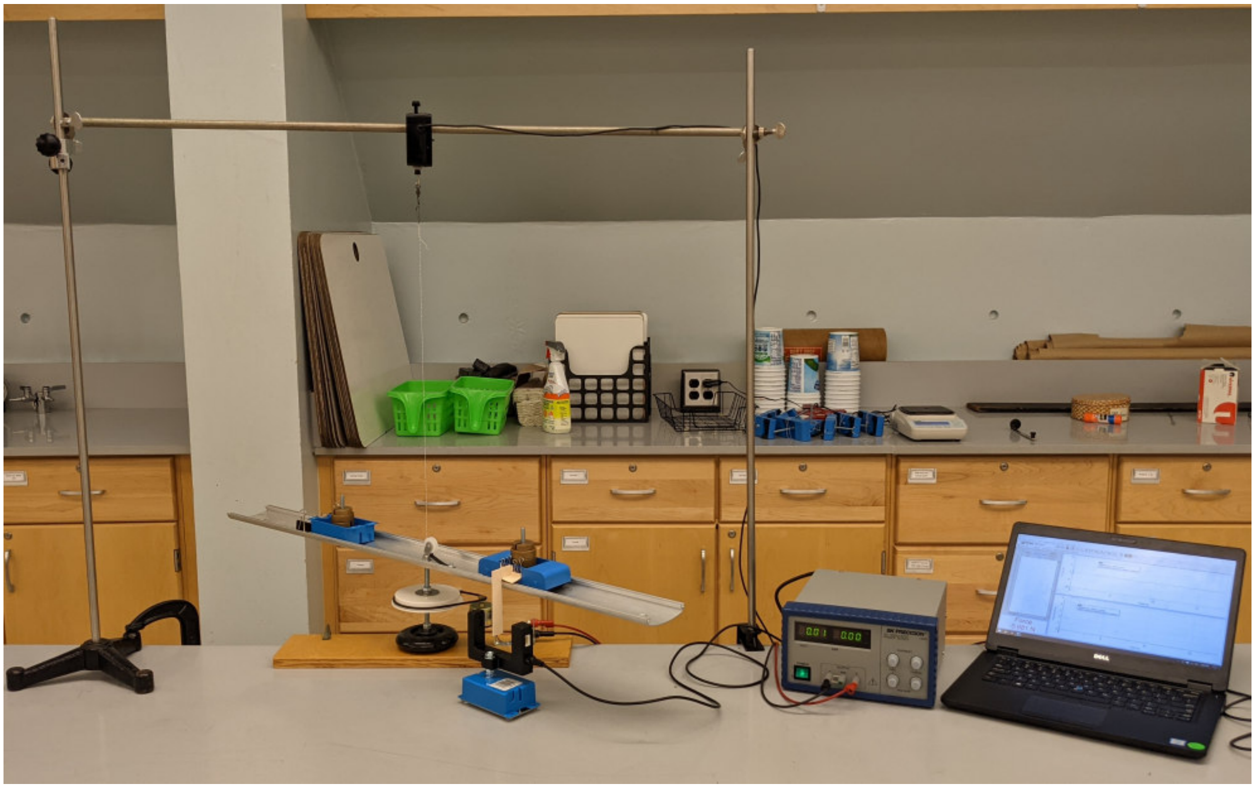
Building the Rex Rice Uniform Circular Motion Apparatus

Unit 7 of the AMTA mechanics curriculum includes Rex Rice's design for a uniform circular motion apparatus. The idea is to make something that does more or less the same thing as the experiments from commercial vendors, but for less than $70 each.



The original instructions are terse, and are clearly aimed at those who are already handy at building their own apparatus. With any luck, this guide will provide encouragement to the less handy and to those who find words useful.

A. Parts

See Appendix A for a list of parts, suppliers for those parts, etc. Most of the stuff comes from Home Depot, although Lowe's or your local hardware would also work. You might find it convenient to order on line so that you don't have to drive around trying to find what you need in different stores (or if there happened to be a gobal pandemic going on). If you order it all at once, Home Depot will deliver most of it for free. (They will make you go to "your store" to pick up the part of the order that happens to be in stock there.) In this section we'll discuss the parts that don't come from Home Depot, or that otherwise merit special attention. (I have nothing against Lowe's, but in my neck of the woods, Home Depot stores outnumber Lowe's by about 10 to 1.)

1. DC Motor

Before you do anything else, you need to find the motor that you will use to drive the rotation. Bought new, an appropriate motor will be too expensive (more than $100 each). Rex found the motor that he used on a surplus equipment web site. Not surprisingly, that motor is now sold out.

I found the one I'm using on a different site (https://www.surplussales.com), using a Google Image search for "DC motor with pulley." I scrolled through the results until I found this image:

which led to this item:

(As of July, 2021 this motor is still available.) Find one with the small pulley already attached. Finding an appropriate pulley to match some random motor will be "challenging."

If you are using this motor, or a similarly wimpy one, get spares. Your students *will* burn them out.

