Corso di Percezione Robotica (PRo)

Prof.ssa Cecilia Laschi

Fondamenti di Robotica Biomimetica

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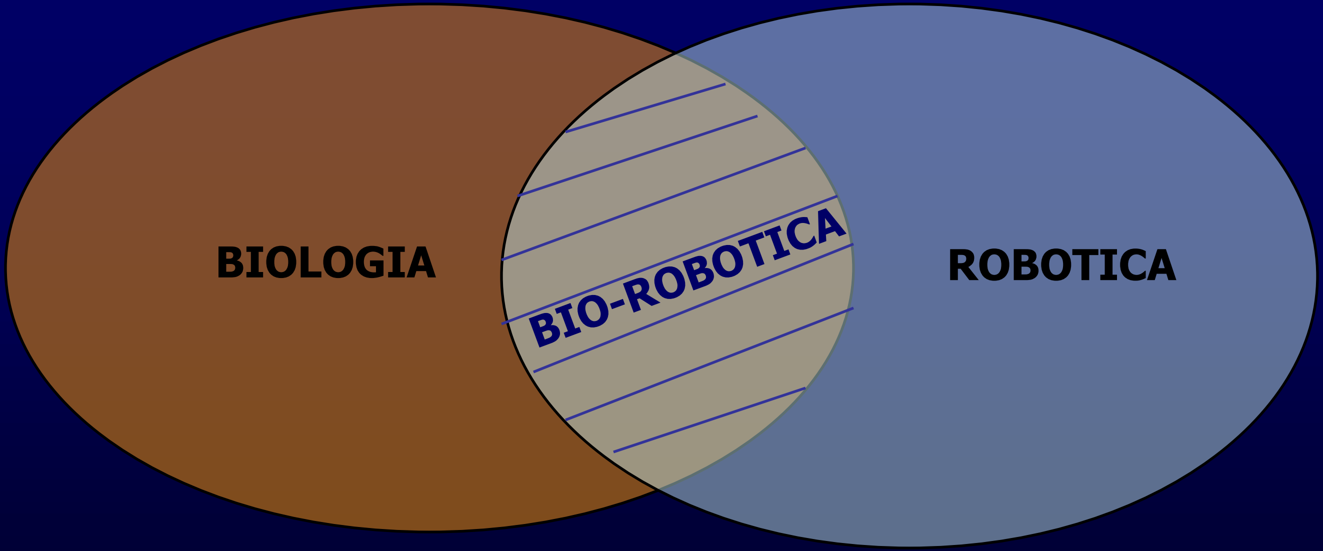
Contenuti del modulo

- Introduzione alla biorobotica
- Classificazione degli organismi viventi
- Fondamenti della zoologia
- 1° caso studio: robot ispirati agli artropodi
- 2° caso studio: robot ispirati al geco
- Tecniche di fabbricazione: Shape Deposition Manufacturing

INTRODUZIONE ALLA BIOROBOTICA

Introduzione

Biorobotica può essere definita come l'intersezione tra la biologia e la robotica (Webb, B., 2001)



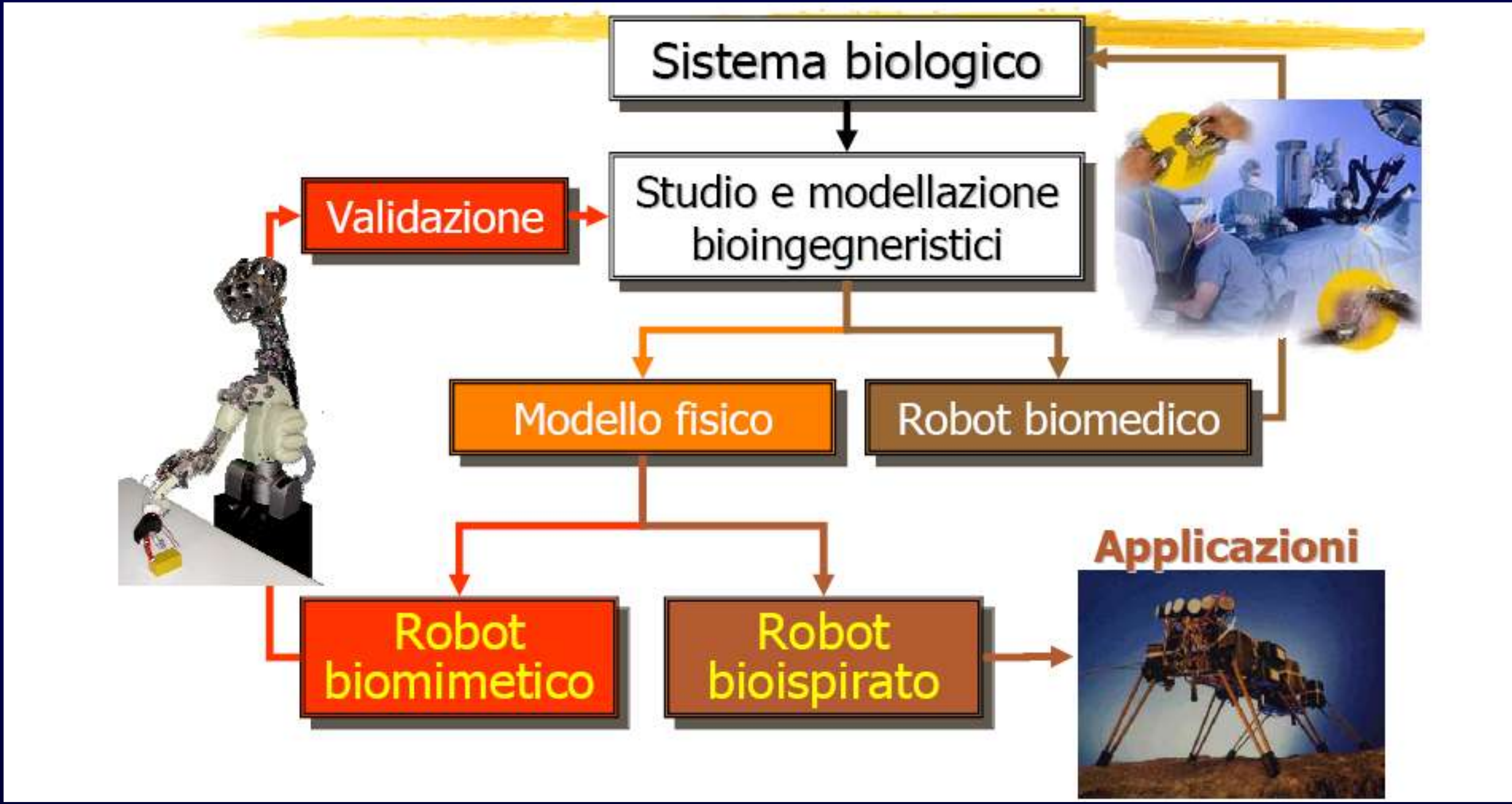
Obiettivi della Robotica Bioispirata

Analizzare e capire come funzionano i sistemi biologici e prendere **ispirazione** da questa conoscenza per progettare nuovi e migliori sistemi robotici

Obiettivi della Robotica Biomimetica

- Analizzare e studiare come funzionano i sistemi biologici e usare questi modelli per progettare nuovi e migliori sistemi robotici che **imitano** le funzionalità della loro controparte biologica
- Sviluppare piattaforme fisiche **equivalenti** ai sistemi biologici, al fine di testare sperimentalmente “modelli” di sistemi viventi e i loro principi funzionali

Robotica bio-ispirata


Sistema biologico

Validazione

Studio e modellazione bioingegneristici

Modello fisico

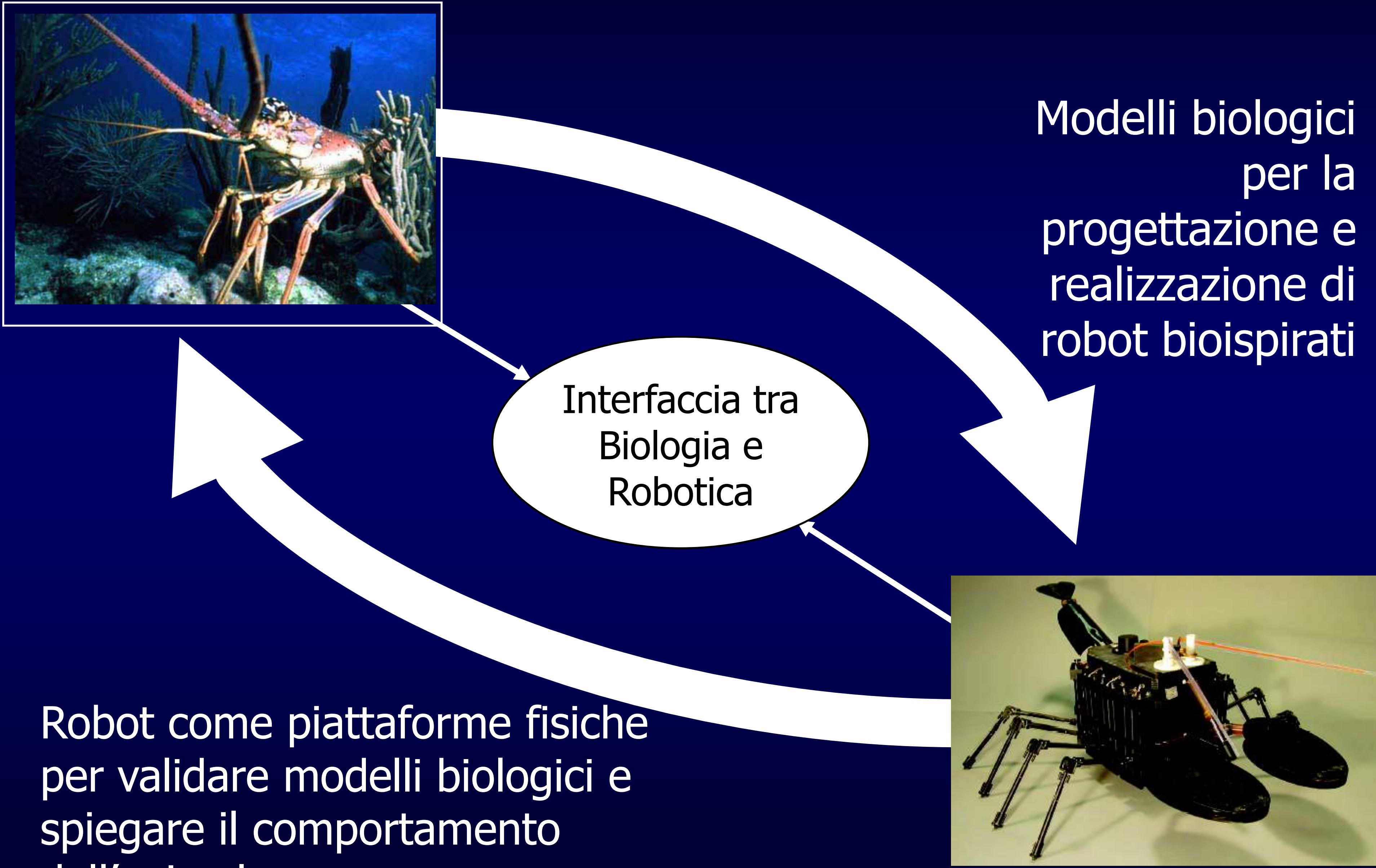
Robot biomedico

Robot biomimetico

Robot bioispirato

Applicazioni

I robot e il modello biologico



Modelli biologici per la progettazione e realizzazione di robot bioispirati

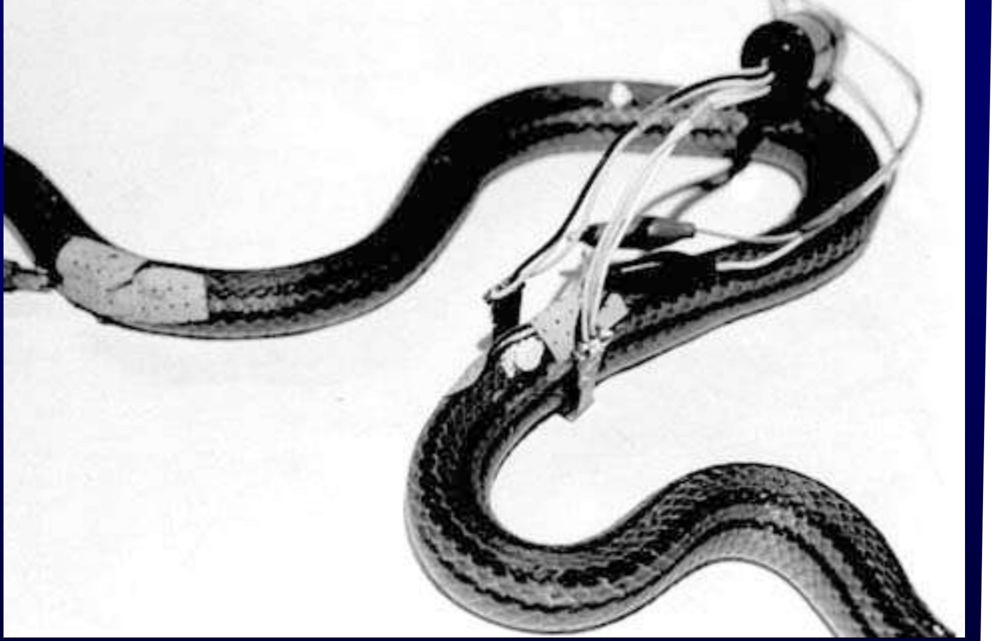
Interfaccia tra Biologia e Robotica

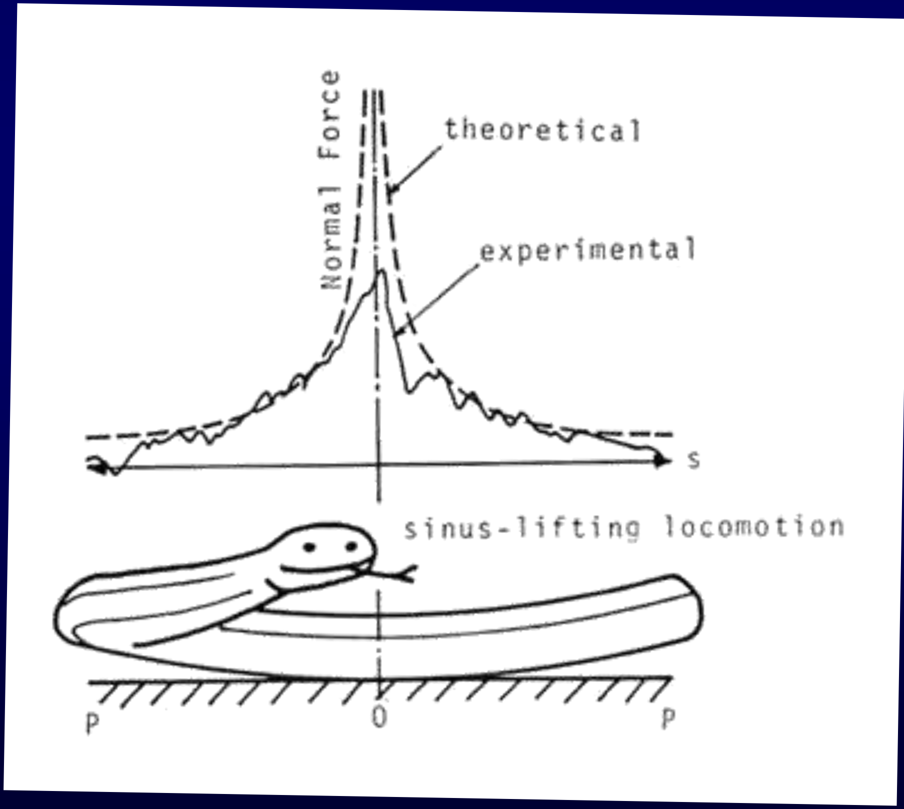
Robot come piattaforme fisiche per validare modelli biologici e spiegare il comportamento dell’animale

Ricerche sui robot ispirati ai serpenti (TIT, Giappone)

"How is it that a snake can go forward without legs?
This question largely remained unanswered, and this required an engineering analysis‟

Shigeo Hirose, Tokyo Institute of Technology, Japan





Cosa significa essere biologicamente ispirato?

Sono possibili molti **livelli di bioispirazione**, da una vaga somiglianza ad una stretta emulazione.

Nel caso della locomozione di robot ispirati ad insetti

- **Semplici esempi** di ispirazione biologica (ad es. osservare che gli animali usano le zampe anziché le ruote, o che l'uso di sei zampe nell'insetto fornisce maggiore stabilità);
- **Emulare**, in ogni dettaglio, una particolare specie di insetto;
- Studiare il numero e la configurazione dei **gradi di libertà della zampa** utilizzati dall'insetto per attraversare terreni accidentati e, sulla base degli effetti di torsione che questi gradi di libertà esercitano, selezionare la migliore geometria del robot;
- Esaminare in dettaglio i tipi di **informazioni sensoriali** che l'insetto usa per ben adattare I movimenti delle zampe;
- Cercare di emulare le differenti **strategie comportamentali** che l'insetto usa per attraversare terreni di varia natura;
- Cercare di basare la progettazione **dei controllori del cammino** per robot su zampe sui principi architetturali e funzionali dei circuiti nervosi implicati nel controllo del cammino dell'insetto.

Biomimetica

La Biomimetica è stata applicata ad un ampio numero di settori (cibernetica, intelligenza di sciame, neuroni artificiali, reti di neuroni artificiali, robotica, ecc.)

Generalmente sono tre le aree della biologia alle quali si ispirano le soluzioni tecnologiche:

- Replicare i metodi naturali di **fabbricazione di composti chimici** prodotti dalle piante e dagli animali (e.g. soft tissues, such as muscle; rubber produced by plants -*Ficus elastica*-; etc.)

- Imitare i **meccanismi** presenti in Natura, come quelli del Velcro e "Adesivo modello Geco"

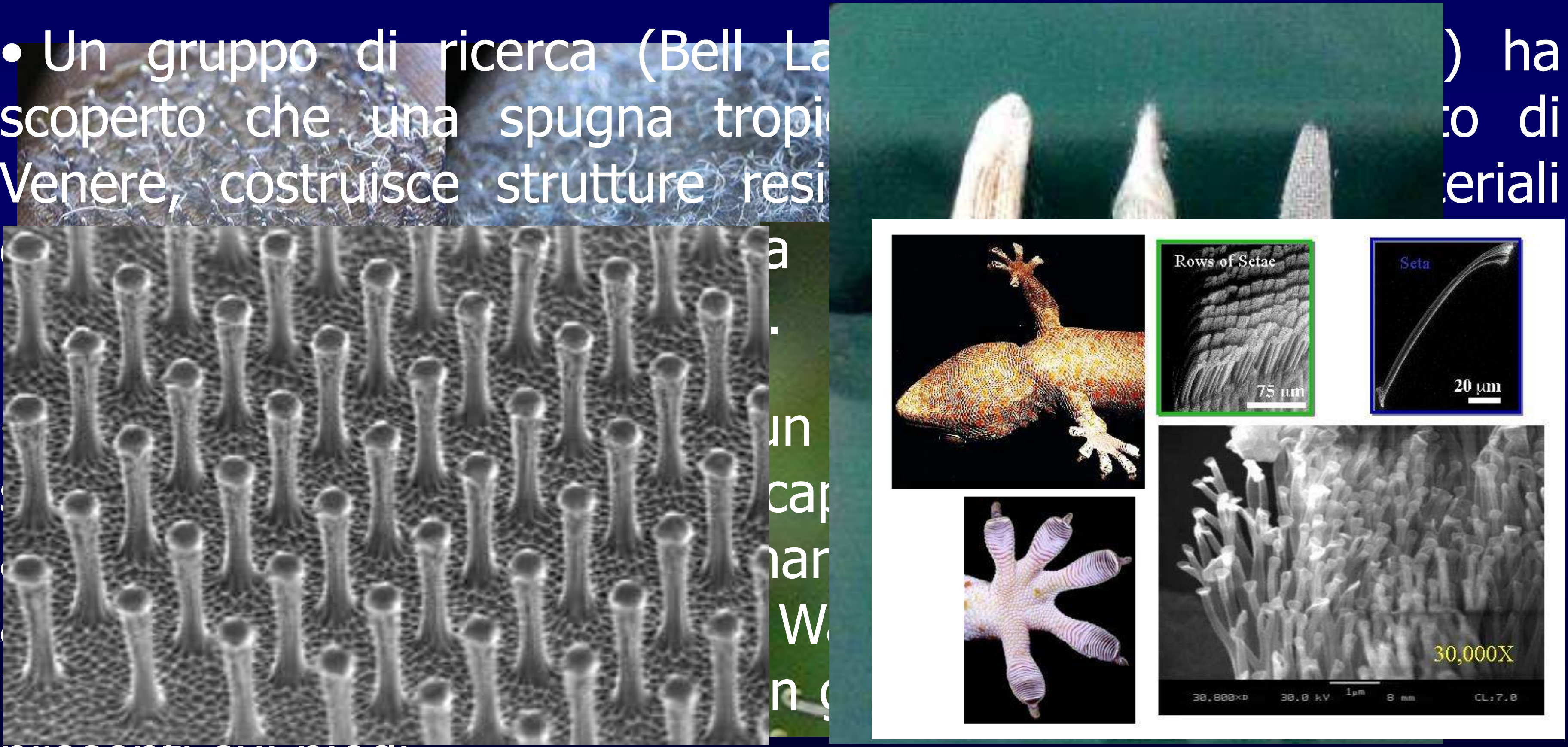
- Imitare i principi dei **comportamenti sociali** di organismi come le formiche, le api e i microorganismi.

