Bikes, Forces, and Torques

Pre-Lab: Bicycles as Simple Machines

A Bit of History

> "The bicycle has been with us in various forms for quite a long time and it has had a far greater impact on human society than one might guess. Today it is assuming even greater importance in the affairs of man. In many countries, particularly in Asia and Africa, it is by far the most important means of transportation. Even in our own affluent society, we find people relying more and more on bicycles for basic transportation needs. Bikes are relatively cheap and readily available. In many cities, traffic problems are so severe that bicycles offer the quickest means of travel from point-to-point. They are non-polluting and actually healthful to the rider. And perhaps most importantly, they are the most energy-efficient means of conveyance known. Not only do they not consume fossil fuels, electricity or nuclear power, but they use human-produced energy so well that a person on a bicycle is a more efficient transporter of mass than even fish or a horse, not to mention automobiles or airplanes."

The above quote seems like something that you might read today on http://sustainability.wustl.edu/, but it actually is historical. In his 1978 tour de force, *The Bicycle*, Philip DiLavore outlines the impact that this simple machine has had on societies across the globe. If we can learn anything from history it is that the bicycle, which started as a design by Leonardo da Vinci, has had and will continue to have a lasting impact on human life.

In modern times we ride bicycles for a variety of reasons: to get from point A to point B; to feel the wind in our hair; to unlock our inner hipster. Whatever your reason may be, bicycles have some utility. This week we are going to quantify this utility and relate it to concepts we have learned in class.

Mechanical Advantage

In addition to looking at the forces and torques on our bicycles we will quantify how well they function as simple machines. The utility of a simple machine is described in terms of the *Mechanical Advantage* (MA) of that machine. Mechanical Advantage can be thought of as a number which describes how effectively the machine aids in the task at hand.

Do This: Find the link to the Bozeman Science video on simple machines using the Pre-Lab Links page on the lab website. (This website has lots of other quality videos as well.)

PL1. List the six simple machines mentioned in the video.

PL2. What is the definition of a simple machine?

Read This: Simple machines can be classified as either *force multipliers* or *distance multipliers*. Force multipliers use a small input force exerted over a large distance to get a large output force over a short distance; distance multipliers use a large input force over a small distance to get a small output force over a large distance. A wheel and axel, a key component of a bicycle, is an example of distance multiplier. In this week's lab we will use a bicycle to study a distance multiplier.

PL3. Based on what you learned in the video, would you expect the MA of a bicycle to be greater than 1, less than 1, or equal to 1? Explain briefly.

Getting to Know Our Bikes

When you get to lab, you will find a bicycle which has been mounted on a stand. Typically these stands are used by cyclists who want to turn their standard bicycle into a stationary bike which they can use to exercise indoors. Other than the stand, the only modification to the bicycle is the replacement of the pedal with a *pedal bar.* This pedal bar will allow us to easily attach weights to the bicycle where the pedal would normally be located.

Most of this week's experiments will involve applying a force to the pedal bar and reading the corresponding output force the rear wheel would exert on the ground. Before we can do these experiments we should get familiar with some of the terminology we will use throughout this lab. Figure 1 is a picture of the front part of the drive train of our bicycle. The key components of our bike are labeled.

Figure 1: The front part of the drive train of our bicycle. Applying an appropriate force to the pedal bar causes it, the crank arm, and the front gears to rotate. All of these components together will be referred to as the *crankset*.

Read This: The pedal bar, crank arm, and front gears are all rigidly fastened together. All of these components together will be referred to as the *crankset*. If an appropriate force is applied to the pedal bar, the crankset will rotate as a single unit.

Read This: When you are performing the experiments you will set up the situation shown in Figure 2. You will attach a disk mass to the pedal bar. You will then connect a force sensor (via a string, carabiner, and zip tie) to the rear wheel. Using the force sensor to record the output force from the rear wheel you will be able to answer questions about the forces and torques at play in the bicycle drive train.