2. Drive belt

The drive belt is a rubber o-ring, which you can buy from an industrial supplier. I use McMaster-Carr. The most appropriate ring material is "hard buna-N". You can get 25 appropriately sized o-rings for about $10. Don't select your o-ring until you have the motor in hand. You want the thickness of the o-ring to work well with the pulley. For my motor and pulley, 1/8" thick o-rings work well ("dash number 246:" 4.5" ID, 4.75" OD). McMaster also sells o-rings that are actually made to work as drive belts, but they cost about $5 each. The ones we're getting are made of the "wrong" rubber to be a drive belt, but just about everything else we are doing is a "wrong" use of the part.

3. Scooter Wheel

Get these on Amazon. There are lots of choices, all about $10 for a pair of wheels. Just make sure that you get ones that have an open slot in the spokes.

Yes.

No.

4. Hall's Car

Why is this called a "Hall's" car? At any rate, these are available from more than one supplier. Carolina Biological Supply offers a version with a hole for the string already drilled. I discovered this after I'd ordered mine (without the hole) from Science Lab Supplies.

5. Banana Jacks

These are available from multiple sources. I always uses banana style connectors made by Pomona Electronics because they are very reliable.

6. Bulldog Clips

Bulldog clips are used to set the position of the counterweight. The ones that are 1.25" (3 cm) wide are grippy enough to do the job.

7. Ball Bearing Fishing Swivel

There are *barrel* swivels and there are *ball bearing* swivels. Get the ball bearing kind and put a drop of high grade lubricating oil inside.. I use size #5 swivels purchased on Amazon. They work well enough, but not as well as I'd like. It turns out a thin, flexible string is not an efficient transmitter of torque...

Other stuff you will need but probably already have:

1. Weights

You will probably use weights you already have in your lab for this, but they should be the kind that fit onto a round pin. I use some really nice brass slotted weights that fit onto a ¼" pin. They have been at my school for considerably longer than I have, but I recently found very similar ones from Science Lab Supplies.

2. Power Supply

You will need an appropriate power supply. Exactly what you need will depend on the motor you wind up with, but it will probably be in the neighborhood of 12V. The motors I use draw less than 1 amp. The finer the voltage control, the better.

3. Data Acquisition

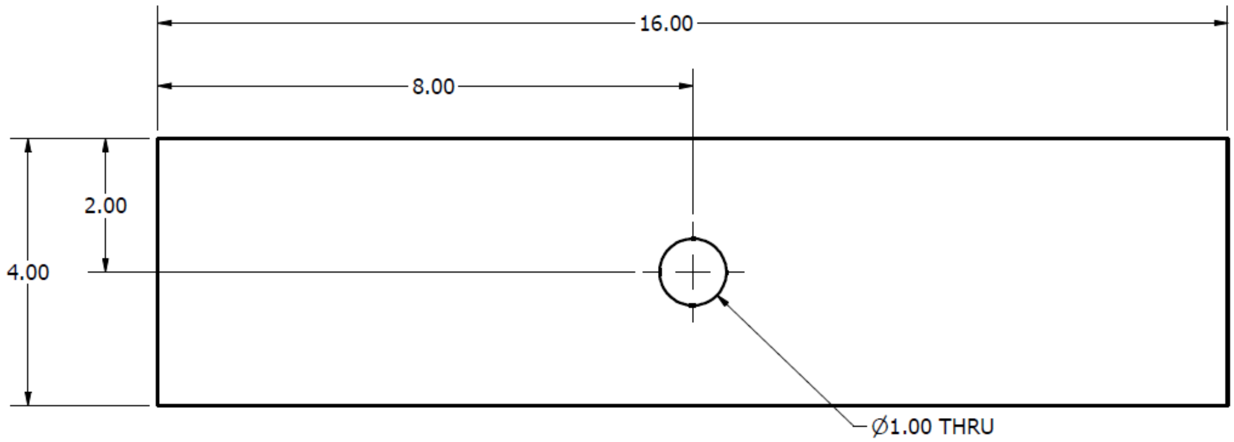
The speed of the mass is measured with a photogate, and the centripetal force with a force sensor, so you will need those and the rest of your data stuff (from Vernier, PASCO, or whomever).

4. Rods, Clamps, and Etc.

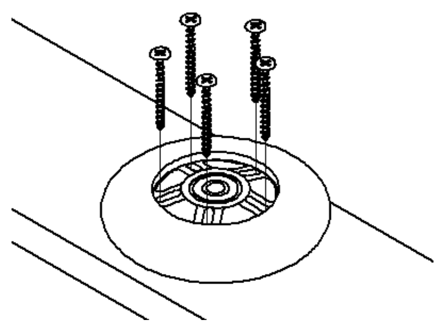
Per the photo at the start of this document, you will need a collection of these, which you probably already have.

