This is a low-resolution printable version of the teacher-presentation information. The original PowerPoint slides are clearer and animated to assist the teacher in delivering quality content to the students.

Licensed users of the EST Foundations curriculum have access to:

- the original animated PowerPoint files
- accompanying handouts
- detailed homework assignments
- lesson plans including online reading and research assignments, and
- suggestions on integrating this project-based curriculum.

Topic 7 (ver 1.0) **Embodiment Design**

Content of this module

- Bell work 7.1
- Discuss objectives, rules and steps of embodiment design
- Discuss embodiment design principles
- Bell work 7.2
- Discuss center of gravity
- Discuss torque output of an electric motor
- Bell work 7.3
- Discuss practical levers
- Discuss practical springs
- Bell work 7.4
- Discuss internal stress
- Bell work 7.5
- Discuss Gear Ratios
- Look for applications on the project machine

7.1 Embodiment Design: General Guidelines (Mechanical Design)

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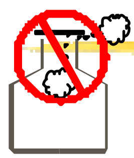
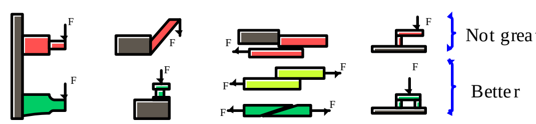
Bell Work 7.1

- In the conceptual design phase, the design team worked hard to choose a general idea pursue.
- In your journal...
- Before production can start, what needs to be done in regards to developing the design?

Today's Agenda



- Discuss objectives, rules, and basic steps of embodiment design
- Discuss general principles that should be considered during embodiment design



Embodiment Design: Objectives

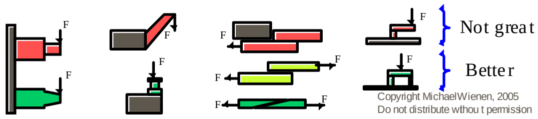
- The solution concept has been elaborately described already, but now it is time to flesh out some of the detail.
- Objectives:
  - Define the overall layout (arrangement of systems and spatial compatibility)
  - Define the form of all components (component shapes and materials)
  - Define the required production procedure
- Deliverables:
  - Scaled assembly drawing
  - Dimensioned component drawings
  - Detailed production schedule

Basic Rules of Embodiment Design

- There are three basic rules that all embodiment designs should adhere to.
  - **Clarity.** The specific function of all components must be clearly defined and the relationships between various sub-functions should be unambiguous. For example, if the job of part A is to carry a horizontal load, and the job of part B is to carry a vertical load, then both should be designed so that they do not help the other at all. Otherwise you'll never be sure who is doing what job. There should be a mathematically **predictable relationship between the input to each system** and its response so we know the practical limits of the design.
  - **Simplicity.** Fewer parts means lower production costs. Additionally, each component should have a simple layout and shape.
  - **Safety.** "Direct" safety methods refer to choosing solutions that preclude danger, "indirect" safety methods refer to constructing special protective systems, "warning" safety methods refer to simply pointing out the danger. Direct methods are always preferred and Warning methods should be avoided.

Principles of Embodiment Design - force transmission

- There are some characteristics that are generally desirable in a mechanical design (though not all are equally important to any specific design):
  - Plan smooth flow lines for force transmission. Meaning, no sudden changes in deflection or cross section of parts. (example below: should use fillets or tapered shaft)
  - Use shortest possible path to transmit force. **If deformation is an issue**, then transmit forces and moments using the shortest possible path. Also, use pure tension or pure compression loading. (example below: red member might tear away from wall)
  - Matched Deformations. Where two parts are adhered together, both parts should have similar tendencies to deform. (e.g., If one is being compressed while the other is being pulled, then the joint is more likely to fail.)
  - Balance unneeded forces. Unbalanced forces add unnecessary stress and accelerate failure. (example below: bending tendency is eliminated with a second leg)

