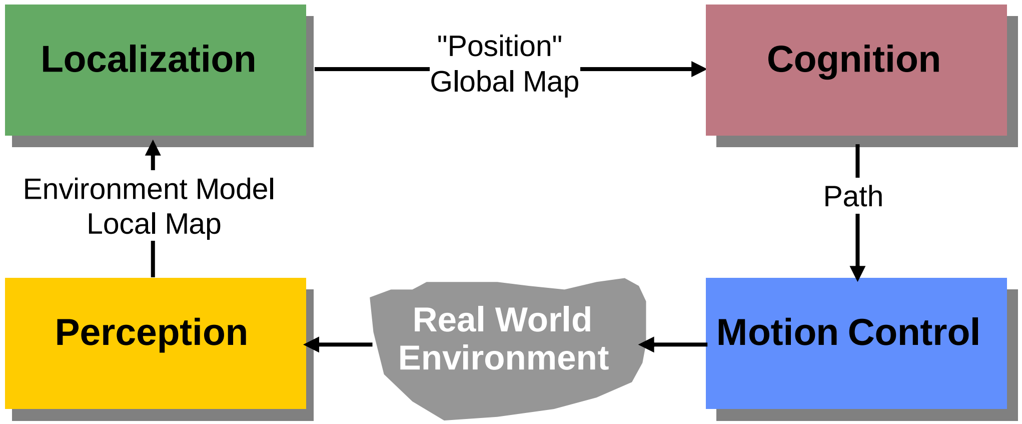


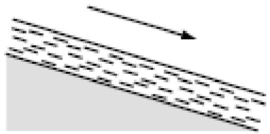
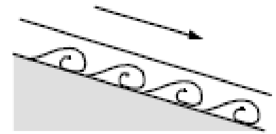
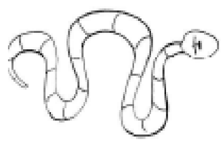
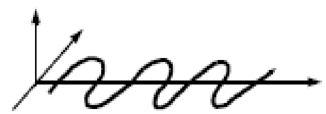
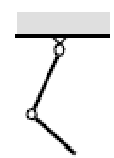
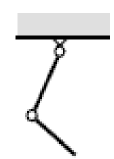
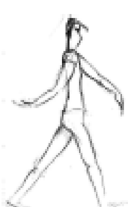
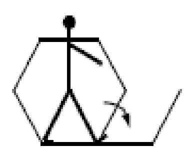
Locomotion Concepts

Concepts

Legged Locomotion

Wheeled Locomotion

Locomotion Concepts: Principles Found in Nature

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) 

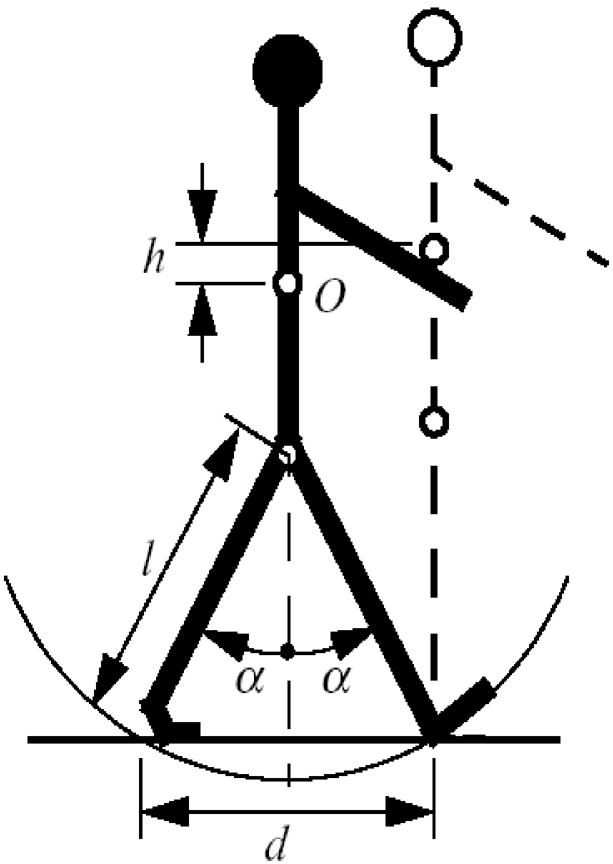
Locomotion Concepts

- Nature came up with a multitude of locomotion concepts
  - Adaptation to environmental characteristics
  - Adaptation to the perceived environment (e.g. size)

- Concepts found in nature
  - Difficult to imitate technically
  - Do not employ wheels
  - Sometimes imitate wheels (bipedal walking)

- Most technical systems today use wheels or caterpillars
  - Legged locomotion is still mostly a research topic

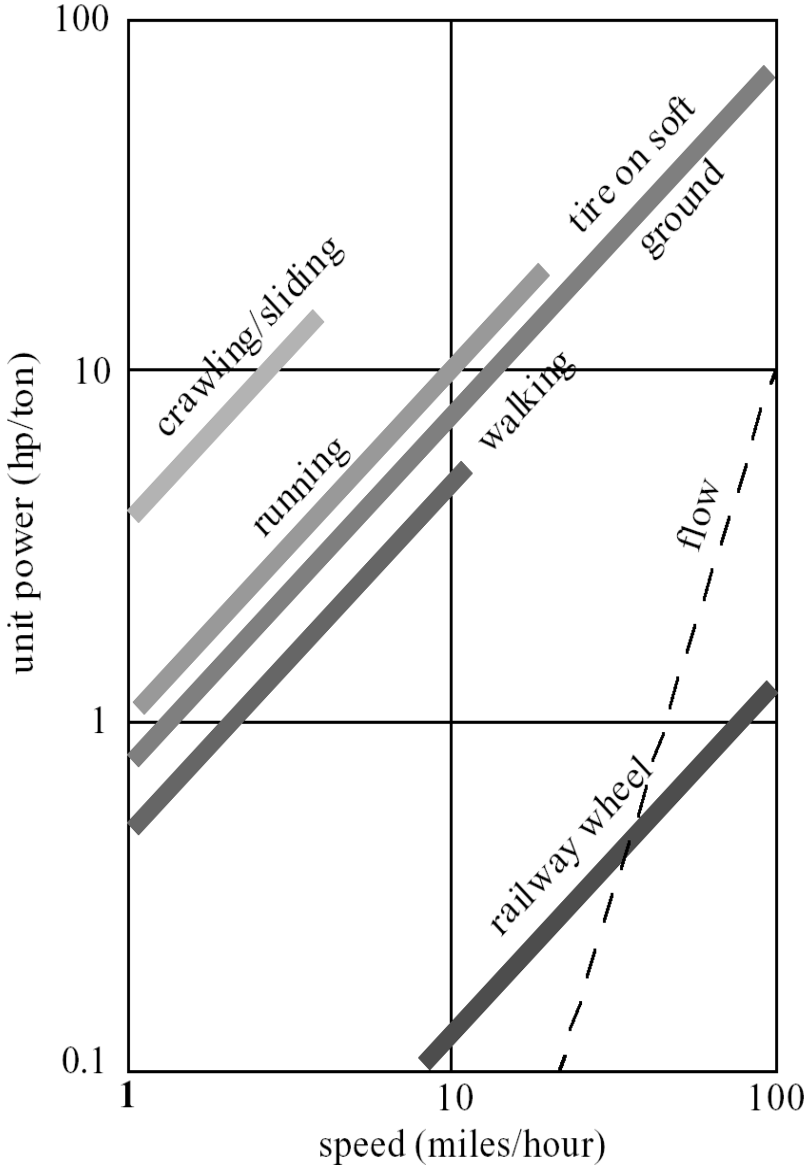
Biped Walking



- Biped walking mechanism
  - not too far from real rolling
  - rolling of a polygon with side length equal to the length of the step
  - the smaller the step gets, the more the polygon tends to a circle (wheel)
- But…
  - rotating joint was not invented by nature
  - Work against gravity is required
  - More detailled analysis follows later in this presentation

Walking or rolling?

- 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



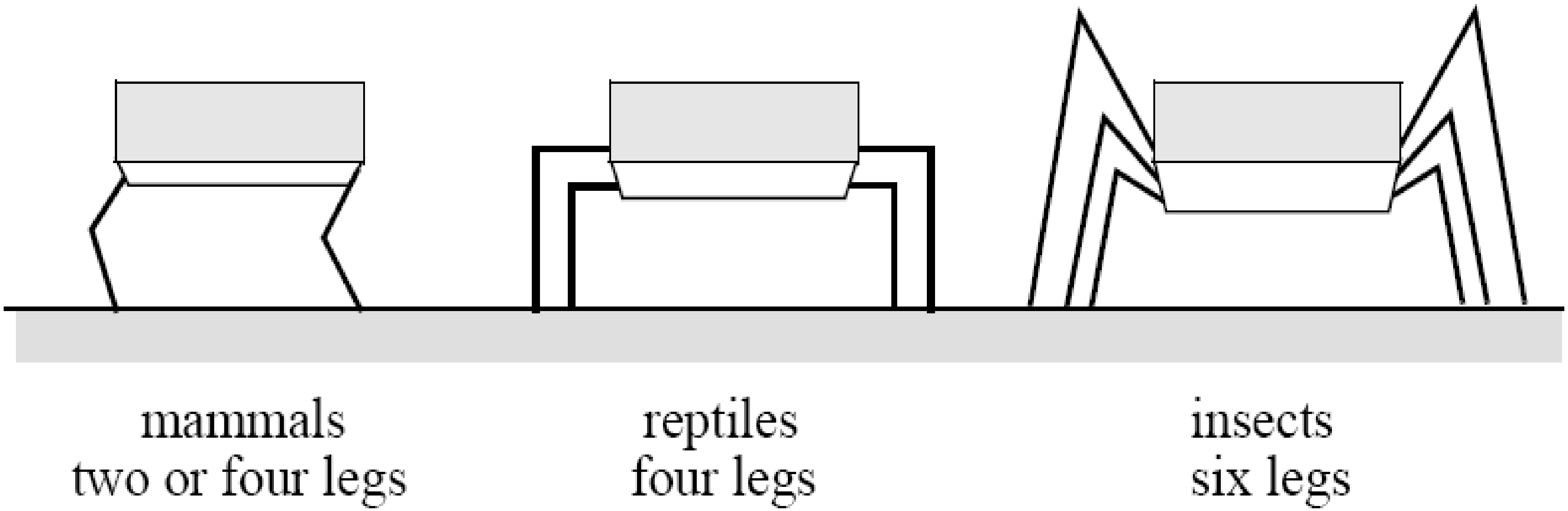
Characterization of locomotion concept

- Locomotion
  - physical interaction between the vehicle and its environment.
- Locomotion is concerned with **interaction forces**, and the **mechanisms** and **actuators** that generate them.