B. Building the Apparatus

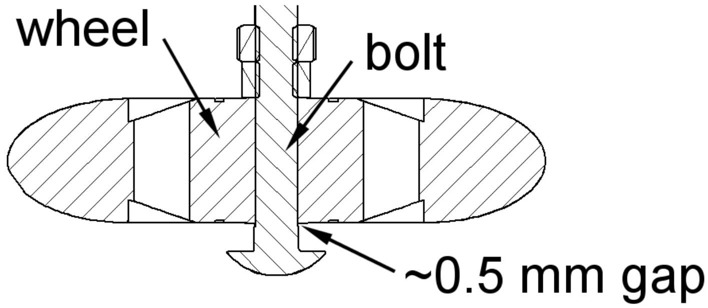
1. Cut the base from ¾" thick plywood. If you don't have access to a table saw, become friends with someone who does, or get it cut where you bought it. The hole in the middle is drilled with a 1 inch spade bit. Sand the edges and corners to prevent splinter injuries. If you have some polyurethane, you could slap on a couple of coats. You don't need a lot of plywood for this. You can get 8 bases out of a single 2' x 2' "project panel" ($15 to $20, depending on your choice of hardwood for the "nice" side). Plan ahead. The saw will eat about 1/8" per cut.

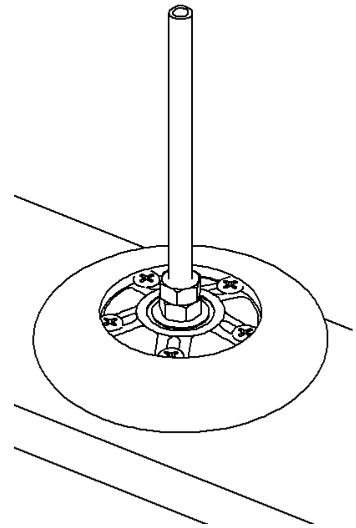


2. Center the scooter wheel over the hole in the base and attach it with five #6 by 1.5" drywall screws. This is an unusual length and will almost certainly not be in stock at your local Home Depot. Order a box of them through the web site. If you prefer, you can use the more common 1 5/8" screws and file/grind down the points that will be sticking through the bottom of the board.

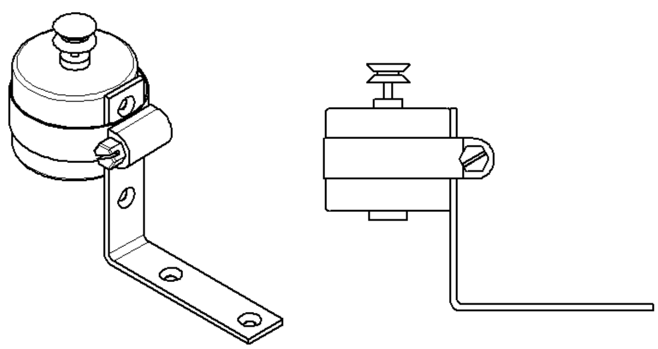


3. Put the 5/16-18 by 6 inch carriage bolt up through the board and thread a pair of nuts onto the bolt. You need to be very careful not to over tighten this assembly. The motor that I found is very small, and will quickly burn out if too much torque is demanded from it. After you tighten the second nut hard against the first, the lower nut should rest on the scooter wheel, leaving a very small (~0.5 mm) gap between the square shank of the carriage bolt and the bottom of the wheel bearing. The bolt will have more side-to-side wobble that maybe you would like, but this is guerilla design, not precision engineering.





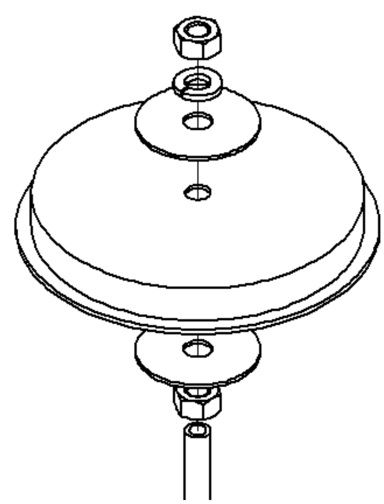
4. Attach the motor to a 2.5" tall corner brace using a hose clamp, as shown in the drawing below.



5. Drill a 5/16" hole in the center of the 4 inch PVC test cap. It's kind of important to get the hole in the exact center of the cap, so use a drill press if you have access to one, and clamp down a couple of wood blocks to act as a centering jig. Then thread:

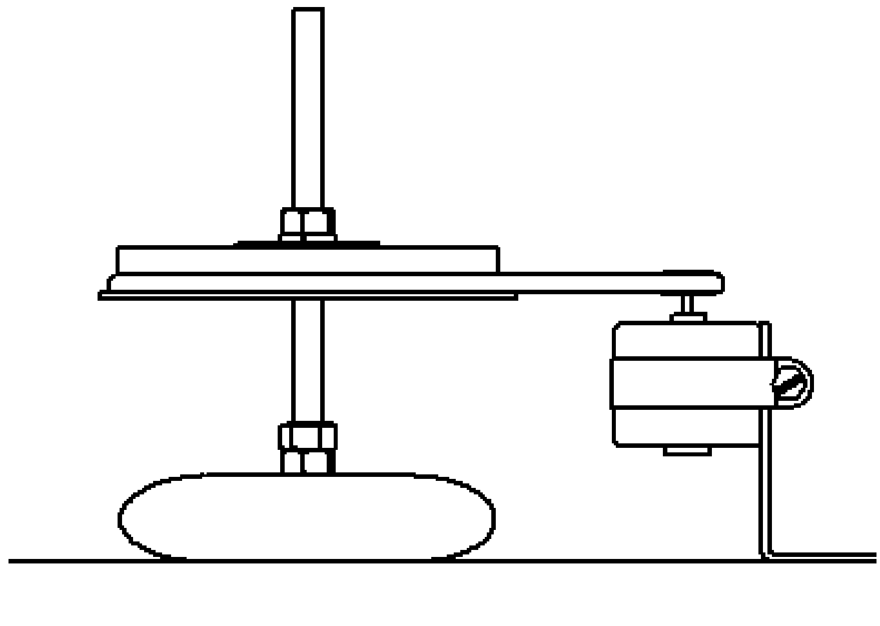
   a 5/16-18 hex nut
   a 5/16 "fender" washer (1.5 in. diameter)
   the PVC cap
   a second 5/16 fender washer
   a 5/16 lock washer
   a second 5/16 hex nut

   onto the carriage bolt, in that order. Don't tighten anything down just yet.



6. Clamp the motor assembly to the base (with a C-clamp or something) in such a way that you can stretch the o-ring drive belt over the motor pulley and the test cap. Adjust the nut under

the test cap until the drive belt runs flat, as shown below, then tighten the upper nut (firmly!). Don’t let the lower nut spin as you tighten.



7. With the belt still on, mark the position of the motor mount. You want to stretch the o-ring a bit, but not too much. It needs to be pulled tight enough that it won’t slip, but not so tight that you overstress the rubber. Think “firm” but not “hard,” kind of like we need to be with our students sometimes Mark the location of the two screw holes, pre-drill them using a 1/16 inch drill, and fasten down the motor using a pair of #6 by 3/4” wood screws. (Don’t leave the belt under tension when you store the apparatus.)

8. Drill out the central hole in the aluminum threshold (that serves as the rotating arm of the apparatus) with a 5/16” drill. Use a 3/8” or larger drill to clear out the two end holes. We are not using these holes for anything. We’re just trying to completely remove the cones and prevent them from interfering with the cart or counterweight. If you don’t have a deburring tool, use a 1/2” drill bit as a hand tool to de-burr these larger holes. (Parents do not like it when their children bleed.) You don’t need to worry about de-burring the central hole, although it wouldn’t hurt.

9. Next up you need to drill a hole in the threshold to attach the tension roller. This roller guides the string between the cart and the force sensor. You need to position this roller so that the vertical section of string is aligned with the center of rotation. The mounting hole for the roller

will be *approximately* 2.1 inches from the center hole for the axle. But you should really mount the threshold on a temporary basis with a couple of nuts and washers, and then position the roller and mark the location of the mounting hole. This photo shows what it will look like in the end. Try to bend it as if it was fully mounted to get the hole in the right place. If you are making multiple copies of the apparatus, you can do this once and then measure where the hole goes.

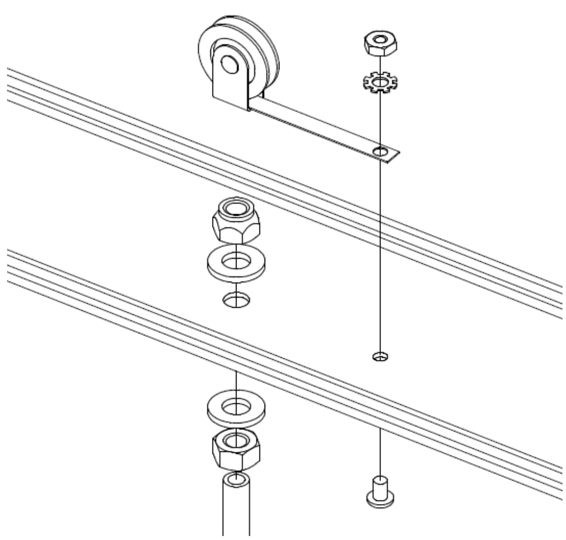
The mounting hole should be large enough to accept a #8 screw, which—officially—should be done with a #16 drill. But you most likely don't have a set of number drills, so use a 3/32" drill instead.

