CS 188 Robotics Week 1

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Robots

What is a robot

- "A robot is defined as intelligence embodied in an engineered construct, with the ability to process information, sense, plan, and move within or substantially alter its working environment.
- Here intelligence includes a broad class of methods that enable a robot to solve problems or to make contextually appropriate decisions and act upon them.
- Therefore, the following count as robots:
  - Roombas
  - Automatic sliding doors (which may use facial recognition, or just a simple proximity sensor)
  - Suprisingly, "robotic arms" used in assembly lines may not be considered robots, because they do not process information or take stimuli from the environment. They only follow a preprogrammed routine over and over again.

Robotics

- Robots must be able to move (physically), or interact with its environment in some way. There are three sectors of robotics:
  - **Kinematics**: the study of motion *without* considering forces or torques
  - **Dynamics**: the study of motion considering the forces and torques that caused it.
  - **Control**: how to execute the desired motion
  - **Perception**: how to understand the world using sensors
  - **Planning**: how to reach a goal

Course Objectives

- Develop a foundational understanding of *kinematics, dynamics, and control* for modeling and managing robotic motion
- Become familiar with *sensors and pereption algorithms* to interpret environmental data for robotic decision-making
- Understand principles of *state estimation*, as well as *task and motion planning*, to enable reliable and efficient robot behaviors.
- Explore basic ideas of *AI in robotics*, including imitation learning and human-robot interactions, for advanced autonomous capabilities.
- Gain *hands-on experience* in simulation tools to design, test, and refine robitic systems in a virtual environment

- Reflect on the *ethical implications* of robotics, fostering responsible development and deployment of robotic technologies

Designing a Robot

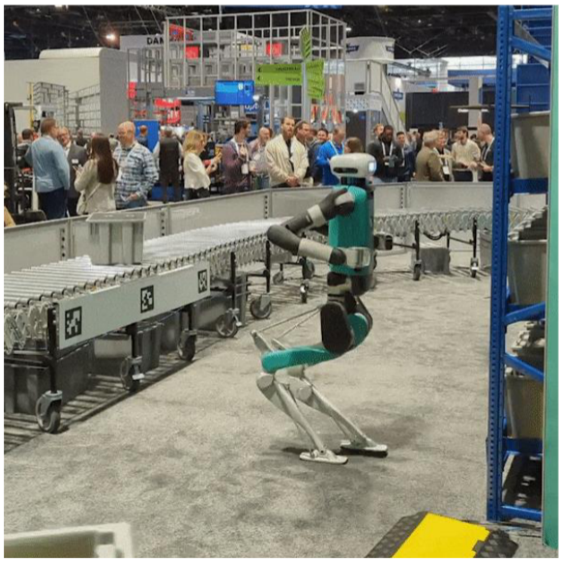
Considerations:

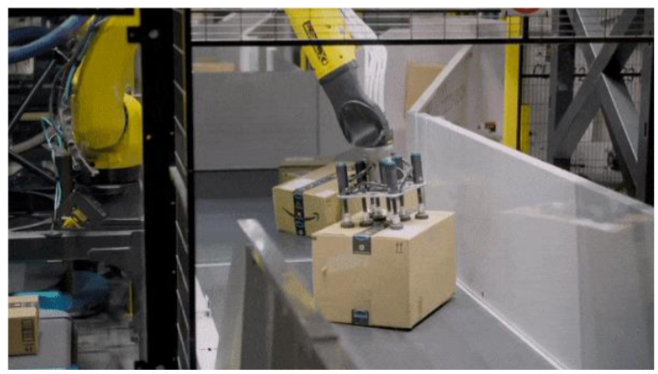
1. Tasks and Operating Environments
    - Define specific tasks the robot will perform.
    - Analyze working environments: indoor/outdoor, structured/unstructured, temperature, terrain, obstacles, etc.
2. Hardware Design
    - Mechanical Structure: Chassis, joints, degrees of freedom
    - Actuators: Motors, servos, pneumatic or hydraulic systems
    - Power System: Battery type, power efficiency, backup options
3. Firmware and Embedded Systems
    - Computing Units: Microcontrollers, onboard processors
    - Sensor integration: Cameras, IMUs, LiDAR, GPS, force sensors
    - Communication Interfaces: Wired/wireless protocols (e.g., I2C, SPI, UART, CAN, Wi-Fi, Bluetooth)
4. Software Architecture
    - Control Algorithms: Motion planning, PID control, pathfinding
    - Autonomy and Intelligence: SLAM, AI/ML models, obstacle avoidance
    - User Interface: Remote control, dashboards, or autonomous modes.

Where are we?

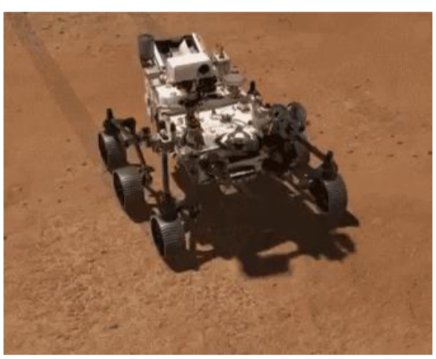
Logistics and Warehouse Robots

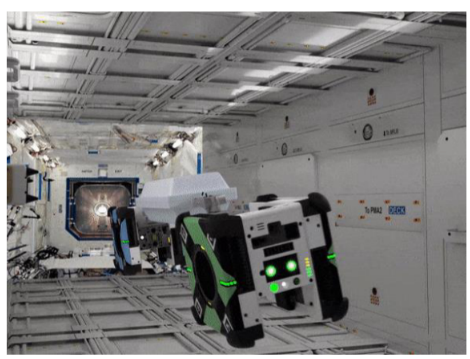
Space Robots



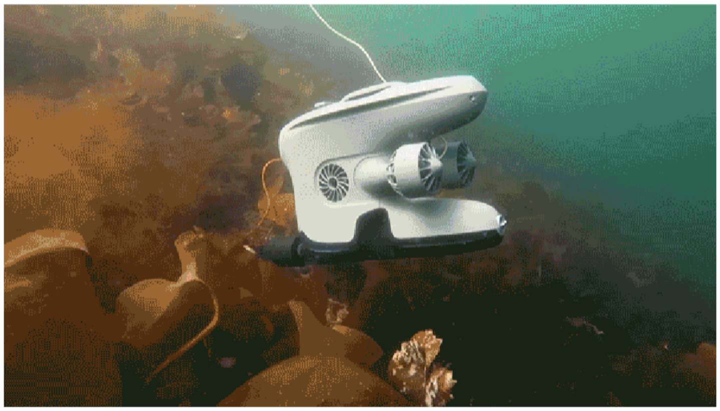


Deepsea Robots





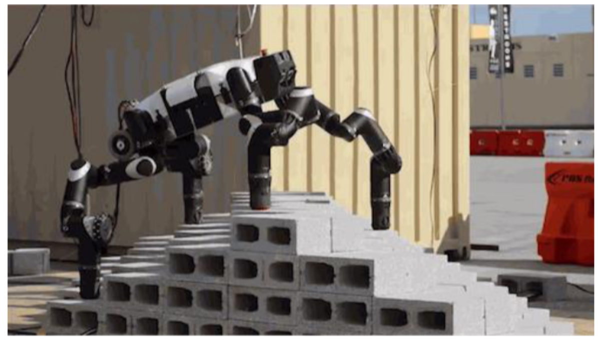
Healthcare and Medical Robots (?)