- The most important issues in locomotion are:
  - **stability**
    - number of contact points
    - center of gravity
    - static/dynamic stabilization
    - inclination of terrain
  - **characteristics of contact**
    - contact point or contact area
    - angle of contact
    - friction
  - **type of environment**
    - structure
    - medium (water, air, soft or hard ground)

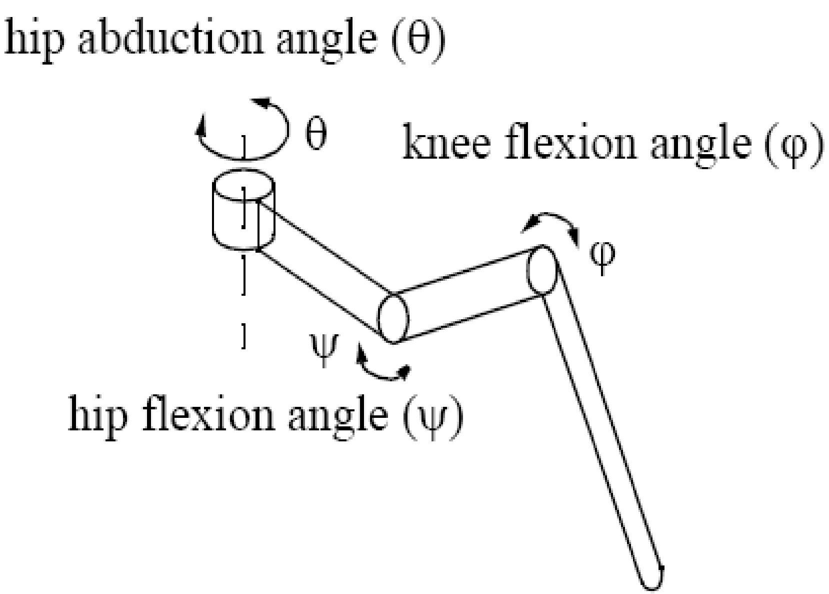
Mobile Robots with legs (walking machines)

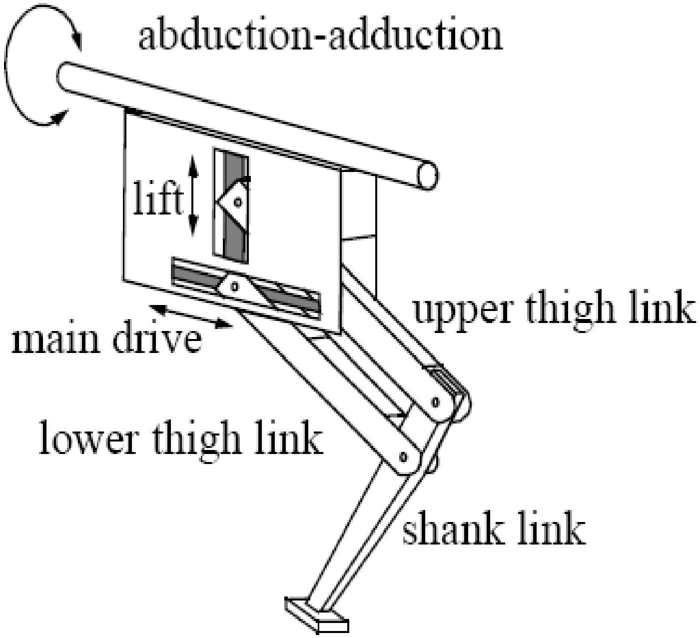
- The fewer legs the more complicated becomes locomotion
  - Stability with point contact- at least three legs are required for static stability
  - Stability with surface contact – at least one leg is required
- During walking some (usually half) of the legs are lifted
  - thus loosing stability?
- For static walking at least 4 (or 6) legs are required
  - Animals usually move two legs at a time
  - Humans require more than a year to stand and then walk on two legs.



Number of Joints of Each Leg (DOF: degrees of freedom)

- A minimum of two DOF is required to move a leg forward
  - a *lift* and a *swing* motion.
  - Sliding-free motion in more than one direction not possible
- Three DOF for each leg in most cases (as pictured below)
- 4th DOF for the ankle joint
  - might improve walking and stability
  - additional joint (DOF) increases the complexity of the design and especially of the locomotion control.





The number of distinct event sequences (gaits)

- The gait is characterized as the distinct sequence of **lift and release events** of the individual legs
  - it depends on the number of legs.
  - the number of possible events N for a walking machine with k legs is:

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

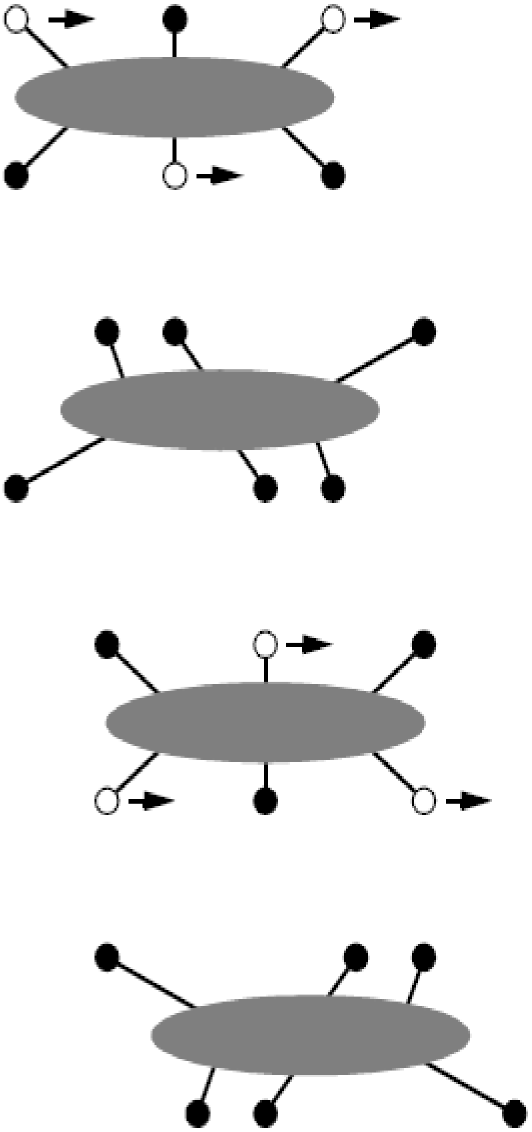
- For a biped walker (k=2) the number of possible events N is:

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

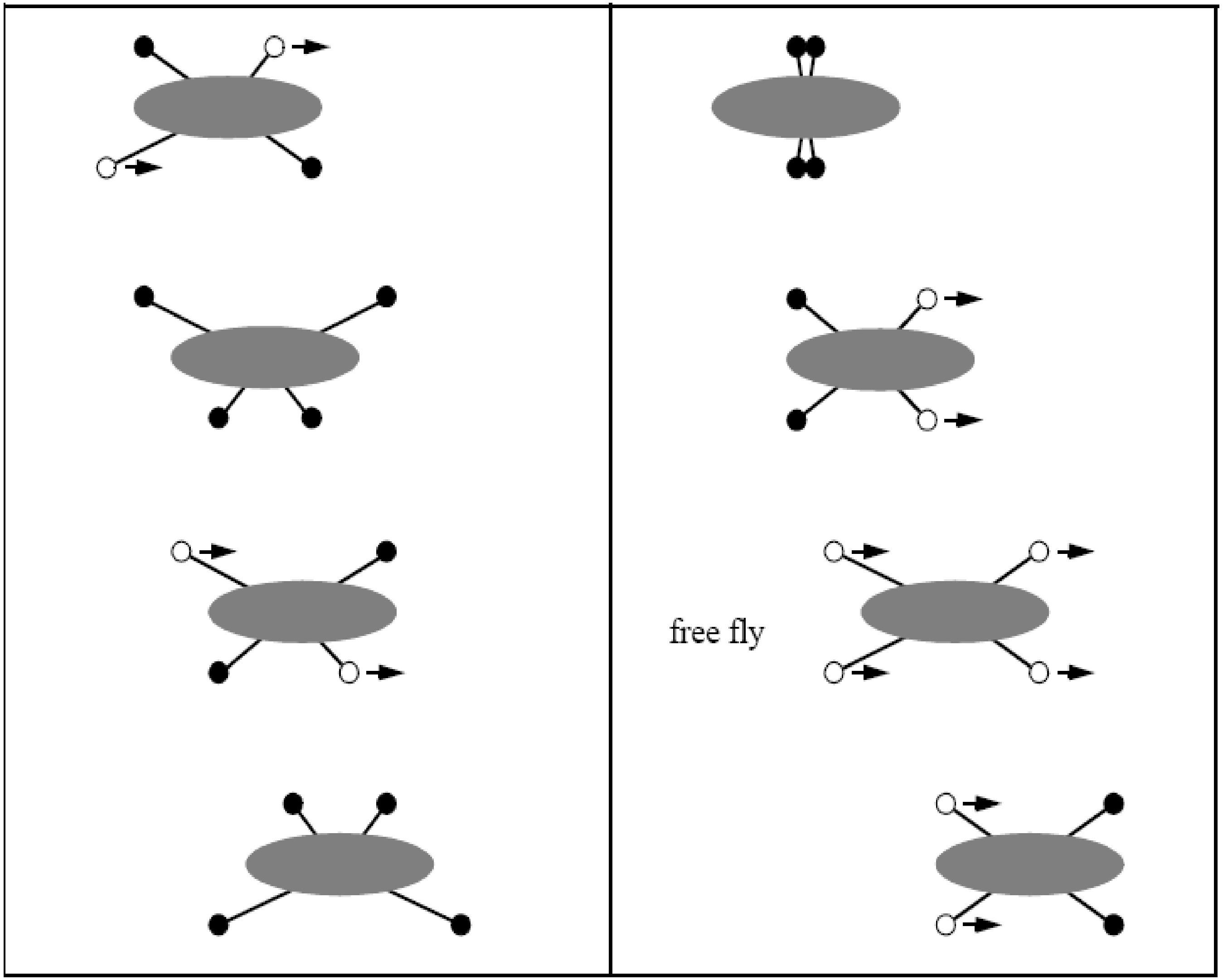
- For a robot with 6 legs (hexapod) N is already

