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PHYSICS WITH A CATAPULT AIRPLANE

Students will work in teams to build/fly a catapult airplane following instructions, and the model shall serve to discuss principals of flight and forces acting on an airplane. Students will then analyze forces and energy for the experiment.

LESSON PLAN

Lesson Objectives

The students will:
- Construct/fly a catapult airplane by following instructions
- Investigate the forces acting on the flyer
- Measure the thrust force with a spring balance
- Calculate the stored energy in the rubber band

Goal
In this lesson, students will fly a plane, measure forces, and learn about Newtonian mechanics.

Background
To develop an idea of the motivation behind this experiment, consider attempting to throw a paper airplane by only moving your wrist. With such a short path to accelerate, it is challenging! Now think about how you would want to fly the plane if you only had a runway the same length of your wrist's movement? How should we approach this problem?

In order to take off, an airplane needs to generate enough lift (the upward fundamental force of flight) to overcome its weight (the downward fundamental force of flight). As the airplane travels faster, the greater the lift generated. For commercial airplanes, the runway is generally very long to ensure adequate time to meet the velocity required for take-off. Conversely, they require a lot of space to decelerate and land safely.

Aircraft carriers are a great example where this is a limitation, where even the longest aircraft carrier is around 1,000 feet long. In order for most aircraft to launch with this short of a distance, they often have a catapult to launch them safely into the air. This is done in a more sophisticated manner than a rubber band as we shall use, but they use things such as pneumatic (air) or electromagnets to very rapidly accelerate the plane.

Grade Level: 9 - 12

Ohio Learning Standards/Science (2018)
Expectation of Learning
Nature of Science

Physical Science
PS.FM.1: Motion
PS.FM.2: Forces
PS.FM.3: Dynamics
Physics
P.M.2: Motion graphs
P.M.3: Projectile motion
P.F.3: Elastic Forces
P.F.6: Forces in two dimensions

Ohio Learning Standards/Mathematics (2017)

Numbers & Quantity Standards (-quantities & -vectors)
N.Q.1: Use units to understand problems
(+) N.VM.1: Recognize vector quantities
(+) N.VM.3: Solve problems involving velocity
Algebra
A.SSE.1: Interpret expressions in its context
A.CED.4: Rearrange formulas for quantities of interest
A.REI.1: Explain each step in solving an equation
A.REI.3: Solve linear equation

Materials Required:
- Catapult flyer (see references for DIY option)
- Spring balance (0-10 N)
- Meter-stick or Measuring tape
- Stopwatch
- Electric balance
- Launching platform (varies by flyer model)
- Microsoft Excel

Physics!

We will be examining potential energy, kinetic energy, balanced and unbalanced forces, Hooke's law, and distance calculations. As a primer, here are some definitions and their associated formulas in RED. These will help build understanding for the lab portion of the experiment, and the activity afterwards.

Potential Energy (denoted by U): Energy that is present in a system that can be converted to useful energy but is **stored**. Two examples of this are gravitational potential energy and elastic potential energy.

$$Gravitational\ potential\ energy: U_{Grav} = mgh$$

Where U_{Grav} is the potential energy due to gravity, measured in Joules (J equivalent to N*m), *m* is the mass of the object, *g* is the acceleration due to gravity in m/s^2 (generally taken as 10 m/s^2 or 9.81 m/s^2), and *h* is the height of the object. The second example of stored energy is elastic potential energy which we will treat like a spring using Hooke's law.

