Designing and Prototyping Interactive Fluid Dynamics Exhibits for the Carnegie Science Center: An Undergraduate Team Project Experience

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Abstract *- This paper describes a team project experience at Carnegie Mellon University in which undergraduate students designed and prototyped interactive exhibits to teach principles of fluid dynamics. The client for the exhibits was the Carnegie Science Center (CSC) in Pittsburgh. The CSC promotes science awareness, focusing primarily on stimulating science appreciation in pre-teenagers through interactive exhibits that create an intuitive understanding of scientific principles. The students participating in this project first researched basic child development concepts, child motivation techniques, and the science museum's practices. Then students conducted brainstorming sessions to identify fluid dynamics principles and to create a list of design criteria for the exhibits. Twelve exhibit ideas were selected and presented to the CSC from which six were chosen to further analyze, design and prototype.*

Introduction

During the summer of 1995, seven undergraduates from five different disciplines worked on a National Science Foundation Research Experience for Undergraduates project at the Engineering Design Research Center (EDRC) at Carnegie Mellon University. The project involved the design of exhibits for the CSC to help children learn principles of fluid dynamics. The CSC asked students working at EDRC for the summer to help them design an exhibit that demonstrated concepts of fluid mechanics. The students' main objective was to design a working prototype of an exhibit for at least one principle of fluid mechanics.

Design of science exhibits is an open-ended problem with multiple goals and constraints. The team of students was given the following list of requirements generated by the CSC. The exhibit should

- be interactive. Children should be able to touch, stand on, listen to, and interact with the exhibit;
- teach fluid dynamics. The lesson should be basic enough to be understood by children as young as eight or nine years old, yet retain relevance and substance;
- be self-explanatory. How to interact with the display should be obvious. Children this age rarely have the attention span for written directions, so the directions should be implicit in the exhibit;
- be attractive and fun for children. These qualities are necessary to grab the child's attention and encourage the child to approach the exhibit;
- fit into the space allotted by the CSC, both physically and esthetically;
- be safe. Toxic chemicals, sharp edges, small parts, water contamination, or other physical dangers must be considered for an exhibit used by children;
- be durable. The exhibit must be able to withstand abuse from countless energetic children;
- be inexpensive to construct. The CSC has a small budget for construction of these displays; and,
- be possible to construct in the manufacturing facilities at the CSC.

Given these requirements, along with advice and guidance from their advisors, the students set out to design and prototype fluid dynamic exhibits by the end of the summer. The next section of this paper is based on the students' journals and reports of their experience. (Some of the students' reports and journals are available from http://www.cs.cmu.edu/~rapidproto/csc/firstpage.html)

Exhibit Design Process

Background Research

Before starting to generate ideas for their exhibits, the students made a list of what they needed to know to get started. They divided the research tasks among themselves. One student looked at fluids textbooks and the EIT exam to generate a list of fluid dynamics principles that could potentially be used in exhibits. These principles included hydrostatics, Archimedes' principle, hydraulic force converter, Bernoulli's principle and Venturi Tubes. Two students researched basic child development concepts to understand the cognitive skills of the age range that the

exhibits had to appeal to. Their main concern was how children learn [1, 2]. Another student researched ways to motivate children in the target age range [3, 4]. This research took about a week and the students continued to meet for group discussions about what they had learned and what they still needed to find out.

The students researched about how children learn through discovery as well as through direct instruction. Since the goal of the exhibits was to teach through discovery, they read about some of the problems that can arise with this pedagogical method [5, 6]. One problem is that children can make incorrect models about the underlying physical phenomenon. Without a teacher there to correct the model, children may go away with incorrect ideas about how things work. Another problem is that if an exhibit does not arouse children's curiosity, they may play with the exhibit and have fun, but learn nothing. One of the exhibit designers at the CSC said they could put out buckets of water and ping pong balls and call it a fluids exhibit. Everyone would have fun playing with it and think it was a great exhibit, but it would not fulfil the goal of getting children to think about the physics of fluids.

Another pedagogical principle is that children need to interact with concrete materials. They learn best when they relate new ideas to familiar concepts (scaffolding). Attracting a child to an exhibit only requires something to grab the child's attention. However, the child must be motivated to continue to interact. Basically there are two types of motivation: extrinsic and intrinsic. Extrinsic motivation is based on achieving a goal to gain a tangible reward. Intrinsic motivation derives from how a person feels when he/she accomplishes something on his/her own. Both of these are important in the design of the exhibit.