Biomimetica

Alcuni esempi di biomimetica:

- Il Velcro è stato ideato nel 1941 da un ingegnere svizzero, George de Mestral, notando che gli uncini di una pianta (*Arctium lappa*) si attaccavano al pelo del suo cane.

- Un gruppo di ricerca (Bell La) ha scoperto che una spugna tropi to di Venere, costruisce strutture resi teriali



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presenti sui piedi.

Biomimetica

- DaimlerChrysler sta sviluppando un nuovo modello di veicolo a basso consumo energetico ispirato alla forma del corpo del pesce scatola, un pesce che si trova comunemente nei mari tropicali. La macchina bionica offrirà un 20% di consumo di carburante in meno e una riduzione superiore all'80% di emissione di NO_2.

Biomimetica

Tuttavia..

"We think blind copying is exactly what you don't want to do," says Robert Full, a biologist at the University of Berkeley, California. "You will fail miserably, because nature is way too complex."

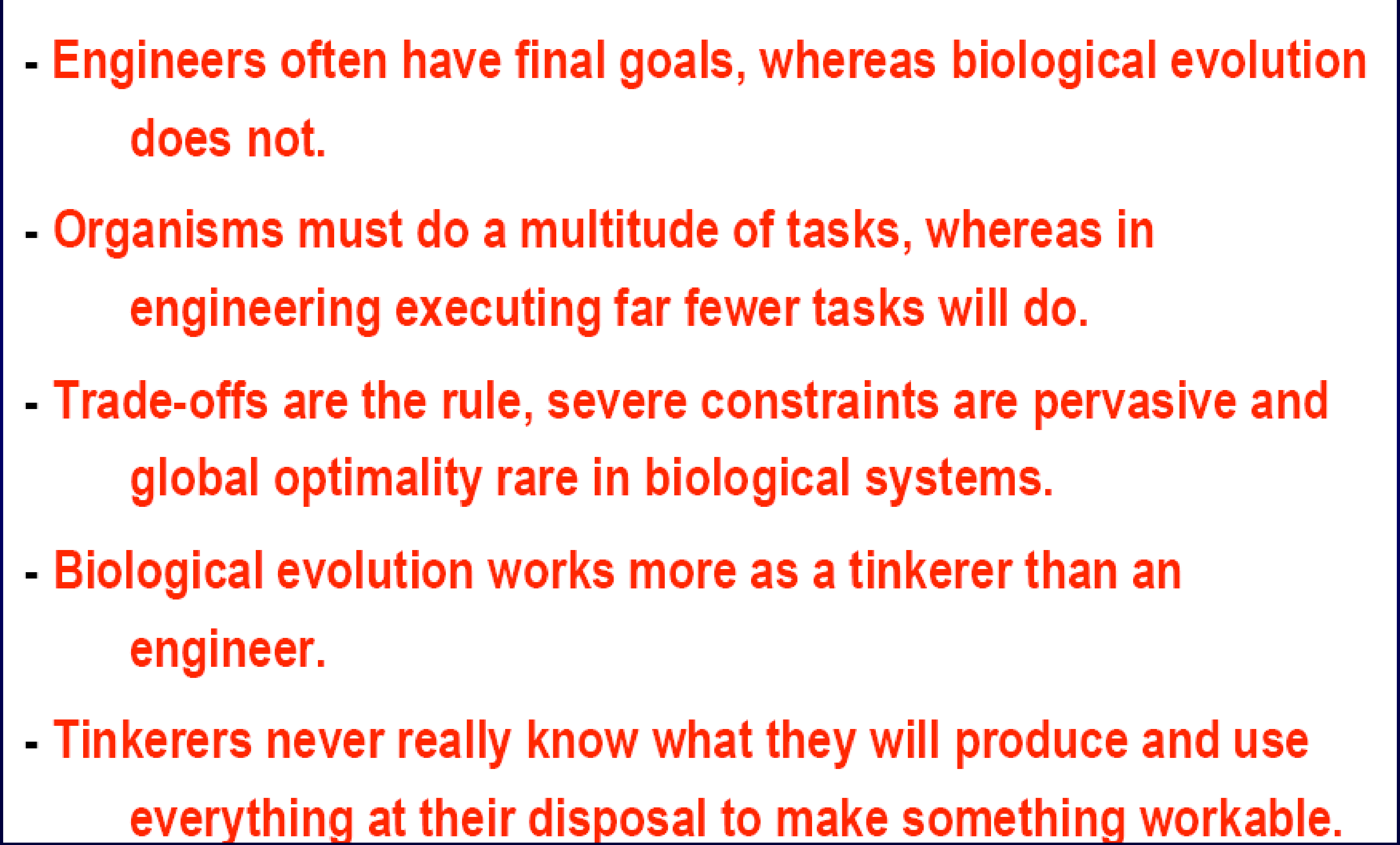
La selezione naturale non è Ingegneria

Attraverso l'**evoluzione**, la Natura ha "sperimentato" varie soluzioni e selezionato quelle più vantaggiose in relazione all'ambiente. Gli organismi in grado di sopravvivere **non sono necessariamente la soluzione ottimale** per le loro performance tecniche. Devono sopravvivere sufficientemente a lungo per riprodursi.

Esempi di alcuni dei più importanti risultati ingegneristici del 20° secolo

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Evoluzione vs Ingegneria



- Engineers often have final goals, whereas biological evolution does not.
- Organisms must do a multitude of tasks, whereas in engineering executing far fewer tasks will do.
- Trade-offs are the rule, severe constraints are pervasive and global optimality rare in biological systems.
- Biological evolution works more as a tinkerer than an engineer.
- Tinkerers never really know what they will produce and use everything at their disposal to make something workable.

Biology as a model

In order to harness the most from Nature’s inventions it is critical **to bridge between the fields of biology and engineering.**

This bridging effort can be a key **to turning Nature’s inventions into engineering capabilities, tools, and mechanisms.**

The job of the biomimeticist is <u>to identify</u> the system (or systems) responsible for producing the desired characteristic, <u>to extract</u> the key principles underlying their biological function, and then <u>to translate</u> them to a technological solution. Consequently, one cannot simply copy Nature, but rather carefully choose Nature’s behaviour of focus, and extract the underlying principle at a level of description that is actually possible to implement.

Biological Inspiration

Biology

Passive, Dynamic,
Self-stabilization

RHex

UPenn, Boston Dynamics, Berkeley

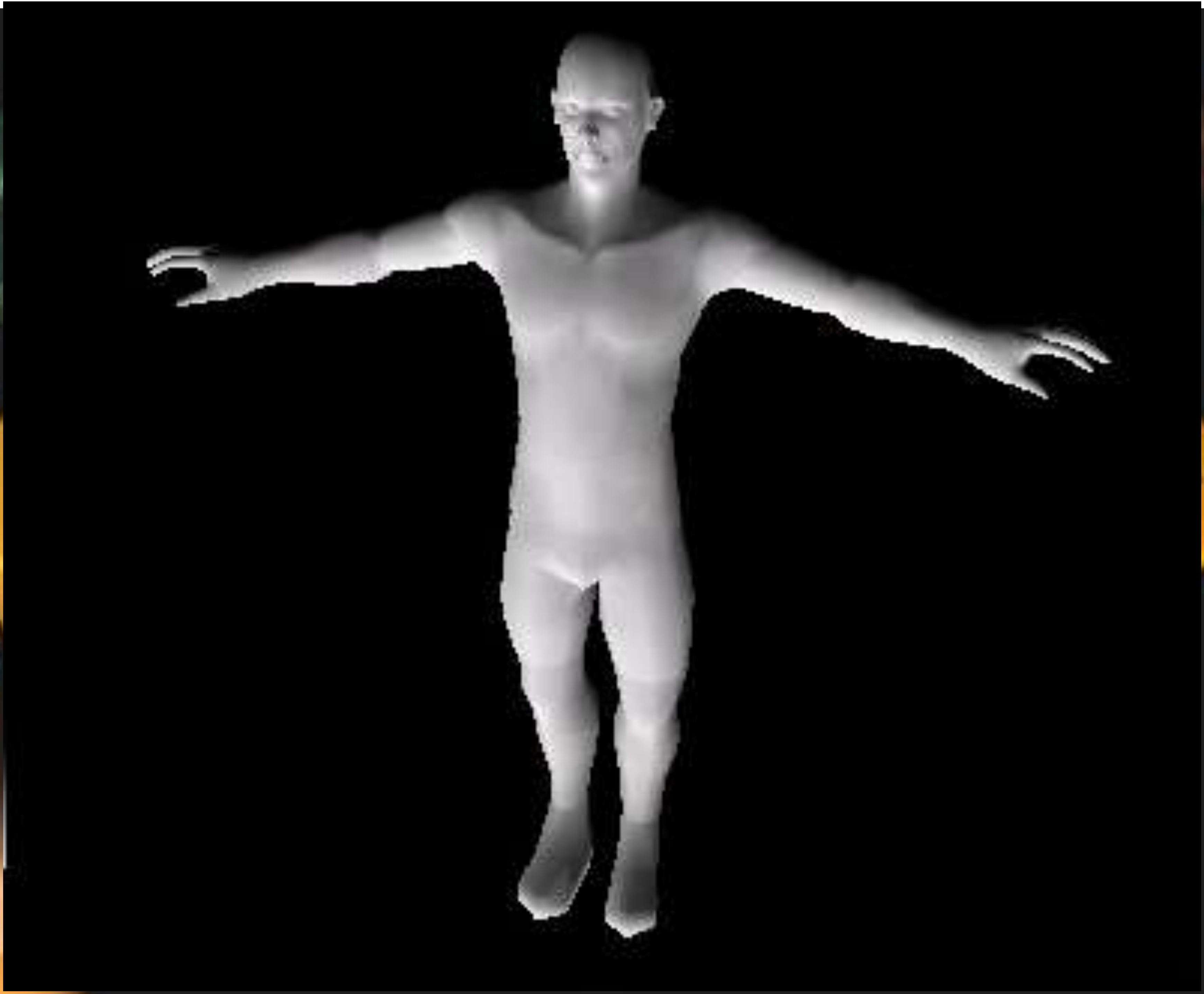
Engineering

Electric Motor

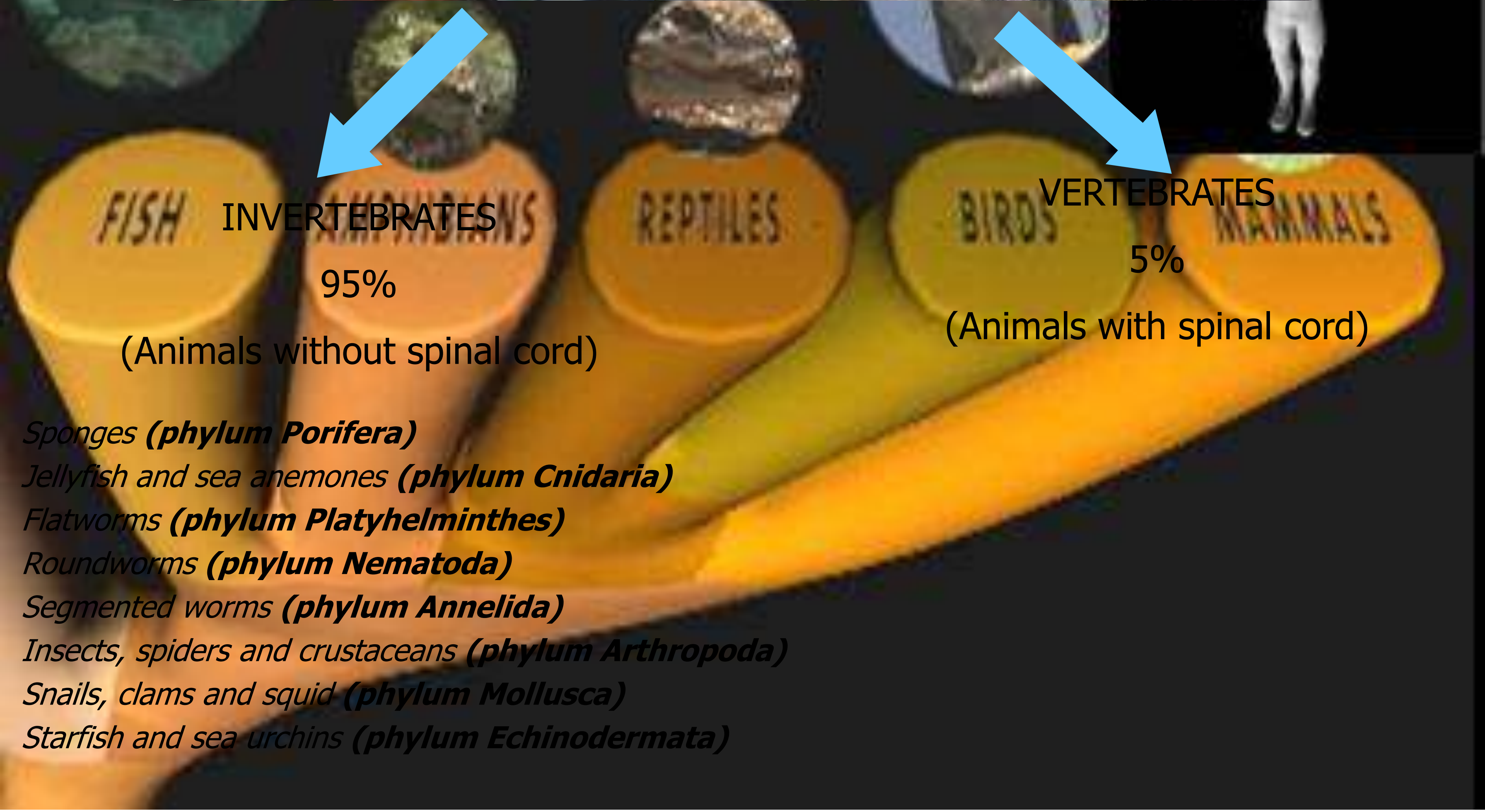
Use Principles and Analogies from Biology when Advantageous. Integrate with Best Human Engineering

II PARTE

GLI ORGANISMI VIVENTI



The Animalia Kingdom



INVERTEBRATES

95%

(Animals without spinal cord)

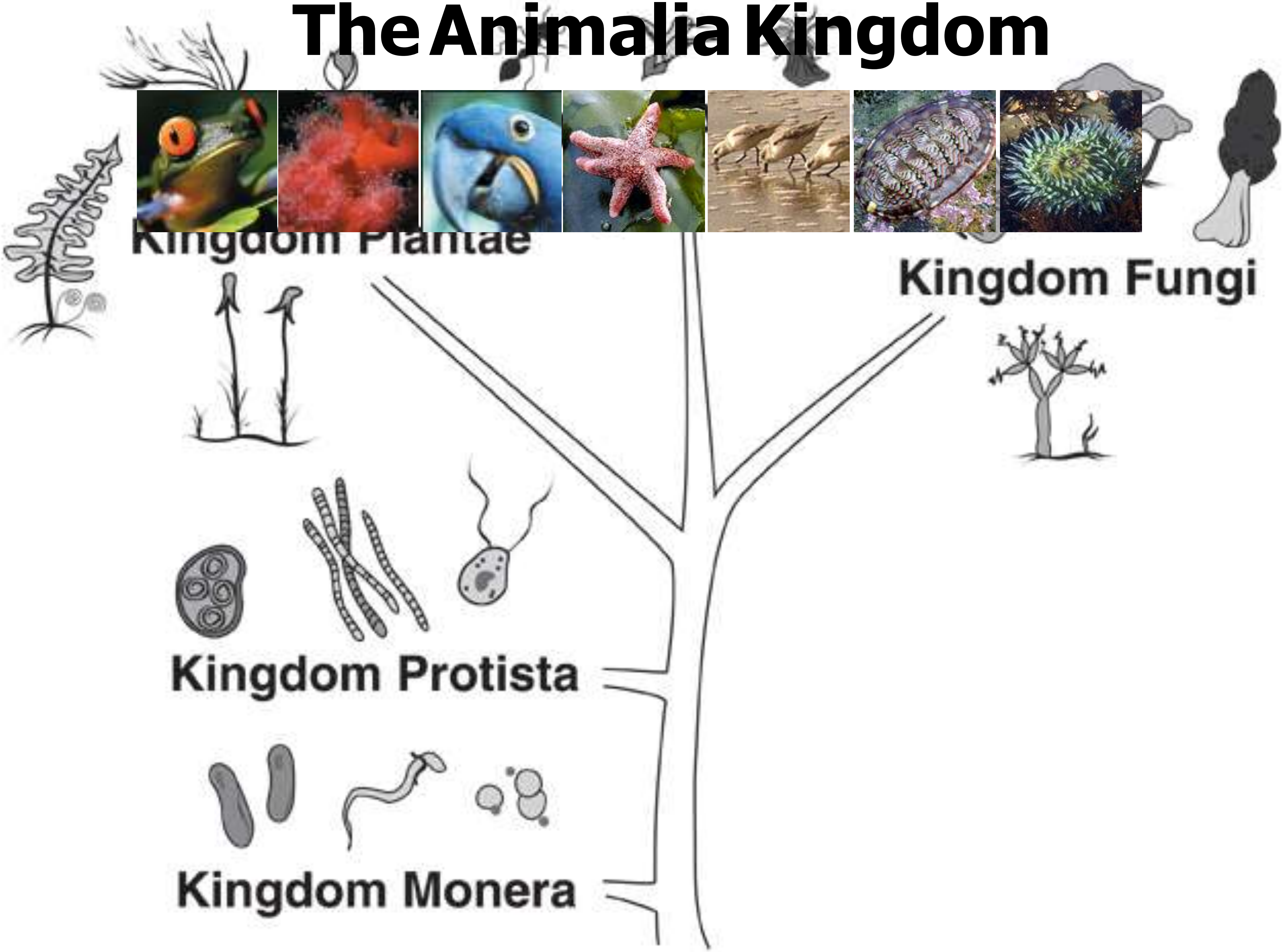
VERTEBRATES

5%

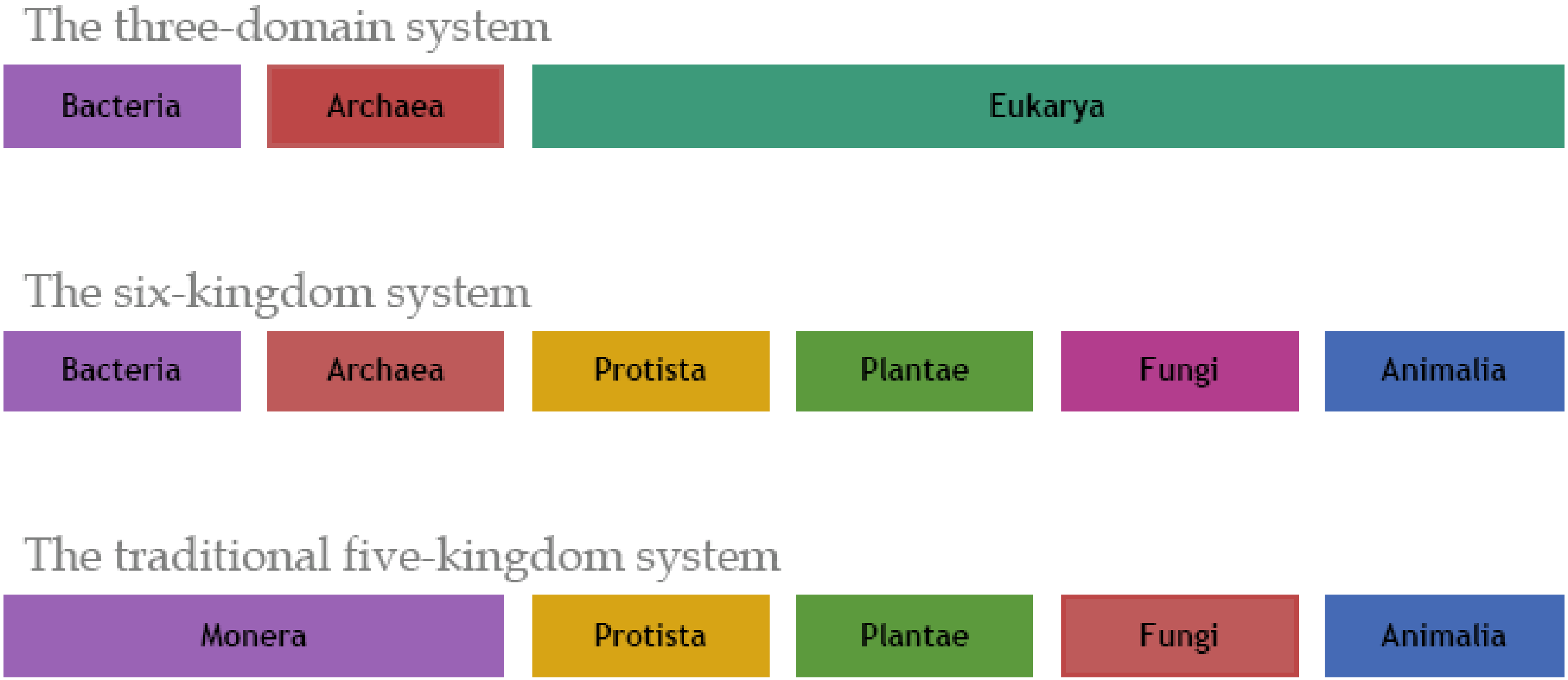
(Animals with spinal cord)