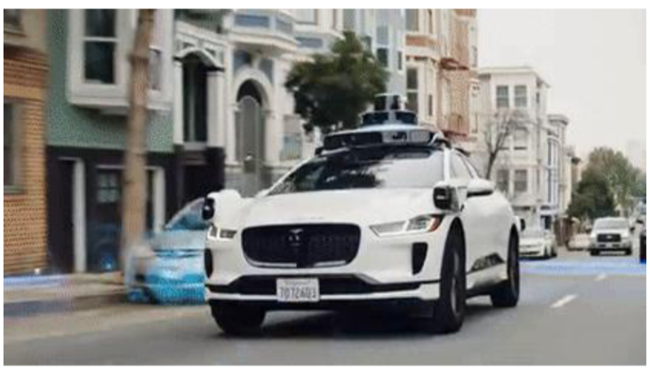
Agricultural Robots

Disaster Response Robots

Service and Hospitality Robots



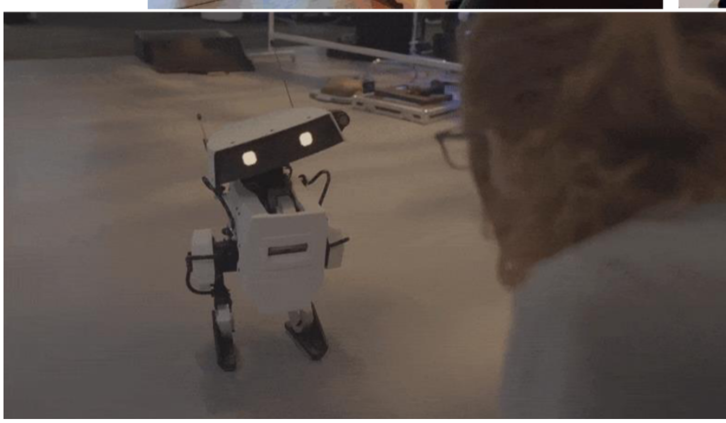
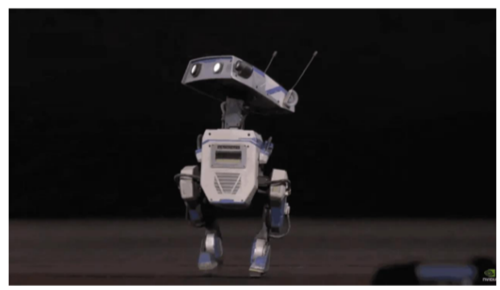
Education, Entertainment, and Companion Robots



Humanoids | Tesla Optimus, Unitree H1, 1x, Figure





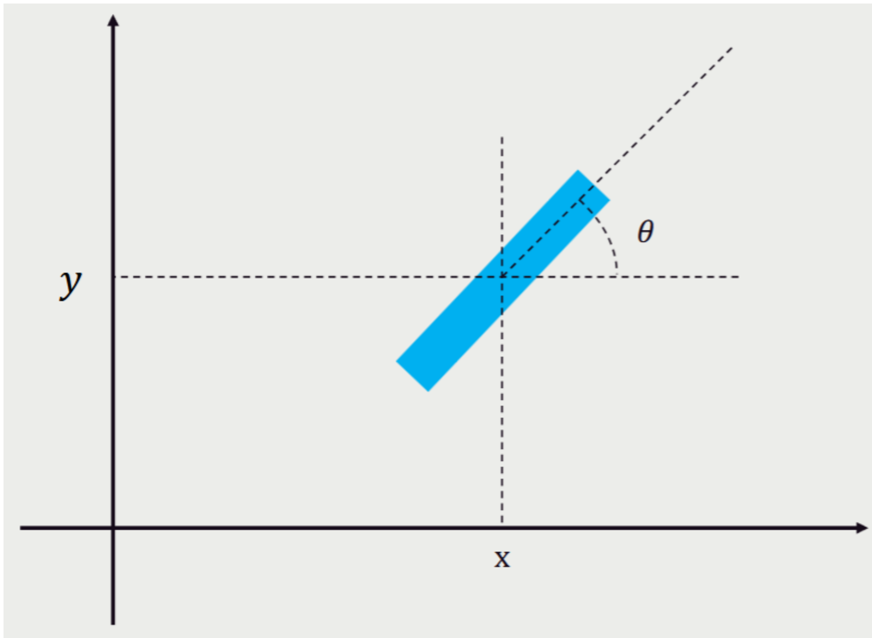
Robot Operating System

Robot operating system (ROS) is

- a **middleware**: it sits between your robot's hardware and your application logic.
- A collection of **tools, libraries, and conventions** to help you build complex and robust robot behavior.
- A **communication system**: It allows different parts of a robot (sensors, motors, processors, etc.) to talk to each other using a publisher/subscriber model.

How do we describe the state of the robot?

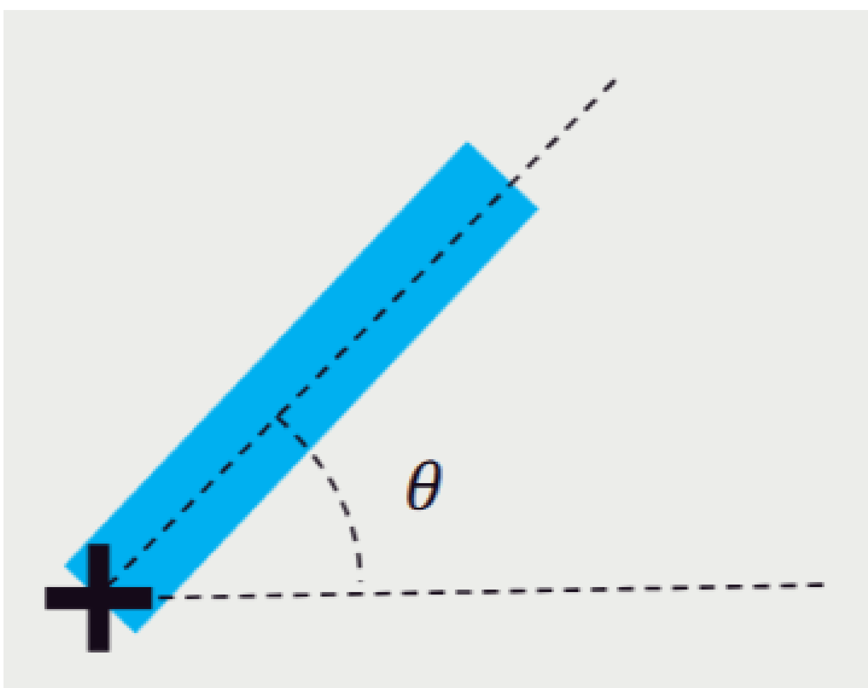
Rigid Body in 2D space:



How many variables do we need to fully describe the configuration of this **rigid body** in 2D?

