

Rube Goldberg Machines

An inquiry-based STEM approach

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Michael Harms
National Board Certified Teacher
michael@thescienceguru.com
www.thescienceguru.com



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Rube Goldberg Machines

Project Overview, Rationale, & Lesson Plans

SECTION ONE: OVERVIEW

From the children's game Mousetrap, to the convoluted breakfast-making machine in the opening scene of *Pee-Wee's Big Adventure*, to a Honda commercial in which a two-minute chain reaction involving rolling, bumping, and swinging car parts triggers the ignition of a new car, inventions inspired by the work of cartoonist Rube Goldberg have permeated American pop culture. An artist whose illustrations appeared in major newspapers across the United States throughout the first half of the 20th century, Rube Goldberg drew intricate machines that offered exceedingly complex methods to achieve everyday tasks such as wiping one's mouth with a napkin or scratching one's back (Kennedy, 2008). Defined by Webster's Dictionary as "accomplishing by complex means what seemingly could be done simply (Rube Goldberg, 2008)," his illustrations combine simple machines and every day objects into elaborate schemes. While Rube's machines lived only in his illustrations, they have inspired countless sculptors, artists, students, and inventors to create physical models of these complex contraptions.

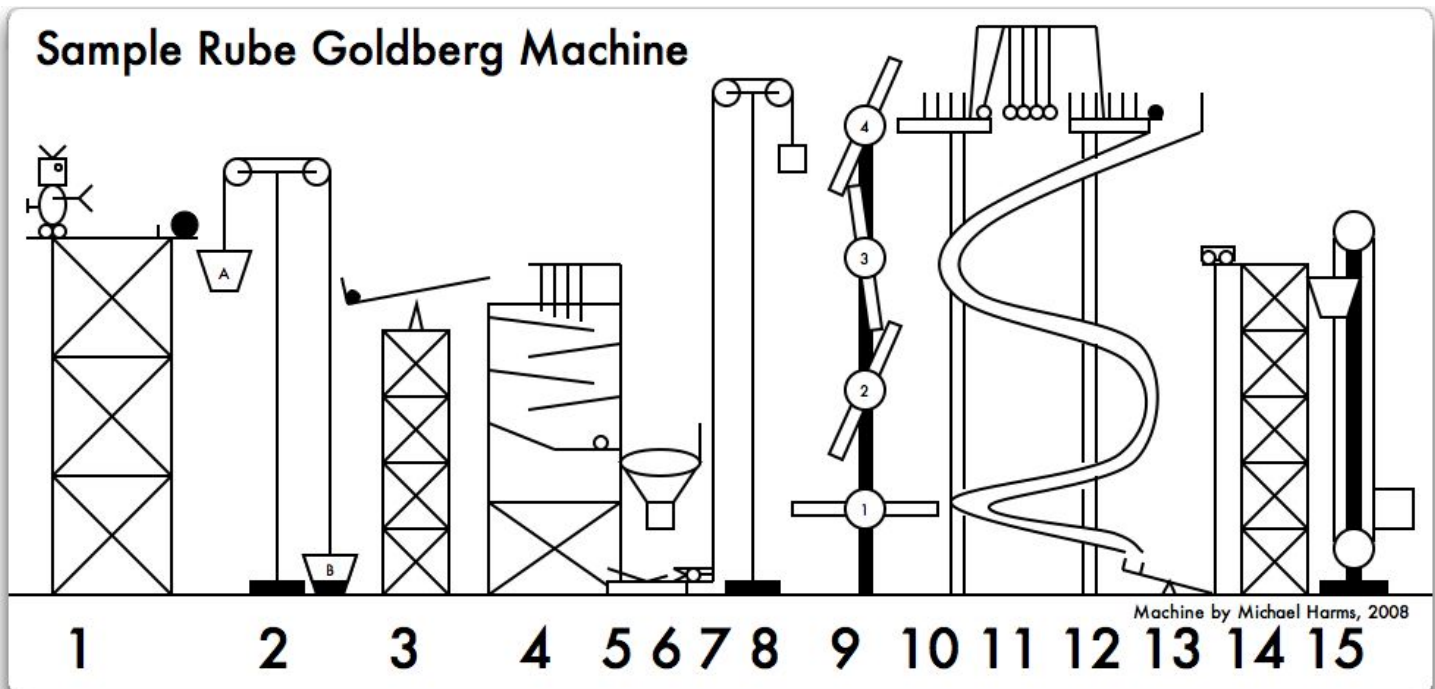
This project brings together Physics concepts with Rube Goldberg inspired machines in a culminating unit project for middle school students. It challenges students to apply their understanding of Physics concepts to create a multi-step machine that raises a flag into the air. With rolling marbles, toppling dominoes, rotating gears, spinning pulleys, and cars rolling down inclined planes, students' machines integrate concepts from throughout the unit and allow them to use quantitative data and scientific explanations to demonstrate their understanding in a creative, engaging manner.

