

Designing Episode Content for *Design Squad*, a New Educational Engineering Children's Television Program: The Human Powered Water Pump as a Design Challenge

by

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Mika A. Tomczak

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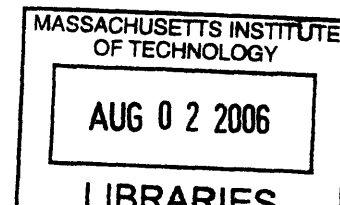
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ABSTRACT

In recent years, problems have emerged in the realm of engineering and engineering education in the United States. Technology literacy is low, there are insufficient numbers of engineering students, and there are misconceptions surrounding the engineering profession. To remedy these problems, WGBH Boston and MIT have created a reality-style engineering-based television program for 9- to 13-year-old children, entitled *Design Squad*. One episode of the show will challenge the 8 child contestants to build a human-powered waterslide pump, to be used at a community swimming pool.

Two potential design solutions are proposed for the design challenge: a ball-and-chain pump and a positive-displacement plunger pump. The design process of each solution and an evaluation of each solution's feasibility are presented. Criteria for a successful episode of the show are discussed in relation to the challenge. Prototype experimentation and analysis suggest that the human-powered waterslide challenge will invoke an engaging episode of *Design Squad*.

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1. Introduction

In recent years, some problems have emerged in the realm of engineering and engineering education. America's technology literacy is low relative to other competitive nations, there is an insufficient number of students in the engineering pipeline in high school and university, and there are many misconceptions surrounding the engineering profession. As a result, WGBH Boston and MIT have decided to create an engineering-based television program that caters to 9- to 13-year-old children.

The program, entitled *Design Squad*, will be presented in a reality television format. Like other "reality" programs, this one will remain unscripted and will capture events as they unfold. The children in the cast will create the solutions on their own, with little to no adult intervention. The show will feature eight 16- to 18-year-old high school students who will be given a different design challenge at the start of each episode. The children, who will be divided into two teams of four players, will be given two days to create a solution to the design challenge by executing the design process from the brainstorming phase to the prototype execution phase.

The first season of *Design Squad* will consist of thirteen half-hour episodes, all of which will be filmed over a two-month period in the summer of 2006. Each of the episode challenges will be presented to the cast by a real client interested in a solution to a problem he or she faces in his or her everyday life. Before the filming of the show, it must be determined that each design challenge has multiple solutions, because each team of four kids will pursue its own solution.

One design challenge proposed by WGBH and the content director of *Design Squad* involves the creation of a human-powered water-lifting mechanism to lubricate a waterslide at a local pond or swimming pool. The "water slide challenge" will require each team to design and construct a human-powered water supply device useable on a nearby waterslide; the work completed for this thesis discusses the design process of two different solutions to the challenge, and considers the factors necessary to designing for a children's reality television program.

The first solution to the water pump challenge, known as the ball-and-chain design, features a continuous loop of balls on a string that are drawn through a pipe of an inner radius that is just larger than the outer radius of the balls. The base of the tube sits in the water source, and columns of water are drawn to the top of the tube as the string of balls is pulled through. The second solution is a variant on a positive displacement diaphragm or piston pump. It is made using common household and store-bought components, including a polyethylene bellows toilet plunger and two one-way check valves sold for sump pumps.

The two solutions are very different in nature and both can be constructed by a team of four high school students over the course of two days. Each challenge satisfies a list of feasibility requirements that are critical to each potential episode concept and each challenge solution. The episode challenge is sufficiently "fun" and relevant to the lives of 9- to 13-year-old children, and the episode concept will ultimately be used as one of the thirteen design challenges during the first season of *Design Squad*.

2 Background

2.1 Motivation

WGBH Boston is Boston's public television station and the producer of educational materials in many media, including television, radio, movies, and the internet. With a small team from MIT's Department of Mechanical Engineering, it was decided that a television program and associated outreach programs about engineering should be developed to engage young children in engineering.

The development of a children's television program about engineering is motivated by three interrelated issues: (1) the poor state of technology literacy in America's society today, (2) the increasingly inadequate number and diversity of students in the educational pipeline for engineering, and (3) widely held misconceptions of the engineering profession [1].

The products of the engineering profession have had a revolutionary impact on the lives of people throughout the United States and the rest of the world. People throughout the world are deeply dependent on the products and infrastructures represented by telephones, automobiles, household running water, and electrification [2]. As the planet's population continues to grow, the worldwide dependence on engineered products will increase.

Despite a growing reliance on technology, most US citizens do not understand how modern technologies work or how they are used in everyday products, as was demonstrated by the results of a quiz on science and technology administered to over 30,000 respondents in the US and Europe. Fewer than half of the respondents to the quiz correctly answered the question, "True or false: lasers work by focusing sound waves [3]." Most people do not make the mental connection between the lines of red light that scan their purchases at the grocery store check-out counter and the technology used to implement these functions. [1]

As technology advances to better serve the needs of the public, technology literacy may decline even further. For example, parents engage their children much less frequently in performing basic car engine maintenance because of modern cars' computerized control systems that enable higher mileage and lower emissions [1].

The National Science Foundation has identified a dearth of students, especially from the female and minority populations, who enroll in engineering programs at the college level. Despite the fact that, from 1980 to 2000, science and engineering jobs in the United States more than doubled, the enrollment in undergraduate engineering programs has remained almost constant [4]. Consequently, compared to other nations, there has been a shortfall in the US pipeline. For example, about 30% of all bachelor's degrees in the US are in science and engineering, whereas about 60% of all bachelor's degrees are related to science and engineering in China.

Undergraduate engineering enrollment declined through most of the 1980s and 1990s. It rose again from 2000 to 2003. The Undergraduate engineering enrollment rebounded from 361,000 in 1999 to 422,000 in 2003, yet of the first-year undergraduates starting their university careers, only 9% planned to major in engineering [4].

There are consistently inequalities in engineering education. In 2002, despite the fact that women earned more than half of all bachelor's degrees in science and engineering in 2002, women earned only 21% of the bachelor's degrees awarded in engineering in the United States. Similarly, women made up only 22% of the graduate engineering enrollment in 2002 [4].

Not only are there inequalities in engineering education, but there are inequalities in the engineering workforce as well. Women represented only 25% of those employed in the science and engineering sector in 2000. And although the representation of African-Americans in science and engineering occupations increased from 2.6% in 1980 to 6.9% in 2000, and the representation of Hispanics increased from 2.0% to 3.2%, these increases are proportionally less than the corresponding increases in the population during these years [4].

It is believed that the inequities in the engineering workforce are correlated to the public's perceptions of engineering. A 1998 survey showed that the US public feels uninformed about the engineering profession and revealed a strong tendency to underestimate the role of engineers in research, technology development, and social welfare [5]. For example, the mechanical engineering workforce, which was over 92% male in 1999 [6], is frequently associated with construction equipment, which has historically appealed more to boys than to girls [1].

What is perhaps the most significant factor in the poor reputation of engineering is the fact that it is perceived by a large portion of the public as inaccessible, boring, and serious. Engineers are seen as nerdy and socially inept [1]. Although it may be argued that these perceptions are partially true, the dynamic, creative, rich nature of engineering is not successfully being showcased at the present time. There exists a need to bring the positive aspects of the engineering profession to the forefront of the public's understanding.

It has been determined that, because of the aforementioned challenges faced by the field of engineering, popular media must play a major role in the solution [1]. The television and the internet are the main sources of the public's information about science and technology. In fact, television is cited as a source of science and technology information more than twice as often as newspapers and more than ten times as often as either books or family and friends [3]. Although this fact may seem frightening, it must be acknowledged as solutions are sought to the public perception of engineering.

In response to the problems described above, WGBH Boston, MIT, and their collaborators are in the process of developing a children's television program about engineering. The show, named *Design Squad*, will "explore modern technology, reach a broad audience, and present an image of engineering as enjoyable, accessible, creative, humane, socially relevant, and personally fulfilling [1]."

2.2 Project Background

2.2.1 Concept of the Program

The goal of *Design Squad* is to engage children in engineering; to achieve its goal, the television show must cater to kids of an appropriate age. Because the show is meant to be transformative, it must cater to precisely the correct age group. Although the children's shows that aired on public broadcasting are typically geared to children less than 8 years of age, children of that age bracket are considered too young to appreciate a show about engineering; conversely, by the age of 13, most children have decided that math and science are not for them [7]. As a result, *Design Squad* is being created for children between 9 and 12 years of age.

To have a significant impact, the show must cater to the majority of the target audience. It has been observed that a large amount of the television programming watched by children in the target age group is live-action, adult programming. Because the reality genre is so popular with the target age range, *Design Squad* will be created using a reality format [1].

It has been seen that kids emulate and imitate other children, and especially those they watch on TV. To ensure successful, appropriate role models for the target audience of 9- to 12-year-old children, WGBH Boston has cast eight children between the ages of 16 and 18. The children of this age group will both appeal to the target viewing audience and will have the capacity to acquire the skills and content knowledge needed to solve the engineering challenges [1].

Because one of the goals of the television show is to immerse the viewers in real engineering, it must have substantive and sufficiently advanced content. The show will be as “hands-on” as possible; viewers will see other children taking raw materials and transforming them into workable solutions with minimal adult intervention [1].

To be successful, *Design Squad* must be distinct from other children’s programs. Although *Operation Junkyard*, a program shown on Discovery Kids’ NBC Saturday, has already attempted a reality format children’s show, *Design Squad* will differ from it in three ways. First, there will be a much greater emphasis on the educational mission of the program, including the engineering process and the science and technology content. It will also feature more modern technologies in the solution. Finally, the *Design Squad* challenges will be inspired by the lives of children rather than “socially-meaningless challenges posed by adults [1]”.

2.2.2 Description of the Program

Design Squad, will air weekly on PBS. Each week, eight players between the ages of 16 and 18 will tackle challenges posed by kids from the viewing audience. The challenges may stem from the everyday lives of children; they may also be inspired by the needs of their schools or neighborhoods. Throughout the episodes, the show will highlight key messages about creative thinking, experimentation, teamwork, and the informed use of math, science, and technology [1].

The start of each episode will feature a client that will explain the challenge being presented to the players on *Design Squad*. The show’s participants, who will be divided into two teams, will proceed to develop different solutions to the challenge posed. Throughout the episode, the viewers will witness two design processes unfolding, and will watch the development of design alternatives, analysis of feasibility, the search for needed materials, the fabrication of components, and the testing of the solutions [1].

The entire season will consist of thirteen episodes, each of which will feature the same group of eight children. The composition of the two teams of four will vary so that different interpersonal interactions play out in each episode [1]. Because the show will be filmed and edited in a reality format, there will be no script for the action in each episode. Instead, what is filmed and ultimately shown in the episode will be the result of real events influenced by little adult intervention.

The directors and producers of the show will edit the footage to compose a program that will:

- (i) Foster a positive public image of engineering, especially among girls and minorities
- (ii) Emphasize the inherent rewards and enjoyment of creative, technical work
- (iii) Illustrate physical principles behind the engineering solutions
- (iv) Present role models exhibiting intelligence, persistence, teamwork, and gracious competition
- (v) Illustrate effective skills for design, including convergent and divergent questioning, estimation, planning and analysis of experiments, and coordination of diverse teams

(vi) Accommodate the variety of learning styles that are likely to be reflected in the viewing audience.

2.2.3 Criteria for Each Design Challenge

The challenges must successfully satisfy the needs and desires of two groups of children: the 9- to 12-year-olds to whom the episodes cater, and then 16- to 18-year-olds who complete the challenges on camera. Accordingly, when designing the engineering challenges that will be presented to the players throughout the season, many factors must be considered to judge the feasibility of each potential challenge as a workable episode concept. Each design challenge and its solutions will be roughly measured against the criteria delineated here, for a qualitative measure of how promising an episode a challenge is expected to be.

The primary focus of each design challenge must be the possibility of many distinct solutions. Because one of the goals of the show is to showcase the flexible, diverse nature of engineering, each team will take on a different method of solving the proposed problem, and the two solutions will be presented simultaneously to viewers. It is therefore critical that each design challenge has at least two distinctly different solutions that are comparable in scope, breadth, and effectiveness.

Because each episode will be filmed over the course of two days, the ability for each of the solutions to be conceived, discussed, and built with relative speed, is critical. It is comparable to propose that an experienced engineer can design and prototype the challenge solutions in one day. Thus, when prototyping design challenges and their solutions, if they are unable to be built by a single experienced engineer in under a day, it is considered too large a scope for the children who will be designing and constructing the solution for the actual show.

The challenge proposed must stem from a problem that is deemed “important” of the targeted viewing audience. That is to say, the challenges that are presented to the two teams of children by a viewer each episode must resonate with the daily lives of the 9- to 12-year-olds who will be watching the show. Whether the challenge seeks to make completing daily chores more efficient, or to solve a problem proposed by the child’s school or neighborhood, the challenges and their solutions must be easily understood by the viewing audience.

Solutions should be both “fun” for the viewing audience and deemed “creative” by those involved and those who watch the show. The solutions to the challenges, and the challenges themselves, should have a “coolness” factor that will engage the minds of 9- to 12-year-olds. Furthermore, because the use of creativity will be showcased as part of the design process, each challenge solution should meet a certain qualitative measure of creativity.

Logistically, it is desirable that the solutions to each challenge remain within the show’s budget. Although it is difficult to say exactly what constitutes an extravagant purchase, the players on the show will be required to purchase their own supplies, and will be acting with discretion when doing so. Solutions need not require purchases that seem outlandishly expensive.

2.3 Past Work on the Project

Prior to the work on the water slide challenge discussed in this paper, background work for *Design Squad* had been underway for about two years. Three prototype episodes were filmed and edited over the course of the two years; each was subject to formative assessment by potential viewers and by expert advisors, the feedback from which was used to develop the next prototype episode [1].

Each prototype video was subject to discussion group-based feedback. Each episode was shown to dozens of groups of three to five children throughout New England; in total, over 100 children viewed each of the first two prototype episodes. The episodes and the results of the focus groups were reviewed with a panel of advisors, including experts in children's education, television production, engineering, and science [1].

Results from the focus groups were generally positive. In terms of the show's appeal, children became very engaged with the show and sided with particular characters or teams. The focus groups seemed to react more strongly to challenges that would "make things easier" or help others. In terms of the educational effectiveness of the programs, some scientific and technical terminology eluded the participants, while abstract concepts were able to be grasped. For example, although viewers understood that eggs will move faster down a tube if the tube is vertical, and not slanted, they did not use the words "friction" or "potential energy" as presented in the episode [1].