Read This: In order to hit the ground running when you get to lab, you should answer a few questions pertaining to the setup shown in Figure 2. To answer these questions you need to know that the bottom part of the chain is under no tension. As such, it can exert no force on either of the gears. If you don't believe this, check it out for yourself on one of the many bikes you see around campus.

Figure 2: The essential static setup. The crank arm is horizontal and holds disk masses on the pedal bar. The rear wheel is held stationary. A carabiner is attached to a zip tie that is zipped around the rear wheel, directly above the rear axle. The carabiner is attached to a string that is pulled horizontally to the left. The other (unseen) side of the string is attached to a force sensor. The force sensor measures the tension in the string.

PL4. Draw two free-body diagrams: one of the crankset and one of the rear wheel. Label the following forces: gravitational force on the disk mass, F_{in}; tension force from the chain acting on the front gear, F_T; tension force from the chain acting on the rear gear, F_T; force measured by force sensor, F_{out}. Also indicate the point where each of these forces is acting. (Please ignore forces that act on the center of mass of the crankset and the rear wheel as these forces will not produce a torque on the body.)

PL5. Showing your work, use your free-body diagrams to derive an equation for the force on the force sensor, F_{out}, in terms of the following quantities:

- the gravitational force on the mass attached to the pedal bar, F_{in}
- the length of the crank arm, r_{in}
- the radius of the front gear, r_{front}
- the radius of the rear gear, r_{rear}
- the radius of the wheel, r_{out}.

(Hint: Recall that this is a *static* system. The rear wheel is static. The crankset is static.)

Part I: Forces and Torques

Any force, F_{in}, that is applied to an object at a distance r_{in} away from a given axis will put a torque, τ_{in}, on the object about that axis. If all of the forces and torques on the object sum to zero we say the object is static (*i.e.* the object doesn't accelerate linearly or angularly). However, if the torques on the object do not add to zero the object's angular momentum about the axis will change (*i.e.* the object's rate of rotation will either increase or decrease – if it is at rest, it will start to rotate). Whether you think about it or not, when riding a bicycle you impart a torque to the crankset to get from here to there.

For the sake of clarity let's put all of the parameters mentioned in the opening paragraph in terms of our bicycle's parts pictured in Figure 1 of the Pre-Lab.

- F_{in} – force the rider's foot applies to the pedal
- r_{in} – Distance between pedal (where the force is applied) and crank bolt (axis of rotation)
- τ_{in} – the torque on the crankset about the axis through the crank bolt, due to the force F_{in}
- Axis – the axis of rotation of the crankset – the axis passing through the crank bolt
- Object – the pedal bar, crank arm, and front gears which are all fixed together into the crankset

When using a bicycle, a torque is applied to the crank arm and the crankset rotates, pulling the chain with it. In turn the tension in the chain puts a force on the edge of the rear gear which is connected to the rear wheel. This force is some distance away from the rear axle (the distance depends on which gear the chain is connected to), meaning that a torque is imparted to the rear gear and the rear wheel. The rear wheel then imparts a force to the ground. According to Newton's third law, the ground imparts an equal and opposite force on the wheel. It is this force on the wheel, from the ground, which propels the bicycle (and its rider) forward.

In Part I of this week's lab we will investigate how all of these factors affect the output force, and ultimately the acceleration, of our bicycle.

Equipment

- **Geared bicycle (Appendix A gives information regarding the radii of the gears)**
- **Force sensor with string attached**
- **Disk masses (three 1-kg masses)**
- **Protractor**
- **Meter stick**

1. Dependence of Output Force on Input Force

In this part of the experiment we are going to put a force on the pedal bar, analogous to the force a rider would put on the pedal with their foot. This force will be communicated, through the gears and chain, to the rear wheel of the bike. If the bike were on the ground it would be propelled forward as described above.

