FIRST Robotics: The Curriculum

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Lesson 1: Mechanical Physics

Topics Covered:

- Force and Free Body Diagrams
- Friction
- Rotational forces

Assumptions:

- The ability to solve algebraic equations

Required Materials:

- Force gauge (or a spring and a way to measure its length)
- Weights/masses (or a book or water bottle)
- Torque demonstration bar (see below)

Importance to FIRST:

Physics is a model for the world around us. Using this model allows us to predict the behavior and motion of objects, specifically in this case FIRST robots and their appendages. A strong grasp of physics allows the replacement of guesswork with calculations that will work the first time. While physics does not determine a design, it does inform the process and provide a ruling on what is possible and what isn't. While physics can impact the design of all parts of a robot, it is especially applicable to the design of moving parts and the actuators driving those parts.

Further Resources:

- Free, online physics textbooks: http://en.wikibooks.org/wiki/Physics
- FIRST related lessons: http://www.usfirst.org/community/frc/content.aspx?id=1108

Lesson Plan:

Introduction

Ask the students “What is physics?”

Allow a few students to give their answers, and summarize at the end.

One good summary is “Physics is a numerical model of our world that allows for prediction.”

Ask for or list a few uses of physics. Examples:

- Making buildings strong enough to survive earthquakes
- Calculating rocket trajectories
- Designing an appropriate car engine

Ask for or list a few FIRST-specific uses of physics. Examples:

- Determining a gear ratio for the drive train
- Choosing a motor for an arm
- Selecting a piston bore to produce enough force to lift a robot

Explain what topics won’t be covered:

- Kinematics (the study of motion)
- Energy methods (using the conservation of energy to solve problems)
- Electricity and Magnetism.

Explain that these topics aren’t being covered for two reasons:

- It’s impossible to teach an entire year of physics in one session
- These topics are less important to the FIRST design process.

Forces

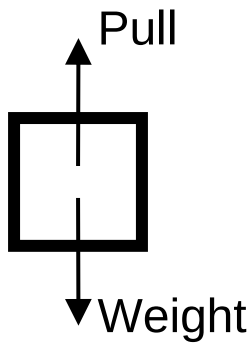
Begin by offering the students a definition for force. A simple, easy to understand one is hard to come by, but “An influence on an object that causes a change in motion” may be a good place to start.

Ask for or list the typical kinds of forces that students will see. A good list:

- Weight
- Pushes and Pulls
- Friction (covered in the next section)
- Normal Forces (supporting forces from stationary objects, such as the ground or a table)

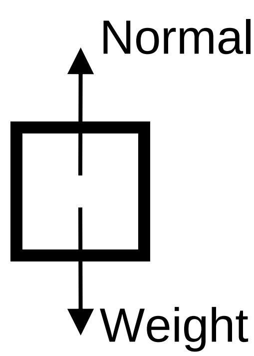
Show the students a force gauge. (If you have enough, distribute force gauges to the students and let them play along with you) Explain to them that it measures forces. Hang an object from it and read the force to the students. This force is equal to the weight of the object.

Begin drawing a diagram of the weight, showing the forces acting upon it. Initially, only draw the pull of the force gauge, and see if the students can guess that the weight of the object should be added, resulting in a diagram like this:



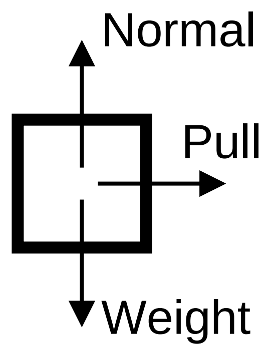
While simple, this diagram offers an opportunity for learning. First ask "How does this situation agree with our earlier definition of forces being something that caused motion?" The weight is not moving, but forces are acting on it. The explanation is that although forces are acting on the weight, they cancel out, resulting in no total force.

Now place the mass on a table, and have a student construct a diagram of it in its current situation. In this situation, the tricky part is not the weight of the mass, but the normal, supporting force from the table. If this force is not initially included, ask the student, "What could be taking the place of the force gauge in the previous example? What could provide a force to cancel the weight of the object and hold it still?" Eventually, you should have a diagram like this:

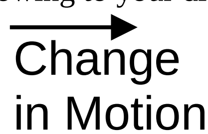


This situation offers a good chance to explain the idea of a normal force. Essentially, a normal force is a supportive force. It's called a normal force because "normal" is a fancy term for perpendicular or at a right angle. Explain that normal forces are always perpendicular to their surfaces, but not necessarily to gravity, such as in the case of a ramp.

