Drivetrain Design

featuring the Kitbot on Steroids

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Outline

- Drivetrain Selection
  - Purpose of a drivetrain
  - Types of wheels
  - Types of drivetrains
  - Compare drivetrain strengths and weaknesses
  - Evaluate your resources and needs
  - Which drivetrain is best for you?
- Designing a Tank-Style Drivetrain
  - Key Principles in designing a tank-style drivetrain
  - Applying Key Principles
  - Types of tank-style drivetrains
- Kitbot Design Review & Upgrades
  - Standard FRC Kitbot Design Review
  - Review of “Kitbot on Steroids” upgrades
  - Other potential Kitbot upgrades
  - How to assemble a “Kitbot on Steroids”

Ben Bennett

- 5 years of FIRST experience
- Founder and Lead Student for Team 2166 (2007)
  - GTR Rookie All-Star Award
- Lead Mentor for Team 2166 (2008-2009)
  - 1 regional championship
- Mechanical Design Mentor for Team 1114 (2010-present)
  - 6 regional championships, 2010 world finalists
  - 2 chairmans awards
- 4th Year Mechatronics Engineering Student at UOIT
- Current member of GTR East (UOIT) Regional Planning Committee

Purpose of a Drivetrain

- Move around field
  - Typically 27’ x 54’ carpeted surface
- Push/Pull Objects and Robots
- Climb up ramps or over/around obstacles
- Most important sub-system, without mobility it is nearly impossible to score or prevent points
- Must be durable and reliable to be successful
- Speed, Pushing Force, and Agility important abilities

Types of Wheels

- "Traction" Wheels
  - Standard wheels with varying amounts of traction, strength & weight
    - Kit of Parts (KOP)
    - AndyMark (AM) or VEX Pro
    - Pneumatic
    - Slick
    - Custom

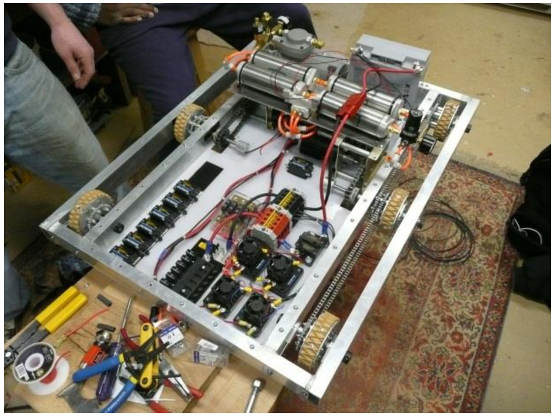
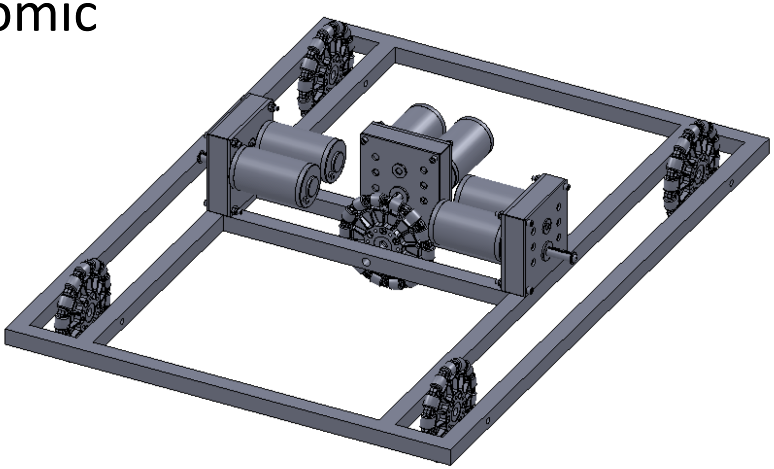
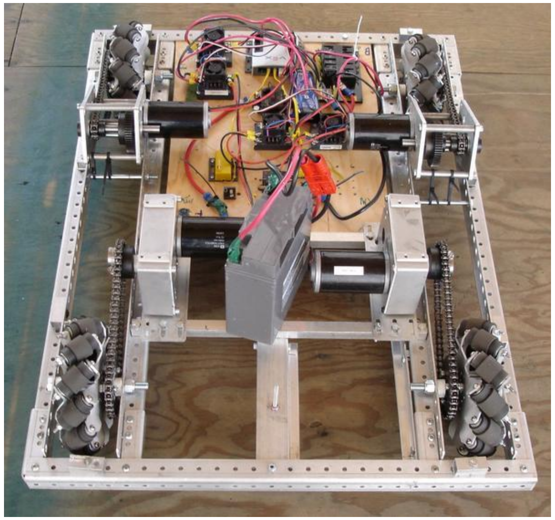
Types of Wheels

- Omni
  - Rollers are attached to the circumference, perpendicular to the axis of rotation of the wheel
  - Allows for omni directional motion

- Mecanum
  - Rollers are attached to the circumference, on a 45 degree angle to the axis of rotation of the wheel
  - Allows for omni directional motion

Types of Drivetrains

- Tank
- Swerve
- Slide
- Mecanum
- Holonomic

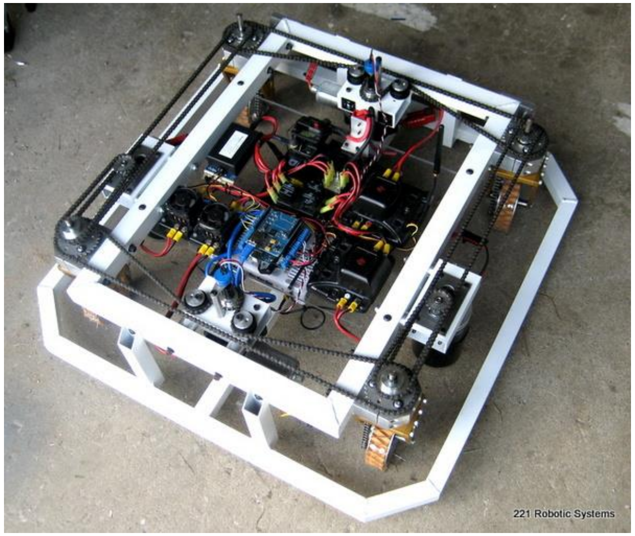





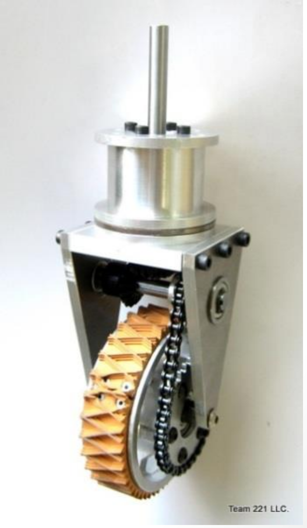
Type of Drivetrains

- Tank
  - Left and right wheel(s) are driven independently
  - Typically in sets of two (1-4 sets is common, sometimes higher)
  - Strengths
    - Simple & cheap to design, build, and program
    - Easy to drive
    - Potential for high speed and/or pushing force
  - Weaknesses
    - *Slightly* less agile than other drivetrains

Type of Drivetrains

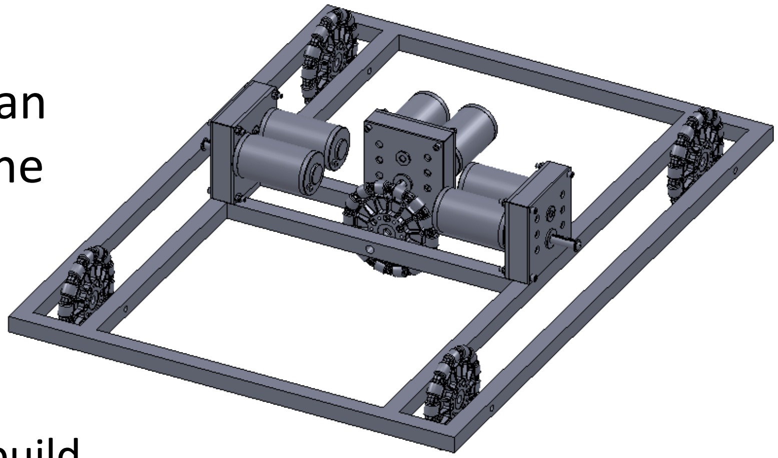
- Swerve/Crab
  - Wheels modules rotate on the vertical axis to control direction
  - Typically 4 traction wheels
  - Strengths
    - Potential for high speed and/or pushing force
    - Agile
  - Weaknesses
    - Very complex and expensive to design, build and program
    - Extra motors required to be able to rotate robot frame





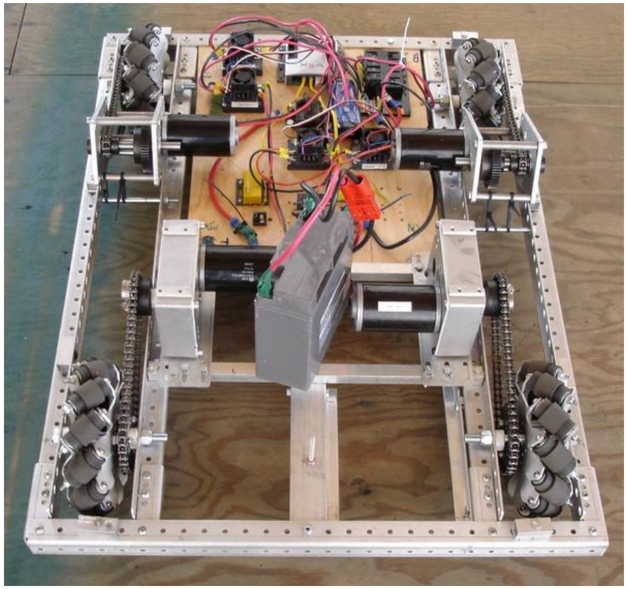
Type of Drivetrains

- Slide
  - Similar layout to tank drive, with an extra wheel(s) perpendicular to the rest
  - Must use all omni wheels
  - Strengths
    - Fairly easy and cheap to design, build, and program
    - Agile
  - Weaknesses
    - No potential for high pushing force
    - Extra wheel(s)/motor(s)/gearbox(es) required to allow robot translate sideways



Type of Drivetrains

- Mecanum
  - Similar layout to tank drive, but each wheel must be driven independently
  - Must use 4 mecanum wheels
  - Strengths
    - Fairly easy to design & build
    - Agile
  - Weaknesses
    - No potential for high pushing force
    - Challenging to program and learn to drive well
    - Requires extra gearboxes
    - Wheels are expensive



Type of Drivetrains

- Holonomic
  - 4 omni wheels positioned on 45 deg angle in the corners of the frame
  - Each wheel must be driven independently
  - Strengths
    - Agile
  - Weaknesses
    - No potential for high pushing force
    - Very challenging to program and learn to drive well
    - Requires extra gearboxes

Compare Drivetrains

- Choosing the right drivetrain is critical to the success of an FRC robot
- Several drivetrains to choose from
  - Each one has its own strengths and weaknesses
- Important to **quantitatively** evaluate all options to ensure optimal solution is chosen
  - Best method to do this is a “Weighted Objectives Table”

Compare Drivetrains

- Define drivetrain attributes to compare
  - Agility
    - Ability to translate in the x and y axis as well as rotate about the z axis simultaneously
  - Strength
    - Push robots and/or game pieces
    - Resist defense from all sides of the drivetrain
  - Number of Motors
    - Number of motors allowed on an FRC robot is limited
    - Most drivetrains use 4 CIM motors to power wheels
    - Additional motors to rotate wheel modules or translate sideways may take away from motors for other robot functions

Compare Drivetrains

- Define drivetrain attributes to compare
  - Programming
    - Ideally does not require sensor feedback (eg. wheel module angle)
    - Ideally does not require advanced algorithm to calculate individual wheel speed/power
  - Ease to Drive
    - Intuitive to control so little practice is required to be competitive
    - Just because some drivetrains have the ability to move sideways doesn't mean the driver will use the ability
      - Often drivers end up turning the robot because it is more natural or going sideways feels (or actually is) slower
  - Traverse Obstacles
    - The ability of a drivetrain to traverse ramps, bumps or steps

Compare Drivetrains

- Define drivetrain attributes to compare
  - Design
    - This is a very general heading. Sub headings grouped as there is a strong relationship between them
      - Cost
      - Ease to design (select components and choose dimensions)
      - Ease to manufacture
      - Ease to assemble
      - Ease to maintain/repair
      - Weight

Compare Drivetrains

- Give each attribute of each drivetrain a relative score between 1 and 5
- Weights are dependant on
  - Strategic analysis of the game (priority list)
  - Teams resources

	Weight	Tank	Swerve	Slide	Mecan	Holo
Agility	?	3	5	5	5	5
Strength	?	4	5	1	1	1
Motors	?	5	1	3	5	5
Program	?	5	1	4	3	2
Drive	?	5	3	3	2	1
Traverse	?	5	4	4	3	1
Design	?	5	1	4	4	3

Compare Drivetrains

- Agility, Strength & Ability to traverse obstacles
  - Relative to #1 priory, reliability
    - 0 = not important or required
    - 10 = equally as important as reliability
- Number of Motors
  - Depends on complexity of other robot features and ability to design with all motors
    - 0 = no other features/very strong ability to design with all motors
    - 10 = very complex/little ability to design with other motors
- Programming
  - Depends on strength of programming team (# of students/mentors, experience, ect)
- Ease to Drive
  - Depends on amount of available practice
    - 0 = have a full practice field and practice robot with committed drivers that train every day
    - 10 = no practice field/robot, no time in build season to practice

Compare Drivetrains

- Design
  - How many students/mentors do you have?
  - How much experience do you have?
  - What tools are available to you (hand tools < bandsaw < mill)?
  - How many hours are your shop facilities available/will you use them?
  - How much money do you have?
  - Drivetrains with a low design score require significant resources to design a reliably
    - 0 = lots of experience, students, mentors, tools, money
    - 0 = The desired drivetrain has been used in a previous season or prototyped in the off season
    - 10 = No experience, few students, mentors, tools, money