$$N = 11! = 39'916'800$$

Most Obvious Gait with 6 Legs is Static



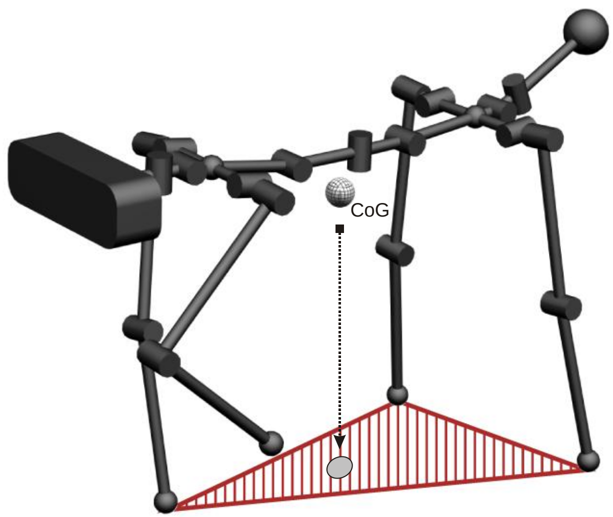
Most Obvious Natural Gaits with 4 Legs are Dynamic



Changeover Walking Galloping

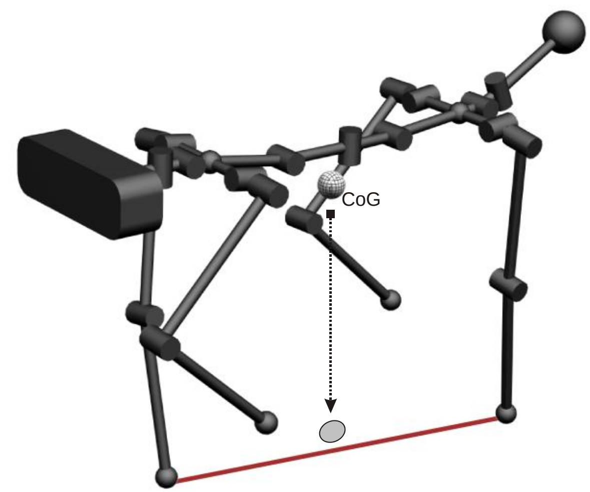
Dynamic Walking vs. Static Walking

- **Statically stable**



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

- **Dynamic walking**



  - The robot will fall if not continuously moving
  - Less than three legs can be in ground contact
  - fast, efficient ↔ demanding for actuation and control

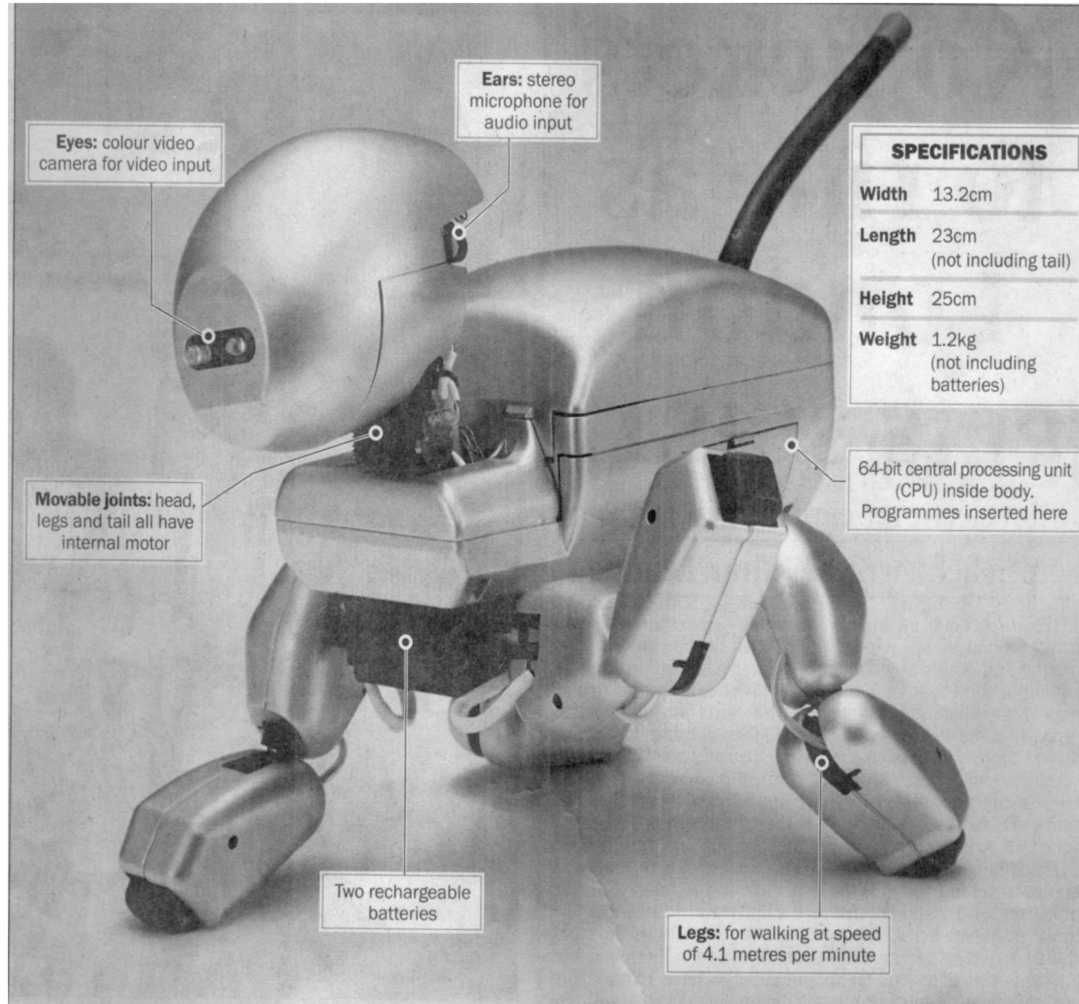
Most Simplistic Artificial Gait with 4 Legs is Static

- Titan VIII quadruped robot

C Arikawa, K. & Hirose, S., Tokyo Inst. of Technol.

Walking Robots with Four Legs (Quadruped)

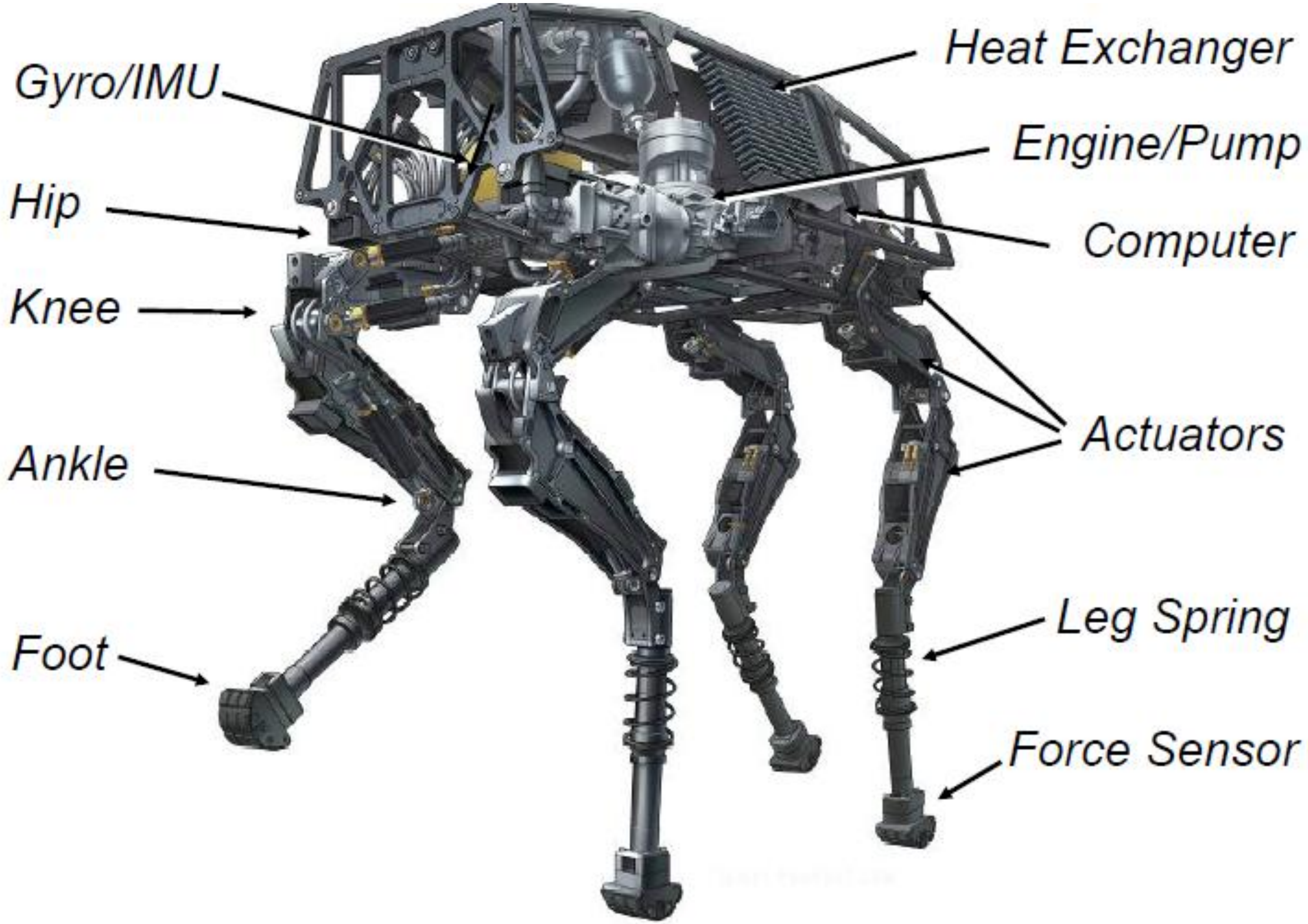
- Artificial Dog Aibo from Sony, Japan



Sony's new computer canine will chase a ball or sit when asked, but cleaning up will be a thing of the past

