SPRING LOADED

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Student Workbook

Name:

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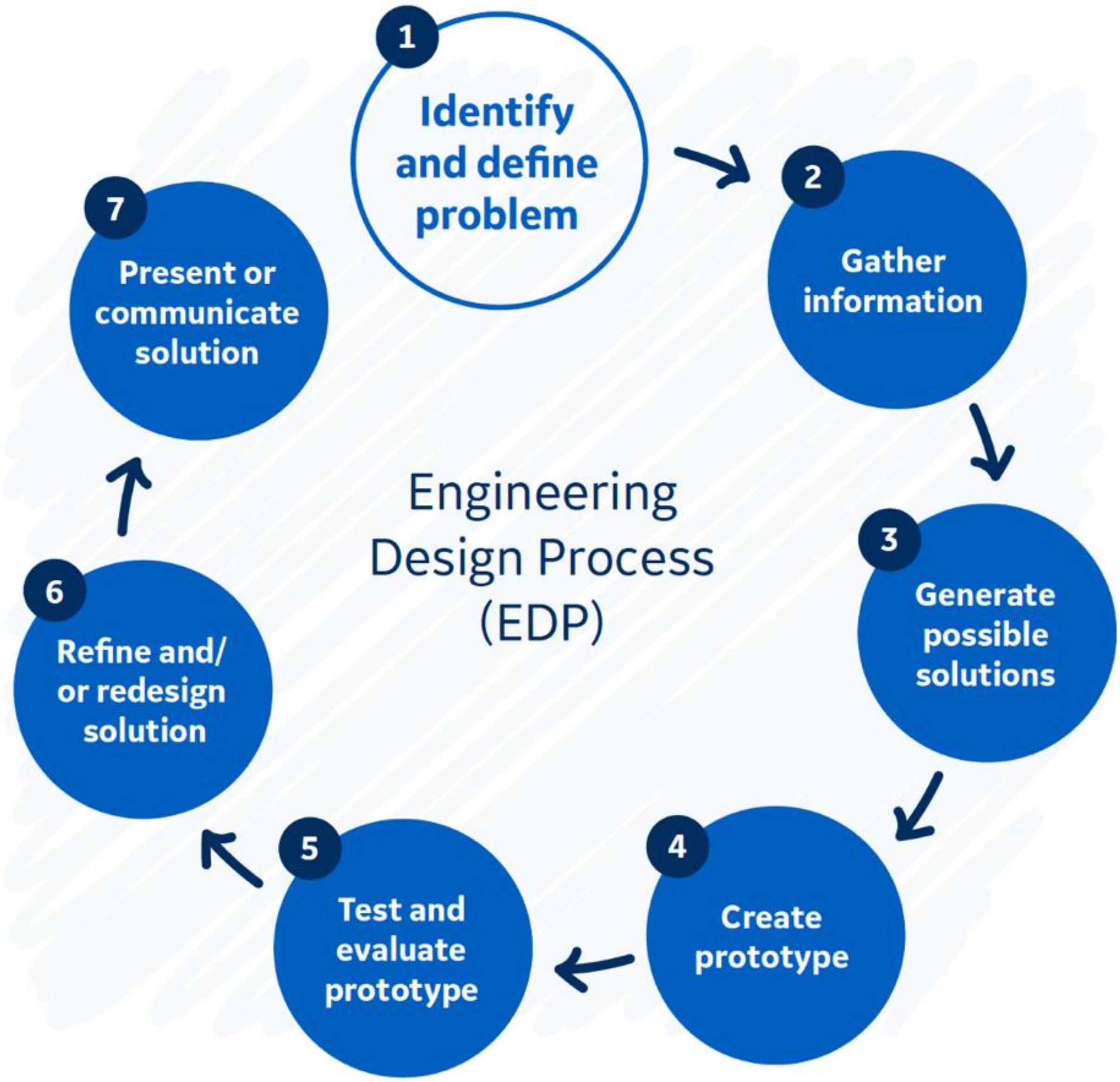
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Introduction

Today, people and goods can travel farther, more quickly, more safely, and more economically than ever before. Modern transportation has greatly increased the economic potential and productivity of millions of people, and access to work opportunities has lifted millions more out of poverty.

In addition, foods and other essentials are now available more reliably and at less cost to more people than ever before. In short, modern transportation has accelerated human economic development.

This remarkable progress has been driven by fossil fuels. Over the years, major improvements to the internal combustion engine and catalytic converters have resulted in cleaner and more efficient vehicles. But burning fossil fuels does still come at a cost.

Globally, transportation accounts for about 16.2% of all CO_2 emissions[1]. Almost 75% of this is due to road vehicles, with passenger vehicles making up the majority[2]. This means that about 9.5% of all CO_2 emissions are because of the cars we drive.

Reducing emissions from cars (and transport in general) can result in sizable cuts in global CO_2 emissions and reductions in environmental pollution. Electric vehicles are often touted as a key driver in this regard. But is this really the case?

Electric vehicles require electricity and, currently, only about 35% of electricity is produced from low-carbon sources (especially nuclear and renewables)[3]. Indeed, the energy required to manufacture the batteries for electric vehicles (most often from fossil fuels) means that it reaches the showroom floor having been responsible for about double the CO_2 emissions of an ordinary vehicle. By some estimations, an electric vehicle would need to be driven for more than 200 000 miles (about 320 000 km) before the ordinary vehicle becomes ‘dirtier’. Instead of solving the problem, electric vehicles often just move it.

This is a systemic problem, and it requires a systemic response. We cannot afford to become fixated on any single intervention. We need to be doing lots of things at the same time and we need to be mindful of the impact that each action has on the entire system and on the economic well-being of ordinary people, especially those in the developing world.

Reducing emissions from transportation, for example, requires a multipronged response including all the following:

NOTES

[1] https://ourworldindata.org/emissions-by-sector. Accessed 10 September 2021
[2] https://ourworldindata.org/co2-emissions-from-transport. Accessed 10 September 2021
[3] https://ourworldindata.org/grapher/electricity-prod-source-stacked

- **Fuel switching** - Using fuels that emit less CO_2 like hydrogen fuel cells and electricity from low-carbon sources, such as wind, solar, and nuclear.
- **Improving fuel efficiencies** - Using better and more advanced vehicle and drive train designs, materials, and technologies. Hybrids have an important role to play here.
- **Improving operating practices** - Adopting practices that minimize fuel use, including improved driving practices and vehicle maintenance.
- **Reducing travel demand** - Adopting urban planning that reduces the number of kilometers that people need to travel each day, making biking and walking more feasible, as well as implementing effective and efficient public transport.

Three of the four strategies above are efficiency-based, using the energy available to achieve more. Improving energy efficiency is all too often overlooked.

Key outcomes

By the end of this design challenge you will be able to:

- Define energy.
- Explain the difference between kinetic energy and potential energy.
- Calculate kinetic energy.
- Calculate elastic potential energy.
- Define and identify instances of friction and air resistance.
- Define and explain mechanical advantage.
- Calculate the overall energy efficiency of your mousetrap vehicle.

Essential questions

During this challenge, you will need to try and answer the following important questions.

- What are potential energy and kinetic energy and how can we efficiently convert potential energy into kinetic energy?
- What is mechanical advantage?
- What is the effect of mechanical advantage on making our vehicle go farther or faster?
- What are friction and air resistance?
- How can we minimize friction and air resistance?
- What is traction?
- How can we improve the traction of our wheels?
- How do we measure speed and distance?
- How can we improve our vehicle's acceleration?

The public presentation

At the end of the design challenge, you and your team will present your mousetrap vehicle to a public audience. **Your presentation should be a maximum of 10 minutes**.