Compare Drivetrains

- Typical Weights for a rookie or low resource team
  - 5 - Agility
  - 5 - Strength
  - 5 - Number of Motors
  - 10 - Programming
  - 10 - Ease to Drive
  - 0 - Traverse Obstacles
  - 10 – Design
- Resources are low, so it is more important to build a simple drivetrain that is easy to program and learn how to drive to ensure reliability.
- The performance of the drivetrain (agility & strength) are not as important as reliability
- The number of motors is not as important because additional features should be very basic and require few (or no) motors

Compare Drivetrains

- Rookie/low resource team weighted table
  - Tank drivetrain much higher score than others
  - Slide drive second best

	Weight	Tank	Swerve	Slide	Mecan	Holo
Agility	5	3 (15)	5 (25)	5 (25)	5 (25)	5 (25)
Strength	5	4 (20)	5 (25)	1 (5)	1 (5)	1 (5)
Motors	5	5 (25)	1 (5)	3 (15)	5 (25)	5 (25)
Program	10	5 (50)	1 (10)	4 (40)	3 (30)	2 (20)
Drive	10	5 (50)	3 (30)	3 (30)	2 (20)	1 (10)
Traverse	0	5 (0)	4 (0)	4 (0)	3 (0)	1 (0)
Design	10	5 (50)	1 (10)	4 (40)	4 (40)	3 (30)
Total	225	93% (210)	47% (105)	69% (155)	64% (145)	51% (115)

Compare Drivetrains

- Comparison of weighted tables for different resource teams

	Rookie	Average	Strong
Agility	5	8	10
Strength	5	8	10
Motors	5	6	5
Program	10	7	3
Drive	10	7	3
Traverse	0	0	0
Design	10	7	3

	Tank	Swerve	Slide	Mecan	Holo
Rookie	93%	47%	69%	64%	51%
Average	89%	56%	67%	66%	56%
Strong	82%	71%	64%	66%	61%

Compare Drivetrains

	Swerve
Agility	10
Strength	10
Motors	2
Program	2
Drive	2
Traverse	0
Design	2

- When to choose a swerve drive
  - Strength & Agility equally as important as reliability
  - Lots of students/mentors
  - Access to advanced tooling
  - Large budget
  - Team has strong ability to use other motors for robot function
  - Team has practice field and practice robot
  - Team has used a swerve in a previous season, or prototyped one in the off season

	Tank	Swerve	Slide	Mecan	Holo
Swerve	79%	80%	63%	63%	59%

Compare Drivetrains

	Slide
Agility	10
Strength	0
Motors	1
Program	3
Drive	1
Traverse	0
Design	3

- When to choose a slide drive
  - Agility equally as important as reliability
  - Strength is not required (game has no interaction with opponents)
  - Team has practice field and practice robot
  - Team has used a slide in a previous season, or prototyped one in the off season
  - Lots of students/mentors
  - Team has strong ability to use other motors for robot function

	Tank	Swerve	Slide	Mecan	Holo
Slide	78%	67%	89%	87%	79%

Compare Drivetrains

	Mecan
Agility	10
Strength	0
Motors	5
Program	2
Drive	2
Traverse	0
Design	3

- When to choose a mecanum drive
  - Agility equally as important as reliability
  - Strength is not required (game has no interaction with opponents)
  - Team has practice field and practice robot
  - Team has used a mecanum in a previous season, or prototyped one in the off season
  - Strong programing ability
  - Lots of students/mentors

	Tank	Swerve	Slide	Mecan	Holo
Mecan	82%	60%	83%	88%	82%

Designing a Tank Drivetrain

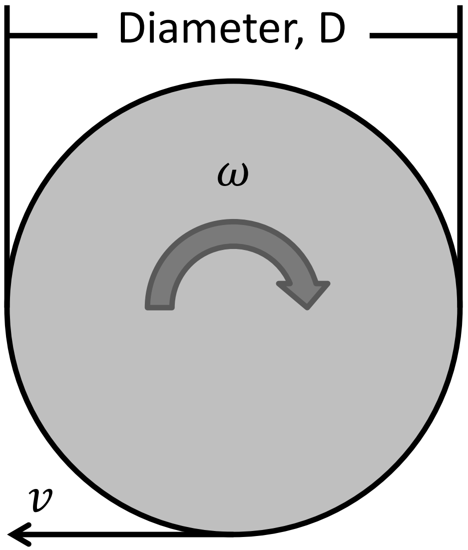
- At this point we have concluded Tank-Style Drivetrain is usually the best option for all teams, regardless of the game or the teams resources
- Why don't all teams use Tank-Style Drivetrains?
  - Some (few) teams have **a lot** of resources
  - Trying new things to learn new skills/gain new experiences
    - Understanding this choice will make them less competitive
  - Improper strategic analysis of the game and evaluation of team resources
  - Improper analysis of strengths and weakness of various drivetrains
    - Omni directional drivetrains have a significant "cool factor" that distract teams

Key Principles

- Key Principles
  - Converting from angular to linear velocity
  - Torque
  - Gearing
  - Force Distribution
  - Calculating Centre of Gravity
  - Friction

Key Principles

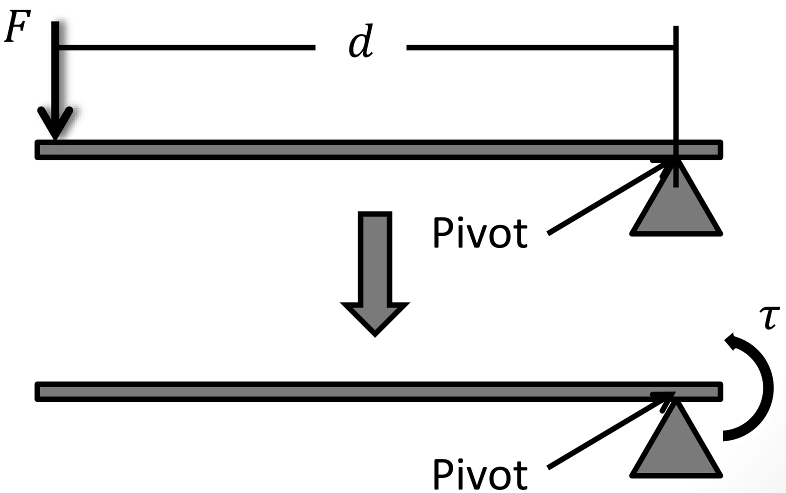
- Converting from angular to linear velocity
  - Angular velocity (ω, “omega”) – the rate something rotates about an axis
    - degrees/second, rad/second, revolutions/minute (rpm)
  - Linear velocity (v) – the rate something is displaced (moves)
    - kilometers/hour, meters/second, feet/second



  - For each rotation of a cylinder, it moves a distance equal to its circumference
    - Circumference = distance/revolution $= \pi \cdot D$
    - Therefore linear velocity is the rotation rate times circumference
    - $v = \omega \cdot \pi \cdot D$

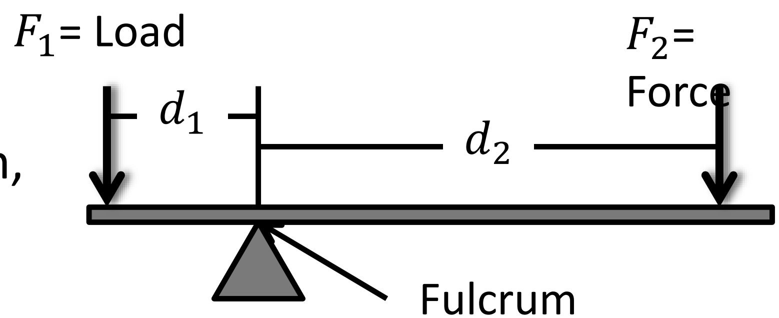
Key Principles

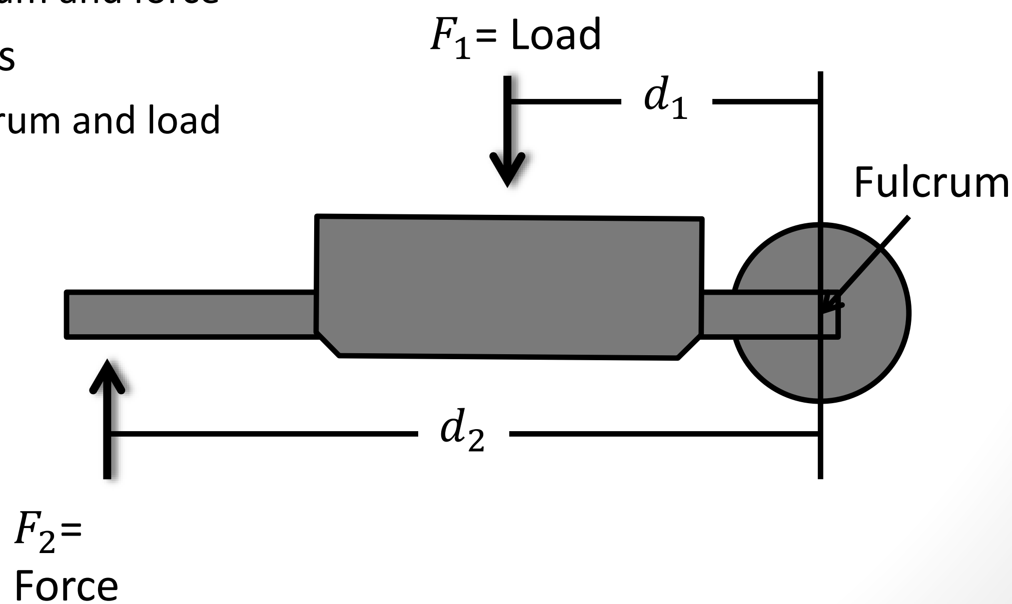
- Torque
  - Rotational or twisting force (τ, "tau")
  - The product of force, distance, and the angle between force and lever arm
    - $\tau = F \cdot d \cdot \sin\theta$
  - In the applications we will discuss today, the force and lever arm will be perpendicular, therefore
    - $\theta = 90$ and $\sin 90 = 1$
  - So we get
    - $\tau = F \cdot d$
  - Given a fixed torque,
    - Larger distance → less force
    - Smaller distance → more force



Key Principles

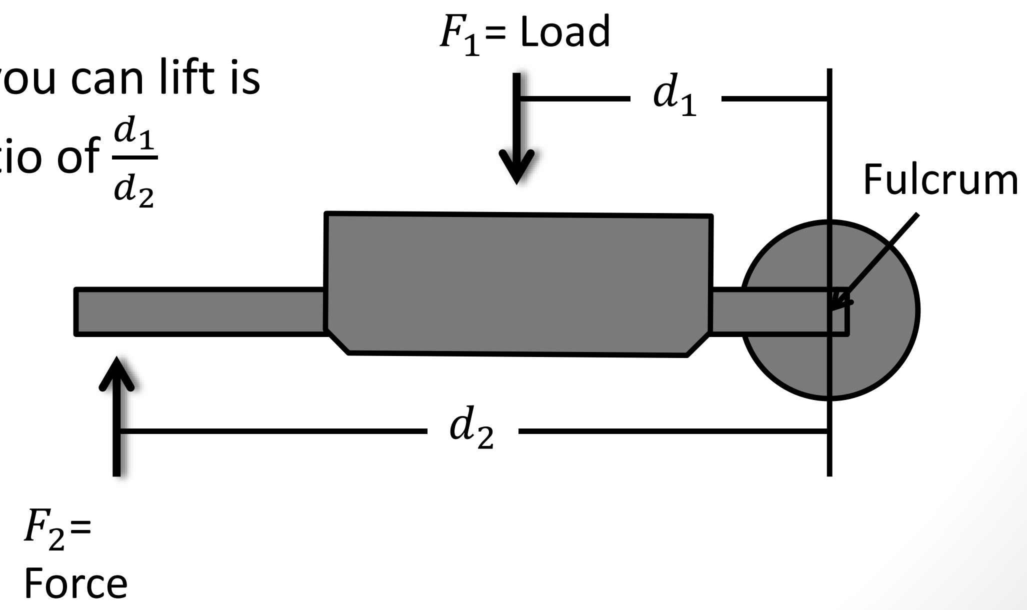
- Torque
  - Key principle in levers (fulcrum, load, force)
    - First class: Crowbar
      - fulcrum between load and force
    - Second class: Wheelbarrow
      - load between fulcrum and force
    - Third class: Tweezers
      - force between fulcrum and load





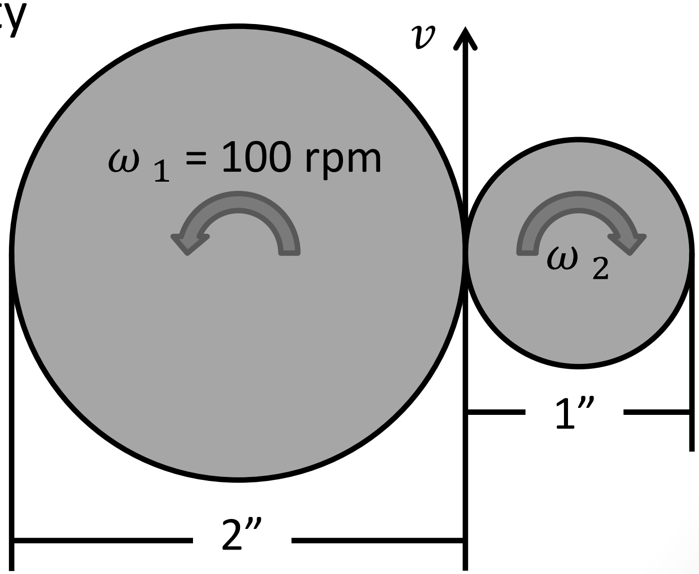
Key Principles

- Torque
  - You can add and subtract torques when multiple forces are acting about the same pivot point (eq. raising or lowering a wheelbarrow)
  - When the system is static (wheelbarrow is not being raised or lowered, such as while you are moving it from point A to B), torques are equal
  - The amount of load you can lift is dependant on the ratio of $\frac{d_1}{d_2}$
    - $\tau_1 = \tau_2$
    - $F_1 \cdot d_1 = F_2 \cdot d_2$
    - $F_2 = \frac{d_1}{d_2} \cdot F_1$