Dynamic Walking Robots with Four Legs (Quadruped)

- Boston Dynamics Big Dog

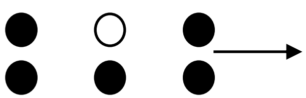


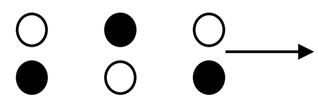
C Boston Dynamics

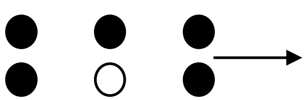
The number of distinct event sequences for biped:

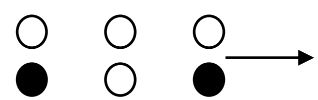
- With two legs (biped) one can have four different states
  - 1) Both legs down ●●
  - 2) Right leg down, left leg up ○●
  - 3) Right leg up, left leg down ●○
  - 4) Both leg up ○○
- A distinct event sequence can be considered as a change from one state to another and back.
- So we have the following $N = (2k-1)! = 6$ distinct event sequences (change of states) for a biped:

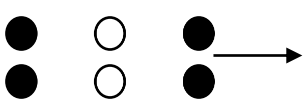
● *Leg down*
○ *Leg up*

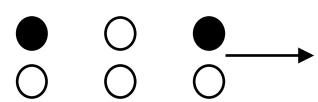
1 -> 2 -> 1

turning on right leg

2 -> 3 -> 2

walking running

1 -> 3 -> 1

turning on left leg

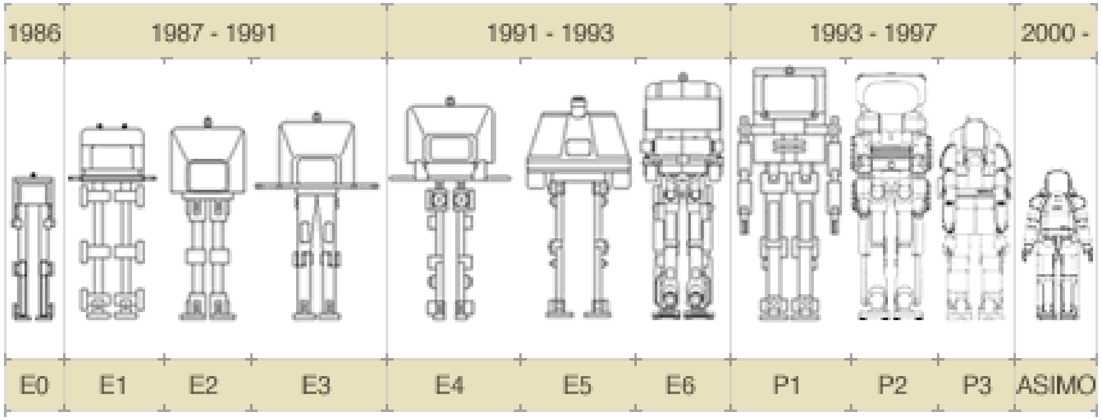
2 -> 4 -> 2

hopping right leg

1 -> 4 -> 1

hopping with two legs

3 -> 4 -> 3

hopping left leg

Case Study: Stiff 2 Legged Walking

- P2, P3 and Asimo from Honda, Japan
- P2
  - Maximum Speed: 2 km/h
  - Autonomy: 15 min
  - Weight: 210 kg
  - Height: 1.82 m
  - Leg DOF: 2x6
  - Arm DOF: 2x7



C Honda corp.

Stiff Robots are Dangerous

C DLR

Case Study: Passive Dynamic Walker

- Forward falling combined with passive leg swing
- Storage of energy: potential ←→ kinetic in combination with low friction

C youtube material

Efficiency Comparison

- Efficiency = c_{mt} = |mech. energy| / (weight x dist. traveled)

$c_{mt}^{est.} \approx 1.6$

Collins *et al.* 2005

$c_{mt} \approx 0.31$

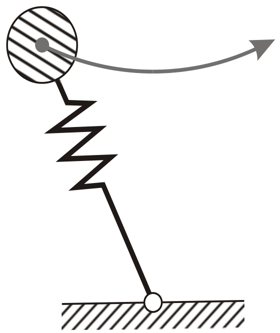
$c_{mt} \approx 0.055$

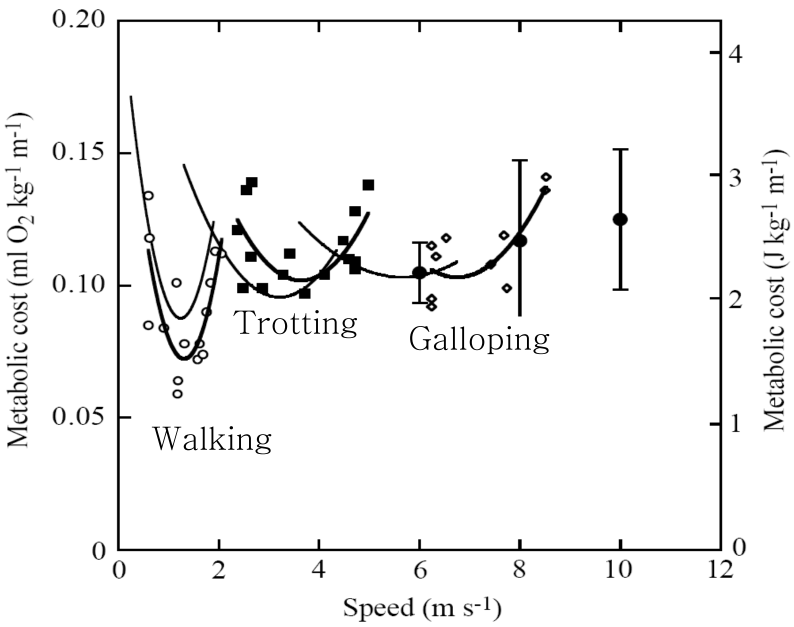
Collins *et al.* 2005

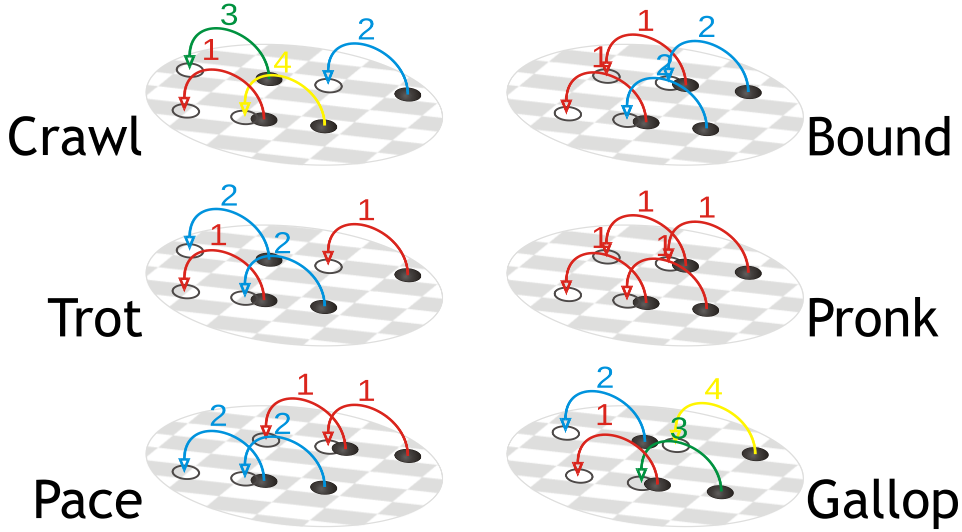
C J. Braun, University of Edinburgh, UK

Towards Efficient Dynamic Walking: Optimizing Gaits

- Nature optimizes its gaits
- Storage of "elastic" energy
- To allow locomotion at varying frequencies and speeds, different gaits have to utilize these elements differently





