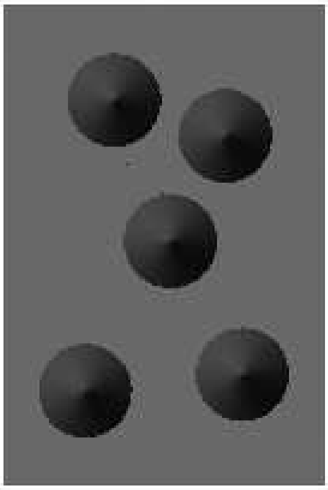

Crushed

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Fall 2002

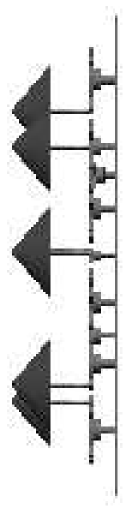

Figure 1: Side View of Assembled Front Pieces

The sculpture "Crushed" is a fusion of mechanical principle and artistic statement. Artistically, the sculpture is a playful look at the motion of gears, translated into rotating cocktail umbrellas. The sculpture defines itself as a kinetic piece because the entire process of motion is easily discernible to the viewer and the artistic value is intrinsic to the motion. The viewer will be able to witness balls generate power by falling through a turnstile. As that turnstile turns, the power is translated to Delrin gears to create a moving gear train. Attached to the gears are cocktail umbrellas, placed at different angles, heights and locations, which spin with the gears to create an interesting visual. In terms of mechanics, the sculpture is a multilayered structure with the ability to spin on a large bearing, as shown in figure 1. The backboard of the sculpture will be warm wood which offers a pleasing contrast with the brightly colored cocktail umbrellas(figure 2) and sparkling acrylic gearboard.

1 "Crushed" Overview

The creation of a kinetic sculpture is like any other engineering project. To effectively create something, one has to undergo the three stages of creation: design, construction, and redesign. The fall semester has been one filled with the designing, constructing and redesigning "Crushed." This report is intended to relay this process to the reader by giving a careful illustration of the design/modeling process, fabrication procedure, and conclusions forced by redesign that Team Estrogen experienced.

Figure 2: Cocktail Umbrella

2 Design and Modeling

2.1 Design and Motion: How "Crushed" Works

2.1.1 Bearing balls fall, gears turn, and umbrellas spin

Artistically, "Crushed" is intended as a critical examination of the relation between mass and motion, force and fragility. The sculpture playfully looks at the motion of gears as it is translated into the rotation of cocktail umbrellas. The piece is composed of three components or layers: the back board; the reservoir board; the gear board. Through the simple process of mass falling through a turnstile, the viewer can witness the entire piece come to life. The motion of "Crushed" begins when the sculpture is rotated 180^o by the viewer, thus initializing the generation of power. The power structure is reminiscent of a water wheel. Recessed into the reservoir board are the two large angular holding tanks filled with small, metal balls separated by a turnstile. When the piece is rotated, small metal balls are stacked in the upper reservoir. Due to gravity, the balls filter through a small opening leading to the turnstile. The turnstile is a wooden disc with 8 levers cut into it, in other words, a wooden asterisk (figure 6). The levers catch the balls and create a torque force. The torque forces the axle to rotate, thus the potential energy of the bearing balls is converted into mechanical energy of a spinning axle. The face of the reservoir and turnstile system has a clear, plexiglass front so the viewer witnesses this entire kinetic process. The axle of the turnstile is responsible for transmitting the bearing ball power to the gear train. The axle spans the power structure and the gear board. The rotational motion of the axle begins the movement of the gear train. All the gears are extremely low friction, Delrin gears. Relative to the other gears, the driving gear is extremely small in diameter (only 0.5"). This means the driving gear turns significantly faster than the others(figure 8). From the 3" gears, the train splits into four branches, each consisting of three additional gears. The gears in each branch go from a diameter of 1" to 2" and finally 3" (figure 4). Due to the range in size, the viewer will be able to witness various velocities of the gears. Relative to the axle, the one inch gear turns at the velocity, the two inch gear turns at $\frac{1}{4}$ the velocity, and finally the three inch gear at $\frac{1}{6}$ the velocity. The piece de resistance of "Crushed" is the cocktail umbrella effect. With gears spinning at velocities ranging from fast to slow to fast to slow, the umbrellas augment this difference. These small, multicolored umbrellas are attached to the individual gears by pieces of cork, likely attached with epoxy (figure 2). A pleasing pattern is developed by placing the umbrellas at different heights and angles. Thus, balls fall, gears turn, and umbrellas spin.