10. Mount the threshold onto the top of the axle by placing:

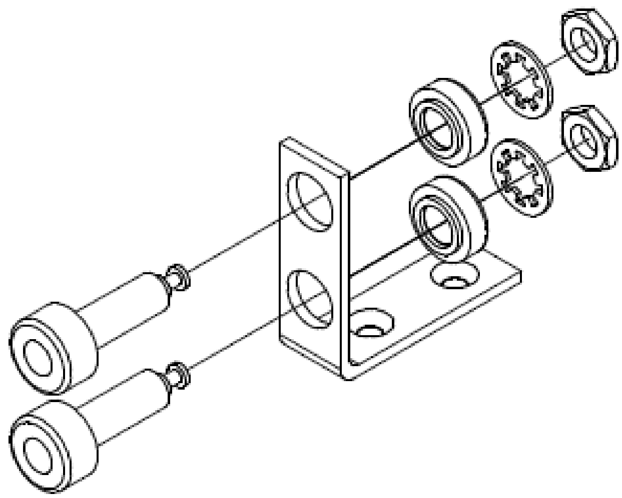
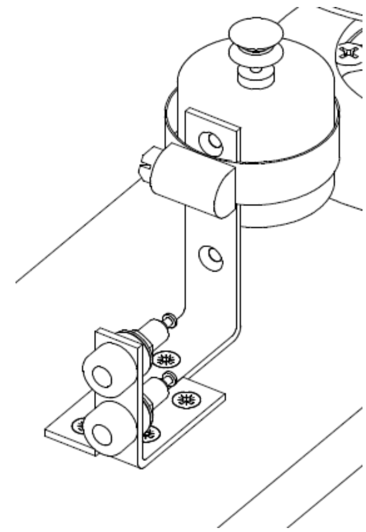
    a 5/16-18 hex nut
    a 5/16 (regular) washer
    the threshold
    a second 5/16 washer
    a 5/16 nylon insert "jam" nut

    The top of the jam nut should be flush with the end of the axle. Tighten this assembly like you mean it

11. Attach the tension roller using an 8-32 x 0.375" Philips head screw, and a matching nut and lock washer. It doesn't matter whether you put the screw down from the top or up from the bottom (as I drew it). Whatever seems easiest. Make sure the roller is properly aligned before you fully tighten the screw.



12. Use a 3/8" drill to enlarge two adjacent holes in the 1.5" corner brace. This will go better if the brace is clamped in a vise. Unfortunately these holes are not quite ¾" apart. If you don't know why that is unfortunate, then never mind. It will make no difference to you. Then assemble the two banana plug receptacles onto the brace as shown. I used one red receptacle and one black receptacle because I am that way, but the electrons don't really care about the color.

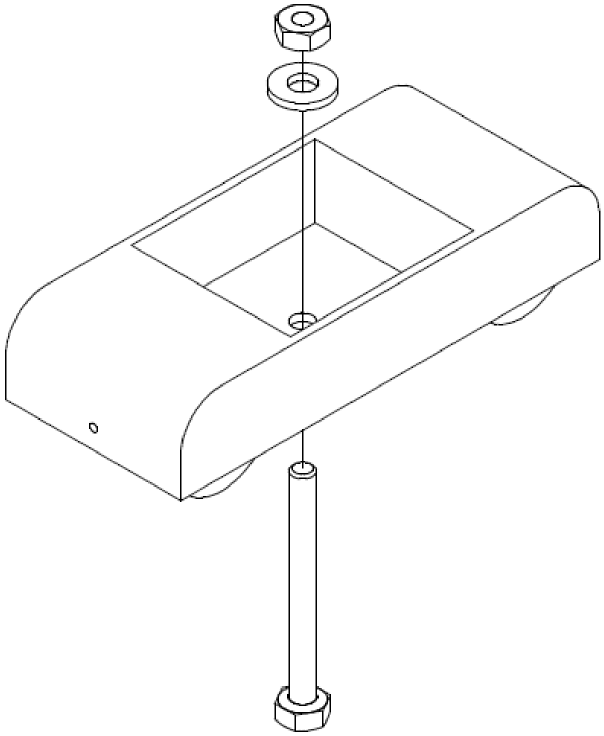
13. Attach this power input assembly to the plywood base just as you did the motor mount: mark the hole locations, pre-drill with a 1/16" bit, and use two #6 x 0.75" wood screws. Where you put this is not critical. It just has to be close enough to the motor that the wires reach.

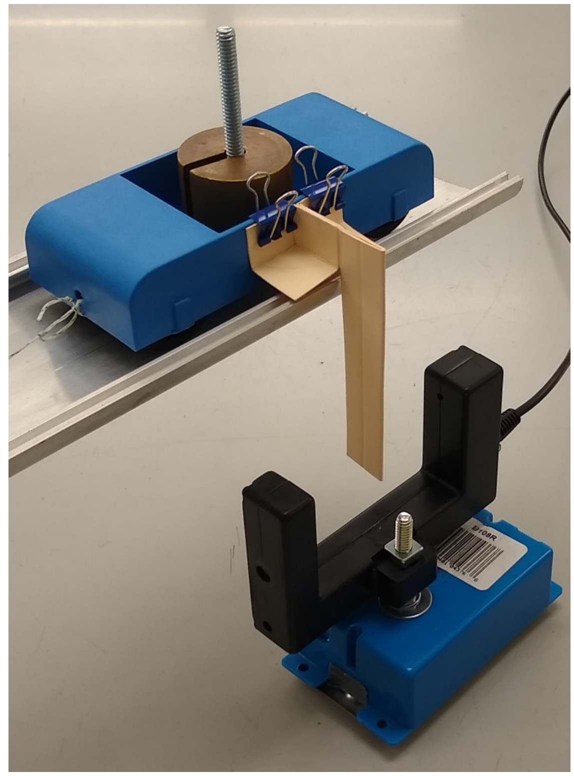
14. Solder the motor wires to the two connectors (red to red, if you like that sort of thing), and the main assembly is done!