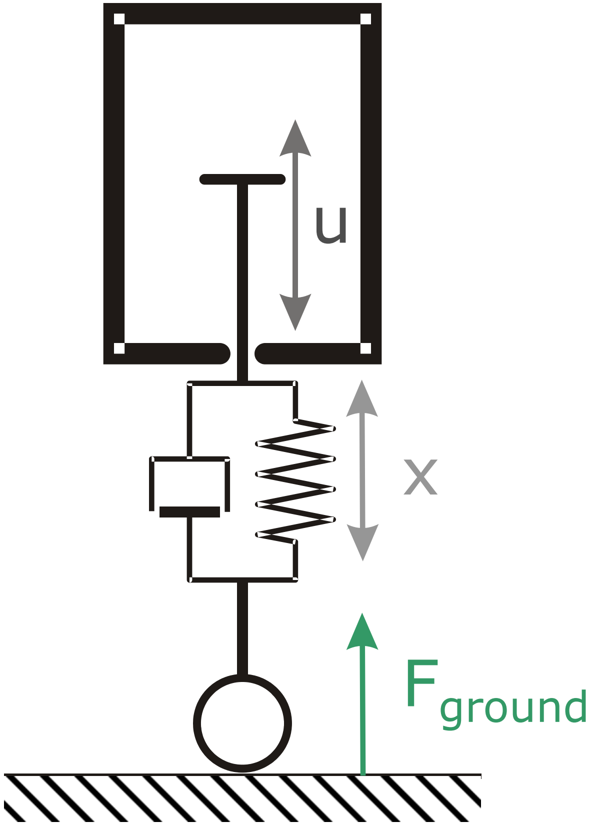


- The energetically most economic gait is a function of desired speed.
  (Figure [Minetti et al. 2002])

Towards Efficient Dynamic Walking: Optimizing Gaits

C Structure and motion laboratory
University of London

Towards Efficient Dynamic Walking: Series Elastic Actuation

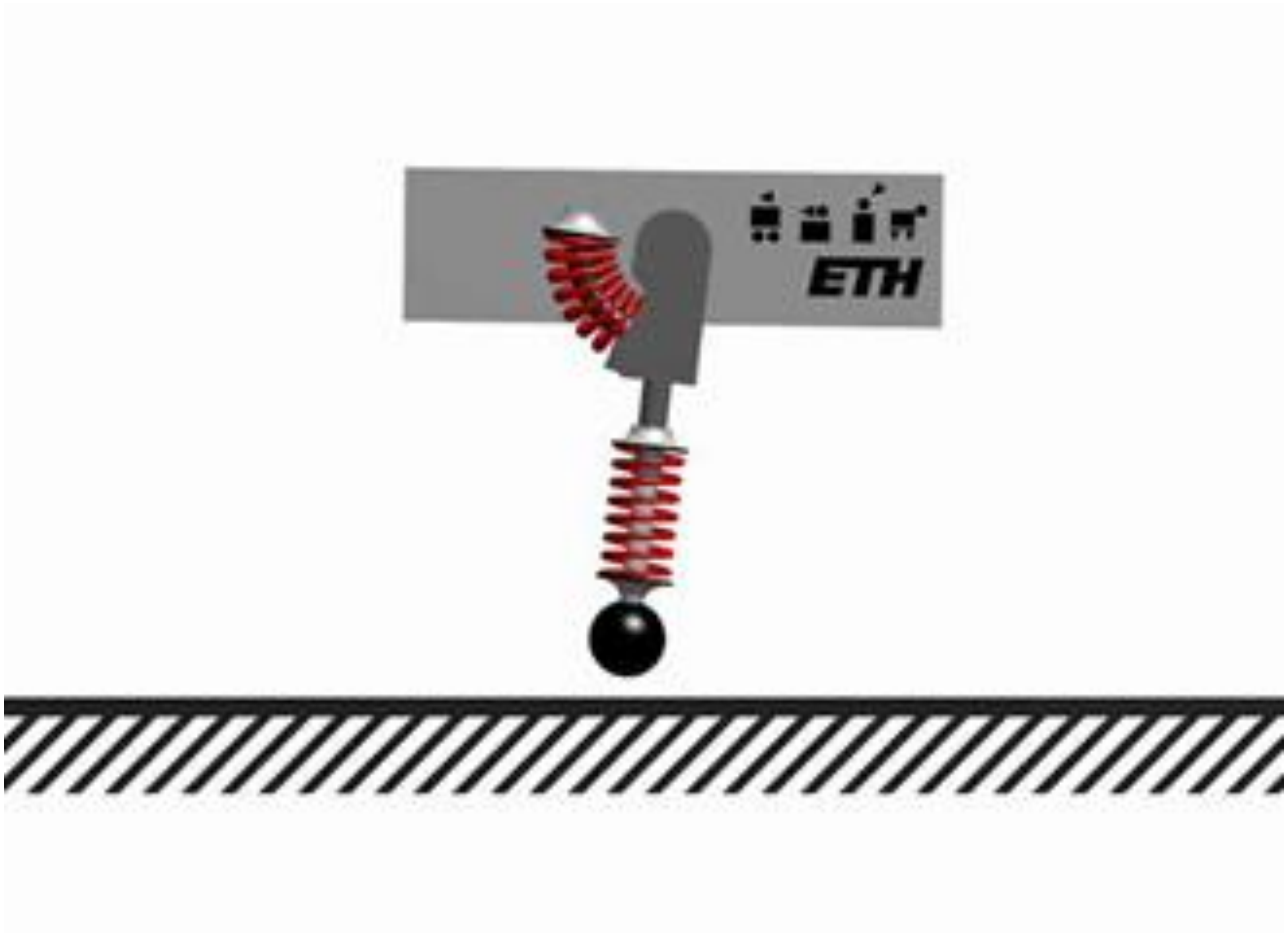


Series Elastic Actuator

- The optimal actuator for such a purpose should
  - be **backdrivable** to allow unimpeded natural dynamics
  - be able to **perform negative work**
  - have a low inertia and gear ratio to keep the reflected inertia small
  - have an adjustable actuator compliance
  - be **highly efficient**
- Series Elastic Actuators can emulate some of these properties
  - However, they come at the cost of active energy consumption
  - Some of the efficiency-benefits of passive dynamic locomotion are only shown as ‘proof of concept’

:Case Study: Efficient Walking with Springs

- ETH-ASL Hopping Leg

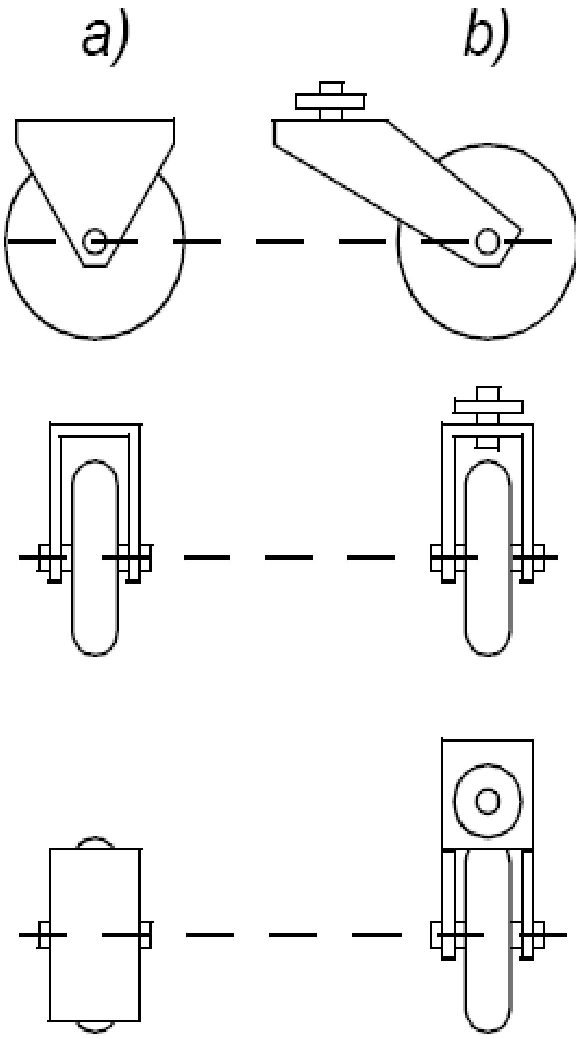


Mobile Robots with Wheels

- Wheels are the most appropriate solution for most applications
- Three wheels are sufficient to guarantee stability
- With more than three wheels an appropriate suspension is required
- Selection of wheels depends on the application

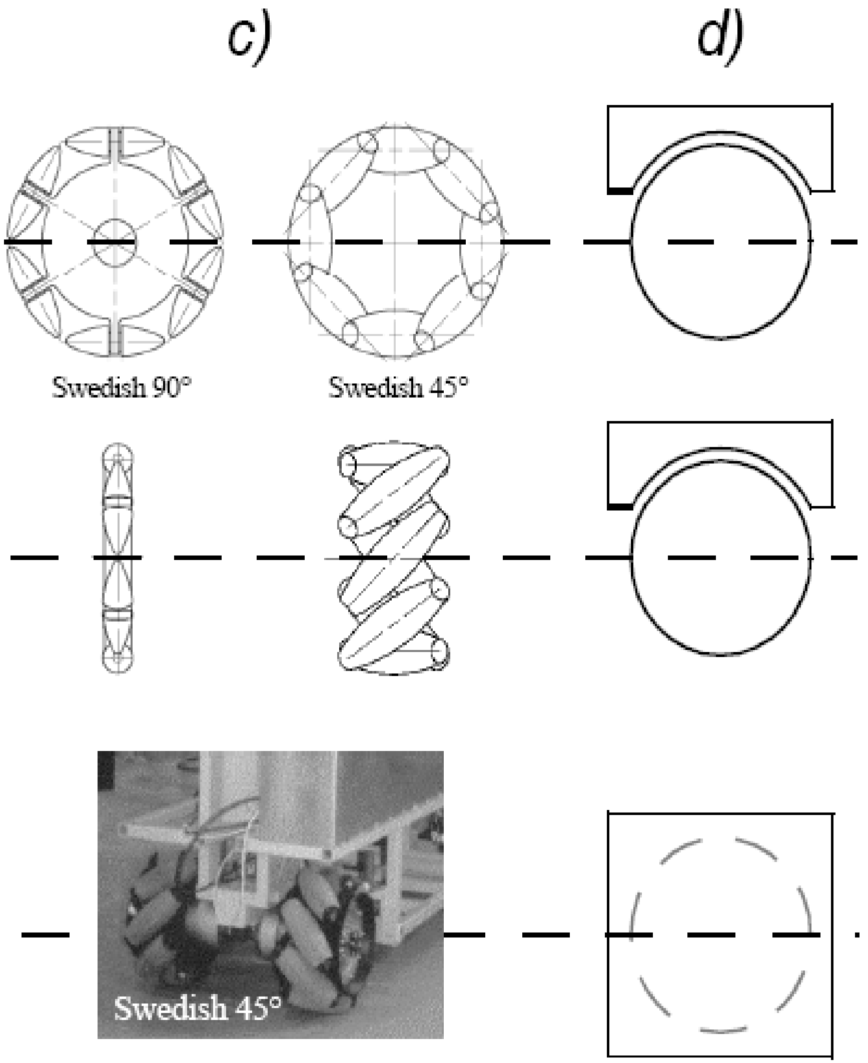
The Four Basic Wheels Types

- a) Standard wheel: Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point
- b) Castor wheel: Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle



The Four Basic Wheels Types

- c) Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point
- d) Ball or spherical wheel: Suspension technically not solved

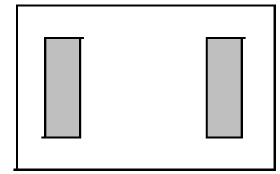


Characteristics of Wheeled Robots and Vehicles

- **Stability** of a vehicle is be guaranteed with **3 wheels**
  - If center of gravity is within the triangle which is formed by the ground contact point of the wheels.
- Stability is improved by 4 and more wheel
  - however, this arrangements are hyper static and require a flexible suspension system.
- **Bigger wheels** allow to overcome **higher obstac**les
  - but they require higher torque or reductions in the gear box.
- Most arrangements are **non-holonomic** (see chapter 3)
  - require high control effort
- Combining actuation and steering on one wheel makes the design complex and adds additional errors for odometry.

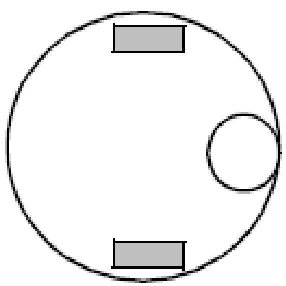
Different Arrangements of Wheels I

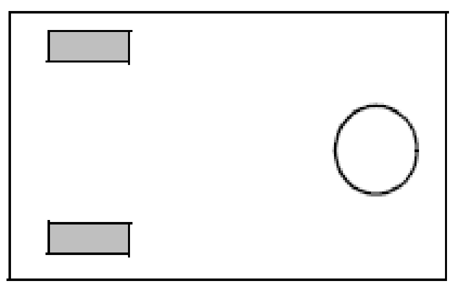
- Two wheels

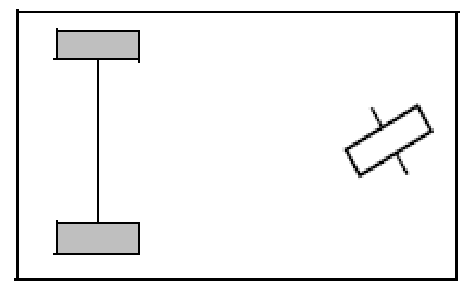


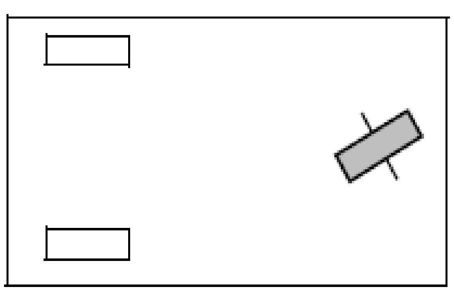
COG below axle

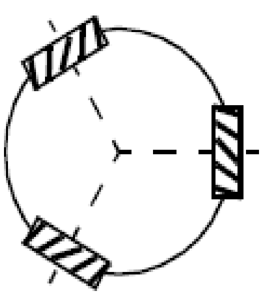
- Three wheels



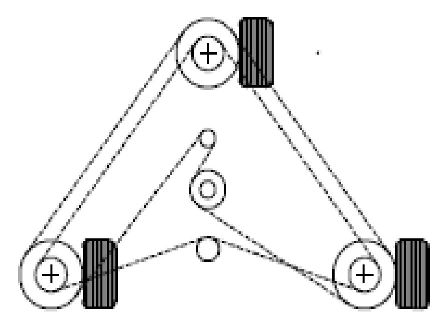








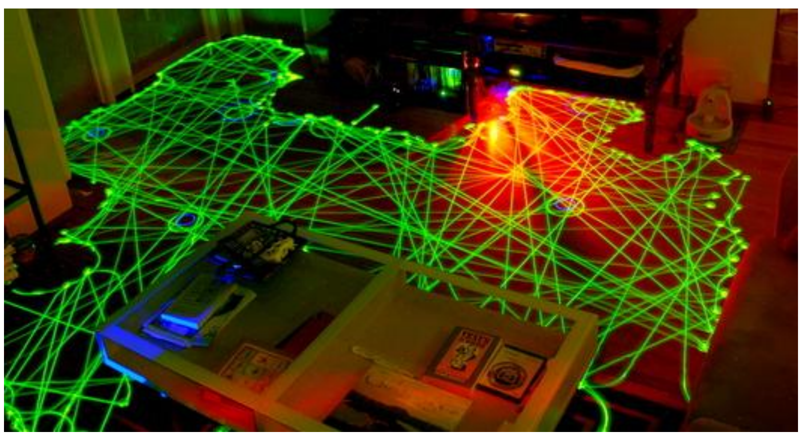
Omnidirectional Drive



Synchro Drive

Case Study: Vacuum Cleaning Robots

- iRobot Roomba vs.
- Neato XV-11

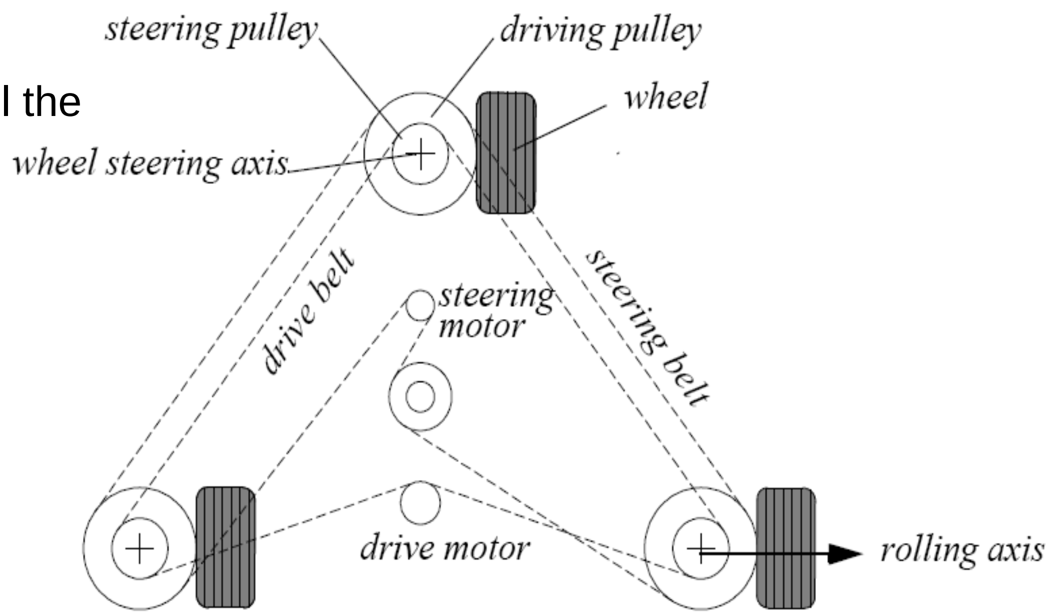


Images courtesy http://www.botjunkie.com

Synchro Drive

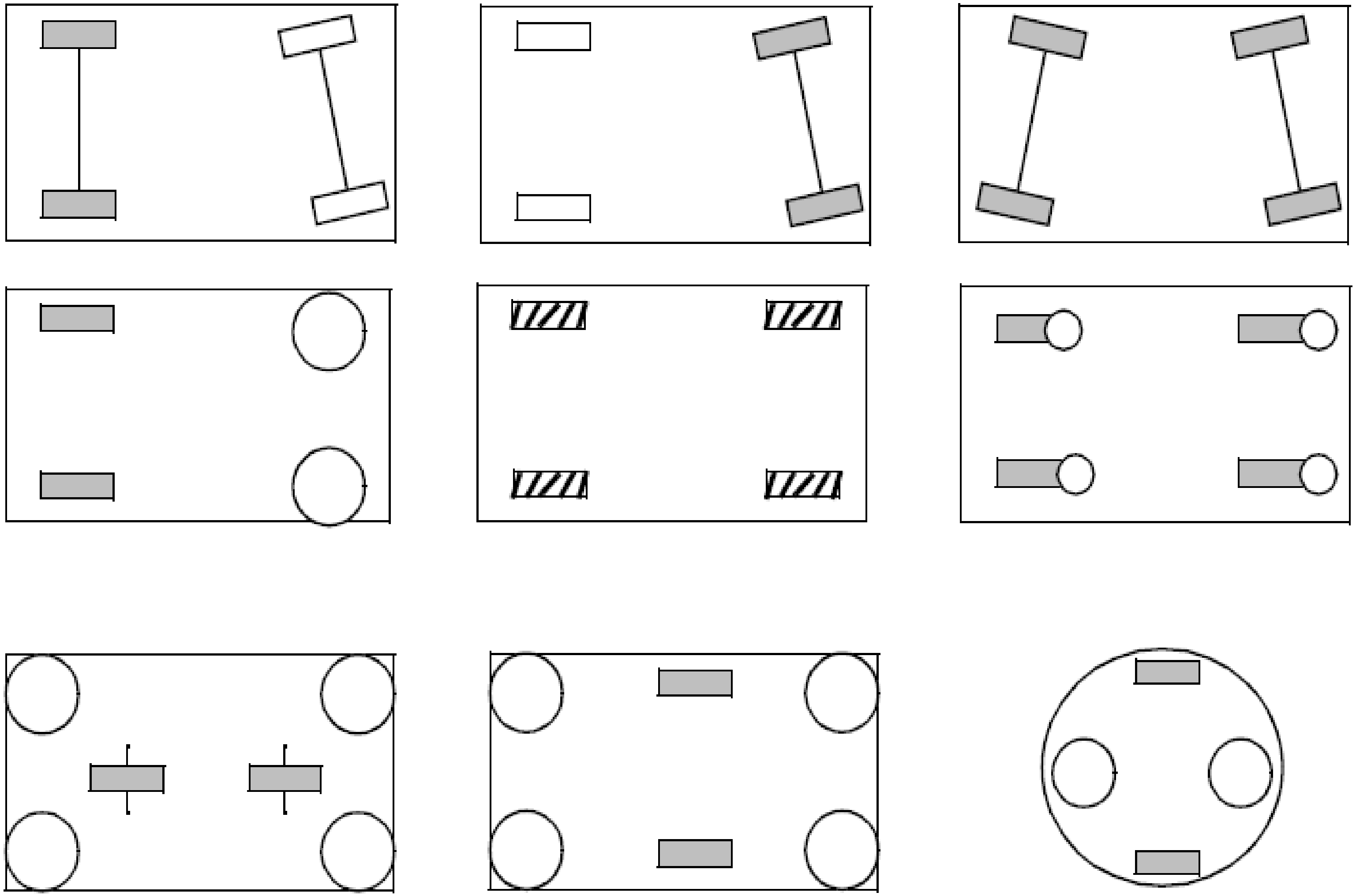
- All wheels are actuated synchronously by one motor
  - defines the speed of the vehicle
- All wheels steered synchronously by a second motor
  - sets the heading of the vehicle