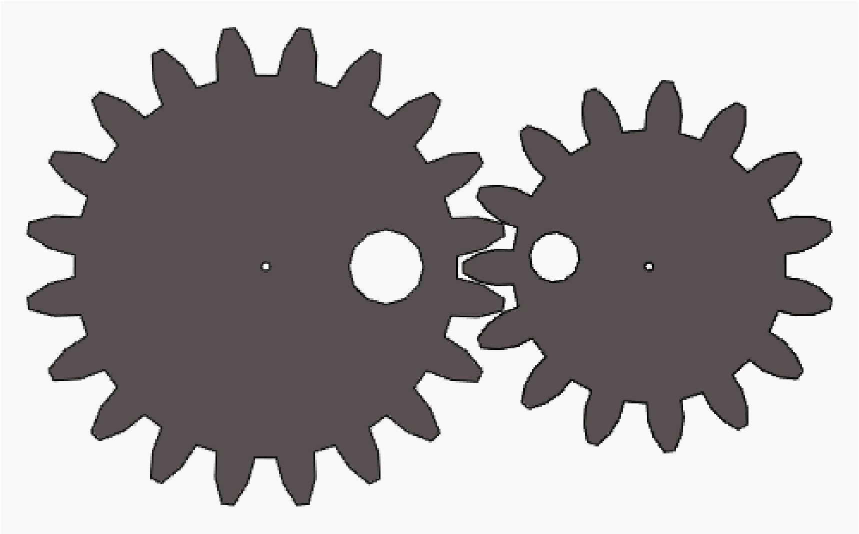
Key Principles

- Gearing
  - Gear to increase or decrease speed (angular velocity) and torque
  - Speed is inversely dependant on torque
    - As speed increases, torque decreases (and vise versa)
  - Meshing gears may have different angular velocities, but they will always have the same linear velocity
    - $v_1 = v_2 = v$
    - $\omega_1 \cdot \pi \cdot D_1 = \omega_2 \cdot \pi \cdot D_2$
    - $\frac{\omega_1}{\omega_2} = \frac{D_2}{D_1}$
    - $\omega_2 = \omega_1 \cdot \frac{D_1}{D_2}$
    - $\omega_2 = 100(rpm) \cdot \frac{2"}{1"} = 200rpm$



Key Principles

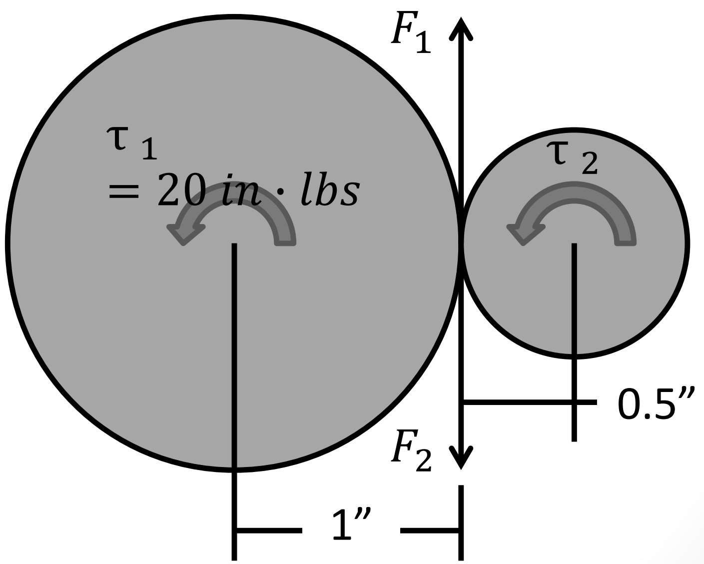
- Gearing
  - Example: Gear 1 has 20 teeth, gear 2 gear has 15 teeth
    - $\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} = \frac{15}{20}$
    - $\omega_1 = \frac{3}{4} \cdot \omega_2$
  - For every 3 revolutions of gear 1, gear 2 revolves 4 times



Key Principles

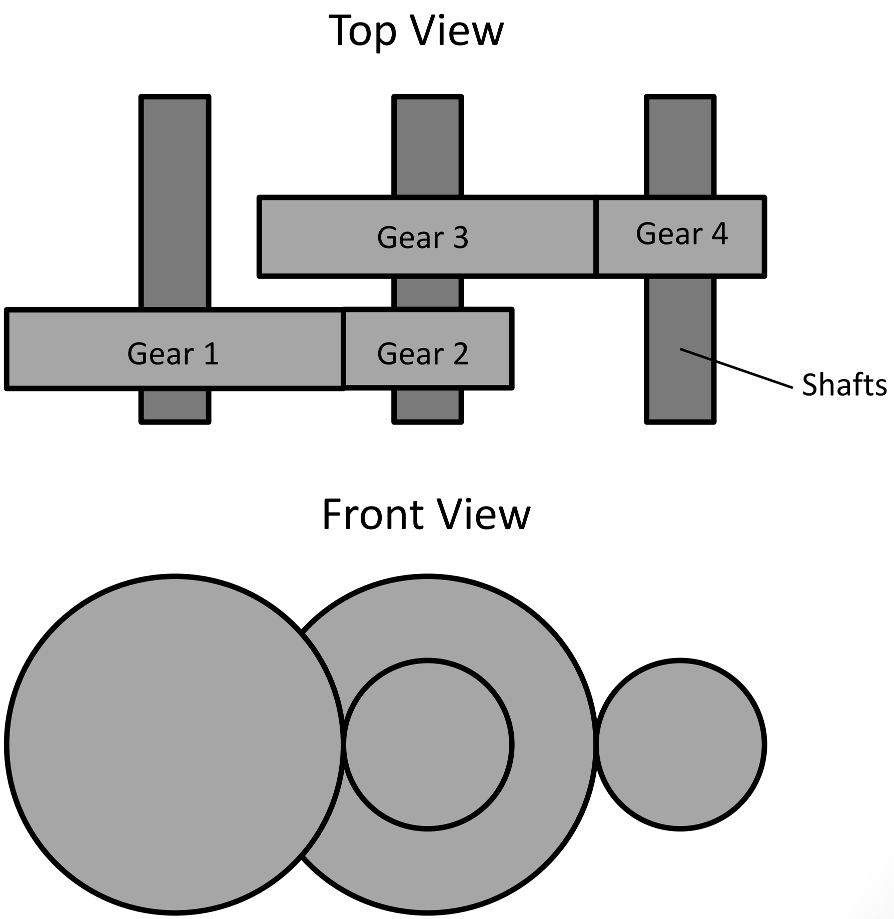
- Gearing
  - Meshing gears may have different torques, but when they are static (motor is stalled) they will have an equal, but opposite force

- $F_1 = F_2$
- $\frac{\tau_1}{d_1} = \frac{\tau_2}{d_2}$
- $\frac{\tau_1}{\tau_2} = \frac{d_1}{d_2}$
- $\tau_2 = \frac{d_2}{d_1} \cdot \tau_1$
- $\tau_2 = \frac{0.5"}{1"} \cdot 20\ in \cdot lbs = 10\ in \cdot lbs$



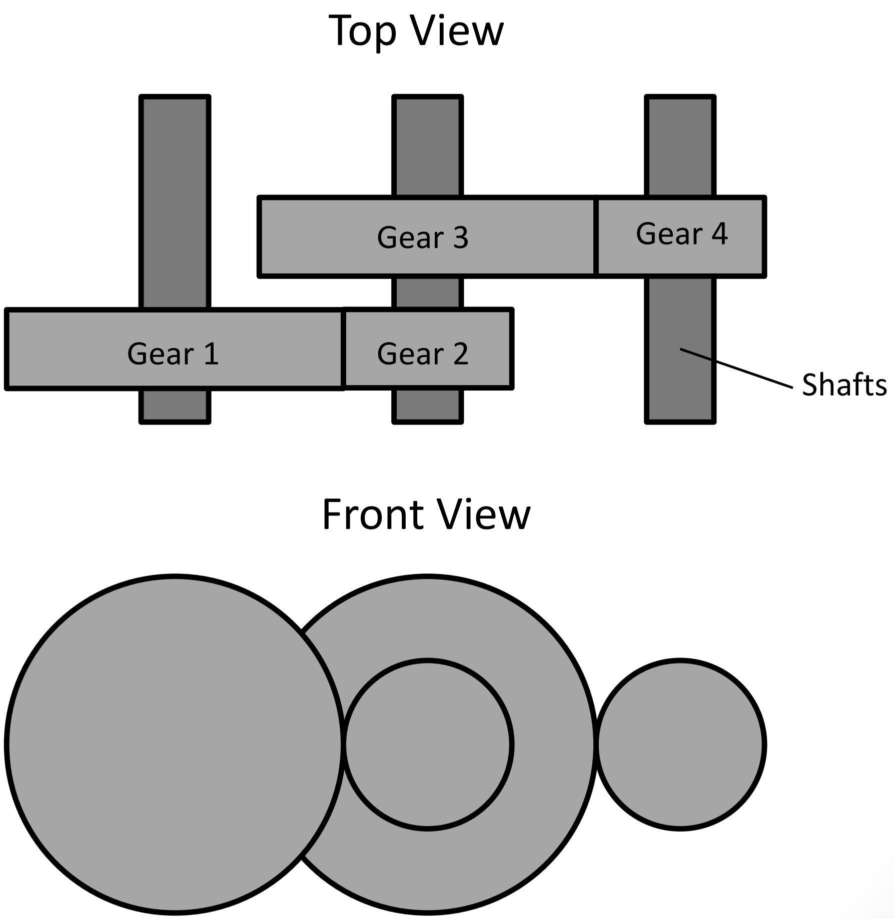
Key Principles

- Gearing
  - Gears fixed on the same shaft (2 and 3) have the same angular velocity
  - Therefore
    - $\omega_1 \cdot \frac{D_1}{D_2} = \omega_2$
    - $\omega_3 = \omega_4 \cdot \frac{D_4}{D_3}$
    - $\omega_2 = \omega_3$
    - $\omega_1 \cdot \frac{D_1}{D_2} = \omega_4 \cdot \frac{D_4}{D_3}$
    - $\frac{\omega_1}{\omega_4} = \frac{D_2}{D_1} \cdot \frac{D_4}{D_3}$
  - Gear ratios from each stage are multiplied



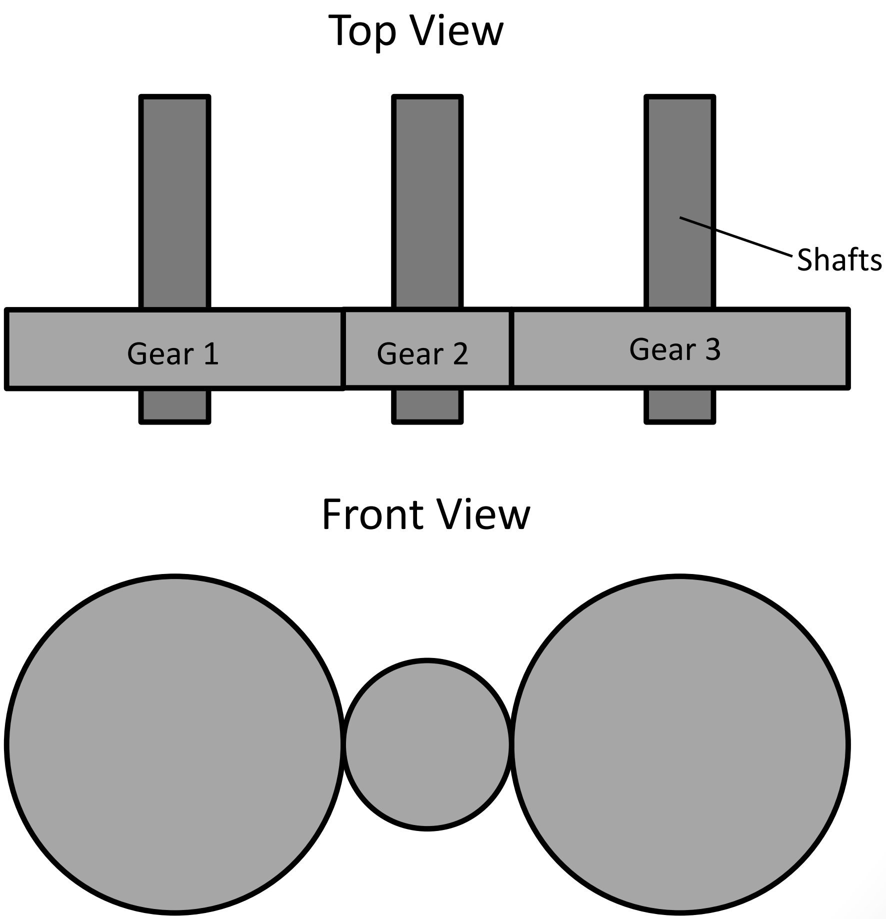
Key Principles

- Gearing
  - Gears fixed on the same shaft (2 and 3) also have the same torque
  - Therefore
    - $\tau_1 \cdot \frac{d_2}{d_1} = \tau_2$
    - $\tau_3 = \tau_4 \cdot \frac{d_3}{d_4}$
    - $\tau_2 = \tau_3$
    - $\tau_1 \cdot \frac{d_2}{d_1} = \tau_4 \cdot \frac{d_3}{d_4}$
    - $\frac{\tau_1}{\tau_4} = \frac{d_1}{d_2} \cdot \frac{d_3}{d_4}$
  - Again, gear ratios from each stage are multiplied