The prototype also revealed that the viewing audience preferred a cast of children who were younger than the 17- to 20- year-olds who were used in the pilot episodes; they preferred a younger cast of kids who are not in college. Others indicated that they would prefer "more fun and whimsical challenges" [1]. It was indicated that the competitive aspects of the show should be emphasized more, including rivalry between the teams and a clearer definition of what the winning team would gain.

In the last of the three prototype episodes filmed, a new element was added: each team was given a budget and told to purchase the materials needed to construct their solution to the proposed challenges. The children were filmed on their shopping trips, to add a natural way to include descriptions of the materials and components while avoiding a "kit inventory" process that might lose the interest of viewers [1]. This method of making a shopping trip each episode may be altered for the actual show; the teams may instead be given a trailer filled with materials, from which they can select their inventory of choice.

3 Introduction to the Water Pump Project

3.1 Concept Development

After seeing the work done on human-powered water pumps by one of the authors in a design course offered by the mechanical engineering department, the content director of *Design Squad* suggested that a human-powered waterslide might present a promising challenge concept for the show. The team at WGBH agreed that the concept sounded viable, and the authors of this paper were given the go-ahead to fully develop the challenge, and design and build two distinct prototype solutions.

The parameters of the challenge were loosely developed; it was not until much later in the design process that WGBH was able to confirm a waterslide location available for the shoot. It was decided that the players on each team would be asked to build a water source to lubricate a small water slide for a local pool or pond, where electricity-driven water slides are neither desirable nor feasible.

Initial reflection on the proposed challenge seemed to indicate that the episode had the potential to fulfill the criteria discussed in section 2.2.3. If the challenge were proposed in a manner that highlights the ability to use engineering to enhance an otherwise mundane situation, or to be more environmentally effective by creating something that operates using human power instead of electricity, the challenge would encourage creative solutions to important problems and situations to which 9- to 12-year-olds can easily relate.

As established earlier, it was decided that each prototype solution to the challenge should be able to be built by a single senior in mechanical engineering in under a day; if this were not possible, then inexperienced teenaged children should not be expected to successfully design and construct the challenge within the two-day time limit. Accordingly, a strict time limit was imposed on the design, parts acquisition, and construction of each solution.

Additionally, because the location of the final episode shoot was unknown at the time of construction, each solution needed to remain adaptable to many conditions and, more specifically, waterslide heights. Although commercial waterslides that are commonly installed in backyard pools are typically six to eight feet in height, waterslides at community pools can be up to ten or fifteen feet in height. This variance in potential maximum slide heights was necessarily factored into the design and construction of each solution.

3.2 Two Proposed Solutions

The overall parameters of the challenge solutions dictated that two unique solutions be developed to the waterslide concept; during the filming of the show, each team will develop and build its own distinct solution to the challenge posed. Therefore, it was not only desired to design and build two workable solutions, but it was preferred to also create two solutions that pump water using very different techniques.

There are many different methods used to pump water; several categories of commercial water pumps exist. Although it was explicitly stated by WGBH that neither of the challenge solutions was to utilize a commercial, off-the-shelf water pump, the use of commonplace household items as parts of design solutions was encouraged. Additionally, common plump designs were certainly available to use as models for the prototype solutions.

The first solution to the human-powered waterslide challenge is an advanced variation on the classic rope-and-bucket method of drawing water from a well or other water source. Instead of attaching a series of buckets to a continuous loop of rope that travels upward on a pulley system, as is done in the classic system, a series of small balls is strung on a cable, and the balls are drawn through a vertical tube whose base rests in the water source. Between each consecutive set of balls, a column of water is drawn up the tube as the string is pulled. Like the rope-and-bucket system, at the highest point in the cycle, the water is discharged from the system and directed to its destination, or the top of a water slide.

The second solution is a type of positive displacement pump, similar in nature to a piston or diaphragm pump, constructed with common household materials. A polyethylene bathroom plunger is attached to two swing-check valves, and the plunger is pumped up and down. The pumping action draws water into its bellows, and then pushes it out maintaining the same flow direction. The one-way valves prevent the water from flowing in the wrong direction. The components used to construct the pump were all purchased locally from Home Depot or over the internet from the commercial vendor McMaster-Carr, and are all objects that might be found in plumbing networks or bathrooms in the typical American home.

4 The Ball-and-chain Pump

4.1 Introduction

One simple solution to the human powered water slide challenge is the “ball-and-chain pump”. The ball-and-chain pump consists of a string of balls that are pulled through a partially submerged tube, trapping and carrying water as the balls move upward. This concept demonstrates that everyday materials can be combined in unusual ways to form a functional device, with moderate fabrication effort. The action of pulling a string of balls through a tube can be used to effectively pump water up to some height, where it can flow out onto a higher structure such as a water slide. The force required to pull the balls is supplied by the user, so that the pump is fully human powered and provides a creative solution to the waterslide pump design challenge.

4.2 Ball-and-chain Pump Theory

Consider the ball-and-chain pump shown in Figure 1 below:

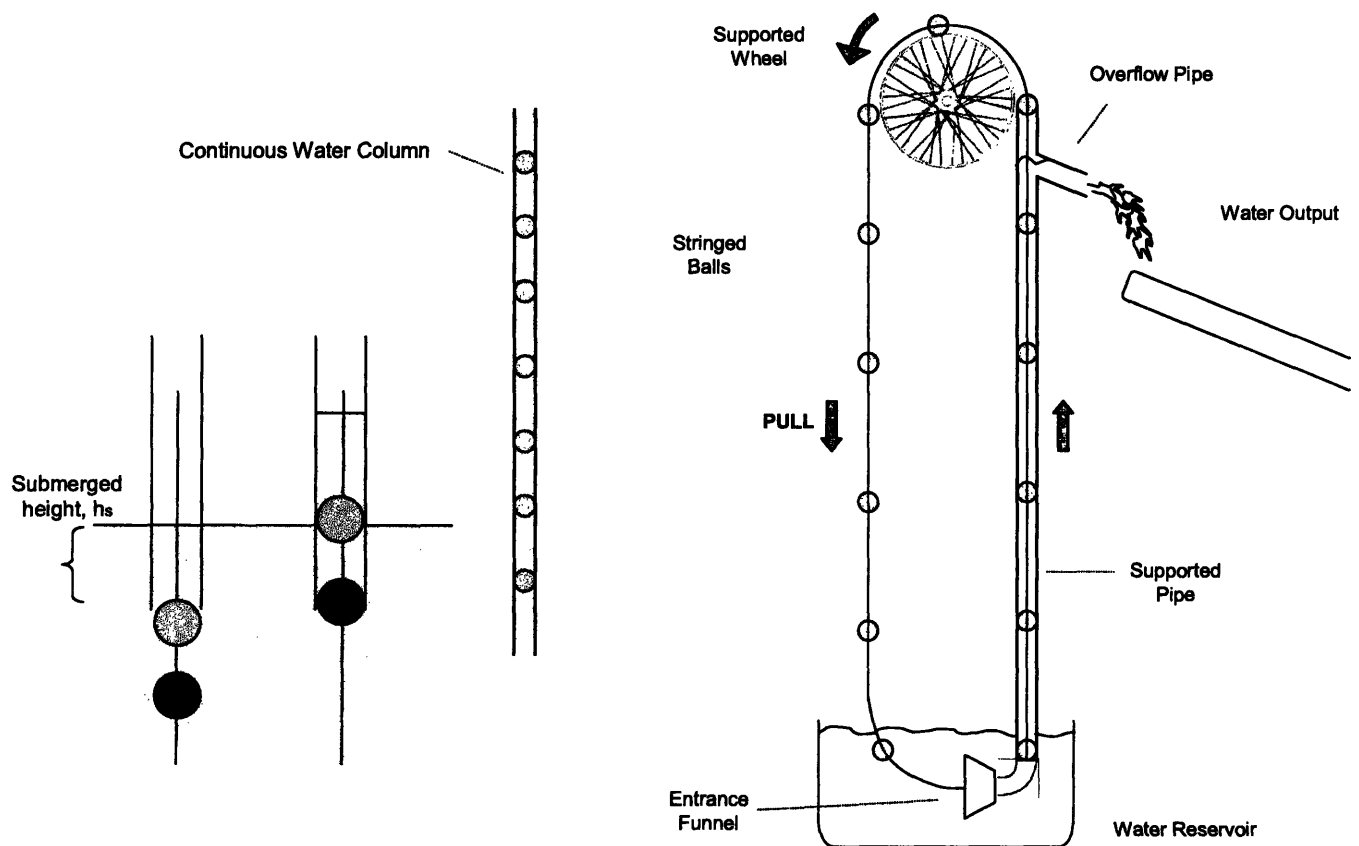


Figure 1: Schematic diagram of the ball-and-chain pump.

As the string is pulled downward, balls of diameter, d , are cycled anti-clockwise through the system and pulled upward into the supported pipe, of larger diameter D . The end of the pipe is submerged so that a volume of water, V_p , is located within the lower pipe section. The first ball enters the submerged end of the pipe, where a volume of water equal to V_p is displaced into the tube and carried upward. An equivalent piston-tube system is formed with some continuous downwards water leak rate m_{leak} , where the flow rate of leaking is dependent on system variables such as the clearance between the ball and tube, pipe angle and ball spacing. As the balls moves upward through the tube, a low pressure vacuum is created in the previously occupied volume so that a pressure difference acts to drive water up into the tube water from the water reservoir beneath. After the first ball has traveled some distance, a subsequent ball enters the funnel so that a volume of water $V_{interball}$ is trapped between both balls. The cycle continues and results in continuously rising chain of water. Near the top of the pipe, an overflow valve redirects the water flow so that water is continuously drawn in at the inlet, and expelled at the outlet.

The maximum amount of water that can be trapped above each ball will be equal to that of the inter-ball volume, $V_{interball}$, which can be made larger by adjusting the spacing, h_{ball} , between balls of radius R as given by :

$$V_{interball} = \pi R_{ball}^2 h_{ball} - \frac{4}{3} \pi R^3 \quad (1)$$

4.2.1 Volumetric Flow Rate in the Case of no Leak

Assuming a continuous column of water, and a negligible leak, the resulting output flow rate will depend on the speed at which the balls are pulled. If the user pulls the balls at a speed v_{pull} the balls will carry water at an equal rate. The resulting mass flow rate can be estimated by:

$$\dot{m}_{ideal} = \rho A_{pipe} v_{pull} \quad (2)$$

where ρ is the density of the pumped fluid and A_{pipe} is the cross-sectional area of the pipe. The pull velocity used in Eqn (3) represents an averaged velocity over the period of operation.

The required power to achieve the flow rate in Eqn (3) is given by:

$$P_{ideal} = F_{pull} v_{pull} \quad (3)$$

where the actual force necessary to pull the column of water upwards will be a combination of factors including :

- i) The gravitational force acting on the water column.
- ii) Frictional losses between n number of balls rubbing along the pipe walls.
- iii) Fluid shear losses depending on the pull velocity, fluid viscosity and flow rate.

The total force input required by the user can be expressed by:

$$F_{pull,total} = F_{grav} + F_{fric} + F_{shear} \quad (4)$$

expanding Eqn (4) gives an expression :

$$F_{pull,total} = M_w g + \mu N + \tau A_s \quad (5)$$

where μ is an effective friction coefficient, N is the average normal force exerted by all the balls on pipe walls, τ is the fluid shear stress acting on a the total ball surface area A_s , g is the gravitational constant, and M_w is the total weight of the water column. For a pipe with N balls inside at any one time, F_{grav} can be given by:

$$F_{grav} = M_w g = \rho g V_{w,total} \quad (6)$$

where the total volume of water, $V_{w,total}$, in the pipe with N number of balls is:

$$V_{w,total} = \Pi R_{pipe}^2 L_{pipe} - N_{balls} \frac{4}{3} \Pi R_{ball}^3 \quad (7)$$

As the number of balls increases the total instantaneous volume of water in the pipe decreases so that the force necessary to pull at a particular velocity decreases. However, when the balls account for a significant part of the internal pipe volume, the overall flow rate will decrease according to a modified version of Eqn (2). The expression below takes into account that the regular distribution of balls in the water column will negatively affect the flow rate every $t_{interrupt}$ seconds. If the balls spaced apart by a distance, h_{ball} , are traveling with velocity v_{pull} , a ball will pass the outlet overflow pipe in regular intervals of:

$$t_{interrupt} = \frac{h_{ball}}{v_{pull}} \quad (8)$$

Each time a ball passes the outlet, the mass flow rate temporarily decreases due to the decrease in fluid volume. These fluctuations can be taken into account over a period of time so that an average flow rate can be estimated by:

$$\dot{m}_{ave} = \rho A_{pipe} v_{pull} - \rho V_{ball,total} \frac{1}{t_{interrupt}} \quad (9)$$

where $V_{ball,total}$ is the average volume of the balls in the pipe so that Eqn (9) becomes:

$$\dot{m}_{ave} = \rho A_{pipe} v_{pull} - \rho \left[N_{balls} \frac{4}{3} \Pi R_{ball}^3 \right] \frac{v_{pull}}{h_{ball}} \quad (10)$$

The equation for mass flow rate above is limited to the case where water does not leak down across the small gaps between balls and the pipe walls. As the gap width increases, the contribution of the mass flow rate loss due to leakage becomes more significant so that Eqn (10) becomes:

$$\dot{m}_{ave} = \rho A_{pipe} v_{pull} - \rho \left[N_{balls} \frac{4}{3} \Pi R_{ball}^3 \right] \frac{v_{pull}}{h_{ball}} - \dot{m}_{leak} \quad (11)$$

The value of \dot{m}_{leak} will depend on many factors, including the ball gap width, pipe height, pipe angle, fluid viscosity and pull velocity. The leak rate will be examined in the following section.