3 Modeling of "Crushed"

Modeling is a necessary step in the design process. While modeling can never guarantee functionality, it is useful in predicting what will happen. The major issue in designing this piece was whether the power structure would generate enough torque to create an acceptable aesthetic effect.

3.1 Angular Velocity

3.1.1 Summary

A major issue in the functionality of "Crushed" is whether a single ball can initiate the motion of the entire gear train by striking a levered turnstile, as in figure 3.

The following calculations were performed in order to demonstrate that the motion of the entire sculpture can be initiated by the fall of the first bearing ball. It is assumed that all of the potential energy of the ball is converted into kinetic energy of the sculpture. Thus, the potential energy can be related to the angular velocity, ω, of the sculpture components. If the angular velocity calculations show a reasonable magnitude for the components, the feasibility of the initiation of motion will be supported. The torque, τ, caused by the single ball is also estimated in order to determine if the torque of one ball is sufficient for the entire sculpture. Since the torque caused by one ball can be related to the angular acceleration, α of each component, rough angular acceleration calculations were made to show that the one ball can create a torque sufficient to power the sculpture.

As for the gear train, first, density, dimensions and mass of each object in question is found. Then, basic potential and kinetic energy equations are remembered. Angular velocities (omega) can then be defined in terms of a "master" velocity - the omega of the 1 inch gear. Moments of inertia are then calculated for each gear type. From that, the kinetic energy of the gear train can be formulated, and solved for by assuming no loss of energy from potential energy. Therefore, the angular acceleration of each gear is known, in a perfect world. Please reference figure 4 for gear train construction.

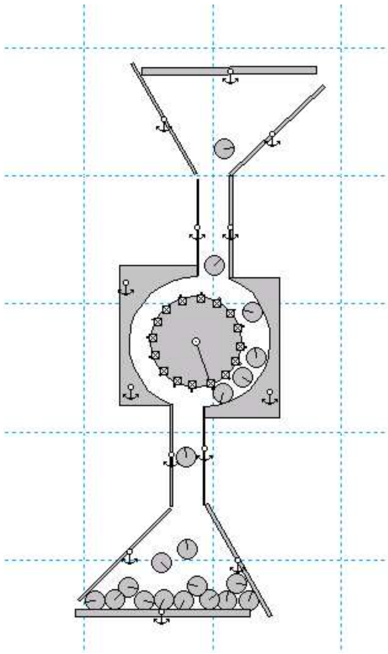

Figure 3: Rough Working Model of Drive Mechanism

3.1.2 Density, Dimensions and Mass

Using MatWeb and basic equations, the following properties of sculpture materials were found:

- Acrylic (for turnstile)
  - Density:
    - 1.15 g/cc = 1150 kg/m^3
  - Dimensions of lever:
    - length 3.9 inches = 0.0991 m
    - height 1 inch = 0.0254 m
    - depth 3/16 inch = 0.00476 m
  - Mass:
    - m = density x volume (length x height x depth)
    - m = .0138 kg
- Delrin (for gears)
  - Density:
    - 1.5 g/cc = 1500 kg/m^3

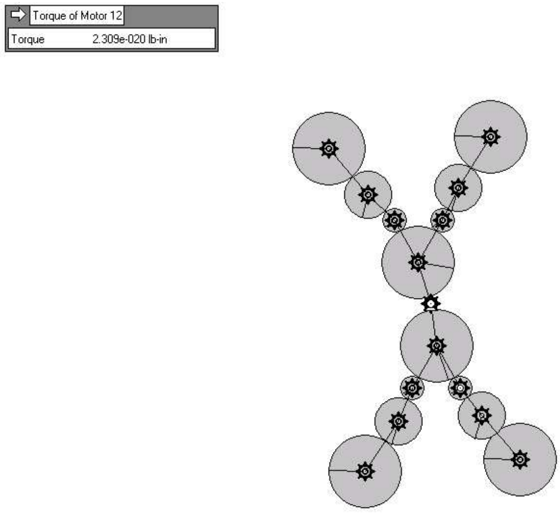

Figure 4: Potential Gear Train

- Dimensions:
  - ∗ thickness 5/16 inch = 0.00794 m
  - ∗ radius (3 inch) gear = 0.0381 m
  - ∗ radius (2 inch) gear = 0.0254 m
  - ∗ radius (1 inch) gear = 0.0127 m
  - ∗ radius (0.5 inch) gear = 0.00635 m
- Mass:
  - ∗ m = density x volume (/pi x r$^{2} x thickness) m(3 inch) = 0.0543 kg$