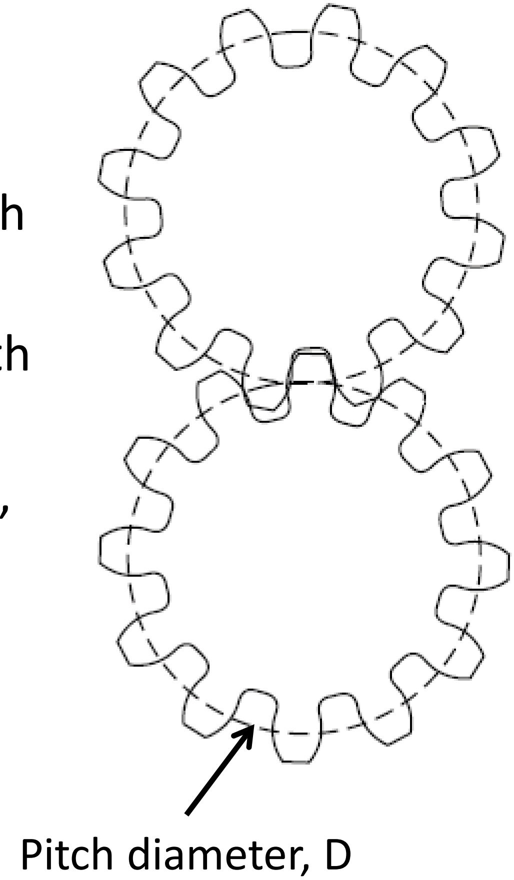
Key Principles

- Gearing
  - Common mistake, **do not** multiply gear ratios from inline gears
    - $\tau_1 \cdot \frac{d_2}{d_1} = \tau_2$
    - $\tau_2 = \tau_3 \cdot \frac{d_2}{d_3}$
    - $\tau_1 \cdot \frac{d_2}{d_1} = \tau_3 \cdot \frac{d_2}{d_3}$
    - $\frac{\tau_1}{\tau_3} = \frac{d_1}{d_2} \cdot \frac{d_2}{d_3} = \frac{d_1}{d_3}$
  - **Not**
    - $\frac{\tau_1}{\tau_3} = \frac{d_1}{d_2} \cdot \frac{d_3}{d_2}$
  - Middle gear is “idle”, it does not effect the overall gear ratio



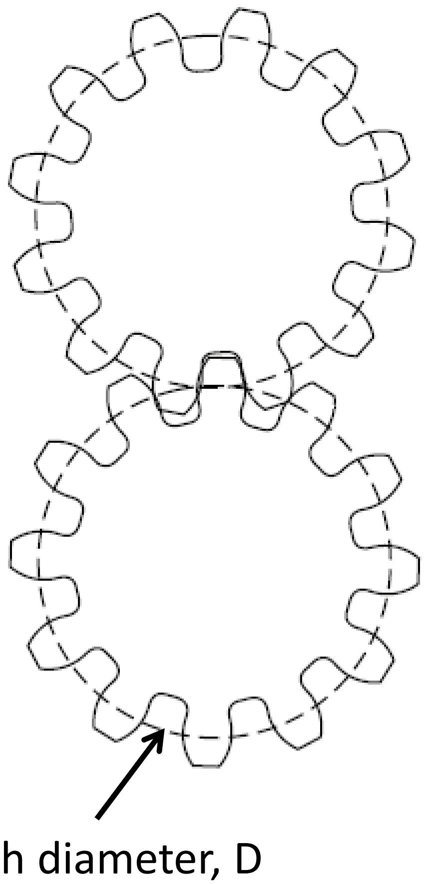
Key Principles

- Gearing
  - In gears, the diameter used to calculate speed and torque ratios is called the pitch diameter
  - It isn't possible to measure this value with callipers
  - Instead, we can use the number of teeth, which can easily be counted



Key Principles

- Gearing
  - So we get,
    - $\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1}$
    - $\frac{\tau_1}{\tau_2} = \frac{N_1}{N_2}$
  - Combining these, we verify how speed (angular velocity) and torque are inversely proportional in gear trains
    - $\boxed{\frac{\tau_1}{\tau_2} = \frac{\omega_2}{\omega_1}}$
  - These equations can also be applied to sprockets & chain and pulleys & belts

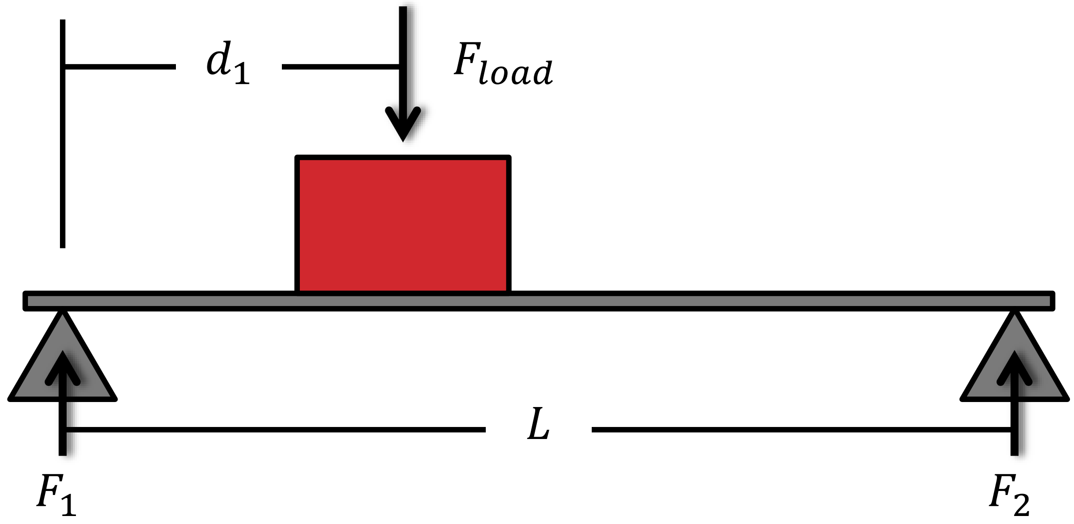


Key Principles

- Force Distribution
  - The force of the load will be distributed across all points supporting the load
    - This is how people are able to lay on a bed of nails without getting hurt

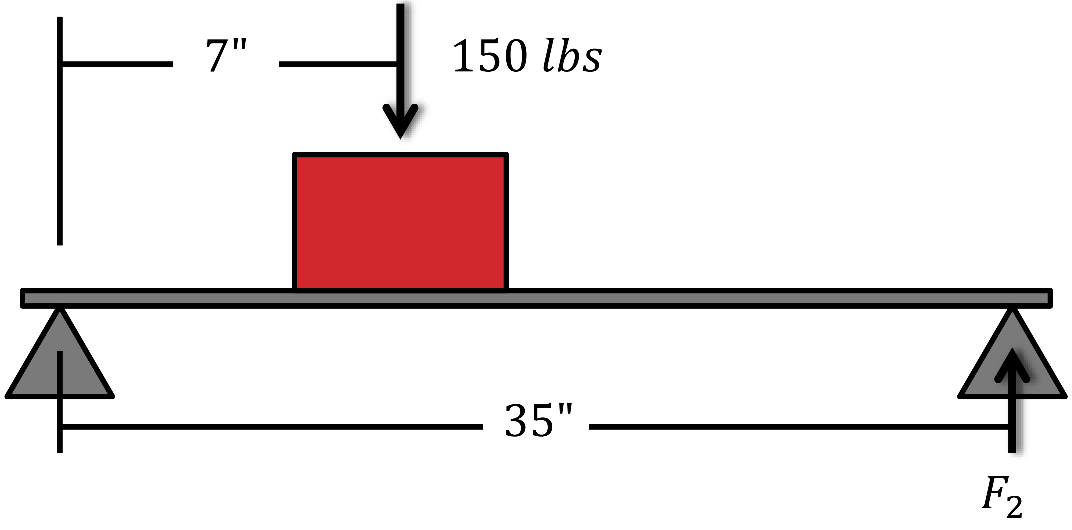
Key Principles

- Force Distribution
  - The amount of force each support provides depends on the distance from the support to the load (torque)
  - The sum of the forces from all supports is equal to the load force



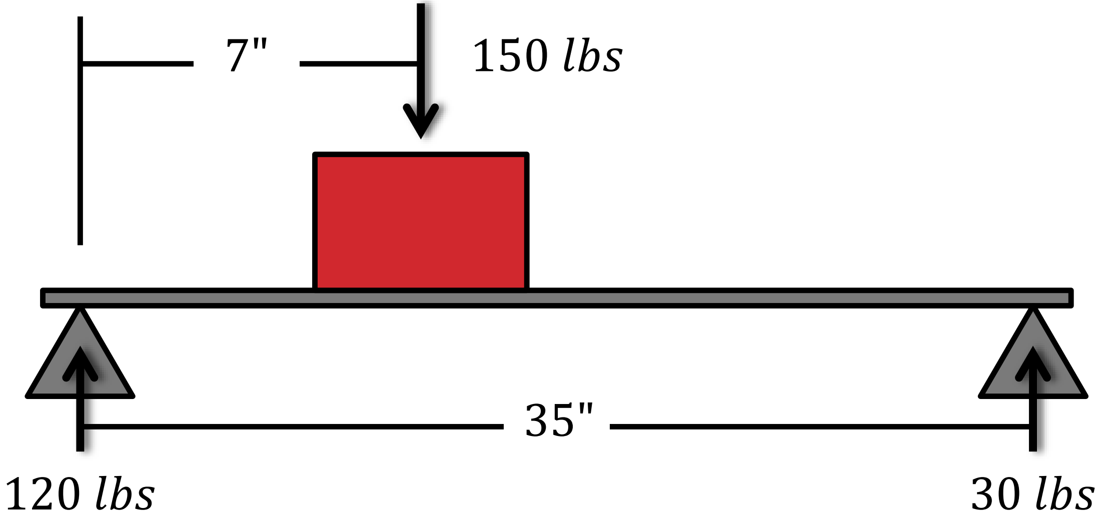
Key Principles

- Force Distribution
  - Consider the support at F_1 to be a fulcrum or pivot
  - Similar to the wheelbarrow problem, we can derive the following equation
    - $F_2 = \frac{d_1}{L} \cdot F_{load}$
    - $F_2 = \frac{7"}{35"} \cdot 150\ lbs = 30\ lbs$



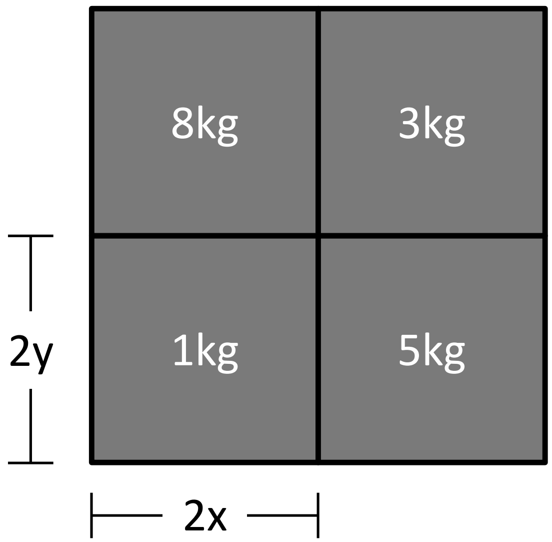
Key Principles

- Force Distribution
  - Since there are only two supports, the total force between them must be equal to the load
    - $F_1 + F_2 = F_{load}$
    - $F_1 = F_{load} - F_2$
    - $F_2 = 150\ lbs - 30\ lbs = 120\ lbs$



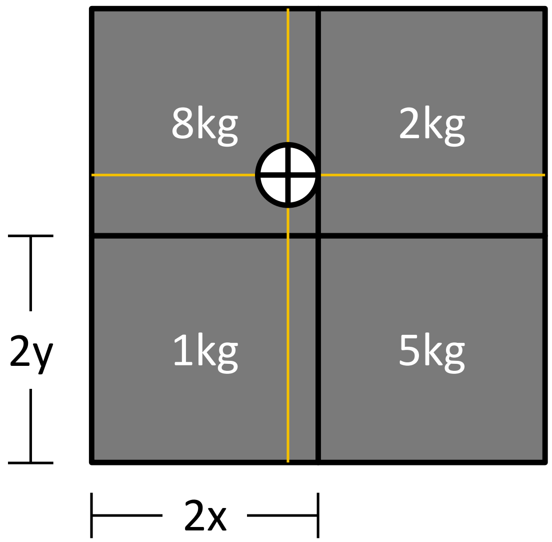
Key Principles

- Centre of Gravity (CoG)
  - Simplifying a object with distributed weight to a centroid location at which the weight of the object acts
  - Found by using a weighted average of the CoG of each part within object



Key Principles

- Centre of Gravity (CoG)
  - $m_{object} \cdot x_{CoG} = \sum m_i \cdot x_i$
  - $(8 + 1 + 2 + 5) \cdot x_{CoG} = 8 \cdot x + 1 \cdot x + 2 \cdot (3 \cdot x) + 5 \cdot (3 \cdot x)$
  - $x_{CoG} = \frac{8+1+2 \cdot 3+5 \cdot 3}{8+1+2+5} \cdot x = \frac{30}{16} \cdot x = 1.88 \cdot x$
  - $y_{CoG} = \frac{8 \cdot 3+1+2 \cdot 3+5}{8+1+2+5} \cdot \mathrm{y} = \frac{36}{16} \cdot y = 2.25 \cdot y$