4.2.2 Estimating the Leak Rate

In order to estimate \dot{m}_{leak} a few assumptions must be made. Firstly, it is assumed that the system of connected spherical balls moving through a tube of diameter D , can be approximated by some equivalent geometry of flat disks with diameter d and height h as shown in Figure 2 below:

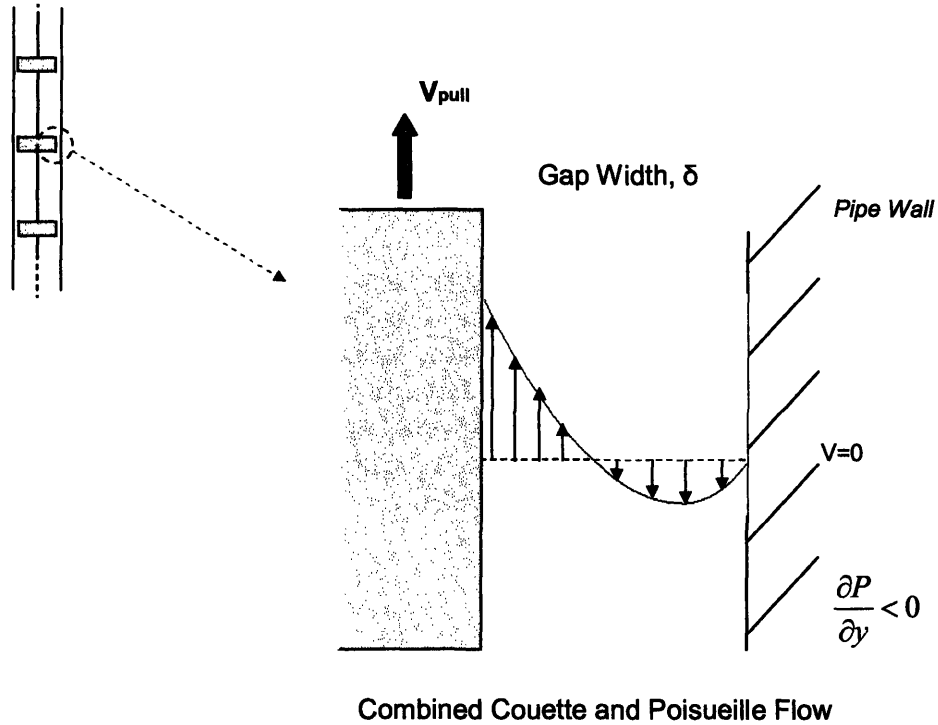


Figure 2: Diagram showing spherical balls approximated as equivalent flat disks.

If the width of the gap is very small compared to the radius of the balls, it can be assumed that the gap interface can be modeled as two flat plates with the wall of the pipe modeled as a stationary flat wall and the edge of the disk modeled as flat plate moving with a velocity v_{pull} . A conservative estimate on Reynolds number can be used to determine the validity of a laminar flow assumption so that:

$$Re = \frac{\rho v D_c}{\mu} = \frac{\left(1000 \frac{kg}{m^3}\right) \left(1 \frac{m}{s}\right) (.0028m)}{1.0 \times 10^{-3} \frac{Ns}{m^2}} = 2800 \quad (12)$$

From Eqn (12) it can be seen that for pull velocity of 1 m/s and a gap width of less than 2.8mm the flow will remain laminar. Since there is both a moving wall boundary due to the disk's velocity, and an opposing pressure gradient due to the weight of water over each disk, the flow in the gap can be modeled as a combination of Couette and Poiseuille flow. Figure 3 shows possible resulting velocity profile for such a situation. The pressure difference across each ball is assumed to be a constant, dP/dy .

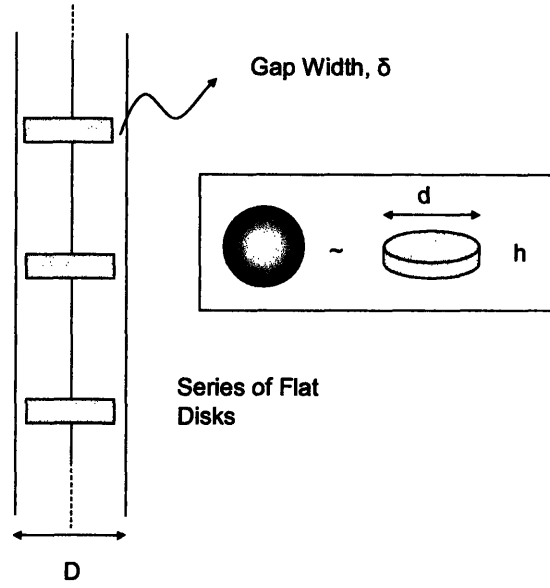


Figure 3: Diagram showing the velocity distribution for a combine Couette and Poiseuille Flow where the gap between the ball and pipe wall is modeled as two flat plates.

To solve the case of combined Couette and Poiseuille flow, consider the Navier Stokes equation applied in the vertical direction:

$$\rho \left[\frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right] = \rho g_y - \frac{dP}{dy} + \mu \left[\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right] \quad (13)$$

Additionally continuity requires that :

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \quad (14)$$

Assuming steady, fully developed flow that is independent of the y and z directions, and also noting that Eqn (12) requires that $v_y=0$ everywhere, Eqn (13) can be reduced to:

$$\frac{\partial^2 v_y}{\partial x^2} = -\rho g_y + \frac{dP}{dy} \quad (15)$$

with no-slip boundary conditions of:

$$v(d) = v_{pull}, \quad v(0) = 0. \quad (16)$$

By integrating Eqn (15) with the above boundary conditions, an expression for the resulting velocity profile $v_y(y)$ and fluid shear stress $\tau_{xy}(y)$ can be given by:

$$v_y(x) = \frac{v_c x}{h} + \frac{x}{2\mu} \left(-\rho g_y + \frac{dP}{dy} \right) (x-h), \quad (17)$$

$$\tau_{xy}(x) = \frac{v_c \mu}{\delta} + \left(-\rho g_y + \frac{dP}{dy} \right) \left(x - \frac{\delta}{2} \right). \quad (18)$$

Finally the volumetric and mass flow rate of the leaking water can be calculated by integrating Eqn (17) over the area of the gap to give:

$$\dot{V} = 2\pi R \int_0^{\delta} v_y(x) dx = 2\pi R \left(\frac{v_{pull}(t)\delta}{2} - \frac{\delta^3}{12\mu} \left(-\rho g_y + \frac{dP}{dy} \right) \right), \quad (19)$$

$$\dot{m}_{leak} = \rho \dot{V} = 2\pi R \rho \left(\frac{v_{pull}(t)\delta}{2} - \frac{\delta^3}{12\mu} \left(-\rho g_y + \frac{dP}{dy} \right) \right). \quad (20)$$

The expression for water leak rate in Eqn (20) can then be substituted in the previous expression for average mass flow rate of the pump to give:

$$\dot{m}_{ave} = \rho A_{pipe} v_{pull} - \rho \left(N_{balls} \frac{4}{3} \pi R_{ball}^3 \right) \frac{v_{pull}}{h_{ball}} - 2\pi R \rho \left(\frac{v_{pull}(t)\delta}{2} - \frac{\delta^3}{12\mu} \left(-\rho g_y + \frac{dP}{dy} \right) \right) \quad (21)$$

From Eqn (21) it can be seen that in order to get a net flow of water out of the pipe, the velocity of pulling the balls around the system must be fast enough to overcome the water's tendency to leak across each ball back into the water reservoir. Additionally, the leak rate can be greatly reduced by decreasing the gap size between the ball and the tube.

4.2.3 Effect of Pipe Angle

Introducing an angle in the orientation of the pipe will cause a change in the magnitude of the vertical component of gravity acting on the rising water column. The coordinate system is oriented so that the y-direction corresponds to the axial direction as show in Figure 4 below:

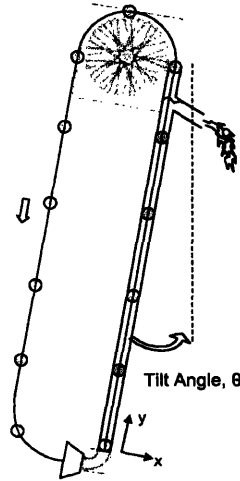


Figure 4: Ball-and-chain pump assembly with the water column at an angle θ .

With the pipe at an angle θ with respect to the vertical, the Navier-Stokes equation in the y-direction becomes:

$$\frac{\partial^2 v_y}{\partial x^2} = -\rho g_y \cos \theta + \frac{dP}{dy}, \quad (22)$$

where the gravitational component now includes a cosine term. Re-deriving the expression for average mass flow rate, with a modified gravitational term, Eqn (21) then becomes:

$$\dot{m}_{ave} = \rho A_{pipe} v_{pull} - \rho \left(N_{balls} \frac{4}{3} \Pi R_{ball}^3 \right) \frac{v_{pull}}{h_{ball}} - 2\pi R \rho \left(\frac{v_{pull}(t)\delta}{2} - \frac{\delta^3}{12\mu} \left(-\rho g_y \cos \theta + \frac{dP}{dy} \right) \right). \quad (23)$$

Eqn (23) can be used to estimate the expected water flow rate for a ball-and-chain system where N_{ball} number of balls, with of radius R_{ball} and spacing h_{ball} , are pulled though a pipe of radius R_{pipe} and angle θ , with an average velocity v_{pull} . This expression shows that as the angle of the pipe offset from the vertical, the leak rate decreases.

4.4 The Ball-and-chain Pump Design

In order to test the feasibility of the ball-and-chain pump as a design challenge, a prototype pump was designed, fabricated and tested. Figure 5 below shows a picture alongside a schematic diagram of the prototype ball-and-chain pump:

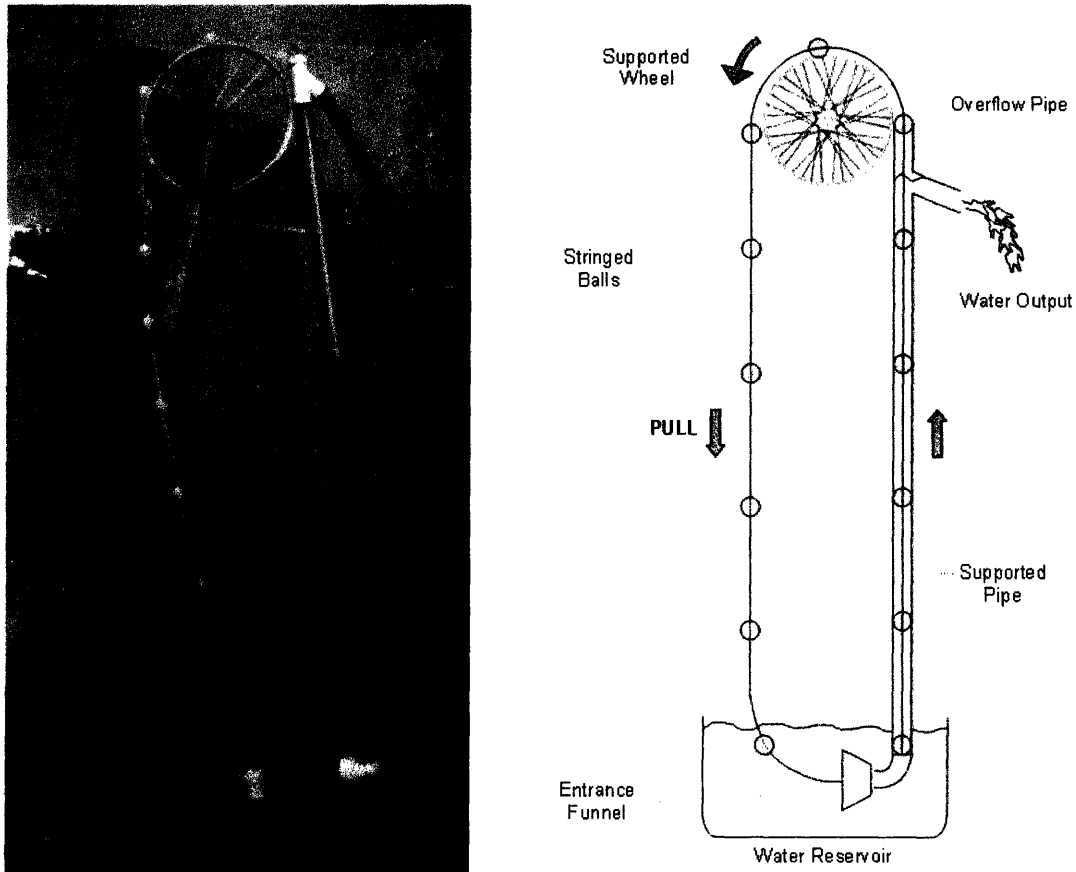


Figure 5: Photograph (water reservoir not shown) and schematic diagram of the ball-and-chain pump.

The components of the ball-and-chain pump can be decoupled into three main subsystems: (i) Stringed Balls System, (ii) Tube Assembly, and (iii) Frame Support. Figure 6 below shows a general block diagram of the system components with the input and outputs:

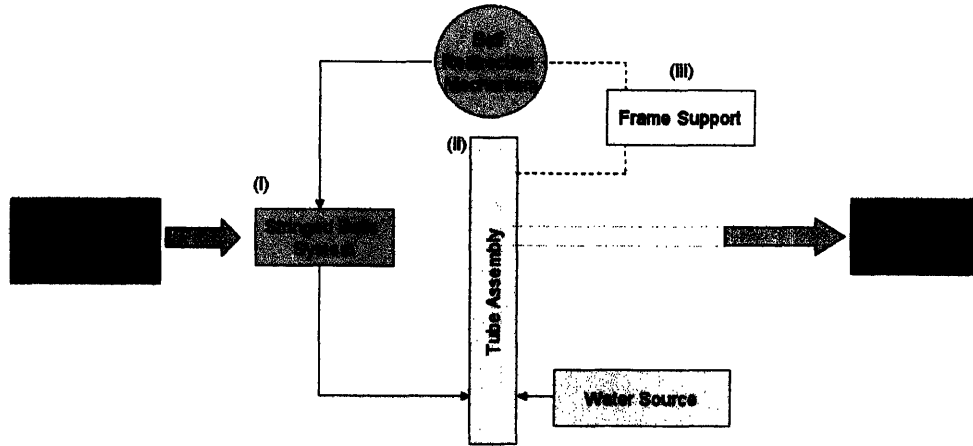


Figure 6 : Block diagram showing the general components of the ball-and-chain pump.