Concept Generation

The students started to narrow which fluid dynamics principles could be learned through interaction with an exhibit. They had several brainstorming sessions, in which any and all exhibit ideas were brought to the surface and discussed. To encourage as many ideas as possible, no matter how silly, the students used brainstorming exercises and games. "We discovered that brainstorming dramatically improved our thought processes."

In the beginning of the group brainstorming session, the ideas were very general (viscosity, sound and light change, *etc.*) but soon became more specific, such as the evaporation tank concept. Brainstorming techniques helped them to understand the problem statement better. They tried not to censor ideas but rather to explore each idea. This led to a wide range of realistic and functional ideas with which to experiment. Next they made thumbnail sketches of their better ideas. Figure 1 shows some of the sketches from this phase. The sketches helped the students understand the problem from a visual standpoint. Visuals also enabled them to convey their ideas effectively to others. Then they researched their favorite ideas. "The overall experience proved to be very beneficial and exciting for all the group members."

Concept Selection

The students visited the CSC several times to experience the exhibits already in place and to understand the goals and practices of CSC. This helped them generate and consolidate the list of ideas for potential exhibits. The students arranged their ideas into principles and applications and then explored different ways these principles could be demonstrated in certain applications. They made a list of the final ideas. They proposed a list of twelve exhibit ideas to the CSC:

- Sound Propagation
- Circulatory System
- Rescue Kong
- Stability Booths
- Compressibility Box
- Natural Water Systems
- Water Powered Remote Control Cars
- Submerged Balloon
- Sand Dunes Vapor
- Pressure Tank
- Open Pipe Flow
- The Wheel of Water
- Drag in Different Fluids
- 3-D Water Table
- Pressure vs. Height
- Volcano Simulation

From this initial proposal the Science Center chose six ideas, based on previous experience and expertise in designing exhibits, that they wanted the students to develop and prototype. The next two sections describe two of the exhibits in more detail.

Rescue Kong

This exhibit demonstrates an application of Pascal's Law and the mechanical advantage of a hydraulic ram. Children pushing on one side of a hydraulic force converter witness their ability to lift considerably more than their own weight on the other side of the converter. This exhibit consists of a pile of rocks with Kong, or a gorilla, trapped inside. Kong asks the children to help free him. As the children apply more force, the rocks rise. To accomplish this task, children must work together. Lifting the rocks triggers sound and light. Thus, their achievements are acknowledged and encouraged even if they do not raise the rocks high enough to rescue Kong.