Hooke's law states that force that is required to stretch or compress a spring by some distance (suppose we call it x) is linearly proportional.

$$F_{spring} = -kx$$

Where F_{spring} is the force exerted by the spring in N, *k* is some spring constant that is unique to a given spring (in N/m), and x is the displacement of the spring (in m, positive displacements are stretches and negative displacements are compressions). You may wonder why there is a negative sign? For an easy comparison, think of a click-pen: when you try to click the pen, the spring in the pen 'pushes back' or opposes the motion, which you are trying to impose upon it. It is this opposing force that requires the negative sign in this formula. Elastic potential energy can be calculated as the following:

$$Elastic\ potential\ energy : U_{EPE} = \frac{1}{2}kx^2$$

Kinetic Energy (denoted by K): Energy of movement and motion.

$$Kinetic\ Energy: K = \frac{1}{2}mv^2$$

Here, the K is the kinetic energy of the system, which is measured in the same units as potential energy, (Joules), *m* is the mass of the object in motion, and *v* is the velocity of the object in m/s.

The total energy of the system (E) is the sum of all of the energy contributions of the system. Because of the law of conservation of energy, all of the energy of a closed system must be held constant This means that energy can be converted to different types of energy, but it cannot be created or destroyed. There are some reasons though, that a system may seem to 'lose' energy, and that is usually due to friction, air resistance, and thermal losses.

$$E = K + U_{EPE} + U_{grav} + E_{other\ sources}$$

We can assume that the energy of our system should stay constant, and we will neglect the "other sources for now.

Force (denoted by F): A push, pull, or acceleration in some direction with some magnitude dependent upon the object's mass and acceleration.

$$F = m * \boldsymbol{a}$$

Here, *F* is the force (in N), *m* is the mass of the object and Forces are **vectors** meaning they have some magnitude (for example, 500 N) and a direction (such as down). Forces are typically drawn on a **free body diagram**. *Important: If an object is not accelerating or decelerating (such as a car constantly at 40 mph or a block of wood stationary on a ramp, etc.), the sum of all forces is zero.*

Acceleration (denoted as **a**): The rate at which something changes from one velocity to another. Acceleration is **vector,** so there must be a direction for acceleration. An example of this is the acceleration due to gravity, which is generally **9.81 m/s^2 downward.** Acceleration can be calculated in different ways. Some describe the *average* acceleration, which is the difference in two velocities over a time period. Others may describe the *instantaneous* acceleration which is the acceleration at a specific point in time. The instantaneous acceleration is the slope of the line of velocity versus time.

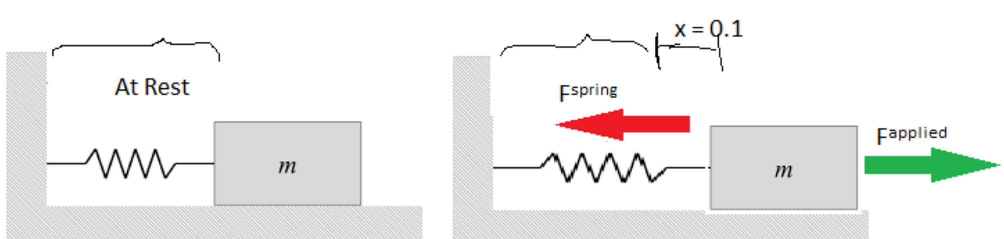
$$average\ acceleration: \boldsymbol{a_{avg}} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

Velocity (denoted as **v**): The rate at which something moves from one position to another. Like acceleration and forces, velocity is a **vector**. It is very similar to acceleration, except it instead describes the difference in position in relation to time. Velocity is also very similar to speed, but speed is not a vector. An example of velocity would be a car travelling at 15 m/s north: the velocity is 15 m/s north, the speed is simply 15 m/s. Like acceleration, we can describe the average velocity and the instantaneous velocity. The instantaneous velocity is the slope of the line of position versus time.

$$average\ velocity: \boldsymbol{v_{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}$$

Next, we will work out an example that will be similar to the experiment to be performed.

Example: Consider a spring that is attached to a wall and a mass that has a mass of 1 kg. The mass is sitting on a frictionless surface, so forces due to friction can be ignored. The spring has a force constant of *k* = 20 N/m. From the initial position, the mass is pulled back 0.1 m, causing the spring to tug back on the mass with an equal force.