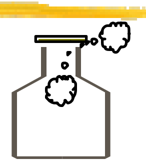


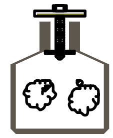
Principles of Embodiment Design - division of tasks

- Two questions must be asked:
  - What sub-functions can be fulfilled with one single function carrier (i.e., component)?
  - What sub-functions must be carried by different components?
- For example if we need a drive shaft to transmit torque and a beam to transmit a force, should we combine the functions and let the drive shaft also transmit the force?
- Simplicity (which is always good) suggests that we combine as many sub-functions as possible into as few components as possible...But,
- Dividing tasks increases the maximum load capacity and creates a clearer picture of the relationship between the individual forces and their effects. (e.g., if we ask a drive shaft to also transmit forces, then the maximum torque that the shaft can carry will be reduced)

Principles of Embodiment Design - self help

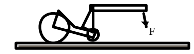
- We create components to have a particular effect. For example, a cover is added to a container to keep the pressurized gas inside. Let's say we simply start with some threads on the cover to hold it to the container.
- As the pressure increases, then the cover threads have to do more and more to keep the gas inside.
- A "self-help" design would be one that used the pressure to actually create a better seal... Can you think of one?
- A second component can be added to the cover which is inserted into the container. The two "covers" are loosely bolted together to create the initial seal. As the pressure increased, the seal force actually increases.

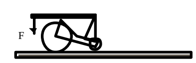




Principles of Embodiment Design - self help

- Example: A wheeled vehicle must have friction between the driven wheel and the road surface in order to move about (imagine a car on an ice rink...no friction means "no can go")
- Typically, we represent this type of friction $f = N \cdot \mu$ where, N is the force of the wheel pushing down on the ground and μ (Greek letter "mu") is a number between 0 and 1
- This simply means that the more the wheel pushes down on the road, the more it can push itself forward (or backwards) on the road.
- If we are free to drive either the small wheel, or the large wheel (but not both), which wheel does "self-help" say we connect the motor to?
- Is there another modification that we should consider to the design of this vehicle?



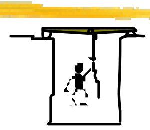


How's this for an improvement?

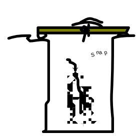
Answer: connect the motor to the front wheel because the force, F, tends to lift the back wheel off the ground... i.e. "no can go"

Principles of Embodiment Design - self help

- Another type of "self help" strategy is to build in protection for components that are sometimes overloaded...we don't want them to break.
- For example, let's say we are pulling on a valuable beam with a chain. If too much force is applied to the chain, the beam will break.



- One engineer might propose a self-help solution where the chain is replaced by a weaker rope. Then, if too much force is applied, the inexpensive rope will break instead of the beam. (though this is a self-help solution, this engineer might need some training in worker safety)



7.2 Embodiment Math Overview Part I

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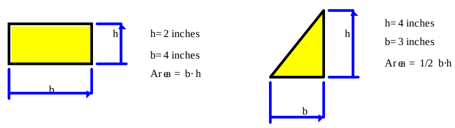
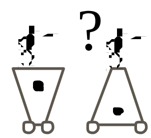
Bell Work 7.2

- In your journal…
- Calculate the area of each of the shapes.
- Is there a point on the rectangle that you could attach a string and the rectangle would hang evenly (just as shown on this page without tilting to one side or the other? (is it the "center" of the rectangle?)
- Does the triangle also have such a point? If so, where is it?



Today's Agenda

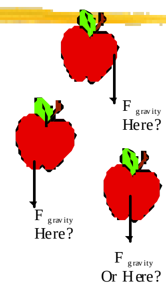
$$x_{total} = \frac{x_1W_1 + x_2W_2 + x_3W_3 + ...}{W_{total}}$$



- Discuss some simple formulas and practical guides to analyze a robot embodiment
  - Center of Gravity
  - Torque output of an electric motor
- Teacher: This information should be quickly covered in class and then allow students to study it later at their own pace. The algebra might challenge some students. It is recommended that you perform experiments/ demonstrations in class as you cover this material. (Because resources vary, I've left it to you to develop such demonstrations…but they should be simple.)
- In ALL cases direct student focus on the pictures…NOT the words.