SECTION TWO: PHYSICS CONCEPTS

Students will demonstrate their understanding of Physics not only through the planning and construction process but also through a detailed analysis of their finished machine. A Rube Goldberg Build is a rigorous, meaningful culminating project because of the way it can challenge students to connect, combine, and explain Physics concepts. While one can expect great diversity in the complexity, structure, and sequence of students' machines, outstanding work demonstrates understanding of the following six Physics themes. These themes include:

- A) Describing types of motion
- B) Describing displacement, velocity, & acceleration
- C) Describing forces involve
- D) Describing energy transfers
- E) Describing collisions in term of momentum
- F) Describing consequences of the conservation of energy and conservation of momentum

The following machine is offered to illustrate the application of these six themes to a Rube Goldberg Machine.



Explanation of Machine:

Step	Explanation
1	Windup robot toy is released. Toy moves rightward across platform, knocking the ball off the platform.
2	The ball rolls off of the platform and falls into cup A. This upsets the balance of the Atwood Machine, causing cup A to accelerate downward while cup B accelerates upward.
3	Cup B knocks the left side of the lever upwards. The lifting up of the left side of the lever causes a steel marble to roll downwards into the set of marble tracks.
4	The marble zigzags down the angled tracks. During the first section, the marble rolls through a set of chimes of varying length. After the last ramp, the steel marble collides with a lighter steel ball.
5	The ball rolls from the angled tracks into a funnel where it falls onto the trigger of a mousetrap.
6	The mousetrap goes off, with its metal arm swinging from left to right.
7	The clothespin is squeezed open by the swinging arm of the mousetrap, releasing a string.
8	The released string causes the weight on the opposite side of the pulley system to accelerate downwards.
9	The downward accelerating mass collides with the arm of a rotating lever. The bottom lever spins counter-clockwise, knocking into the arm of the lever above it. The levers continue to spin, transferring the energy upward to the top lever.
10	The top lever swings into a domino, beginning another chain of falling dominoes. The final domino collides with a ball from a Newton's Cradle toy that sits perched on the platform with the dominoes.
11	The first ball of the Newton's Cradle swings into the other four balls. The rightmost ball swings forward, knocking into a domino on the adjacent platform where they initiate another chain of domino collisions, eventually knocking into a marble.
12	The marble rolls down through the curved tubing into the left compartment of a lever.
13	The weight of the marble causes the left side of the lever to move. The upward motion of the right side of the lever lifts the rod that supports the platform above.
14	The left side of the platform lifts upwards, causing the car to roll downwards from left to right, eventually falling into a cup that is attached to a string and pulley system.
15	The car falling into the cup causes the cup to accelerate downwards. The string on the opposite side of the pulleys moves upwards, raising the flag and finishing the machine.