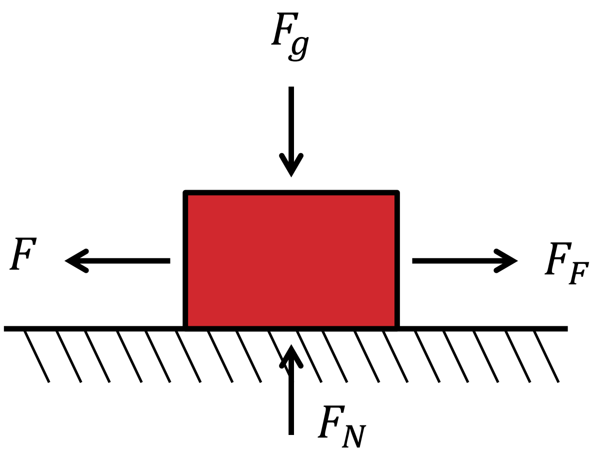


Key Principles

- Friction
  - An equal and opposite force created when an object is slid across a surface
  - Dependant on
    - the normal force (usually the mass of the object)
    - the co-efficient of friction (μ, "mu") between the surface and the object
  - μ is an experimental value, when comparing the μ of different materials, it is best to test yourself
    - The published μ for 2009 wheels was not found to be the actual value
  - Two different co-efficients of friction depending if the object is already moving (kinetic) or not (static)
    - You may have noticed when trying to slide a heavy object, it’s really hard to get started, but once it starts moving, it’s easy to continue moving

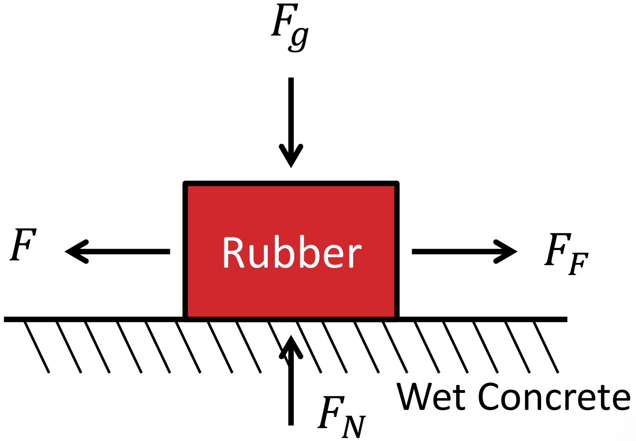
Key Principles

- Friction
  - F = applied force
    - The amount of force used to try and move the object across the surface
  - F_g = gravitational force of object $\left(F_g = m \cdot g\right)$
    - The mass of the object multiplied by gravitational acceleration
    - $F_g = m \cdot g$
    - $g = 9.81 \frac{m}{s^2} = 32.2 \frac{ft}{s^2}$
  - F_F = friction force
    - The amount of force the object and surface are resisting due to friction
  - F_N = normal force
    - the amount of force the surface is providing to support the object



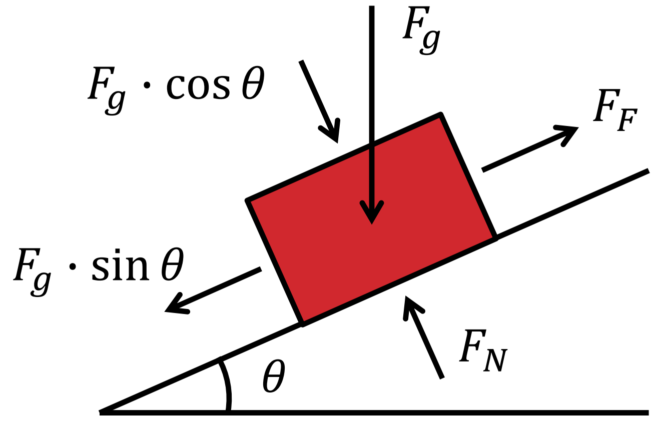
Key Principles

- Friction
  - General friction force equation
    - $F_F = \mu \cdot F_N$
  - In this example, $F_g = F_N$
    - $F_F = \mu \cdot m \cdot g$
  - Static co-efficient of friction between wet concrete and rubber
    - $\mu_{static} \cong 0.3$
  - Rubber object weights 50 lbs (22.7 kg)
    - $F_F = \mu_{static} \cdot m \cdot g$
    - $F_F = 0.3 \cdot 50\ lbs = 15\ lbs$
    - $F_F = 0.3 \cdot 22.7\ kg \cdot 9.81 \frac{m}{s^2} = 66.8\ \mathrm{N}$
  - In order to move this object, you must apply a force greater than 15 lbs or 66.8 N



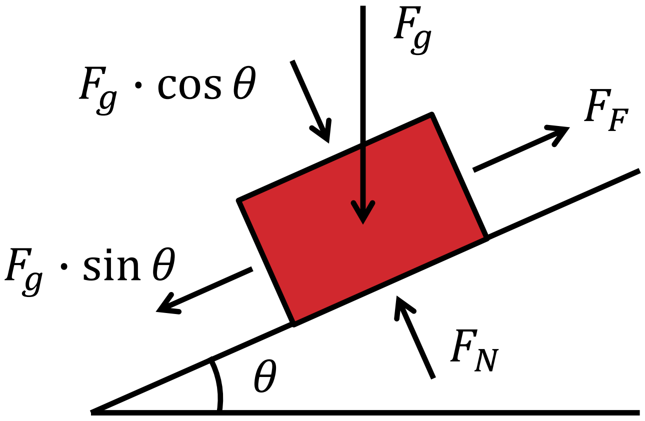
Key Principles

- Friction
  - Testing static co-efficient of friction
  - Place object on surface of interest material
    - ie. place wheels on FRC carpet (or terrain for specific game)
  - Increase the angle of the surface until the object begins to slide
    - Ensure object cannot roll on surface
  - Record the angle (θ, “theta”) at which the object begins to slide
    - $\mu_{static} = \tan\theta$



Key Principles

- Friction
  - When the object beings to slide
    - $F_N = F_g \cdot \sin\theta$
  - Recall the general friction equation
    - $F_F = \mu \cdot F_N$
  - In this example, $F_N = F_g \cdot \cos\theta$
    - $F_g \cdot \sin\theta = \mu_{static} \cdot \cos\theta$
    - $\mu_{static} = \frac{F_g}{F_g} \cdot \frac{\sin\theta}{\cos\theta}$
  - Therefore
    - $\mu_{static} = \tan\theta$



Key Principles

- Review of important equations
  - Relationship between linear and angular velocity
    - $v = \omega \cdot \pi \cdot D$
  - Relationship between torque and force
    - $\tau = F \cdot d$
  - Relating angular velocity, torque, and tooth count
    - $\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1}$
    - $\frac{\tau_1}{\tau_2} = \frac{N_1}{N_2}$
    - $\frac{\tau_1}{\tau_2} = \frac{\omega_2}{\omega_1}$
  - Friction force equation
    - $F_F = \mu \cdot F_N$
  - Measuring static co-efficient of friction
    - $\mu_{static} = \tan\theta$

Applying Principles

- Speed Reduction
- Sprocket Selection
- Chain Selection
- Wheel Size Selection
- Centre of gravity
- Traction
- Turning a tank drivetrain

Speed Reduction

- If you gear your robot too high
  - It won't have enough torque to move (accelerate)
  - If you can accelerate, it will be very difficult to control
- If you gear your robot too low
  - You will have so much torque, your wheels will slip before you reach max power
  - You will move too slow to be effective
- A good robot speed is 8-12 ft/s
- Design your robot so sprockets can be changed easily
  - Start at a slow speed, with practice if the driver gets comfortable, change sprockets to increase speed
- Some teams have successfully gone as high as 18 ft/s or as low as 4 ft/s
  - Require 2 speed gearbox, cannot rely only on 4 or 18 ft/s speed
  - Drivers need a lot of practice to control robots that fast

Speed Reduction

- The CIM motor has an angular velocity of 5310 rpm (+/- 10%)
  - Directly using a 6” wheel would convert to 139 ft/s (> 150 km/h)
- Therefore, you must reduce the angular velocity between the motor and the wheel
  - This can be done with gears, sprockets, or belts
- Generally, most of the reduction is first done with a gearbox (1 or more stages of gear reduction), then sprockets or belts do the rest
- Coupling motors on the same gearbox increases torque but angular velocity does **not** change
  - This will allow you to accelerate faster and push harder but it will not increase your top speed

Speed Reduction

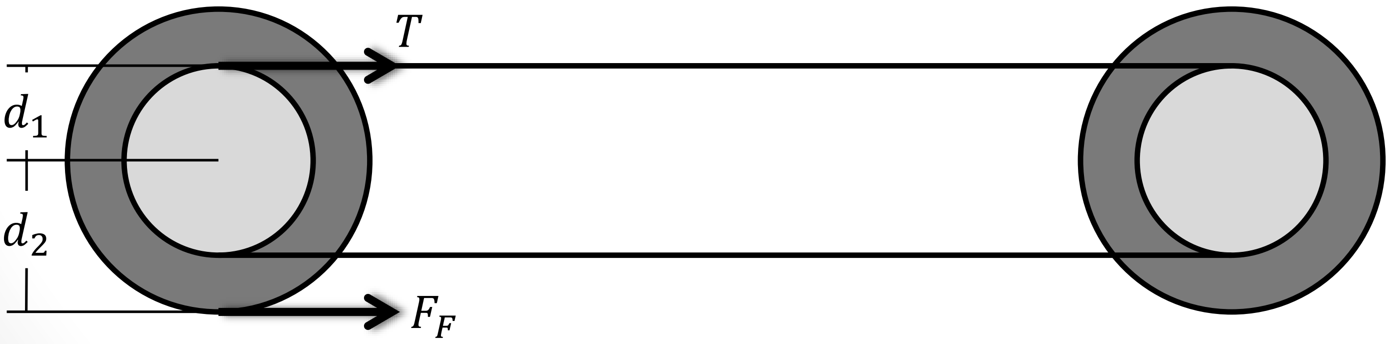
- To create a gear ratio using sprockets, the number of teeth on the output of the gearbox should be different that the number of teeth on a sprocket on the driven wheel
  - A larger sprocket on the wheel will reduce speed and increase torque
    - This is generally what is required to achieve desired speed
  - A larger sprocket on the gearbox output will increase speed and reduce torque
- There should not be a sprocket gear ratio between wheels
  - The number of teeth on the sprockets that connect the wheels should be the same
- The number of teeth on the sprockets connecting the wheels do not have to be the same as the number of teeth on the sprocket connecting the driven wheel to the gearbox

Speed Reduction

- How to convert from motor angular velocity to robot linear velocity
  - $v = \frac{\omega \cdot N_G \cdot D \cdot \pi}{x \cdot N_W \cdot 720}$
    - $\omega = motor\ angular\ velocity\ (rpm)$
    - $x = gearbox\ ratio$
    - $N_G = \#\ of\ teeth\ on\ sprocket\ or\ pulley\ on\ gearbox\ output$
    - $N_W = \#\ of\ teeth\ on\ sprocket\ or\ pulley\ on\ wheel$
    - $D = wheel\ diameter\ (inches)$
    - $v = robot\ linear\ velocity\ \left(\frac{ft}{s}\right)$
  - This equation is very general and does not account for efficiency losses, current, acceleration, etc

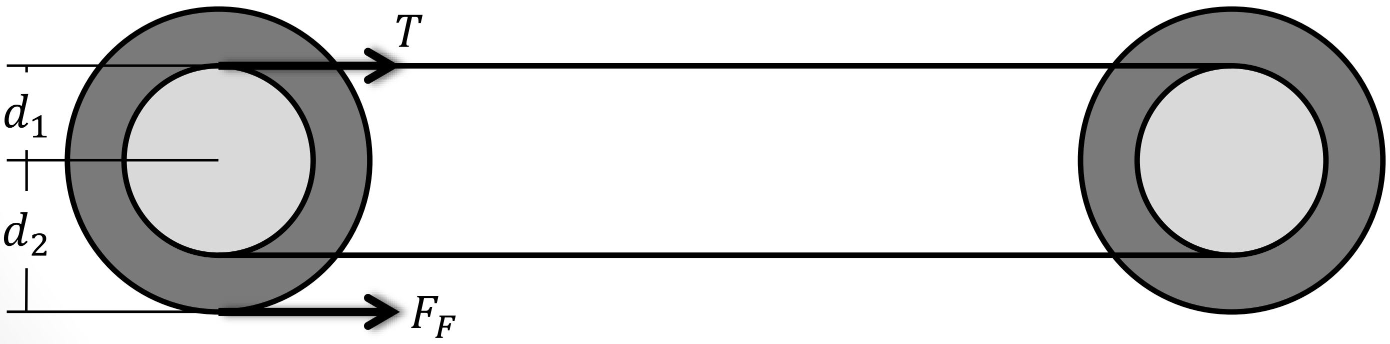
Sprocket Selection

- The amount of tension in the chains is largely effected by sprocket size
- Assuming torque is fixed, a larger sprocket is equivalent to a longer moment arm, and therefore less force (tension)
  - Max torque is dependant on the amount of friction, which is a fixed value
- To minimize tension, choose the largest sprocket that provides enough ground clearance between the playing surface and chain



Sprocket Selection

- The smaller the $\frac{d_2}{d_1}$ ratio, the less tension there will be
  - $d_1 = d_2 - ground\ clearance$
  - If tension is a concern, assuming the desired ground clearance is independent of wheel size, it is best to use a larger wheel size to reduce the above ratio
  - Note: the ground clearance used above may be less than the clearance between the base of the robot and the ground. This is because the chain is driven and may be able to free itself if it contacts an obstacle.



