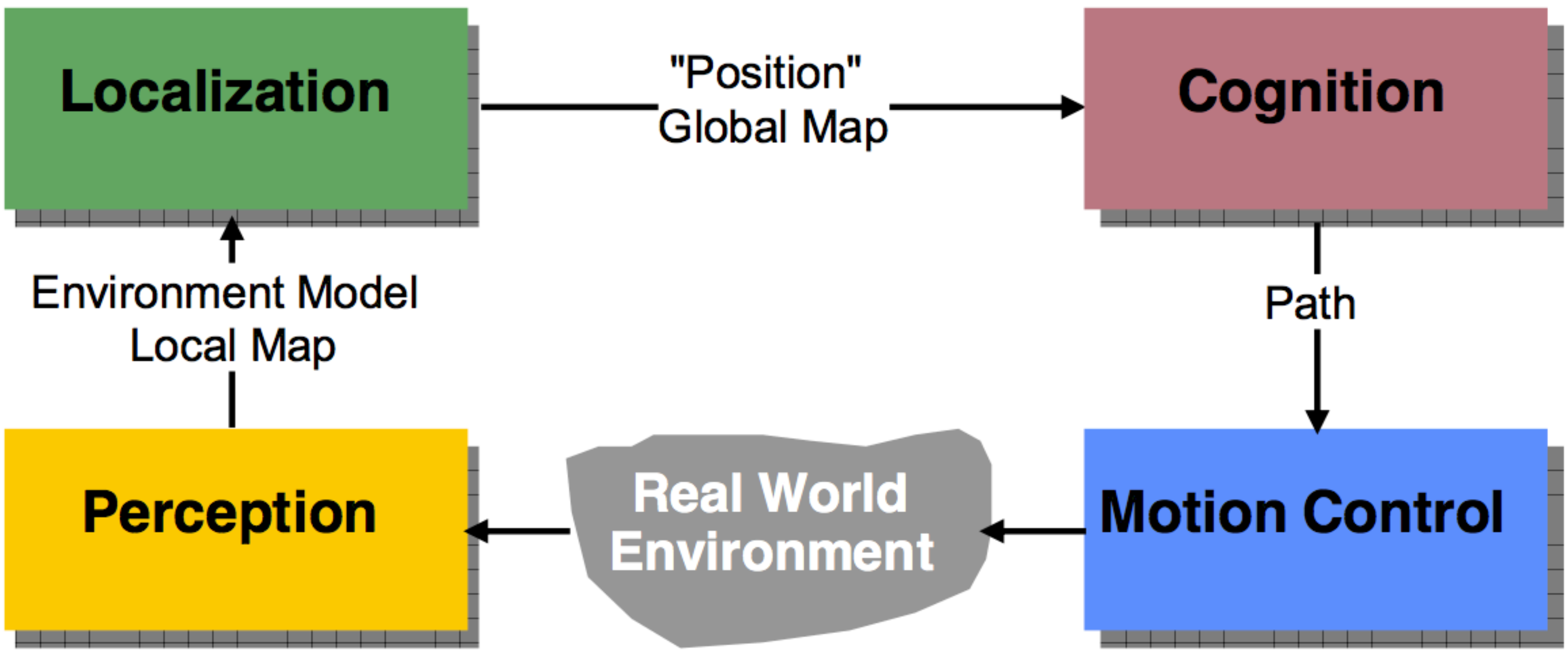
Mobility
Legs, Wheels, and Wings



Today's Class

- Useful terminology
  - Degrees of Freedom
  - Compliance and back-drive
  - Actuator saturation
  - Slip
- Mechanics: 3 most common mobility actuators
  - Legs, wheels, wings/propellers
- Other mobile actuators
- Walking wheels, passive flight, swimming, …

Characterizing Locomotion

- Locomotion:
  - Physical interaction between robot and environment.
  - Locomotion is concerned with:
    - Interaction forces; mechanisms and actuators that generate them
- The most important issues in locomotion are:
  - Stability
    - Center of gravity
    - Static/dynamic stabilization
    - Inclination of terrain
  - Contact
    - Contact point(s)
    - Contact area
    - Angle of Contact
    - Friction
- Type of environment
  - Water, air, soft or hard ground