Sponges ***(phylum Porifera)***
Jellyfish and sea anemones ***(phylum Cnidaria)***
Flatworms ***(phylum Platyhelminthes)***
Roundworms ***(phylum Nematoda)***
Segmented worms ***(phylum Annelida)***
Insects, spiders and crustaceans ***(phylum Arthropoda)***
Snails, clams and squid ***(phylum Mollusca)***
Starfish and sea urchins ***(phylum Echinodermata)***

The Animalia Kingdom



Kingdoms and Domains



The three-domain system

Bacteria
Archaea
Eukarya

The six-kingdom system

Bacteria
Archaea
Protista
Plantae
Fungi
Animalia

The traditional five-kingdom system

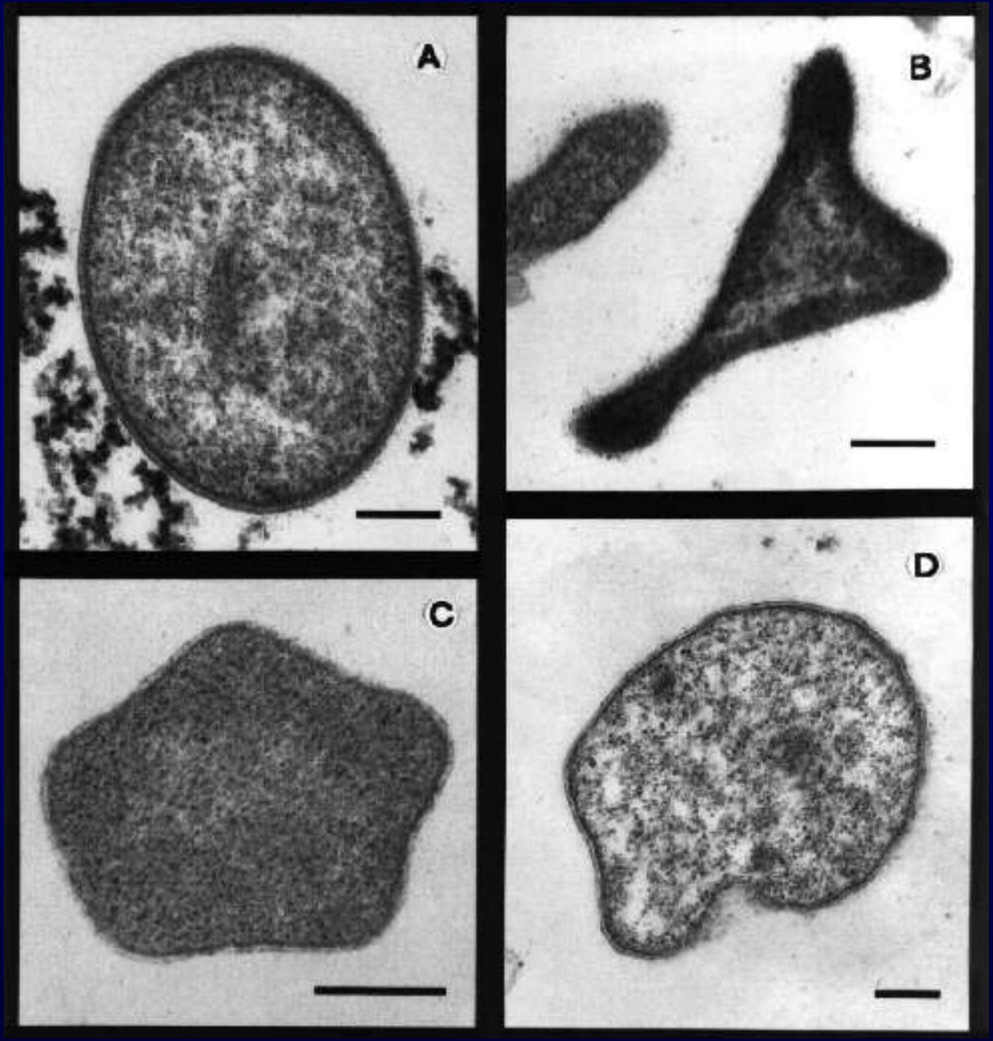
Monera
Protista
Plantae
Fungi
Animalia

The classification of living organisms

Domain Archaea

Archaea are microbes. Most live in extreme environments. These are called **extremophyles**. Other Archaea species are not extremophiles and live in ordinary temperatures and salinities. Some even live in our guts. Archaea was originally thought to be just like bacteria, **but archaea is a much different and simpler form of life.** It may also be the oldest form of life on Earth!

Archaea requires neither sunlight for photosynthesis as do plants, nor oxygen. Archaea absorbs CO_2, N_2, or H_2S and gives off methane gas as a waste product the same way humans breathe in oxygen and breathe out carbon dioxide.
Planets which contain an environment wherein archaea might survive include Venus, the past environment of Mars, Jupiter, Saturn, and Jupiter's moon Io.



The classification of living organisms

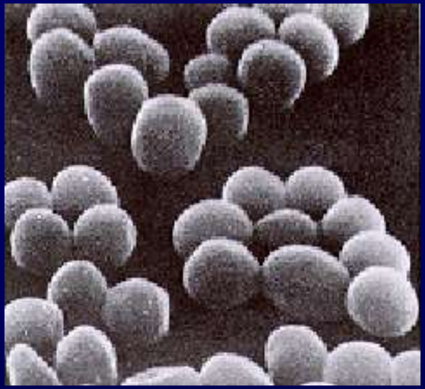
Domain Eubacteria

Eubacteria are microscopic **prokaryotic cells.**

Cyanobacteria, also called blue-green algae, are Eubacteria that have been living on our planet for over 3 billion years.

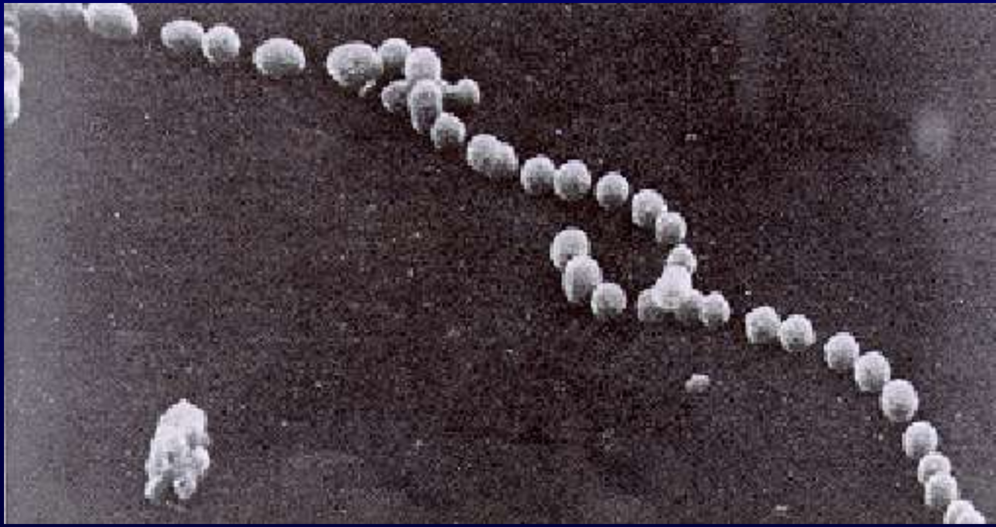
Through photosynthesis, which produces oxygen, billions of tiny bacteria were able to add oxygen to Earth’s atmosphere.

Some Eubacteria can cause health problems like strep throat and food poisoning. **Bacteria** such as E.coli and Salmonella are sometimes found in undercooked meat and eggs and can make people sick.



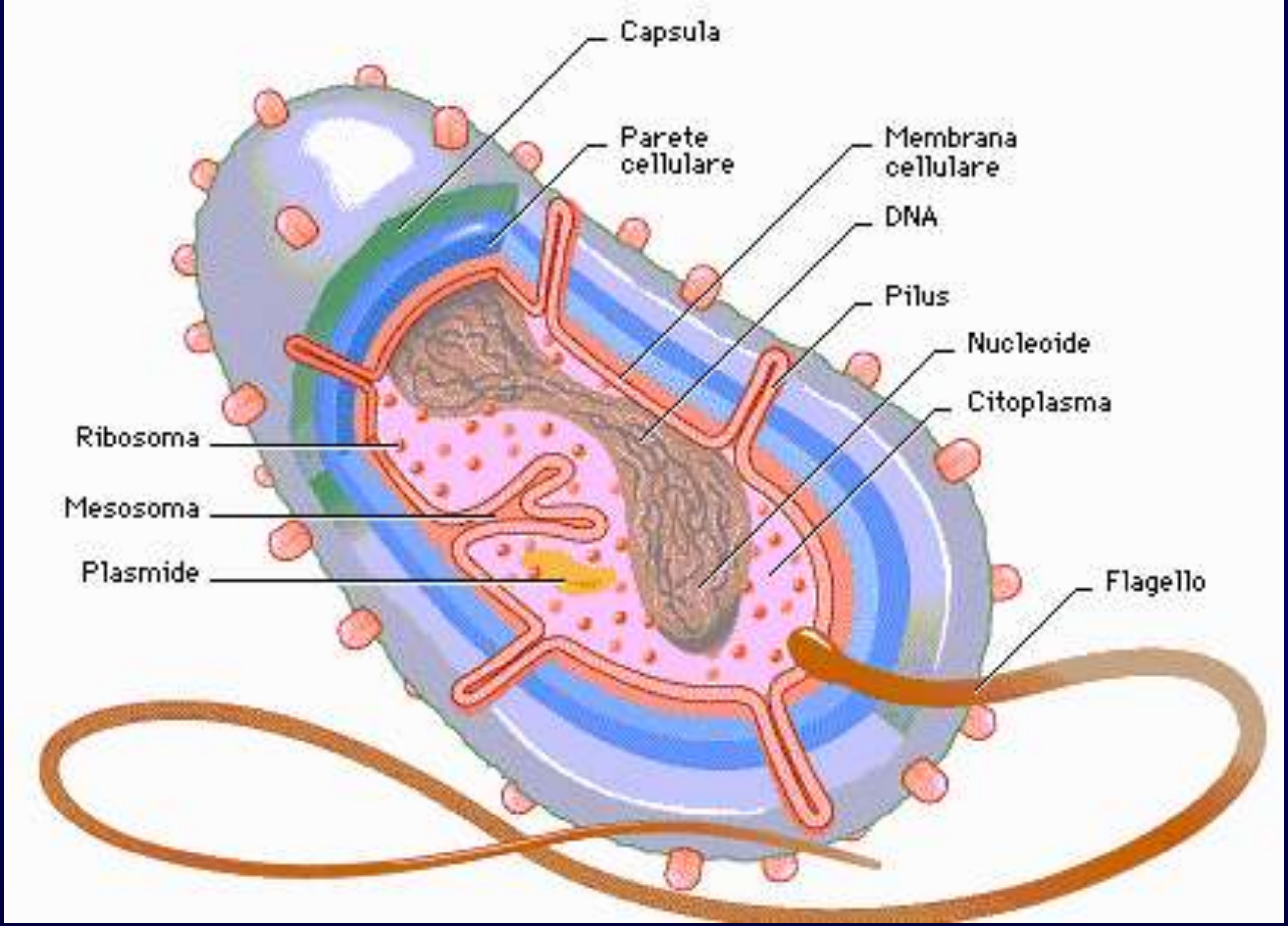
Staphylococcus

Escherichia coli

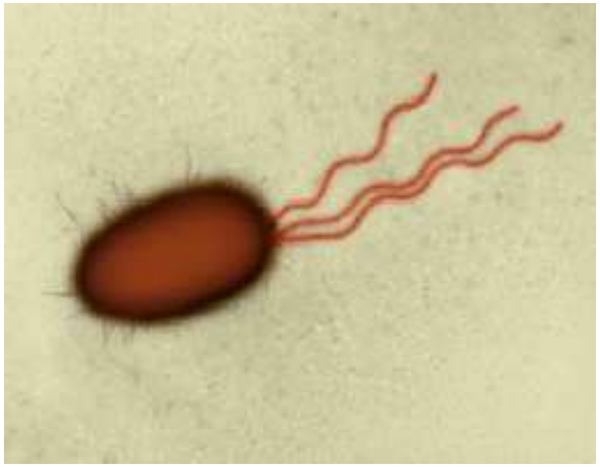


Streptococcus

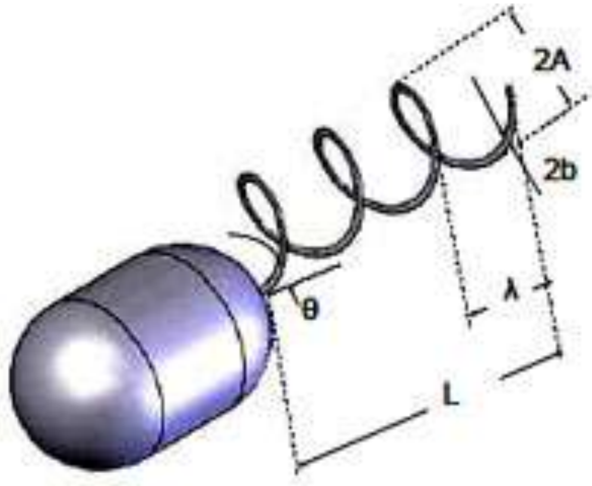
Monera - Procariota



Monera - Procariota



Transmission Electron Microscopy (TEM) image of *E. Coli* (x3515)



Schematic of the swimming microrobot propelled by flagellar motion

Future Micro Swimming Robots for medical applications

Behkam and Sitti, 2004 –
Carnegie Mellon University

Swimming Microrobots

✓ Swimming microrobots by Fukuda *et al*., 1994 (Nagoya University)

- 50 mm in length, 6 mm in width. Actuated by PiezoPZT($Pb(Zr,Ti)O_3$) (resonance condition)

✓ Swimming microrobots by Guo *et al*., 2001 (Kagawa University)

- 45 mm long, 10 mm wide, using ionic conductive polymer film (ICPF) actuators that produce undulatory motion.

PROBLEMS

FURTHER MINIATURIZATION OF THE FISH-LIKE BIOMIMETIC DEVICES WILL MAKE THEM INEFFECTIVE BECAUSE THEY RELY ON INERTIAL FORCES FOR PROPULSION

(AMBIENT WITH VERY SMALL REYNOLDS NUMBERS)

Swimming Microrobots

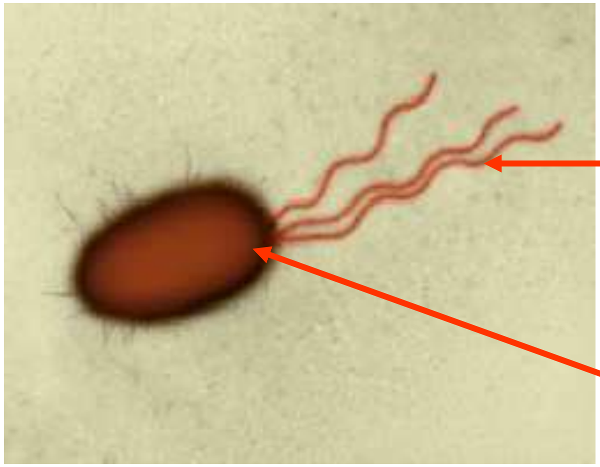
✓ Micro-swimming robots by Ishiyama et al., 1999 (Tohuku University); McNeil et al., 1995, University of Virginia; Mathieu et al., 2003, Ecole Polytechnique de Montreal

- micro-swimming robots rotated and moved by using Magnetic Resonance Imaging (MRI) for magnetic propulsion

PROBLEMS

1. Dangerous for patients with pacemakers, metal implants, etc.
2. Considering the low speed of the robot, patients have to stay in the magnetic field for longer than the time allowed by FDA regulations
3. Magnetic gradient fields can produce eddy currents in the patient and cause local heating
4. Control and positioning of the magnetically propelled robot is another important unsolved problem

Monera - Procariota



6-8 filaments extended into the external medium

Long ~10 μm, thin ~20 nm

Reversible rotary motor embedded in the cell wall to cause the bacterium to swim

Helix 0.5 μm diameter

Speed ~100 Hz

E. coli size and speed yields very low Reynolds number regime (*Re* $=10^{-4}$)

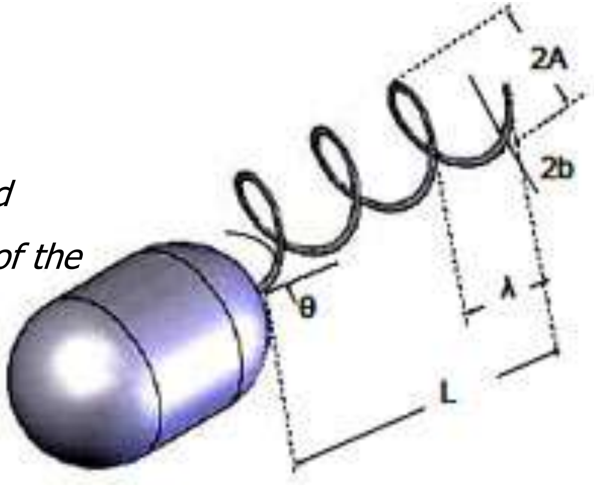
$$\mathrm{Re} = \frac{\rho V l}{\mu}$$

ρ = density of the fluid

μ = dynamic viscosity of the fluid

V = flow velocity

l = dimension of the object



Dimension of the swimming microrobot

Half of the thickness of the flagellum, b	23 µm
Amplitude of the flagellum, A	3.3 mm
Wavelength of the flagellum, λ	3.8 mm
Length of the flagellum, L	2.3 cm

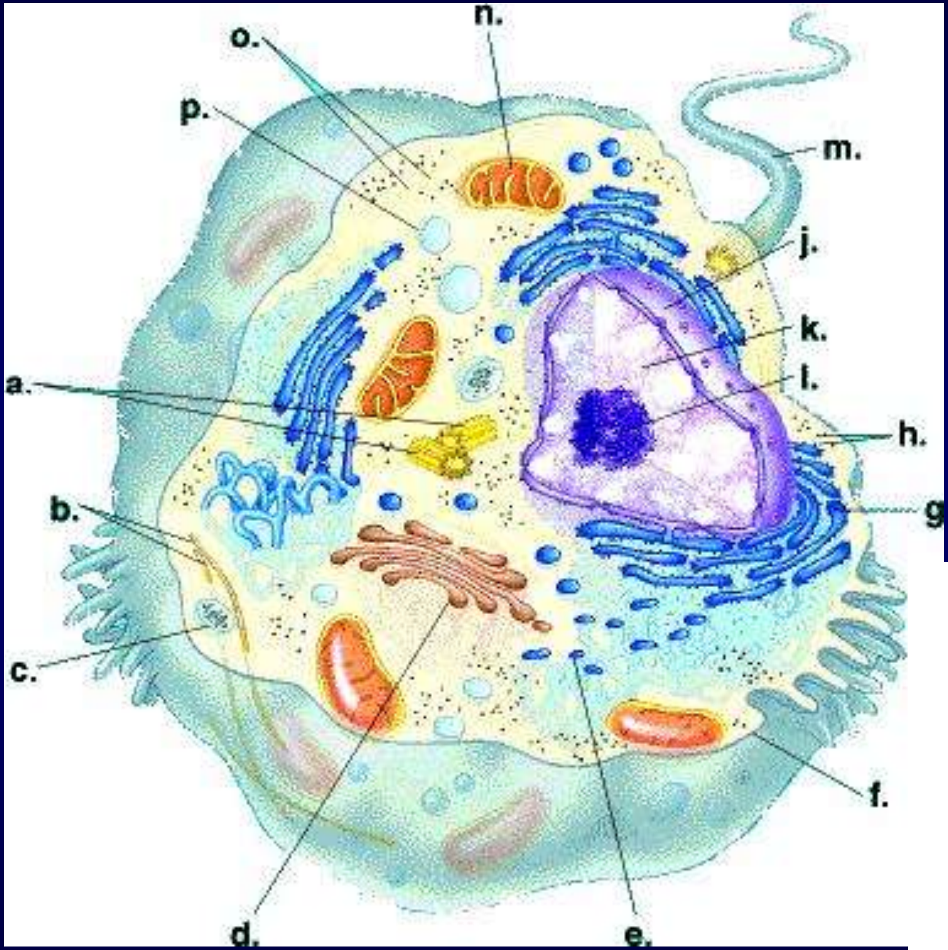
The classification of living organisms

Domain Eukaryota

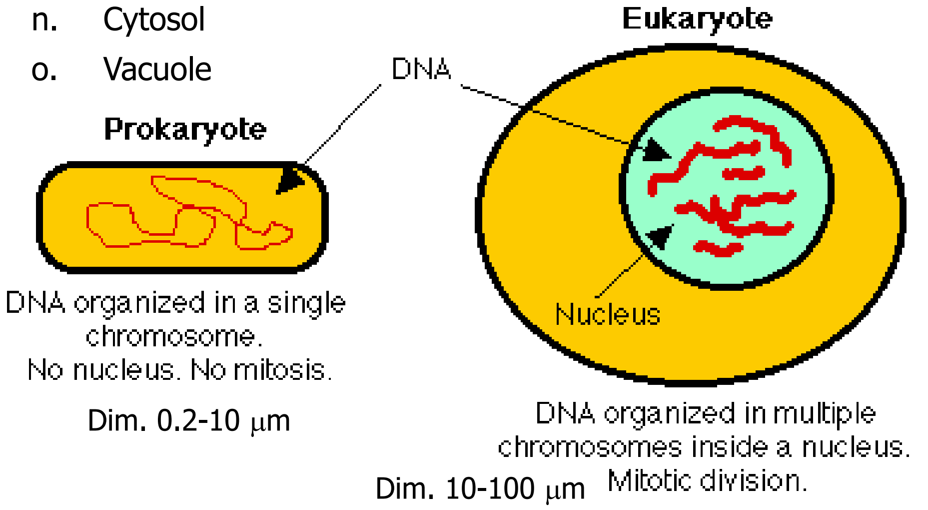
Plants, animals, protists, and fungi are all members of the domain.