Your facilitator will explain when and where you will do this presentation and who will be in this audience, although it is likely that it will include your parents, your teachers, and GE engineers.

You must describe the process you went through to design, test, and refine your vehicle. In addition, you must present answers to the following questions:

- What problems related to friction did you encounter and how did you overcome these?
- What kind of wheels did you use? Why did you choose them?
- What was the total approximate elastic potential energy stored in your mousetrap?
- What was the total mechanical advantage of your vehicle?
- What was the acceleration of your vehicle while under power?
- What was the maximum velocity achieved by your mousetrap vehicle?
- How did the theoretical distance your vehicle might have covered compare to the actual distance it covered and what was responsible for this difference?
- What was the force of friction acting in the opposite direction to the motion of your vehicle?

!

STUDENT NOTE

Make sure that you keep lots of detailed notes in this workbook and take videos and photos of what you do at each step so that you have information to refer back to and draw on when you build your presentation.

- What was the overall efficiency of your vehicle in converting potential energy to kinetic energy? How might this be improved through additional optimization?

You must also be prepared to answer questions on your design and the process you followed from members of the audience.

Section 1

Think about the following questions. Use the space provided to write down your answers.

1. If we can use a mousetrap as a battery, what else could we use as a battery? Where or how would the energy be stored?

2. Could we design a car that runs on a mousetrap battery? What kinds of problems would we need to solve to make this possible?

3. What else might we power with a mousetrap battery?

Section 2

Make a note of the specific criteria and constraints you have for this challenge.

The design challenge:

Criteria	Constraints

CRITERIA AND CONSTRAINTS

Success criteria are the conditions the design must satisfy to be considered successful.

Constraints are the limitations within which the design must remain.

Section 3

Energy is all around us but is invisible. Like the wind, we can see the effects of energy when things move. Energy is defined as the ability to do work and to move something from one position to another.

Sometimes work is done to move a huge ship. Sometimes work is done to move a single electron. Without energy to do work, the universe would be motionless and dead.

Energy can take two main forms

1. **Kinetic energy** is the energy a moving object has. When you walk or run, you have kinetic energy. A swinging wrecking ball has enough kinetic energy to do the work to destroy a building.
2. **Potential energy** is the energy that is stored because of the position or arrangement of matter. Energy can be stored in many ways.
    a. **Gravitational potential energy** is the energy of an object held above the ground. A stationary wrecking ball held above a car has the potential to do work if released.
    b. **Chemical potential energy** is the energy stored in the chemical bonds between atoms and molecules. When coal or oil is burned, this chemical potential energy is released as thermal energy.
    c. **Elastic potential energy** is the energy stored when an object, like a rubber band or spring, is stretched or deformed. This energy is released when the object regains its normal shape.
    d. **Electric (or electromagnetic) potential energy** is the energy stored because of a charged particle's position in an electric field or its position relative to another charged particle. We can think of this like the energy needed to hold two opposite magnetic poles apart. As soon as we let go, this potential energy is converted into the kinetic energy of the magnets as they move together.

All energy (potential and kinetic) follows one basic rule – it cannot be created or destroyed. It can only be converted or transformed from one form to another. This is called the **Law of Conservation of Energy**. The total amount of energy in the whole universe is fixed – it never changes.

The gravitational potential energy of the wrecking ball held above the car is converted into kinetic energy as it falls. All its potential energy is converted into kinetic energy by the time it reaches the ground.

By twisting the spring on a mousetrap, the mousetrap will store energy in the spring as elastic potential energy. This stored potential energy will turn into kinetic energy of the trap when the spring returns to its normal shape.

Both energy and work are measured in Joules (J). We say that 1 J of energy is needed to do 1 J of work.

Work is calculated as force times distance or $W = F \times d$ where W is work (J), F is force (N) and d is distance (m).

If it requires 30 N of force to push a chair and you push it 2 m across the floor, you will have done $30\ \mathrm{N} \times 2\ \mathrm{m} = 60\ \mathrm{J}$ of work (or put in 60 J of energy).

We can easily calculate the kinetic energy of moving objects with this equation:

$$KE = \frac{1}{2} m \times v^2$$

where m is the mass of the object (kg) and v is its velocity (m/s)

We can see from this that the heavier on object is or the faster it travels, the more kinetic energy it will have.

1. What is the kinetic energy of a 0.45 kg mousetrap vehicle moving at 3.2 m/s?

2. A mousetrap vehicle has 1.46 J of kinetic energy. If it has a mass of 327 g, what is its velocity?

Section 4

To design an effective mousetrap vehicle, we need to understand something about how and why things move and also stop moving.

Newton's Laws of Motion

Newton's laws of motion help us to understand why and how things move the way they do when acted on by forces.

Newton's First Law of Motion
Newton's first law of motion states that if an object is at rest or moving at a constant speed in a straight line, it will remain at rest or keep moving in a straight line at constant speed unless it is acted upon by a force.

If a mousetrap vehicle is at rest, it will not move unless a force is applied to it. This makes sense. But why then do we see things that are moving at a constant speed in a straight line eventually stop? In the real world, moving objects always encounter friction, which is a force acting in the opposite direction to their motion.

Friction leads us to Newton's second law.

Newton's Second Law of Motion
If you want to change the motion of an object (make it move, speed it up, slow it down, or change its direction), you must do work on the object by applying a force.

Newton's second law of motion is often written as an equation:

$$F = ma$$

where F is the force (N), m is the mass of the object (kg) and a is the acceleration (m/s^2 - a measure of the object's change in motion).

We can see from this equation that the heavier your mousetrap vehicle is, the more force you will need to get it going, but also the more force you will need to slow it down and stop it. That's quite a balancing act! Only through experimentation will you find the best mass.

Watch the video called *STEMonstrations: Newton's 2nd Law of Motion* (2:39) for an excellent visual demonstration of Newton's second law of motion done on the International Space Station.

- *STEMonstrations: Newton's 2nd Law of Motion* (2:39)
  https://www.youtube.com/watch?v=sPZ2bjW53c8

NEWTON'S LAWS OF MOTION

- **Law 1**: Objects at rest will stay at rest and objects in motion will stay in motion unless acted upon by a net external force.
- **Law 2**: $F = ma$
- **Law 3:** When two objects interact, they apply forces to one another that are equal in magnitude and opposite in direction.

Newton's Third Law of Motion

Newton's third law of motion is often called the law of action and reaction. It states that when two objects interact, they apply forces to one another that are equal in magnitude and opposite in direction.

For example, when you catch a ball, you apply a force on the ball that changes its motion (stops it). But the ball also applies a force on your hand. The more kinetic energy the ball has, the more force it can exert on your hand. This is why baseball players have catcher’s mitts.

So whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. This is going to be very important when you consider your wheels. As they turn, the wheels will exert a force on the ground. But the ground will also exert an equal but opposite force on the wheels. If the wheels push the ground ‘backwards’, the ground will push the wheels (and your vehicle) forward.

Friction

In a perfect world your mousetrap (or any vehicle for that matter) would roll forever in a straight line until a net force acts on it to change its motion. But in our universe, there is **friction**. Friction is a force that acts **against** the motion of all moving objects.

NET FORCE

If we have a force of 50 N accelerating a vehicle (in the positive direction) and a force of friction of 20 N acting in the opposite direction (the negative direction), we have a net (or overall) force of 30 N accelerating the vehicle (in the positive direction).

If the force pushing the vehicle forward is only 10 N, then the net force will be -10 N or 10 N in the negative direction, i.e., 10 N decelerating the vehicle.