Because it isn't practical to investigate the force between the wheel and the ground by having a member of every lab group ride a bicycle around the lab, we will investigate these forces in a slightly different way. Specifically, during this part of the experiment the rear wheel will remain *static* (*i.e.* all of the forces on the wheel are balanced AND all the torques on the wheel are balanced). To do this we will connect a force sensor to the rear wheel. Measurements from this force sensor will give us information about the force the rear wheel would apply to the ground if it were not on this stand. That's the force that would move you forward. Figure 3 shows the basic experimental setup.

Do This: Inspect your bicycle and make sure that the chain is passing over the front gear with the largest diameter and the rear gear with the smallest diameter. This particular configuration is termed the *highest speed*. If the chain is not passing over the appropriate gears adjust it, using the gear levers on the handle bars, until it is in the correct spot. (Note: In order to change the gears, you must spin the pedal as if you were pedaling the bicycle forward. The front gear is changed using the gear levers on the left side of the handle bars and the rear gear is changed using the gear levers on the right side of the handle bars.)

Figure 3: The essential static setup. The crank arm is horizontal and holds disk masses on the pedal bar. The rear wheel is held stationary. A carabiner is attached to a zip tie that is zipped around the rear wheel, directly above the rear axle. The carabiner is attached to a string that is pulled horizontally to the left. The other (unseen) side of the string is attached to a force sensor. The force sensor measures the tension in the string.

Read This: The next few instructions will ask you to make your station look like the one shown in Figure 3. Keep in mind that everything is static. Nothing is moving. All of your force measurements today will be on static systems. Setting up the system and keeping it static will likely take some teamwork.

Do This: Attach the force sensor to the rear wheel by attaching the carabiner to the zip tie that is zipped around the rear wheel. The zip tie should be located directly above the axle. Things should look a lot like Figure 3. You should always be pulling horizontally.

Do This: While holding the rear wheel, rotate the crank arm **counterclockwise** until it is horizontal, pointing toward the front of the bike as shown in Figure 3. Place 2 kg on the pedal bar and secure it in place with the nut.

Read This: Is the experimental setup clear? When you have reproduced the static system shown in Figure 3 you may move on to the next step.

Largest gear in the front (in terms of radius), Smallest gear in the rear (in terms of radius)

1.1. Your bike should be in the largest gear in the front and the smallest gear in the back. Further, there should be 2 kg on the pedal bar. Using the formula you derived in Step PL5, *predict* what the reading on the force sensor will be. Explain and show your work. (Appendix A gives information regarding the radii of the various gears on the bike. You might want to reference this appendix occasionally during this lab, perhaps even right now.)

Read This: Now that you have made your prediction, you will set up the software in order to test the prediction.

Do This: Open Logger Pro.

Read This: In the lower left corner you should see a white box which says "Force" on the first line and "XXX N" on the second line where XXX is a numerical value. This is the instantaneous force reading from the force sensor. This value can jump around a bit, so we will average it over a small period of time.

Do This: Time to test your prediction. To measure a force click the green "Start Collection" button which is the far right button along the top row. At this point you should see data appear in the spreadsheet on the left and a red line appear on the graph. After 10 seconds have elapsed data is no longer being collected. Highlight a portion of the plot that looks smooth. Then click the "Statistics" button (the seventh button from the right, this looks like the fraction 1/2). At this point a box shows up. The "mean" value displayed on the third line of this box is the force measurement we are interested in.

1.2. Record the mean force read by the force sensor. Was your prediction in Step 1.1 accurate? Explain what may account for any differences between your prediction and your experimental value. (Important note: Each 1-kg mass can be up to 50 grams heavier than the quoted value.)

Read This: At this point we want to see how changing the magnitude of the input force affects the magnitude of the output force.

Do This: Add a third disk mass to the pedal bar, bringing the total mass to 3 kg.

1.3. *Predict* what value the force sensor will read with 3 kg on the pedal bar. Explain your reasoning and show your work.

Do This: Put the prediction you made in Step 1.3 to the test with an experiment.

1.4. What is the mean force read by the force sensor when 3 kg are placed on the pedal bar? Was your prediction in Step 1.3 correct? If not, explain what may account for any differences between your prediction and your experimental value.