∗ m(2 inch) = 0.0240 kg
∗ m(1 inch) = 0.00603 kg
∗ m(0.5 inch) = 0.00151 kg

- Steel (bearing balls)
  - Density:
    - ∗ 7.85 g/cc = 7850 kg/m3
  - Ball Dimensions:
    - ∗ radius 3/8 inch = 0.00953 m
  - Mass:
    - ∗ m = density x volume (4/3 x pi x r3)
    - ∗ m = 0.0138 kg

3.1.3 Basic Energy Equations

Potential energy is given by U = mgh. So, potential energy of the ball is

$$U = (.0285)(9.81)(0.091) \tag{1}$$

$$U = 0.0277J \tag{2}$$

The kinetic energy of the entire system, summing the energy for all the components of the sculpture, is given by

$$K = \Sigma(\frac{1}{2}Iw^2) \tag{3}$$

3.1.4 Gear Ratios

Using the principle of gear ratios and the angular velocity, omega of the 1 inch diameter gear can be related to all the other components of the train (treating the turnstile as a gear 3.9 inches in diameter) - thus writing all the other angular velocities in terms of the angular velocity of the 1 inch gear. Thus,

$$1inchgear = \omega \tag{4}$$

$$2inchgear = \frac{1}{2}\omega \tag{5}$$

$$3inchgear = \frac{1}{3}\omega \tag{6}$$

$$3.9inchgear(turnstile) = \frac{1}{3.9}\omega \tag{7}$$

$$\frac{1}{2}inch(driving)gear = 2\omega \tag{8}$$

This makes sense, since gears of different sizes running against each other will go at different speeds.

3.1.5 Moments of Inertia

Moment of inertia aids in the next step, as it is a proportionality constant relating angular momentum to angular velocity. To simplify the calculations for the moment of inertia, I, of each component, the gears are treated like discs, while the turnstile is treated as 8 rectangular plates. By definition, the moment of inertia for a disc is

$$I = \frac{1}{2}mR^2 \tag{9}$$

and the moment for a rectangular plate is

$$I = \frac{1}{12}m(l2 + \omega^2) \tag{10}$$

The moment for the turnstile is

$$I = 8 * (\frac{1}{12}(.0138) * ((0.0991)^2 + (0.0254)^2)) \tag{11}$$

$$I = 9.63E - 5Kg * m^2 \tag{12}$$

The moments for the gears are

- 3 Inch:
$$I = \frac{1}{2}(0.0543)(0.0381)^2 \tag{13}$$
$$I = 3.94 \times 10^{-5} Kg * m^2 \tag{14}$$

- 2 Inch:
$$I = \frac{1}{2}(0.0240)(0.0254)^2 \tag{15}$$
$$I = 7.74 \times 10^{-6} Kg * m^2 \tag{16}$$

- 1 Inch:
$$I = \frac{1}{2}(0.00603)(0.0127)^2 \tag{17}$$
$$I = 4.90 \times 10^{-7} Kg * m^2 \tag{18}$$

- $\frac{1}{2}$ Inch:
$$I = \frac{1}{2}(0.00151)(0.00635)^2 \tag{19}$$
$$I = 3.00 \times 10^{-8} Kg * m^2 \tag{20}$$

Knowing gear ratios and that the sculpture consists of six 3 inch gears, four 2 inch gears, four 1 inch gears, one $frac12$ inch gear, and one 3.9 inch gear/turnstile, and by referring back to equation , the equation for total kinetic energy can be reduced to

$$K = \frac{1}{2}(6(I_{3inch}(\frac{1}{3}\omega)^2) + 4(I_{2inch}(\frac{1}{2}\omega)^2) + 4I_{1inch}\omega + I_{halfinch}(2\omega)^2 + I_{turnstile}(\frac{1}{3.9}\omega)^2) \tag{21}$$

This simplifies to

$$K = \frac{1}{2}\omega^2(\frac{2}{3}(I_{3inch}) + I_{2inch} + 4I_{1inch} + 4I_{halfinch} + (\frac{1}{15.2}I_{turnstile})$$