Now, drag the object across the table using the force gauge. Ignoring friction for the moment, ask a student to diagram this situation. The normal force and the weight are still present, and a pull force from the force gauge is added to the mix, resulting in the following diagram:



Encourage the students to note that the total force is no longer zero. Asking "Which forces cancel each other out?" and "Which force is not canceled out?" may help to clarify the situation for the students. Follow this understanding up with "How does this situation relate to our original definition of a force?" Obviously, this situation shows an unbalanced force causing a change in motion, which is perfectly in line with our original definition. It may be best to note that the unbalanced force results in motion by adding the following to your diagram:



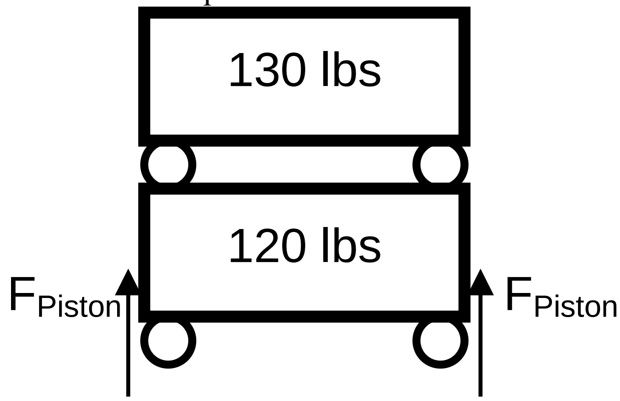
If you feel it won't be confusing, now is the time to introduce F=ma to your students. Explain that acceleration is a change in motion and that the same force will accelerate a less massive object more than a greater object. Hopefully, this brief explanation will make sense for now.

Explain that the diagrams you have been drawing are called "Free Body Diagrams" and are used as a starting point for a force analysis. Add that, while they may seem simple, it's easy to leave off a force, so being diligent and thorough in drawing free body diagrams is very important.

Ask the students "What produces forces in a FIRST robot?" Motors and pneumatic pistons are the two primary sources, but springs may be given as an answer. Explain that the biggest application of these force analyses is determining which motor or piston to use by calculating the required actuator force. Rather than dealing with the complication that an imbalance of forces creates, we just look for an actuator that reaches a static condition (no net force) after applying a factor of safety to the actuator (up to halving its maximum output), ensuring that it can cause a change in motion.

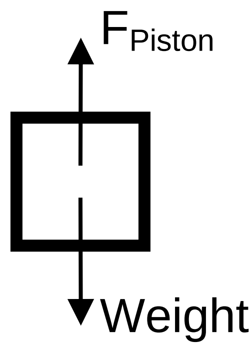
Example #1:
Given that a 1 ½" pneumatic piston operating at 60 psi can exert 106 lbs of force, how many pistons will it take to lift your 120 lb robot with your

partner's 130 lb robot on top of it?



Solution:

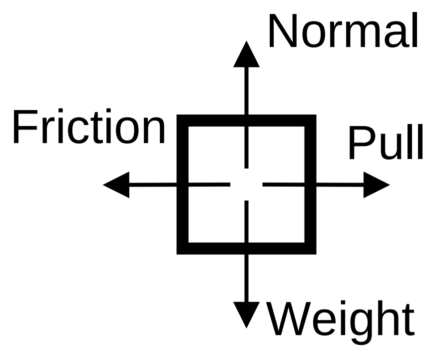
Students' methods for working this problem will vary, but a complete solution should include a free body diagram:



As the total weight of the robots is 250 lbs, at least three cylinders would be required (resulting in 318 lbs of lifting force). While 3 is the minimum number of cylinders, some students may suggest that 4 cylinders would be better, ensuring that there is enough extra lifting force and providing force at all four corners, two good reasons. This is an opportunity to point that physics only provides a starting point for design. Add that while we could have 3 or 4 cylinders, we now know that we don't need 6 and that 2 would not be enough.