STOP

Do This: Disconnect the carabiner from the zip tie on the rear wheel.

2. Radial Dependence

Now that we understand how changing the input force affects the output force, we are ready to move on and investigate how changing the locations where the forces are applied affects the output force. First we will change the location where the force sensor is connected to wheel, then we change the gears. In both cases we will see how these actions affect the output force.

Largest front gear,
Smallest rear gear

Do This: There should be 3 kg on the pedal bar. Remove 1 kg leaving a mass of 2 kg on the bar.

2.1. *Predict* how the output force will compare to the measurement recorded in Step 1.2 if the force sensor is connected to a ***spoke*** instead of to the zip tie. That is, will the new force be greater than, less than, or equal to the force that you recorded in Step 1.2. Explain.[1]

Do This: Attach the force sensor to the rear wheel by attaching the carabiner to one of the ***spokes*** on the rear wheel. Do NOT attach the carabiner to the zip tie. When you make your force measurement, you should still make sure that the carabiner is directly above the axle.

Do This: Test the prediction you made in Step 2.1 by making a measurement with the force sensor.

2.2. Record the output force. Was the prediction you made in Step 2.1 correct? If not, explain where your reasoning failed.

Read This: When we change the speed of our bicycle we are changing the location where forces are being applied to the wheel. We are now ready to see how this affects the output force. Until now we have worked with this bicycle's highest speed, because we have been in the highest gears: 3 and 7. Let's now investigate a different speed, one where the chain passes over that largest gear on the rear wheel.

STOP

Do This: Disconnect the carabiner from the spoke on the rear wheel. You are about to spin the wheel. In addition, please remove any masses from the pedal bar.

Do This: Use the gear shifter on the right side of the handlebars to adjust the rear gear until the chain is passing over the rear gear with the largest radius. This is rear gear 1. You must pedal the bike forward as you change gears. Then add 2 kg back to the pedal bar.

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[1] **Hint for Step 2.1:** There are at least two very good ways to make this prediction. One would be to use your equation from Step PL5. A second approach is more intuitive. You could start by saying, "Nothing has changed on the crankset simply because I moved the carabiner. Therefore, moving the carabiner does not affect the tension in the chain. And since the rear gear has not changed, the torque that the chain exerts on the rear wheel has not changed." You could take it from there!

Largest front gear,
Largest rear gear

2.3. Your bike should be in the largest gear in the front and the largest gear in the back. Further, there should be 2 kg on the pedal. *Predict* whether the output force will be greater than, less than, or equal to the force you recorded in Step 1.2. Explain.[2]

Do This: Reconnect the carabiner to the zip tie on the rear wheel such that the zip tie is directly above the axle just as you did before Step 1.2. Test the prediction you made in Step 2.3 with an experiment.

2.4. Record the output force. Was the prediction you made in Step 2.3 correct? If not, explain where your reasoning failed.

STOP

Do This: Disconnect the carabiner from the zip tie on the rear wheel. You are about to spin the wheel. In addition, please remove any masses from the pedal bar.

Read This: Now let's see what happens when we change the front gear.

Smallest front gear,
Smallest rear gear

Do This: We want to adjust the gears such that the chain passes over the smallest gear in the front and the smallest gear in the back. Use the gear lever on the right side of the handle bars to change the rear gear to gear 7. Use the gear lever on the left side of the handle bars to change the front gear to gear 1. Then add 2 kg back to the pedal bar.

2.5. Your bike should be in the smallest gear in the front and the smallest gear in the back. Further, there should be 2 kg on the pedal. *Predict* whether the output force will be greater than, less than, or equal to the force you recorded in Step 1.2. Explain.[3]

Do This: Reconnect the carabiner to the zip tie on the rear wheel such that the zip tie is directly above the axle and test the prediction you made in Step 2.5. Add 2 kg back to the pedal bar.