Chain Selection

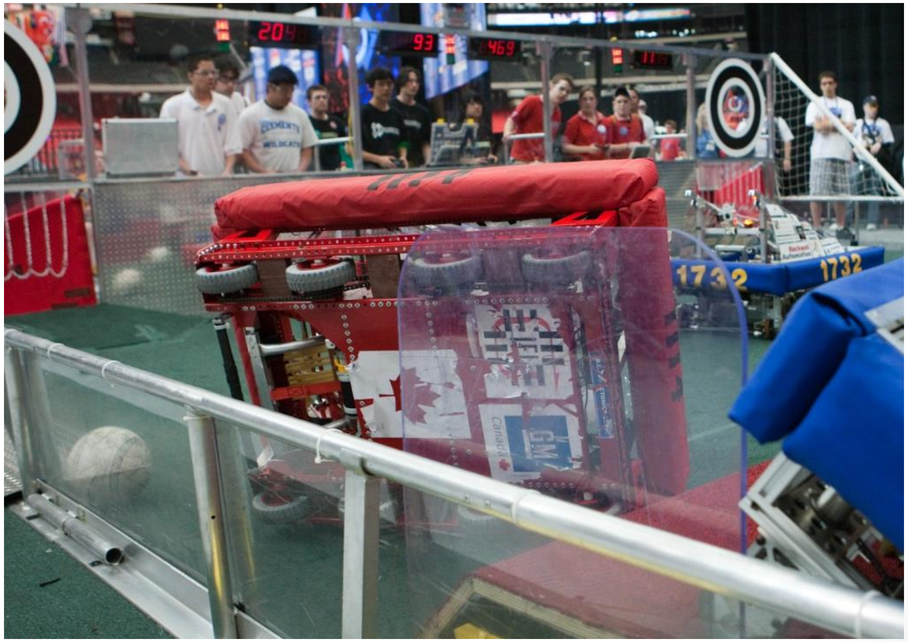
- Two standard sizes used in FIRST
  - ANSI 25: 1/4” pitch, 115 lb working load (McMaster-Carr)
  - ANSI 35: 3/8” pitch, 269 lb working load (McMaster-Carr)
- Chain stretches/wears over time
  - If lengthening is significant chain will skip teeth
    - If this happens, chain will need to be tensioned
- Higher tension causes chain lengthening to occur faster
- If large sprockets are used with 35 chain, tensioning can be avoided
  - If tensioning is not used, it is important to space wheels such that a whole number of chain links are need to span the distance
  - The distance between wheels should be a multiple of the chain pitch
    - If the distance between two wheels is 15.5” when using 35 chain (0.375” pitch), 41.33 links are needs, so 42 links will be used, which totals 15.75”. There will now be 0.25” of slack which is enough for the chain to skip teeth and a tensioning system will be needed to correct this, defeating the purpose of using thick chain and large sprockets. It would be better to use a wheel spacing of 15.375” or 15.75” so a whole number of chain links are needed.

Wheel Size Selection

- Smaller wheel
  - Pros
    - Less gear reduction needed
    - Less weight
      - smaller wheel & sprocket, less chain, less gear reduction
    - Lower CoF
- Large wheel
  - Pros
    - Lower RPM for same linear velocity
      - Less tread wear, less frequent tread replacement
    - Larger sprocket to wheel diameter ratio
      - Less tension on chain → 25 chain may be used without tensioning

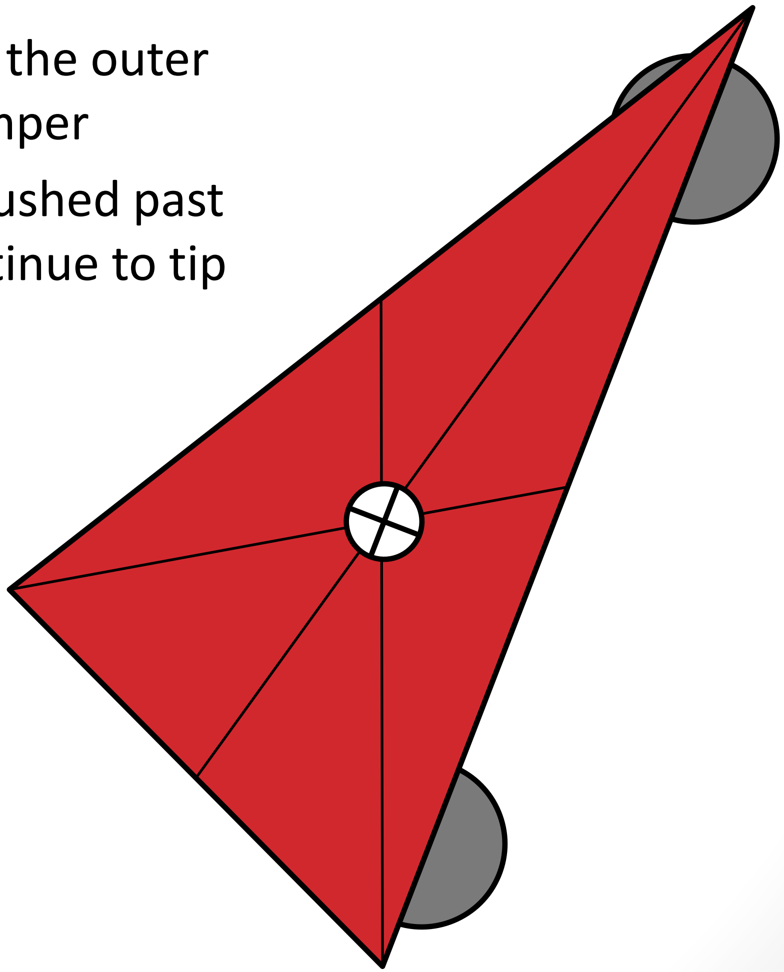
Applying Principles

- Centre of Gravity (CoG)
  - The lower and more centred your centre of gravity
    - The less likely your robot will tip, very important when traversing obstacles
    - The better your robot will “handle” (accelerates and turns smoother)
  - CoG dictates how much force each wheel provides to support the robot
    - This is important for turning and pushing



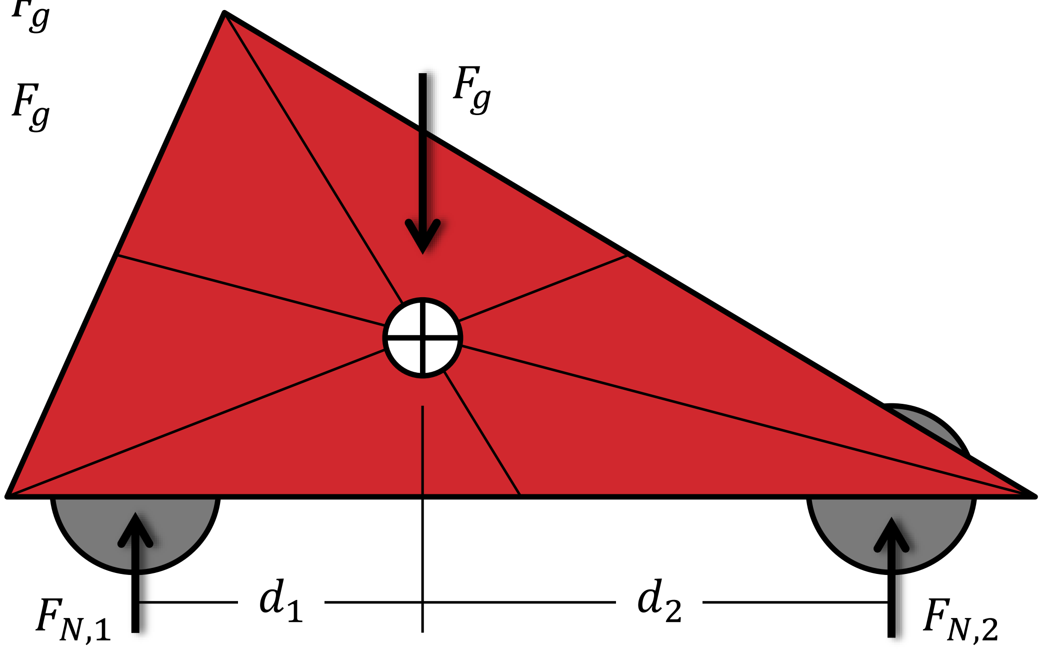
Applying Principles

- Centre of Gravity
  - For tipping, the fulcrum will be the outer edge of the robot frame or bumper
  - Once the Centre of Gravity is pushed past the fulcrum, the robot will continue to tip under its own weight



Applying Principles

- CoG and Force Distribution
  - The closer the centre of gravity to a support, the more normal force the support (wheel) will have
  - From previous analysis, we know
    - $F_{N,1} = \frac{d_2}{L} \cdot F_g$
    - $F_{N,2} = \frac{d_1}{L} \cdot F_g$
    - $\frac{F_{N,1}}{F_{N,2}} = \frac{d_2}{d_1}$



Applying Principles

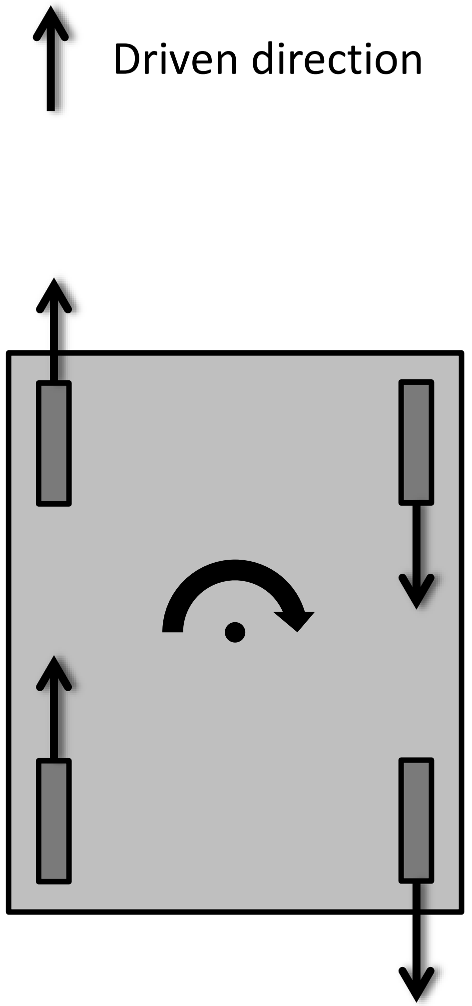
- Traction
  - From friction, we know
    - $F_F = \mu \cdot F_N$
  - If the applied force on an object is greater than the friction force, then the object will slide
    - Therefore if the torque on a wheel creates more force than the friction force, the wheel will slip
    - $\tau = F \cdot d$
    - Max pushing force for each wheel is when $F = F_F$
    - $F_F = \frac{\tau}{d}$
    - If a wheel is not driven, it has no torque
      - Therefore, $F_F = 0$ for un-driven wheels

Applying Principles

- Traction
  - As we just saw, all the wheels of the drivetrain share the robot weight
    - The amount each wheel supports (normal force) may be different
    - The total max drivetrain pushing force is the sum of the max pushing force of each wheel
    - $F_{push} = F_{F,1} + F_{F,2} = \mu_1 \cdot F_{N,1} + \mu_2 \cdot F_{N,2}$
    - Therefore
      - Un-driven wheels reduces pushing force
      - Using a combination of low traction and high traction wheels reduces pushing force

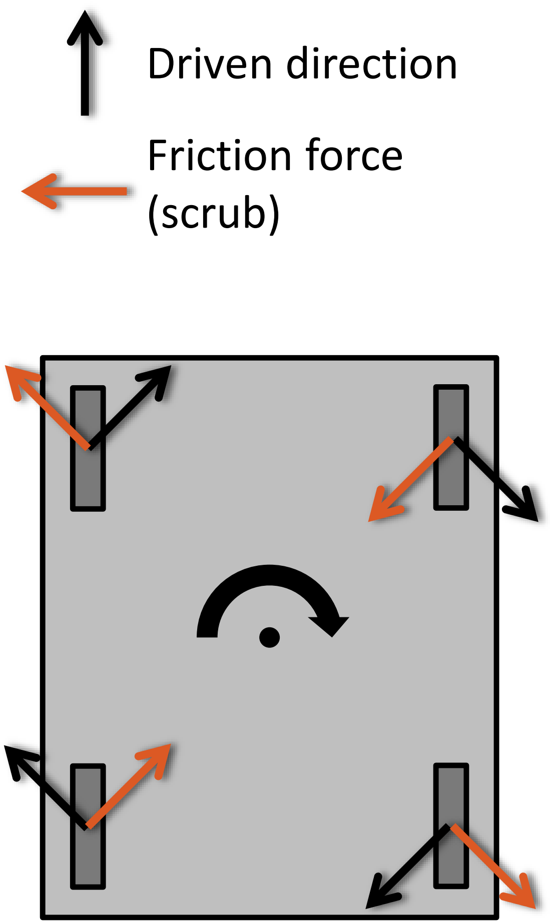
Applying Principles

- Turning a tank drivetrain
  - Drive left and right sides different speeds to turn
  - Drive left and right sides at opposite speeds to "turn on the spot"
  - Location of the "spot" is dependant on wheel material and the CoG



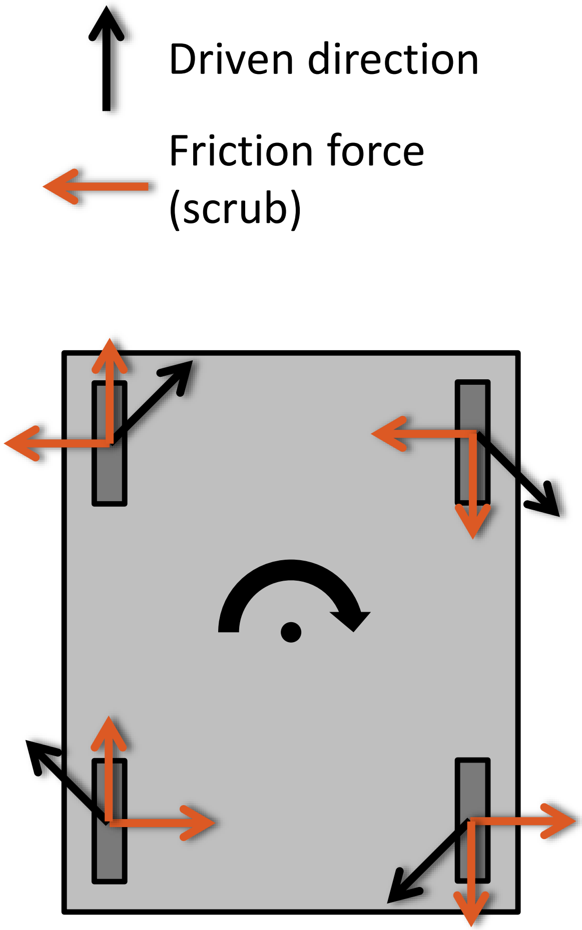
Applying Principles

- Turning a tank drivetrain
  - Since the wheels are not facing the direction the robot is trying to turn there will be some scrub
    - Scrub is the amount of friction resisting the turning motion
  - This scrub is useful when being defended or defending