All members of the domain Euraryota have eukaryotic cells. And it is the only domain whose members have this cell type. Eukaryotic cells contain a special part called a nucleus that contains genetic material within chromosomes.

Eukaryotic Cell



a. Centrioles
b. Intermediate filamentes
c. Lysosome
d. Smooth endoplasmic reticulum
e. Ribosomes
f. Membrane cell
g. Rough endoplasmatic reticulum
h. Golgi body
i. Nucleolus
j. Nuclear envelope
k. Nucleus
l. Flagellus
m. Mitochindrion
n. Cytosol
o. Vacuole



DNA organized in a single chromosome.
No nucleus. No mitosis.

Dim. 0.2-10 µm

DNA organized in multiple chromosomes inside a nucleus.
Mitotic division.

Dim. 10-100 µm

Differences between prokaryote and eukaryote

The classification of living organisms

Kingdom Plantae

Kingdom Plantae contains almost 300,000 different species of plants. In the process known as "**photosynthesis**", plants use the energy of the Sun to convert water and carbon dioxide into food (sugars) and oxygen. Photosynthesis by plants provides almost all the oxygen in Earth's atmosphere. Because plants can **make their own food (autotrophs)**, they are the first step to many food chains in the world.

The first plants lived on land about 450 million years ago. Since then, plants have taken on many forms and are found in most places on Earth. Plants can live in dry places or wet places, low places or high places, hot places or cold places. Humans can't live in a world without plants.

The classification of living organisms

Kingdom Animalia

With over 9 million species, Kingdom Animalia is the largest of the kingdoms in terms of its species diversity.

Over half of all the animal species belong to a group of animals known as arthropods. Arthropods include animals such as centipedes, crabs, insects, and spiders.

Animals are "multicellular" (composed of many cells). In most animals, these cells are organized into tissues that make up different organs and organ systems. All animals are **heterotrophs** (= "other feeder"), meaning that they **must get their food by eating other organisms, such as plants, fungi, and other animals**. In addition, all animals require oxygen for their metabolism, can sense and respond to their environment, and have the capacity to reproduce sexually (though many reproduce asexually as well). During their development from a fertilized egg to adult, all animals pass through a series of embryonic stages as part of their normal life cycle.

The classification of living organisms

Kingdom Protista

Members of the Kingdom Protista are the **simplest of the eukaryotes**. Some members of Kingdom Protista are unicellular, others are colonial, and yet others are multicellular. Protists are an unusual group of organisms that were put together because they don't really seem to belong to any other group. Some protists perform **photosynthesis** like plants while others move around and **act like animals**, but protists are neither plants nor animals, and they're not fungi either. Protists are grouped into three major, unofficial categories based on means by which they obtain nutrition. These are the Protozoa, the Algae, and the Fungus-like Protists.

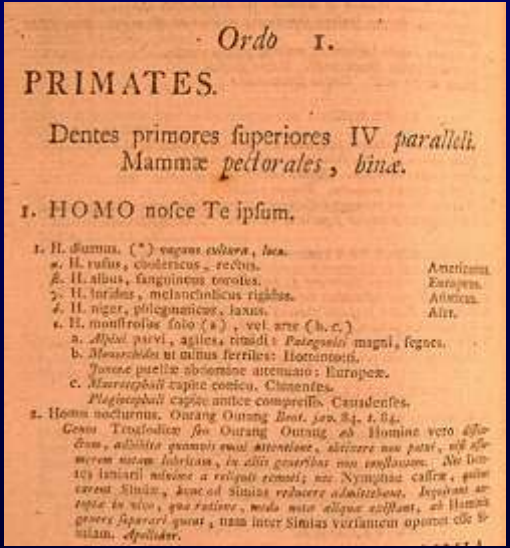
The classification of living organisms

Kingdom Fungi

Though the appearance of many fungi may resemble plants, they are probably more closely related to animals. Fungi **are not capable of performing photosynthesis**, so must get their nourishment from other sources. Many fungi absorb nutrients directly from the soil. Many others feed on dead and decaying organisms and therefore have an important role in the recycling of nutrients in natural systems. Still others feed on living organisms.

Fungi come in a wide variety of sizes and forms, and many have great **economic importance**. Tiny, one-celled yeasts are important for baking breads and fermenting wines, beers and vinegars. Many medicines are produced with the help of fungi, most notably, the antibiotic, Penicillin.

The Linnaeus's classification



Ordo I.

PRIMATES.

Dentes primores ſuperiores IV *paralleli.*
Mammæ *pectorales*, *binæ.*

1. HOMO noſce Te ipſum.

Carl von Linnè (1707-1778)

Swedish naturalist (botanic scientist)

Creationistic theory: his system for naming, ranking, and classifying organisms is still in wide use today (with many changes).

Species subsist as metaphysic entities or "types" and individuals are copies of the model.

1735 Systema naturae

Natural classification, distributes species of organisms in real entities, which could be grouped into higher categories:

Species, Genus, Orders, Classes, Kingdom.

(the denomination of Phylum has been introduced by *Georges Cuvier*)

Two Kingdoms: Animalia and Plantae

The Linnaeus’s classification

Linnaeus simplified naming immensely by designating one Latin name to indicate the genus, and one as a "shorthand" name for the species. The two names make up the **binomial** ("two names") species name.

Genus species

Capitalized

italicized

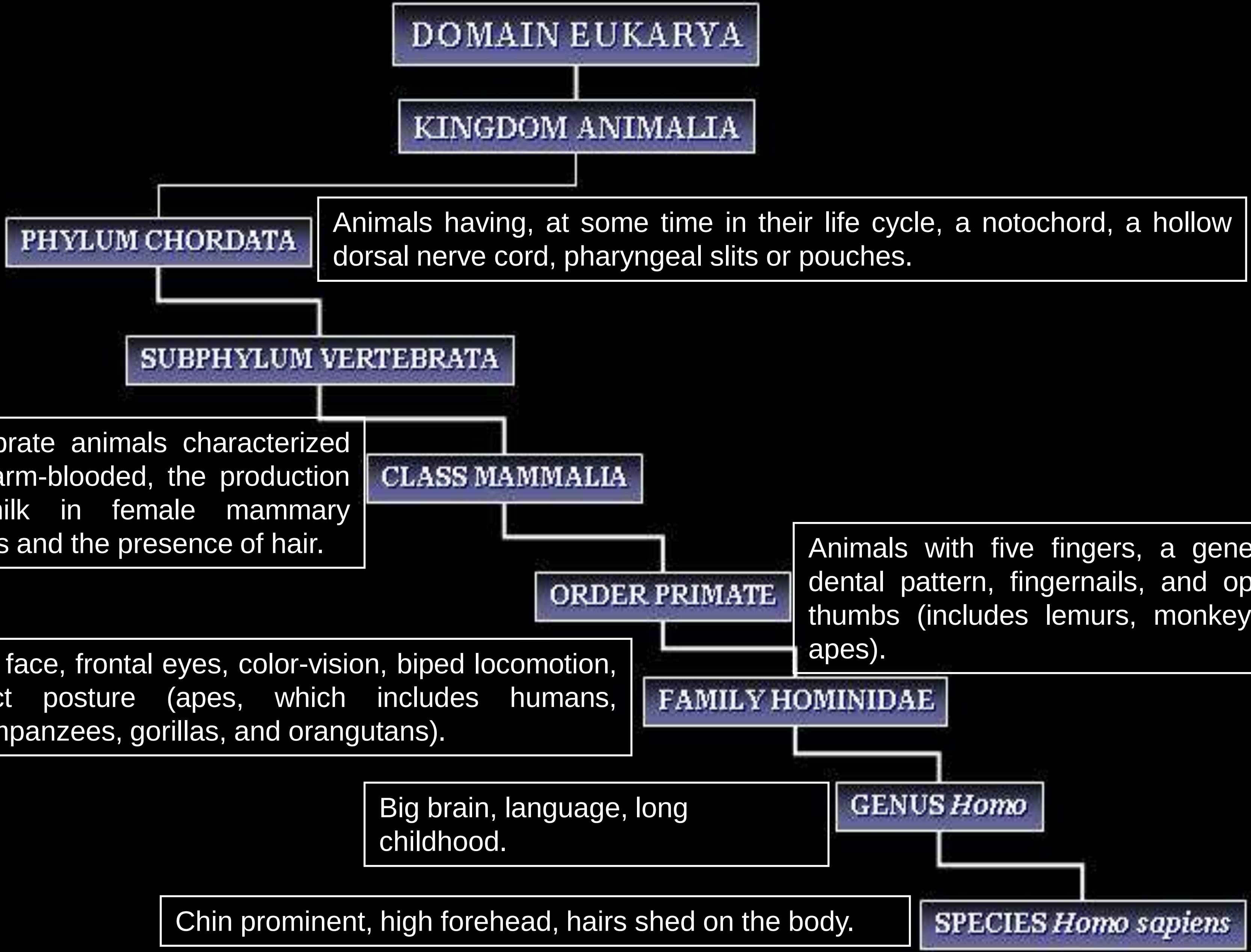
lower case

italicized

Usually Latin

Examples: *Felis domesticus; Homo sapiens*

CLASSIFICATION OF *Homo sapiens*



DOMAIN EUKARYA

KINGDOM ANIMALIA

PHYLUM CHORDATA

Animals having, at some time in their life cycle, a notochord, a hollow dorsal nerve cord, pharyngeal slits or pouches.

SUBPHYLUM VERTEBRATA

Vertebrate animals characterized by warm-blooded, the production of milk in female mammary glands and the presence of hair.

CLASS MAMMALIA

Animals with five fingers, a generalized dental pattern, fingernails, and opposing thumbs (includes lemurs, monkeys, and apes).

ORDER PRIMATE

Flat face, frontal eyes, color-vision, biped locomotion, erect posture (apes, which includes humans, chimpanzees, gorillas, and orangutans).

FAMILY HOMINIDAE

Big brain, language, long childhood.

GENUS *Homo*

Chin prominent, high forehead, hairs shed on the body.

SPECIES *Homo sapiens*

Phylum Arthropoda

- ✓ Subphylum Trilobitomorpha (extinct)

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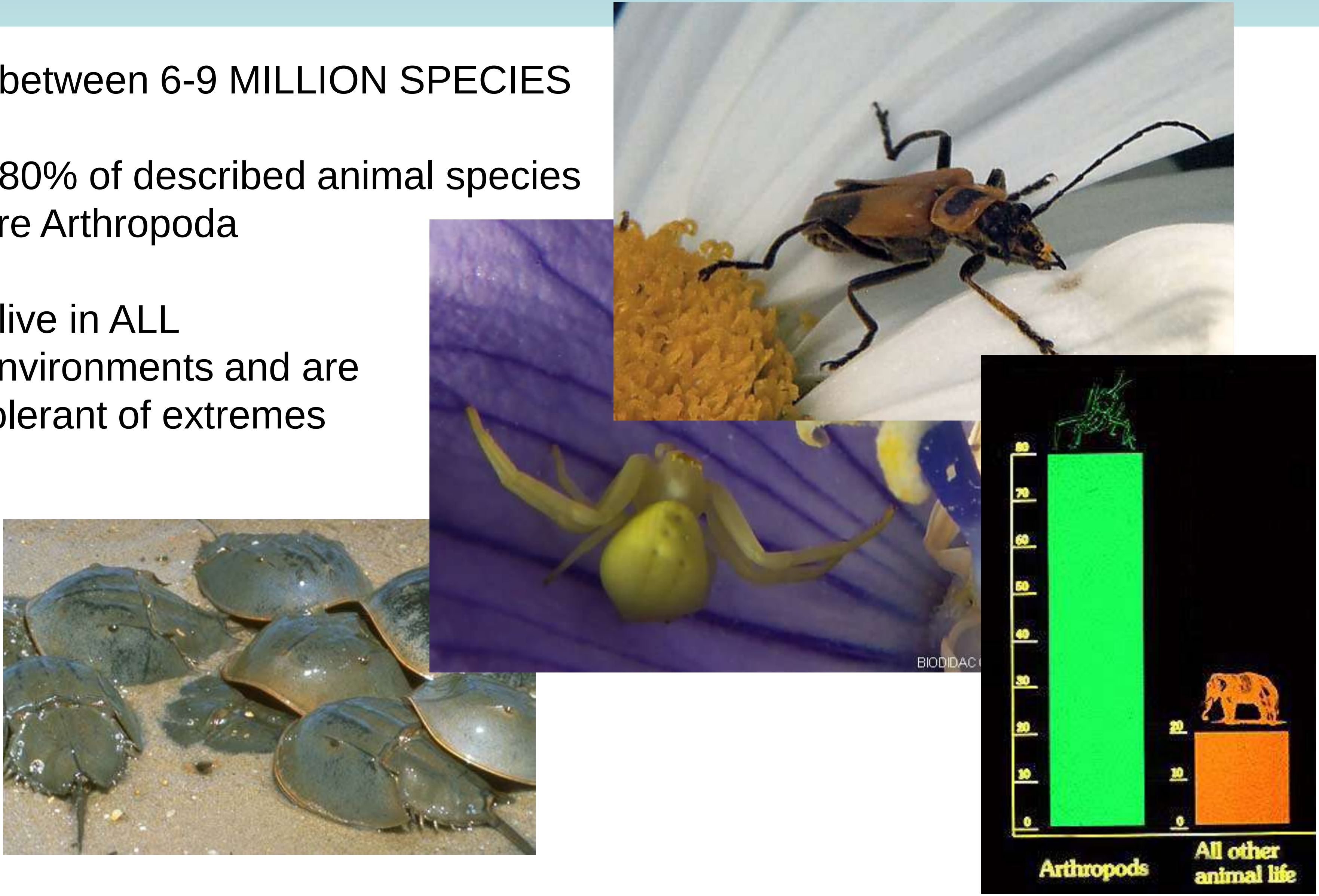
PHYLUM ARTHROPODA

arthro = joint - poda = foot ----» jointed legs

- between 6-9 MILLION SPECIES

- 80% of described animal species are Arthropoda

- live in ALL environments and are tolerant of extremes

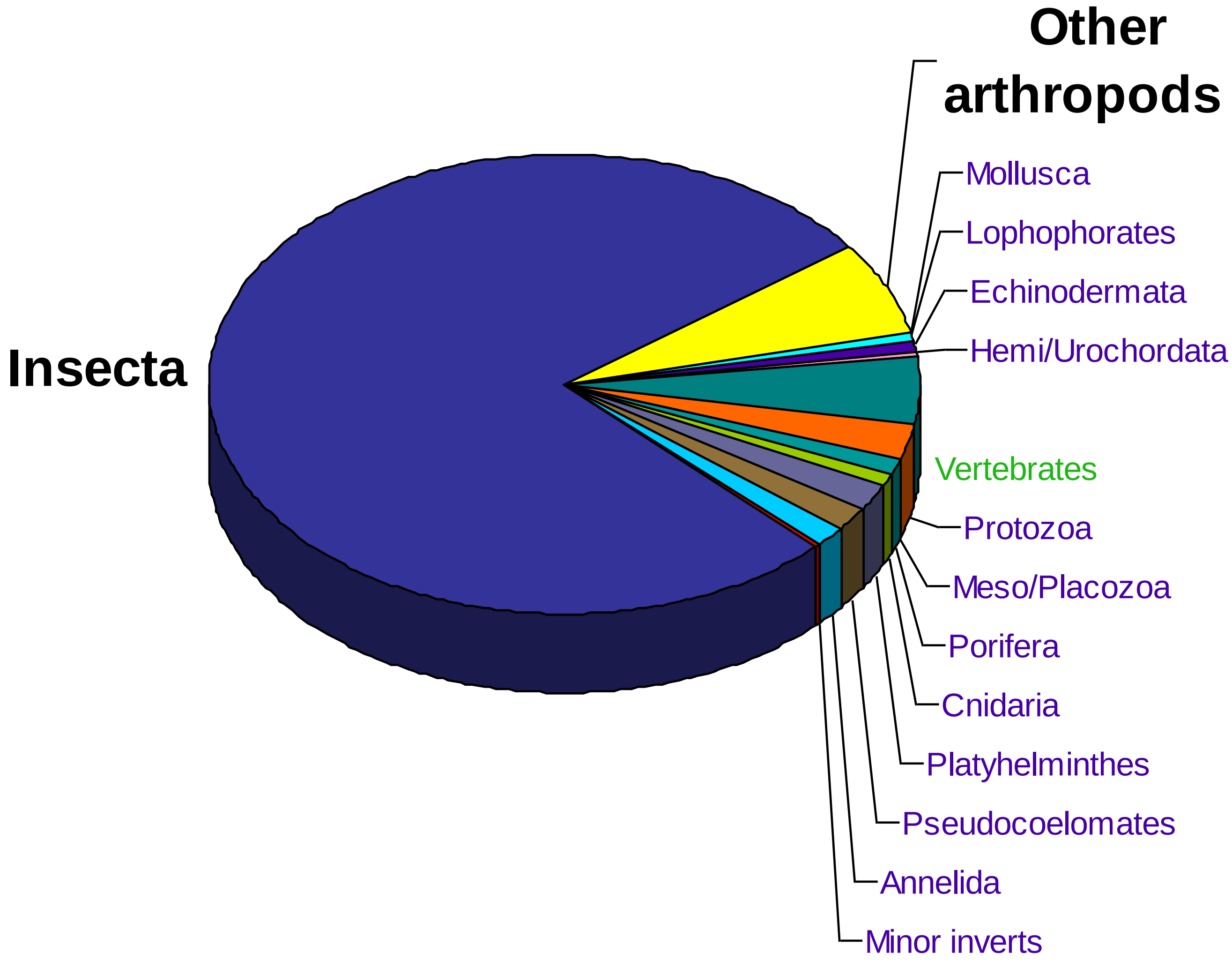


Habitats

- 10,000 m deep in ocean – 6,000 high in mountains
- Air, land, fresh water, salt water, parasitic
- Some are social, live in groups

Arthropoda - abundance

There are more species of insects than all other plants and animals together



Reasons for Success

1. Exoskeleton – protective, mobile
2. Segmentation & appendages – better locomotion
3. Tracheal system – more oxygen gets to cells
4. Sensory organs – highly developed to capture food, evade enemies
5. Complex behavior patterns/instincts – survival
6. Reduced competition for food – larvae eat different food than adult form eats

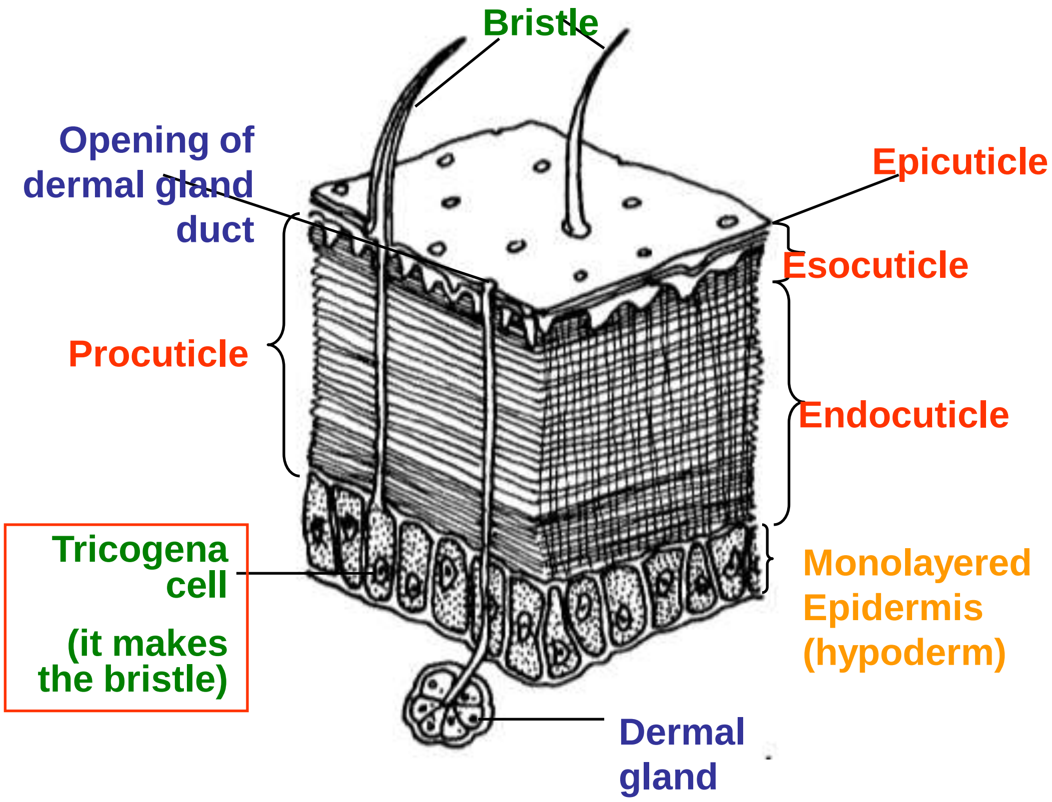
Phylum Arthropoda

How do Arthropods support themselves and move?

1. EXOSKELETON

The arthropod exoskeleton is made of **chitin** (N-acetylglucosamine, also found in the cell walls of fungi)

Secreted by **epidermis**.
In crustacea and millipedes, the cuticle is hardened by the addition of **calcium**; in insects, the cuticle is **tanned**, chemically bonded with protein.