Energy is always needed to overcome friction. The greater the amount of friction, the less **efficient** the system will be. Friction converts energy into heat and sound. This removes the energy from the motion of the vehicle and causes it to roll to a stop. All its kinetic energy is eventually removed. Heat and sound are normally considered lost forms of energy because it is hard to recapture this energy once it has been turned into heat and sound.

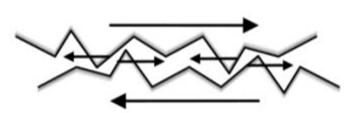
If the stored energy in the mousetrap does **positive work** on a vehicle to move it forward, friction does **negative work**. Your challenge is to produce a vehicle that has the least possible friction. The smaller the frictional force, the farther and faster the energy in the mousetrap will propel your vehicle.

You will need to evaluate every part on your vehicle and decrease the amount of friction at each point. As a rule of thumb, the more moving parts a machine has, the greater the force of friction will be and the greater the energy lost will be.

Friction occurs anytime two surfaces slip, slide, touch, and/or move against one another. There are two basic types of friction - surface friction and fluid friction.

Surface friction

Surface friction occurs any time two surfaces touch and/or rub against one another. The cause of surface friction is mutual contact of microscopic irregularities that exists on all surfaces. These microscopic irregularities act like tiny obstructions to motion. Even surfaces that look or feel perfectly smooth have irregularities when viewed under a microscope.



Surface friction
https://commons.wikimedia.org/wiki/File:Friction.png

The amount of surface friction acting between two objects depends on

1. the kinds of material from which the two objects are made
2. how hard the two surfaces are pressed together.

There will be less friction between a wooden block and a sheet of glass than between the same wooden block and a concrete sidewalk. If a mass is placed on top of the wooden block, there will be more weight (or force) pressing the block onto the other surface (the glass or concrete), increasing the friction in both cases. As any two surfaces are pressed harder and harder together, their irregularities will require more and more force to overcome.

Surface friction can be reduced by smoothing out these irregularities and/or by adding a **lubricant**. The smoother the two surfaces can be made, the less friction that will exists between them, to a point. We can never totally eliminate surface friction.

Fluid friction
This has to do with the friction a moving object experiences because it is moving through a fluid like water or air. It is sometimes also called **drag**. Drag increases if the velocity of the object increases or if its surface area increases. It is unlikely that drag will be a significant factor for your mousetrap vehicle, but to be sure, keep your vehicle as sleek as possible.

Now open the following interactive simulation. Click on the **Acceleration** button. Spend some time exploring force, friction, motion, speed, and acceleration for yourself.

- *Force and Motion: Basics*
  https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html

Now answer the following questions in the space provided.

1. What will make a mousetrap vehicle at rest accelerate and start moving?

2. Why will your mousetrap vehicle eventually come to rest again?

3. If the force applied by your mousetrap is greater than the force of friction, how will the motion of vehicle change?

4. When will your mousetrap vehicle start to slow down again?

5. Under the same force, which will accelerate more quickly, a lighter or a heavier vehicle?

6. What would you have to do to increase the acceleration of your mousetrap vehicle if you did not change the force applied by the mousetrap?

7. What would you have to do to increase the distance your mousetrap vehicle can travel if you did not change the initial force applied by the mousetrap?

Pause and reflect 1

1. Write down THREE things you have learned about energy, motion, and friction so far.

2. Write down TWO things you have learned about yourself so far.

3. Write down ONE thing you have learned about working in a team so far.

4. Write down your response to each of the following prompts and then share your thoughts with your team.
   a. Describe ONE thing you think your team has done well so far.

   b. Describe ONE thing you think you have done well so far.

   c. Describe ONE thing you think your team can improve on going forward.

   d. Describe ONE thing you think you can improve on going forward.

Section 5

Complete the following steps to see how you can change the mechanical advantage of your mousetrap.

1. Measure the length of your mousetrap spring arm in mm.

2. Calculate the length of the arc through which the mousetrap arm travels as it closes. Remember that the circumference of a circle is $2\pi r$ where r is the radius of the circle.

   Note: some mousetraps do not operate over a full 180°. You may need to approximate the percentage of the semi-circle through which the arm does travel and multiply your answer by this amount. For example, if the arm travels through 90% of the semi-circle, multiply the answer by 0.9.

3. If you connected the wheels of a vehicle directly to the mousetrap arm, what do you think would happen? How far would the vehicle travel?

4. Using the materials you have, create a device that will reduce the size of the output force but apply it over a greater distance.

5. If you have not yet done so, connect your dowel or skewer to the mousetrap arm with the cable ties or electrical tape. Which arm, the original arm or the extended arm, travels through a greater distance?

MOUSETRAP SAFETY TIPS

- Never leave the trap set
- Never trigger the trap while holding it. Always lay it on a surface.
- Never trigger the trap with your finger. Always use a pen, pencil, or other object.

6. Is the force greater at the end of the original arm or the extended arm? Why?

7. Measure the length of the extended arm and calculate the arc length through which the end travels.

8. We can think of the original arm as the input arm and the extended arm as the output arm. Calculate the mechanical advantage of this simple machine.

9. By creating this simple lever machine with a mechanical advantage less than one, we *increase* the distance through which the output force is applied while *decreasing* the magnitude of this output force. How will this help us design a better mousetrap vehicle?

Section 6

Use the space below to write down your own list of brainstorming do's and don'ts.
Afterwards, you will share these with the group.

Section 7

As you think about how to design your mousetrap vehicle, here are some important questions for you to think about.

1. How can the energy stored in the spring be used to turn the vehicle's wheels?
2. How can the energy stored in the spring be released in a slow and controlled manner?
3. How can the friction experienced by the vehicle be reduced?
4. How can enough traction between the wheels and the ground be created so that the wheels don't just spin without the vehicle moving forward?
5. What is the best lever length to use?
6. How will the mass of the vehicle affect its performance?
7. What is the best size of wheel to use?
8. How will the mass of the wheels affect the vehicle's performance?
9. Are you going to use a front or rear wheel drive design?
10. What is the best material to use to attach your lever to your axle?
11. What is the best diameter of axle to use?
12. How can we ensure the vehicle travels in a straight line?

To help you think about these questions, review the following two resources, and read the notes below. You will find many helpful design hints.

- ***1st place Mousetrap Car Ideas- using SCIENCE*** (14:05)
  https://www.youtube.com/watch?v=b7zWwo9dbiU

- ***Mousetrap Cars: Construction tips*** Website
  https://www.docfizzix.com/topics/construction-tips/Mouse-Trap-Cars/

Mechanical advantage

The only source of power your vehicle has is the mousetrap. Ordinarily, we think of mechanical advantage as allowing us to amplify a small input force to produce a bigger output force. The price we pay is having to apply the input force over a greater distance. Machines that amplify the **output force** have a mechanical advantage **greater than one**.

$$\text{Mechanical advantage} = \frac{\text{output force}}{\text{input force}}$$

or

$$\text{Mechanical advantage} = \frac{\text{input distance}}{\text{output distance}}$$

In the case of your mousetrap vehicle, you need to think about mechanical advantage in reverse. You are trying to **increase** the distance over which the force is applied and the price you pay for this is a reduction in the force. Machines that amplify the **output distance** have a mechanical advantage of **less than one**.

Extending the length of your mousetrap arm, will extend the distance through which the end of the arm travels, but this will come at the expense of the force at the end of the extended arm being reduced.