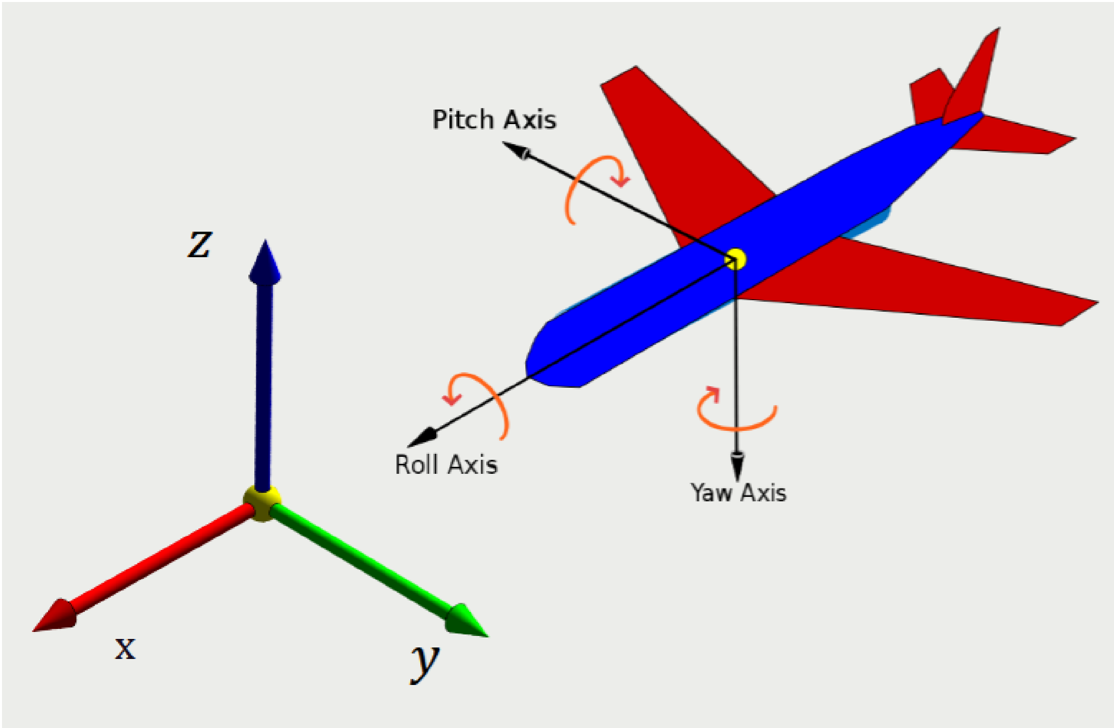
- Answer: 3. (x, y, θ)

What if an endpoint is fixed?



- Answer: 1. (θ)

Rigid Body in 3D space:

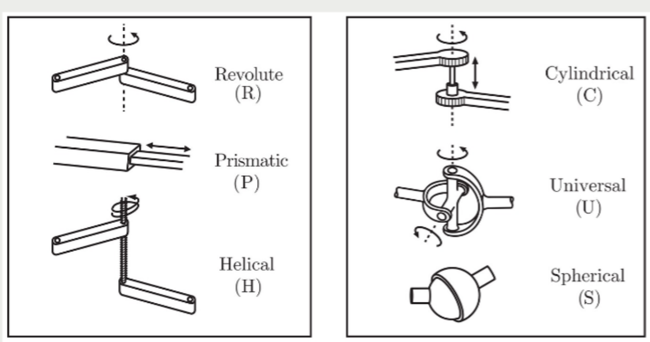


How many DoF does it have?

- $6 = 3$ for position $+ 3$ for orientation

Joints and DoF

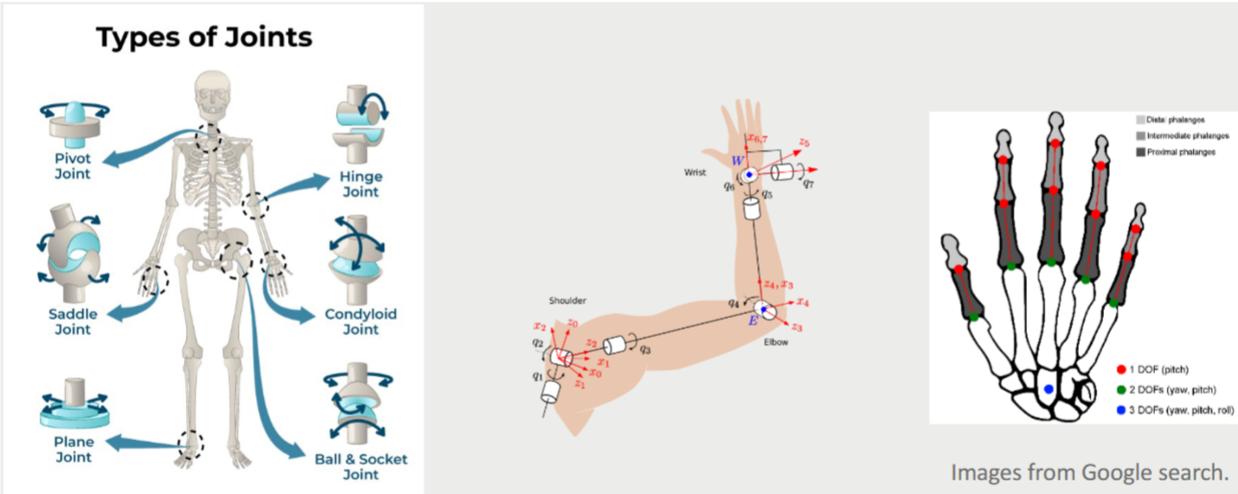
Common Joints



Joint type	dof f	2D robot Constraints c between two planar rigid bodies	3D robot Constraints c between two spatial rigid bodies
Revolute (R)	1	2	5
Prismatic (P)	1	2	5
Helical (H)	1	N/A	5
Cylindrical (C)	2	N/A	4
Universal (U)	2	N/A	4
Spherical (S)	3	N/A	3

MODERN ROBOTICS
Kevin M. Lynch and Frank C. Park May 3, 2017

How many DoF do you have?