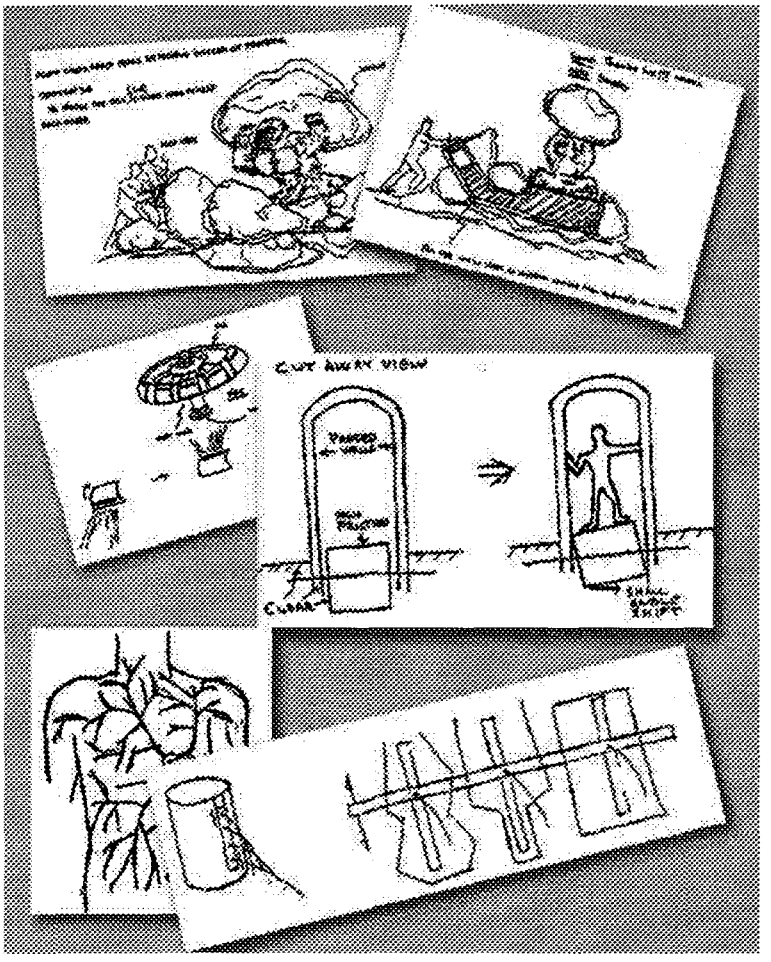

Figure 1. Concept Sketches for Exhibits on Fluid Dynamics

One side of the exhibit is transparent so that children can see there are no motors or gears. It is their force pushing on a small panel that raises the platform. A side exhibit lets children try to lift the same weight without assistance. The weight in the exhibit is designed to be lifted by three 12-year-olds. Esthetically, the exhibit looks like rocks and forest. The setting of the exhibit along with the sound and light effects attracts children to it to learn the basic principles of the hydraulic ram inside.

Water Table

The goal of the Water Table exhibit is to illustrate the concepts of drag, flow separation, unsteadiness, laminar flow and turbulent flow by observing streamlines of fluids flowing at different velocity around objects of various shapes (*e.g.*, squares, circles and airfoils). To visualize flow pattern changes, streamlines and vortex shedding, different objects are placed inside a closed see-through water channel. The objects have embedded magnets so children can rotate and move the objects using another magnet outside the channel walls.

Children are attracted to this exhibit because of the intrinsic beauty of the flow lines, which are made visible by particles suspended in the water. The magnets that allow the children to move the objects in the Water Table must be designed in such a way that they are easy to grasp and manipulate and so that their function to anyone walking up to the exhibit. Because there are several objects in the flow stream, more than one child can play with the exhibit at a time. Children can move and rotate individual objects and they can also see how the flow lines change when objects are moved together or apart.

Detailed Design

The students presented the ideas to the CSC, who chose six they wanted to see developed further. These ideas were: hydraulic ram, circulatory system, compressibility box, buoyancy/stability, water table, and sound propagation.

The students again visited the CSC to measure the space allocated for the exhibit and to get a better sense of how their exhibits would fit in with the existing exhibits. They conducted another brainstorming session to further explore the six ideas. They revisited their earlier research and discussed how to make the exhibits interactive, motivating, educational, and fun.

Since there were seven students and six ideas, one team member took primary responsibility for each concept. The seventh student took on a co-ordination and documentation role. This student, an English major, was interested in documenting both verbally and visually the journey that the engineering students took during their design process.

Prototyping

As the designs progressed, the students began to construct prototypes to test their ideas. Most of the prototypes were functional, but a few were visual prototypes. That is, most prototypes looked like lab experiments constructed from the materials at hand, but which functioned as the final exhibit would function. Other prototypes were visual models that showed what the final exhibit would look like but did not function. Often it is impossible to see what part of a design will and will not work until a physical model is created.

Prototypes help bring to the surface flaws and weaknesses in the designs before the final exhibit is constructed. F or example in constructing the prototype for the Water Table, the students encountered various issues that required further investigation and analysis. The most important issues were: visualization techniques, uniform distribution of the flow at the water channel entrance, prediction of flow viscous losses and required pump power, and control of the object shapes to avoid being dragged downstream. The students decided to use tracers as the flow visualization method and investigated different methods based on the use of particles, either liquid tracers, solid tracers, or gas tracers, in suspension within the fluid. Polystyrene beads were finally chosen as the solid tracer due to their ability to appear as bubbles suspended and floating in the fluid. To achieve uniform distribution of the flow, the students designed a set of diverging channels to distribute the water at the channel entrance and used a honeycomb structure to straighten the flow.

By the end of the summer, the students had constructed functional prototypes of three of the six exhibits. Figure 2 shows the prototypes for Rescue Kong and the Water Table. These prototypes are designed to answer questions such as: how should the pistons on the hydraulic ram be sealed and what tolerances are required to prevent leakage?

Experiences

The first thing one of the students noticed was the team's diversity. "We had people from all around the world (Indonesia, Hawaii, Puerto Rico, and various parts of the United States), and all of them seemed to have different aptitudes and abilities. We had a mixture of everything: analytical scientists, technical draftsmen, business managers, practical engineers, ideal engineers, writers, artists, designers, *etc.*" During the brainstorming period some people didn't contribute a lot of ideas, but they could really improve the initial ideas. During the meetings we had with our project advisors the ideas often were not explained by the creators but by the most outgoing members of the group.