Application of Physics Themes to Sample Machine

A) Describe types of motion

- The windup robot toy move horizontally across the platform powered by the potential energy stored in the robot's spring. *(Step 1)*
- The objects attached to the pulleys move vertically because they are subjected to the force of gravity. Some objects, such as Cup B, move upward because the pulley system (Atwood Machine) changes the direction of their motion. *(Steps 2, 8, 15)*
- When the small steel ball rolls off the tracks and into the funnel, the ball's motion can be described with both vertical and horizontal components. For the moment that the ball is airborne (between the end of the track and the funnel), it follows a projectile path. *(Step 5)*
- The arms of the rotating levers rotate freely around their axis. As the ends of these arms remain a constant distance from the center of rotation, it can be said that they exhibit uniform circular motion. *(Step 9)*

B) Describe displacement, velocity, & acceleration

- The balls rolling down the tracks and tubing travel a great distance (the length of the track/tubing), while their displacement is significantly less (the distance between where they start and end). *(Steps 4, 12)*
- The rightmost ball of the Newton's cradle will swing back and forth several times, but will end up back in its starting location. The total distance that the ball travels will likely approach one-meter, although its displacement will be zero. *(Step 11)*
- Assuming a straight downward path, cup A's displacement and distance traveled will be equal. *(Step 2)*

- The moving objects attached to pulleys will accelerate at a constant rate due to Earth's gravity (with increasing velocities in the same direction as each object's acceleration). While some objects will accelerate downward (cup A), others will accelerate upwards (cup B). The pulley system causes this change in the direction of acceleration. *(Steps 2, 8, 15)*
- As most parts of this machine are dependent on gravity, we will not see objects moving at constant velocity. It can be expected that the wind-up robot toy moves at a near constant velocity (although variations in the spring may make this untrue. A battery-powered robot would move at a constant velocity). *(Step 1)*

C) Describe forces involved

- The robot depends on friction to move forward. The robot applies a forward force backwards while the friction acts on the robot in the opposite direction. Without friction, the robot would spin out rather than move forward. *(Step 1)*
- Gravity plays an essential role in this machine working. From the cups and blocks moving downward on pulleys *(Steps 2, 8, 15)* to marbles rolling down slopes, tracks, & tubing *(Steps 3, 4, 12)*, the force of gravity causes objects to accelerate throughout the contraption.
- The falling ball applies a downward force (caused by its acceleration due to gravity) on the mousetrap's trigger. *(Step 5)*
- The robot strikes the ball with a forward force, causing it to accelerate in the same forward direction. *(Steps 1, 2)*
- The downward force applied by the steel marble on the left side of the lever causes an upward force on the supporting rod on the right side of the lever. This simple machine changes the direction of the force. *(Steps 13)*

- The swinging arm of the mousetrap applies a downward force on the clothespin, causing it to open. (*Step 7*)

D) Describe energy transfers

- The triggering of the mousetrap causes the potential energy stored in the spring of the mousetrap to be transferred into kinetic energy. As the lever swings, kinetic energy increases as potential energy decreases. (*Step 6*)
- The winding of the toy robot stores potential energy in the spring. When the robot is released, this potential energy is transferred into kinetic energy (the robot moves forward). As the spring uncoils, the robot's potential energy decreases. (*Step 1*)
- At the beginning of the run, cup A has gravitational potential energy while cup B does not because it rests on the ground. When the ball rolls into cup A, it increases the potential energy of the cup (the cup, now contains additional mass, meaning an increase in potential energy). The additional mass and downward momentum of cup A upsets the balance between the two cups and causes cup A to move downwards. As cup A moves downward accelerating due to gravity, its potential energy decreases while its kinetic energy increases. Simultaneously, cup B rises due to the force applied by cup A's downward acceleration. As cup B rises, it increases in both kinetic energy and potential energy until it hits the lever above. When the apparatus comes to a stop, both cups will have zero kinetic energy and cup B will have gravitational potential because of its position above the ground cup A will have none because it rests on the ground. (*Step 2*)
- Some of the rolling marble's kinetic energy is transferred into sound energy as it rolls through the set of chimes. The sound waves travel through the air causing vibrations in the eardrums of those watching the machine. (*Step 4*)

- This machine's success is dependent on the operator storing potential energy throughout the machine that will be turned into kinetic energy once the machine is started. Examples of storing potential energy include:
 - a) winding the robot's spring (*Step 1*)
 - b) raising the ball to the first platform (*Step 1*)
 - c) raising cup A to the level of the first platform (*Step 2*)
 - d) placing the marble on the lever above the marble tracks (*Step 3*)
 - e) setting the mousetrap (*Step 5*)
 - f) raising the weight on the second pulley (*Step 8*)
 - g) raising the dominoes from a horizontal position to a vertical position, increasing the height of their center of gravity, preparing them to topple when knocked over (*Steps 10, 11*)
 - h) lifting the first ball the Newton's cradle to the platform (*Step 11*)
 - i) raising the marble to the top of the domino tower (*Step 12*)
 - j) placing the small car on top of the end platform, setting it up to roll downward due to gravity once the ramp is lifted (*Step 14*)

Initiating the first event (releasing the robot) starts a chain of events that moves forward through the transition of this potential energy into kinetic energy.