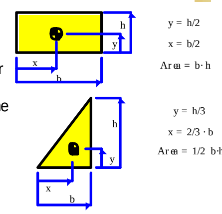
Embodiment Math: Center of Gravity - definition

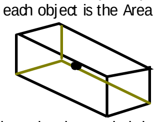
- Gravity acts on every molecule in a solid object. When we want to lift the object we have to counteract the force of gravity on each and every molecule.
- In a solid object, all these little forces add up to give us one big force (resultant force) that we call the weight of the object. (Which you can easily measure using a scale.)
- But if we want to really know how this resultant force affects the object we also need to know at what point it acts. Why?
- Consider the three apples. If the resultant force acts off-center, what happens to the apple? In addition to moving downward, it also spins.
- The theoretical point that we can say this force acts is called the "Center of Gravity."



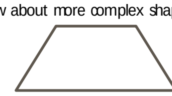
Embodiment Math: Center of Gravity - in practice

- For objects that have uniform density, the Center of Gravity (or C.G.) is at the **geometric center** of the object.
- Of course, we can't forget that most of our concerns are with 3-D objects. (And, the volume of each object is the Area times the depth.)

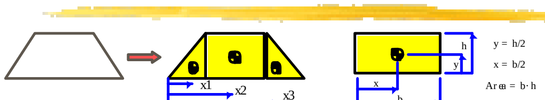




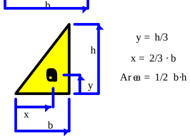
- Rectangles, triangles, and circles are easy.
- But how about more complex shapes?



Embodiment Math: Center of Gravity - in practice



- Note that the trapezoid is really a composite of more basic shapes. To find the overall composite Center of Gravity use the formula:



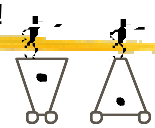
$$x_{total} = \frac{x_1W_1 + x_2W_2 + x_3W_3 + ...}{W_{total}}$$

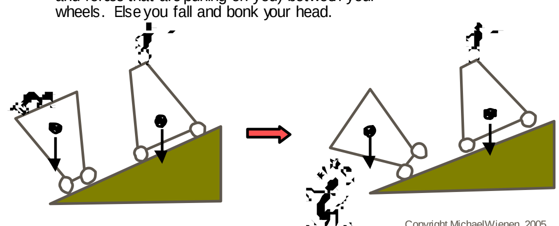
Note: All the x values are measured from the **same place**!

- So for a robot, just add the products of the weight and geometric center for each component and divide the total by the total weight of the machine. You can calculate the other two dimensions as well…

Embodiment Math: Center of Gravity - Why!

- Why is it important to know the center of gravity?
- Because, at all times you must keep your center of gravity (accounting for loads you are carrying and forces that are pulling on you) between your wheels. Else you fall and bonk your head.





Embodiment Math:
Torque output of an electric motor

- Torque is the amount of "spinning force."
- It can be measured in units of ounce-inches (or oz.in.)
- A motor torque of 16 oz.in means that at a distance of one inch the motor can lift 1 lb (1 pound = 16 oz)...at a distance of 12 inches, it could only lift 1.3 oz.
- Torque output of an electric motor is calculated by the equation:

$$T_{shaft} = K_T \cdot I_a$$

- Where K_T is the "torque constant" from the motor's data sheet (refer to the "analyzing motors" lesson to learn how to verify this value) and I_a is the current going through the motor.