The user inputs some force on the stringed ball system which cycles the balls through the tube assembly, thereby drawing water from a water source. The water travels up the tube assembly to its top, where water is redirected out of the tube. A frame is necessary to support the tube assembly, as well as the mechanism for redirecting the balls downwards after exiting the tube. In this design, support is achieved with a wooden frame onto which a long pipe is attached. Water output is obtained at the top of the pipe by means of an overflow pipe. A bicycle wheel acts as a redirection mechanism for the exiting balls so that the pump is operated by pulling downwards on a string of plastic balls in a cyclical fashion, as shown in Figure 7 below:

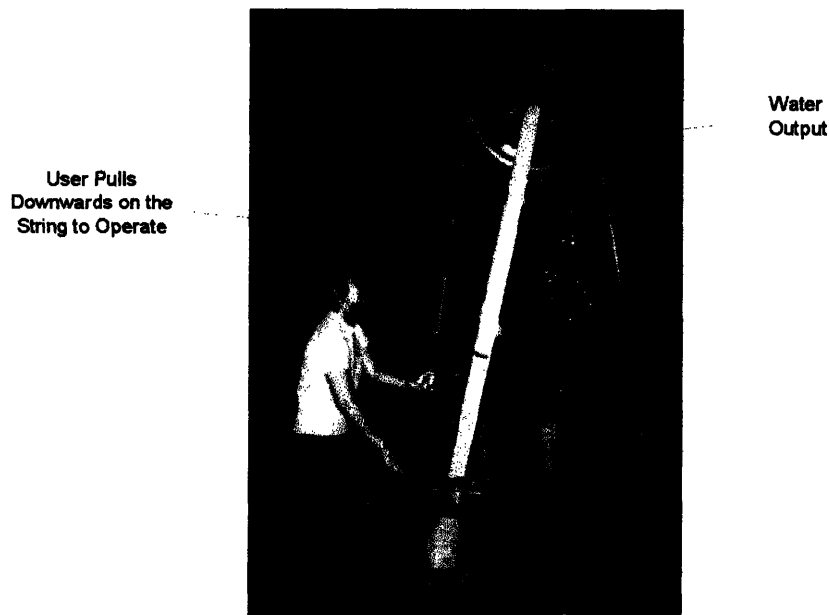


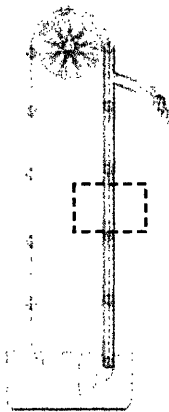
Figure 7 : The ball-and-chain pump during the pumping cycle (over flow tube not shown).

Polypropylene balls of diameter 50mm strung were together at regular intervals with 3.175mm diameter, 6m long polyester rope. Each ball has a clearance hole through which the rope was threaded. Balls were constrained from shifting along the length of the rope by knots that were tied at the top and bottom ends of the balls as shown in Figure 8.



Figure 8 : Polypropylene balls constrained on polyester rope.

The series of stringed balls was run through a clear PVC pipe of height 2.44 m, and inner diameter 52mm, so that there was a slight clearance between the balls and the walls of the pipe. The pipe assembly was supported by a wooden frame, and was constrained from sliding by fixing two hose clamps on either side of a wooden strut as shown in Figure 9:



Pipe Clamps

Figure 9 : Close up picture of the pipe assembly supported by the wooden frame and pipe clamps.

The balls that are cycled through the system enter the supported tube from the bottom and leave through the top. To facilitate the entrance of the balls into the tube, a funnel is attached in the form of a 90 degree curved section of PVC with a standard mating inner diameter of 60.3 mm. The area of the funnel can be optionally enlarged by fitting a 120.6mm to 60.3 mm, reducing PVC coupling the 90 degree elbow. Figure 7 shows a picture of the implemented funnel on the end of the pipe assembly:

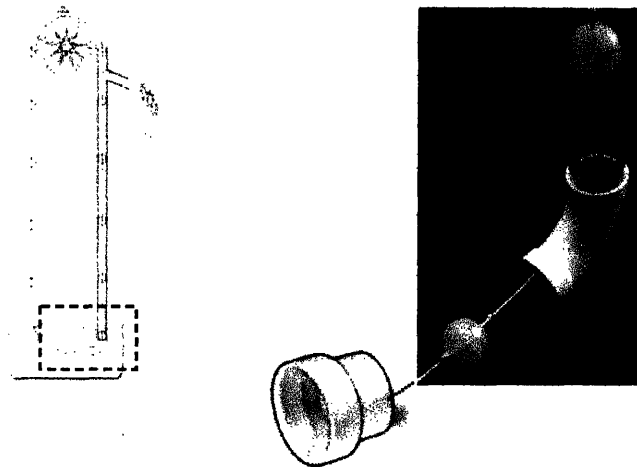


Figure 10 : Picture of the PVC couplings used to make a funnel at the bottom of the pipe assembly.

As the water column rises in the pipe assembly, the water eventually reaches the top portion of the pipe, where an overflow tube is used to redirect the water to another location such as a water slide. A 45 degree PVC wye is coupled to the top end of the pipe to allow the water to fall down the overflow tube. Balls that exit the pipe are redirected downward by passing over a bicycle wheel whose bearing shaft is cantilevered to the wooden frame. The rim of the bicycle wheel is wide enough to allow the balls sit securely within the groove. Figure 11 shows the top end view of the pipe assembly:

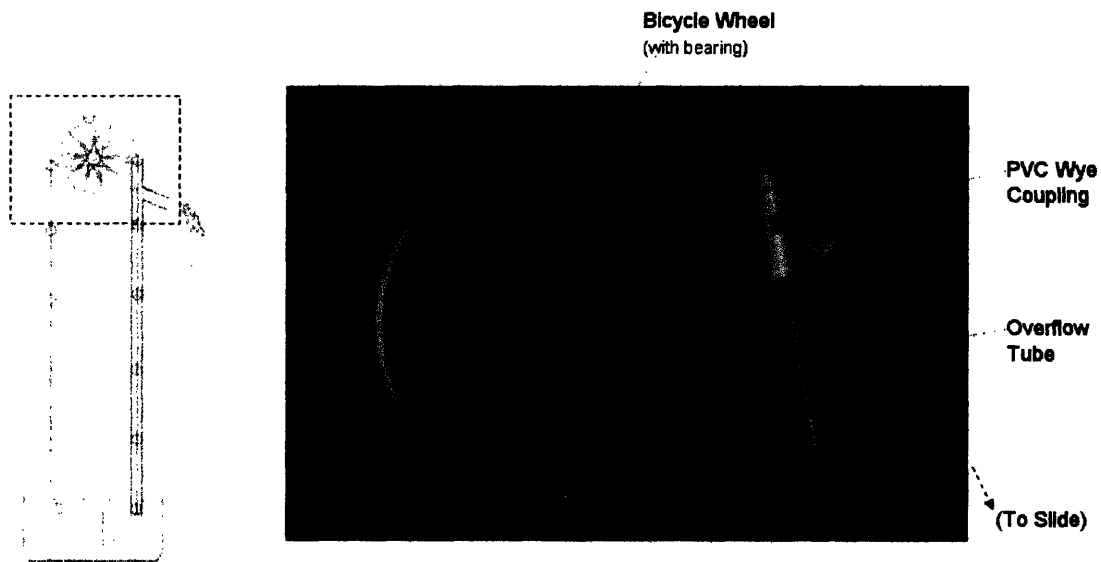


Figure 11 : Close up view of the top pipe assembly showing the overflow control and balls going around the supported bicycle wheel.

4.5 Design Process

4.5.1 Brainstorming and Concept Generation

Given the challenge of designing a human powered water pump, it was desired to come up with a solution that would elegantly address the problem but that would not exceed the constraints of complexity, cost, time and flexibility, for the children's television show. The ball-and-chain pump was selected out of a number of concepts because it offered a creative solution to the problem, yet remained inherently simple and robust. The physical construction of an effective ball-and-chain pump does not require elaborate or time consuming fabrication techniques, nor are the materials prohibitively costly or difficult to obtain. Based on these factors, the ball-and-chain pump appeared to be a strong candidate to be designed and tested as a prototype solution to the water slide challenge.

The inspiration to pursue the ball-and-chain pump design was derived from the author's previous experience with various types of human powered pumps. Historically, a number of unconventional human powered water pumps have been used for various applications such as irrigation, well water pumping and sump pumping. A few of these solutions are illustrated in Figure 12 below [8]:

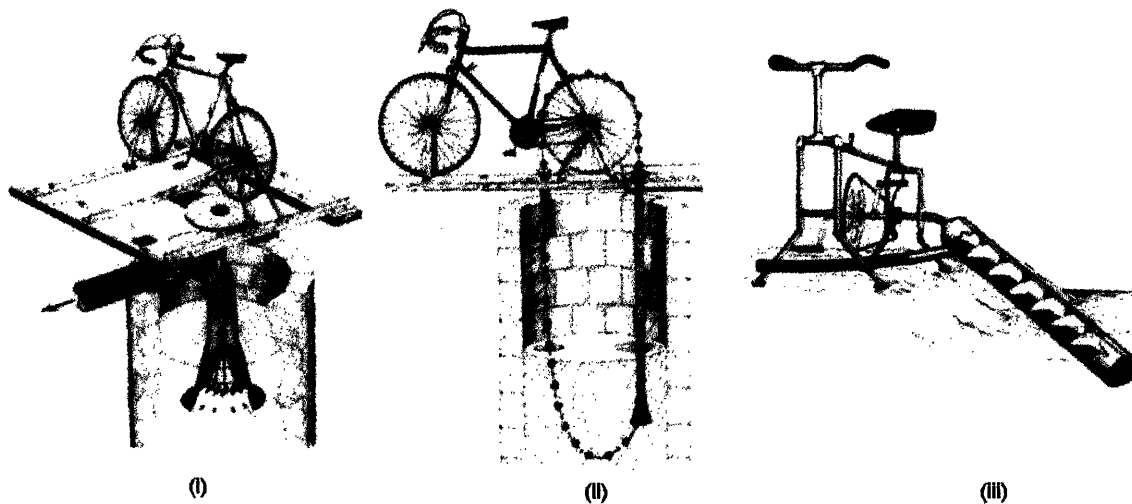


Figure 12 : Artist's rendition of various pedal powered water pumps i) Axial Water Pump ii) Ball-and-chain Pump iii) Archimedean Screw Pump [8].

Of the generated concepts, the ball-and-chain pump concept stood out as one that had potential to be modified into an effective solution prototype for the television show.

4.5.2 Component Selection

In order to design an effective ball-and-chain pump, a number of variables must be taken into account, including the considerations of material choice, component interfacing and overall component dimensions for the pump. It was decided that the main components of the ball-and-

chain pump must to include (i) a method of stringing balls in series, (ii) a conduit in which to guide water and balls, and (iii) a frame with which to support the components.

In the component selection of the ball-and-chain pump, all material choices were based around components that could be purchased from a local hardware store, at a low cost. For the ball-string system, it was decided that nylon rope could be used to tie various types of balls together, ranging in material, dimensions and inter-ball spacing. Plastic, rubber and wooden balls of roughly 50mm diameter were chosen as test materials. Circular conduit was chosen as a means to guide the balls and water through the pump. The tubular sections of the design were chosen around commonly available polyvinyl chloride pipe sections, which have standardized dimensions and convenient mating capabilities. For the main vertical pipe, clear PVC was chosen so that the flow of water, and movement of balls, could be observed during operation. The inner diameter of tubular sections and outer diameter of the balls were chosen so that clearance would vary with ball diameter, from 2 mm to a close fit. Using standard PVC piping for the main tube had the added advantage of allowing various component couplings to be added in a modular fashion. For example, both the entrance funnel and exit overflow components could be fabricated by simply attaching the matching diameter of existing PVC elbows and wye fittings, respectively.

For the pump support, wooden boards of thickness 25mm, width 15 mm, and varying length, were chosen as a sufficiently strong, light, and easily assembled frame material. A 50 cm diameter bicycle wheel, with the tire removed, was selected as a mechanism for allowing the balls to move in an arc upon exiting the top of the main pipe. After considering the overall pump dimensions, a main pipe height of 2.5 m was chosen, which would adequately demonstrate the pump's ability to pump water from ground level, to the height of a typical water slide. Taking into account the space required for the supporting wooden structure, the entire pump was designed to fit within in a 1.3 m² floor space with 2.7 m of vertical clearance. The major ball-and-chain pump components used in the final prototype are listed in Appendix 1.

4.5.3 Design Refinement and Construction

Once the necessary components were purchased for the ball-and-chain pump, as outlined in Section 4.5.2, the apparatus was constructed according to the design described in Section 4.4. In order to construct a string of balls in series, a clearance hole was first drilled through the center of each ball. The end of the nylon rope was threaded through the drilled holes and each ball was secured in place a double knot on either side of its hole. The process was repeated until a string of evenly spaced balls was constructed with sufficient length to go through the main PVC pipe in a cyclical fashion.

The pipe assembly was constructed by directly attaching the various additional PVC fittings to the ends of the main pipe. This frictional mate was decided to be sufficiently leak-proof due to the tight mating tolerances of the fittings, which were specifically purchased to match the pipe diameter. Once the over flow 'wye' and the inlet funnel were attached to the ends of the main pipe, a wooden frame was constructed to support the pipe vertically. The frame was constructed out of several lengths of 1-inch thick board, held together by woodscrews. The board segments were cut to shape and assembled using a band-saw and a hand drill. A large diameter hole, slightly larger than the main pipe diameter, was cut in the end of the wooden cantilever pipe support using a circular saw. The pipe assembly was held in this hole, and constrained from shifting vertically by placing pipe clamps on either side of cantilevered the

main tube. The vertical height of the main pipe was approximately 8 ft, which is sufficient height to demonstrate the overall pumping ability of the ball-and-chain pump.

For the ball redirection mechanism at the top of the pump, a bicycle wheel was obtained with the tire and inner tube removed. The axle of the bearing hub was replaced with a bolt long enough to fasten the wheel to the top of the wooden frame. The chain of balls was assembled so that the balls exiting the main pipe would be carried around in the groove of the bicycle wheel, and redirected downwards back into the pipe inlet funnel.

The assembled ball-and-chain pump was constructed using only common tools that will be available to the children in the workshop. The tools used to make the prototype included a band saw and hole saw for cutting, hand drills to make through-holes and drive woodscrews, and wrenches and screw drivers for fastening and tightening. The entire ball-and-chain pump construction time was less than approximately three hours.

4.6 The Ball-and-chain Pump Test Setup

The ball-and-chain pump was tested on its pumping ability, where a measure of performance included factors such as pump reliability, robustness for continuous use, and the resulting water flow rates for a given pulling force and ball speed. The apparatus was set up as shown in Figure 5, with the end of the pipe assembly submerged 15 cm into a water reservoir. The balls were pulled through the tube at an approximately constant speed, so that the flow rate of the pump could be calculated from the total amount of water expelled at the output over the time of pumping.