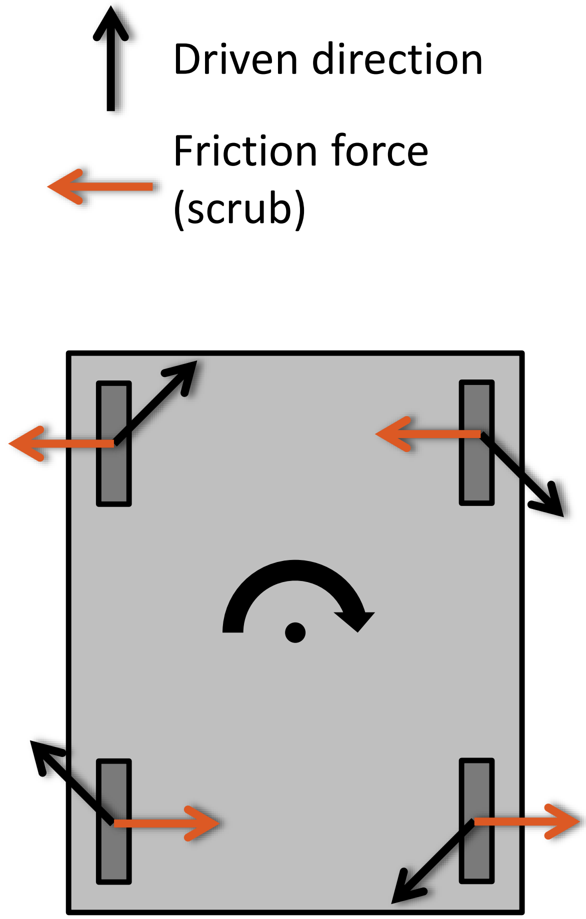
Applying Principles

- Turning a tank drivetrain
  - To ease analysis, we resolve the friction force into x (horizontal) and y (vertical) components
  - Since wheels are able to rotate, the friction force perpendicular to the axis of rotation of the wheels is 0



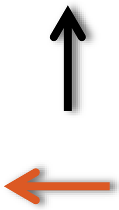
Applying Principles

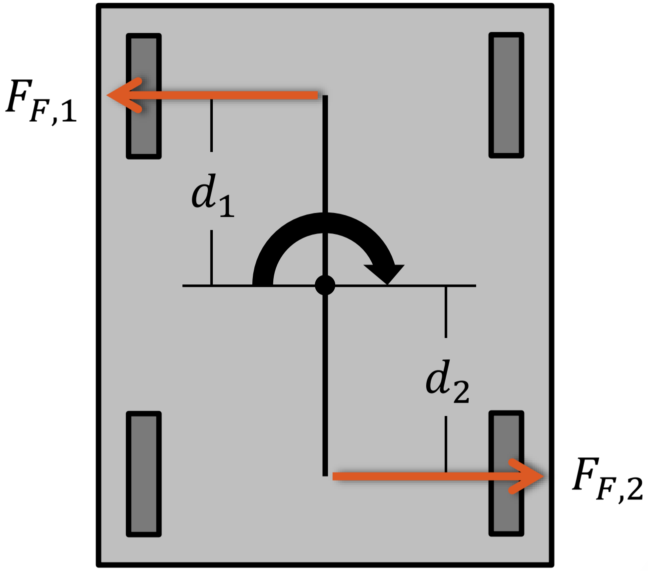
- Turning a tank drivetrain
  - Assuming pairs of wheels (one left and one right wheel)
    - Have the same traction material
    - Are inline (distance from centre of robot is equal)
  - The forces can be simplified



Applying Principles

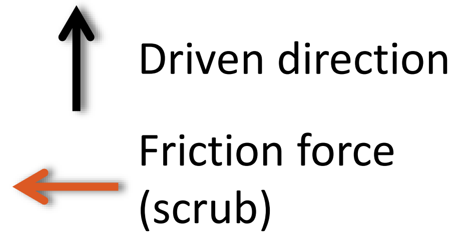
- Turning a tank drivetrain
  - We get a torque diagram
  - The pivot point of the torque arm is not fixed, it will be located where the torques balance
    - $\tau_1 = \tau_2$
    - $F_{F,1} \cdot d_1 = F_{F,2} \cdot d_2$
    - $\frac{d_1}{d_2} = \frac{F_{F,2}}{F_{F,1}}$
    - $\frac{d_1}{d_2} = \frac{\mu_2 \cdot F_{N,2}}{\mu_1 \cdot F_{N,1}}$
    - $d_1 + d_2 = L$

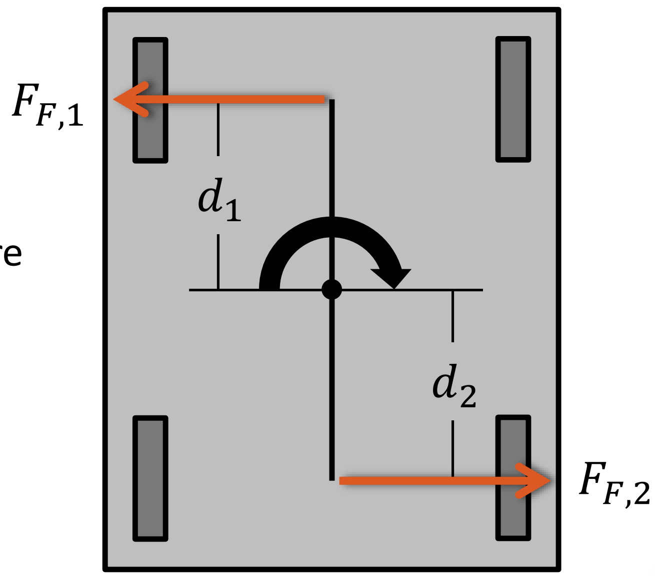




Applying Principles

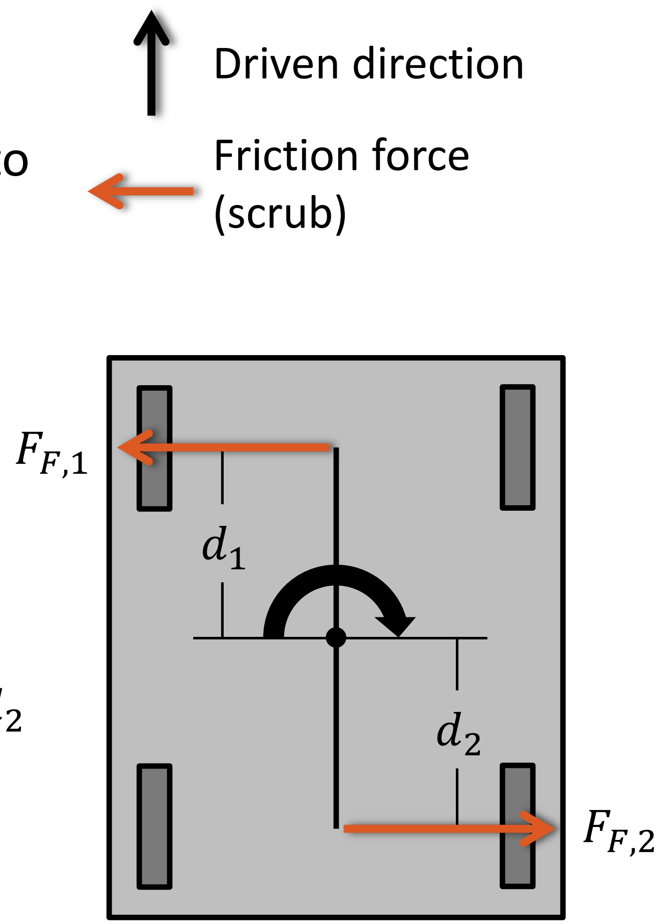
- Turning a tank drivetrain
  - $\frac{d_1}{d_2} = \frac{\mu_2 \cdot F_{N,2}}{\mu_1 \cdot F_{N,1}}$
  - What does this mean?
    - If $\mu_2 > \mu_1$ then $d_2 < d_1$
      - The drivetrain will turn on a "spot" closer to the higher traction wheels
    - If $F_{N,2} > F_{N,1}$ then $d_2 < d_1$
      - The drivetrain will turn on a "spot" closer to the wheels that support more weight





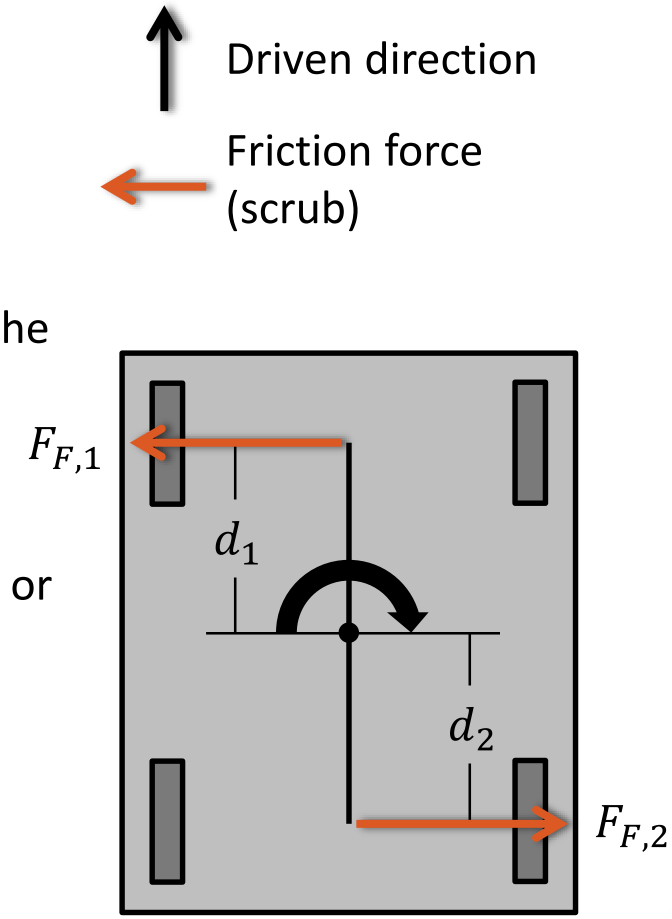
Applying Principles

- Turning a tank drivetrain
  - How much friction force do the wheels need to over come in order to turn?
    - $\tau_{driven} = \tau_1 + \tau_2$
    - $\tau_{driven} = F_{F,1} \cdot d_1 + F_{F,2} \cdot d_2$
  - Recall
    - $\frac{d_1}{d_2} = \frac{F_{F,2}}{F_{F,1}}$ or $d_1 = \frac{F_{F,2}}{F_{F,1}} \cdot d_2$
  - Combine
    - $\tau_{driven} = F_{F,1} \cdot \left(\frac{F_{F,2}}{F_{F,1}} \cdot d_2\right) + F_{F,2} \cdot d_2$
    - $\tau_{driven} = 2 \cdot F_{F,2} \cdot d_2$
  - Also
    - $\tau_{driven} = 2 \cdot F_{F,1} \cdot d_1$



Applying Principles

- Turning a tank drivetrain
    - $\tau_{driven} = 2 \cdot F_{F,1} \cdot d_1$
    - $\tau_{driven} = 2 \cdot F_{F,2} \cdot d_2$
- What does this mean?
    - The smaller you make $F_{F,1}$ or $F_{F,2}$, the less force is needed to over come friction
    - $F_F = \mu \cdot F_N$
    - Therefore must reduce μ_1, μ_2, $F_{N,1}$, or $F_{N,2}$ to ease turning



Applying Principles

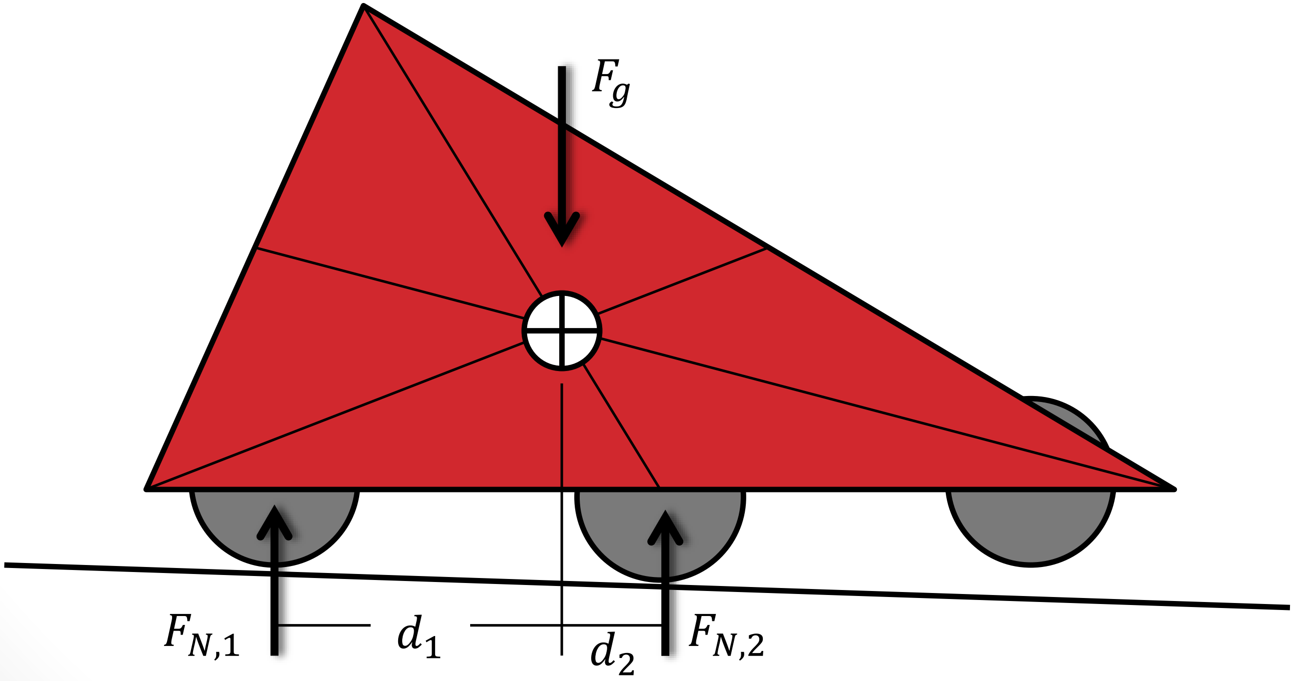
- Turning a tank drivetrain
  - Often it requires too much power to turn 4 wheel drivetrains due to friction force
    - $\tau_{driven} = 2 \cdot \mu_i \cdot F_{N,i} \cdot d_i$
  - How can this be over come?
    - Reduce $F_{N,1}$ or $F_{N,2}$
      - Means shifting CoG to one end
      - May not be able to shift far enough to be effective
      - Increase likelihood of tipping
    - Reduce μ_1 or μ_2
      - Means using low traction material on one set of wheels
      - Lose traction for pushing
    - Reduce d_1 and d_2 (reduce L)
      - Wide drivetrains are difficult to navigate through narrow spaces
      - May need length for robot functions
    - What about combining points 1 and 3?