15. To prepare the Halls car you will need to drill a hole in the end for the string, if it doesn't already have one. I used a 1/8" drill, but it's not critical. What you do for the other hole—the one for the bolt that holds the weights—depends on the weights you will be using. I have slotted weights with a ¼" hole in the middle, and a 2.5" long bolt will hold 400 g of them. If your weight sets are different, you will need to drill a hole for a bolt that matches. In any case, put the hole in the middle of the cargo area of the cart.

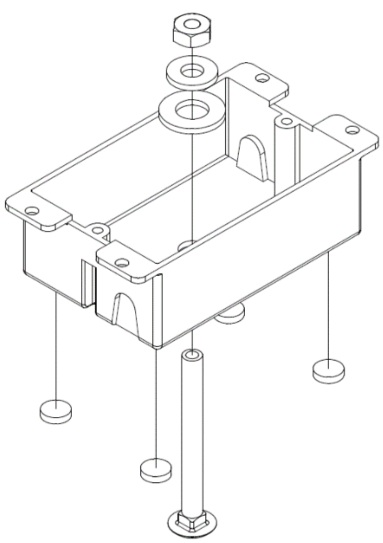
    VERY IMPORTANT! You ***must*** clamp the cart or hold it in a vise while drilling! The plastic is very tough, but also very grabby. The drill will easily snatch the cart from your hand and fling it across the room.

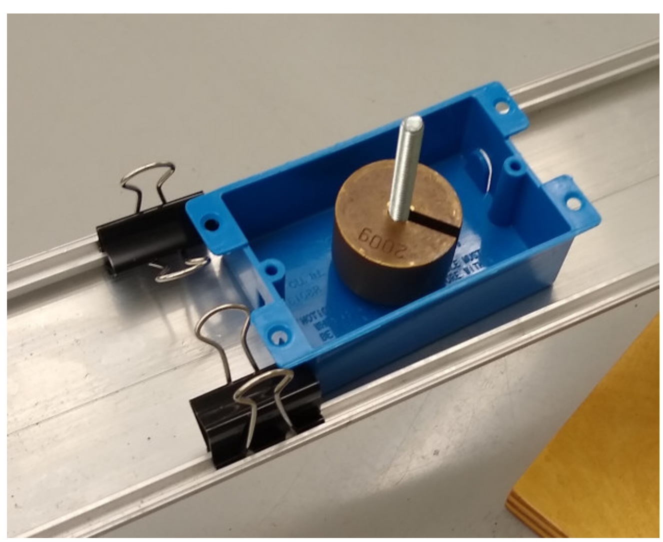
16. The fin used for recording the velocity of the cart is cut from an ordinary manila folder using the template in Appendix B. Use a higher quality, heavier weight folder, and cut through both layers so that the folded edge becomes one side of the fin. If you fold along the dotted lines (but in opposite directions on opposite sides of the edge fold) and use some tape and/or glue, you wind up with something that can be clipped onto the cart as shown in the photo.





17. The counterweight carriage is similar in concept to the cart, except that it is made from a very cheap electrical box. Use a carriage bolt instead of a hex bolt. The hole in the box needs to be large enough to accept the square shank of the bolt. In the case of a ¼" bolt, that's 11/32 of an inch. Use two washers on the inside. The lower one is a 3/8" washer large enough to accommodate the square shank. Even the low profile head of the carriage bolt is too tall to allow the counterweight to sit nicely in the rotating arm. I ground a bit off the head of each bolt with a belt sander because I have one. But you could just as easily solve this issue by sticking self-adhesive felt furniture pads onto the bottom of the box. The counterweight can be held in position on the rotating arm with a couple of bulldog clips.





18. Optional item: A stand to hold the photogate. You can see what I did in the photo at the top of the previous page. It's another electrical box, a ¼-20 by 1.5" long hex bolt, and some nuts and washers. Two nuts between the photogate and the box puts the gate at a nice height. You can't see it in the photo, but there is a standard face plate (with felt pad feet) on the underside of the box. Put about 0.5 kg of BBs (available at Walmart or other fine firearms dealer near you) into a small ziploc bag and stuff that in the box to give it some heft.
19. For the string between the cart and the swivel, I used 30 lb test Izor Line, because that's what I use for everything. PASCO sells this as "braided physics string," but you can get it on Amazon for less. Tie the string to the cart, but not to the swivel. Just put a loop in the end that you can slip onto the "clip" end of the swivel after threading the string through the tension roller.

C. Required Tools

Safety glasses

Hearing protection

Set of drills in 1/32 inch increments up to 1/2".