Embodiment Math:
Torque output of an electric motor

$$T_{shaft} = K_T \cdot I_a$$

- If all you have is a battery connected to your motor, and the motor is completely stalled, then you can calculate the current as:

$$I = \frac{V_{battery}}{R_{motor}}$$

- Where current is measured in ampere, voltage in volts and resistance in ohms.
- Using this value of current, you can calculate the stall torque of the motor. Stall Torque is the theoretical maximum that the motor can produce. **If this elevated torque loading is maintained for any length of time you will probably burn up the motor.**
- Please refer to "analyzing motors" lesson to learn more.

7.3 Embodiment Math Overview Part II

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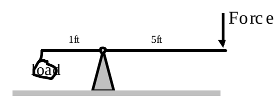
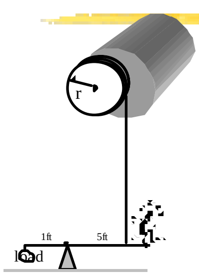
Bell Work 7.3

- If the load weighs 10 pounds about how much force do you think you would have to apply to the see-saw to lift it? Why?



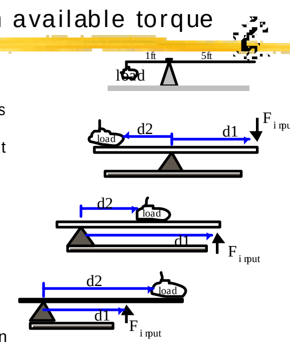
Today's Agenda



- Discuss some simple formulas and practical guides to analyze a robot embodiment
  - Lever arms based on available torque
  - Forces in Springs
- Teacher: This information should be quickly covered in class and then allow students to study it later at their own pace. The algebra might challenge some students. It is recommended that you perform experiments/ demonstrations in class as you cover this material. (Because resources vary, I've left it to you to develop such demonstrations...but they should be simple)
- In ALL cases direct student focus on the pictures...NOT the words.

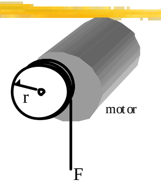
Embodiment Math:
Lever arms based on available torque

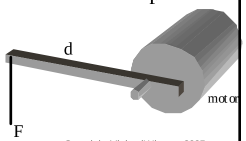
- A lever is a rigid object using a fulcrum or pivot point to gain a mechanical advantage. Three types have been defined based on the relationship of the input and output to the fulcrum
  - First Class Lever
  - Second Class Lever
  - Third Class Lever
- Each case will be stationary only if d1· F_{input} = d2· (Weight of the load)
- If you want the load to actually move, you will need more F
- If you have a limited amount of F, then you need to choose d1 and d2 to lift the required load.



Embodiment Math:
Lever arms based on available torque

- How much force can our motor apply for levers like those on on the previous slide? There are two options.
  - If you attach a reel to the motor and use it to pull a rope then the amount of force is
    $F = T_{motor}$ / radius of reel
    (units: F is in ounces, T is in ounce-inches and r is in inches)
  - Second, you can mount the motor directly to the lever to act as the pivot point
    The motor must work its hardest when the load is perpendicular to the lever. So, the most load that the motor can move is
    $F = T_{motor} / d$



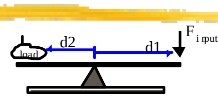


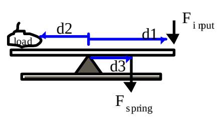
Embodiment Math:
Forces in Springs

- A mechanical "spring" is any object whose purpose is to be deformed, store potential energy, and use that energy to restore its original shape.
- For simple springs, the amount of force required to cause a given deformation can be easily calculated.
- $F_{spring} = k \cdot dx$ where dx is the amount of deformation in the spring (inches), F is the force in the spring (pounds), and k is the "spring constant" (pounds/inch).
- As long as you don't stretch the spring (or flexible cord) too far, you can predict just how much force is associated with any deflection:
  - If you use the spring as a counter weight for an arm...how much force will it provide to assist the motor in moving a lever?
  - If you use it to close a jaw, how much force will the jaw apply to the object?

