Lab Handout

Lab 5. Force, Mass, and Acceleration: What Is the Mathematical Relationship Among the Net Force Exerted on an Object, the Object's Inertial Mass, and Its Acceleration?

Introduction

Western scientific thought was dominated by Aristotle's views on physics for thousands of years. According to Aristotle, all objects in the universe were made of four elements: earth, water, fire, and air. Furthermore, all objects were believed to have both a *natural motion* and a *forced motion*. The natural motion of an element was toward the center of the universe (which, in Aristotle's view, was at the center of the Earth). Not all of the elements, however, had the same degree of natural motion. The elements of earth and water can move close to the center of the universe more easily than the elements of fire and air can. The natural motion of any object, as a result, depended on the relative amount of each element in it. For example, an object made up of half earth and half water would move closer to the center of the universe than an object made up of half earth and half air. The Earth exists, according to Aristotle, because objects made up of "earth" have come to rest as close as possible to the center of the universe. Forced motion, in contrast, was all the other types of motion that could not be described by natural motion. Later theorists elaborated on Aristotle's views and introduced the concept of *impetus*, the property of an object that created forced motion. When an object lost its impetus, it would then move with natural motion toward the center of the universe. In this view, when a ball is thrown in the air, the person throwing it "imparts impetus to the ball." When the ball runs out of impetus, its natural motion causes it to fall back down.

Beginning in the late Middle Ages, several scientists, including Galileo, Copernicus, and Newton, began to question Aristotle's explanation for how objects move. Galileo, for example, demonstrated that objects fall at the same rate independent of their mass, which was contrary to Aristotle's claims that heavy objects fall faster than lighter ones due to their natural motion. Galileo also observed moons orbiting Jupiter, a phenomenon that could not be explained using Aristotle's ideas. Copernicus later claimed that the Sun, and not the Earth, was at the center of the solar system. This claim, along with Galileo's observations of the moons of Jupiter, directly contradicted Aristotle's idea of natural motion because the Earth was no longer viewed as being located at the center of the universe. Isaac Newton delivered the final blow to Aristotle's explanation about how and why things move in his book *Philosophiae Naturalis Principia Mathematica* (commonly known as the *Principia*), which was published in 1687. In the *Principia,* Newton discarded natural and forced motion as an explanatory framework and introduced three basic laws of motion. *Newton's first law,* as it has become known, states that absent a net force acting on an object, an object at rest will stay at rest and an object in motion will move in a straight line with constant velocity. This law also means that when a net force acts on an object, it will cause it to change how it is moving. In other words, a net force on an object will cause that object to accelerate. This law is so important that the unit for force is called a newton (N).

There are several important implications of Newton's first law. First, the idea of a net force is important, because Newton realized that multiple forces could act on an object at once. The net force, according to Newton, is just the sum of all the forces with respect to their direction. Newton showed that pushing an object to the right with a force of 10 N and pulling the object to the right with a force of 5 N is the same as if only one force of 15 N was moving the object to the right. Figure L5.1 shows another implication of Newton's first law. In this case, two people are each pushing on the box with a force of 25 N, but in opposite directions. According to Newton's first law, a push of 25 N to the left and a push of 25 N to the right results in a net force of zero (0 N). The final implication of Newton's first law is that the net force and the resulting change in motion must be in the same direction. For example, pushing an object with a force of 10 N to the right will cause it to accelerate to the right, and not upward toward the sky. Acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.

FIGURE L5.1

Two people pushing on a box with equal forces but in opposite directions

In the *Principia,* Newton also provided a mathematical relationship among the net force acting on an object, that object's mass, and the acceleration of the object. This mathematical relationship is now known as Newton's second law. This mathematical relationship was revolutionary at the time because it not only explained how objects move but also allowed for people to predict changes in an object's motion. In fact, physicists still use this mathematical relationship today to predict the motion of an object when a force acts on it and to determine the amount of force needed to move heavy objects.

LAB 5

Your Task

Use what you know about forces and motion, causal relationships, and the importance of scales, proportions, and quantity in science to design and carry out an investigation that will allow you to determine the mathematical relationship among the net force acting on an object, its mass, and its acceleration.

The guiding question of this investigation is, ***What is the mathematical relationship among the net force exerted on an object, the object's inertial mass, and its acceleration?***

Materials

You may use any of the following materials during your investigation:

Consumables
- String or fishing line
- Tape

Equipment
- Safety glasses or goggles (required)
- Dynamics cart
- Dynamics track
- Set of masses
- Electronic or triple beam balance
- 2 Pulleys
- Stopwatch
- Ruler
- Meterstick

If you have access to the following equipment, you may also consider using a video camera and computer or tablet with video analysis software.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses or goggles during lab setup, hands-on activity, and takedown.
2. Keep fingers and toes out of the way of moving objects.
3. Wash hands with soap and water after completing the lab.