If the length of the mousetrap arm is 2 cm, for example, and you extend it to be 30 cm, then the mechanical advantage will be

$$\text{MA}=\frac{5\text{ cm}}{30\text{ cm}}=\frac{1}{6}$$

The same kind of calculation can be done between the wheels and axles. If the diameter of the axle is less than the diameter of the wheels, then a mechanical advantage of less than one will result – the distance through which the axle rotates will be amplified by the larger wheels but this will come at the expense of the force applied by the wheels on the ground.

If the diameter of the axle is 1 cm, for example, and the wheels have a diameter of 12 cm, then the mechanical advantage will be

$$\text{MA}=\frac{1\text{ cm}}{12\text{ cm}}=\frac{1}{12}$$

The total mechanical advantage of the entire system would be

$$\text{MA}=\frac{1}{6}\times\frac{1}{12}=\frac{1}{72}$$

The greater the denominator of your mechanical advantage fraction, the more you will have amplified the distance of the output arm but the less force that will be available to turn the wheels. In other words, the greater the denominator of your mechanical advantage fraction, the greater time it will take the energy in the mousetrap to transfer to the wheels but the smaller the force at the wheels will be.

Vehicle mass

The heavier an object, the more force is required to accelerate it. This is just another way of expressing Newton's Second Law of Motion $F = ma$. We say that heavier objects have greater **inertia**. They are harder to get going.

Therefore, if your vehicle is too heavy and you have a very small mechanical advantage (a fraction with a very large denominator), the force available may not be big enough to get the vehicle moving. Remember, no push starts are allowed!

However, heavier objects, once moving, have more momentum. This means that they are harder to stop. This means that the heavier your vehicle, the farther it is likely to coast once the mousetrap has been fully released and is no longer applying any force.

Wheel mass

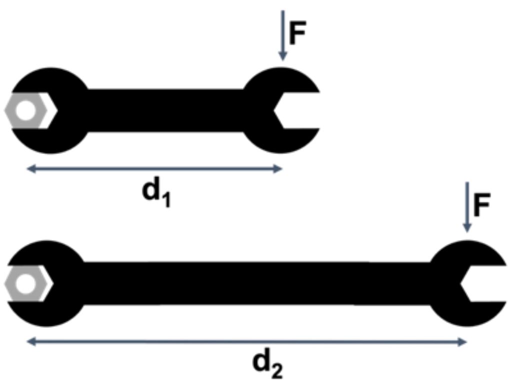
In the same way as the overall mass of your vehicle will affect its performance, the mass of your wheels will also play a roll. Heavier wheels have greater inertia. They are harder to start turning. But heavier wheels also have greater momentum once they are turning. Big wheels are a good idea if you want to reduce the mechanical advantage (make the denominator in the fraction bigger) but bigger wheels also tend to weigh more. How will you balance these?

Torque

Torque is the rotational (or turning) equivalent of a linear force. It is a measure of the amount of force required to twist or turn an object. Every time you twist a door handle or tighten a screw, you apply torque.

The energy in your mousetrap spring will ultimately drive your vehicle forward by applying a torque to your wheels to turn them.

Torque takes advantage of mechanical advantage. The amount of torque applied depends on the force applied and the distance at which that force is applied from the point of rotation. It is much easier to loosen a bolt with a long spanner (or wrench) than a short spanner. This is because with a long spanner, you can apply the force farther away from the point of rotation and therefore get more torque for the same force.



In other words, more torque will be applied to the bolt by the longer spanner because the distance at which the force is being applied (d_2) is greater than for the other spanner (d_1), even though the size of the force is the same.

Torque is calculated by multiplying the force (F) in N by the distance (d) in m and, therefore, is measured in N.m (newton meters).

Watch the video called *torque explained* (6:17) if you want to learn more.

TORQUE

Torque is the name given to the turning force. When you turn a door handle, you apply torque. The spring in your vehicle will apply torque to your wheels.

- *torque explained* (6:17)
  https://www.youtube.com/watch?v=ekpSQHxXFBM

Traction

Newton's third law of motion says that when two objects interact, they apply forces to one another that are equal in magnitude and opposite in direction. Another way of saying this is that you can only push as hard as something can push back.

When you walk, you push backwards on the floor and the floor pushes forwards on you. If the floor does not push back, you do not move. This happens when you try walk on ice of a tiled floor in socks.

A car is propelled forward because the drive wheels push on the road and the road pushes back against the wheels of the car, causing the wheels and the car to move. A vehicle's acceleration is limited by the interaction the vehicle's wheels have with the road. Any vehicle that produces a lot of **torque** (the force turning the wheels) also needs good **traction** with the road or the wheels just spin.

Drag racer by PXfuel.com is licensed as free for commercial use

Therefore, if the floor cannot push back with the same force as the wheels of your vehicle push, then your wheels will just spin in place and the car will not accelerate to its full potential.

Traction, in this context, is a good form of friction. The more friction there is between your wheels and the ground, the less likely it will be that they will just slip past each other.

You can try to deal with the problem of traction in two main ways. First, you can design wheels that have better 'grip'. Second, you can design your vehicle so that the energy from the spring gets released more slowly. In other words, you apply a

TRACTION

Traction is a useful form of friction that stops the wheels of your vehicle from slipping across the ground. Instead, more of the rotation of your wheels gets converted in the forward motion of your vehicle.

smaller force but over a longer time. You decrease the mechanical advantage (make the denominator of the fraction bigger).
The grip a wheel has can be changed by changing what the wheel is made of. Cars have rubber tires rather than running on their steel rims because there is more friction between rubber and the road than there would be between steel and the road.

Grip can also be increased by pushing the wheels onto the ground with more force. The greater the force, the greater the friction. Therefore, you will not only need to think about how heavy your vehicle is but also where most of this mass is. If you can get it most of the mass over the drive wheels, you will improve your traction. Another way of saying this is to try and get the **center of mass** of your vehicle as close to the drive wheels as possible.

Center of mass

The center of mass is the location in space where the mass of an object can be thought to be concentrated and where the mass can be treated as a point mass. For symmetrical objects of uniform density like a brick, the center of mass is the same as the geometrical center.

For irregularly shaped and non-uniform objects like a spade or hammer, the center of mass will be closer to one side of the object than the other, i.e., it will be different from its geometrical center. Some objects can even have a center of mass 'outside' the object itself.

Bird toy showing center of gravity by APN MJM is licensed under a CC BY-SA 3.0 licence
https://commons.wikimedia.org/wiki/File:Bird_toy_showing_center_of_gravity.jpg

Center of mass and wheels
Wheels that are forced to rotate around a point that is not their center of mass will wobble and consume more energy than if allowed to rotate around their center of mass. The farther the center of rotation is from the center of mass, the greater the wobble and the more energy will be lost.

Larger wheels are affected more by an offset center of mass than smaller wheels. For this reason, the bigger your wheels the more important it is that they are balanced and rotate about their center of mass.

CENTER OF MASS

The center of mass (sometimes also called the center of gravity) of an object can be estimated by finding the location where it balances on the end of a pen or pencil. This works very well for 2D or flatter objects but is less accurate for 3D objects.

To balance a wheel, you should hold the wheel by the axle and allow it to turn freely. The heavier side of the wheel will fall towards the bottom. Once the heavier side is marked, mass can be added to the opposite side until the wheel has no tendency to rotate when suspended freely by the axle.

Steering

The straighter your vehicle travels, the farther from the start line it will go. However, getting your vehicle to travel in a straight line can be harder than it seems. You need to not only make sure that your front wheels run parallel to the body of your vehicle body but that they run parallel to each other.

Do front wheel drive vehicles naturally go straighter than rear wheel drive vehicles? This is something you will need to test.