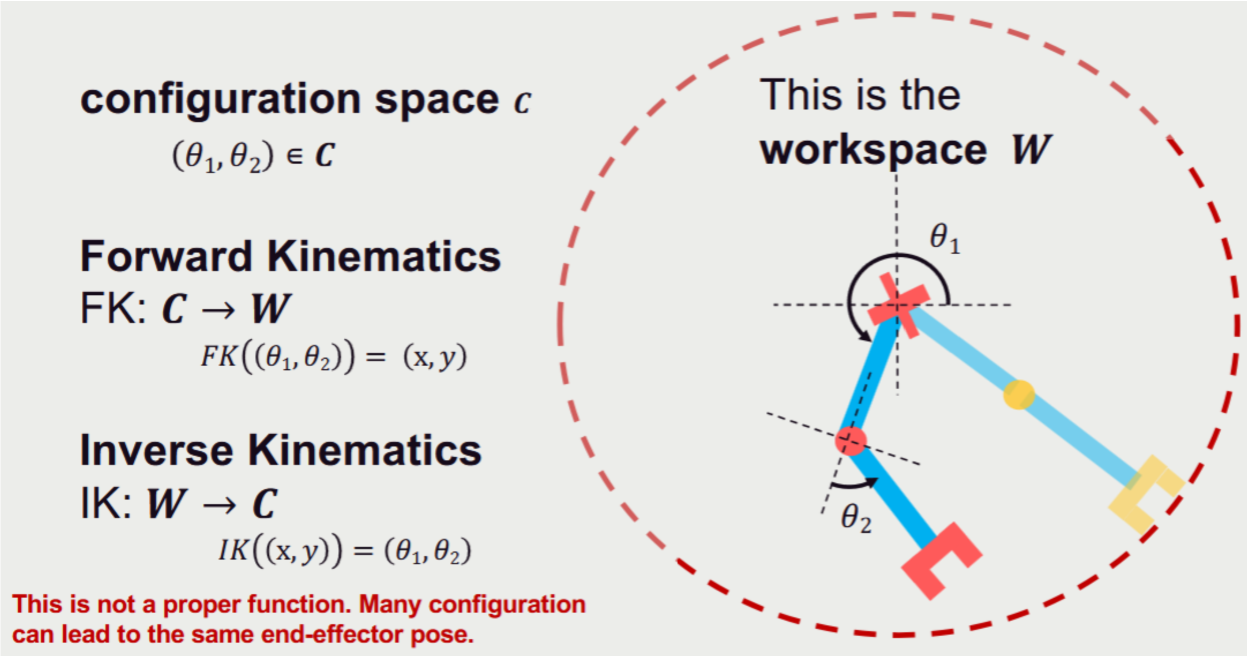
Whole body: 30 DoF (major joints)

Grübler's Formula

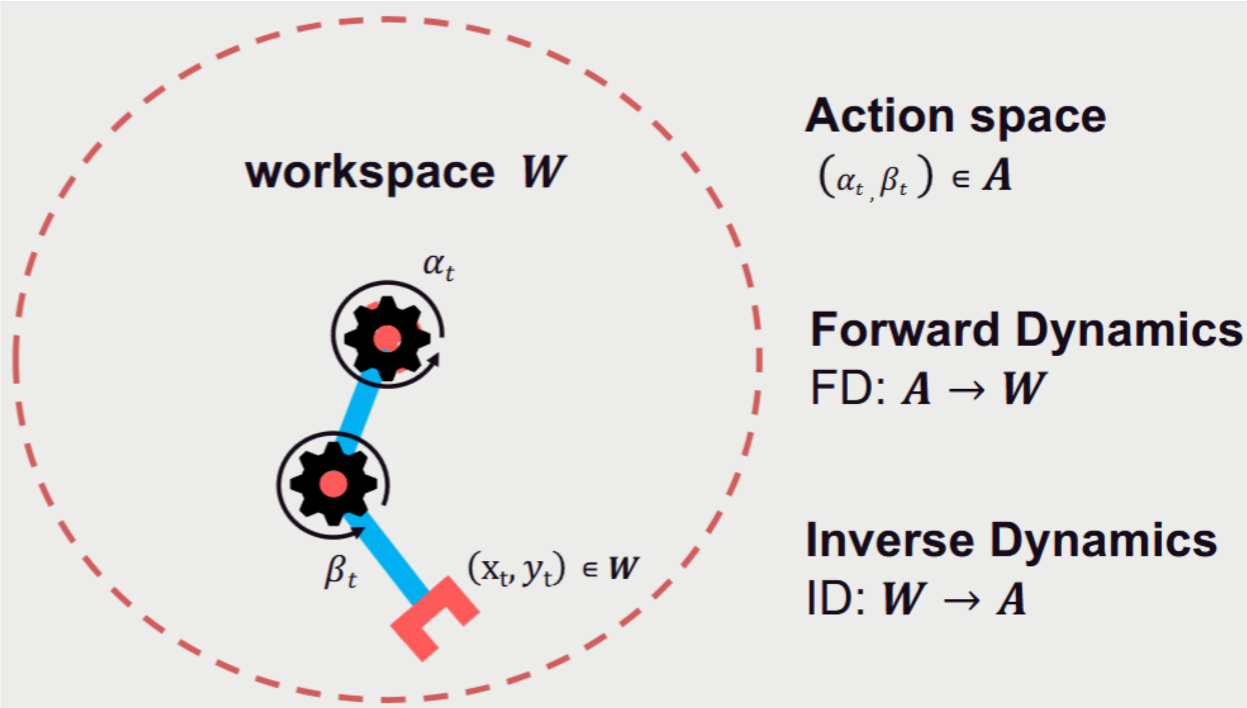
$$
\begin{aligned}
\text{def} &= m(N-1) - \sum_{i=1}^{J} c_i \\
&= m(N-1) - \sum_{i=1}^{J} (m - f_i) \\
&= m(N-1-J) + \sum_{i=1}^{J} f_i
\end{aligned}
$$

- The term $m(N-1)$ represents the number of rigid body freedoms
- The term $\sum_{i=1}^{J} c_i$ represents the number of joint constraints.
- We would use $m = 3$ for two-dimensional rigid bodies (planar mechanisms), and $m = 6$ for three-dimensional rigid bodies (spatial mechanisms).

Acrobot (Double Pendulum)



- You can only move the first joint; the second is completely free moving.
- The tip is called the **end effector**.
- The entire circle that the robot can reach is called the **work space.**



- The action space looks at the motion of the robot rather than the positions like kinematics.

How to detect the state of a robot?