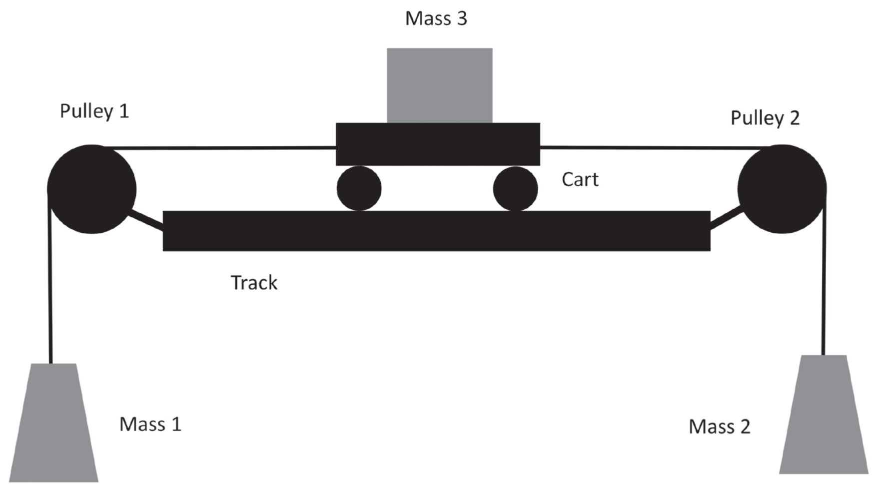
Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out at least two different experiments. You will need to first determine how changing the force acting on an object of a constant mass affects the acceleration of the object. Then you will need to determine how applying the same force to an object of different mass affects the acceleration of the object. You can conduct these two experiments using a cart-and-track system; Figure L5.2 shows the basic setup of the system.

FIGURE L5.2

Cart-and-track system that can be used to determine the mathematical relationship among the net force acting on an object, its mass, and its acceleration



Before you can design and carry out these two experiments, you will need to decide what type of data you need to collect, how you will collect it, and how you will analyze it.

To determine *what type of data you need to collect,* think about the following questions:

- What are the boundaries and components of the system you are studying?
- How do the components of the system interact with each other?
- Which factors might control the rate of change in this system?
- How could you keep track of changes in this system quantitatively?
- What information will you need to be able to determine the acceleration of the cart?
- How will you measure the net force acting on the cart?
- What will be the independent variable and the dependent variable for each experiment?

To determine *how you will collect the data,* think about the following questions:

- How will you change the mass of the cart?
- How will you change the net force acting on the cart?
- What equipment will you need to collect the data?
- What conditions need to be satisfied to establish a cause-and-effect relationship?
- How will you measure the magnitude and direction of any vector quantities?

- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?

To determine *how you will analyze the data,* think about the following questions:

- How could you use mathematics to describe a relationship between variables?
- What type of calculations will you need to make?
- What types of graphs and equations signify a proportional relationship?
- What type of table or graph could you create to help make sense of your data?

Once you have carried out your experiments, your group will need to develop a mathematical function that you can use to predict the acceleration of an object based on its mass and the net force acting on it. The last step in this investigation will be to test your function. To accomplish this goal, you can use a different amount of mass on the cart and a different net force to determine if your function leads to accurate predictions about acceleration of the cart under different conditions. If you are able to use your function to make accurate predictions about the motion of the cart under different conditions, then you will be able to generate the evidence you need to convince others that the function you developed is valid.

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

As you work through your investigation, you may want to consider

- how scientific knowledge changes over time, and
- the difference between laws and theories in science.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your argument must include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L5.3.

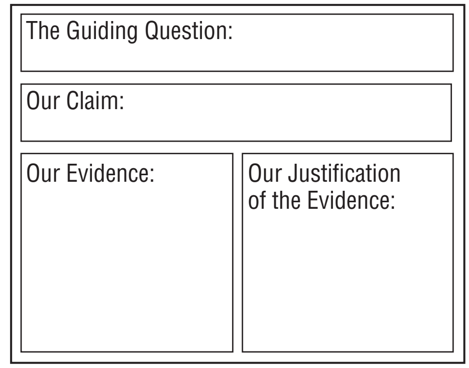
Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

FIGURE L5.3

Argument presentation on a whiteboard



If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an investigation report that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

Reference

Newton, I. 1687. *Philosophiae naturalis principia mathematica* [Mathematical principles of natural philosophy]. London: S. Pepys.