Arthropoda - Exoskeleton

Advantages:

1. Protection from drying - allowed invasion of land
2. Protection from predators

Disadvantages:

1. Does not permit growth - have to moult
2. Does not bend - need to insert breaks (joints) in it to permit movement

Phylum Arthropoda

Characteristics

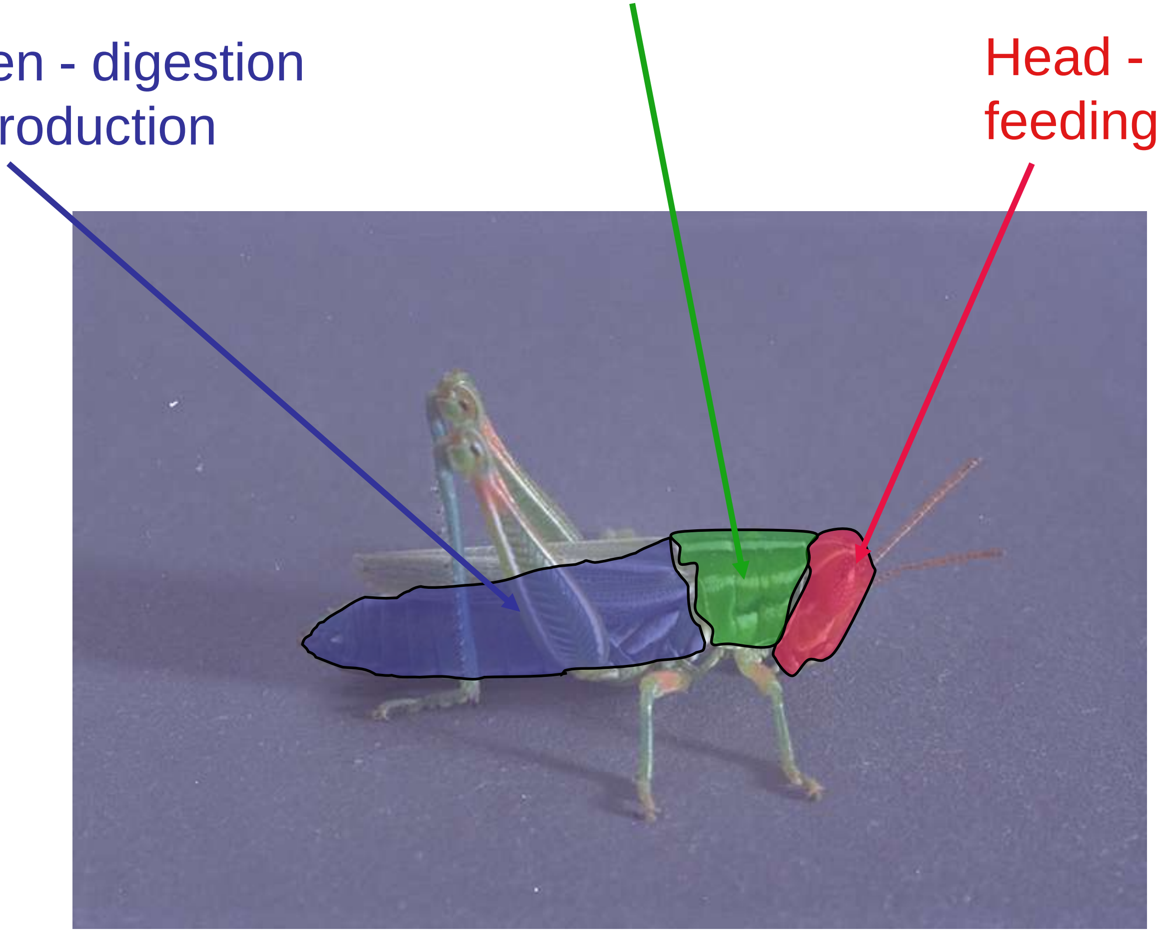
2. BODY SECTIONS

METAMERISM Body composed of **numerous segments** (somites), segmented condition may be concealed. In the primitive Arthropod, the body was thought to be a series of **metameres, each, except for the first and last, with a pair of appendages.** Metamerism is an example of an important biological trait, that of replication and modification to develop new traits and capabilities.

Phylum Arthropoda

Characteristics

2. BODY SECTIONS



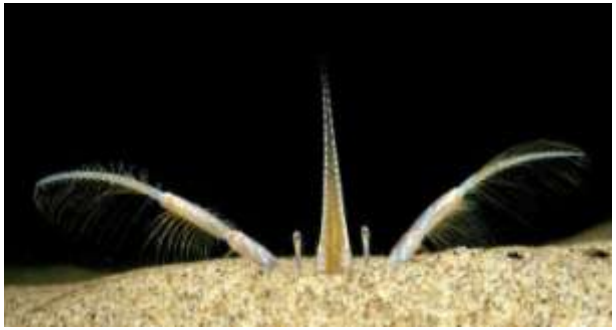
Thorax - locomotory

Abdomen - digestion and reproduction

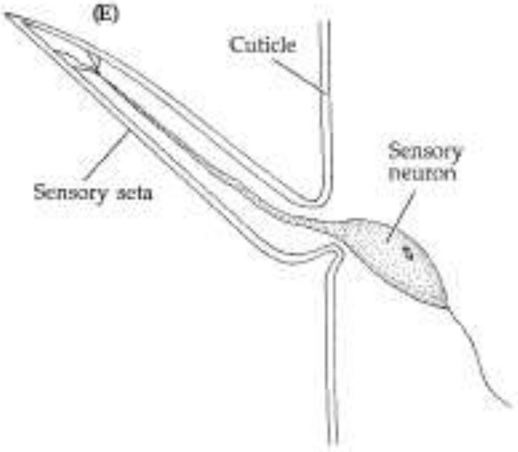
Head - sensory and feeding

Phylum Arthropoda

5. **SENSE ORGANS.** Exoskeletal sense organs include hairs sensitive to sound, touch, odour, taste, humidity or temperature, and often 2 compound eyes and 1 or more simple eyes.



Sense organs (sensilla) protrude out of cuticle.



Sense Organs

- Tactile hairs – on antennae, mouth parts, telson function in taste receptors (eg. pectines, tactile hairs, sensilla = mechanoreceptors)

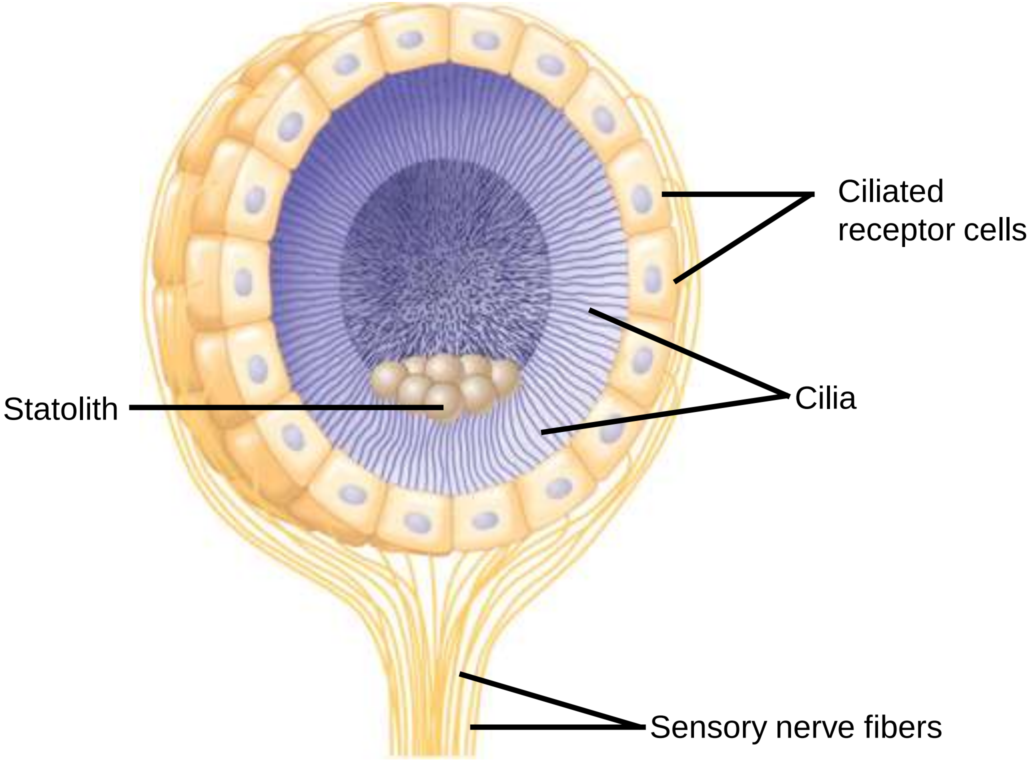
- Chemoreceptors for olfaction (smell) on or near mouthparts

- Statocyst – located on first pair of antenna, for determining changes in body position (equilibrium)

- Simple or Compound eyes (photoreceptors) – made up of units called ommatidia

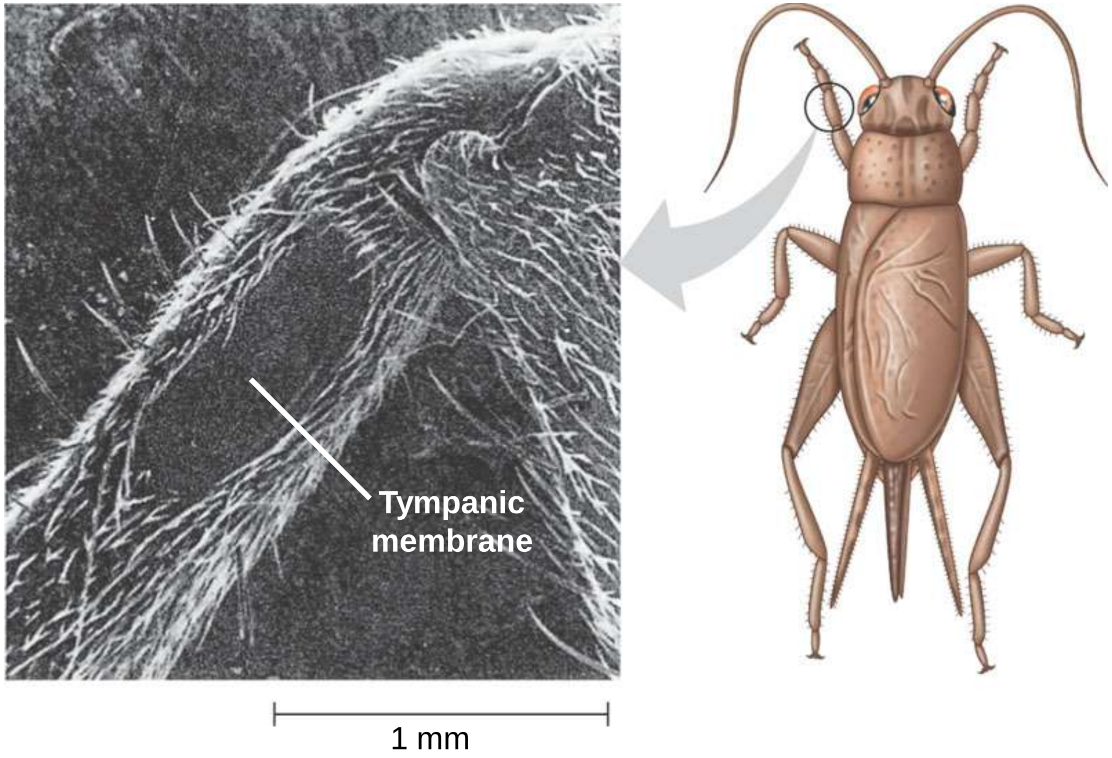
Sense Organs

- Most artrhopoda have sensory organs called statocysts
  - That contain mechanoreceptors and function in their sense of equilibrium



Sense Organs

- Many arthropods sense sounds with body hairs that vibrate
  - Or with localized “ears” consisting of a tympanic membrane and receptor cells



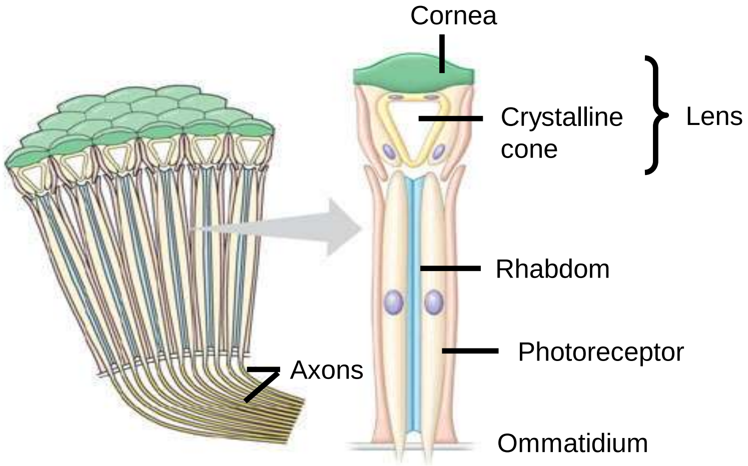
Sense Organs

Compound eyes are found in insects and crustaceans

and consist of up to several thousand light detectors called ommatidia

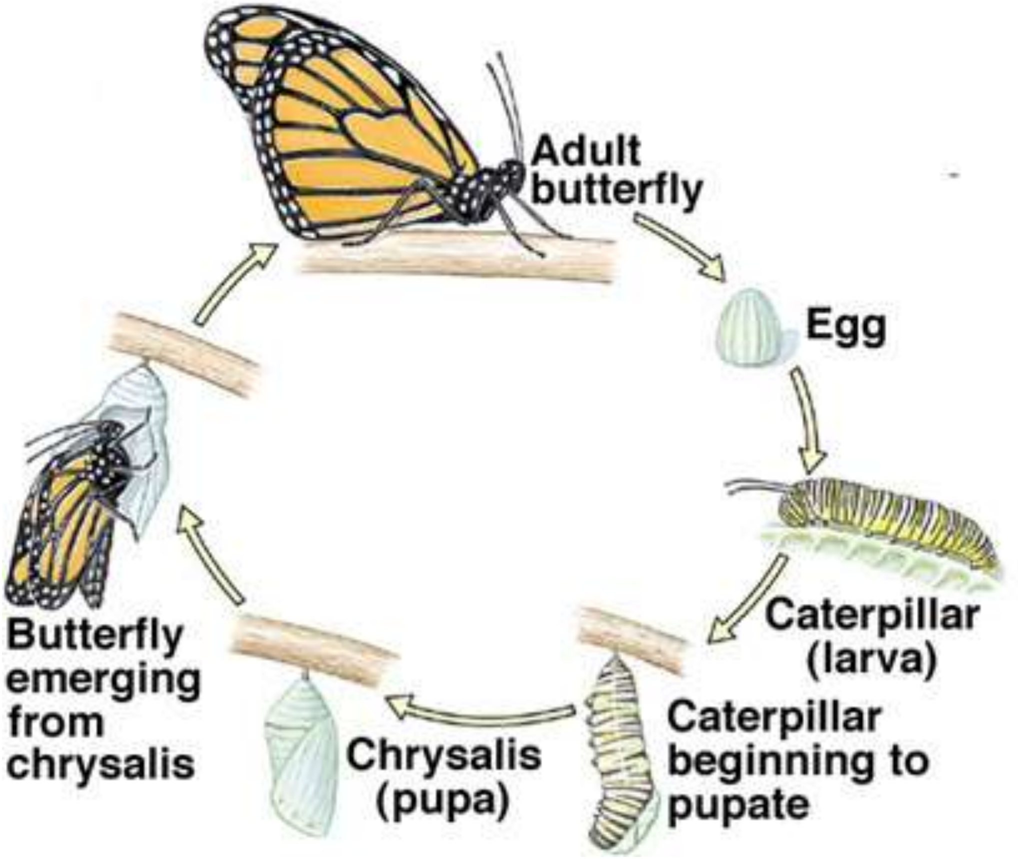
(a) The faceted eyes on the head of a fly, photographed with a stereomicroscope.

(b) The cornea and crystalline cone of each ommatidium function as a lens that focuses light on the rhabdom, a stack of pigmented plates inside a circle of photoreceptors. The rhabdom traps light and guides it to photoreceptors. The image formed by a compound eye is a mosaic of dots produced by different intensities of light entering the many ommatidia from different angles.

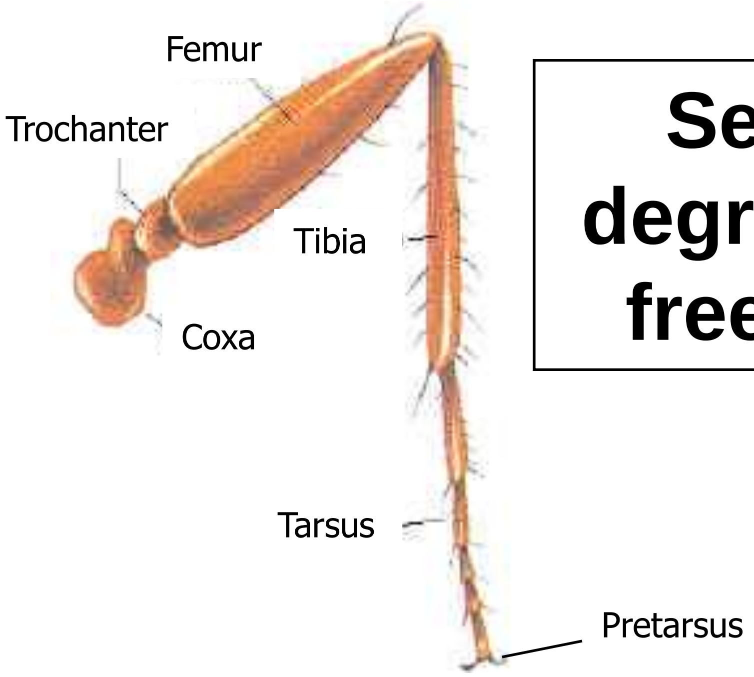


Complete Metamorphosis (Holometabolous)

- Each of the developmental stages is structurally and functionally very different
- The egg develops into an immature **larva;** eats voraciously
- Followed by a transitional stage - **pupa,** contained within cocoon
- Metamorphosis occurs within the pupal exoskeleton, yielding a sexually mature **adult**



