge Designer (see page 4-16). Each team then optimizes the member selections for its assigned truss configuration, *without changing the shape of the truss*. At the end of the project, each team reports its optimum cost, and these costs are compared to determine which configuration is most economical.

■ Students can be asked to model and design an actual bridge—preferably one familiar to them. If there is an appropriate truss bridge near the school, the teacher can take photographs of it and provide copies to the students. The students can use the Bridge Designer to model this structure as accurately as possible, then test and optimize it. (Since the West Point Bridge Designer does not allow the user to change the span length of a design, students will only be able to model the shape and configuration of the actual bridge, not its specific dimensions.)   This sort of project helps to reinforce the connection between the computer simulation and the actual structure it represents. If no appropriate truss bridges are located near the school, the teacher can use the ones provided in the Gallery of Truss Bridges (Appendix A).
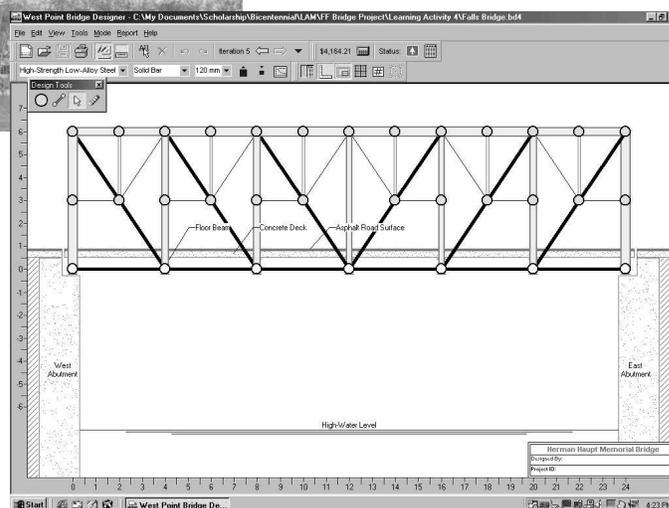
■ No matter how the West Point Bridge Designer is used, students are more likely to learn from the experience if they are asked to write a reflective essay at the end of the project. In their essays, they can be asked to comment on what they learned about bridges, about how structures carry load, and about the engineering design process.