Embodiment Math:
Forces in Springs - Example

- Remember that for the lever to be stationary,
- $d1 \cdot F_{input} = d2 \cdot$ (Weight of the load)
- Let's say that d1 = 6 inches and d2 is 12 inches
- If the motor is configured to provide 1 pound of force (so, F_{input} = 1 lb), then, the maximum load is:
- $d1/d2 \cdot F_{input} = Weight_{max} = 0.5$ lbs
- But, we can stretch a spring and attach it to the lever so that the force in the spring also helps to lift the load...
- It turns out that all you do is add "$d3 \cdot F_{spring}$" to the lever equation...but you add it to whichever side that the spring is helping. In this example, it is helping the F_{input}.
- So, $d3 \cdot F_{spring} + d1 \cdot F_{input} = d2 \cdot Weight_{max}$





Embodiment Math:
Forces in Springs - finding k

- But, how do you find k?
- Remember, $F_{spring} = k \cdot dx$ where dx is the amount of deformation in the spring (inches), F is the force in the spring (pounds), and k is the "spring constant" (pounds/inch)...Let's call this "the spring equation."
- So, all you do is run a little test. Apply a known weight and measure the deformation of the spring. Apply a different weight and measure the deformation again...repeat this a couple times for different weights (because that is a smart thing to do when performing experiments).
- Then plug all your force and deflection measurements into the spring equation and calculate what k must be...you should be able to take an average from each of your experiments to find a good value (Caution...don't stretch the spring too far, or the spring equation won't be valid anymore)
- For more information look up "spring (device)" at www.wikipedia.com .

7.4 Embodiment Math Overview Part III

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Bell Work 7.4

- Realizing that solid objects are made up of a bunch of molecules that are attracted to each other, answer these two questions:
  - What does it take to break an object (like a ruler)?
  - When you push on one end of a stick, how does the force get to the other end of the stick?

Today's Agenda

- Discuss some simple formulas and practical guides to analyze a robot embodiment
  - Bending stress and part geometry
- Teacher: This information should be quickly covered in class and then allow students to study it later at their own pace. The algebra might challenge some students. It is recommended that you perform experiments/ demonstrations in class as you cover this material. (Because resources vary, I've left it to you to develop such demonstrations...but they should be simple)
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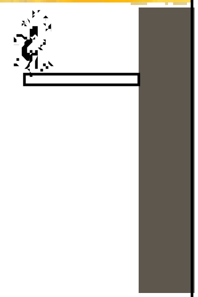
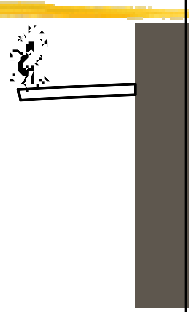
Embodiment Math:
Bending stress and part geometry



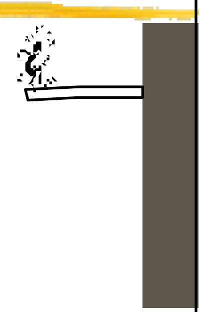
- A funny thing happens in real life with remarkable consistency. Take a rigid "beam" and anchor it to a wall and push on it really hard as shown in the picture...where does it typically break? If you can't break it, where does it typically bend? (same concept as holding something off the edge of a table to break or bend it)
- Assuming there are not cracks in the beam (that is another embodiment engineering issue), it will generally "give" somewhere close to the wall.
- Is the force any greater there? Is there some magical force that we can't see which likes to break things at walls?
- No, it breaks because of something engineers call "internal stresses" due to the "bending moment."

Embodiment Math:
Bending stress and part geometry



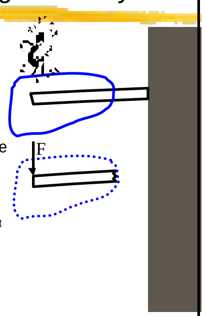
- First we need to define what "stress" means.
- "Stress" is what happens internally to an object when we apply external loads (forces and moments) to the object. How these internal stresses are distributed is the key to where the object will fail.
- Generally, it is not the "amount of force applied" that breaks something. It is the "amount of force applied **per unit of area**". For example, if you push on a stick of cold butter with a spoon, it will take a lot of force to penetrate the butter. However, if you use a sharp knife it takes very little force to penetrate the butter.
- For the same force, the stress is much higher using the knife because the spoon has a large area.
- In general stress = force / area
- Simply put, High stress tends to break things!