E) Describe collisions in term of momentum

- The Newton's Cradle step illustrates the conservation of momentum. The leftmost swinging marble collides with the four hanging marbles, causing only the rightmost marble to swing forward. The momentum of the swinging ball is transferred through all four balls until it causes the last ball (of equal mass) to swing outward. This is an example of an elastic collision. (*Step 11*)
- Some of the momentum of the downward falling mass is transferred to the

first rotating lever. This transfer of momentum causes the first lever to rotate counter-clockwise. The lever rotates until it collides with the next lever, transferring its momentum to lever 2, which then begins to rotate. This sequence of momentum transfers continues until lever four transfers its momentum to the first domino, knocking it over. *(Step 9)*

- The falling dominoes knock into one another, transferring their momentum to one another. *(Steps 10, 11)*
- When the car rolls over the edge of the ramp, it begins to accelerate downward due to gravity. When it collides with the bottom of the cup, the momentum of the car is transferred to the cup, and the two begins to move downward. *(Step 15)*
- The momentum of rising cup B just before the collision will be the same as the momentum of cup B and the lever after the collision, although the velocity will be less due to the increase in mass. *(Step 3)*
- The momentum of the rolling steel marble will be transferred to the lighter steel ball. Momentum will be conserved during this collision. However, because the smaller ball has a lesser mass than the first ball, it will move forward with a greater velocity (compared to the first marble). *(Step 4)*

F) Describe consequences of the conservation of energy and conservation of momentum

- Taken together the conservation of energy and the conservation of momentum allows energy transfers to continue moving forward through the machine. For example, if momentum were lost when the first ball of the Newton's Cradle collided with the other balls, the 5th ball wouldn't swing forward, the dominoes wouldn't be knocked over, and the machine would come to a stop. *(Step 11)*

- The conservation of energy means that the stored energy at the beginning of the machine's run will match its total energy at every stage of the chain of events and at the at the end of the run. In our calculations to demonstrate the conservation of energy, we must be careful to consider any "new" stored potential energy (i.e., cup B now at a higher location), losses due to heat, energy leaving the system as sound energy, and other energy losses (i.e., transfers of energy to the table or the surrounding air).

SECTION THREE: COLLECTING DATA: CLASSROOM IMPLEMENTATION

Students will construct their Rube Goldberg machines during science class. The process will follow the San Jose Tech Museum of Innovation's "Design in Mind," framework during which students cycle through phases of planning, building, and reflecting (Design, 2006). The assignment is designed to take place over eight 50-minute class periods using the following schedule:

Day One:	Planning & Design
Day Two:	Construction
Day Three:	Construction
Day Four:	Reflection & Redesign
Day Five:	Construction
Day Six:	Construction
Day Seven:	Analysis & Calculations
Day Eight:	Presentations

Student work will be evaluated using a rubric on the following criteria:

- Eight or more unique stages
- Inclusion of four or more different simple machines
- Written analysis of energy conversions
- Physics calculations of the following values, each using a single machine stage:
 - Potential energy
 - Kinetic energy
 - Force of impact
 - Acceleration due to gravity
 - Conservation of momentum
 - Distance versus displacement

- Average acceleration (using initial velocity and final velocity)

Below are examples of the above calculations using the sample Rube Goldberg

Machine:

Calculation	Stage	Explanation
Potential Energy	8	After measuring the mass of the hanging object and its height above the table, use the equation $GPE = mgh$ to calculate the object's potential energy.
Kinetic Energy	8	Using the potential energy calculation from above, the object's mass, and the equation $KE = \frac{1}{2}mv^2$, calculate the expected velocity upon impact. Using available equipment (camera & computer), use Vernier LoggerPro software to perform a video analysis of the falling object, comparing the calculated final velocity to the measured final velocity.
Force of Impact	8	Calculate the impact force of the falling mass using the equation $F = ma$. Drop the mass on to a Vernier force plate to calculate the actual force of impact. Compare these two values and offer an explanation for any discrepancy (i.e., equipment inaccuracy, air resistance)
Acceleration due to gravity	2	Adjust the Atwood machine from stage two so that the heavier cup (cup A with the ball) sits near the pulleys. Measure the distance between cup A and the ground. Release the heavier cup, using a stopwatch to record the time it takes for the cup to reach the ground. Use the equations $d = \frac{1}{2}at^2$ and $a = g \frac{m_a - m_b}{m_a + m_b}$ to calculate the acceleration due to the force of gravity.

Conservation of momentum	4	Place a BeeSpi velocity sensor or photogate directly in front of the larger steel ball (just before where the collision occurs). Use the velocity sensor to measure the instantaneous velocity just before the collision. After measuring the mass of both balls, calculate the expected velocity of the smaller steel ball after the collision. Move the velocity sensor to just after the smaller ball (immediately after the collision spot) and measure the actual velocity of the second ball after the collision. As an extension, one can experiment with various size balls to see how the relative mass of the two balls affects the velocity of the second ball after the collision.
Distance versus displacement	12	Measure the length of the tubing from start to finish (distance) and compare it to the straight-line distance between the start and finish (displacement).
Average Acceleration	12	Calculate the acceleration of the marble rolling through the tube. Use a stopwatch to record time and the BeeSpi velocity sensor to measure the marble's instantaneous velocity as it exits the tubing. Use the equation $v_f = v_o + at$ to calculate average acceleration of the marble.

SECTION FOUR: ADDRESSING MISCONCEPTION

Not only does this Rube Goldberg project hold the potential for students to demonstrate their mastery of Physics concepts, but it also allows for the identification and “correction” of student misconceptions. One common student misconception is that displacement and distance are synonymous. Explaining the sample machine to students, including an analysis of displacement versus distance using the fifth ball of the Newton’s Cradle and the marble tube, will re-teach the difference between these two concepts using a clear, detailed example. Students will then be challenged to demonstrate their understanding of the relationship between distance and displacement using an example from their own machine.

Secondly, I think that students are often confused about the purpose of simple machines. While they understand the concept of mechanical advantage, they often overlook the fact that simple machines are also affective at changing the direction of motion. This project reinforces this idea by pushing students to use simple machines to maximize the force of gravity. For example, when a marble moves downward, its potential energy decreases. Simple machines, such as the pulley in step two or the rotating levers in step nine, allow for the kinetic energy to be converted back into potential energy by moving motion upwards.

Thirdly, I think that students often incorrectly assume that energy is either created during or lost during this type of machine. For example, students might assume that the falling domino represents “new” energy in the system or that when their machine ends that the total energy of the system has decreased. They often ignore facts such as that the reason the rolling marble rolls down the ramp is because they themselves performed work to increase the potential energy of objects. By focusing on the Rube Goldberg machine setup process as one in which we must perform work to store potential energy, students are challenged to reconsider the conservation of energy. The work (in Joules) that they performed to lift the marble matches the potential energy of the marble at the top of the ram

and the kinetic energy of the marble at the bottom of the ramp. Finally, it is important to also use the clicks, clangs, chimes, crashes, and other “buzz” of a working model to discuss other energy conversions that occur during the machine’s run. From vibrations in supporting platforms to heat generated as parts rub together to the noise made as the marble races through the chimes, acknowledging and discussing these energy conversions is an essential way to teach and reinforce the principles of conversion of energy.