Question 1: What is the magnitude (in Newtons) of the force required to pull the spring back 0.1 m?

Q1: We know that the force the spring is experiencing is equal to F_{spring}= -kx. Since x represents the displacement, which is provided as 0.1 m, and the force constant *k* is given as 20 N/m, we know the force the spring is providing is F_{spring} = - 20 N/m * 0.1 m = -2 N. Since the object is stationary at this point, the force required to pull the spring back must be working to counteract this -2 N force, as the sum of forces must be zero. This means the force required to pull the spring back is equal to 2N.

Question 2: When the mass is pulled back 0.1 m, what is the energy that is stored in the spring?

Q2: This question is asking for the elastic potential energy, which can be computed using the formula above. U_{EPE} = ½ kx^2. We can fill in the same values for k and x to solve accordingly.

$$U_{EPE} = \frac{1}{2} * 20 \frac{N}{m} (0.1m)^2 = 0.1\ N * m = 0.1\ J$$

Question 3: While the weight being held still 0.1 m from relaxation, are there are any additional energy contributions? Are there any kinetic energy contributions? Are there any contributions from gravitational potential energy?

Q3: Since we are dealing with a flat surface, the height of the weight is not changing, so therefore, if there were a contribution due to gravity, it can be neglected, since the gravitational potential energy would be considered constant. Due to this, we can neglect gravitational potential energy. We also can say knowingly that the kinetic energy while the weight is being held is 0, because the object is not moving. Due to the lack of friction, we can assume that our system, even if put into motion should stay constant, and the only form of energy change should be from elastic potential energy to kinetic energy and vice versa.

Question 4: Suppose the mass is released, and the spring and mass system is allowed to oscillate (move back and forth). Where is the elastic potential energy equal to zero, and where is the kinetic energy maximized?

Q4: In the last question, we established that the total energy of the system is constant, and initially we have 0.1J of energy in our system. We also know that the total energy is comprised solely of kinetic energy and elastic potential energy, so we can revisit our equations for the total energy of the system.

$$E = U_{EPE} + K = \frac{1}{2}kx^2 + \frac{1}{2}mv^2$$

From here, we now have to think about elastic potential energy, and cases where it is zero. Since we know that k has a set value of 20 N/m, then we look at cases where x is 0, or where the spring is released. At this point all of the energy in the system has been converted to kinetic energy. So this point is also where the kinetic energy is maximized.

Question 5: Using the previous steps, determine the maximum velocity of the mass.

Q5: We mentioned in the last question that when there is no contributions from elastic potential energy, the kinetic energy is maximized. This is our indicator to use the kinetic energy formula at this point. So since the energy for the system is constant, we allow for K = E, which was determined to be 0.1J.

$$0.1\,J = \frac{1}{2}mv^2 => 2 * \frac{0.1J}{kg} = v^2 => \pm\sqrt{.2\frac{m^2}{s^2}} = \pm.4\frac{m}{s}$$

This provides an idea on some of the forces, and equations we will deal with for the experiment.

Experiment: The Catapult Glider

SAFETY FIRST!! Do NOT aim or fly the aircraft into any student or spectator. Use caution when flying the models. Create a single direction flight zone. Have all students stand behind the "takeoff" line. Give an "all clear" signal when it is time to fly the planes and do not allow students to cross the "takeoff" line to retrieve airplanes that have already landed until a "retrieve all planes" signal has been given.

Begin separating into teams of four. Within each of the teams, determine who will hold the following roles.