Embodiment Math:
Bending stress and part geometry



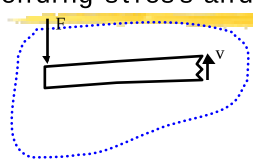
- Research has shown that the maximum stress in the beam (as shown) is predictable. The equation is really quite simple, stress = $c \cdot M / I$
- Where, c is a constant, M is called the "Bending Moment," and I is the "moment of inertia."
- So if high stress tends to break things, **then all we have to do is keep M as small as possible, and make I as large as possible.**
- Let's tackle M, the bending moment, first.

Embodiment Math:
Bending stress and part geometry



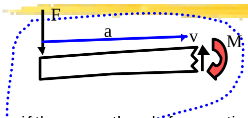
- Before we can study this beam, we need to isolate it. Imagine if we could draw a circle around any "object" that we wanted to study and magically separate it from the universe but still have all the effects of the universe acting on it.
- The specific "object" that we want to study is the left end of the beam (the part that is circled).
- The drawing of this object is pretty boring. But notice that on the right hand side of the circle, we actually had to cut through the object.
- Now, we need to see if we can represent everything that the universe is doing to the object (because we want to study it just the way it was).
- The only thing the universe really does (as far as this problem is concerned) is apply forces and moments. The dude jumping on the end is part of the universe, right?...that's just a force.

Embodiment Math:
Bending stress and part geometry



- We've zoomed up a bit. If "F" was the only force acting on this object (as drawn above), what would happen?
- It would quickly fall to the floor (according to Newton). So, what in the universe is holding it in place?
- Answer: The rest of the object, of course (which is in turn nailed to the wall).
- The rest of the object must be applying forces on our circled object in order to hold it in place. Such effects are called "internal forces." (We'll call this one "v.")

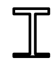
Embodiment Math: Bending stress and part geometry

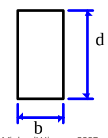


- Now, if these were the only forces acting on this object (as drawn above), what would happen?
- According to Newton, it would start spinning uncontrollably counterclockwise...right?
- So, the rest of the beam must be doing something to counteract the spinning that "F" is trying to cause. This internal reaction is called the "bending moment"...and we use "M" to represent it.
- In another lecture we can do the actual math, but for now you'll just have to believe that we can calculate the value of this bending moment to be:
- M = a·F Note: As we move further to the right on the beam, the bending moment gets bigger!

Embodiment Math: Bending stress and part geometry

- So, now we know that the bending moment is our culprit (stress = c·M / I)
- Remember, High stress tends to break things!
- To reduce the stress, we need to make "I" bigger.
- "I" (the "moment of inertia") is only a function of the cross section of the beam.
- Mathematics can be applied to calculate "I" for any shape (you can find the formulas on line).
- We will only look at one of the formulas...a simple one.
- Imagine looking down the length of a standard wood 2"x4"...you would see a rectangle like this one.
- For such a shape, math shows us that $I = (b \cdot d^3)/12$
- So, which is more important, b or d?
- Can you see why the shape shown below is so popular?

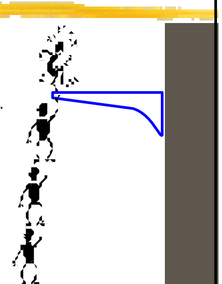




A beam with this shape is called an I-beam. It is very common in industry because it has the "tall" feature to prevent bending, but it doesn't weigh as much as if it was a solid rectangle.