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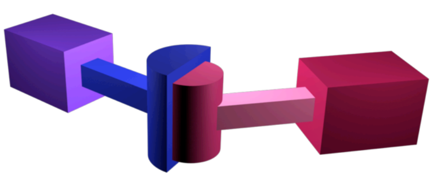
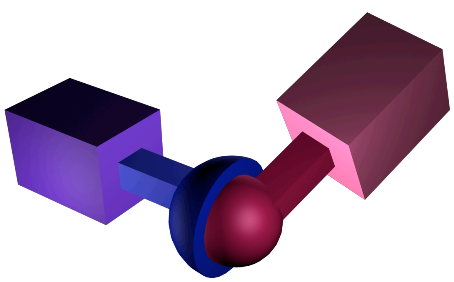
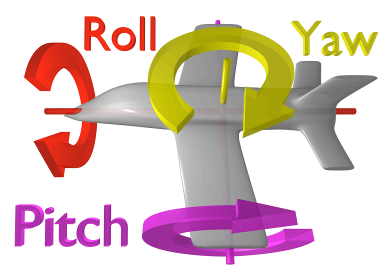
Degrees of Freedom

- DoFs
  - Number of independent parameters that define the **state** (not location!) of a physical system.









https://en.wikipedia.org/wiki/Degrees_of_freedom_%28mechanics%29

Compliance / Back-drive

- Motion of a DoF in response to external force
  - High compliance: moves a lot when stressed
  - Low compliance: stiff system when stressed
- Active compliance: software recognizes motion
- Passive compliance: mechanical structure
- Back-driveable means that you can physically move it (without breaking it) – passive compliance
  - Mostly a product of motor and gear type

Slip and Saturation

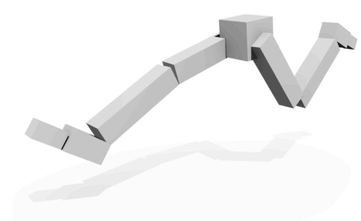
- Actuator saturation: physical performance limit
- Generally, saturation is a nonlinear response.
- Example: electric motor
  - Driving circuit has amp limit
  - Result: torque or speed limit.
  - When limit is exceeded, components start to burn out
  - Hard, nonlinear limit
- Slip: some interface (friction, gears, …) fail to catch
  - Examples: tires on snow; overdriven motor

Legged Locomotion

- Locomotion Concepts
- Nature came up with many approaches
  - Difficult to imitate technically
  - Do not employ wheels
  - Sometimes imitate wheels (bipedal walking)
- Adaptation to environment
- Most technical systems today use wheels
  - Legged locomotion is still mostly research