Screw drivers (Philips and flat blade)

Electic drill that can also function as a screw gun

Small adustable wrench

A vise

A helpful selection of C-clamps

Drill press (optional, but really helpful)

Table saw (or a friend with a table saw)

1 inch spade bit or 1 inch hole saw

Appendix A

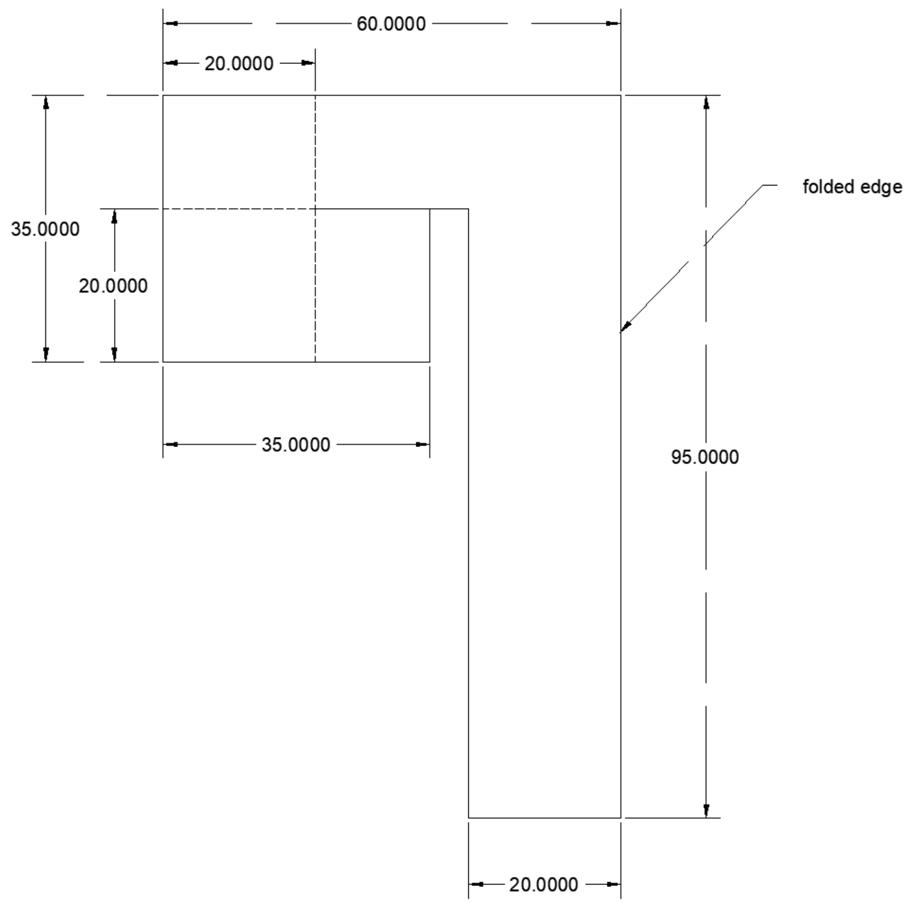
Prices are as of July, 2021. Home Depot keeps changing the packaging format for fasteners sold on-line, so for the more common nuts and bolts, you are better off just making a trip to the store. Everything is sized assuming a "batch" of eight set-ups.

Description	Vendor	Part No.	Price	Qty	Ext. Price	Source/notes
Halls Carriage Cart	Science Lab Supplies	633-28	$ 8.60	8	$ 87.96	https://www.sciencelabsupplies.com/Halls-Carriage-Cart.html
Motorola Seguin Motor	Surplus Sales of Nebraska	?	$ 2.25	8	$ 30.00	http://www.surplussales.com/Motors/Motors-3.html
Scooter wheel	Amazon		$ 10.95	4	$ 43.80	lots of choices, all 100 mm in diameter, sold in pairs, need 8 wheels
O-ring (belt) - pack of 25	McMaster-Carr	5308T291	$ 9.78	1	$ 9.78	https://www.mcmaster.com/5308T291
# 5 fishing swivel	Amazon		$ 10.50	1	$ 10.50	pack of 20 swivels, need 8
Banana jack, red	Digi-Key	501-1080-ND	$ 2.07	8	$ 16.56	https://www.digikey.com/products/en?keywords=501-1080-ND
Banana jack, black	Digi-Key	501-1078-ND	$ 2.07	8	$ 25.55	https://www.digikey.com/products/en?keywords=501-1078-ND
Saddle threshold	Home Depot	Internet #100159493	$ 16.98	8	$ 135.84	E/O 3-1/2 in. x 36 in. Silver Smooth-Top Saddle Threshold for Low Rugs
Plywood	Home Depot		$ 20.00	1	$ 20.00	2' X 2' project panel
4" knockout test cap	Home Depot	Internet #100113503	$ 0.63	8	$ 5.04	Store SKU #508288
tension roller	Home Depot	Internet #100138195	$ 3.02	4	$ 12.08	1 in. Nylon Sliding Screen Door Rollers with 2-1/2 in. Tension Springs (2-Pack)
5/16" x 6" carriage bolt	Home Depot	Internet #204281336	$ 20.47	1	$ 20.47	5/16 in. x 6 in. Zinc Carriage Bolt (25-Pack, need 8 bolts)
5/16-18 hex nut	Home Depot	Internet #204274092	$ 3.08	2	$ 6.16	5/16 in.-18 tpi Zinc-Plated Hex Nut (25-Piece per Bag, need 32 nuts)
5/16-18 locking nut	Home Depot	Internet #204325605	$ 1.87	1	$ 1.87	5/16 in. -18 nylon insert lock nut (15-Pack, need 8 lock nuts)
5/16 lock washer	Home Depot	Internet #204604723	$ 2.95	1	$ 2.95	5/16 in. Chrome Lock Washer (8-Pack) $0.20 each for zinc plated in the store, need 8
5/16 fender washer	Home Depot	Internet #204276339	$ 1.18	3	$ 3.54	5/16 in. x 1-1/2 in. Zinc-Plated Steel Fender Washer (6 per Pack, need 16)

