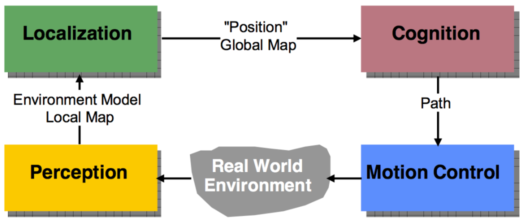
Mobility

Legs, Wheels, and Wings



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Today's Class

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- 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, …

Locomotion in Nature

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Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel	Hydrodynamic forces	Eddies
Crawl	Friction forces	Longitudinal vibration
Sliding	Friction forces	Transverse vibration
Running	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Jumping	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Walking	Gravitational forces	Rolling of a polygon (see figure 2.2)

Locomotion in Nature

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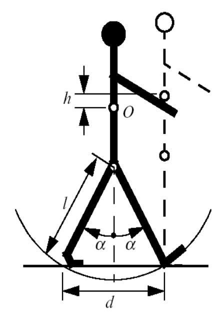
- Concepts found in nature
  - Difficult to imitate technically
  - Why?
- Most technical systems use wheels or caterpillars
  - Rolling is most efficient, but not found in nature
  - Nature never invented the wheel!
- However, the movement of a walking biped is close to rolling



Walking or Rolling?

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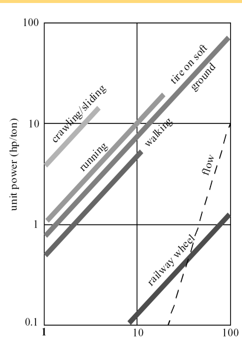
- Number of actuators
- Structural complexity
- Control expense
- Energy efficient
  - Terrain (flat ground, soft ground, climbing..)
- Movement of the involved masses
  - Walking / running includes up and down movement of COG
  - Some extra losses



Passive Dynamic Walking

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- Gravity-powered walking with bipedal gait

We saw this last time – now we're looking at similarity to rolling

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

Characterizing Locomotion

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

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Degrees of Freedom

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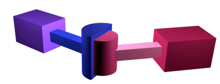
- DoFs: Number of independent parameters that define the **state** (not location) of a physical system
- How many numbers define how parts can move with respect to each other?



- This arm can be straight, or bent some amount
- To know its state, you need to know 1 thing: θ

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

Compliance / Back-drive

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- 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
  - If you grab my arm and bend it, the elbow joint moves
  - Mostly a product of motor and gear type

Slip and Saturation

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- 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 Motion

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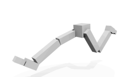
- Fewer legs → more complicated mechanically
  - Static stability
    - With **point** contact - at least three legs are required for static stability
    - With **surface** contact – at least one leg is required
- During walking some (usually half) of legs are lifted
  - Losing stability?
- For **static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



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Leg Joints (DoFs)

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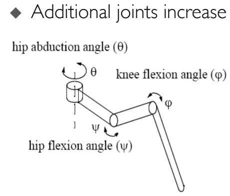
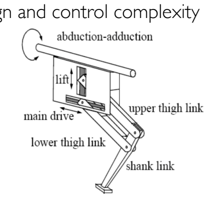
- 2+ DoFs to move a leg forward: **lift** and **swing**
- Three DoFs for each leg in most cases
  - 4th DOF for the ankle joint
  - Might improve walking and stability
  - Additional joints increase design and control complexity





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Gait Options

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- 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

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- 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

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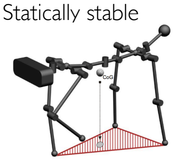
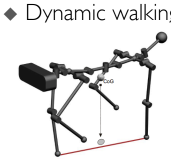
- Statically stable



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

- Dynamic walking



  - 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

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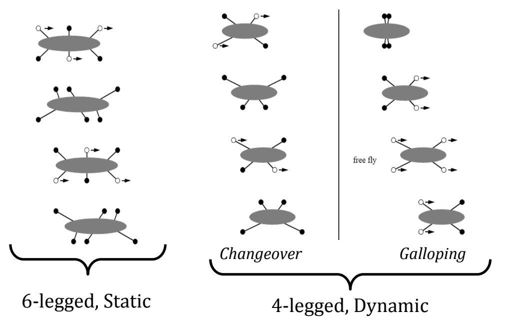
- Whether robot is stable at all times during walking (static)