- The orientation in space of the robot frame will always remain the same
  - It is therefore not possible to control the orientation of the robot frame.



Different Arrangements of Wheels II

- Four wheels



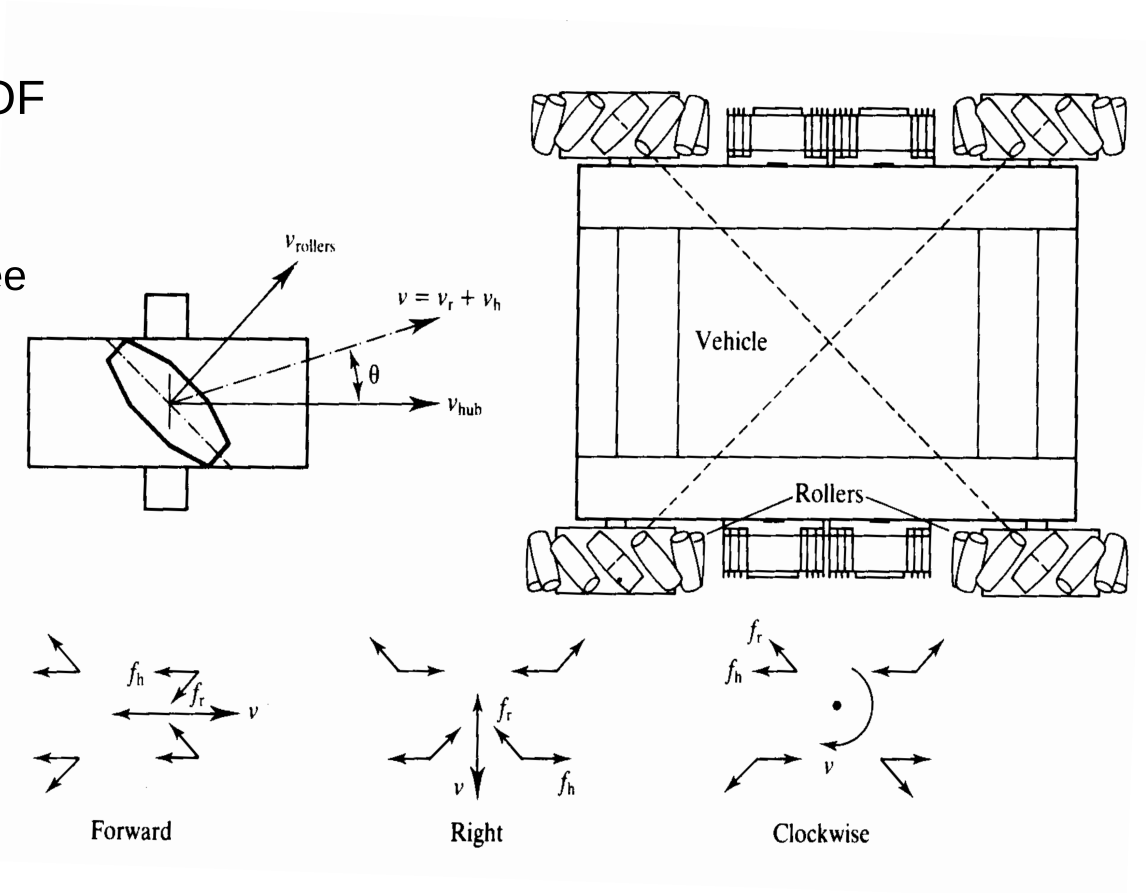
Case Study: Willow Garage‘s PR2

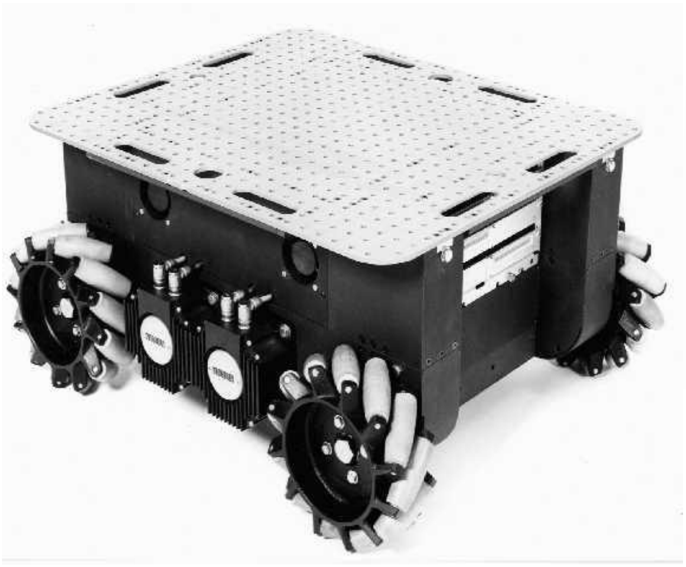
- Four powered castor wheels with active steering
- Results in omni-drive-like behaviour
- Results in simplified high-level planning (see chapter 6)

C Willow Garage

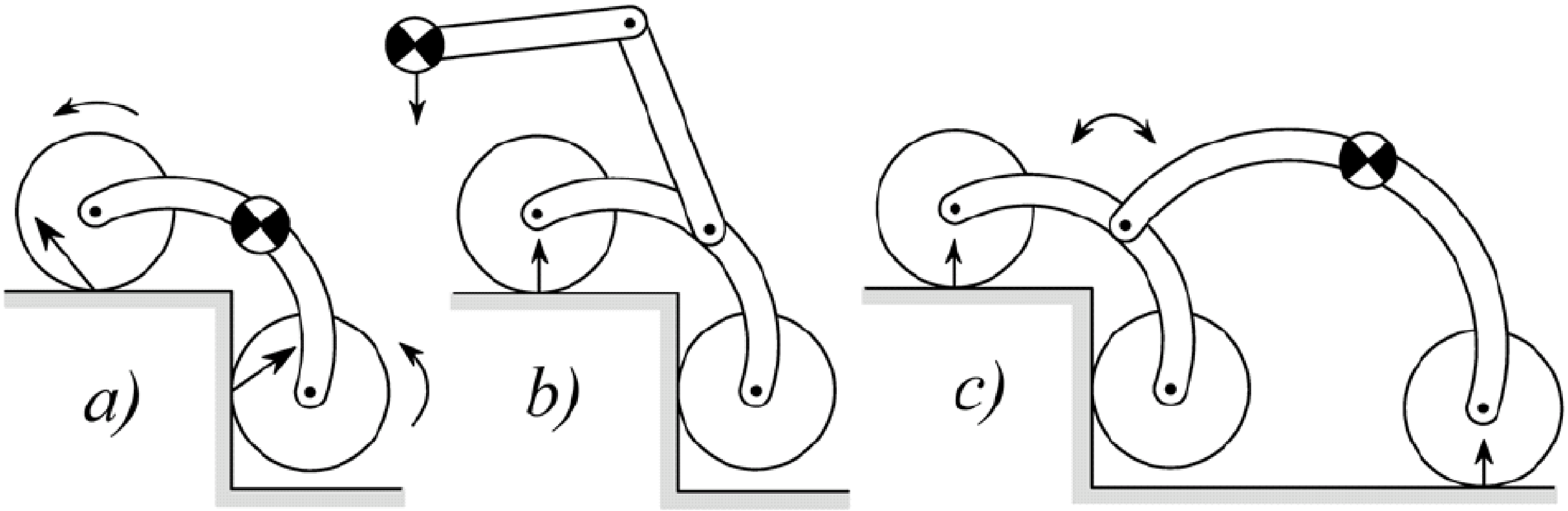
CMU Uranus: Omnidirectional Drive with 4 Wheels

- Movement in the plane has 3 DOF
  - thus only three wheels can be independently controlled
  - It might be better to arrange three swedish wheels in a triangle





Wheeled Rovers: Concepts for Object Climbing



Purely friction based

Change of center of gravity (CoG)