General design considerations

To maximize the performance of your vehicle, here are some general design tips. You will notice that some of these tips seem contradictory. You will have to find the right balance.

- A longer lever attached to your mousetrap will reduce the mechanical advantage (make the denominator of the fraction bigger).
- The lower the mechanical advantage, the less force will be applied to your vehicle's wheels but over a longer period. Therefore, your vehicle will accelerate slower. Smaller mechanical advantage is usually good to increase the distance your vehicle can cover.
- The greater the mechanical advantage, the more force will be applied to your vehicle's wheels but over a shorter period. Therefore, your vehicle will accelerate faster. Larger mechanical advantage is usually good to increase the acceleration your vehicle can achieve.
- A longer lever needs a bigger vehicle which will usually have more mass.
- The frictional forces (internal and external) must be kept as small as possible.
- Lighter vehicles are easier to accelerate. Mass can be removed by removing unnecessary material.
- Heavier vehicles, while harder to accelerate, have more momentum and so will roll on their own for longer.
- Rigid and thin wheels will roll more easily over the ground.
- Softer and wider wheels will have more traction.
- A center of mass closer to the drive wheels will help improve traction.
- Air resistance may not play a huge role, but every little bit helps.
- Larger drive wheels will reduce your mechanical advantage (make the denominator bigger).
- Larger wheels have a greater mass.
- Larger wheels wobble more and lose more energy if they do not rotate about their center of mass.
- A thinner axle will reduce your mechanical advantage (make the denominator bigger).
- Thinner axles have less mass but are less rigid and may bend out of shape.
- The straighter your vehicle travels, the farther it will travel from the start line.

Section 8

Use the space below to capture your design ideas. These do not need to be fully developed. Use words and sketches to describe them. Engineers often use sketches, especially **annotated sketches**, to communicate their ideas. An annotated sketch is a picture (or series of pictures) with detailed labels that shows what a design looks like, describes what it will be made of, and explains how it will work.

Here are some questions to get the juices flowing.

1. What basic mechanism will you use to get the mousetrap to turn the wheels?
2. How will the frame of your vehicle be constructed and what materials will you use?
3. What will you use for your axles?
4. What will you use for your wheels? How big should they be?
5. Where will you position your mousetrap – in the front, the back, or the middle?
6. How will your axles connect to your frame?

TEAM TIP

From this point in the challenge, your team may find it beneficial to start to assign and fulfill specific roles. Some examples might be researcher, notetaker, designer, tester, or media capturer.

It is important to note that having the role of researcher, for example, does not mean that nobody else in the team can do research. It means that the 'researcher' takes responsibility for making sure that the correct research is done and that the results are properly organized.

Your team can define these roles and their responsibilities as you like or in consultation with your facilitator.

Section 9

You can use the Decision Matrix to help you evaluate your team's different design ideas and choose the one you think is the strongest.

	Criteria							
Idea	Affordability	Simplicity	Development time	Buildability	Safety	Ease of use	Durability	Total

Section 10

Use the space below to help you write a design brief.

The design statement

A brief description of the chosen design solution

Annotated design sketches

A set of simple sketches that describe the materials to be used, the important features of the design, how it will be constructed, and a brief explanation of how it will work.

DESIGN STATEMENT

The design statement describes what the solution should do, its specific success criteria and constraints, and what the designer plans to do about it (create a plan or design, build, test, etc.). An example of a design statement is:
We will design, prototype, and test a shopping bag that can carry 5 kg of shopping, has comfortable handles, costs less than 5 c to manufacture, is made from recycled paper, and is no larger than the current bags in use.

ANNOTATED SKETCH

An annotated sketch is a combination of simple labelled drawings and explanatory notes that describe and explain a design idea. They are not polished pieces of art but are meant to help designers communicate complex ideas. They can be revised and changed throughout the design process. See the end of the workbook for examples.

Equipment and materials list

Item description and number	Approximate cost	Where it can be obtained

Pause and reflect 2

Write down your responses to the following prompts.

1. The most surprising thing I have learned so far is…

2. One thing I would like to improve on is…

3. The thing I am most anxious about in this challenge is…

4. I think working in a team is/is not an important skill to learn because…

5. I like/dislike doing hard things because…

6. Sometimes it is important/unimportant to do things I don't enjoy very much because…

7. I think engineering is/is not the career for me because…

Section 11

As you build the first iterations of your mousetrap vehicle you will need to do some testing. Here are some of the things you might want to test.

1. What effect does changing the length of the lever arm have on distance covered and/or the rate of acceleration?
2. What effect does changing the diameter of the axle and/or the wheels have on distance covered and/or the rate of acceleration?
3. What effect does using wheels of different mass have on distance covered and/or the rate of acceleration?
4. What effect does using wheels of different materials or adding other materials to the outside of your wheels have on the performance of your vehicle.
5. What effect does using different kinds of string or thread have on vehicle performance and how does how it is attached to the lever arm and axle affect performance?
6. What effect does increasing or decreasing the mass or the distribution of this mass have on the performance of your vehicle?
7. What effect does changing the position of your mousetrap have on the performance of your vehicle.
8. What effect does using bearings or other friction reducing methods, especially between your axles and frame, have on the performance of your vehicle?
9. What effect do better balanced wheels and/or axles and wheels that don't move side to side have on the performance of your vehicle?
10. What mechanisms can you use to make sure your vehicle goes straight?
11. Do front-wheel drive or rear-wheel drive vehicles perform better?

It can be tempting to just jump in and start running tests. Often, however, you get better, more accurate, and more useful results if you plan what and how you will test more carefully. For each test you want to carry out, think about the following questions.

1. What aspect(s) of your prototype will you test?
2. How will you test? What testing procedure will you follow?
3. What are your criteria for success? How will you know if your design works or not, or which parts of it need to be refined and/or redesigned?
4. What data will you collect? How will you collect this data?
5. How will you analyze this data to draw accurate conclusions?

For example, if you are testing the effect of the diameter of your axle, you need to decide what diameters you will test and change only this feature of your design. Then run a few tests at each diameter to get an average and then plot the diameter of the axle vs the distance your vehicle travelled to help you analyze the effect of this change. Is there an ideal diameter that results in the best performance?

You can use a similar process to test other aspects of your vehicle, like wheel size and mass, lever arm length, the position of your mousetrap in your vehicle etc.

Use the table below to help you plan some of your tests.

What are we testing?	How will we test and what are the success criteria?	What data will we collect and how?

Use the following space or your own notebook to describe the results of each test and record any data you collect.

Section 12

Now that you have completed some testing, use the space below to describe the results and outcomes of your tests. Think especially about the following questions.

1. What worked and what failed?
2. What the problems did you encounter?
3. What changes or modifications do you want to make?

Remember that you can use the decision matrix tool if you need to decide between several new or modified design options.

Also remember that, based on any improvements or changes that you would like to make, you need to update your materials list and start collecting the materials you need.

What worked and what failed?

What problems did you encounter?

What changes or modifications do you want to make?

Section 13

As you continue to test and optimize your vehicle, here are some additional design and troubleshooting tips.

Tips for building distance vehicles:

1. The more string you can pull off your axle, the more times you can rotate your wheels and the farther your vehicle will travel under the mousetrap's pulling force. More string means a longer lever arm. But a longer lever arm means a longer vehicle which usually means a heavier vehicle.
2. The larger your drive wheels, the more distance your vehicle will cover for each rotation. But remember bigger wheels usually mean heavier wheels and heavier wheels need more energy to get them rotating. They have greater rotational inertia.
3. The smaller your drive axle, the more axle turns (and hence wheel turns) you can achieve for a given length of string.
4. Vehicles that accelerate slowly tend to travel farther. Reducing the force at the wheels through a smaller mechanical advantage will reduce the acceleration.
5. Lighter vehicles need less energy to get going and keep moving.
6. Friction is not your friend! Where is your vehicle experiencing friction? How can you reduce this friction to an absolute minimum?
7. Wheels that wobble waste energy.
8. Vehicles that don't go straight waste energy.