Substituting for I and setting K equal to U,

$$0.0554 = \omega^2(0.0000424) \tag{23}$$
$$\omega^2 = 1306 \tag{24}$$
$$\omega = 36.1 rad/sec \tag{25}$$

Returning to gear ratios, the specific angular velocities of each gear are as follows:

– 3 inch gear:

$$\omega = 12.0 rad/sec \tag{26}$$

– 2 inch gear:

$$\omega = 18.1 rad/sec \tag{27}$$

– 1 inch gear:

$$\omega = 36.1 rad/sec \tag{28}$$

– Turnstile:

$$\omega = 9.26 rad/sec \tag{29}$$

– 1/2 inch (driving) gear:

$$\omega = 72.2 rad/sec \tag{30}$$

These results show that in an ideal world, the potential energy of one bearing ball falling through the turnstile will produce a considerable angular velocity for the entire system.

3.2 Torque and Angular Acceleration

Another challenge to the project is projecting the amount of torque produced and the acceleration produced by the proposed system, and ensuring that these figures are reasonable. Once again, all calculations are made based upon a perfect, frictionless world.

3.2.1 Summary

Using some basic equations for torque, constants and variables can be replaced by actual values from sculpture components. By creating a reusable acceleration variable α, the angular acceleration of each gear is solvable.

3.2.2 Basic Torque Equations

In order to study torque of the system, calculations were made to determine the torque(τ)exerted on the system by one bearing ball. Torque is given by the equation:

$$\tau = rFsin\theta \tag{31}$$

Where θ is the angle between r and F and force is the force. However, knowing that the only force applying a torque to the system is the weight of the bearing ball and also noting that the collision between the ball and the turnstile occurs perpendicularly, this equation can be simplified to:

$$\tau = rmgsin\theta \quad (32)$$

Substituting previously determined constants into the equation yields:

$$\tau = 0.0258Nm \quad (33)$$

3.2.3 Angular Acceleration

Knowing the initial torque, the angular acceleration of each component can be calculated to show significant motion in the entire train. Converting the angular accelerations of each gear to one variable, the angular acceleration (α) of the one inch gear, by utilizing gear ratios gives

$$\alpha_{2inch} = \alpha/2 \quad (34)$$

$$\alpha_{3inch} = \alpha/3 \quad (35)$$

$$\alpha_{turnstile} = \alpha/3.9 \quad (36)$$

$$\alpha_{halfinch} = 2\alpha \quad (37)$$

3.2.4 Solving for Angular Acceleration

Since torque is given by the equation

$$\tau = I\alpha \quad (38)$$

one can determine that

$$\tau = \alpha(4I_{1inch} + 2I_{2inch} + 2I_{3inch} + \frac{1}{3.9}I_{turnstile} + 2I_{halfinch}) \quad (39)$$

Therefore, the effective angular acceleration is

$$0.0258 = 0.00121\alpha \quad (40)$$

$$\alpha = 213rad/sec^2 \quad (41)$$

Reusing gear ratios to back out angular acceleration for each component

$$1inch : \alpha = 213rad/sec^2 \quad (42)$$

$$2inch : \alpha = 107rad/sec^2 \quad (43)$$

$$3inch : \alpha = 71rad/sec^2 \quad (44)$$

$$1/2inch : \alpha = 426rad/sec^2 \quad (45)$$

$$Turnstile : \alpha = 54.6rad/sec^2 \quad (46)$$

4 Computer Simulations

The computer program Working Model was used as another method for calculating torque. In Working Model, a gear train was created and connected to a motor. The motor then calculated the minimum amount of torque necessary to move the gear train with negligible friction. Once the simulation was run, our calculation of $\tau = 0.0258Nm$ was verified.

For the drive mechanism, the original plan of bearing balls appeared to be confirmed by Working Model (figure **??**). However, once the prototype was made and jamming occurred, Team Estrogen went back to the drawing board. The new solution is to use much smaller balls to power the sculpture, and have many attack the turnstile at a time. More simulations were made, though faith in Working Model was low (figure **??**). For animations of this simulation, please consult the Team Estrogen website

Working Model simulations, along with SolidWorks renderings can be seen on the Team Estrogen website

5 Sculpture Fabrication

5.1 Drive Mechanism

5.1.1 Reservoir

The reservoir is constructed from basic plywood with a scratch resistant, plexiglass front. See figure 5. Rough construction was with the miter or panel saw and any refinements were done on the band saw or sander. Wood glue bonded the sides of the reservoir and screws hold the plexiglass front.