Arthropoda locomotion



Insect Leg

Seven degrees of freedom

Crab Leg

Honeybee leg

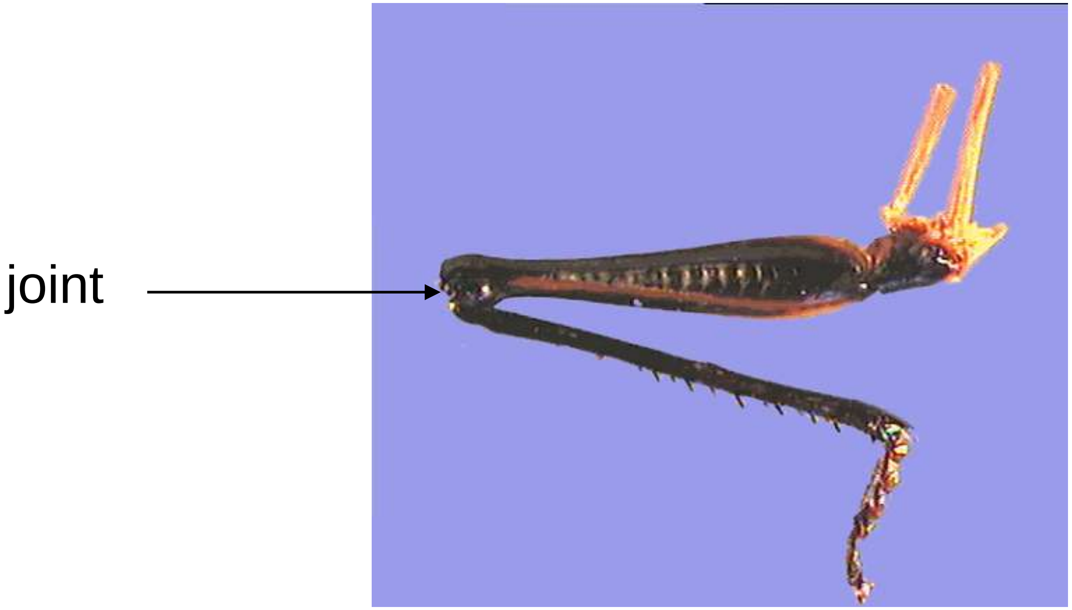
Mole Cricket leg

Water Beetle leg

ARTHROPOD EXOSKELETON

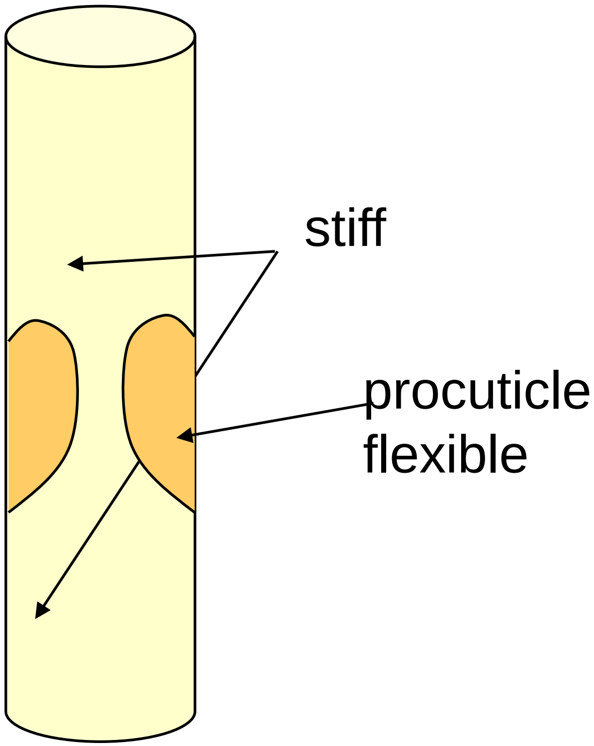
Mechanics

1. Flexible joints form lever system
2. Exoskeleton provides high stiffness per weight



ARTHROPOD EXOSKELETON

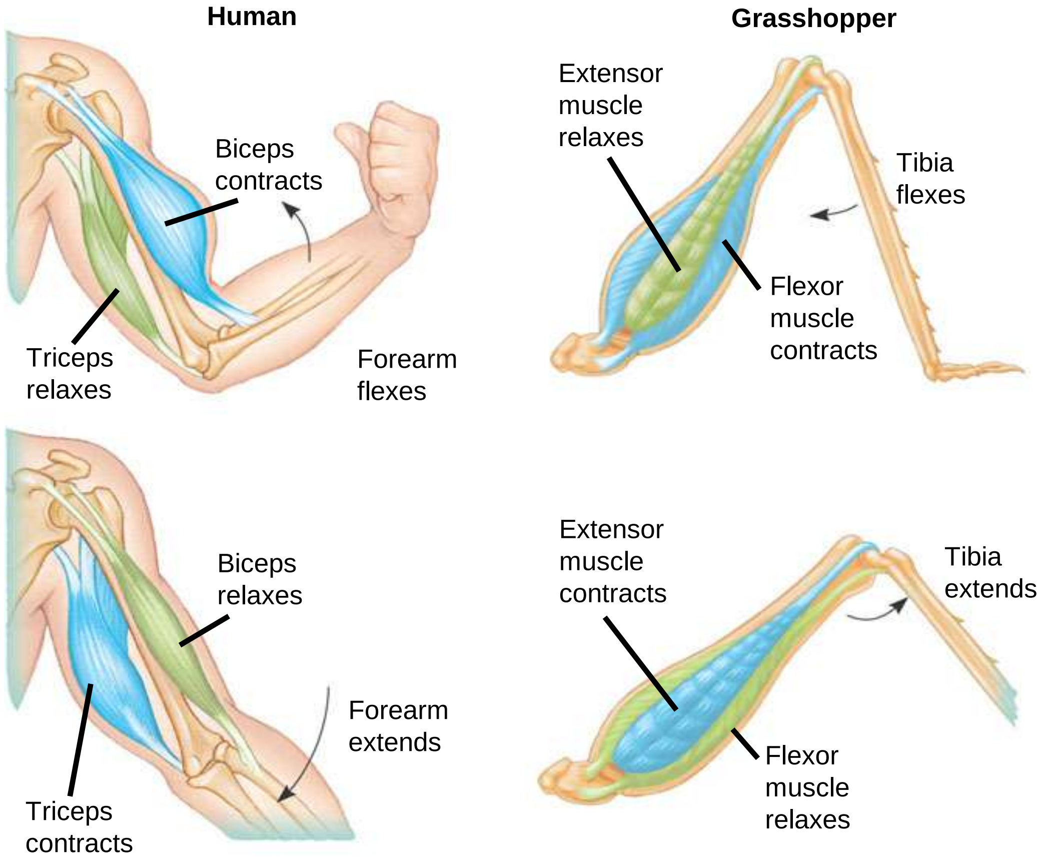
Mechanics



Weight can be placed on foot without compressing leg but joint is still flexible.

Skeletal muscles are attached to the skeleton in antagonistic pairs

With each member of the pair working against each other



Arthropoda locomotion - Summary

Since **exocuticle is absent from joints**, arthropods can move appendages and flex one body segment on another.

Movement results from **contraction and relaxation of striated muscle fibres**. Most arthropods use their appendages for movement, for example, as paddles in aquatic species or as legs in terrestrial ones.

Muscular System

- complex, demonstrating **antagonistic muscle actions**
- **striated, skeletal muscles** for rapid movement
- **smooth muscles** for movement of internal organs

Mechanism/Mode of Locomotion

- **antagonistic muscle action in jointed appendages** for walking, swimming and/or flying
- flying may be via **direct or indirect muscle contraction** in thorax of insects

CASE STUDIES ON ARTHROPODA INSPIRED ROBOTS

Artropod Inspired - Biomimetic robots

GOAL of the research: development of a new class of biologically inspired robots that exhibit much greater robustness in performance in unstructured environments than today's robots. This new class of robots will be substantially more compliant and stable than current robots, and will take advantage of new developments in materials, fabrication technologies, sensors and actuators.

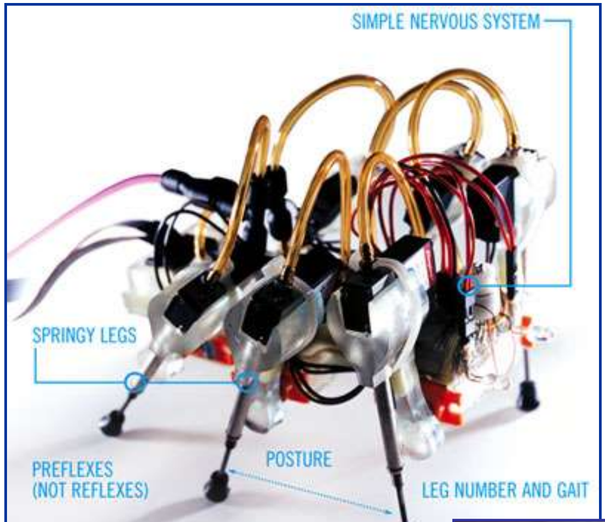
Artropod Inspired - Biomimetic robots

A strict bio-mimicry startegy is rarely if ever successful for several reasons

1. Even though insects are often referred to as simple animals, their **mechanical** and **nervous systems** are far more complex than that found in any current robot
2. Each **leg** has seven degrees of freedom
3. The **muscles** that control those movements are more efficient than any artificial actuators currently available
4. **Thoracic ganglia** contain thousands of neurons and head ganglia represent sophisticated sensory processing regions, memory banks and motor control centers
5. Hundreds of **sensors** are found associated with each leg and on the head, antennae may have hundreds of thousands of sensors associated with them
6. Insects are **small** creatures and body plans may be optimized for the size and materials found in their bodies. As one scales up to larger devices typical of most robots and changes to materials such as aluminum or plastic, it is not clear that these designs will still be appropriate
7. **Neural circuits** are rarely understood in their entirety and again have co-evolved with the size and materials of the insect’s body

Stanford-Barkley approach to the problem: The Rhex and Sprawl robot series

R.J. Full
Dept. of Integrative Biology
U.C. Berkeley

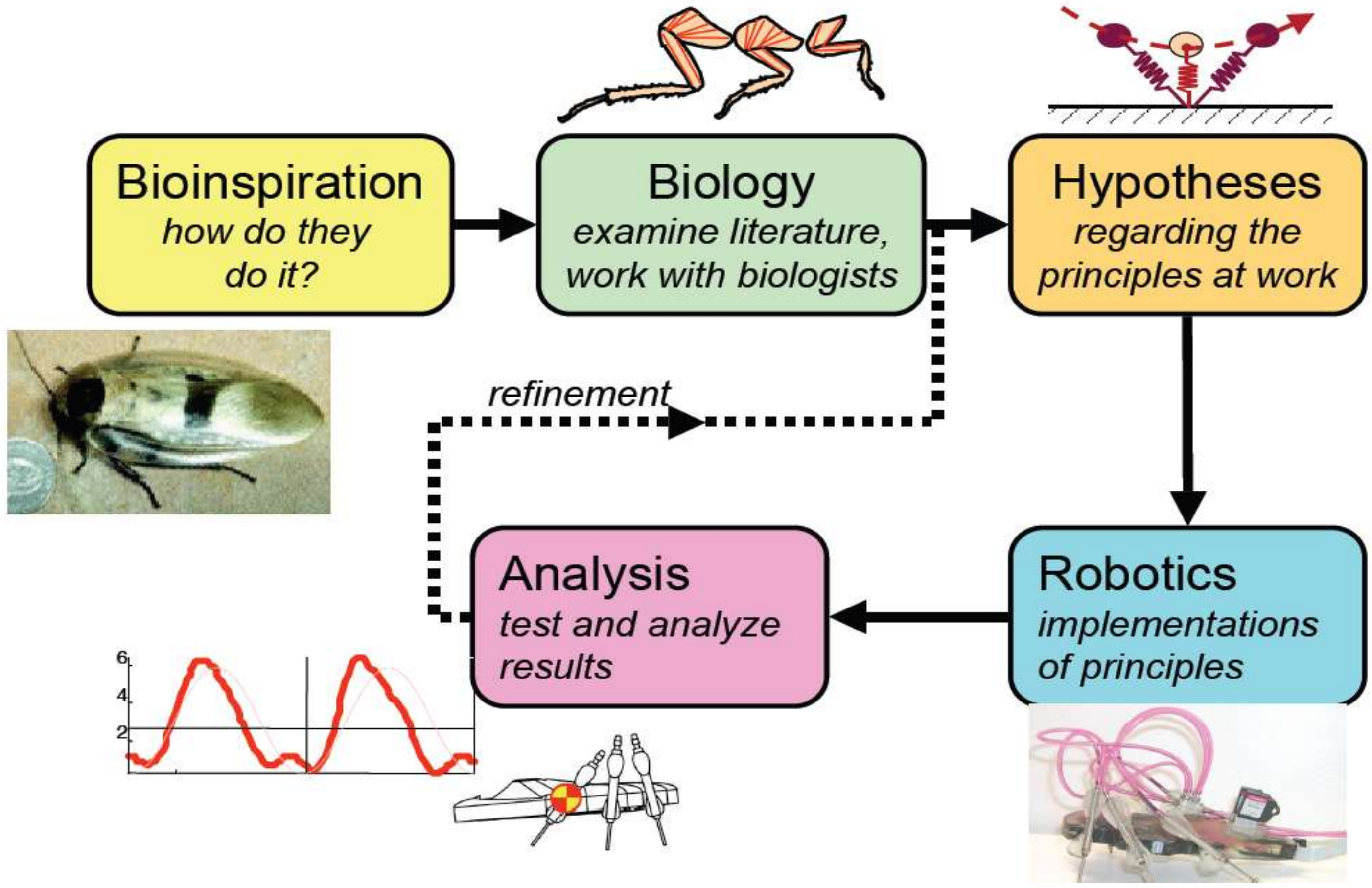


M.R. Cutkosky
Center for Design Research
Stanford University

Mechanical aspects of legged locomotion control

“Rather than seeking to copy any specific morphological or even physiological detail, we hypothesize functional principles of biological design and test their validity in animal and physical models”

Bioinspiration for **hexapedal running**



Motivation

- Hazardous tasks for humans

- Access to areas inaccessible to wheeled vehicles

- Legged animals are faster and more agile in rough terrain

Stanford-Barkley approach

DESIGN INSPIRATION FROM BIOLOGY

WHY ARTHROPODS: are capable of remarkable **speed** and **stability** over uneven and uncertain terrain. ***Periplaneta americana*** can achieve speeds of up to **50 body-lengths per second** (1.5 m/s) (**Full and Tu, 1991**). ***Blaberus discoidalis*** is capable of traversing uneven terrain with **obstacles of up to three times the height of its center of mass** without appreciably slowing down (**Full et al., 1998**) and achieves 30-40 cm/s.

Studies of these cockroaches suggest design principles for fast, stable, running hexapods:

1. **Self-stabilizing posture**
2. **Thrusting and stabilizing leg function**
3. **Passive visco-elastic structure**
4. **Timed, open-loop/feedforward control**

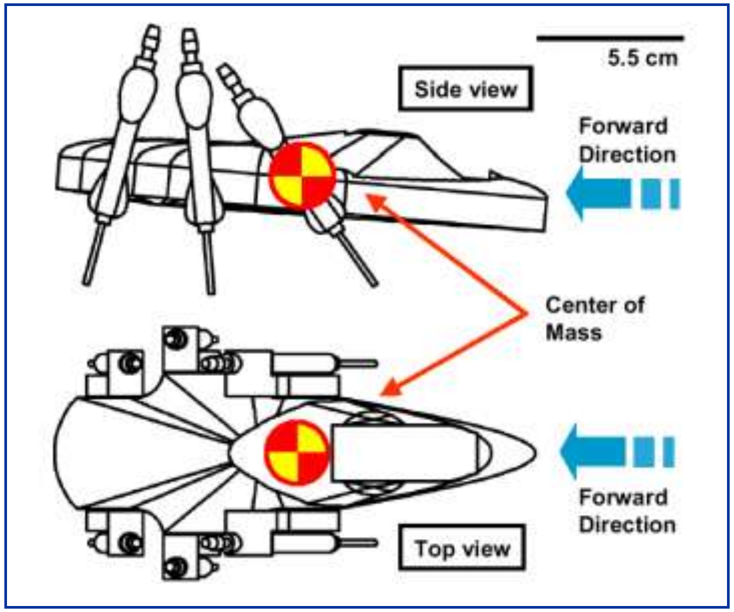
1. Self-stabilizing Posture

STABILITY is essential to the performance of terrestrial locomotion.
Arthropods are often viewed as the quintessential example of a **statically stable** design.

POSTURE: Arthropod legs generally **radiate outwards**, providing a wide base of support. Their **center of mass** is often so low that their body nearly scrapes the ground.
Their sprawled postures reduce **over-turning moments**.

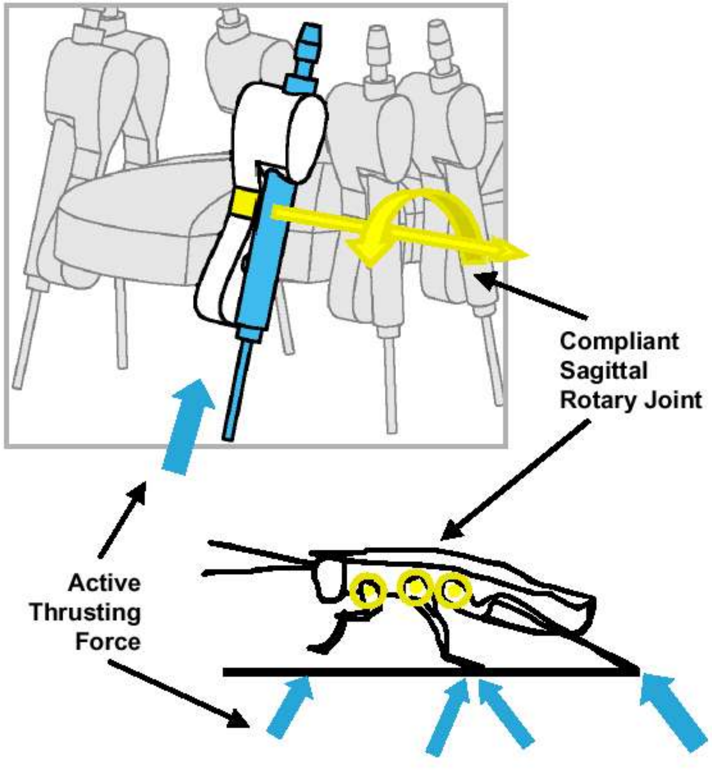
Periplaneta americana

***Self-stabilizing posture**: A rear and low centre of mass and wide base of support contribute to the over-all stability of locomotion.*



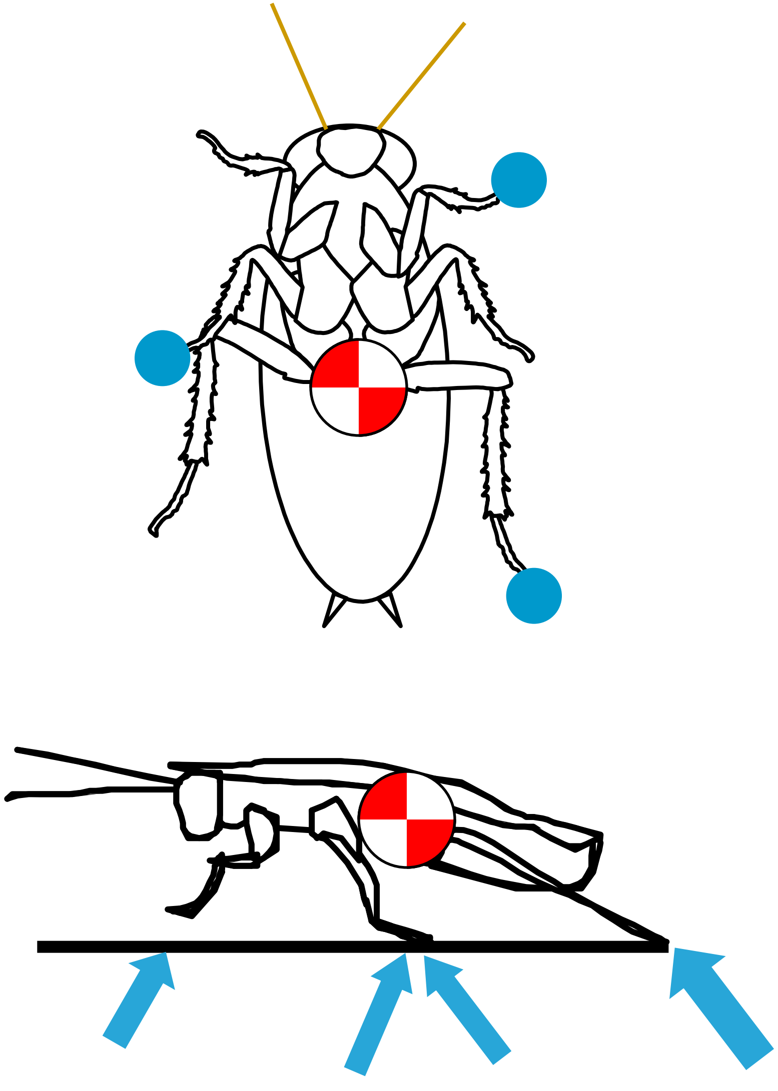
2. Thrusting and Stabilizing Leg Function (I)

In the cockroach's wide sprawled posture, the **front legs** apply this thrusting mainly for **deceleration**, while the **hind legs** act as powerful **accelerators**. Middle legs both **accelerate and decelerate** during the stride. The creation of large internal forces may be inefficient for smooth, steady-state running, but there is evidence this contributes to dynamic robustness to perturbations (**Kubow and Full, 1999**) and to rapid turning (**Jindrich and Full, 1999**). A similar leg function has been designed in the robot.



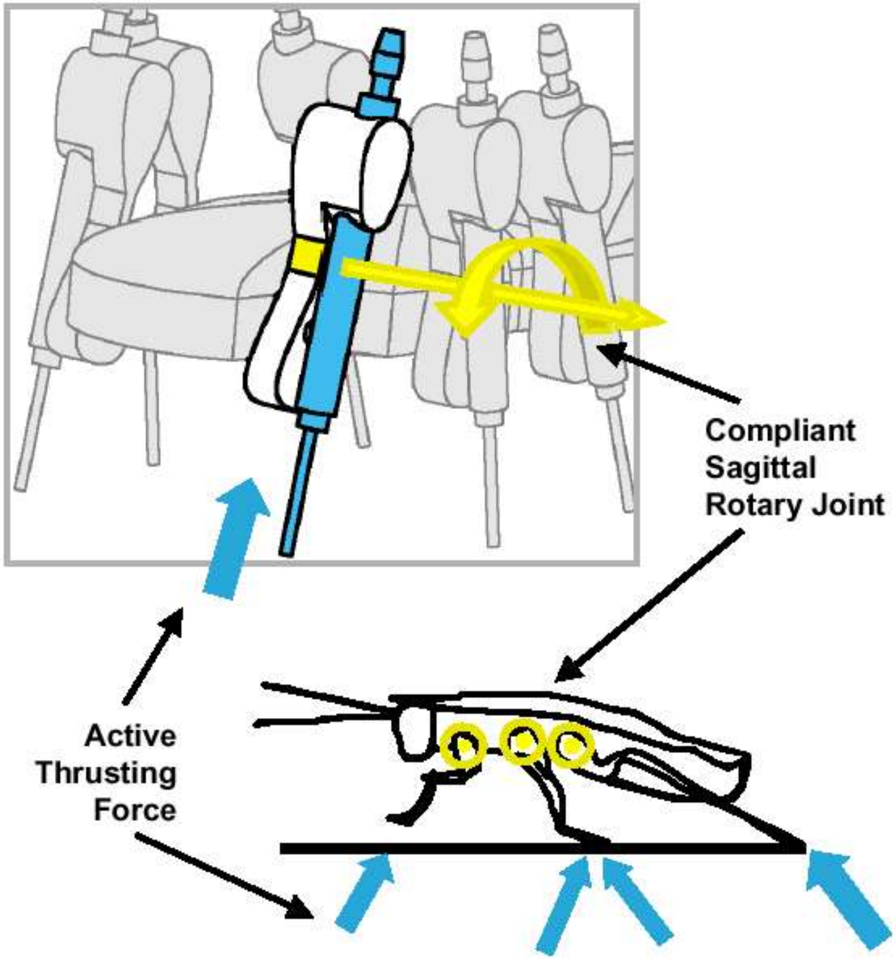
2. Thrusting and Stabilizing Leg Function (I)

- Sprawled posture
- Individual leg function
- Front legs decelerate, hind legs accelerate, middle legs both accelerate and decelerate during the stride
- Self-correcting forces with respect to the geometry



2. Thrusting and Stabilizing Leg Function (II)

Leg Function: *Studies of **ground reaction forces** in cockroach locomotion show that **forces** are directed towards the **hip joints**, essentially acting as **thrusters**.*



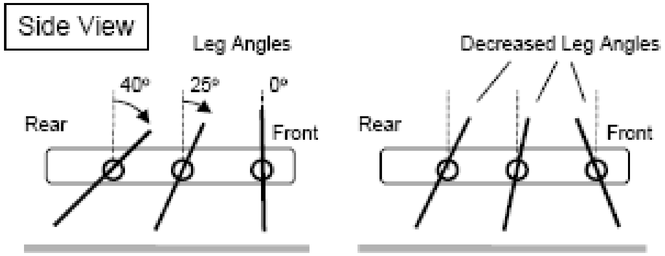
Compliant Sagittal Rotary Joint

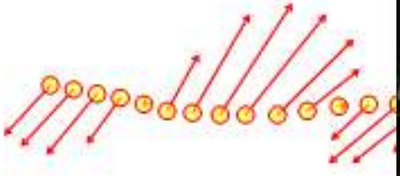
Active Thrusting Force

2. Thrusting and Stabilizing Leg Function (II)

In the first Sprawl robot versions, the primary thrusting action was performed by a ***pneumatic piston***. This piston was attached to the body through a **compliant rotary joint at the hip**. This unactuated rotary joint is based on studies of the cockroach's **<u>compliant trochanter-femur joint</u>**, which is believed to be largely passive.