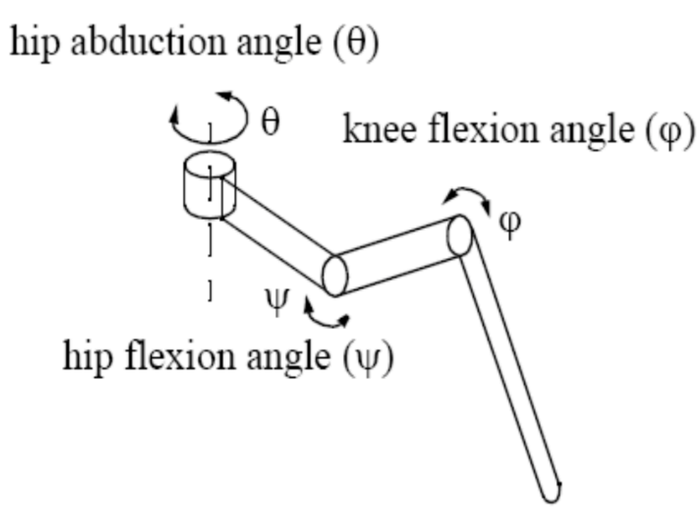
Legged Motion

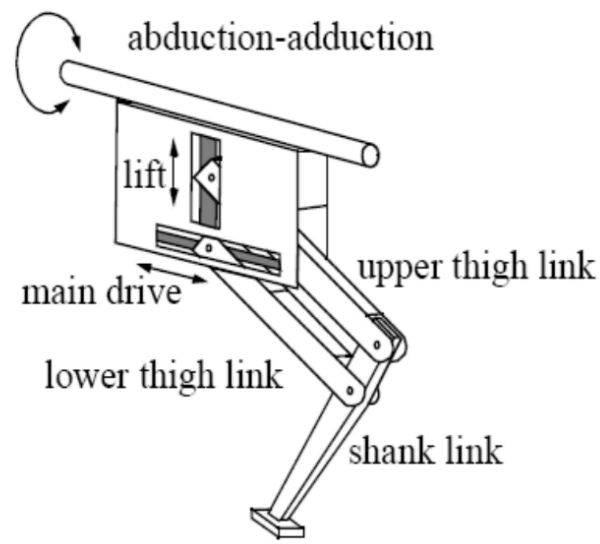
- Fewer legs → more complicated mechanically
  - Static stability
    - With **point** contact - at least three legs are required for static stability
    - With **surface** contact – at least one leg is required
- During walking some (usually half) of legs are lifted
  - Losing stability?
- For **static walking** 4+ legs are required
  - Animals usually move two legs at a time
  - Humans require more than a year



Leg Joints (DoFs)

- 2+ DoFs to move a leg forward: **lift** and **swing**
- Three DoFs for each leg in most cases
  - 4th DOF for the ankle joint
  - Might improve walking and stability
  - Additional joints increase design and control complexity





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Gait Options

- The number of distinct event sequences (gaits)
  - Distinct sequence of lift and release events of individual legs
  - Depends on number of legs
- Number of possible events N with k legs is:

$$N = (2k - 1)!$$

- For a biped (k=2), number of possible events N is:

$$N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6$$

- For a robot with 6 legs (hexapod) N is:

$$N = 11! = 39{,}916{,}800$$

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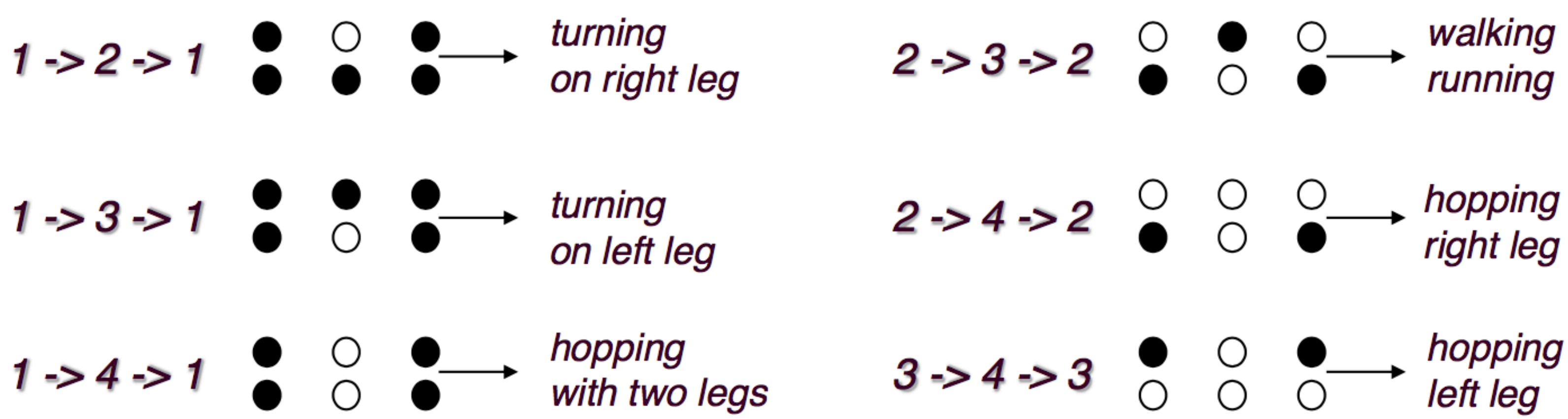
Gait Options

- Two legs (biped) can have four different states:
  - Both legs down
  - Right leg down, left leg up
  - Right leg up, left leg down
  - Both legs up