- **Sensors**: physical devices that provides information about the world
- Internal states → Proprioceptive sensors
- External states → Exteroceptive sensors
- Perception = proprioception + exteroception
- Passive sensors: detects natural energy
- Active sensors: emits signals and detects feedback (thus do not rely on ambient energy)

Motors and Gears

Action and Actuation

- A robot acts through its *actuators* (e.g., motors), which typically drive *effectors* (e.g., wheels, grippers)
- Robotic actuators are very different from biological ones, both are used for:
  - locomotion (moving around, going places)
  - manipulation (handling objects)
- This divides robotics into two areas:
  - Mobile robotics
  - Manipulator robotics

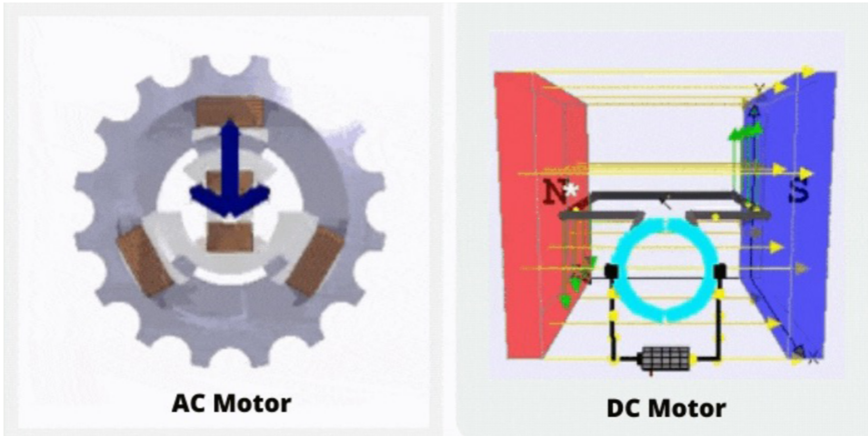
Definition of Effector

- An effector is any device that has an effect on the environment.
- A robot's effectors are used to purposefully <u>create an effect</u> on the environment.
- E.g., legs, wheels, arms, fingers, ...
- *The role of the controller is to get the effectors to produce the desired effect on the environment, based on the robot's task*

Definition of Actuator

- An actuator is the mechanism that enables the effector to execute an action.
- E.g., electric motors, hydraulic or pneumatic cylinders, pumps, ...
- Actuators and effectors are **not** the same thing.

Electric Motors



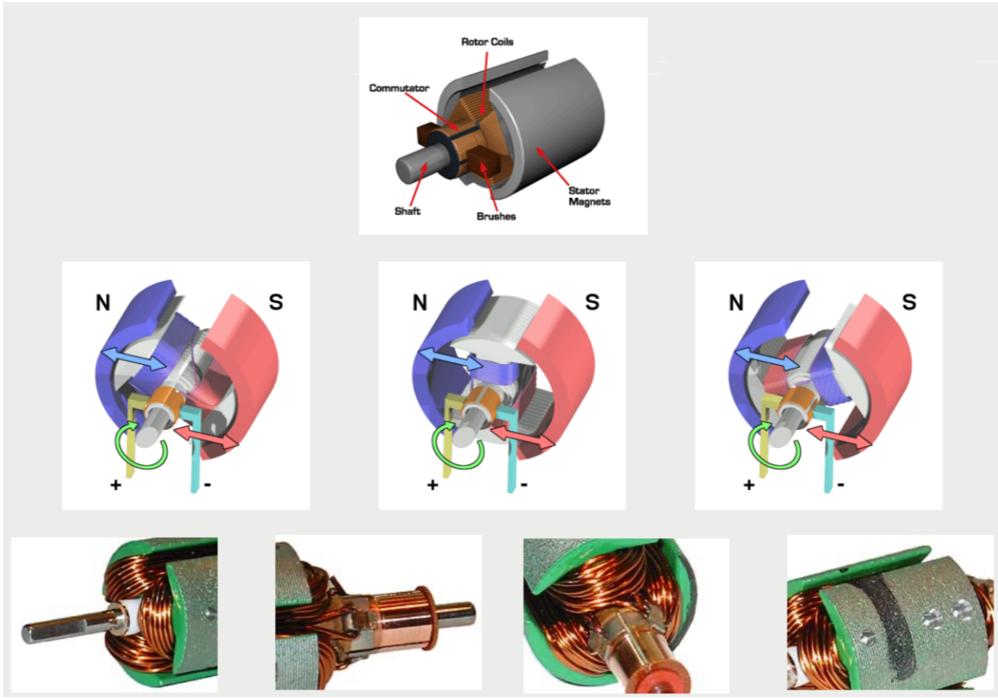
- **AC Motor**
  - Hard to control speed directly
  - Cheaper and more durable → common in household appliances, HVAC, pumps, and fans
- **DC Motor**
  - **The most common actuator in mobile robotics is the direct current (DC) motor**
  - Advantages: simple, cheap, various sizes and packages, easy to interface, easy to clean
  - DC motors convert electrical into mechanical energy

How do DC motors work?

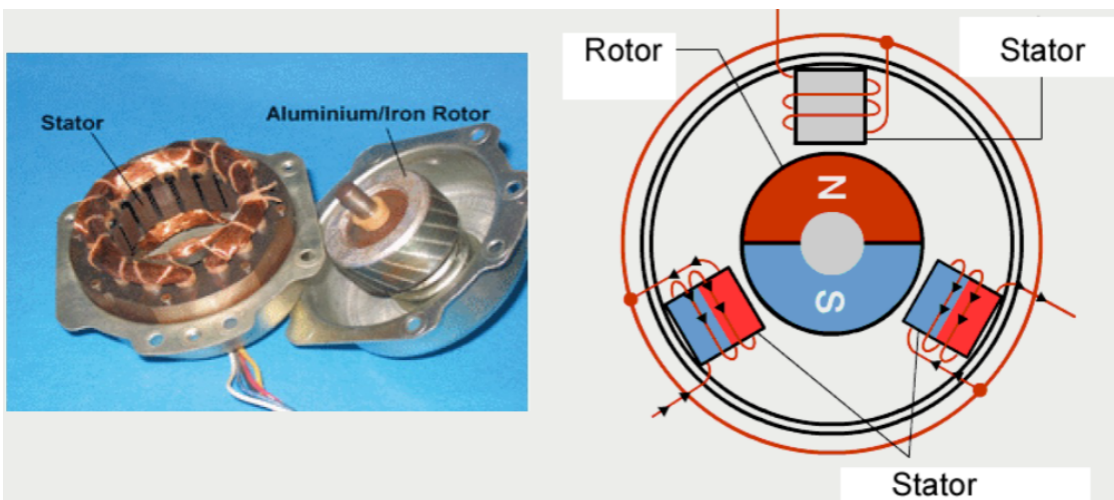
- DC motors consist of permanent magnets with loops of wire inside
- When current is applied, the wire loops generate a **magnetic field**, which reacts against the outside field of the static magnets
- The interaction of the fields produces the movement of the shaft or armature
- A **commutator** switches the direction of the current flow, yielding continuous motion