Friction Ask the students if they can think of any other forces that might be acting in the previous example of dragging your object across the table. If no one guesses friction, a suggestive action, such as rubbing your hands together, may do the trick. If a student suggests air drag, which is a perfectly reasonable force, encourage them to think of a similar force that involves the table top rather than air

Have a student update the object's free body diagram with the friction force, resulting in this:



Ask what factors may affect the amount of friction:

- Materials. The materials involve determine μ, the coefficient of friction. Approximate coefficients of friction of various materials rubbing on steel can be found in the table below:[1]

Material	**Coefficient of Friction on Steel**
Rubber	1.0-2.0
Steel	0.7
Aluminum	0.6
Plexiglas (Acrylic)	0.45
Copper	0.3
Wood	0.2
Diamond	0.15
Graphite	0.1
Teflon	0.04

- Normal force. The frictional force is proportional to the normal force between the two objects.
- Contact area. This is a very common answer, but not generally viewed as correct. In most cases, contact area doesn't affect the frictional force as the force is just spread over a greater area. It is worth conceding that in some situations, especially those involving a mesh or some stickiness between the two objects, this area does play a role.

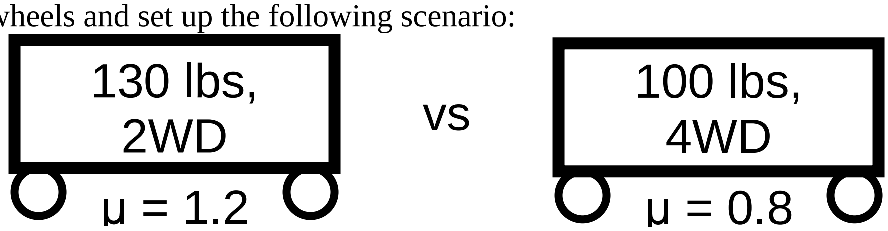
[1] Retrieved from http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm on 4-12-2007

In summary, point out that material and normal force are the two main determinates of the frictional force, so the equation is simply Friction = μN

Poll the students, asking "Is friction usually a good thing, or a bad thing?" Follow this up with "What about traction? Is it usually a good thing or a bad thing?" Generally, friction holds negative connotations and traction holds positive connotations. Point out the contradiction of opinions in these feelings as traction is just friction between wheels and whatever they are driving on. Add that in FIRST, traction wins pushing matches.

Tell the students that recognizing traction as friction can explain why four wheel drive offers a pushing advantage over two wheel drive. Begin with a simple free body diagram of the robot, with only its weight and normal force from the playing field. Ask "Where does the normal force from the playing field push on the robot?" (Answer: the wheels) "How is it split between the wheels?" (Answer: approximately equally, but having a weight concentration closer to a set of wheels will result in more normal force on those wheels) "Because of this, how is the frictional force split?" (Again, approximately equally)

At this point, point out that a robot can only use the traction of its driven wheels and set up the following scenario:

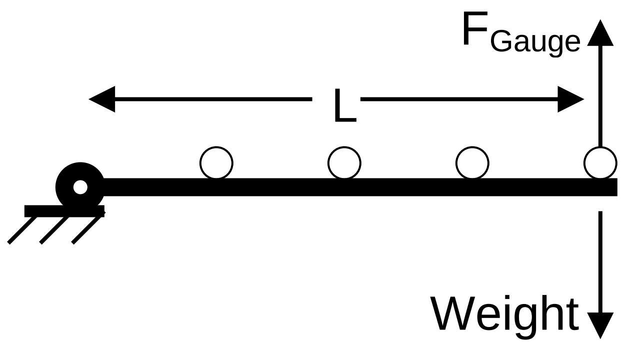


Assuming that a robot's weight (and therefore normal force) is distributed equally between all of its wheels, which one of these robots has more traction?

Answer: The first robot, with only two wheel drive, only receives traction from 65 lbs of its weight. 65 lbs * 1.2 = 78 lbs of traction. The second robot receives traction from its entire weight, resulting in 100 lbs * 0.8 = 80 lbs of traction. Even though the second robot is lighter and has a lower coefficient of friction, it would still win a traction-based pushing match!