● *Leg down*
○ *Leg up*

- **Event sequence**: go from one state to another and back



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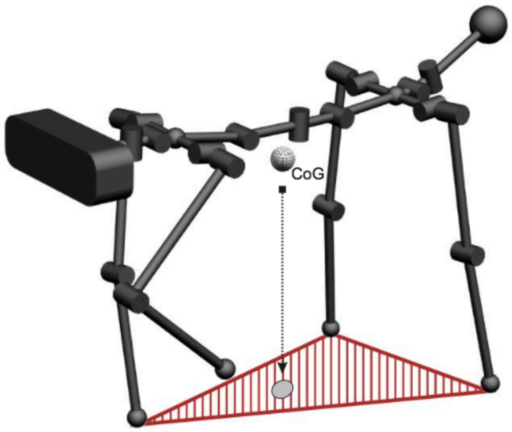
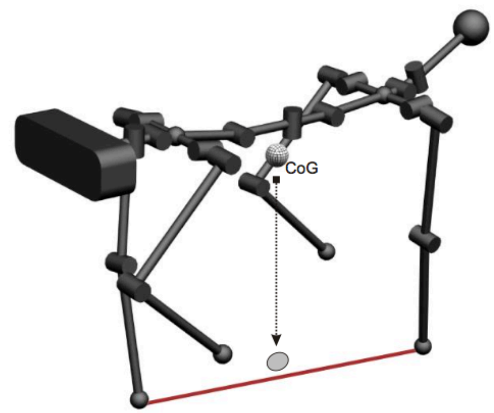
Static vs. Dynamic Walking

- Statically stable



- Dynamic walking



- Bodyweight supported by at least three legs
- Even if all joints freeze, the robot will not fall
- Safe ↔ slow and inefficient

- Robot will fall if not continuously moving
- Fewer than three legs can be in ground contact
- Fast, efficient ↔ harder actuation and control

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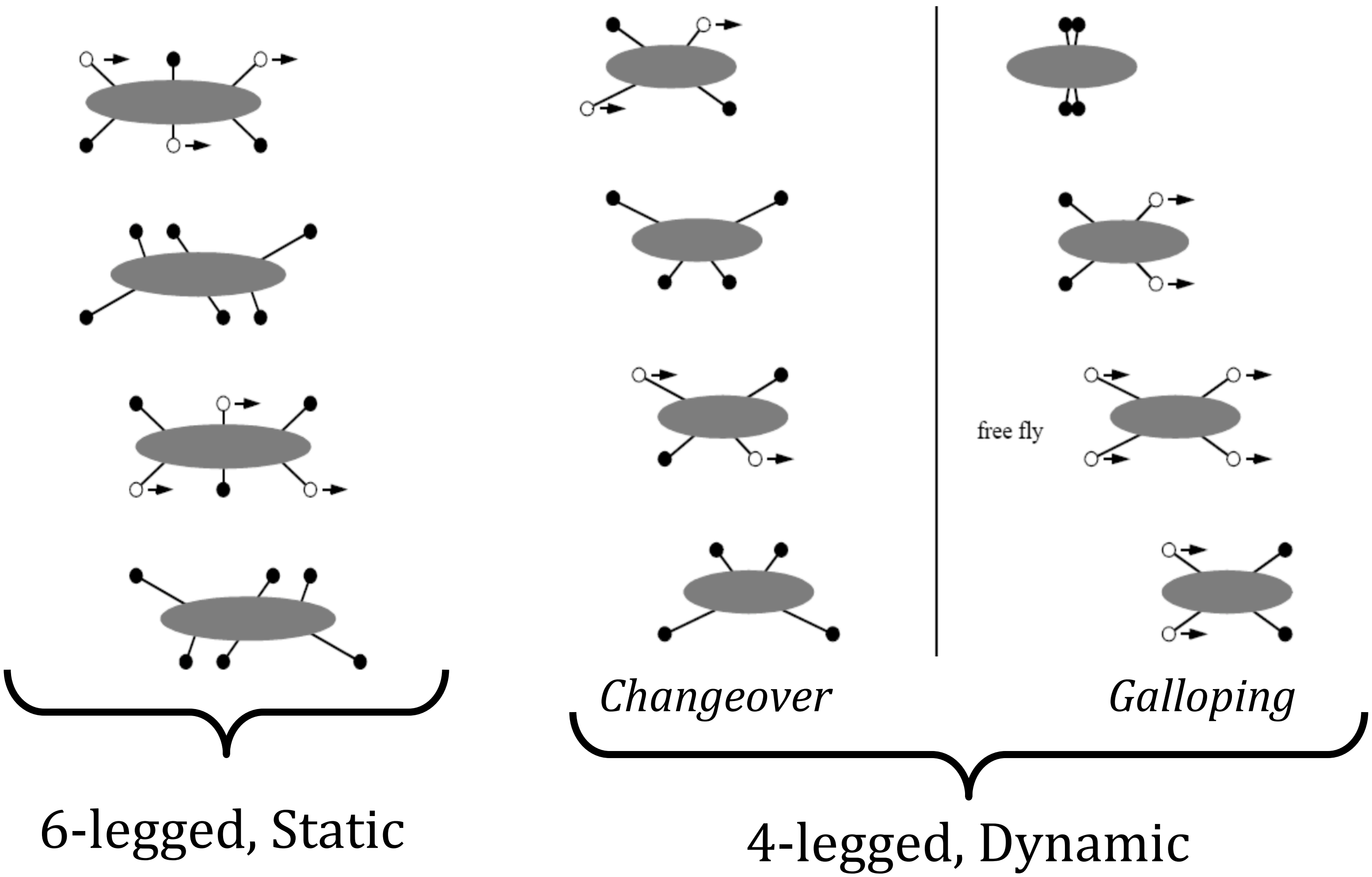
Static vs. Dynamic Gait