Dynamic Quadruped

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- Boston Dynamics BigDog

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

Dynamic Quadruped

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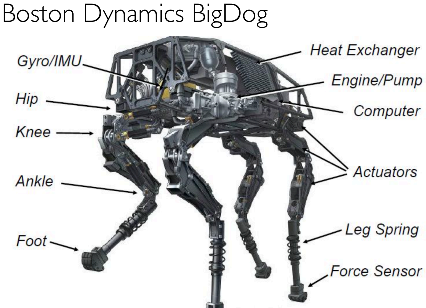
- Boston Dynamics BigDog



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Wheels

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

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Mountings and Axles

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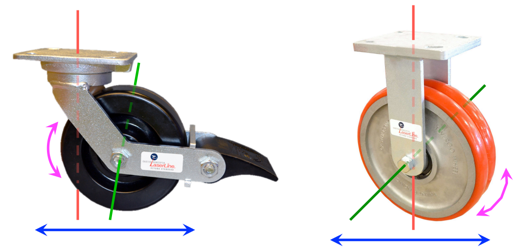
Mounting axis
Axle
Direction of rotation
Direction of translation



4 Basic Wheel Types

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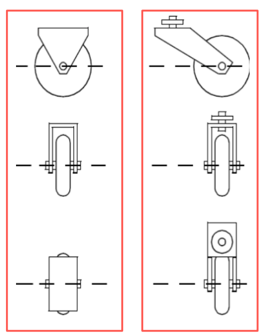
- Standard wheel
  - Two degrees of freedom
  - Rotation around the (motorized) wheel axle and the contact point
- Castor wheel
  - Three degrees of freedom
  - Rotation around the wheel axle, the contact point and the castor axle



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Basic Wheel Types

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

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Basic Wheel Types

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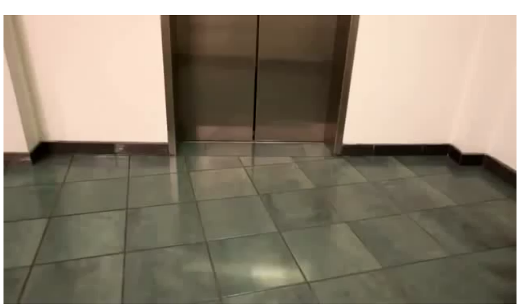

https://www.youtube.com/watch?v=8sH1a511_q4

Basic Wheel Types

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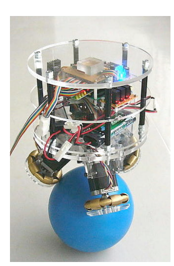
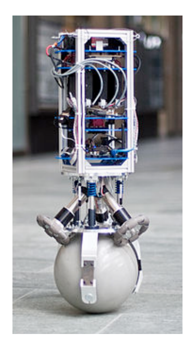
- Ball or spherical wheel
  - Suspension not solved





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

Characterization: Stability

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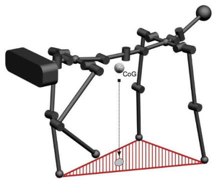
- Stability of a vehicle is guaranteed with 3 wheels
  - If center of gravity is within the triangle which formed by the ground contact point of the wheels



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

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Characterization

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- 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"

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Synchro Drive

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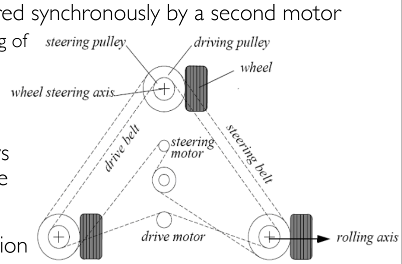
- All wheels are actuated synchronously by one motor
  - Defines the speed of the vehicle
- All wheels steered synchronously by a second motor
  - Sets the heading of the vehicle
- Orientation in space of robot frame will always remain the same
- Not possible to control orientation of robot frame



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