Rotational Forces

Begin talking about rotational forces with the following demonstration:



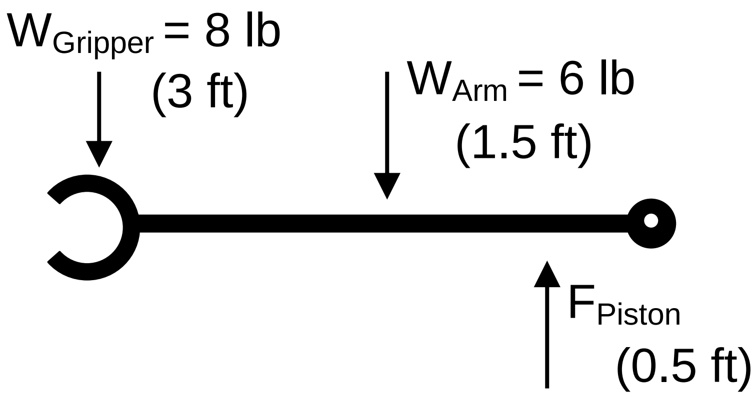
The apparatus consists of a relatively light hinged bar with hooks, loops, or holes at regular intervals that allow the attachment of a force gauge. Additionally, a weight may be hung from the end of the apparatus.

To perform the demonstration, ask for a student volunteer or two; one can operate the apparatus while the other records data on the board. Starting at the other most point, have the operating student attach the force gauge, hold the bar level, and read off the force. The recording student should also write down the distance from the pivot to the force gauge. The operating student should move down the bar, reporting the required force at each point, resulting in a chart that may look like this:

Distance (ft)	3	2.5	2	1.5	1	.5
Force (lbs)	2	2.4	3	4	6	12

Ask “Do you see any patterns or relationships in this data?” Hopefully someone will recognize that the two characteristics are inversely proportional or that their product is a constant. If no one recognizes this on their own, some encouragement and leading may be necessary to get them to this result. Explain that this product, a distance multiplied by a force, is known as a torque. In this case, the weight at the end of the bar resulted in a constant torque that our force gauge had to resist. Just as forces cause motion, torques cause rotation.

Announce that torques allow for additional force analysis and are especially applicable to rotating or pivoting parts. Example:



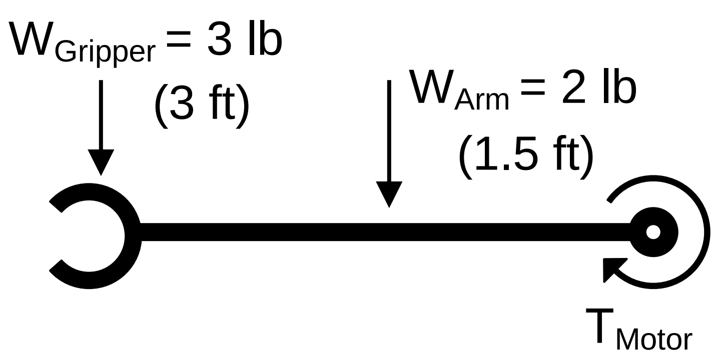
A robot arm is subject to forces as shown above. Which piston bore should you choose to lift the arm, given that a ¾” exerts 26.5 lbs, a 1 ½” bore exerts 106 lbs, and a 2” bore exerts 188 lbs?

Solution: The gripper exerts a torque of 24 lb*ft and the arm exerts 9 lb*ft, totaling 33 lb*ft. A single ¾” bore piston would not suffice, but a 1 ½” bore piston would. If students suggest using two ¾” bore pistons, they should be welcomed. This solution shows some creative thinking, as it was not suggested by the initial question, but is perfectly reasonable.

Explain to the students that, so far, all of our torques have been very plainly forces multiplied by distances, but sometimes it is more convenient to leave this quantity as a torque. One example of this is motors and engines. Just as a car’s engine outputs a maximum torque, an electric motor has a maximum torque as well. We can look these torques up in the FIRST Guidelines, Tips, and Good Practices document under the heading of DC Motors. A few maximum torques are listed in the table below:

Motor	Globe Motor	Keyang Window Motor	Banebots RS-540 Motor
Max Torque (ft*lbs)	12.5	8.85	10.9

Example:
Which of these motors would be able to lift the arm shown below:



Solution: Calculating the total torque exerted by the weights should be straight forward: (3 lbs * 3 ft + 2 lbs * 1.5 ft) = 12 ft*lbs. Only the globe motor outputs this much torque, making it the only viable solution to this problem. Even though its output torque is greater, it is only half a ft*lb more. As we have no better motor to choose from, we may want to connect it to our shaft with a gear ratio that increases its torque. Later, we'll talk more about this in the lesson on mechanical power transmission.