- Whether robot is stable at all times during walking (static)



Passive Dynamic Walking

- Gravity-powered walking with bipedal gait

https://www.youtube.com/watch?v=CK8IFEGmiKY

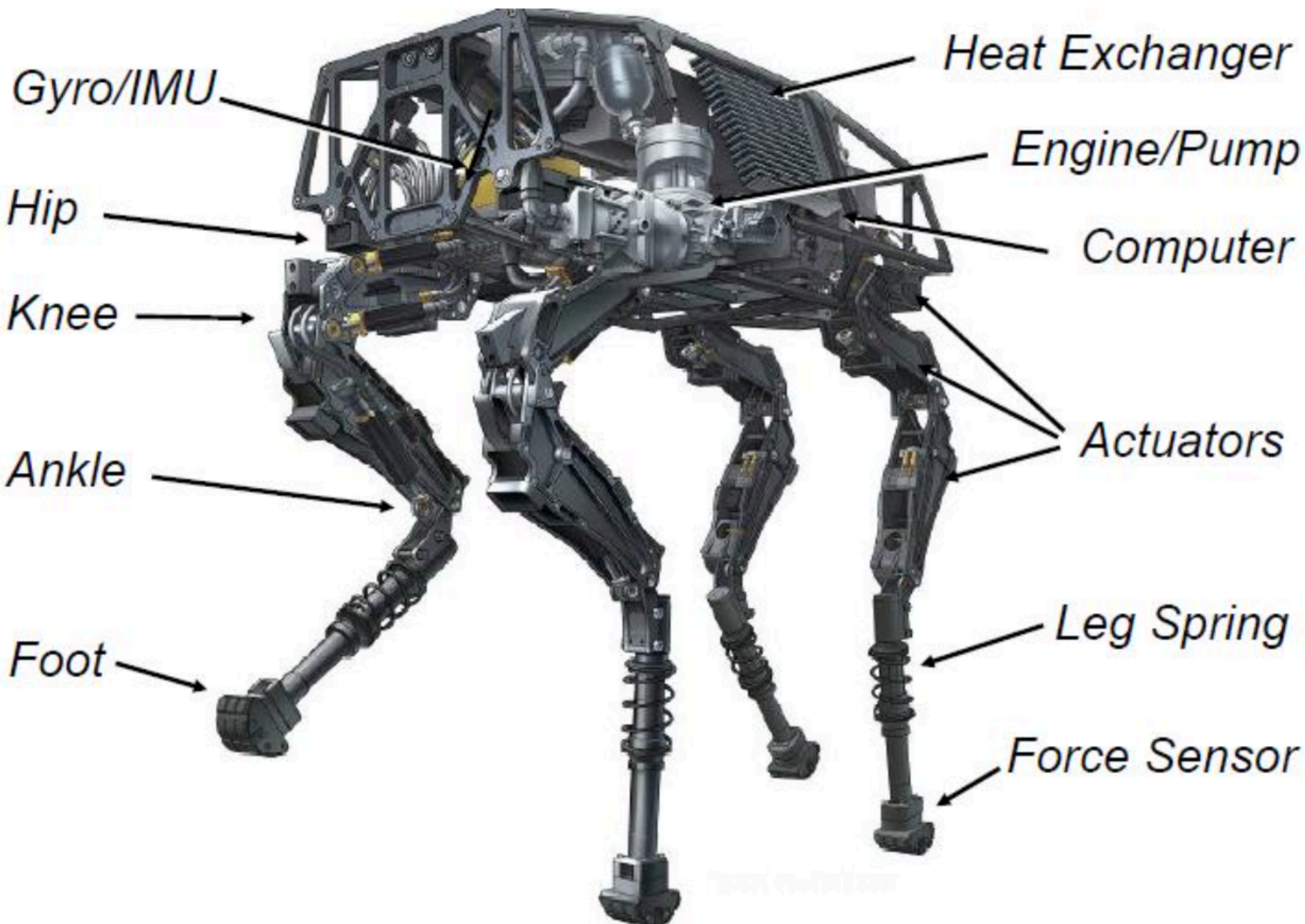
Dynamic Quadruped

- Boston Dynamics BigDog

https://www.youtube.com/watch?v=cNZPRsrwumQ

Dynamic Quadruped

- Boston Dynamics BigDog



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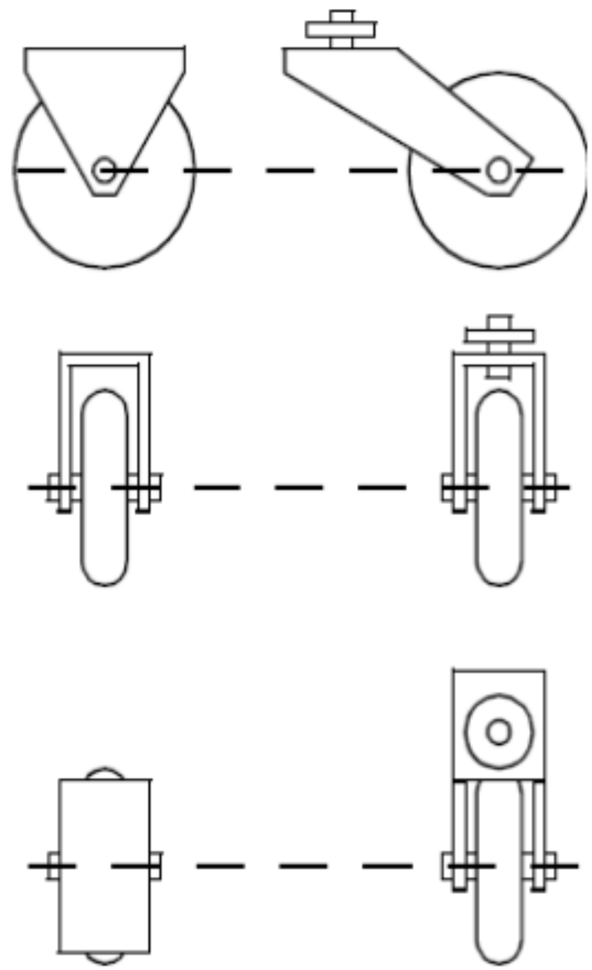
Wheels

- Most appropriate solution for most applications
- Three wheels guarantee stability
- With more than three wheels an appropriate **suspension** is required
  - Why?
- Selection of wheels depends on the application

Basic Wheel Types

- Standard wheel
  - Two degrees of freedom
  - Rotation around the (motorized) wheel axle and the contact point
- Castor wheel
  - Three degrees of freedom
  - Rotation around the wheel axle, the contact point and the castor axle



We will pick up here next time.