6 Wheel Tank Drive

- Add a set of wheels in the centre of the robot, slightly lower than the outer wheels
  - What does this do?
    - Divides the effective wheel base (L) in half
      - Turns the robot into two 4WD sections, depending which half the CoG is on, whether the robot is accelerating/decelerating, or pushing or pulling a game piece or opponent
    - Reduces F_N on outer wheels
      - The closer the CoG is to the middle of the robot, the lower F_N (and therefore F_F) will be on the outer wheels
  - The result?
    - A very smooth turning robot

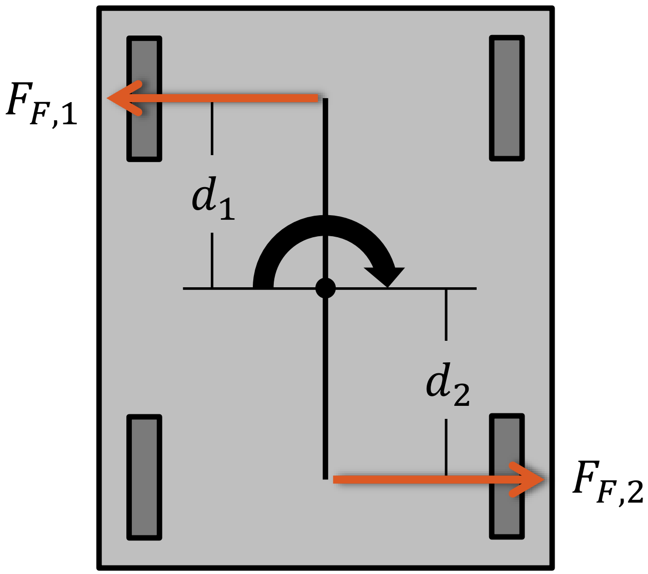
6 Wheel Tank Drive

- Again we get
  - $\frac{F_{N,1}}{F_{N,2}} = \frac{d_2}{d_1}$
- However, this time d_2 should be much less than d_1
  - Therefore $F_{N,1}$ should be much less than $F_{N,2}$



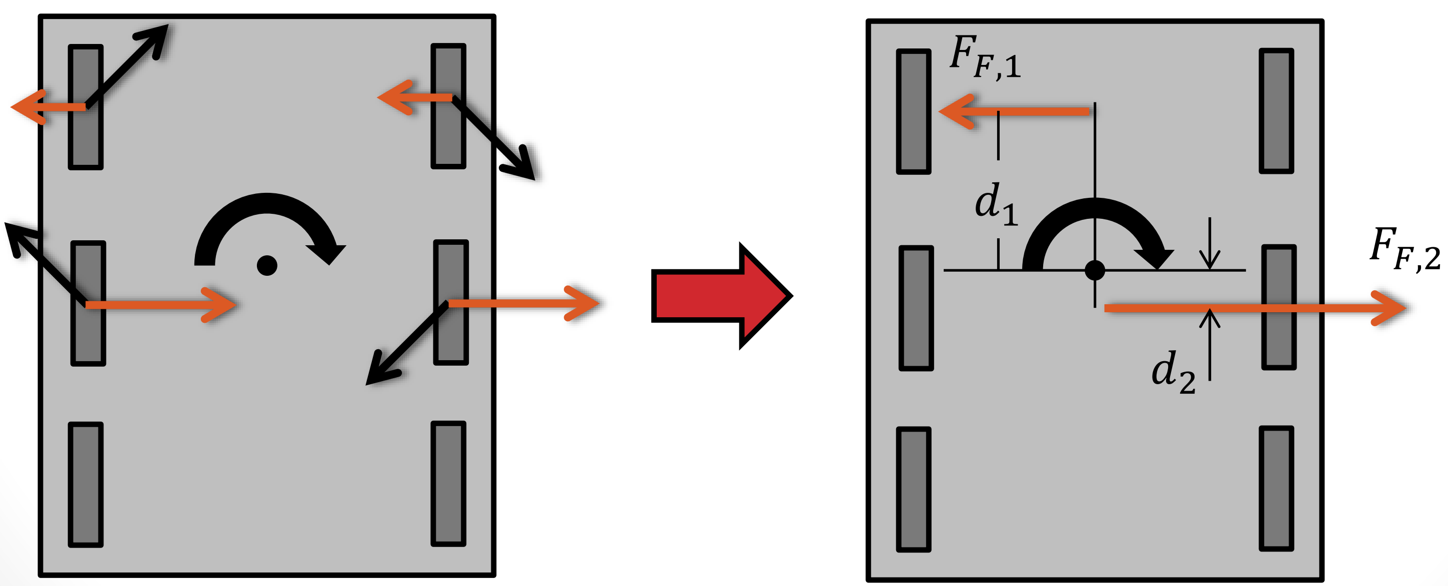
6 Wheel Tank Drive

- Recall from 4WD
  - With 4WD, the closer the CoG was to the middle the closer the robot rotated on its centre
  - However, the closer the CoG was to the middle, the more force was required to overcome friction from the wheels
  - $\frac{d_1}{d_2} = \frac{\mu_2 \cdot F_{N,2}}{\mu_1 \cdot F_{N,1}} = \frac{F_{F,2}}{F_{F,1}}$
  - $\tau_{driven} = 2 \cdot F_{F,1} \cdot d_1$
  - $\tau_{driven} = 2 \cdot F_{F,2} \cdot d_2$



6 Wheel Tank Drive

- The same equations apply to 6WD drive, BUT
  - The closer the CoG is to the middle the closer the robot rotates on its centre
  - AND, the closer the CoG is to the middle, the **<u>less</u>** force is required to overcome friction from the wheels

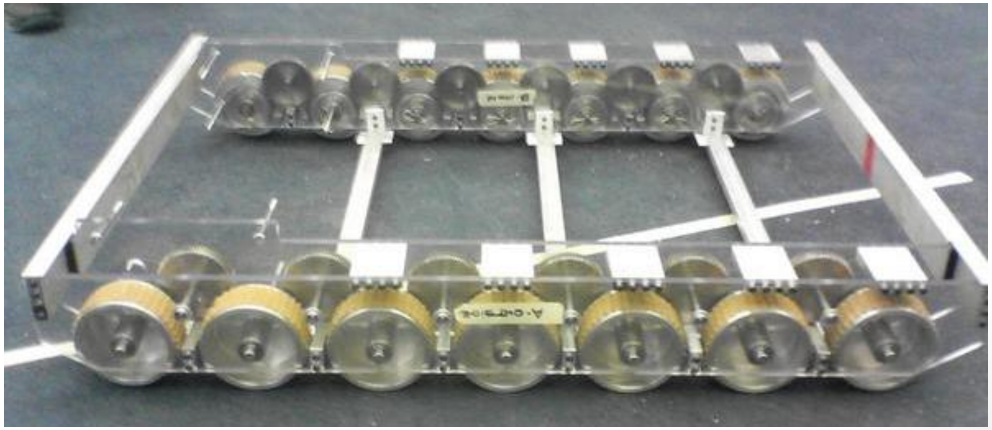


Comparing Tank Drivetrains

- Key features to keep in mind
  - All wheels must be powered for full pushing potential
  - Using lower traction wheels to ease turning will reduce pushing potential
  - Long wheel bases are difficult to turn

Comparing Tank Drivetrains

- All tank drivetrains have
  - Pairs of wheels
  - Left & Right wheels driven independently
  - All motors used to propel robot
- Key variances
  - Number of speeds
  - Type(s) of wheels
  - Number of wheels
    - 2, 4, 6, 8, or more



Comparing Tank Drivetrains

- 2 Wheel Drive (2WD)
  - 2 wheels are driven
  - Unless it is a segway (self-balancing), other methods of supporting the drivetrain are required
    - Casters
    - Slide blocks
    - Low traction, un-driven wheels
  - Advantages
    - Turning is relatively resistance free (no scrub)
  - Disadvantages
    - Since there is no scrub
      - It is difficult to control
      - Easily defended
    - Weight is distributed to supports that do not provide propulsion
      - Lower pushing force
    - Depending on setup, may not turn on centre (may be advantage)

Comparing Tank Drivetrains

- 4 Wheel Drive (4WD)
  - Long wheel base
  - Requires one set of lower traction wheels and/or skewed CoG in order to turn smoothly
  - Advantages
    - ???
  - Disadvantages
    - If lower traction wheels are used to aid turning
      - Lower pushing force
      - Will not turn on centre (may be advantage)
    - If CoG is skewed to aid turning
      - Higher potential for tipping
      - Will not turn on centre (may be advantage)

Comparing Tank Drivetrains

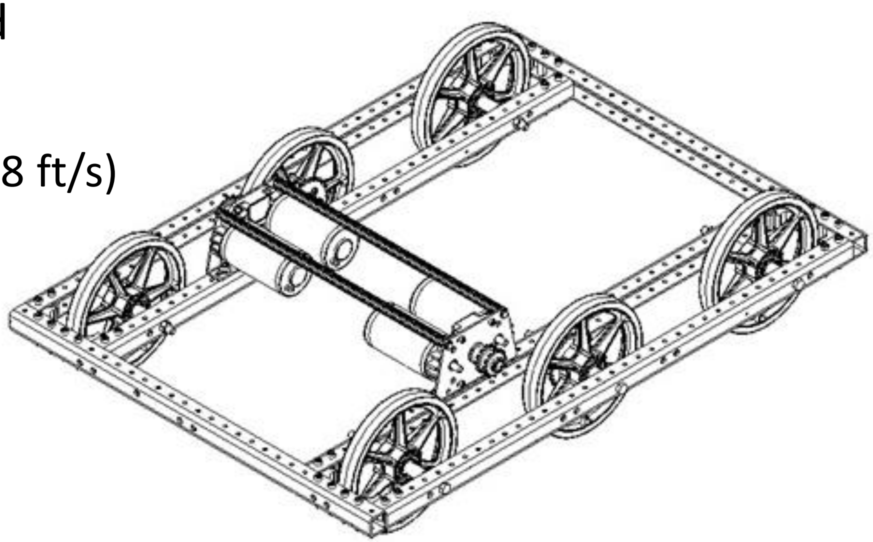
- 6 Wheel Drive (6WD)
  - Long wheel base split in two short wheel bases
  - Middle set of wheels lowered
  - Advantages
    - Great turning with high traction wheels (assuming sufficient drop for surface/wheel and a centred CoG)
    - Full pushing force potential
  - Disadvantages
    - Not great at traversing some types of obstacles
      - Could be said for any drivetrain, very dependant on specific situation
    - Extra set of wheels adds weight

Comparing Tank Drivetrains

- 8 Wheel Drive (8WD) and beyond
  - Advantages/disadvantages are specific to game
  - Advantages generally involve ability to traverse obstacles

Standard Kit of Parts Drivetrain

- 2011 KOP Drivetrain
  - 6WD with dropped center wheel
  - 2 out of 6 wheels are driven
  - Uses 8” FIRST Kit of Parts Wheels
  - Outer wheel holes spaced perfectly for 3/8” chain
    - No tensioners required
  - Has holes for 8WD if required
  - Uses CIMple boxes
    - Geared to drive very fast (>18 ft/s)
    - Gearbox sprocket = 12T
    - Wheel sprocket = 26T
  - Overall, very good drivetrain



Kitbot on Steriods

- Chain all 6 wheels together
  - Full pushing potential
- Replace 8” KoP wheels with 6” AndyMark or VEX Pro traction wheels
  - Higher traction
  - Smaller diameter
    - Requires less sprocket reduction
    - Lower CoG
- Add base plate for rigidity
- Change gear ratio to something a bit more manageable
  - Wheel sprocket
    - 36T → 9.9 ft/s
    - 32T → 11.1 ft/s
    - 30T → 11.9 ft/s
    - 28T → 12.7 ft/s
    - 26T → 13.7 ft/s

- Other potential upgrades
  - Replace CIMple Boxes with 2 speed gearbox
    - Will need to recalculate wheel and gearbox sprockets

Resources

- ChiefDelphi
  - http://www.chiefdelphi.com/forums/portal.php?
    - Most popular and active FIRST forum
- VEX Pro
  - http://www.vexrobotics.com/products/vexpro
    - Supplies victor motor controller
    - Motors, wheels, sprockets, bearings, motor controllers
- AndyMark
  - http://www.andymark.com
    - Supplies the kit of parts drivetrain
    - Motors, wheels, sprockets, bearings, hubs, gearboxes
- Simbotics Website
  - www.simbotics.org
    - Many useful presentations
    - Past robot fact sheets
    - Photos and videos
- Email: benjamin.bennett0@gmail.com