"I also noticed that while the process progressed, the requirements for the group changed, thus demanding different things from all of us at different times. We needed the abilities of our group members at different points of the design process. First, ideal and original people for the brainstorming period; then practical and analytical to bring the brainstorming list down to a considerable number; after that the need for manual labor for the prototypes *etc*...Each individual in the group went through a cycle of frustration/excitement depending the outcome of his/her work at that specific point. We also experienced that as a whole."

"The ideal thinking of 'everything is going to work' was slowly overcome by the reality of 'this is impossible to build. In addition, the relationships between the members of the group and the ever-changing composition of our team got tense at times. It wasn't because of personal problems with the group members, but rather differences in opinion with respect to the process pace ands importance of certain steps. I was not that one or the other was right, but the differences in opinion of how things should have been done. Fortunately, we were able to overcome these differences in a subtle way, mainly through comprehension of everyone's viewpoints."

"For the goal of this summer research, I expected that we would deliver at least one or two final exhibits to the Carnegie Science Center. Later I found out that I was totally wrong. Our goal that I set at the beginning became uncertain. The research did not go as smoothly as we had planned. Our group encountered many problems during the research stages. There were many variables, some indirectly related to our problem such as administration and organization in EDRC."

"In the implementation stage, our problem was getting more and more complicated. There were more external variables we had to be concerned about because we needed to contact many companies and people outside

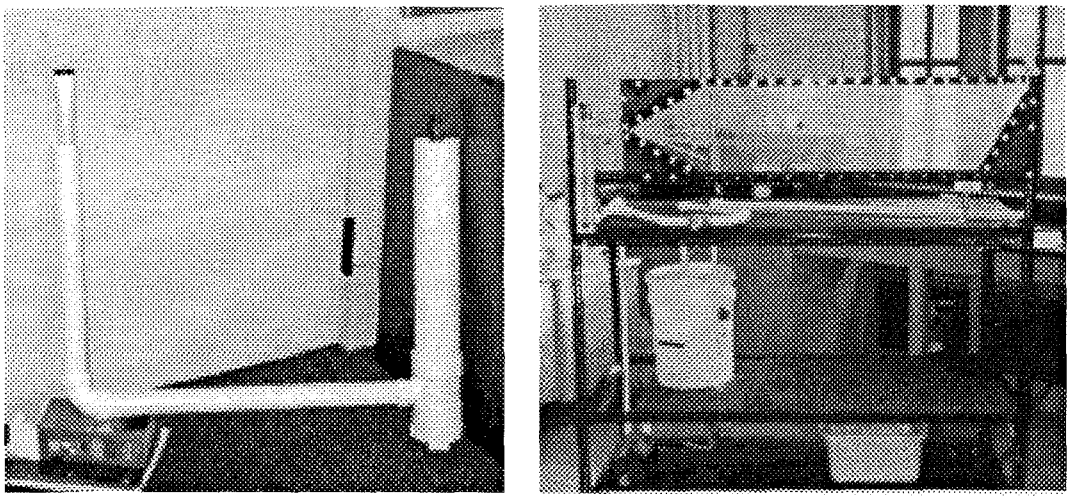

Figure 2. Functional Prototypes of the Hydraulic Ram (Rescue Kong) and the Water Table

of our group for supplies and tools. Time and scheduling were almost beyond our control, thus we learned to have a flexible schedule that could change to accommodate the external variables we were faced with, such as time allotted for shipping orders. During the prototyping process, we experienced that nothing matched our needs perfectly. Many parts we designed prototypes of had to be reconsidered simply because no one was able to manufacture it, otherwise would have had to build them ourselves. Learning that some of our prototypes failed and had to be rethought was very annoying, but it also taught us a good lesson at the same time. We also learned to consider costs and time for prototyping and to consult the expertise in many fields in order to accomplish our goals. Working as a team then became the heart of our project. Furthermore, we knew that presentation was just as important as the research itself. It was a way to get outside support and to publicize our ideas. Personally, the most valuable thing that I learned from this project was getting to know how to conduct research. Although we did not accomplish any outstanding results over the summer months, we did go through almost every process needed in any type of long-term research oriented project. "

Outcomes and Conclusions

In this group project, students learned about cognitive development processes, participated in a design team, and learned about design theory, implementation and requirement satisfaction. They also enhanced their skills in fluid mechanics, creativity, and problem solving. Furthermore, the students were exposed to the complete cycle of design from brainstorming through initial theoretical modeling, identification of design criteria and tradeoffs, to contacting providers, ordering components and materials, and finally to building and testing prototypes.

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