1. Pilot – the student who will be releasing the aircraft from the launch zone
2. Timer – the student who will measure the time from the aircraft's takeoff to landing
3. Measurer – the student who will measure the distance the aircraft travels
4. Recorder – the student who writes down the measurements from the other students for each trial

First, acquire a catapult plane by either purchasing one or following a DIY method (see references section). Next, depending on the version of catapult airplane used, create the launch zone. This should be an area where a rubber band can be affixed securely and the plane needs only to be pulled back and released to allow to fly (preferably on the ground). Using the spring balance, stretch the rubber band and determine the distance (in mm) the rubber band must be pulled for 2.0 N, 4.0 N, 6.0 N, and 8.0 N. Record and mark this distance for use during flight.

Distance Required for 2.0 N: ________________________

Distance Required for 4.0 N: ________________________

Distance Required for 6.0 N: ________________________

Distance Required for 8.0 N: ________________________

Height of the launch platform (if applicable) in meters: _____________________

Next using the electronic scale, mass the plane in kg: ______________________

For launch, pull back the plane in a "launch ready" position with a 2.0 N force, and when given the "all clear" launch the plane, and have the timer record the air time of the air craft and the measurer record the distance travelled. Launch the plane at a 2.0 N force two additional times and record the values for the time traveled and the distance traveled.

Repeat the launch and recording process for the 4.0 N, 6.0 N. and 8.0 N distances, recording similar data. For ease and convenience, a chart has been provided on the next page to record the values for this experiment. See the extension for more exercises related to this this experiment.

References:

DIY Flyer: **https://www.scientificamerican.com/article/build-a-paper-airplane-launcher/**

Physics References: **http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html**

Physics References: **https://www.khanacademy.org/science/physics/work-and-energy/hookes-law/a/what-is-hookes-law**

National Museum of the US Air Force: **https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/196310/north-american-b-25b-mitchell/**

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Name______________

In the following tables, for each trial, record the total distance flown and the air time of each of the planes.

DISTANCE

Force Applied	Trial 1 (m)	Trial 2 (m)	Trial 3 (m)	Average (m)
2.0 N				
4.0 N				
6.0 N				
8.0 N				

TIME

Force Applied	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Average (s)
2.0 N				
4.0 N				
6.0 N				
8.0 N				

Evaluation Questions

Q1: Using Hooke's law – use the stretched distance and force values to find the spring constant of the rubber band. Use the formula Force = k*stretch. Do your values change as you use the 2, 4, 6, or 8 N values?

Q2: Using Microsoft Excel, enter "Stretch Distance" in cell A1 and enter "Force" in cell B1. Enter your Force values underneath force, without the N. Enter the corresponding distances in A2, A3, A4, and A5. In cell C1, type =SLOPE(B2:B5,A2:A5) and hit enter. How does this value compare to the value obtained in Q1?

Q3: Using the mass of your plane, estimate the velocity of the plane the moment it detaches from the launch system. Start by calculating the elastic potential energy of the system before it is released, and relate this to the kinetic of the system.

Q4: Now, if the launch-pad was above the ground, find the total energy (E) of the system by adding the gravitational potential energy to the elastic potential energy value.

Q5: Calculate the average velocity for each force.

Q5: Calculate the average kinetic energy of the flyer for each force, using the average velocity. Compare this answer to Q3.

Q6: Come up with explanations for the why the variations may exist for distance and time flown.

No time for the experiment? Here is some sample data that can be used instead!

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Name___________

In the following tables, for each trial, record the total distance flown, and the air time of each of the planes.

Stretching distance required for 2.0 N: 3.4 cm
Stretching distance required for 4.0 N: 7.0 cm
Stretching distance required for 6.0 N: 10.3 cm
Stretching distance required for 8.0 N: 14 cm
Starting Platform height: 0m

DISTANCE

Force Applied	Trial 1 (m)	Trial 2 (m)	Trial 3 (m)	Average (m)
2.0 N	3.53	3.12	3.23	
4.0 N	8.01	8.98	9.16	
6.0 N	14.70	17.56	16.75	
8.0 N	23.10	20.30	26.40	

TIME

Force Applied	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Average (s)
2.0 N	1.01	0.95	0.98	
4.0 N	1.40	1.45	1.50	
6.0 N	1.65	1.76	1.71	
8.0 N	1.87	1.70	1.99	

Evaluation Questions

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Q2: Using Microsoft Excel, enter “Stretch Distance” in cell A1 and enter “Force” in cell B1. Enter your Force values underneath force, without the N. Enter the corresponding distances in A2, A3, A4, and A5. In cell C1, type =SLOPE(B2:B5,A2:A5) and hit enter. How does this value compare to the value obtained in Q1?