Tips for building speed vehicles:

1. You want the maximum acceleration. Therefore, you don't want too small a mechanical advantage. Shorter lever arms and smaller wheels will increase your mechanical advantage so that you have more force available at your wheels.
2. Wheels spinning looks cool but wastes energy that you could be using getting your vehicle to the finish line first. Try wheels with better grip or traction.
3. Lighter vehicles under the same force will accelerate faster.
4. Friction is not your friend! Where is your vehicle experiencing friction? How can you reduce this friction to an absolute minimum?
5. Wheels that wobble waste energy.
6. Vehicles that don't go straight might miss the finish line.

Some common problems to watch out for:

1. An axle sliding back and forth causing wheels to run against the vehicle frame is a major source of friction. Washers or other sorts of spacers can help.
2. An axle slipping inside a wheel is obviously no good. Some well-aimed glue usually helps.
3. Sometimes the axle you want to use is not the right size to fit your wheels. Masking tape can be used as an effective spacer.
4. String slipping over the axle means that the force is not being transferred to your wheels. Using a hook can help. Just be sure that the string does not stay attached to the axle unless you want to vehicle to stop.

5. If your vehicle does not start moving at all, you probably have a major friction problem. Check where your axles meet your frame first.
6. Vehicles not traveling straight can be a major issue. Make sure your wheels point in the same direction AND are parallel to your frame.
7. If your vehicle is suddenly stopping, check that the string is not remaining attached to the axle.

Section 14

There are 2 major forces acting on your mousetrap vehicle – the force of the mousetrap spring driving the vehicle forward and the force of friction (especially surface friction) acting in the opposite direction and slowing it down.

You need to present calculations for the following as part of your final presentation:

1. The total mechanical advantage of your mousetrap vehicle.
2. The approximate elastic potential energy in your mousetrap
3. The acceleration of your mousetrap vehicle.
4. The maximum velocity achieved by your mousetrap vehicle.
5. A comparison of the theoretical distance covered by your vehicle under power and the actual distance it covered.
6. The force of friction acting in the opposite direction to the motion of your vehicle.
7. The efficiency of your mousetrap vehicle in converting potential energy to kinetic energy.

Below is a table of the different physical quantities you will need to measure to complete all the necessary calculations. It is suggested that you run your vehicle about 5 times and complete the table with the average values.

Total distance covered (m)		**Total time (s)**	
Distance covered under power (m)	**Time under power (s)**	**Mass of vehicle (kg)**	**Total angle through which mousetrap is set (^{o})**
Length of mousetrap arm (m)	**Length of extended arm (m)**	**Diameter of drive axle (m)**	**Diameter of drive wheels (m)**

Below, you will find step-by-step instructions for doing the necessary calculations. Spaces are provided for your calculations.

Calculate the total mechanical advantage of your mousetrap vehicle

1. Calculate the mechanical advantage conferred by your extended mousetrap arm.

$$\mathrm{MA}_{\mathrm{mousetrap}} = \frac{\text{input distance}}{\text{output distance}} = \frac{\text{length of mousetrap arm}}{\text{length of extended mousetrap arm}}$$

2. Calculate the mechanical advantage conferred by the difference between the diameter of your axle and wheels.

$$\mathrm{MA}_{\mathrm{wheels}} = \frac{\text{input distance}}{\text{output distance}} = \frac{\text{diameter of axle}}{\text{diameter of wheel}}$$

3. Calculate the total mechanical advantage.

$$\mathrm{MA}_{\mathrm{total}} = \mathrm{MA}_{\mathrm{mousetrap}} \times \mathrm{MA}_{\mathrm{wheels}}$$

Calculate the approximate elastic potential energy in your mousetrap

To calculate the total elastic potential energy (in Joules (J)) that is stored in your set mousetrap, we can use the following equation.

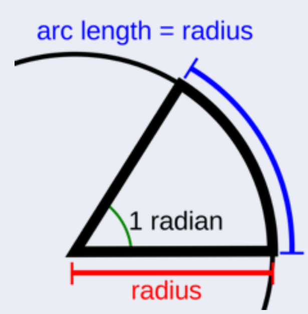
$$PE_{spring} = \frac{1}{2} \times k \times \theta^2$$

MECHANICAL ADVANTAGE

You could also calculate the mechanical advantage conferred by your extended mousetrap lever arm by comparing the length of the arc travelled by the end of the original arm and the length of the arc travelled by the end of the extended arm. Remember that the circumference of a semi-circle is given by πr.

RADIANS

A radian is just another way to measure angles. There are 2π radians in one full revolution (360°). One radian is equivalent to the angle that creates an arc length on the circumference equal to the radius of the circle.



$$1° = \frac{\pi}{180} \text{ radians}$$

Radians are often expressed in terms of π.

where k is called the spring constant (a number unique to each type of spring and determined by the size and material out of which the spring is made) and θ is the angle through which the spring is twisted (in radians).
For your mousetrap, we can assume that $k = 1.3\ \mathrm{N/m}$.

4. Use a protractor to measure the angle through which the arm rotates when setting the mousetrap.

5. Covert this to radians noting that $1° = \frac{\pi}{180}$ radians.

6. Calculate the total elastic potential energy stored in your mousetrap.

Calculate the acceleration of your mousetrap vehicle

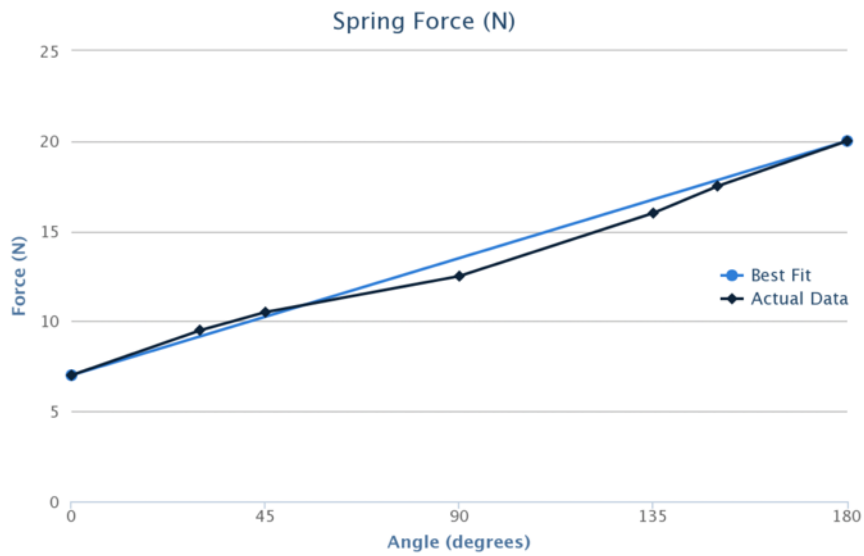
We know from Newton's Second Law of Motion that force, mass, and acceleration are related by the equation

$$F = ma$$

where F is the force applied (N), m is the mass of the object (kg) and a is the acceleration of the object ($\mathrm{m/s^2}$).

To work out the acceleration of our mousetrap vehicle we need to know the force applied to the wheels. We know that the force exerted at the wheels is less than the force exerted by the mousetrap arm because our mechanical advantage is less than one.