Lesson 2: Brainstorming and Design

Topics Covered:

- Brainstorming
- Design Process
- Design Tradeoffs
- Design Matrices

Assumptions:

- Willingness to make mistakes

Required Materials:

- Information about a previous game (Zone Zeal, from 2002 is a good choice and available with this curriculum)

Importance to FIRST:

Idea generation is crucial. Some people go with the first idea they get, but generating many ideas and selecting the best one is a much better way to do things. Once you have many ideas, it's important to be able to compare them objectively. Additionally, you will occasionally find that two good ideas conflict, so being able to choose a balance between them is important.

Further Resources:

- Cornell on Brainstorming: http://www.engineering.cornell.edu/student-services/learning/student-project-teams/resources/research-design/brainstorming.cfm
- FIRST related lessons: http://www.usfirst.org/community/frc/content.aspx?id=1108

Lesson Plan:

Introduction

Explain to the students that they'll be learning and practicing brainstorming and design decisions today, focusing on a game from a previous year. This guide has been created with Zone Zeal (2002) in mind.

Explain the basic rules of the game to the students. Focus on the field layout and how robots or alliances earn points.

Give students a preview of the brainstorming process by briefly explaining the three phases:

1. Ability brainstorming: Generate a long list of possible abilities for the robot. These are things that the robot can accomplish, not how it does them.
2. Feature brainstorming: Generate a long list of possible features that provide one or more of the abilities generated in the first phase.
3. Feature grouping: Generate groups of features that combine to create a competitive robot. Essentially, the feature group dictates the general strategy of a robot.

One analogy that you can use for these three phases is that of music.

1. Abilities can be likened to genres of music (Classical, Jazz, Pop, Rock, etc.)
2. Features are specific songs. Your complete list of features can be likened to a music library.
3. Feature lists are like a play list where all of the included songs sound good together.

Explain that brainstorming relies on generating a long list of possible ideas and then selecting the best idea, rather than hoping that one's first idea will work. Recognize that the idea generation process will produce many bad ideas, but that's expected and for every bad idea, there is frequently a good idea. To encourage the possibility of out of the box ideas, and, more generally, the creation of lots of ideas to choose from, no ideas are rejected during the generating processes.

Ability Brainstorming

For this and future steps, you will need a blackboard stenographer. Recruiting an older student to handle writing things down is valuable

Ask the students, "What should a robot be able to do?" Prompting them with examples, such as "Hold balls" or "Move a goal" or "Move fast" may help to get the group started.

As new abilities are suggested, have the stenographer record them in a column.

During this phase, be sure that the students don't confuse abilities with features. This is likely to happen, so reiterate that an ability is something that a robot can do while a feature is a way of accomplishing this.

Example: Students have the ability to carry a box across a room; their arms and legs are the features that give them this ability.

Continue this activity until one or more of the following conditions are met:

- The students have run out of suggestions or they constantly suggest features rather than abilities
- The students have generated a long, long list of possible abilities
- About 15 minutes have passed

Feature Brainstorming

Begin this phase of brainstorming by asking students "What features could a robot have? What would make a robot able to do what we have already listed?" Again, seeding the discussion with examples, like "A cage to hold balls" or "A claw to grab goals" or "A fast drive train" may help to get the discussion started.

Have the stenographer record these features in a second column next to the abilities list from the previous phase. If a feature maps heavily onto a single ability, writing it next to that ability may be helpful.

Continue asking the students for features until every ability has at least one, preferably more, features addressing it.

Feature Grouping

Begin this phase by asking students "What features could be combined to create a competitive robot?" Remind students that, by grouping these features, they'll be creating strategies for their robot. Ask students to title their strategies. Doing so makes the student's intent clear to everyone.

As before, have the stenographer record the feature groupings in a third column.