Types of DC Motors

- Brushed motors (mechanical commutation)
  - Low-voltage, low-torque, cheap



- Brushless motors (electric commutation)
  - High voltage, high-torque, expensive
  - No friction or wear of brushes



Motor Efficiency

- As any physical system, DC motors are not perfectly efficient
- Energy is not converted perfectly; some is wasted as heat generated by winding resistance and friction
- Inefficiencies are minimized in well-designed (more expensive) motors, and their efficiency can be high.
- Good DC motors can be made to have efficiencies in the 90th percentile
- Cheap DC motors can be as low as 50%
- Other types of effectors, such as miniature electrostatic motors, may have much lower efficiencies still

Speed and Torque

- Motor speed w is proportional to induced voltage V.

$$w = k_v V$$

- Torque is a force that acts in a rotational manner

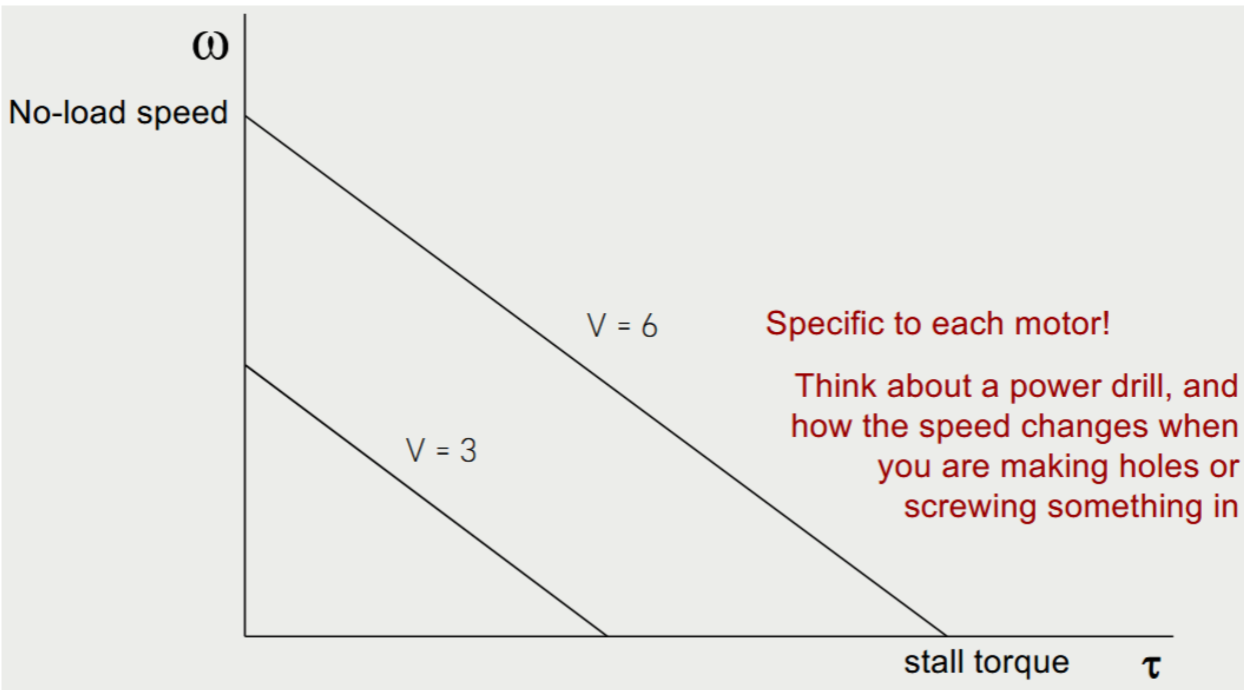
$$t = r \times F$$

- Motor torque t is proportional to applied current I:

$$t = k_I I$$

- Motors have a maximum speed (no-load speed) and a maximum torque (stall torque)

Speed/Torque Relationship



Motor Power

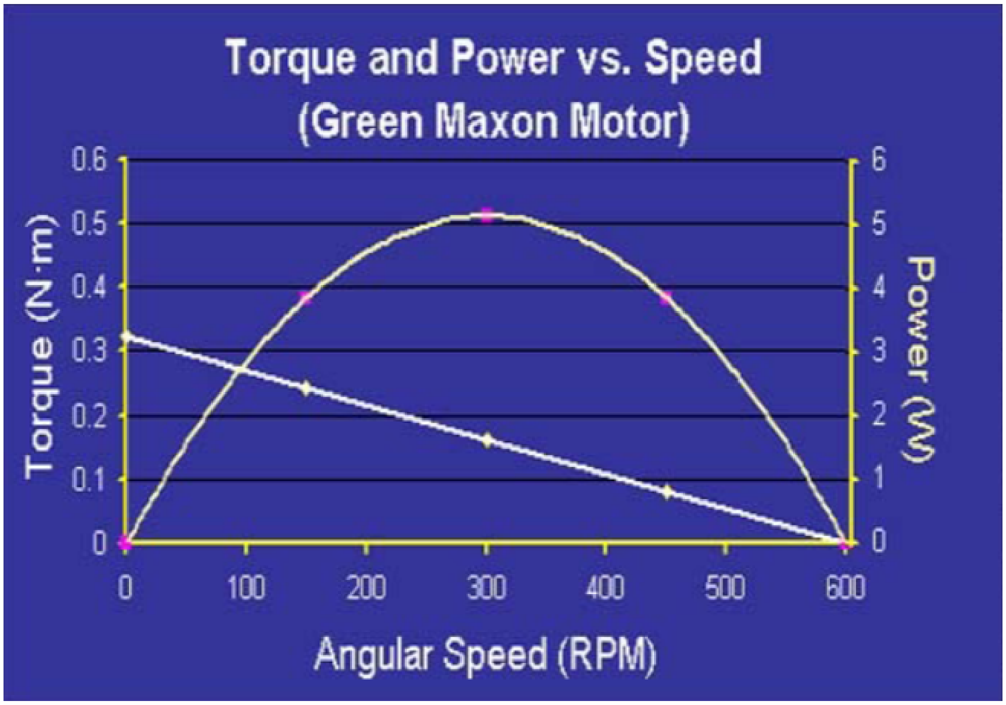
- Output power is the product of speed and torque:

$$P = w \times t$$

- At stall torque and no-load speed, the power is zero!
- Where do we get the most power?