However, the force exerted by the mousetrap changes over time. It is greatest just as it is released and gradually decreases. If you have a spring scale available, you can use it to measure the force required to pull the mousetrap arm through different angles (always pull in the same direction as the rotation of the arm). If you do this, you should find that when you plot the force needed against the angle, that the graph is more or less a straight line (see the graph below).



Because the relationship is linear we can take an estimate of the average force exerted by the mousetrap arm as the force at 90°.

If you don't have a spring scale, you can assume that the force of the mousetrap at 90° (in other words the average force exerted by the mousetrap) is 13.8 N.

We already know the total mechanical advantage of the system. Therefore, we can calculate the average force applied to the wheels.

7. Calculate the average force applied to the wheels in N.

$$MA = \frac{F_{output}}{F_{input}} = \frac{F_{\text{wheels}}}{F_{\text{mousetrap}}}$$

$$\therefore F_{\text{wheels}} = \text{MA} \times F_{\text{mousetrap}}$$

Now that we know the average force applied to the wheels, and we know the mass of the vehicle, we can calculate the vehicle's average acceleration under power (while the mousetrap is pulling).

8. Calculate the average acceleration of the vehicle in m/s^2.

$$F = ma$$
$$\therefore a = \frac{F}{m}$$

STUDENT NOTE

In reality, it is likely that maximum velocity will be reached before the end of period where the vehicle is under power. This is because the force applied by the mousetrap does reduce over time. This means that there is likely to be a point where the force driving the vehicle forward is equalled by the force of friction, meaning that no net force is applied and so there is no acceleration. If the force applied by the mousetrap actually becomes less than the force of friction, the net force will be in the opposite direction and the car will start to decelerate.

Calculate the maximum velocity achieved by your mousetrap vehicle

Knowing the average acceleration of our vehicle means that we can work out its maximum velocity. We can assume that maximum velocity will be achieved at the end of the period where the vehicle is under power. This is just before there is no more net driving force and hence no farther acceleration.

We can use the following equation to calculate this velocity.

$$v = u + at$$

where v is the final velocity (m/s), u is the initial velocity (which we know is 0 m/s), a is the acceleration of the vehicle (m/s^2) and t is the time during which the vehicle was accelerating (s).

9. Calculate the maximum velocity reached by your vehicle in m/s.

$$v = u + at$$

Compare the theoretical distance covered by your vehicle under power and the actual distance it covered

The distance a vehicle travels over a certain time with a known acceleration can be calculated using this equation.

$$s = v_i t + \frac{1}{2}at^2$$

where s is the distance travelled (m), v_i is the initial or starting velocity (m/s), t is the time under acceleration (s), and a is acceleration (m/s^2). In our case, the vehicle started from rest so $v_i = 0$.

10. Calculate the theoretical distance your vehicle should have covered under power in m.

$$d_{\text{theoretical}} = v_i t + \frac{1}{2}at^2$$

11. Compare this to the distance your vehicle actually covered under power. Is it more, less, or the same? Why do you think this is?

Calculate the force of friction acting in the opposite direction to the motion of your vehicle

There are several different methods we can use to calculate the force of friction acting to slow down and stop our vehicle. Each of them requires different assumptions and, therefore, has different pros and cons.

One way is to recognize that once your vehicle starts to coast, (i.e., the mousetrap has stopped applying a driving force), the only force acting on your vehicle is the force of friction. Therefore, from this point, only friction is doing work on your vehicle by applying a force in the opposite direction to its motion over a certain distance.

We can already work out what this stopping distance is (total distance – distance under power). We also know the total work done. Our vehicle started with some kinetic energy and ends with no kinetic energy. Therefore, the work done is equal to this change in our vehicle's kinetic energy.

We also now know our vehicle's maximum velocity and so we can calculate its maximum kinetic energy using this equation:

$$KE = \frac{1}{2}mv^2$$

where m is the mass of the vehicle (kg) and v is the velocity of the vehicle (m/s)

12. Calculate your vehicle's maximum kinetic energy.

$$KE = \frac{1}{2}mv^2$$

We know that $W = F \times d$ and we know that the work done by friction is equivalent to the change in our vehicle's kinetic energy to zero. We also know the distance over which this force is applied.

13. Calculate the force of friction acting on your vehicle.

$$W_{friction} = F_{friction} \times d$$
$$\therefore F_{friction} = \frac{W_{friction}}{d}$$

Calculate the approximate efficiency of your vehicle in converting potential energy to kinetic energy

We have calculated the total elastic potential energy in our mousetrap and we have calculated our vehicle's maximum kinetic energy (while under power). Therefore, we can calculate the percentage efficiency of our vehicle.

14. Calculate the efficiency (%) of your vehicle in converting potential energy to kinetic energy.

$$\text{Efficiency} = \frac{\text{KE}}{\text{PE}} \times 100$$

Section 15

Reflect individually on your experience with the engineering design process by answering the following questions.

1. What was the **most interesting thing** you learned in this challenge?

2. Which step(s) seemed the **most important** to you?

3. Which step(s) seemed the **least important** to you?

4. Which step of the process did you find the **easiest**? Why do you think this was the case?

5. Which step did you find the **most challenging**? Why do you think this was the case?

6. What would you have done **differently** if you had more time or more budget?

7. Describe one or two things you learned about **energy**, **energy transfer**, **motion**, and **friction** that surprised you the most.

8. Describe one or two things you learned about **engineering** or the **engineering design process** that surprised you the most.

9. Have your thoughts about what engineering is, or who engineers are, **changed** because of this design challenge? How?

Section 16

Discuss with your team what your shared experience of the engineering design process has been through this challenge.

1. Name one thing you **appreciate** about or learned from each member of your team.

2. Describe one way in which each member of your team **surprised** you.

3. Which of the following **attributes** do you think each member of your team best exemplifies – systems thinking, adapting, problem-finding, creative problem solving, visualizing, improving?

4. How did your understanding of **teamwork** in the engineering design process change as you went through this challenge?

5. How **effectively** do you think you worked as a team? What did you do well? What do you think you can improve on?

6. What were the most important lessons you learned about **teamwork**?

7. What were the most important lessons you learned about effective **communication**?

8. What would you have done **differently** if you had more time, money, or resources?

9. Would you like to **continue** working on this project together? Why or why not?

Model Answers for Section 14

Note that the following solutions are based on the data contained in the table below. Your vehicle's performance data will be different and, therefore, your final answers will be different.

Total distance covered (m)		Total time (s)	
11.1 m		14.3 s	
Distance covered under power (m)	**Time under power (s)**	**Mass of vehicle (kg)**	**Total angle through which mousetrap is set ($^{\circ}$)**
7.1 m	7.3 s	121 g = 0.121 kg	178°
Length of mousetrap arm (m)	**Length of extended arm (m)**	**Diameter of drive axle (m)**	**Diameter of drive wheels (m)**
4.5 cm = 0.045 m	27 cm = 0.27 m	4 mm = 0.004 m	13 cm = 0.13 m

Calculate the total mechanical advantage of your mousetrap vehicle

1. Calculate the mechanical advantage conferred by your extended mousetrap arm.

$$\mathrm{MA}_{\mathrm{mousetrap}} = \frac{\text{input distance}}{\text{output distance}} = \frac{\text{length of mousetrap arm}}{\text{length of extended mousetrap arm}}$$

$$\therefore \mathrm{MA}_{\mathrm{mousetrap}} = \frac{0.045\ \mathrm{m}}{0.27\ \mathrm{m}} = 0.167$$