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Basic Wheel Types

- Swedish (Mecanum, Ilon) wheel
  - Three degrees of freedom
  - Rotation around the
  - (motorized) wheel axle, rollers, contact point

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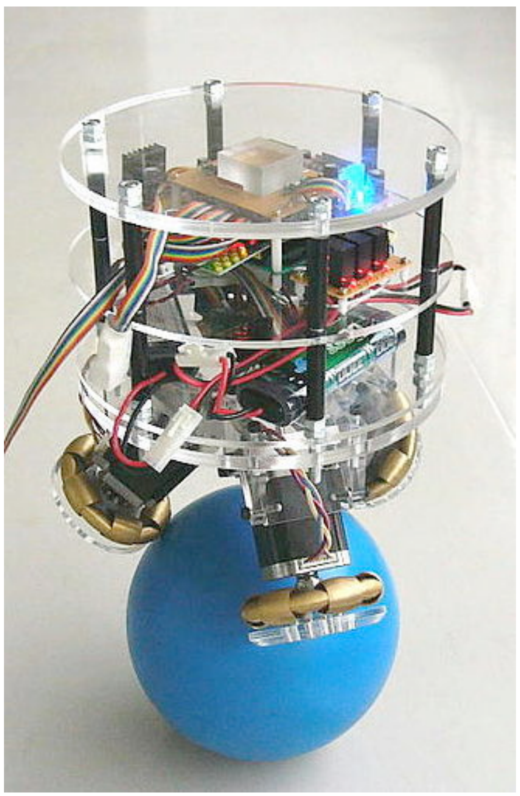
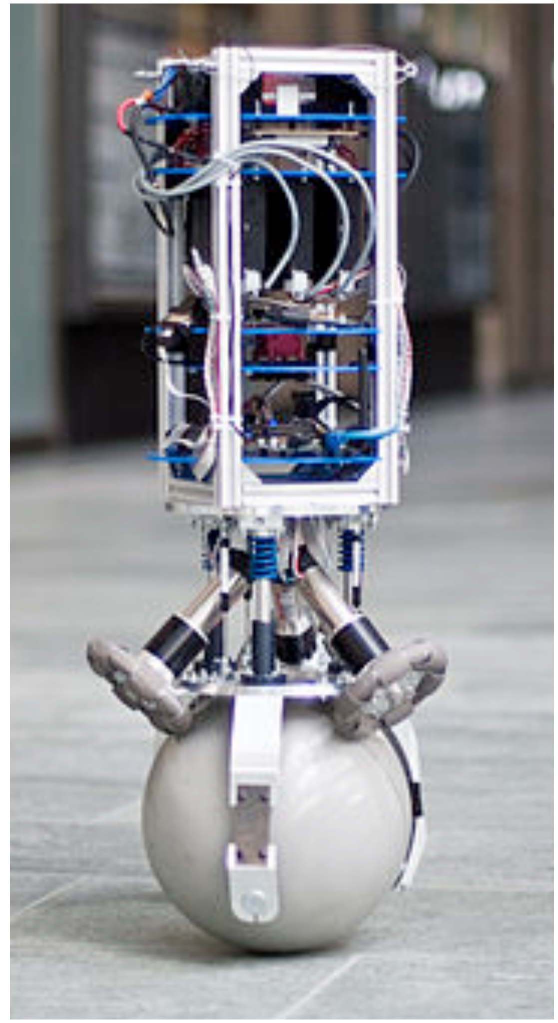
Basic Wheel Types

https://www.youtube.com/watch?v=8sH1a511_q4

Basic Wheel Types

- Ball or spherical wheel
  - Suspension not solved

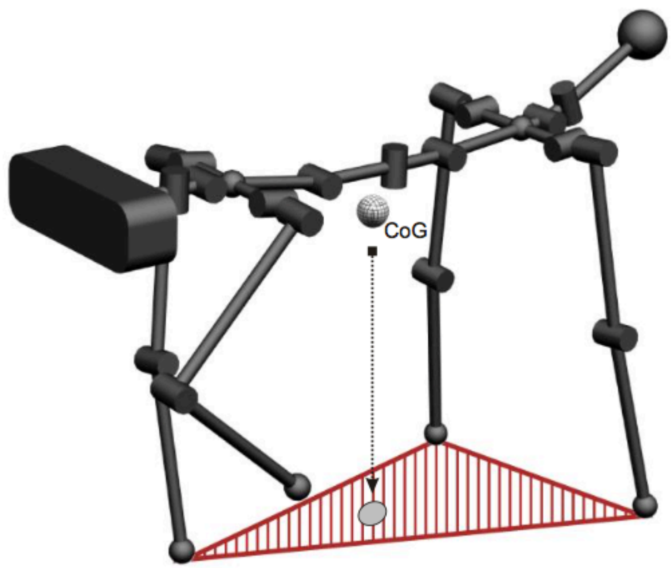




https://en.wikipedia.org/wiki/Ballbot

Characterization: Stability

- Stability of a vehicle is guaranteed with 3 wheels
  - If center of gravity is within the triangle which formed by the ground contact point of the wheels



- Stability is improved by 4+ wheels
  - However, arrangements require a flexible suspension
  - Why?