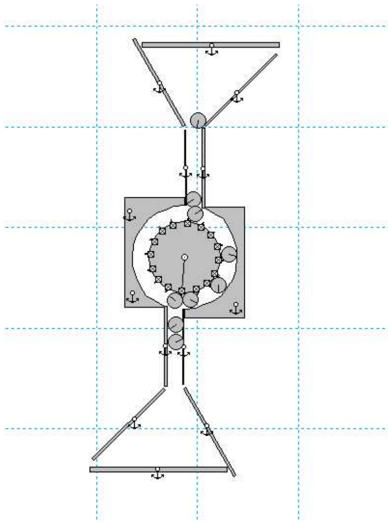

Figure 5: Working Model Simulation with Bearing Balls

5.1.2 Turnstile

The turnstile, depicted by the Solidworks rendition in figure 6, is constructed from a solid wood disc. Fins were initially created using a drill and later refined on the band saw. Multiple holes were drilled into the disc to reduce mass using the drill press. The casing, as seen in figure 7, is constructed of plywood that has been cut into an curve and carefully sanded.

5.1.3 Masses

In order to power the sculpture, 12,000 BBs fill the reservoir.

5.1.4 Gear Train

The Delrin gears, ordered from Small Parts for their extremely low friction, are mounted onto metal axles and secured with cotter pins purchased from the hardware store. These axles are then mounted into holes cautiously drilled in the acrylic sheet above the reservoir. See figure 8.

5.1.5 Gear Board

Drilling the acrylic gear board presented many unexpected challenges due to the brittleness inherent in acrylic. In order to drill holes to mount the axels, a small hole had to be initially drilled, followed

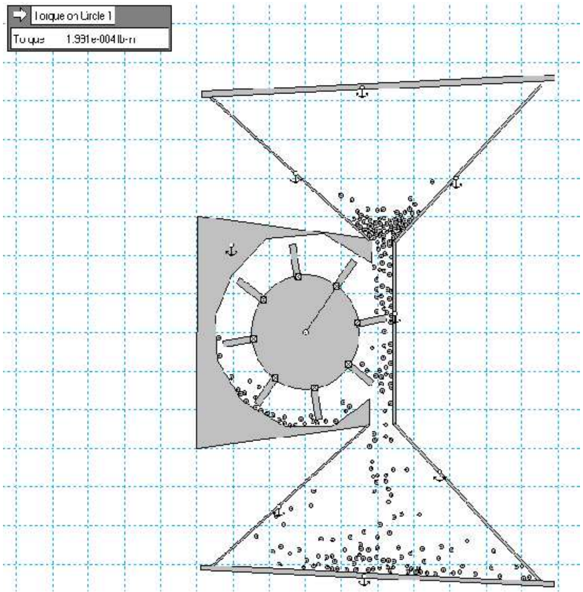

Figure 6: Working Model Simulation with BBs

by successively larger holes. This method prevented cracking in the acrylic.

5.1.6 Umbrellas

Cocktail umbrellas were purchased from a local party store. Inserting the toothpick end of each umbrella into a small piece of cork as a base, these bases are epoxied to the gear faces at random locations.

6 Budget

See Table 1.

7 Results

Construction of "Crushed" yielded many interesting results. First and foremost, Working Model is inaccurate in the prediction of jamming. The opening to the turnstile in relation to the diameter of bearing balls proved to be too small so bearing balls were able to create a lattice structure and jam. Thus, BBs had to replace the bearing balls for their extremely small diameter. Another interesting

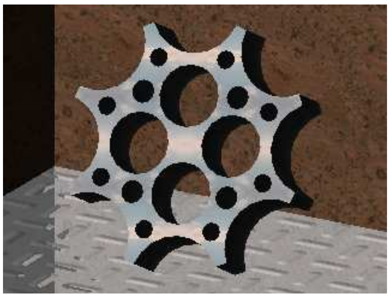

Figure 8: Turnstile

complication revealed by construction was friction. In modeling, friction was assumed to be relatively negligible; viewed more as a positive force for velocity control than as a negative source of power dissipation. However, once the sculpture was assembled, friction proved to be extremely high, thus ball bearings were added to axels. Simulations and calculations of torque and velocity will be different than actual values when the sculpture is finally functioning. Unfortunately, "Crushed" is not currently functioning as aesthetically desired. The last minute change of the turnstile from acrylic to wood increased friction and the moment of inertia. In addition, the axel hole in the center of the turnstile is not straight, so rotation is not feasible when struck by a mass of BBs. Redesign of the power mechanism is obviously in order. The BBs make the reservoirs functional, but their small size allows them to enter undesirable locations so guards will need to be in place. In addition, turnstile calculations have not been

Figure 9: Turnstile Case

Figure 10: 1 Inch Gear

changed yet because experimentation needs to be done in order determine whether it is beneficial to use the wooden turnstile or revert back to the acrylic design known to work.