In order to optimize the water pumping ability of the design, several variables were adjusted across various configurations. In the pumping cycle it was critical to minimize the force and velocity necessary to continuously pull the chain of balls through the tube. For a fixed pipe diameter, the radius of the balls was a key variable in deciding the how much clearance existed between the balls and the pipe walls. By changing the types of balls used in the apparatus, the effects of ball diameter, ball material, and inter-ball spacing were observed. In this case, two types of balls were tested: tight-fitting rubber balls of outer diameter 2 inches, and also loosely fitting plastic balls with approximately 0.01 mm clearance. The tilt of the main pipe was altered by adding spacers to one leg of the tripod wooden frame so that the main pipe could be tilted from vertical by a measurable angle. The resulting leak rate for the different diameter balls was also observed by pumping the water column up to some height and then holding the balls stationary so that the water was free to drain back into the water reservoir.

4.7 Results

The testing of the ball-and-chain pump, for the configuration where the loosely fitting plastic balls were used, showed that that it was possible to pump water from a reservoir up to a height of 8 ft with reasonable pulling power. For a rope-pulling speed of approximately 0.7 m/s, the resulting average water mass flow rate was of the order 1.19 kg/s. In this configuration the input force required from the user was approximately 46.7N. This low required pulling speed and effort implies that the continuous pulling action of the ball-and-chain pump could be achieved and sustained by a child of average strength. Figure 13 below shows a photograph of the typical water output using the loosely fitting plastic balls:

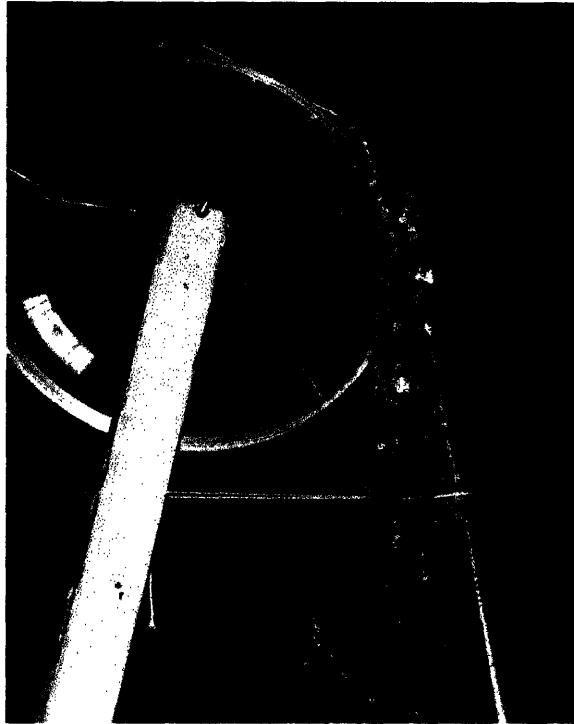


Figure 13 : Photograph of typical water output achieved by the ball-and-chain pump (overflow pipe removed).

Due to the regular interruption of balls at the outlet, the water tended to be expelled in bursts rather than in a purely continuous fashion. However, the observed total flow is sufficient to provide water for a water slide application, provided that the balls are pulled with sufficient velocity, or 0.7 m/s.

In the case where the tightly fitting rubber balls were used, the overall required pulling force became large, due to an increased friction within the pipes. This increased friction was enough to prevent the balls from cycling, and consequently water flow could not be achieved. The diameter of the rubber balls was chosen to closely match the inner diameter of the main pipe, but large variations in rubber ball diameter resulted in some balls' being oversized by up to a millimeter. The compliance of the rubber balls would allow the ball's shape to morph accordingly in the pipe, where a larger ball diameter resulted in a tighter radial fit and increased frictional force. This increase in friction had a particularly large effect within the 90 degree bend at the inlet funnel, where the ball's direction suddenly changes. The radius of any bends in the ball-and-chain system will therefore have a greater effect for configurations with more tightly fitting balls.

The water leak rate measured for the plastic balls with 1 mm clearance was approximately 0.14 kg/s which meant that an estimated 10.5% of the total possible water output was lost due to water leak during operation. For small ball diameters and consequently large gap space, it was expected that the resulting water leakage would be relatively large, but that the friction of the balls' rubbing along the pipe walls would decrease. If the resulting gap size were too large, then the user would have to compensate for a large leak rate by increasing the speed of pulling. In a configuration where the balls fit too tightly within the pipe, the user may have to overcome substantial frictional force, particularly in the case where there are many balls in the

tube at any one time. Therefore as the radius of the balls increases, the system also becomes more sensitive to variations in the number of balls present in the tube, as well as material-specific coefficient of friction between the ball material and the PVC pipe wall. By choosing a ball of relative lower friction coefficient, in conjunction with an undersized ball diameter, the user can sacrifice a percentage of the overall water flow rate due to leak, for increased ease of operation due to reduced friction.

4.8 The Ball-and-chain Pump as a Feasible Prototype for Design Squad

The results show that the ball-and-chain pump design and fabrication represents a feasible and creative solution to a human powered water slide challenge. The pump construction requires neither excessive fabrication time, nor workshop tools beyond basic cutting and drilling. The entire pump assembly can be made in fewer than 3 man-hours with tools that would be readily available the *Design Squad* team. In the actual construction of the pump on the show, the fabrication time will take longer, but will most likely not exceed the timing constraints of the show.

All the materials necessary to make the ball-and-chain pump are readily available from a local hardware store, and can be purchased for reasonable cost. The design itself proves to be flexible in the configuration and choice of components, and if such a design were pursued, there would be adequate creative space to explore different variables for pump optimization. For example, the choice of ball material and diameter, ball spacing, or devising a suitable ball-redirect mechanism at the outlet of the pipe assembly, necessitate testing of the various configurations in order to prove one design superior in the pumping challenge. The ball-and-chain pump therefore has much room for iterative developing and testing.

The educational aspect of the pump introduces many important engineering principles ranging from basic fluid dynamics, to structural and mechanism design. Children may be exposed to many of the types of questions that typically arise in the design process, such as, “How can improve the device performance? How do I reduce the frictional interaction? How can I make the design more stable?” The ball-and-chain pump represents a solution that has adequate technical depth while retaining simplicity, and exemplifies the *Design Squad* theme that diverse solutions are possible with unlikely combinations of everyday materials.

5 Plunger pump

5.1 Introduction

The second solution to the human-powered water slide is based on the design of a more conventional positive-displacement pump; the solution most closely resembles a diaphragm pump in functionality. The solution was designed and constructed with the aim of simulating commonplace, commercially-available pumps but by using readily-available, off-the-shelf components that are not traditionally used to make water pumps.

The solution utilizes a bellows-style toilet plunger to suck water through, and push it out, a series of one-way check valves. Hoses coming from the water source to the pump, and leading from the pump to the top of the water slide contain the displaced water as it flows. The pump unit, or the plunger-valve setup, is constrained by a wooden base that rests on any flat surface from which the user can easily access the plunger handle. The pump is operated by a single user who pumps the polyethylene plunger using the same motion one would use to pump a toilet.

5.2 Plunger Pump Theory

5.2.1 Positive Displacement Pumps

Water pumps are classified into two main categories: positive-displacement pumps and dynamic or momentum-change pumps. The plunger pump that was designed specifically for the *Design Squad* challenge is an example of a positive displacement pump.

Positive displacement pumps, such as the plunger pump discussed here, force the water through the system by volume changes. The water is admitted to the pump through an inlet upon the opening of a cavity. The cavity then closes, and the fluid is squeezed out through an outlet [9].

Positive displacement pumps are generally classified further into two categories: reciprocating designs and rotary designs. The bellows plunger used in the solution to the waterslide challenge best mimics a piston or diaphragm pump, both of which are reciprocating positive displacement pumps. The plunger pump is also a reciprocating design.

Positive displacement pumps operate by delivering a pulsating or periodic flow as the cavity volume opens, traps, and squeezes the water inside. Figure 14 below shows the general schematic of a basic reciprocating piston or plunger pump.

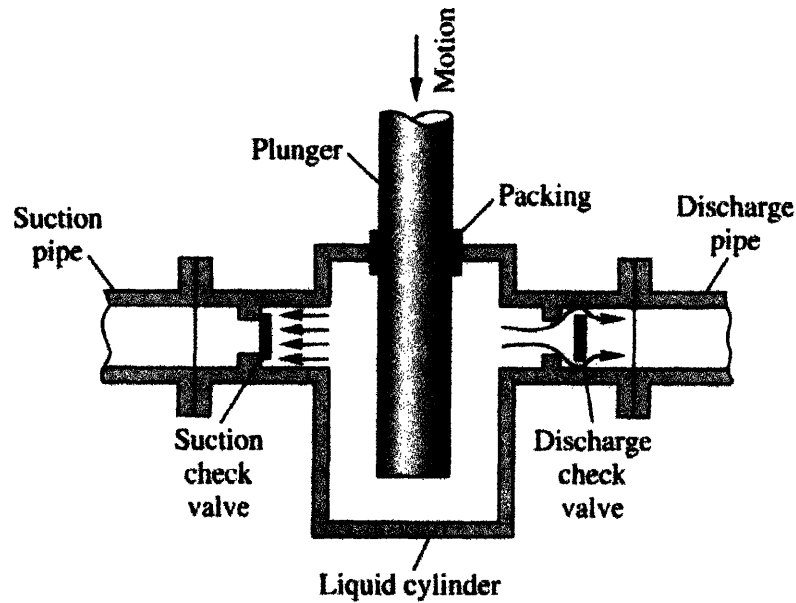


Figure 14: Schematic of a basic piston pump [9]

Because positive displacement pumps mechanically compress against a cavity filled with liquid, they often develop very high pressures if the outlet is closed for any reason. Sturdy construction is required, and the complete shutoff of the outlet valve causes damage if pressure relief valves are not used [9].

5.2.2 General Characterization of Flow in Plunger Pump

Consider the flow of water through the plunger pump setup shown in Figure 15.

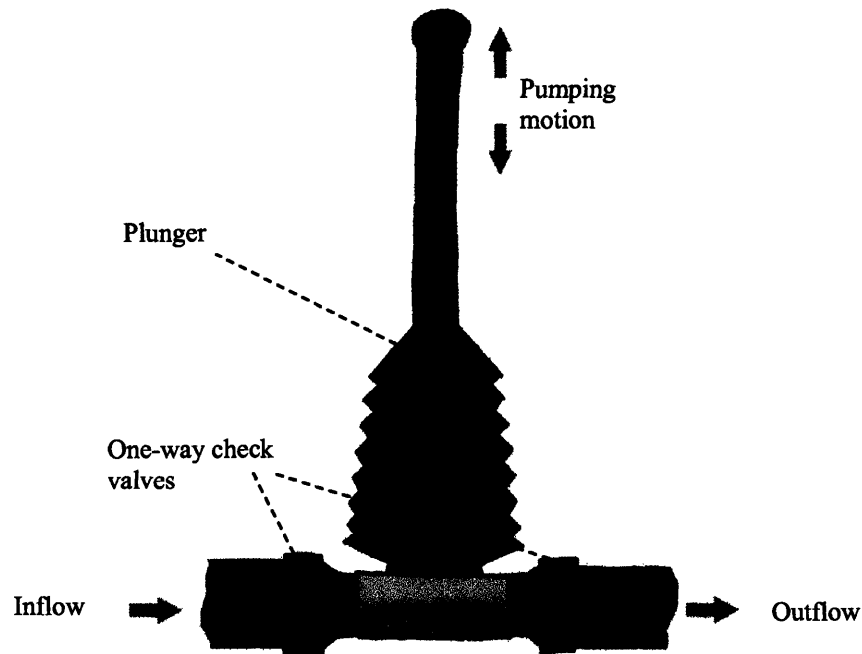


Figure 15: Schematic of the plunger pump setup.

The flow studied in this section of theory, and the flow that is assumed to be seen throughout the plunger pump system, is viscous, internal flow as treated through circular ducts. Internal flow is constrained by the bounding walls, and the viscous effects will grow, meet, and permeate the entire flow [9]. A nearly inviscid flow converges and enters the pump system upstream in the entrance region. Further downstream, viscous boundary layers grow, and the axial flow at the wall of the pipe is retarded. Consequently, the core flow at the center of the pipe is accelerated to maintain continuity as dictated by

$$Q = \int u \cdot dA = \text{constant} . \tag{24}$$

Before calculating critical operational values of the pump, including the force and power required to pump to waterslide height, the nature of the flow must be determined. Using standard Reynolds Number calculations, the flow through the circular ducts of the system can be characterized as either laminar or turbulent. The Reynolds number, as defined in Eqn (12) is the reference velocity of the system, L is the reference length (in this case, the diameter of the pipe through which the water is flowing), and μ is the dynamic viscosity of the water, or 0.89×10^{-3} Pa·S.

Given the geometry of the plunger pump system, the 1.75-liter volumetric displacement capacity of the plunger's bellows with each stroke cycle, and the 3.81 cm inner diameter of the pipe through which the flow passes, a flow rate of about 0.75 l/s is estimated, yielding an approximate reference velocity U of 0.165 m/s. The Reynolds number from Eqn (12) becomes

$$Re = \frac{(1000 \text{ kg} / \text{m}^3)(0.165 \text{ m} / \text{sec})(0.0381 \text{ m})}{(1 \times 10^{-3} \text{ Pa} \cdot \text{S})} = 6287. \tag{25}$$

The accepted design value for pipe flow transition from laminar flow to turbulent flow in the study of viscous flow in ducts is assumed to be

$$Re_{crit} \approx 2300 . \tag{26}$$

[9]. It is therefore seen that the flow through the plunger pump system can be considered turbulent. The profile of turbulent flow through a circular duct, like the ones used in the plunger pump system, is shown below in Figure 16.

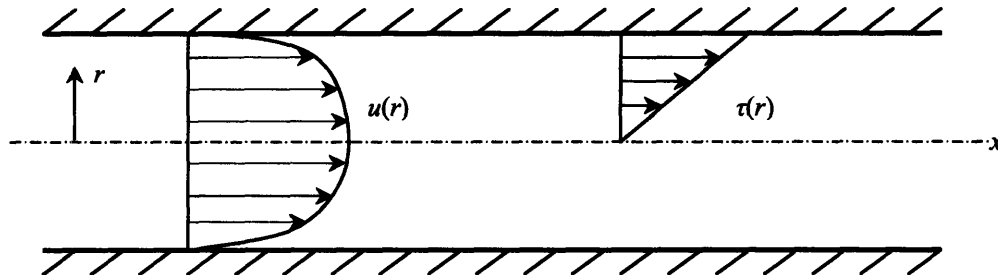


Figure 16: Velocity and shear profiles in fully developed turbulent flow.