Adapted suspension mechanism with passive or active joints

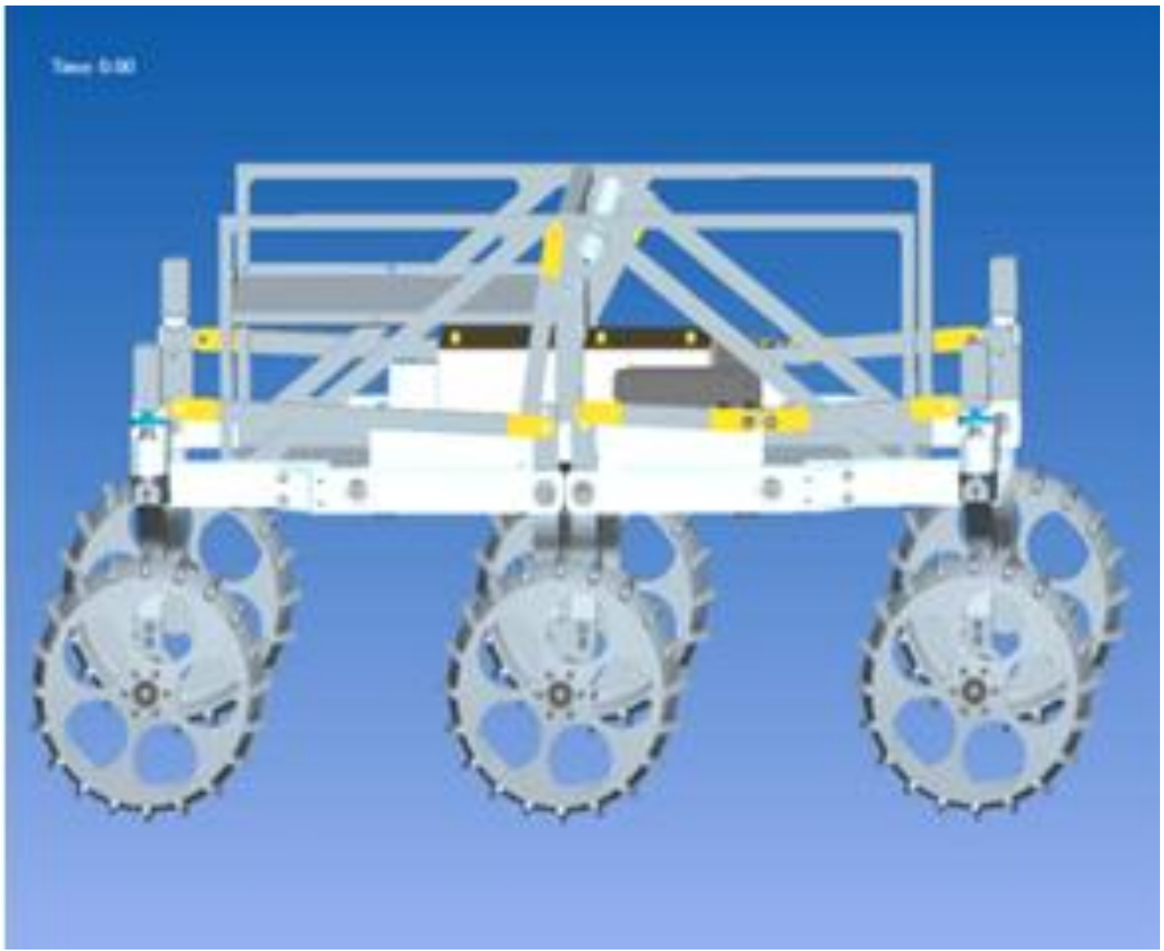
The Personal Rover

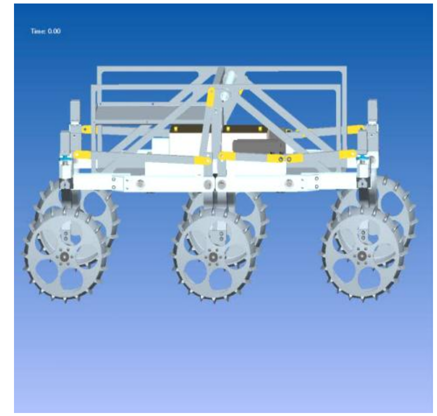
Climbing with Legs: EPFL Shrimp

- Passive locomotion concept
- 6 wheels
  - two boogies on each side
  - fixed wheel in the rear
  - front wheel with spring suspension
- Dimensions
  - length: 60 cm
  - height: 20 cm
- Characteristics
  - highly stable in rough terrain
  - **overcomes obstacles up to 2 times its wheel diameter**

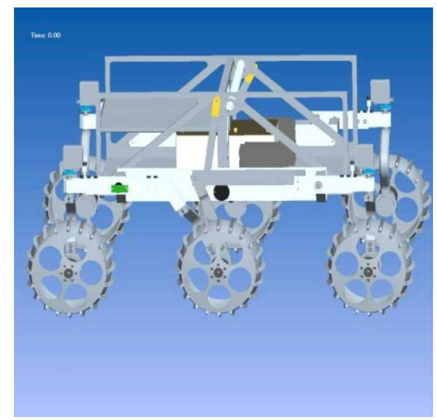
Rover Concepts for Planetary Exploration

- ExoMars: ESA Mission to Mars in ~~2013, 2015~~, 2018
  - Six wheels
  - Symmetric chassis
  - No front fork → intstrument placement

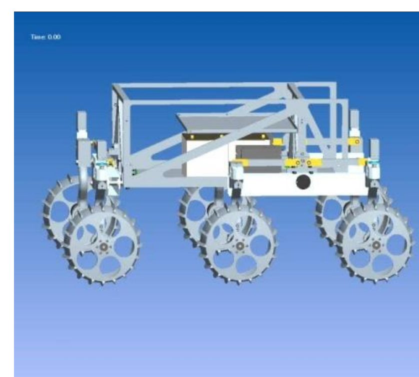




Crab ETH



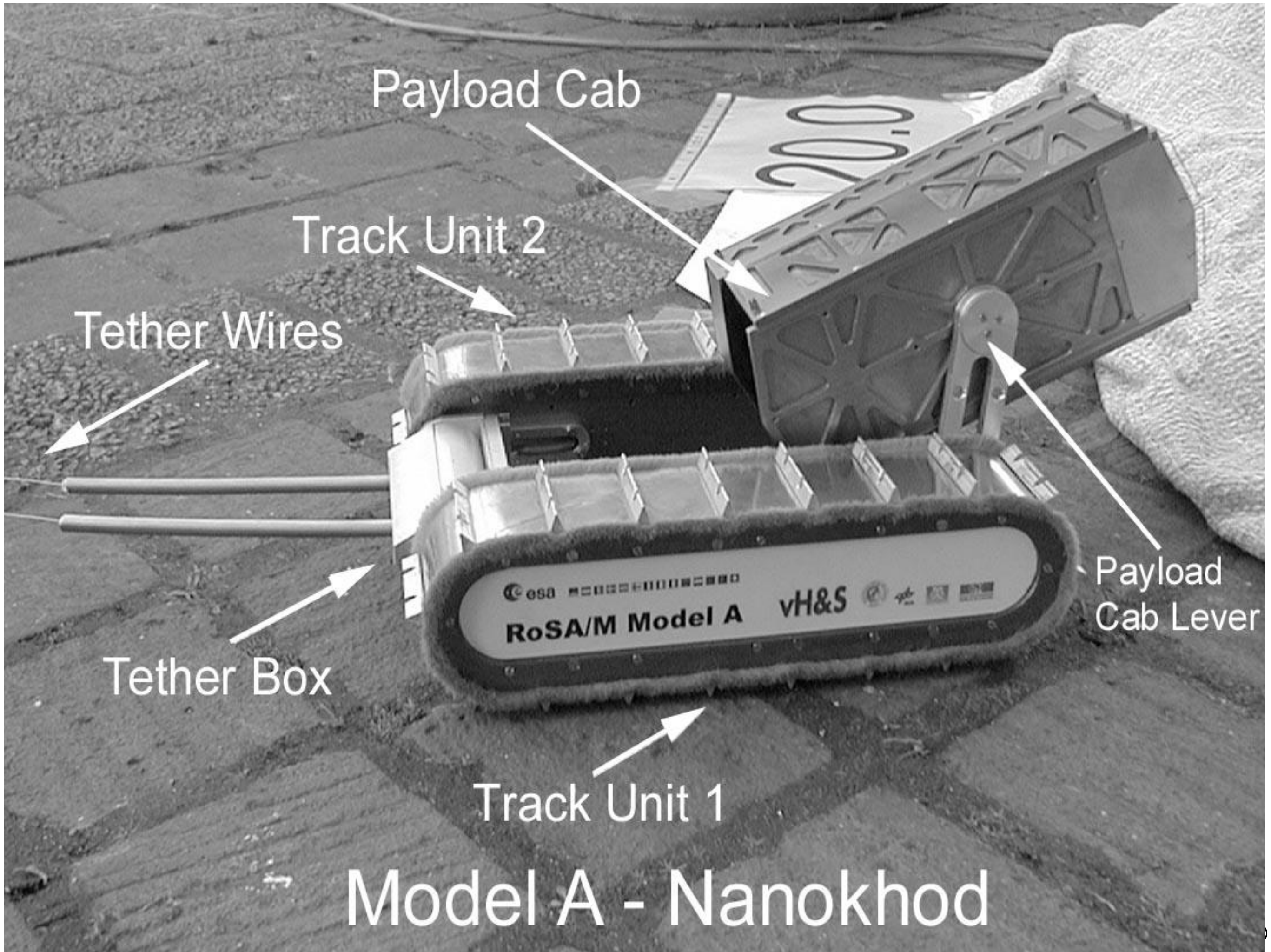
Concept C
RCL Russia



Concept E

Caterpillar

- The NANOKHOD II,
  - developed by von Hoerner & Sulger GmbH and Max Planck Institute, Mainz
  - will probably go to Mars



Other Forms of „Locomotion“: Traditional and Emerging

- Flying

- Swimming

C Essex Univ.