8 Conclusions

The design process has been a valuable experience. While modelling was useful in designing the sculpture, Team Estrogen has learned that math and physics cannot guarantee functionality. Fabrication is easy when being thought about, but material limitations caused unforseen difficulties. Does it Work? Based on our prototype ...no. But that is perhaps the most valuable thing that came out of our prototyping. Once we figured out it didn't work, our prototype brought up a number of issues we had not considered. For example, we realized the rather obvious need for an extra layer of acrylic between our drive

Part	Supplier	Part Name	Part Number	Price
Reservoir (plywood)	Admissions Junk	Plywood Sheet	yoinked	$0
Turnstile (wood)	Jill Crisman	wood disc	free	
Acrylic Cover for Reservoir	McMaster-Carr	Cast Acrylic Sheet	8536K142	$18.92
Acrylic for Gear Board	Home Depot	Cast Acrylic Sheet	$18.92	
Bearing Balls	McMaster-Carr	3/4” Chrome Steel Ball	9528K19	$52.15
BBs	WalMart	Tiny Zinc Balls	$12.00	
Axles	Home Depot	?	?	$40.00
Steel Front Board	McMaster-Carr	1006/1020 Carbon Steel	6544K14	$12.00
3” Gears (x6)	Small Parts	Delrin 3” gear	B-GD-3296	$96.30
2” Gears (x4)	Small Parts	Delrin 2” gear	B-GD-3264	$46.40
1” Gears (x4)	Small Parts	Delrin 1” gear	B-GD-3232	$28.00
1/2” Gear	Small Parts	Delrin 1/2” gear	B-GD-3216	$4.10
Assorted Bearings	McMaster-Carr	steel ball bearings	varies	$69.56
Misc fastenings and spacers	Home Depot	?	?	$50.00

Table 1: Budget Total = $436.35

mechanism and the actual gears – something not shown by design and modelling. We also experienced pretty significant jamming problems that were not foreseen in our two-dimensional Working Model, since the jamming is in – if you will – the z-axis direction, which was not possible in our model. We fixed a few of the many problems that were causing this, like adding a couple of pieces of wood to block where they were doubling up horizontally and jamming; we also realized that our bearing balls were much too large to work as we wanted them too. Given the same principle on which an hourglass works, our driving masses need to be much smaller than their opening; since our opening fits 1.5 of our original bearing balls, we went back on that idea and instead invested in 12 000 BBs. Subsequent tests have shown that with some slight modifications to the dimensions of our turnstile, this should work much, much better.

We are also considering using wood instead of steel. Our source of steel turned out to be not as reliable as we thought, and at this point we are unsure if it is possible for us to procure steel to be properly welded in a timely matter. Besides that, our prototype is really not all that bad, and wood in itself could be aesthetically ... well, cool. Wood is also significantly cheaper and leaves room in the budget for axles to reduce Therefore, we are currently looking into that and are all unanimously enthusiastic about the idea.

9 Acknowledgements

While specifically describing what each team member did seems hypocritical in the spirit of teamwork, for the requirements Team Estrogen will pretend that acknowledgements are a sense of pride. While everyone participated in design and construction, individuals assumed specific responsibilities. Mikell Taylor served as web master, turnstile casing sander, and guru for CAD and Working Model gears. Kim McCraw owned Solidworks, dictated design specifications, and broke, I mean built, the reservoirs. Joelle Arnold developed Working Model power simulations, served as our construction expert, and mastered acrylic gear board drilling. Caitlin Foley worked on math, math, math, math, math, invented physics, and served as the literary artist in LaTeX. Team Estrogen would also like to note the contributions of Jill Crisman in design ideas and turnstile construction, Burt Tilley in modeling help, Zhenya in correction of creative physics, Dave Anderson in construction ideas, and John Stolk for material information and potential polycarbonate fairy.