Accordingly, there are some implications of turbulent flow that must be considered when designing the rest of the plunger pump system. Although negligible in laminar pipe flow, surface

roughness has an effect on friction resistance in turbulent pipe flow. In fact, turbulent flow is strongly affected by roughness. The roughness of interior pipe wall should not be neglected when designing a pump system.

Boundary layers faster in turbulent flow than in laminar flow. Accordingly, the axial distance along the pipe length at which the velocity profile becomes constant, or L_e , occurs at a proportionally shorter distance than in laminar flow. The entrance region of a given turbulent flow can be calculated using Eqn (27),

$$\frac{L_e}{d} \approx 4.4 \text{Re}_d^{1/6}, \quad (27)$$

where d is the diameter of the pipe, and Re_d is the Reynolds number as calculated above in Eqn (3). Using the 1.25-inch diameter of the draw tube, the entrance region in the pump setup is calculated to be of length

$$L_e = 4.4(7060)^{1/6}(1.25\text{in})(2.54\text{cm}/\text{in}) = 61.2\text{cm}. \quad (28)$$

For a draw tube that is greater than two meters in length, this entrance region represents no more than 3 percent of its length. The tube used in the plunger pump solution is at least two meters in length, because it connects the water supply to the pump itself.

The friction factor, f , that is used to characterize frictional losses in a pipe system, is obtained from a Moody chart, using the Reynolds number and the relative roughness of the inside walls of the pipe.

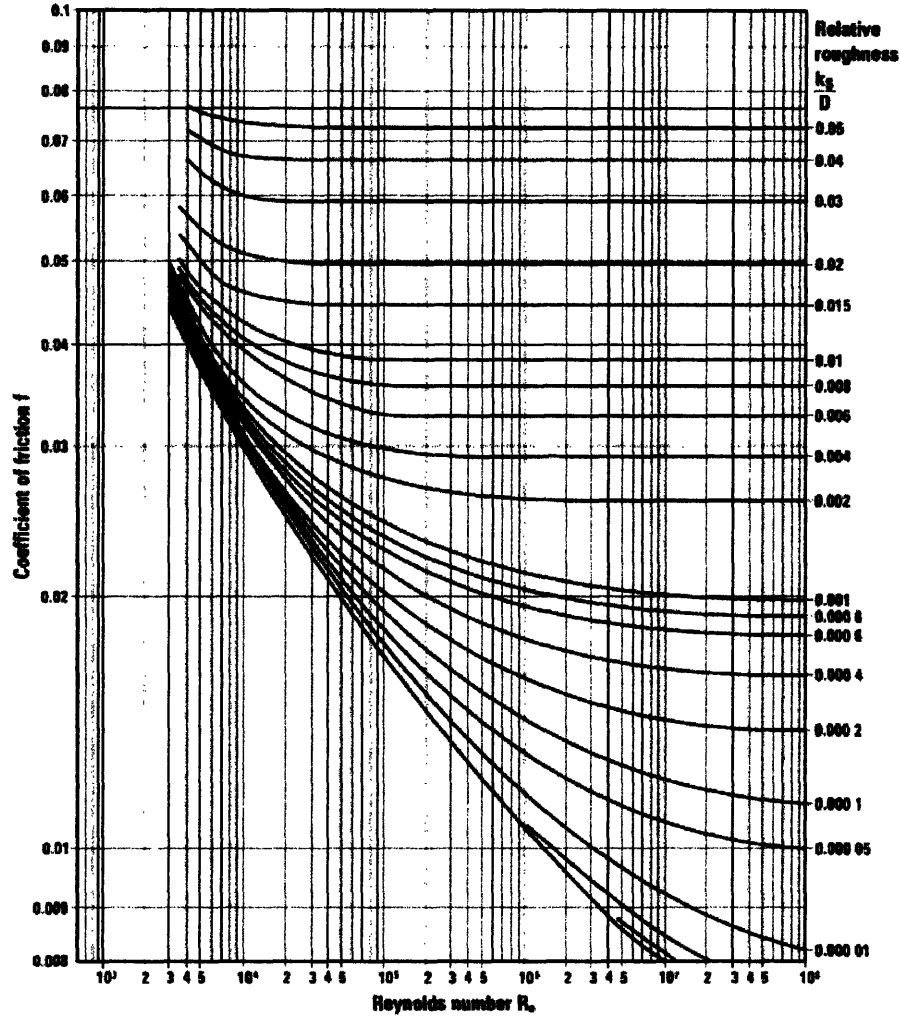


Figure 17: The Moody chart for pipe friction with smooth and rough walls.

The Moody chart, as shown in Figure 17, is a graphical representation of the interpolated solution to determine the friction factor,

$$\frac{1}{f^{1/2}} = -2.0 \log \left(\frac{\varepsilon/d}{3.7} + \frac{2.51}{\text{Re}_d f^{1/2}} \right). \quad (29)$$

The recommended roughness value for commercial pipe, ε , as used in Eqn (29) above (and needed to use the Moody chart) is approximately 0.0015 mm for plastics, including the PVC used in much of the plunger pump system. Therefore, for pipe of 3.81 cm diameter, the relative roughness ε/d is

$$\frac{\varepsilon}{d} = \frac{0.0015 \text{ mm}}{381 \text{ mm}} = 3.937 \times 10^{-6}. \quad (30)$$

It follows from the Moody chart that for the flow under consideration, the coefficient of friction, f , is

$$f = 0.034. \quad (31)$$

We can then calculate the head loss due to friction, by using the following relationship:

$$h_f = f \frac{L V^2}{d 2g}. \quad (33)$$

Inputting values for the plunger pump system reveals that

$$h_f = (0.034)(2.13m / .0381m)(0.165m / s)^2 (2 * 9.81m / s^2)^{-1} = 1.34 \times 10^{-4} m \quad (34)$$

In a seven-foot (or 2.13 meter) long length of pipe, the frictional losses are small; if the height to which the water were being pumped increases, the losses become more significant. An increased flow rate would lead to a drastic increase in losses.

5.2.3 Operational Characteristics of Plunger Pump System

There are a few significant quantities to consider when designing a pump system. The force needed to push down on the plunger is a critical value. Additionally, the power required to operate the pump must be considered; the pump must be operable by a single human.

The force required to successfully collapse the bellows and displace its volume of water is directly related to the weight of the water the pump is moving vertically upward. Assuming the pump is already primed and a steady-state situation is achieved, the weight of the water being displaced upward will be

$$w_{pump} = \rho g \pi \left(\frac{d}{2} \right)^2 h \quad (35)$$

where ρ is the density of the water being pumped, d is the tube diameter, and h is the height difference between the pump level and the top of the water slide. Assuming a seven-foot, or 2.13-meter water slide, and a pump that is sitting on ground-level, the force required to pump the water will approximately equal the weight of the water, or

$$w_{pump} = (1000kg / m^3)(9.81m / s^2)(\pi)(0.0191m)^2(2.13m) = 23.9N. \quad (36)$$

The force required to pump the water will change depending on the height of the waterslide and the location of the pump along the vertical rise of the slide. If a lower pushing force is desired, the pump can be positioned partially up the vertical rise of the slide, so that increased vertical draw is required, but less vertical push force is needed.

The power required to operate the pump is critical; human power output does not typically exceed 100 watts, and even this rate cannot be sustained for long periods of time. The power delivered to the water is a factor of the flow rate being achieved by the pump, the weight of the water, and the change in Bernoulli head, H , of the flow from the pump location to the exit. H is defined as

$$H = \left(\frac{p}{\rho g} + \frac{V^2}{2g} + z \right)_2 - \left(\frac{p}{\rho g} + \frac{V^2}{2g} + z \right)_1 = h_s - h_f \quad (37)$$

where h_s is the pump head supplied and h_f represents the head losses as determined in Eqn (33). The power delivered to the fluid is just the specific weight times the discharge times the net head change, or

$$P = \rho g Q H \quad (38)$$

where Q is the flow rate. Assuming negligible losses for the moment, the power delivered to the column of water via the plunger pump, with a flow rate of roughly 0.75 liters per second, is about

$$P = (1000 \text{ kg} / \text{m}^3)(9.81 \text{ m} / \text{s}^2)(7.5 \times 10^{-4} \text{ m}^3 / \text{s})(2.13 \text{ m} - .000134 \text{ m}) = 15.67 \text{ watts.} \quad (39)$$

5.2.4 Minor Losses in the System

There will be other minor losses in the system due to the various piping components that attach to the pipe. Every fitting and valve used in a duct system brings with it its own losses. A resistance coefficient, defined as

$$K = \frac{h_k}{V^2 / 2g} \quad (40)$$

has been developed for valves, elbows, and tees. From Eqn (39), the head loss due to the fittings, h_k , can be obtained. The plunger pump system features two swing-check valves and one PVC tee, through which the flow passes.

	Nominal diameter, in									
	Screwed					Flanged				
	$\frac{1}{2}$	1	2	4	1	2	4	8	20	
Valves (fully open):										
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5	
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03	
Swing check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0	
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0	
Elbows:										
45° regular	0.39	0.32	0.30	0.29						
45° long radius					0.21	0.20	0.19	0.16	0.14	
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21	
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10	
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20	
180° long radius					0.40	0.30	0.21	0.15	0.10	
Tees:										
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.07	
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41	

Figure 18: Resistance coefficients for open valves, elbows, and tees [9].

The resistance coefficients for 1.5-inch tube can be extrapolated from the coefficients for 1- and 2-inch tube. Each swing check valve has a resistance coefficient of about 2.5; although the flow through the PVC tee is ultimately line flow, it must be treated as two branch flows in series, since the flow is drawn up through the tee branch into the plunger's bellows and pushed out again through the other branch. Each branch's friction coefficient is approximately 1.6.

5.3 Detailed Description of Plunger Pump System

The plunger pump system, as shown in Figure 19, is constructed using a minimal number of components, all of which can be bought off-the-shelf from any large home-supply store (like Home Depot) or any large internet-based supplier (like McMaster-Carr). The total cost of the supplies needed to construct this pump solution is about \$50; the most costly component is the swing-check valve, of which two are needed.

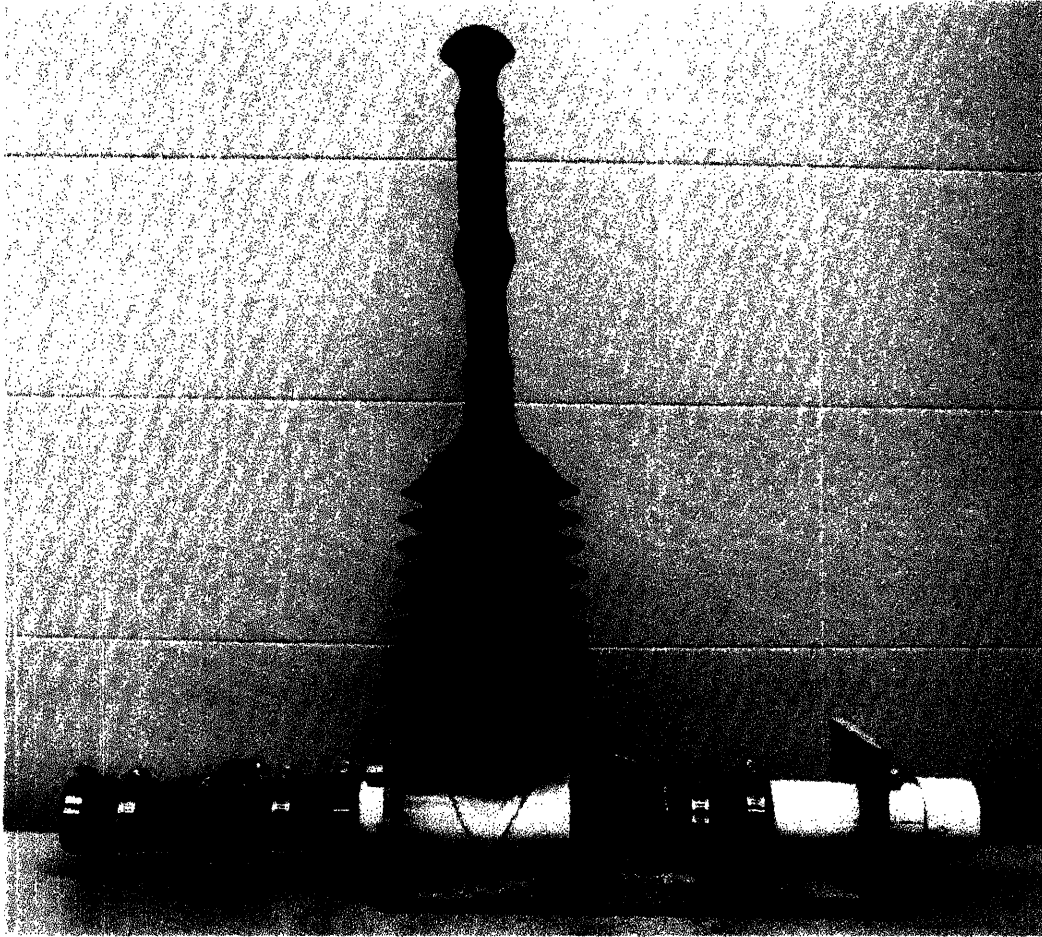


Figure 19: Overall setup of plunger pump system.

The pump unit includes a 1.5-inch PVC tee, as shown in Figure 20, oriented with its long end parallel to the flat surface on which the unit rests.

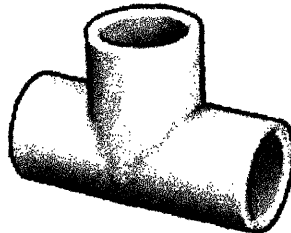


Figure 20: Image of 1.5-inch PVC tee from online vendor McMaster-Carr [10].

Shown in Figure 21, the bellows plunger, made of blue polyethylene plastic, has an opening diameter of 3.25 inches. The bellows of the plunger is about 10 inches in height, has an uncompressed volume capacity of 2 liters, a compressed volume capacity of 0.75 liters, and its handle is 11 inches in length. The plunger is attached to the opening of the tee perpendicular to the directions of inflow and outflow. The air- and water-tight seal between the tee and the plunger is created through the use of a thin, adhesive rubber strip wrapped exactly once around the contact interface between the tee and the plunger.