Q3: Using the mass of your plane, estimate the velocity of the plane the moment it detaches from the launch system. Start by calculating the elastic potential energy of the system before it is released, and relate this to the kinetic of the system.

Q4: Now, if the launch-pad was above the ground, find the total energy (E) of the system by adding the gravitational potential energy to the elastic potential energy value.

Q5: Calculate the average velocity for each force.

Q5: Calculate the average kinetic energy of the flyer for each force, using the average velocity. Compare this answer to Q3.

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Name__KEY____

In the following tables, for each trial, record the total distance flown, and the air time of each of the planes.

Stretching distance required for 2.0 N: 3.4 cm
Stretching distance required for 4.0 N: 7.0 cm
Stretching distance required for 6.0 N: 10.3 cm
Stretching distance required for 8.0 N: 14 cm
Starting platform height: 0 m

DISTANCE

Force Applied	Trial 1 (m)	Trial 2 (m)	Trial 3 (m)	Average (m)
2.0 N	3.53	3.12	3.23	3.29
4.0 N	8.01	8.98	9.16	8.72
6.0 N	14.70	17.56	16.75	16.33
8.0 N	23.10	20.30	26.40	23.27

TIME

Force Applied	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)	Average (s)
2.0 N	1.01	0.95	0.98	0.98
4.0 N	1.40	1.45	1.50	1.45
6.0 N	1.65	1.76	1.71	1.71
8.0 N	1.87	1.70	1.99	1.99

Evaluation Questions

Q1: Using Hooke's law – use the stretched distance and force values to find the spring constant of the rubber band. Use the formula Force = k*stretch. Do your values change as you use the 2, 4, 6, or 8 N values?

For 2N, 58.8 N/m, for 4N, 57.1 N/m, for 6N, 58.3 N/m, for 8N 57.1 N/m.

Q2: Using Microsoft Excel, enter "Stretch Distance" in cell A1 and enter "Force" in cell B1. Enter your Force values underneath force, without the N. Enter the corresponding distances in A2, A3, **A4, and A5. In cell C1,** type =SLOPE(B2:B5,A2:A5) and hit enter. How does this value compare to the value obtained in Q1?

K = 57

Q3: Using the mass of your plane, estimate the velocity of the plane the moment it detaches from the launch system. Start by calculating the elastic potential energy of the system before it is released, and relate this to the kinetic of the system.

For 2N, 3.5 m/s, for 4N, 7.3 m/s, for 6N, 10. m/s, for 8N 15 m/s.

Q4: Now, if the launch-pad was above the ground, find the total energy (E) of the system by adding the gravitational potential energy to the elastic potential energy value.

For 2N, 0.033 J. For 4N, 0.14 J. For 6N, 0.30 J. For 8N, 0.56 J.

Q5: Calculate the average velocity for each force.

For 2N, 3.4 m/s. For 4N, 6.0 m/s. For 6N, 9.6 m/s. For 8N, 13 m/s.

Q5: Calculate the average kinetic energy of the flyer for each force, using the average velocity. Compare this answer to Q3.

For 2N, 0.030 J, For 4N, 0.095 J. For 6N, 0.24J. For 8N, 0.42 J.

Q6: Come up with explanations for the why the variations may exist for distance and time flown.

Answers here can vary. Some explanations that may arise include wind, small variations in launch conditions, plane being damaged in flight, loss of elasticity in the rubber band, among others.