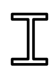
Embodiment Math: Bending stress and part geometry

- In short, the cross-section of the beam should get thicker in the places where there will be a lot of bending moment.
- In this case the largest bending moment is at the wall, so that is where the beam should be thickest.
- If we modified the beam as this picture shows, it would be very hard indeed to break or bend the beam.



Embodiment Math: Bending stress and part geometry

- In practice:
  - Thicken components in places with high bending moments
  - Add "webbing" to stiffen components (like the vertical webbing on the I-beam)
  - Design so that loads follow the component's primary axis as much as possible. (Doing so can eliminate the bending moment all together.)



Recall, A beam with this shape is called an I-beam. It is very common in industry because it has the "tall" feature to prevent bending, but it doesn't weigh as much as if it was a solid rectangle.

7.5 Embodiment Math Overview Part IV

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Bell Work 7.5

- List three ideas you have (or components already in the machine design) to which we should consider applying this week's principles and mathematics.

Today's Agenda

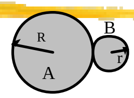
- Discuss some simple formulas and practical guides to analyze a robot embodiment
  - Gear Ratios
- Look for places to apply this week's Embodiment Math on our machine

- Teacher: This information should be quickly covered in class and then allow students to study it later at their own pace. The algebra might challenge some students. It is recommended that you perform experiments/ demonstrations in class as you cover this material. (Because resources vary, I've left it to you to develop such demonstrations...but they should be simple)
- In ALL cases direct student focus to the pictures...NOT the words.

Embodiment Math: Gear Ratios

- It is highly unlikely that an electric motor by itself has the correct shaft speed that we want.
- The output speed of a motor is a function of many physical parameters which the motor designers have implemented in an effort to get an efficient motor.
- If you had to buy a different motor every time you needed a different speed, it would be a very sad world indeed (for the engineering at least).
- Fortunately, gears are available to modify the torque and speed of an output shaft with respect to the input shaft.
- Unfortunately, you cannot pick any combination of torque and speed that you want. The total power that is available is dictated by the motor (and battery).
- Power = Torque x Speed Therefore, if you increase the speed you will have a decrease in torque. If you want more torque, you will have to sacrifice speed.

Embodiment Math: Gear Ratios

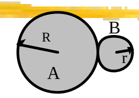


- Consider two gears labeled A and B
- The radius of the large gear is "R" (probably measured in inches but you can use any units that you want) and the radius of the small gear is "r."
- The speed of the large gear is represented by "S_A" (probably measured in rpm) and the speed of the small gear is represented by "S_B".
- Using basic "Kinematics" we derive an equation that relates the two speeds.
- The power that is available for gear B is assumed to be transferred to gear A (or vice versa depending on which gear has the motor). (in other words, $P_A = P_B$)
- Plugging in Power = Torque x Speed on each side and doing some algebra we find the relationship for torque.

$$S_A = S_B \frac{r}{R}$$

$$T_A = T_B \cdot \frac{R}{r}$$

Embodiment Math: Gear Ratio - definition



- "Gear Ratio" is defined as the ratio of the powered gear's rotation (input) to the rotation of the driven gear (output). If gear B is the powered gear, then the gear ratio = R/r. (NOT the ratio of sizes, but the ratio S_B/S_A.)
- So, if the large gear is twice the size of the small gear, then the gear ratio, GR = 2.
- Because the teeth must mesh together and are therefore the same size, the gear ratio is also the relationship between the number of teeth on one gear and the number of teeth on the other gear.
- It is written "powered gear teeth":"driven gear teeth". If the motor is attached to gear B (which makes it the powered gear), the gear ratio is R:r.
- Read more at http://www.howstuffworks.com/

Looking for Applications

- As a class think about the current machine design. Where might we use this week's principles and math to analyze (or incorporate):
  - Principles of Embodiment Design
  - Center of gravity
  - Motor torque capabilities
  - Levers
  - Forces in springs
  - Internal Bending Stresses
  - Gears