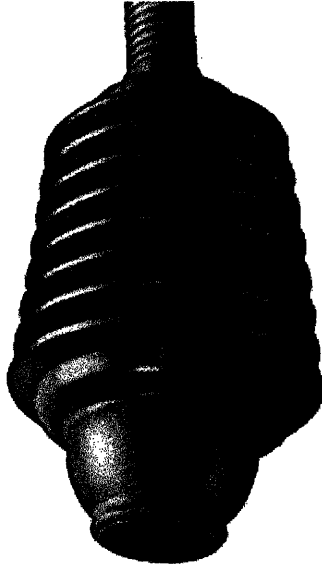


Figure 21: Bellows toilet plunger [10].

Attached to both the inflow and outflow ends of the PVC tee are one-way check valves, as shown in Figure 22. These valves, which are sold at hardware stores as sump-pump attachments, are sized to accept 1.5-inch intake pipe and 1.25-inch outflow pipe. Both valves are oriented in the direction of the water flow. On one side of each valve, there is a direct connection with the PVC tee. On the other side of the valves, the connection to 1.5-inch PVC pipe is made with rubber reducing couplings and hose clamps that are provided with the valve.

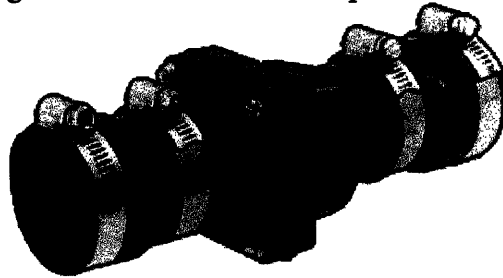


Figure 22: Swing check valve [10].

Attached to the 1.5-inch PVC inflow and outflow tubes are 1.5-inch- diameter PVC couplings. These couplings allow a connection with the hoses that transport the water. A variety of hose can be used, as long as an air-tight seal can be achieved between the hose and the PVC pipe. In this setup, shown in Figure 23, duct tape was wrapped around the end of the hoses until a tight press-fit was created.

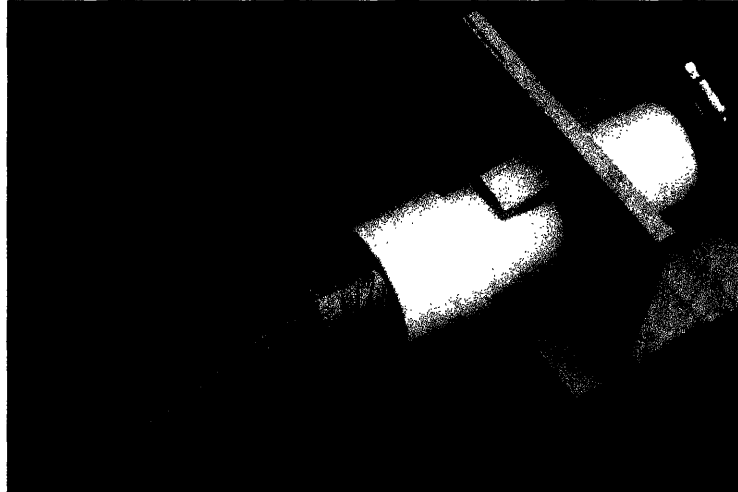


Figure 23: Duct tape seal between hose and coupling.

The wooden stand that holds the pump setup stationary consists of three separate pieces of plywood held together by wood glue and nails. The base of the stand is a 5-inch by 14-inch piece of plywood; the two endplates are made from the same plywood, but feature holes larger than the outer diameter of the PVC pipe to constrain the pipe. The holes on the endplates are positioned vertically so the flat, square face of the check valve rests against the bottom of the base. Small pieces of wood are inserted in the gap between the endplate hole and the pipe through the endplate, to rigidly support the entire fixture in the wooden stand and prevent relative motion between the pump system and the stand.

5.4 Design process

5.4.1 Brainstorming and Concept Generation

It was established by the producers and content directors of *Design Squad* that a conventional “pump-like” method of powering a waterslide should be one of the two solutions established for the water slide challenge. Although the use of simple, commercially-manufactured diaphragm hand pumps was originally proposed, it was decided that a positive displacement-like pump composed of off-the-shelf components available at a home hardware store was more educational, and easier to relate to for the targeted viewer audience than a ready-to-use diaphragm pump.

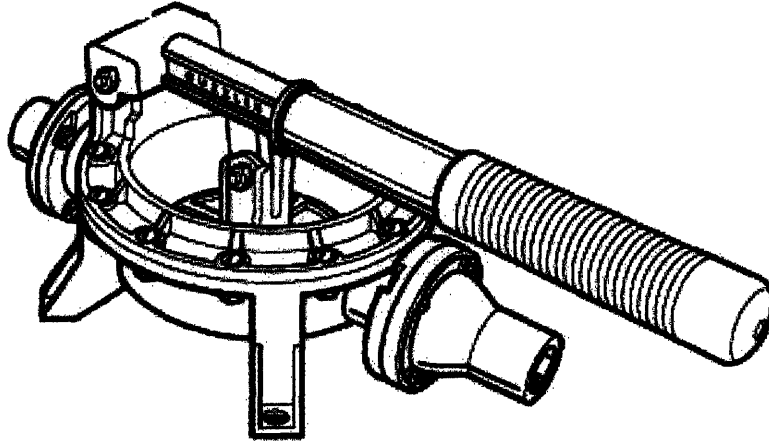


Figure 24: The Bosworth brand diaphragm pump on which the plunger pump is based [13].

The bulk of the design brainstorming involved finding objects that mimic positive displacement pumps. The Bosworth-brand Guzzler pump series, one of which is shown in Figure 24, with which the author was familiar from a previous human-powered pump project, was used as an example pump off of which the adaptive brainstorming was based.

Toilet plungers immediately stood out as commonplace objects that are familiar to children and that articulate sucking and displacing motions. It appeared favorable that a “typical” red rubber toilet plunger is shaped similarly to the rubber diaphragms utilized in Bosworth-brand hand pumps and is also made of rubber. Multiple types of plungers were acquired, to see which worked best as a positive displacement pump mechanism, both functionally and ergonomically.

To successfully draw water from a source, two valves are needed to effectively seal the pump chamber and create suction during the upward motion of the pumping stroke. Although it was established that one-way check valves can be manufactured using rubber reinforced by other rigid material, it was also known that there exist commercially-available check valves that might fit the apparatus.

A way in which to connect the plunger and the two check valves in close proximity was needed. Because there is an extensive range of PVC pipe fittings, it was known that a tee-shaped PVC component in the necessary and not-yet-determined size would be easily available. Finally, a way in which to carry the water being drawn to the pump, and then being pumped up to the top of the waterslide was considered. It was decided that flexible tube of an appropriate diameter would be the most suitable option for the channeling of the water.

When brainstorming and designing the basic plunger pump, no solid modeling software was used. Because the children who will ultimately design and build a similar water pump will have only two days to design, build, and test the apparatus, and because they will not have had prior experience with solid modeling software packages, the only sketching and modeling that was done was completed by hand on paper.

5.4.2 Component Selection

The choosing and acquiring of components to assemble the plunger pump represented a significant portion of the time spent on the design process. All components were purchased either over the internet from the general catalog-based supplier McMaster-Carr, or from The Home Depot. The selection of materials and components to be used for the pump had to be made

deliberately, because everything used in the setup must be available to the contestants when they shop for components at local hardware stores.

It was unclear which style of plunger would work best to pump water in the desired configuration, so multiple types were ordered: two types of rubber-cup plungers and two bellows-style polyethylene cup plungers. A general purpose red plunger with a 6-inch diameter rubber cup and a black toilet-specific rubber plunger with an extra lip and a 3-inch opening were ordered; in addition, a toilet-and-sink bellows plunger with a 3.25-inch opening and a 1.6-gallon bellows plunger with a 1.5-inch opening were ordered. Each is shown in Figure 25.

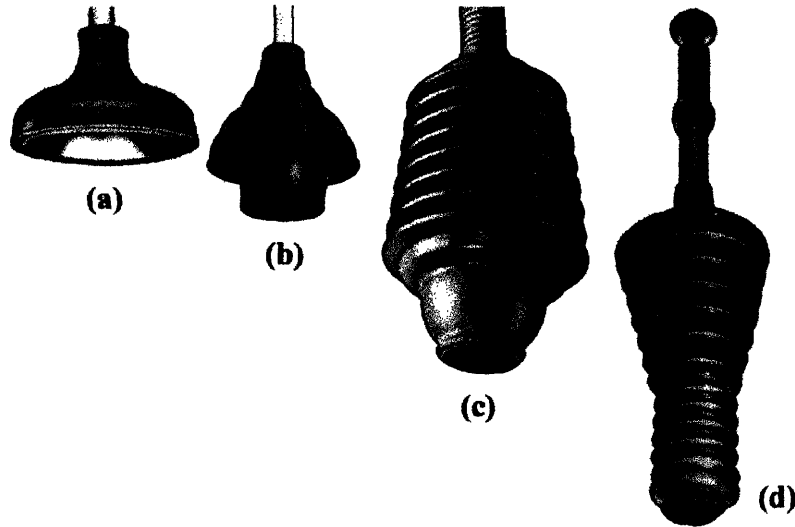


Figure 25: The four potential plungers that were purchased: (a) 6-inch diameter rubber cup, (b) toilet-specific rubber cup, (c) toilet-and-sink bellows, (d) 1.6-gallon bellows.

Because each plunger had to fit tightly around the outside of a PVC tee, multiple tees of different diameters were purchased. Two different sizes of hose clamps, whose circumferences can collectively be adjusted sufficiently to accommodate any of the four plungers, were also purchased. It was assumed that the plungers would be fastened securely around the outside of the tee with a hose clamp.

PVC couplings in a variety of sizes were purchased to accommodate the testing of multiple plunger diameters; reducer couplings were also purchased to allow the pipe size to be 1.5-inches in diameter regardless of the tee size chosen. Accordingly, two five-foot lengths of 1.5-inch diameter PVC pipe were purchased.

A one-inch wide, five-foot length of adhesive-backed polyurethane film was purchased with the knowledge that tight press-fit seals were needed in multiple locations. It was hoped that, in the event that components did not fit together tightly enough in their original states, the use of a layer of the rubber film would increase the press fit between the components and create a sufficient air- and water-proof seal.

Finally, although wood, nails, wood glue, and other common hardware components can be purchased, it was hoped that there is a sufficient amount of each on the set of *Design Squad* that contestants will have it at their disposals. None of the above was purchased for this specific project, but each was considered and eventually utilized during the design and construction process.

5.4.3 Design Refinement and Construction

After purchasing the various components that were thought to be useful, some time was spent experimenting with the various plungers and pipe fitting sizes to see which would yield the most effective plunger pump. It was quickly decided that the general-purpose 6-inch red rubber cup plunger in Figure 25 (a) (with which most people are familiar) has too large a diameter and not enough height to securely attach it to any sort of fitting or pipe. Likewise, it was obvious that the 1.6-gallon bellows plunger, as shown in Figure 25 (d) does not have a sufficiently large opening to be clamped to a PVC pipe.

The remaining two plungers, one rubber cup-style and one polyethylene bellows-style, were each attached to a PVC tee as originally planned. Figure 26 shows the two setups.

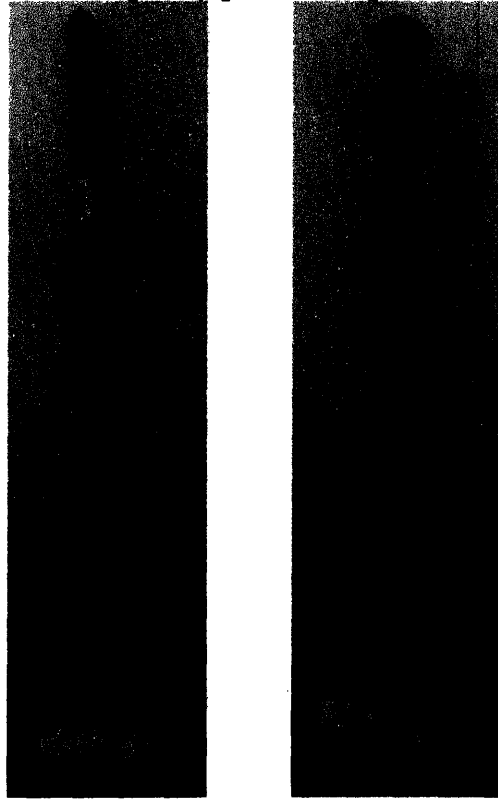


Figure 26: The rubber cup plunger and the bellows plunger, each attached to a PVC tee

After preliminarily configuring the two plungers on the PVC tees, it became obvious that the bellows plunger would provide a larger volume change, and thus larger flow capacity, with each pump stroke. Its pumping motion was also the more ergonomically satisfying of the two plungers. Accordingly, the design proceeded utilizing the polyethylene bellows plunger press-fitted directly onto a 1.5-inch PVC tee.

The remaining components of the originally proposed design were then attached with relative ease. The two sump-pump check valves attached to the PVC tee directly, without the use of intermediate pipe or couplings. Although the hose that was purchased did not directly mate with the PVC tube attached to the inflow and outflow valves, PVC couplings were added to the tube and the hose ends were wrapped in thin strips of duct tape until a tight press-fit seal was achieved. The seal created a sufficiently tight connection between the plunger pump setup and

the inflow and outflow hoses. The plunger pump unit itself and the hose connections took no more than three hours to construct and assemble; they should be able to be easily built by the student contestants within the time frame of the filming of the episode.

A wooden rig was constructed to house the pump unit and to allow it to be self-supporting. Because the check valves have a square cross-sectional area, they allowed the pump unit to be mounted flush to a flat surface. The end pieces of the wooden base were machined using a 2-inch-diameter hole saw in a drill press, and a band saw, both of which students will have on the set of *Design Squad*. The rig was assembled using wood glue and nails; the entire assembly, including the cure time of the glue, took under an hour.

5.5 The Plunger Pump Test Setup

The pump was tested locally, drawing water from a filled basin and pumping into an appropriate water disposal area. Because of the difficulty involved with procuring a waterslide and pond, neither an actual water slide nor a pond was used for the technical testing of the pump.

Preliminary tests of the overall functionality were performed at ground level. No outflow pipe was hooked up to the plunger pump; the water was simply exited the pump system after passing through the second check valve.