5/16 flat washer	Home Depot	Internet #204276388	$ 3.08	2	$ 6.16	1/4 in. Zinc-Plated Flat Washer (25-Piece per Bag, need 32 washers)
2.5" corner brace	Home Depot	Internet #202033901	$ 3.67	2	$ 7.34	2-1/2 in. Zinc-Plated Corner Brace (4-Pack, need 8)
1.5" corner brace	Home Depot	Internet #202033892	$ 2.98	2	$ 5.96	1-1/2 in. Zinc-Plated Corner Brace (4-Pack, need 8)
Carlon B108R electrical box	Home Depot	Internet #100404058	$ 1.73	16	$ 27.68	Blue PVC 1-Gang 8 cu. in. Flanged Shallow Old Work Electrical Outlet Box
Hose clamp	Home Depot	Internet #202262871	$ 9.53	1	$ 9.53	3/4 - 1-3/4 in. Stainless Steel Clamp (10 Pack, need 8)
1-1/2" drywall screws	Home Depot	Internet #100127330	$ 6.58	1	$ 6.58	#6 x 1-1/2 in. Philips Bugle-Head Coarse Thread Sharp Point Drywall Screws (1 lb.-Pack)
1/4-20 x 2.5 in carriage bolt	Home Depot	X	$ 0.25	8	$ 2.00	1/4 in. - 20 tpi x 3 in. Zinc-Plated Coarse Thread Carriage Bolt (buy in store)
1/4-20 x 2.5 in hex bolt	Home Depot	X	$ 0.25	8	$ 2.00	1/4 in.-20 x 2-1/2 in. Zinc Plated Hex Bolt (buy in store)
1/4-20 nut	Home Depot	X	$ 1.28	5	$ 6.40	1/4 in. - 20 tpi Zinc-Plated Steel Hex Nut (10-Pack, need 48 nuts)
1/4-20 washer	Home Depot	X	$ 1.28	4	$ 5.12	1/4 in. Zinc-Plated Steel Flat Washer (12-Pack, need 48 washers)
#8-32 x 3/8" screw & nut	Home Depot	X	$ 1.28	1	$ 1.28	#8-32 x 3/8 in. machine screw and nut (8 pack, need 8 sets)
#8 star lock washer	Home Depot	X	$ 1.28	1	$ 1.28	#8 star-type lock washer (20-pack, need 8 washers)
3/8 felt pads	Home Depot	Internet #203661111	$ 3.97	1	$ 3.97	3/8 in. Self-Adhesive Felt Pads (150 per Pack, need 64 pads)
medium binder clips	Staples	Item #: 669767	$ 2.99	2	$ 5.98	ACCO® Medium Binder Clips, Black, Dozen (A7072050B), need 16 clips
mini binder clips	Staples	Item #: 477981	$ 1.49	2	$ 2.98	ACCO Binder Clips, Mini, Black, Dozen (A7072010), need 16 clips
		Total cost:			$ 526.36	
		Cost per set-up, for 8 set-ups:			$ 65.80	

Appendix B

Template for the velocity fin. All dimensions are in millimeters.



Appendix C

Some recommendations based on actual classroom use.

For $F_c$vs. m, use a short radius. If the radius is large, then very small changes in the motor voltage result in comparatively large changes in the velocity, which makes it difficult to get back to the same velocity at each new mass. For convenience, I would use that same small radius for the F_c vs. v experiment.

A decent F_c vs. r experiment would be a challenge to complete, even in a 90 minute block. I set up my 8 apparati with 8 different radii. Then each group of students needs only to make a single measurement. (I make them measure their radius too.) This will take longer than you think. If you know what you are doing and have experience with tha apparatus, it can still take a while to get it rotating with, eg. $v = 1.0$ m/s. And none of those descriptors apply to your students. (I have not used a similar strategy for the other two experiments, but probably will in the future.)

I set the data acquisition interval to 20 seconds and use the average and spread in the data to decide whether the speed is steady at the right value and to average out the noisy oscillations in the force value. The swivel does not just swivel. It mostly remains stationary as the string twists up. Eventually there is enough torque for the swivel to spin, at which point the string unwinds in a burst and the cycle starts over. You can mitigate but not eliminate this by making sure the swivel is well lubricated. Someday I will have enough wireless force sensors to put one on every apparatus and make this particular problem go away.

Below is some sample data for the most challenging of the three experiments, F_c vs. r. There is a set taken by me and a set taken by students.

The expected value of the constant (200 g in the 80 g carriage, speed at 1 m/s) is 0.28 kg m^2/s^2. I got 0.23 and the students got 0.30.