2. Calculate the mechanical advantage conferred by the difference between the diameter of your axle and wheels.

$$\mathrm{MA}_{\mathrm{wheels}} = \frac{\text{input distance}}{\text{output distance}} = \frac{\text{diameter of axle}}{\text{diameter of wheel}}$$

$$\therefore \mathrm{MA}_{\mathrm{wheels}} = \frac{0.004\ \mathrm{m}}{0.13\ \mathrm{m}} = 0.0308$$

3. Calculate the total mechanical advantage.

$$\mathrm{MA}_{\mathrm{total}} = \mathrm{MA}_{\mathrm{mousetrap}} \times \mathrm{MA}_{\mathrm{wheels}} = 0.167 \times 0.0308 = 0.00514$$

Calculate the approximate elastic potential energy in your mousetrap

4. Use a protractor to measure the angle through which the arm rotates when setting the mousetrap.

This was measured to be 178°

5. Covert this to radians noting that $1° = \frac{\pi}{180}$ radians.

$$178° = 178 \times \frac{\pi}{180} \text{ rad} = 3.107 \text{ rad}$$

6. Calculate the total elastic potential energy stored in your mousetrap.

$$PE_{spring} = \frac{1}{2} \times k \times \theta^2 = \frac{1}{2} \times 1.3 \text{ N/m} \times (3.107)^2 = 6.273 \text{ J}$$

Calculate the acceleration of your mousetrap vehicle

7. Calculate the force applied to the wheels in N.

$$MA = \frac{F_{output}}{F_{input}} = \frac{F_{\text{wheels}}}{F_{\text{mousetrap}}}$$

$$\therefore F_{\text{wheels}} = MA \times F_{\text{mousetrap}} = 0.00513 \times 13.8 \text{ N} = 0.0708 \text{ N}$$

Note: that this calculation assumes a force at the end of the mousetrap arm of 7.5 N.

8. Calculate the acceleration of the vehicle in m/s².

$$F = ma$$
$$\therefore a = \frac{F}{m} = \frac{0.0708 \text{ N}}{0.121 \text{ kg}} = 0.585 \text{ m/s}^2$$

Calculate the maximum velocity achieved by your mousetrap vehicle

9. Calculate the maximum velocity reached by your vehicle in m/s.

$$v = u + at = 0 \text{ m/s} + 0.585 \text{ m/s}^2 \times 7.3 \text{ s} = 4.270 \text{ m/s}$$

Do a comparison of the theoretical distance covered by your vehicle under power and the actual distance it covered

10. Calculate the theoretical distance your vehicle should have covered in m.

$$d_{\text{theoretical}} = v_i t + \frac{1}{2}at^2 = 0 + \frac{1}{2} \times 0.585 \text{ m/s}^2 \times (7.3 \text{ s})^2 = 15.584 \text{ m}$$

Note: the vehicle's initial velocity (v_i) was 0 m/s.

11. Compare this to the distance your vehicle actually covered under power. Is it more, less, or the same? Why do you think this is?

The actual distance covered by the vehicle is less than the theoretical distance because of the effects of friction. Not all of the work done by the spring was available to accelerate the vehicle and drive it forward. Some of it was used to overcome the force of friction acting in the opposite direction.

Calculate the force of friction acting in the opposite direction to the motion of your vehicle

12. Calculate your vehicle's maximum kinetic energy.

$$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.121\ \text{kg} \times (4.270\ \text{m/s})^2 = 1.103\ \text{J}$$

13. Calculate the force of friction acting on your vehicle.

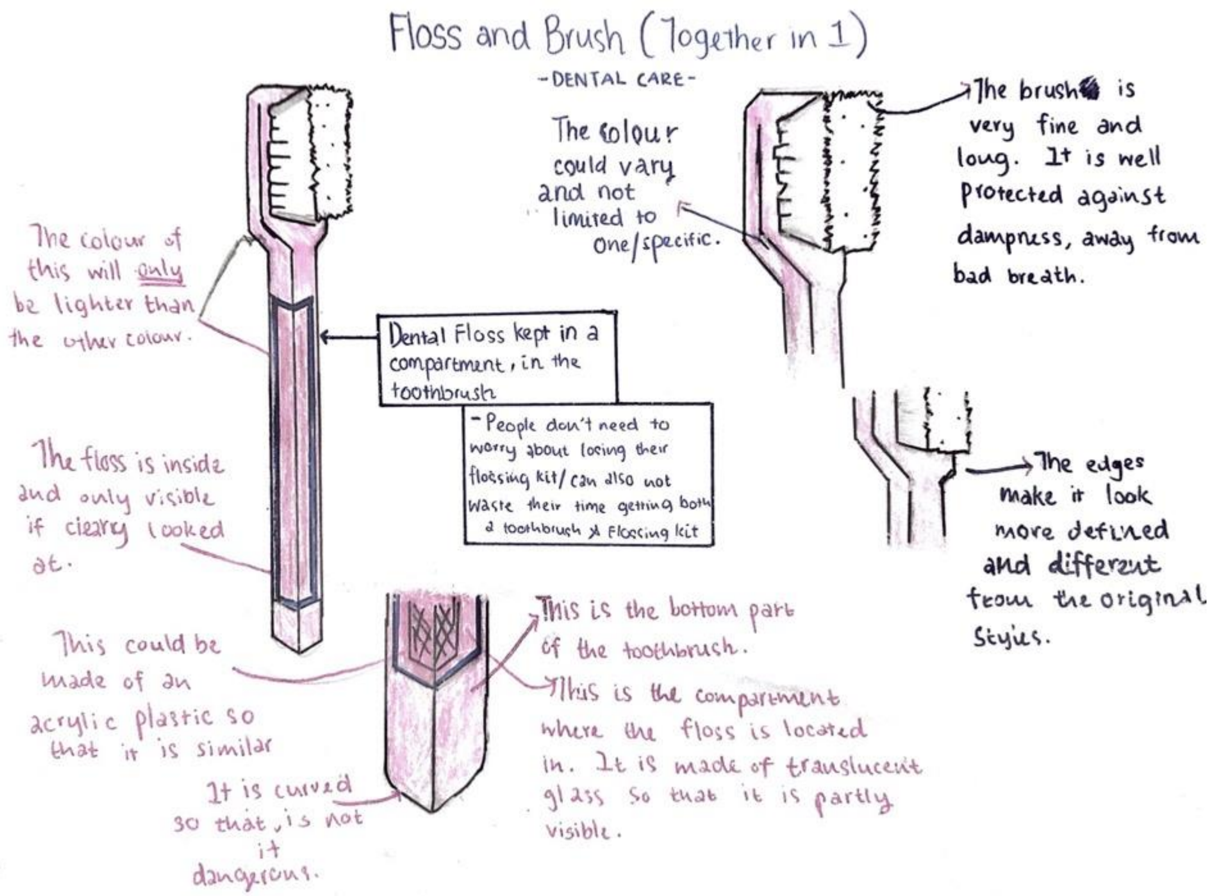
$$W_{friction} = F_{friction} \times d$$
$$\therefore F_{friction} = \frac{W_{friction}}{d} = \frac{1.103\ \text{J}}{4\ \text{m}} = 0.276\ \text{N}$$

Calculate the approximate efficiency of your vehicle in converting potential energy to kinetic energy

14. Calculate the efficiency (%) of your vehicle in converting potential energy to kinetic energy.

$$\text{Efficiency} = \frac{\text{KE}}{\text{PE}} \times 100 = \frac{1.103\ \text{N}}{6.274\ \text{N}} = 17.58\%$$

Annotated Sketches



- The engineer makes an **annotated sketch** of the product and labels all of the visible components.
- This information is used to write up a detailed analysis of the object's sequential operation, or function.