To create a more realistic testing environment, the outflow hose, which was attached to the plunger pump setup on its other end, was raised 7 feet in the air as seen in Figure 27; the 7-foot head used to test the apparatus was intended to simulate the height of the water slide that will be available at the local pond or swimming pool that will be used for the filming of the episode.



Figure 27: The Plunger Pump setup, when pumping to seven feet from ground level.

After it was seen that the bellows structure of the plunger was insufficiently rigid to support the downward push force needed to empty its contents, the testing setup was changed. The plunger pump rig was moved to the top of the vertical ascent, so that the largest force required was in the upstroke. Because rigidity is not a concern when pulling the plunger upward and expanding its volume, the remainder of the testing and utilization of the pump was done with the pump raised relative to the water source. Suction, in stead of pushing, became the primary method of transporting the water, as shown in Figure 28.



Figure 28: The plunger pump being used to draw up to a raised elevation

5.6 Results

The pump was preliminarily tested in two different scenarios; first, its functionality and usability were tested by pumping at zero head. After verifying its functionality, the outflow hose of the plunger pump was raised to 7 feet, to simulate the 7-foot waterslide height that will be encountered by participants in the actual challenge.

The first test performed involved drawing from a standing water source that was level with the pump apparatus, and pumping to the same level. The plunger pump required little effort to operate. Once primed, a volume of water approximately equal to that of the expanded bellows bladder was displaced and pushed through the unit with every stroke.

The pumping action was sustainable for indefinitely long periods of time. Because the total pump head was zero, the power required to operate the pump at about 50 strokes per minute was sustainable by a single person.

When the output end of the hose was raised to a 7-foot height, some unexpected problems arose. After starting with a completely empty plunger and set of hoses, the plunger pump system was fully primed after three strokes; however, it was observed that if the pump was not continuously used after priming, and the outflow stopped, the pressure from the reserve of water that built up in the bellows plunger and in the outflow tube was too large to overcome, and the pump was locked in a static state. The polyethylene bellows was not strong enough to return momentum to the water and force it out of the bladder and up the seven-foot vertical height.

A second problem presented itself; the simple seal between the plunger and the tee as described in section 4.3 was not strong enough to withstand the increased force required to pump at a 7-foot head. After reaching steady state, the upward force required for the draw stroke was greater than the force that could be sustained by the seal. The plunger was pulled off of the tee and rendered unusable until a new seal was found.

A variety of solutions to both problems was considered. To remedy the insufficient rigidity of the bellows structure when pushing down on a volume of water to achieve vertical displacement, the bellows pump was relocated to the top of the height to which the water was being pumped. By locating the pump at the top of the ascent, a large pull force, instead of a large push force, was needed to draw the water up the height. Because the rigidity of the bellows is not a limiting factor when pulling upward on the plunger, the suction created when drawing became the primary mechanism of displacing the water. When actually implemented in *Design Squad* and mounted on the waterslide, the team will have to devise a stable way of mounting the pump to the top of the waterslide, and an ergonomic way to draw the water and sustain the force required to pull.

For added security, a release valve can be added to the base of the outflow tube. This valve, when opened, allows the tube to be emptied by gravity and permits the user to easily start priming and using the pump again. It is advisable to add a release valve like this, especially when being used in the actual television show, because it is probable that the children who make and use the pump will test it and ultimately pump with it in a discontinuous manner.

The problematic seal between the plunger and the tee can be remedied by adding a component that will balance the upward pull force on the plunger. By tightly tying a string around the narrowest part of the neck of the plunger, and then fastening the string to the underside of the PVC tee, when the pump user pulls up on the plunger's handle, the string clamps the mouth of the bellows tightly to the tee in reaction to the pull.

5.7 Discussion

To constitute a successful episode concept for *Design Squad*, a given design challenge must address many requirements from both engineering and entertainment standpoints. A number of criteria established by both the producers and content directors of the television show

must be met or addressed to be confident of an episode's success. After the design and testing of the plunger pump, it was evaluated against these criteria to be sure that it is feasible not only as an engineering project but as an interesting television episode.

An episode concept's feasibility can preliminarily be judged by its logistics. The solution to the design problem must be solvable from start to finish by a group of four high school students in fewer than two days. It is believed that, because the plunger pump was easily constructed by an individual, experienced mechanical engineer in just over half a day, it is reasonable to expect the kids on the show, who have less machining and engineering experience, to build it within the show's time constraints. No complex machining is involved, and the concept is largely adapted from an already-existent pump design.

Most of the components required to reproduce the plunger pump solution to the human-powered waterslide challenge are available as off-the-shelf purchases at local hardware stores, so this challenge in particular has the potential to serve as one of the earlier episodes, while the cast members are still acquainting themselves with machinery.

Although many of the components required to construct the plunger pump were purchased, they were also inexpensive, common household items whose total value was inexpensive. The episode would therefore not be monetarily difficult for the show to produce; the supplies needed are well within the show's budget.

Each solution to a given problem should require a level of creativity and cleverness appropriate to high school students working under extreme time constraints. The plunger pump solution to the human-powered waterslide challenge requires an adequate amount of ingenuity and creativity; participants are required to synthesize the mechanics of and physics principles behind common positive displacement pumps and recreate one using everyday household items.

There is also concern that the solution has a sufficient "coolness" factor. That is to say, will the children who watch the episode be wowed by its content? The plunger pump solution to the human-powered waterslide challenge integrates many common household objects with which children are familiar and comfortable. The integration of these parts yields a solution to a challenge with which children have familiarity and in which they are interested; waterslides and similar attractions have an inherently "cool" aura to them.

6 Discussion of the Ball-and-Chain Pump and Plunger Pump as Solutions

The ball-and-chain pump and plunger pump represent feasible solutions to the proposed water slide design challenge. While both pumps achieve the intended goal of the challenge to some level of performance, the approach taken by each design differs greatly in factors of form and solution. In comparing the two pumps, a set of evaluation criteria can be proposed, where the specific merits and shortcomings for each pump, in the context of the show, can be estimated. An example of such a matrix is shown in Table 1, for which it has been assumed that a superior solution is one that minimizes cost, fabrication time, and complexity while maximizing performance, robustness, ease of use and solution appeal.

Table 1: Evaluation Matrix of the Ball-and-chain and Plunger Pump Solution

Evaluation Criteria	Ball-and-chain Pump	Plunger Pump
Material Cost	-	+
Fabrication Time	-	+
Robustness	-	+
Complexity	-	+
Size and Weight	-	+
Pumping Capability	+	-
Ease of Use	+	-
Design Flexibility	+	-
Solution Elegance	+	-
“Coolness” Factor	+	-

The plunger pump represents a simpler and more traditional pumping solution, which requires fewer components, and consequently less fabrication time and floor space. Both pumps share several types of components, including standard PVC components, flexible tubing, and wooden frames. However, the larger material demand for the ball-and-chain pump makes its cost approximately 1.5 times as great as that of the plunger pump; nonetheless, it remains within reasonable budgetary constraints. Additionally, the simplicity of the plunger pump gives it an advantage in robustness, where the absence of many moving parts makes it more likely to withstand prolonged use.

The added complexity of the ball-and-chain pump can be justified by an increase in pumping performance, where typically higher flow rates can be achieved in comparison with the plunger pump. The intermittent water output of the plunger pump is largely affected by the idle time between the filling and emptying of the bellows, while the ball-and-chain pump achieves a more continuous output of water. In considering the ease of operation, the power stroke of the ball-and-chain can be achieved from a standing position with the ability to use body weight to assist the pull stroke. However, the lower profile plunger pump may require the user to be more awkwardly positioned during operation, with a curved back posture over the bellows. The pull stroke of the ball-and-chain therefore appears to have an advantage in ergonomic form and sustainability of input force.

Both designs have adequate room for flexibility in pursuing a wide variety of component choices and configurations. However, the increased complexity of the ball-and-chain pump gives it slightly more room to for device optimization. In contrast to the plunger pump, for which

moving parts are less of a concern, the presence of a long system of moving balls in the ball-and-chain pump introduces an additional level of design decisions.

Both pumps offer interesting observable mechanisms, as well as a certain “coolness” factor stemming from the use of common household materials, such as bathroom plungers, balls, and bicycle wheels. Compared to more traditional positive displacement hand pumps, the ball-and-chain pump presents a more unconventional and creatively appealing solution. The observable internal moving parts, and increased scale of the ball-and-chain pump, make its operational principles more intuitive and transparent. This “transparency of functionality” is an important strength of the ball-and-chain pump, particularly for the purposes of an educational television program.

While the two pumps have shown certain advantages and disadvantages, the solutions are balanced in their overall approach. While one solution may be simple and robust, the other may be more complex and engaging. A successful design challenge is one that encourages a wide level of creative space so that varied solutions are possible. The simulated design, fabrication and testing of the two very different, but individually feasible, prototype pumps has shown that the challenge of designing a human powered waterslide pump has appropriate levels of flexibility, technical challenge, and appeal for an episode of *Design Squad*.

The overall concept of the human-powered waterslide pump challenge shows promise as an episode for multiple reasons. Children can relate to waterslides as a form of enjoyment and entertainment; the use of waterslides in the episode will be a source of familiarity and excitement to the 9- to 13-year-old viewing population. Viewers will also be exposed to the design process within a fun context to which they can relate. The proposed challenge addresses a problem that has solutions that are appropriate to the skill level of the targeted age group; as a result, the episode will be of greater educational importance.

7 Conclusions

During the first season of WGBH's *Design Squad*, the cast of the show will be presented with the challenge of building a human-powered water pump for a local community pond or swimming pool. Two possible solutions to the challenge have been prototyped: the ball-and-chain pump method, and the plunger-pump positive displacement method.

The ball-and-chain design features a continuous loop of balls on a string that are drawn through a pipe of an inner radius that is just larger than the outer radius of the balls. The base of the tube sits in the water source, and columns of water are drawn to the top of the tube as the string of balls is pulled through. This solution was successfully constructed within the appropriately scaled time constraints that the child cast of the show will have to build it.

The positive displacement diaphragm or piston pump solution is made using common household and store-bought components, including a polyethylene bellows toilet plunger and two one-way check valves sold for sump-pumps. The plunger pump, too, should be easily designed and constructed by the cast within the two-day limit they will be given.

Each of the two water pumps is operable by a single person, and the two pumps have comparable flow rates. Each one falls within the episode's allowed budget, and each is of an appropriate level of complexity for the 16- to 18-year-olds that will be solving the challenges.

The two solutions demonstrate that the human-powered waterslide challenge is a feasible and viable challenge option for the *Design Squad* television show. As required by the desired parameters of each potential challenge, the two very distinct prototypes will permit a variety of solutions to materialize when the cast actually designs and builds the pumps during the shooting of the show. It has been confirmed by WGBH that this episode idea will indeed be one of the thirteen challenges given to the cast during the show's first-season shoot during the summer of 2006.


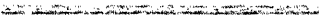







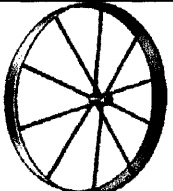
In recent years, problems have emerged in the realm of engineering and engineering education. *Design Squad* aims to address many of these problems by making children more aware of engineering and its uses. The human-powered waterslide pump problem described in this thesis is one of the challenges that will be presented to the cast of the reality television show; the challenge and its solutions meet an assortment of criteria that will positively contribute to the show's mission.

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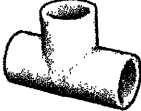


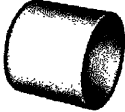
Appendix A

Significant components used in the final ball-and-chain pump prototype. Price estimates are based on McMaster-Carr prices as of March 2006, where possible.

Component	Qnt.	Description of Use	\$ Price (USD)
Polypropylene Ball, Dia. 50mm	40	 Balls that are pulled through pipe	\$14.91
Polyester Rope, Solid Braided 1/8" Diameter, 30' Length	1	 Rope used to string together balls	\$5.68
Clear PVC Pipe 2", Pipe Size 2", 8' Length , Sch 40.	1	 Main pipe	44.46
90 Degree Long PVC Elbow , 2" Size, Socket, Sch 40	1	 Pipe entrance funnel assembly	\$2.04
Reducing PVC Coupling, Sch 40, Fitting 4" Sckt X 2" Sckt	1	 Pipe entrance funnel assembly	\$7.03
PVC Wye, 2" Pipe, 45 Deg, Socket	1	 Pipe exit overflow assembly	\$3.67
Wood Planks 1"X 4"X 2'	7	 Frame construction	\$15.00
Wood Screws, Phillips, No. 8 Size, 2-1/2" Length per Pack	50	 Frame construction	\$2.00
Hose and Tube Clamp, Worm-Drive, 1-1/4" To 2-1/4" Id Range, 9/16" Width	2	 Main Pipe Constraint	\$3.00
Bicycle Wheel, 21" Diameter	1	 Ball redirection mechanism	\$15.00

Total: \$112.79

Significant components used in the final plunger pump prototype. Price estimates are based on McMaster-Carr prices as of March 2006, where possible.

Component	Qnt.	Description of Use	\$ Price (USD)
Bellows Plunger Bellows-Style Polyethylene Cup Plunger Toilet/Sink, 3- 1/4" Bottom Dia, 12- 1/2" Handle	1	 Main pump piston /diaphragm	\$6.28
Swing-check valve ABS Swing Check Sump Pump Valve ABS Body W/Stainless Steel Clamps, 1-1/4"-1-1/2"	2	 Prevents backflow / allows suction	\$11.11
PVC Pipe Std-Wall (Schedule 40) White PVC Unthrd Pipe 1-1/2" Pipe Size X 5' Length	5 ft	 To connect fittings and couplings	\$5.86
PVC Tee White PVC Pipe Fitting 1-1/2" Pipe Size, Tee	1	 Base attachment for plunger and valves	\$2.04
Flexible Hose Economical PVC Water- Suction/Discharge Hose 1-1/2" Id, 1- 13/16" Od, 75 PSI, Green, 20' Length	20 ft	 To transport water to and from pump	\$1.31 / ft
Thin adhesive rubber Polyurethane Adhesive-Backed Film 1" Width	1ft	 To create seals between components	\$1.26 / ft
PVC Coupling Std-Wall (Schedule 40) White PVC Pipe Fitting 1-1/2" Pipe Size, Coupling, 2-5/8" Length	1	 To couple components	\$0.72

Also wood glue, nails, coupling, duct tape and plywood as needed.

Total: \$80.00