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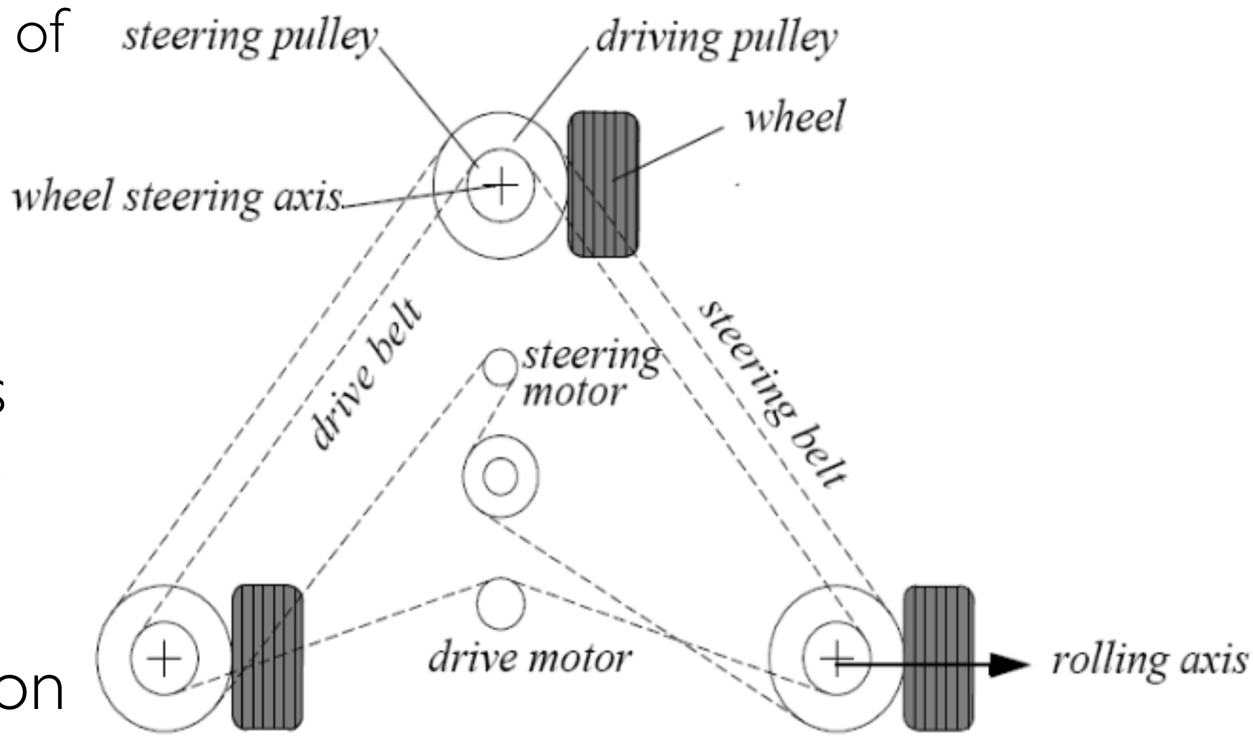
Characterization

- **Bigger wheels** overcome **higher obstacles**
  - But require higher torque or reductions in the gear box
- Most wheel arrangements require high control effort
  - Non-holonomic – we'll get into that in Ch. 3
- Combining actuation and steering on a single wheel
  - Makes the design complex
  - Adds errors for **odometry**
    - Data from motion sensors used to estimate position
    - "Dead reckoning"

Synchro Drive

- All wheels are actuated synchronously by one motor
  - Defines the speed of the vehicle
- All wheels steered synchronously by a second motor
  - Sets the heading of the vehicle
- Orientation in space of robot frame will always remain the same
- Not possible to control orientation of robot frame



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For Next Time…

- Read SNS 4.1