Servo motors rotate the base of the hip with respect to the body, thus setting the nominal, or equilibrium, angle about which the leg will rotate. **By changing this angle, we can affect the function that the leg performs by aiming the thrusting action towards <u>the back (to accelerate) or towards the front (to decelerate)</u>.**



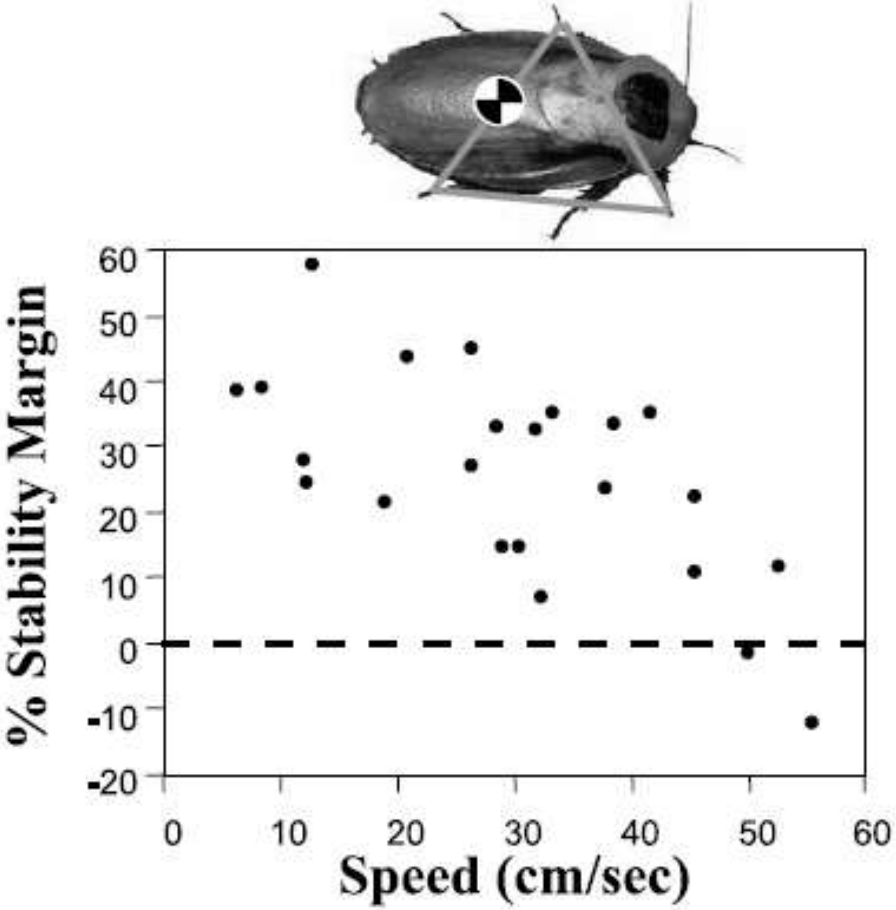


Dynamic stability in arthropod running

Statically stable design for slower arthropod locomotion does not preclude **dynamic** **effects** at faster speeds.

Duty factors (i.e. the fraction of time a leg spends on the ground relative to the stride period) decrease to 0.5 and below as speed increases.

Percent stability margin (i.e. the shorter distance from the center of gravity to the boundaries of support normalized to the maximum possible stability margin) decreases with increasing speed from 60% at 10 cm s^{-1} to values less than zero at speeds faster than 50 cm s^{-1}. Negative percent stability margins indicate static instability.



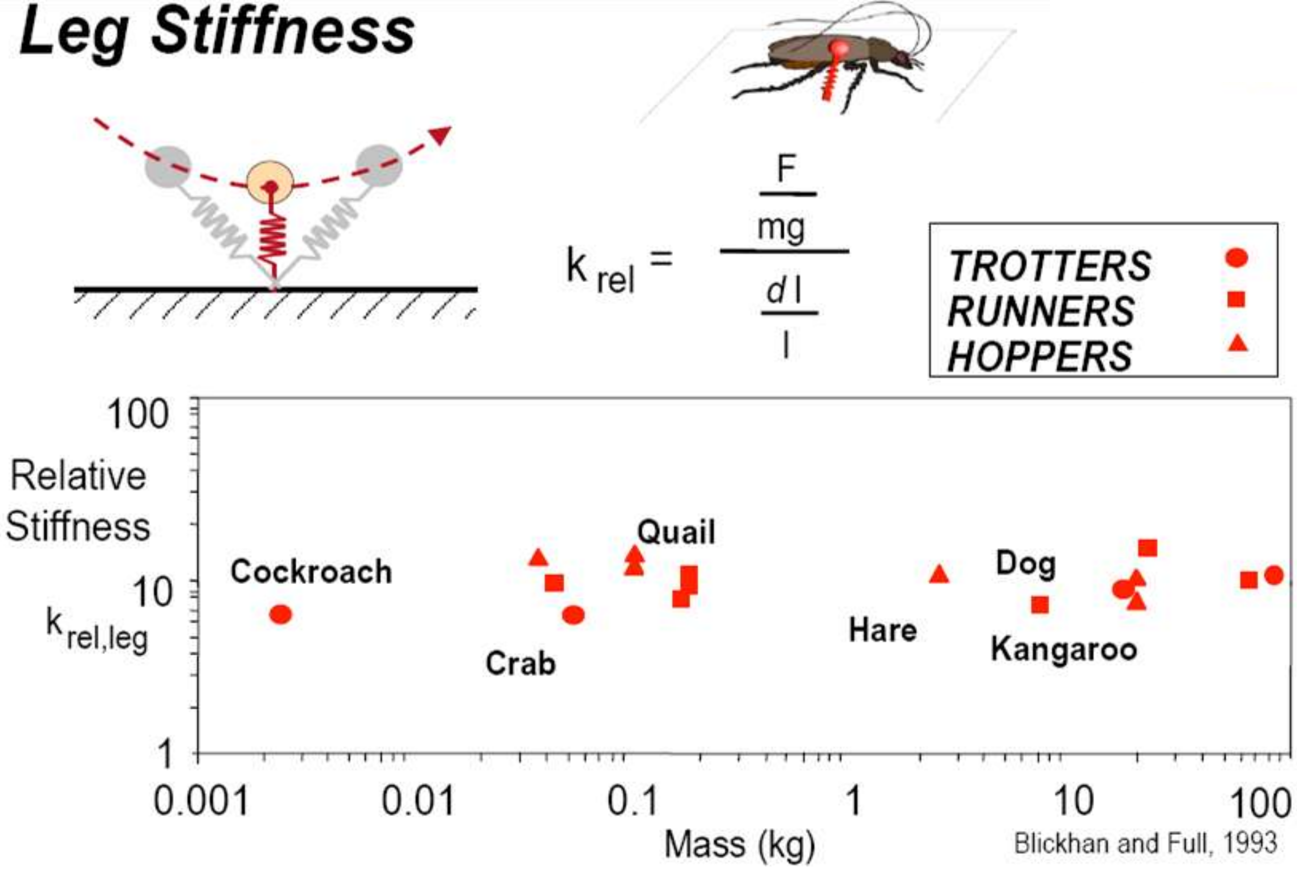
These polypedal runners remain **dynamically stable** because a force in one direction at one instant is later compensated by another force and distributed over time by the forces of inertia – the "dynamics".

Spring-mass dynamics of arthropod running

In faster moving cockroaches and crabs, the mass center can be modeled as a mass (i.e. the body) sitting on the top of a virtual spring (i.e. representing the legs) where the relative stiffness of all the legs acting as one virtual spring (k_{rel}) equals

$K_{rel} = (F_{vert}/mg)/(\Delta l/l)$

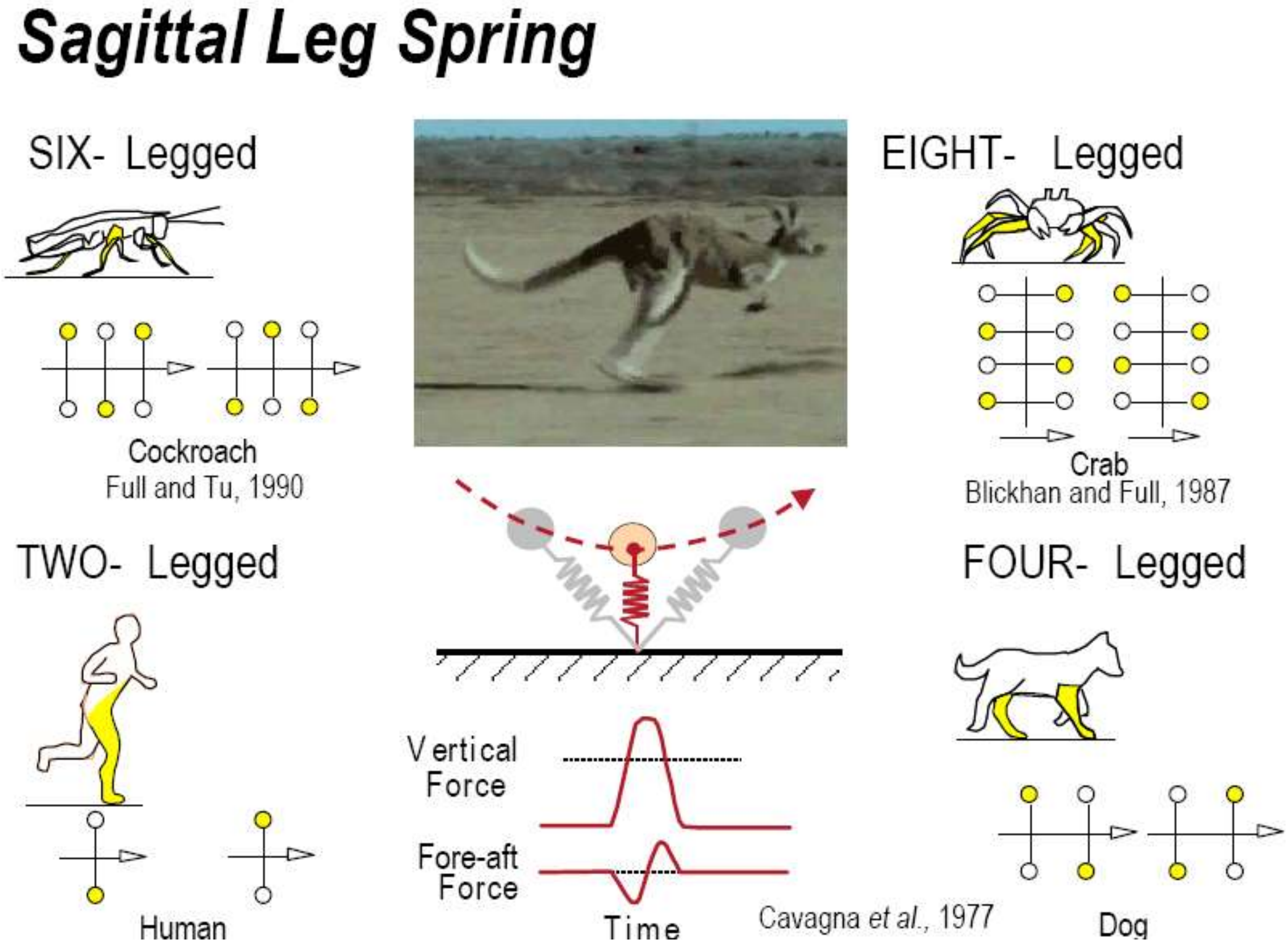
F_{vert} is the vertical ground reaction force of the virtual spring at midstance; Δl is the compression of the leg spring; l is the lenght of the uncompressed leg spring and mg is the weight.



Blickhan and Full, 1993

Spring-mass dynamics of arthropod running

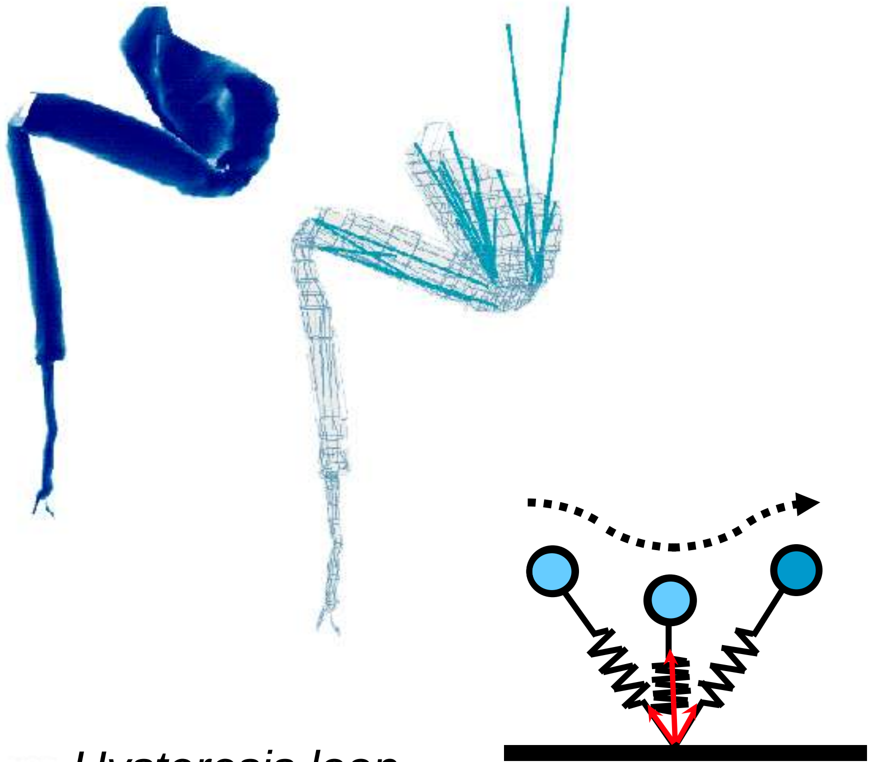
The **ground reaction force pattern** for six- and eight-legged arthropods is fundamentally similar to two-, and four-legged vertebrates, despite the variation in morphology. Running humans, trotting dogs, cockroaches and sideways running crabs can move their bodies by having legs work synergistically, as if they were one **pogo-stick**. **Two** legs in a trotting quadrupedal mammal, **three** legs in an insect and **four** legs in a crab can act as **one** leg does in a biped during ground contact.



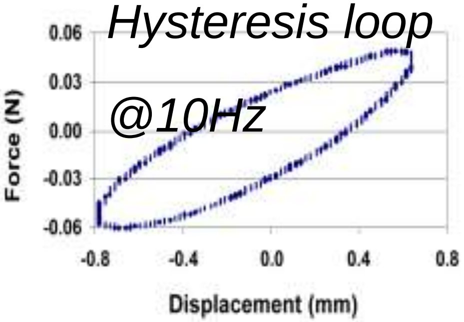
3. Passive Visco-elastic Structure (I)

Studies of the cockroach *Blaberus discoidalis* are revealing the role of the <u>viscoelastic properties of its muscles and exoskeleton in locomotion</u> (Garcia et al., 2000; **Meijer and Full, 2000; Xu et al., 2000**).

- Exoskeleton and muscle properties
- Compliance
- Damping

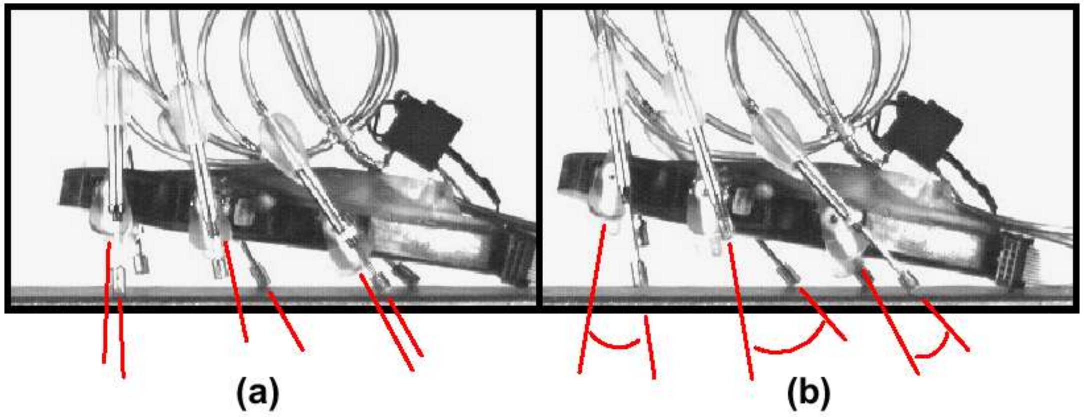


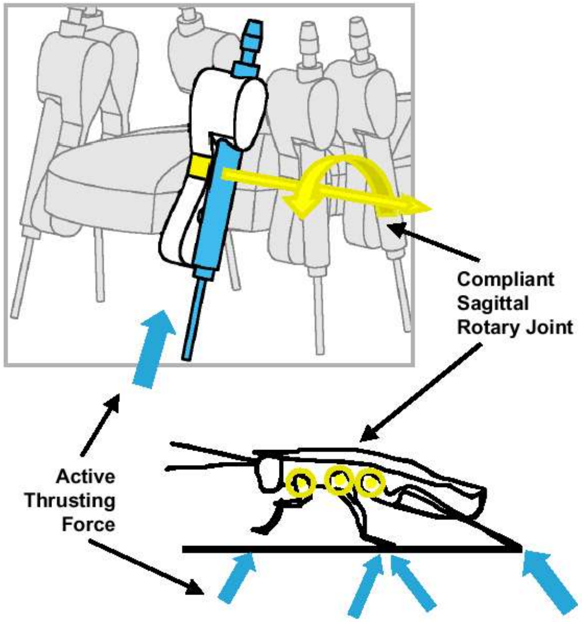
Position, velocity and ground reaction force measurements for the *Blaberus discoidalis* were measured, while cockroach was run along a track with a **force platform** while a **high-speed video system** captured the locomotion at 60 frames/second.



3. Passive Visco-elastic Structure (II)

The prototype's leg design contains a **passive compliant** and damped **rotary hip joint** fabricated as a flexure of **soft viscoelastic polymer urethane** embedded in a leg structure of stiffer plastic.



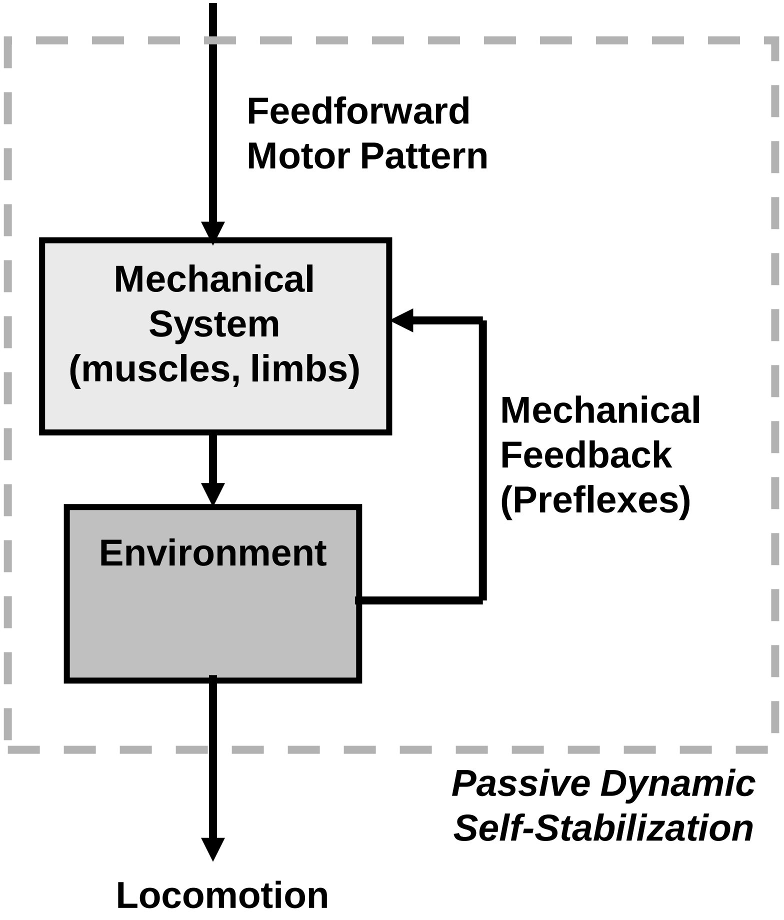


High-speed footage of the running robot in a) mid-stance and b) full extension. As shown, the compliance in the leg plays an important role in the locomotion, as evidenced by the large deflections during the stride.