2.6. Record the output force. Was the prediction you made in Step 2.5 accurate? If your prediction was incorrect, explain where you went wrong.

STOP

Do This: Disconnect the carabiner from the zip tie on the rear wheel. You are about to spin the wheel. In addition, please remove any masses from the pedal bar.

Read This: Now let's look at what happens when you switch into the lowest speed. That's when the chain is on the smallest gear in the front and the largest gear in the back.

[2] **Hint for Step 2.3:** There are at least two very good ways to make this prediction. One would be to use your equation from Step PL5. A second approach is more intuitive. You could start by saying, "Nothing has changed on the crankset simply because I changed the rear gear. Therefore, moving the carabiner does not affect the tension in the chain." You could take it from there by considering how changing the rear gear affects the torque that the chain exerts on the rear wheel.

[3] **Hint for Step 2.5:** There are at least two very good ways to make this prediction. One would be to use your equation from Step PL5. A second approach is more intuitive. You could start by saying, "I have reduced the radius at which the chain exerts its force on the crankset. The torque exerted on the crankset by the hanging mass has not changed. Therefore, in order to keep the crankset static, the tension in the chain must…" You could take it from there by considering how changing the rear gear affects the torque that the chain exerts on the rear wheel.

Smallest front gear,
Largest rear gear

Do This: Adjust your bike such that it is in its lowest speed. The chain should pass over the smallest gear in the front and the largest gear in the back. Add 2 kg back to the pedal bar.

2.7. Your bike should be in the smallest gear in the front and the largest gear in the back. Further, there should be 2 kg on the pedal. *Predict* whether the output force will be greater than, less than, or equal to the force you recorded in Step 1.2. Explain.[4]

Do This: Reconnect the carabiner to the zip tie on the rear wheel such that the zip tie is directly above the axle and test the prediction you made in Step 2.7.

2.8. Record the output force. Was the prediction you made in Step 2.7 accurate? If your prediction was incorrect, explain where you went wrong

STOP

Do This: Disconnect the carabiner from the zip tie on the rear wheel. You are about to spin the wheel. In addition, please remove any masses from the pedal bar.

3. Angular Dependence

The relationship between the input force and the torque which it produces is a vector quantity which depends on both the magnitude and the direction of the vectors involved. In this section we will investigate the directional part of this relationship by looking at the torques on the crankset of the bicycle.

Read This: Before we get started with the experiment let's define a coordinate system. Figure 4 shows the coordinate system we will use for the rest of this section.

3.1. When the crank arm is at $\theta = 0°$ what is the force on the crankset from the 2-kg mass? What is the resulting torque on the crankset about the crank bolt? Explain.

3.2. How does the force on the crankset, from the 2-kg mass, change as θ increases? Explain.

3.3. *Predict* how the torque on the crankset produced by the 2-kg mass changes as θ increases. To answer this, sketch a plot of the input torque, τ_{in}, as a function of angle. Your plot should go from $\theta = 0°$ to $\theta = 180°$. Explain your reasoning.

Read This: We are now going to make measurements which either verify or discredit the prediction you sketched in Step 3.3. To do this we will measure the output force as a function of θ.

Figure 4: $\theta = 0$ is the orientation when the crank arm is directly vertical with the pedal bar above the crank bolt.

[4] No hints this time!

Smallest front gear, Largest rear gear

Though the force sensor doesn't tell us exactly how much torque is being applied to the crankset, the output force does scale with the torque on the crankset. That is to say, if the torque on the crankset increases, the force recorded by the force sensor will increase proportionally. Likewise, if the torque on the crankset decreases, the force recorded by the force sensor will decrease proportionally.

3.4. Put the prediction you made in Step 3.3 to the test by measuring the output force at a sample of different θ values between 0° and 180°. Record your measurements in a data table. You should take enough data to allow you to convincingly compare your prediction and your experimental measurements. Please do not attempt to take a reading at 0°

Plot

3.5. Plot the data you collected and recorded in Step 3.4. Print out the plot and record the title of the plot as your response to this step.