In general, strategies should combine a few features that support a few abilities. It is likely that a student will suggest the ability to do everything well, but that is likely not possible due to weight, time, cost, and space constraints. This may be a good time to introduce KISS – "Keep it simple, silly." Explain that robots that try to do everything rarely do it well, but focused robots can do one or two tasks well and leave other tasks to their alliance partners.

Lastly, encourage students to both create new feature groups and modify other students' groupings. As always, the more ideas the better.

Design Tradeoffs

Hopefully, for the sake of a learning experience, at least one of the strategies created earlier contains two conflicting ideals, such as a fast drive train with great pushing ability or a tall robot with a low center of mass. Point out one of these and explain to the students that conflicting features force design tradeoffs.

Explain to the students that it helps to further define a design tradeoff before making a decision on which feature to favor. One way to do this is to look at the utility of each of the features to your strategy. Another method that may help is finding other factors that limit the effectiveness of each of the features.

Example: Robot Speed vs. Pushing Force
Ask the students "What is the tradeoff in this situation?" The correct answer is

that the drive train's gear ratio determines how much of the drive motors' power is dedicated toward either pushing force or speed. If necessary, this situation can be related to a bicycle with multiple gears; low gears give the rider more pushing force at the expense of speed, while higher gears are the opposite. This trade off is a proportional one – doubling speed halves the available pushing force.

Ask the students for other limitations on either robot speed or pushing force.

- One limit to speed is the ability of the driver to control a very fast robot.
  - Robots faster than 10 ft/sec are generally hard to control.
- One limit to pushing is the traction of the robot's wheels, resulting in a
  - maximum pushing force of about 150 lbs (130 lb robot * 1.2 μ).

Explain that by selecting drive motors and using physics, it is possible to discover the true limits of your range. If these other limitations heavily restrict your range, then there isn't really much of a tradeoff at all. If, however, there is still a wide range of possibilities, then you still have a choice to make. In these cases, focus on what roles your robot is expected to play in a game, and then chose whether you want to stay near one of the extremes or strike a good balance. For instance, if you expect to be focusing on defense or dragging goals around the field, more pushing force is worth the speed trade off.

Reiterate that more information can help in the design process when two features conflict.

Design Matrices

Point out to the students that you now have a number of possible strategies to take, but it is hard to decide which one to pursue. Just as is the case with design tradeoffs, you could simply choose one of the options based on a gut feeling, or try to further define their benefits and costs.

Introduce design matrices as one method used to make quantitative comparisons. Note that they can be used for a variety of design choices, ranging from whether to pursue an offensive or defensive strategy to whether to use four or six bolts to attach an arm.

Explain the steps of using a design matrix:
- Decide which categories should be used to compare the designs in (Examples: cost, weight, complexity, time to build, robustness, etc.)
- Grade each of the designs in those categories with a + (good), - (bad), or 0 (neutral).
- Sum the totals for each design (+ is +1, - is -1, 0 is nothing), and compare the totals
- The design with the highest total is recommended for use

Example:

	2 Wheel Drive	4 Wheel Drive
Cost	+	-
Reliability	0	+
Space	+	-
Traction	-	+
Weight	+	-
Total	2	-1

Point out the obvious problem that this clearly recommends 2-wheel drive, but lots of robots use 4, or even 6, wheel drive. Ask the students "What are the shortcomings of this method?" Possible answers:
- Selecting the wrong categories to compare designs in.
- Assigning equal importance to all the categories. For instance, this assumes that saving some money is worth the same amount as improving traction, which may or may not be true based on a team's financial situation.

Show that this assumption of equal importance can actually be dealt with by assigning each category an importance, as shown below:

	Importance	2 Wheel Drive	4 Wheel Drive
Cost	1	+ 1	- 1
Reliability	4	0	+ 4
Space	2	+ 2	- 2
Traction	5	- 5	+ 5
Weight	3	+ 3	- 3
Total		1	3

Explain that adding an importance to the various categories resulted in an outcome that seems to be supported by the FIRST community. Mention that after computing a design matrix like this, the next step would be to further develop a 4-wheel drive design and ensure its compatibility with other systems. If it turns out that only a 2-wheel drive system would due to interference with a more important system, a 2-wheel drive system would be used. Conclude that, although design matrices provide substantial support for design decisions, the final decision is not made until the robot is complete; every decision is still flexible until then.