Power as a function of τ, ω

$$P_{motor}(\omega) = -\frac{\tau_s}{\omega_n}\omega^2 + \tau_s \omega$$
$$P_{motor}(\tau) = -\frac{\omega_n}{\tau_s}\tau^2 + \omega_n \tau$$



Operating Voltage and Speed

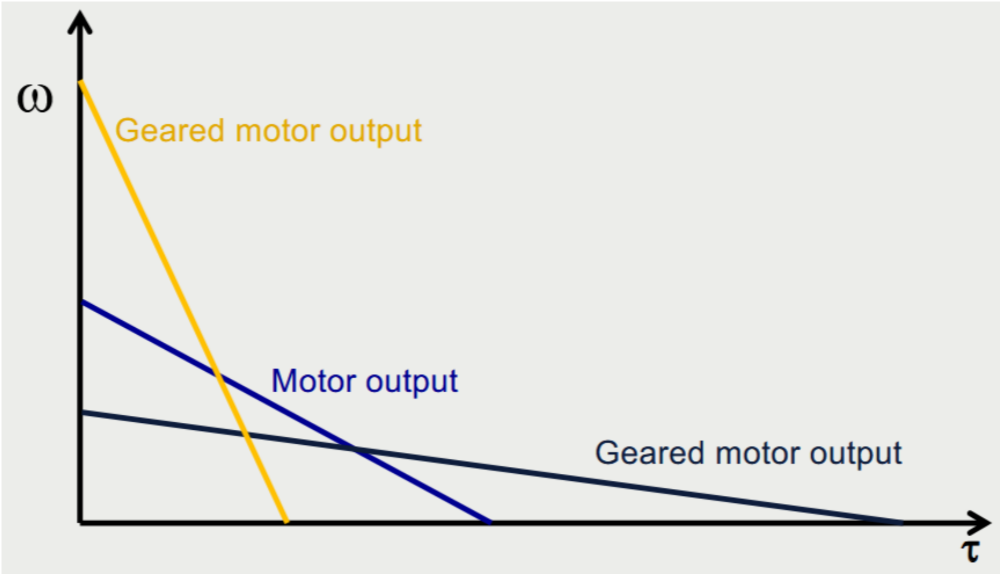
- Motors have maximum voltage
  - Higher voltages may overheat windings
- Motors have maximum speed rating
  - Higher speeds may destroy bearings or commutator
- Operating motors at higher speeds/voltage will reduce their life expectancy

DC motors and Robots

- DC motors have high-speed, low torque
- Typical speed range:
  - 9000 to 12000 RPM
  - 150 to 200 Hz
- Robots require low-speed, high torque.
  - What do we do about this? (We use gears!)

Gearing

- Gears are used to alter the output speed/torque of a motor (slope of speed/torque graph)



Gear Fundamentals

- The force F at the edge of a gear of radius r is given by:

$$F = \tau / r$$

- The linear speed v at the edge of a gear of radius r is given by:

$$v = \omega r$$

Combining Gears

- Meshing gears have equal linear speeds.

$$v_1 = v_2$$

- Thus the output speed is:

$$v = \omega r, \ \therefore \omega_2 = \frac{r_1}{r_2}\omega_1$$

- And the output torque is:

$$F = \tau / r \ \ \therefore \tau_2 = \frac{r_2}{r_1}\tau_1$$

- r_2/r_1 is known as the *gear ratio*

Examples:

- Gearing down:

$$r_1 = 1, r_2 = 2$$

  - 2:1 gear ratio doubles the torque and halves speed

- Gearing up:

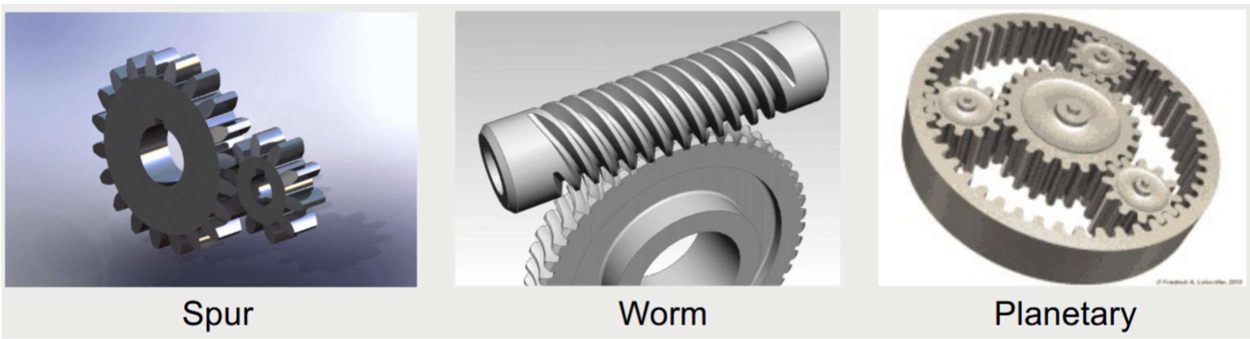
$$r_1 = 2, r_2 = 1$$

  - 1:2 gear ratio halves torque and doubles speed

Gear Stages

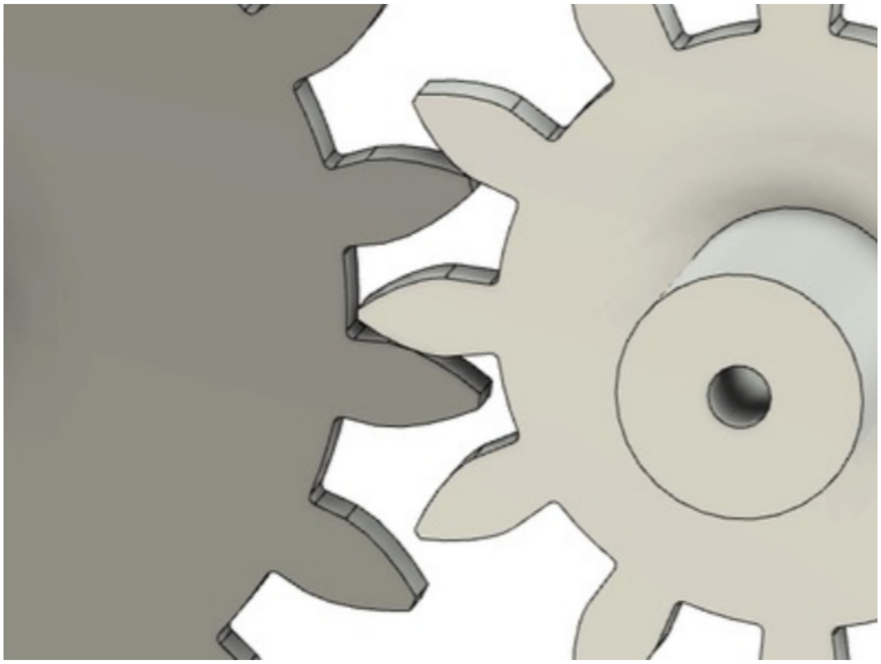
- Usually, it is not possible to achieve a sufficient gear ratio with a single pair of gears
- Gears can be arranged *in stages*
- The tortal gear ratio is the product of gear ratios for each stage
  - E.g., $3:1 \times 3:1 = 9:1$