3.6. Compare your plot to the prediction you made in Step 3.3. Comment on similarities and differences. Explain what may account for differences between your prediction and your plot.

STOP

Do This: Disconnect the carabiner from the zip tie on the rear wheel. You are about to spin the wheel. In addition, please remove any masses from the pedal bar.

3.7. One of your friends claims that he can put a constant force on the pedal as he is riding his bicycle. As such, he says that when he is riding he accelerates forward at a constant rate. Assuming your friend can put a constant force on his pedal, is his statement necessarily correct? Explain.

Part II: Mechanical Advantage

In this part of the lab we will quantify the utility of our bicycle as a simple machine. Specifically we are going to investigate how the Mechanical Advantage (MA) of our bicycle depends on the speed it is in.

According to the Cambridge English Dictionary a distance multiplier is "a system or machine that uses effort over a short distance to move a load through a longer distance." This definition probably describes why you ride a bicycle: to get from point A to point B quickly. In terms of MA, machines with a MA less than one are said to be distance multipliers. The lower the value of the MA, the better the bicycle is as a distance multiplier. Conversely, a bicycle with a MA very close to one is not a very good distance multiplier.

At this point you might be asking yourself, why not ride the bicycle that is the best distance multiplier? Well in practice, a good distance multiplier requires a large input force and thus can be tough to ride in certain situations – for instance, riding a bike up Art Hill. So when riding a bike, there is a tradeoff between quickly arriving at your destination and inputting a reasonable force to the bike pedal.

Let's investigate this trade-off in different ways.

4. Determining the Mechanical Advantage of Your Bike

Let's look at the Mechanical Advantage in terms of the force input to the pedal and the force output to the road. The MA of a bicycle is defined as

$$MA \equiv \frac{F_{out}}{F_{in}} \qquad \text{Eq. 1}$$

where F_{out} is the magnitude of the force that the rear wheel puts on the road and F_{in} is the magnitude of the force you apply to the pedal.

By considering conservation of energy we can rewrite the equation above in terms of distances instead of forces. We find

$$MA = \frac{d_{in}}{d_{out}} \qquad \text{Eq. 2}$$

where d_{in} corresponds to the distance that the pedal moves and d_{out} corresponds to the distance that a point on the outside of the tire moves. You will now analyze these relationships both qualitatively and quantitatively.

Do This: Remove all masses from the pedal. Make sure your bicycle is in its lowest speed. That means the chain should be on the smallest gear in the front and the largest gear in the back.

Do This: Now you will add some resistance to the rear wheel. Turn the screw on the bottom of the bike stand until the metallic cylinder is in contact with the rear wheel. As you spin the rear wheel with your hand you should feel that there is more resistance than before.

4.1. Start spinning the wheel by turning the pedal. Pay attention to how difficult it feels to get the wheel turning. As you continue turning the pedal, shift the bicycle into higher gears, paying attention to how this changes how difficult it is to turn the pedal. Document your experience in a well written sentence or two. (No explanation is needed. Just document your experience.)

Read This: In the following steps you will determine the Mechanical Advantage of the bicycle in its lowest gear and in its highest gear. But first, we want you to make a couple of predictions.

4.2. A bicycle is typically used as a distance multiplier. Knowing this, *predict* whether the mechanical advantage of your bicycle will be less than one or greater than one. Explain.

4.3. Based on your experience in Step 4.1, *predict* how the Mechanical Advantage of the lowest speed will compare to the Mechanical Advantage of the highest speed. Explain.

Read This: The following steps will put those predictions to the test. You will begin by finding the MA of the bike in its lowest speed using two independent methods.

Largest front gear,
Smallest rear gear

4.4. Use your data from Step 1.2 to determine the MA of the bike in its highest speed. (The highest speed means the chain is on the largest gear in the front and the smallest gear in the back.) Show your work.

Read This: In the next steps you'll find the MA of the bike in its highest speed using distance measurements.