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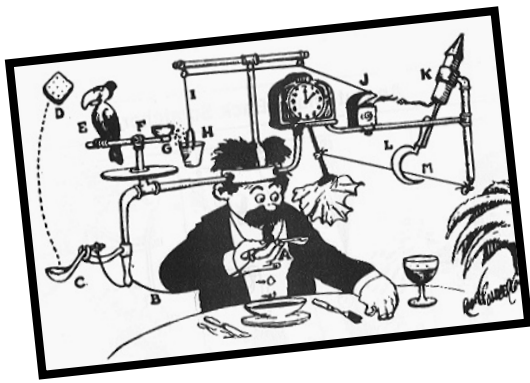
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Rube Goldberg Build

A comically involved, complicated invention, laboriously contrived to perform a simple operation – Webster's New World Dictionary

*8th Grade Science Final Project on Forces and Motion
May 2011 – Michael Harms*

The Task: Demonstrate your understanding of forces and motion by building a working Rube Goldberg machine. Your build will consist of three phases:

- Phase One: Planning and design
- Phase Two: Building and testing
- Phase Three: Presentation of Completed Machine

Your work will be evaluated using the following rubric:

Evaluation Criteria		Points
<i>Phase One – Planning and Design – 10 points</i>		
	Detailed brainstorming & plans – written words or annotated diagrams	10
<i>Phase Two – Building and Testing – 30 points</i>		
	Collaboration and teamwork during build	10
	Problem solving to resolve problems, mistakes, and challenges	10
	Materials management (clean work area, materials not wasted, share materials)	5
	Consistently cleaning up completely and on time	5
<i>Phase Three – Presentation of Completed Machine – 60 points</i>		
	Machine successfully completes task	5
	Machine comprised of 8 or more unique steps	12
	Originality – at least one unique step	3
	Repeatable – 2 consecutive successful runs within 5 minute presentation time	5
	5 or more different labeled simple machines <i>(lever, pulley, wheel & axle, gear, inclined plane, screw, wedge)</i>	10
	Physics calculations	10
	5 or more labeled kinetic energy/potential energy changes	5
	Self-evaluation of process and outcome	10
<i>Penalties and Bonuses</i>		
	Each touch of machine during presentation run	-1 each touch
	Each skipped step during presentation run	-3 each skip
	Most spectacular failure	Up to +3
	Creative display or presentation (pizzazz bonus!)	Up to +3
	Engineering marvel bonus (creative & inventive design & construction)	Up to +3
TOTAL POINTS		Up to 100

Rube Goldberg Build

Phase One: Planning and Design BRAINSTORMING

Build Team: _____

Rube Goldberg Build

Phase One: Planning and Design LABELED DIAGRAM

Build Team: _____

Rube Goldberg Build

Phase One: Planning and Design MATERIALS LIST

Build Team: _____

Rube Goldberg Build

Phase One: Planning and Design WRITTEN PLAN

Build Team: _____

Rube Goldberg Build

Build Team: _____

Our machine's task:

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8

Simple Machines:

- Lever Pulley Gear Inclined Plane Screw Wedge Wheel & Axle

Rube Goldberg Build

Group Members: _____

Physics Analysis

Directions: thinking about your machine, answer the following questions in as much detail as possible. Each group member should complete one of the questions below. If your group has two or three members, some group members may complete a second question.

Give two examples of where you had to overcome Newton's First Law of Motion to get your machine to work.

Describe a situation in which you needed to play with the balance of $F = ma$. Did you need to increase the force of some object hitting another to overcome its mass? How did you increase acceleration?

Rube Goldberg Build

Where did your machine demonstrate Newton's Third Law of Motion? Was there a place where the machine did not have enough strength to give "equal but opposite force?"

Explain three sections of your machine in which there were changes in kinetic and potential energy. Your explanations should include details on what happened during the step and how both kinetic and potential energy changed during the machine's run. Also, calculate the theoretical GPE for one resting marble in your machine.

Rube Goldberg Build

Name: _____

Self Reflection:

Please complete the following phrases – be thorough for full credit.

Overall, I contributed to my group by...

My greatest contribution was...

I could have been more helpful if I...

My group worked well together because we...

My group had challenges in the following areas...

I tried to overcome these challenges by...

If I could rate my contributions, I'd give myself _____ out of 10 because...

If I could rate my group members, I'd give:

_____ a _____ out of 10 because...

_____ a _____ out of 10 because...

_____ a _____ out of 10 because...