Types of Gears



Backlash

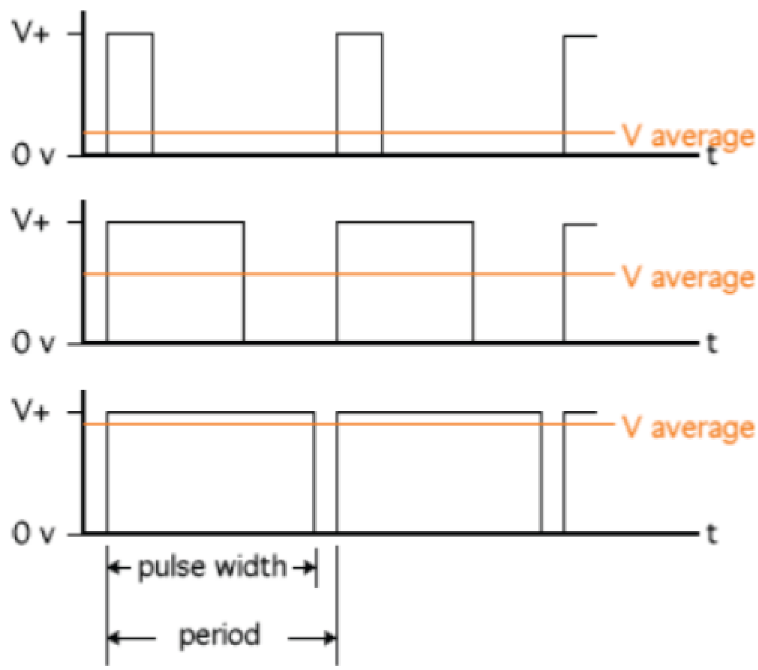
- Simple gears suffer from *backlash* (teeth not meshing completely)
- Although sometimes this is needed, it reduces the control you have



Control of Motors

Controlling Speed: Pulse Width Modulation (PWM)

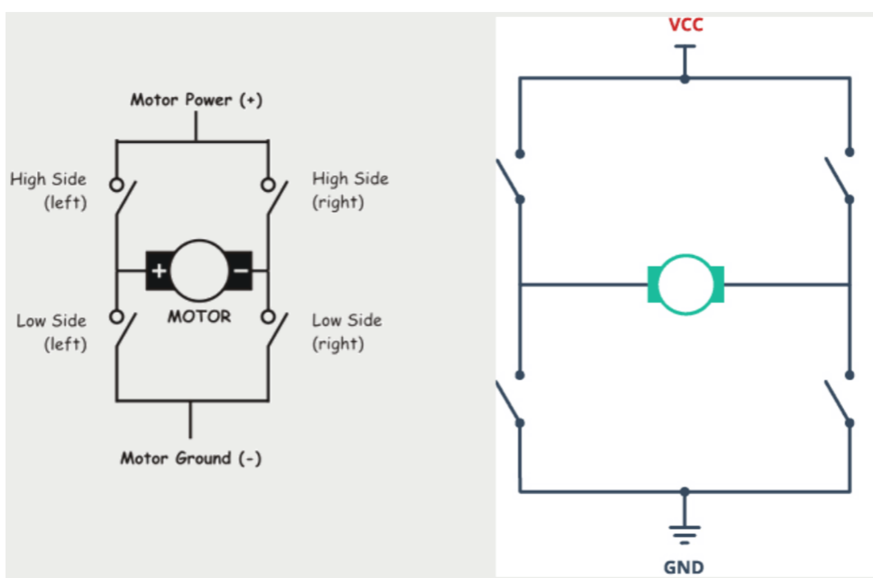
$$\omega = k_v V_{\text{average}}$$



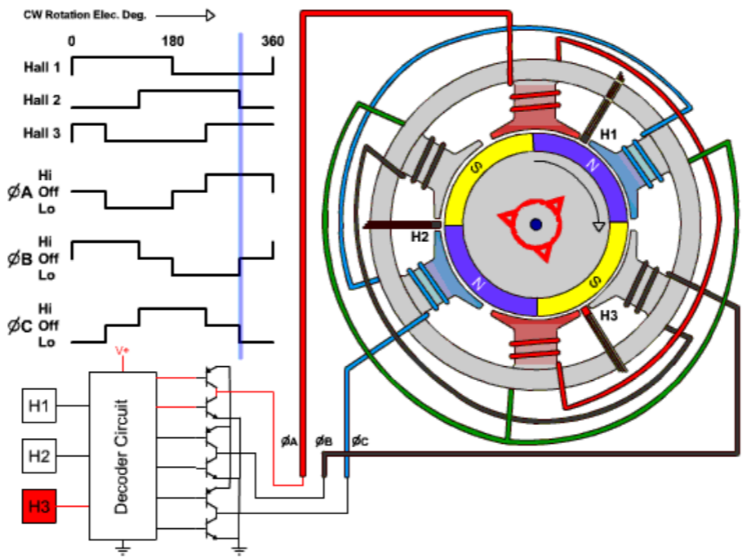
What is the duty cycle?

- Percentage of one period in which a signal is active.

Controlling Direction: H-Bridge



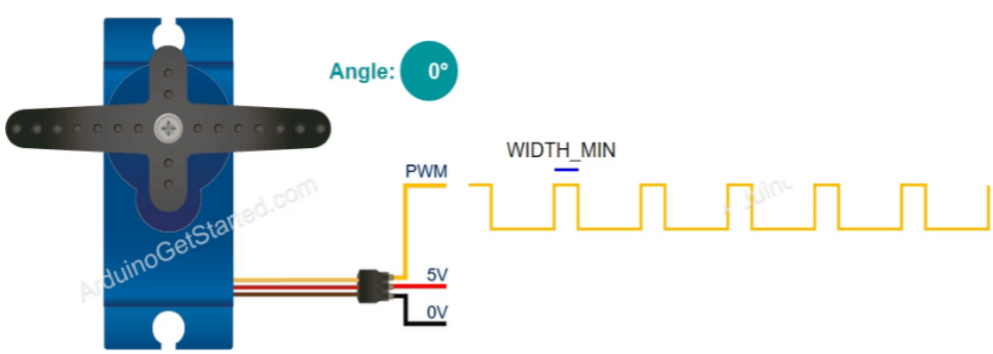
Control of Motors



Servo Motors

- Servo motors are adapted DC motors:
  - Gear reduction
  - position sensor (encoder, potentiometer)
  - electric controller
- Range of at least 180 degrees

PWM Position Control



- Not defined by PWM duty cycle but only **duration** of the pulse!
- Pulse width must be very accurate
  - Noise in width ⇒ noise in position
- Pulse rate may be variable
  - Noise in rate ⇒ no change