Do This: Make sure the bike is in its highest speed. That's the largest gear in the front and the smallest gear in the back. Make sure there is still resistance between the metal cylinder and the wheel. The wheel should not spin unless you make it spin. It should not "freewheel."

4.5. Record the number of times the rear wheel turns as you slowly rotate the pedal once. (It is helpful to note that there are 36 evenly spaced spokes per revolution.)

4.6. Use your response to Step 4.5 along with Equation 2 to determine the MA of the bike in its highest speed.

4.7. Are your responses to Step 4.4 and Step 4.6 consistent? What might account for any small differences?

4.8. Was the prediction you made in Step 4.2 correct? If not, explain where your reasoning failed.

Smallest front gear,
Largest rear gear

Do This: Shift the bike into its lowest speed so that you can put the prediction you made in Step 4.3 to the test. The chain should be on the smallest gear in the front and the largest gear in the back.

4.9. Use your data from Step 2.8 to determine the MA of the bike in its lowest speed. Show your work.

Read This: In the next steps you'll find the MA of the bike in its lowest speed using distance measurements.

4.10. Record the number of times the rear wheel turns as you slowly rotate the pedal once. (It is helpful to note that there are 36 evenly spaced spokes per revolution.)

4.11. Use your response to Step 4.10 along with Equation 2 to determine the MA of the bike in its lowest speed.

4.12. Are your responses to Step 4.9 and Step 4.11 consistent? What might account for any small differences?

4.13. Was the prediction you made in Step 4.3 correct? If not, explain where your reasoning failed.

4.14. Which speed are you most likely to use if you are riding up Art Hill? Explain, making sure to mention something about mechanical advantage, distance multipliers, or force multipliers.

4.15. Which speed are you most likely to use if you are riding in RAGBRAI? Explain, making sure to mention something about mechanical advantage, distance multipliers, or force multipliers.

Part III: Bicycle Statics

5. One Last Question

This lab will conclude with a Head-Scratcher that is a pretty tricky statics problem.

5.1. In Figure 5 the chain passes over front gear of largest diameter and rear gear of largest diameter. If the mass on the pedal bar is 1 kg, $\theta_{in} = 50^{\circ}$, and $\theta_{out} = 30°$, what value would you expect the force sensor to read? Give your response in newtons. Show your work.

Largest front gear,
Largest rear gear

Figure 5: A 1-kg mass is attached to the pedal bar which is at an angle of $\theta_{in} = 50^{\circ}$. The carabiner is attached to the zip tie such that $\theta_{out} = 30°$. The string is pulling horizontally to the left. The string is attached to a force sensor. The chain is passing over the front gear of largest diameter and the rear gear of largest diameter.

Head-Scratchers

Don't forget to complete the following problems. They should be at the end of your lab report. If you want to work on them during lab, start a new page in your lab notebook.

- 3.7
- 4.14
- 4.15
- 5.1

Appendix A: Speeds and Gears

Figure 1 shows the front part of the drive train of our bicycle, including the front set of gear. In addition to these gears, there is a set of seven gears which are attached to the rear wheel of the bicycle. The front and rear sets of gears are connected by a chain. Any particular front gear-chain-rear gear combination is termed a *speed*. Our bike has 21 possible gear combinations (3×7) so we say it is a 21-speed bicycle. By adjusting the combination of front and rear gears the chain is connected to, the rider is able to control their riding experience. Table 1 lists the specifications of both the front and rear sets of gears which will be useful during this week's experiments.

These measurements have an uncertainty of approximately 2 mm.

Front Gears			Rear Gears		
Gear #	Radius [cm]	# of Teeth	Gear #	Radius [cm]	# of Teeth
1	5.5	28	7	2.6	14
2	7.5	38	6	3.1	16
3	10.0	48	5	3.5	18
----	----	----	4	3.8	20
----	----	----	3	4.2	22
----	----	----	2	4.7	24
----	----	----	1	5.5	28

Table 1: Data for the front and rear gears for our bicycles.