4. Open-loop/Feed-forward Control (I)

Preflexes: *The self-stabilizing properties of the visco-elastic mechanical system provide an immediate, or "zero-order" response to perturbations without the delays of neural reflexes*

- Passive properties of the mechanical system…
- …that stabilize and reject disturbances
- Immediate response
- No delays associated with sense-compute-command loops


Feedforward Motor Pattern

Mechanical System (muscles, limbs)

Environment

Mechanical Feedback (Preflexes)

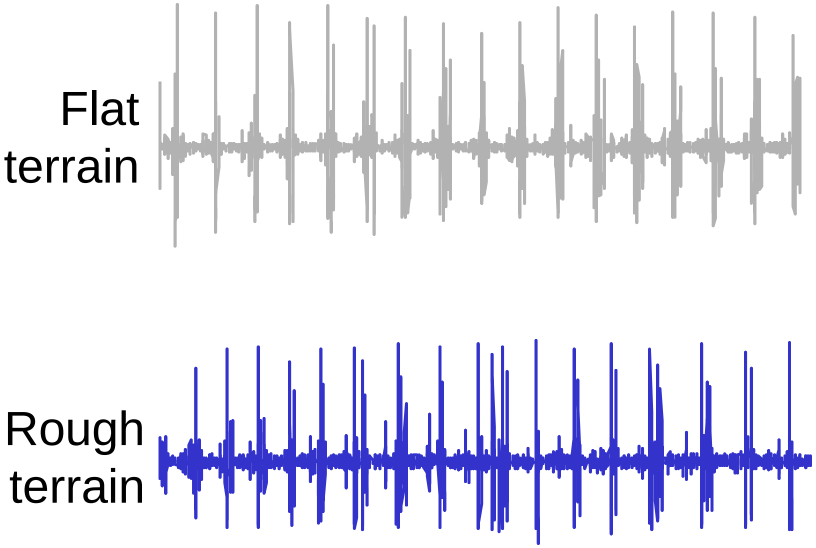
Passive Dynamic Self-Stabilization

Locomotion

Biological Inspiration

- When transitioning from flat to rough terrain…

- …impulses sent to the muscles did not noticeably change
- Similar activation despite large changes in events

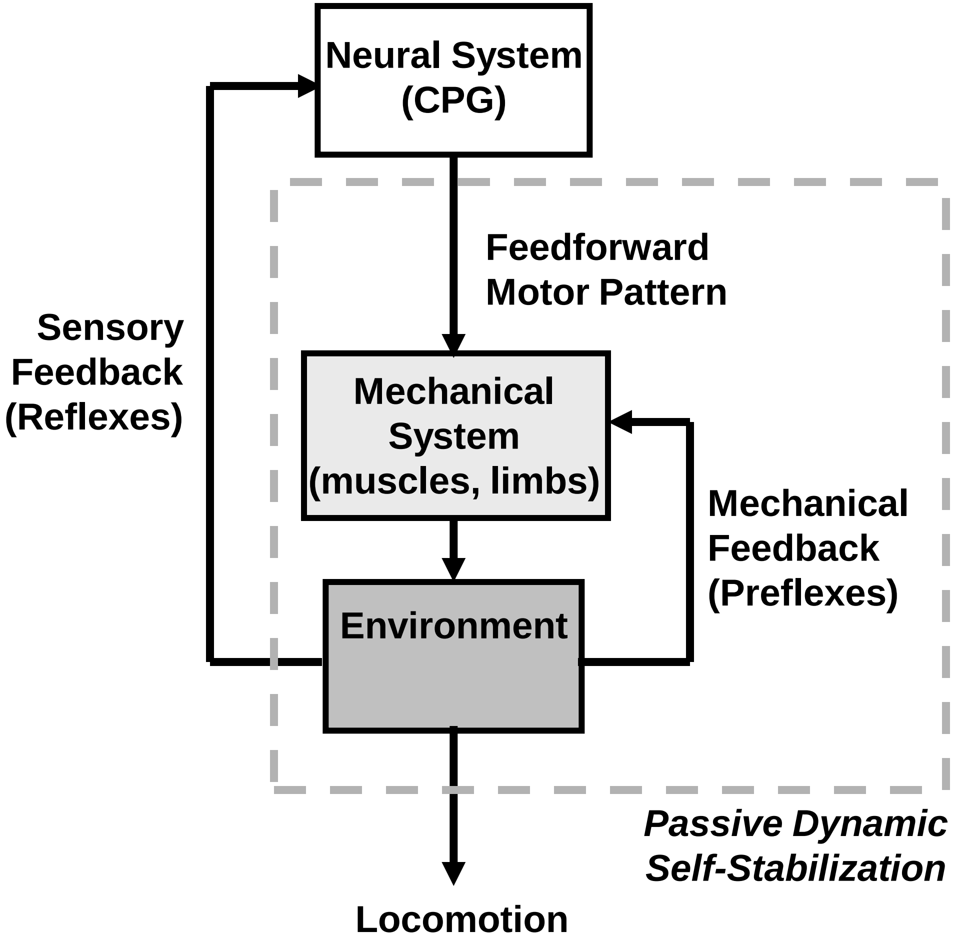


Biological Inspiration

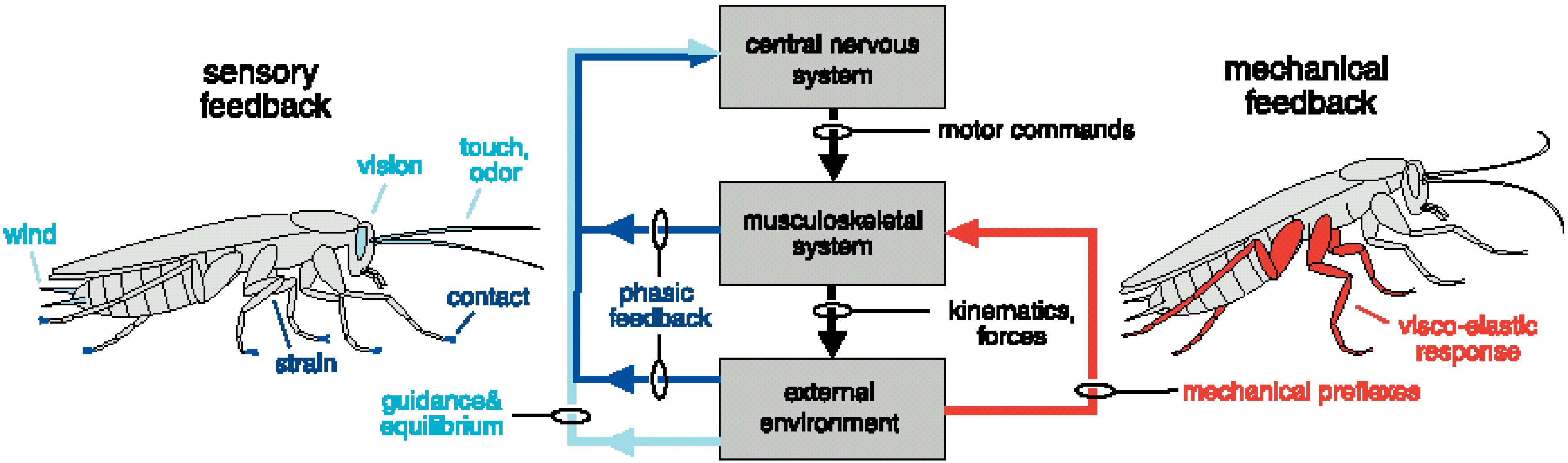
- Implies exclusion of sensory feedback
- No precise foot-placement or “follow-the-leader gait”
- But still able to traverse rough terrain..!

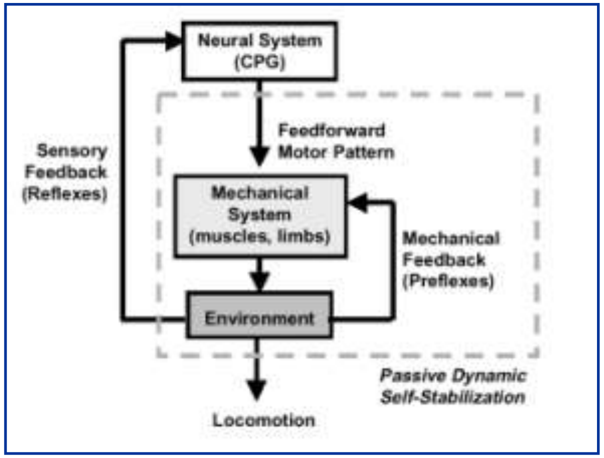
Control Hierarchy

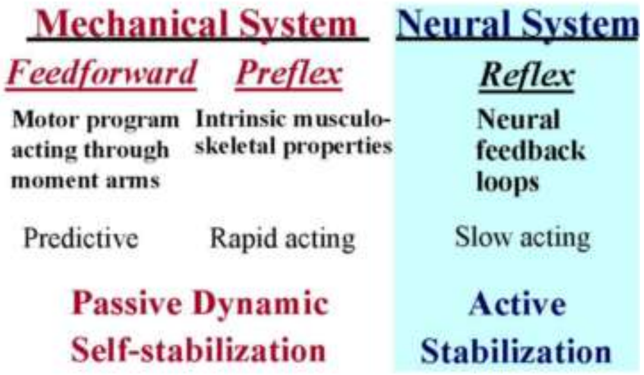
- **Preflexes** provide immediate stabilization for repetitive task
- **Reflexes** and neural feedback adapt to changing conditions…
- …through the feedforward pattern



4. Open-loop/Feed-forward Control (II)







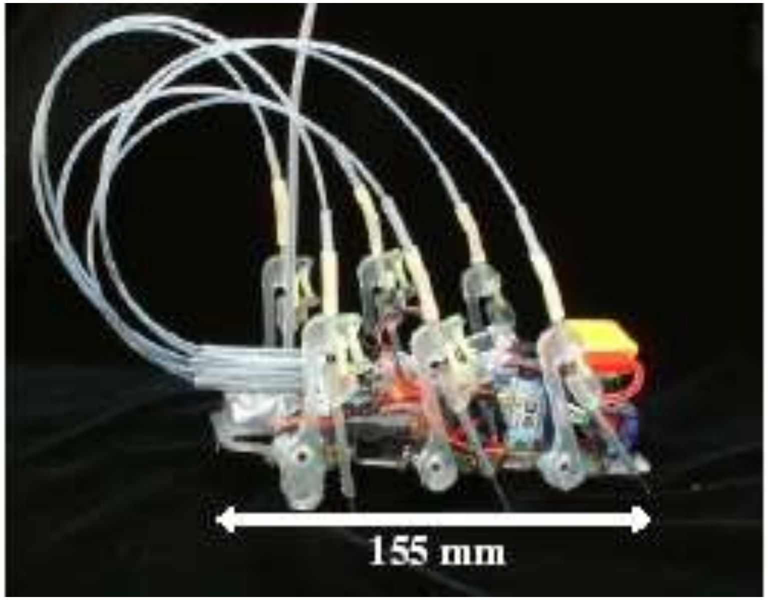
Mechanical System		Neural System
Feedforward	*Preflex*	*Reflex*
Motor program acting through moment arms	Intrinsic musculo-skeletal properties	Neural feedback loops
Predictive	Rapid acting	Slow acting
Passive Dynamic Self-stabilization		Active Stabilization

Both neural and mechanical feedback play roles in controlling locomotion

M.H. Dickinson et al., How Animals Move: An Integrative View, SCIENCE, vol 288 (2000)

4. Open-loop/Feed-forward Control (III)

Each of the tripods is pressurized by a separate **3-way valve, which connects the pistons to either a pressurized reservoir or the atmosphere**.



i-Sprawl: a fully **autonomous** hexapedal robot driven by an **electric motor (lithium polymer batteries)** and flexible push-pull cables (autonomous version of sprawl robot)

Velocity of the *iSprawl* robot = 15 body-lengths/second (2.3 m/s)

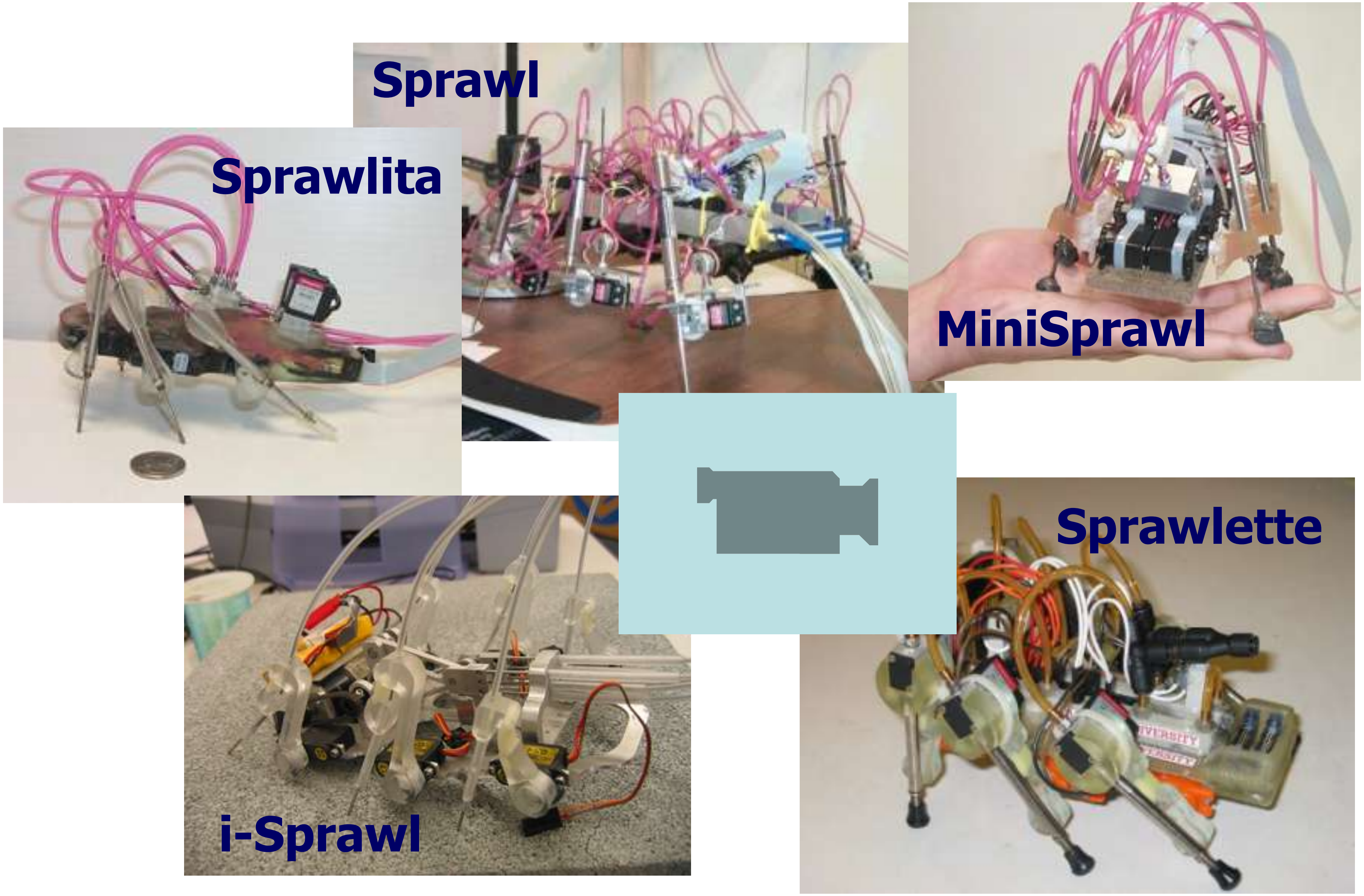
Weight = 0.3 Kg

iSprawl: Autonomous Open-Loop Running

In the case of the Sprawl family of robots, the main principles adapted from insects, the cockroach in particular, are:

- a **sprawled** posture, with a wide stance and rear legs directed backward;
- a bouncing, alternating **tripod gait** based on an open-loop motor pattern;
- **specialization** in which the rear legs primarily accelerate the robot while the front legs decelerate it;
- a **single active degree of freedom** per leg, in which thrusting is directed along the axis of the leg;
- **passive “hip” joints** that swing the legs forward between steps;
- **compliance** and **damping** that absorb perturbations.

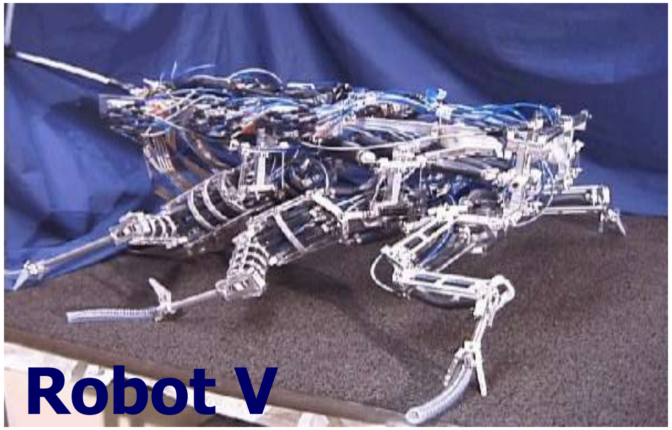
Sprawl robot series



Another approach to the problem: The CWRU's Robot serie

Roger Quinn
Case Western
Reserve University

Roy Ritzmann
Case Western
Reserve University



Another approach to the problem:
The CWRU’s Robot serie

Robot V is a hexapod with kinematics based on studies of the cockroach ***Blaberus discoidalis*** performed in the **Ritzmann Lab in the Biology Department at CWRU**. It has a total of **24 degrees of freedom:**

- **five for each front leg,**
- **four for the middle legs**
- **three for the rear legs**.

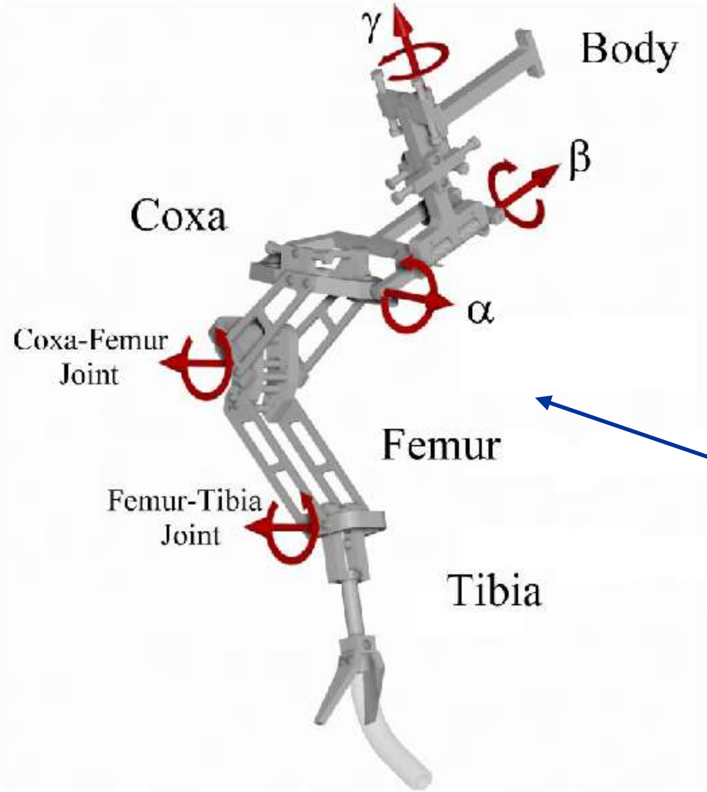
The robot is pneumatically actuated using off the shelf cylinders and blocks of **three-way pneumatic valves**. Weight of the robot = 15 Kg.

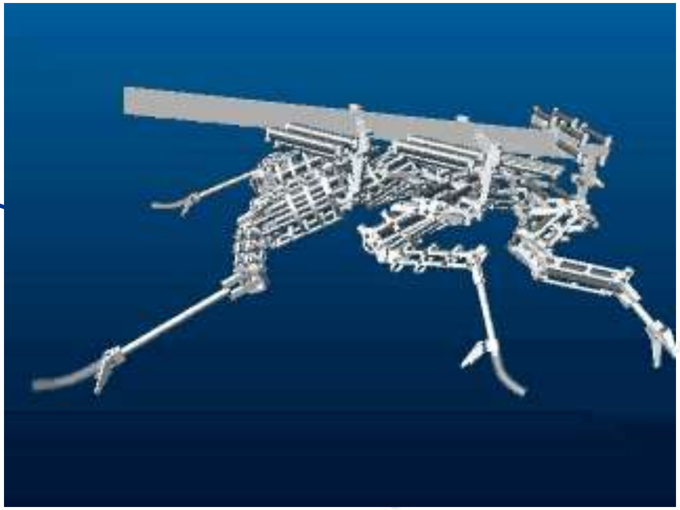
Robot V followed the biology as default strategy and was based **as closely as possible on the structure and walking strategies** that were observed in the death head cockroach ***Blaberus discoidalis*** (Watson and Ritzmann, 1998, Bachmann, 2000, Watson et al. 2002).

Robot V has in the **front legs three joints** between the body and coxa (**γ, β and α**). The **two** remaining joints are between the **coxa and femur** and the **femur and tibia**.

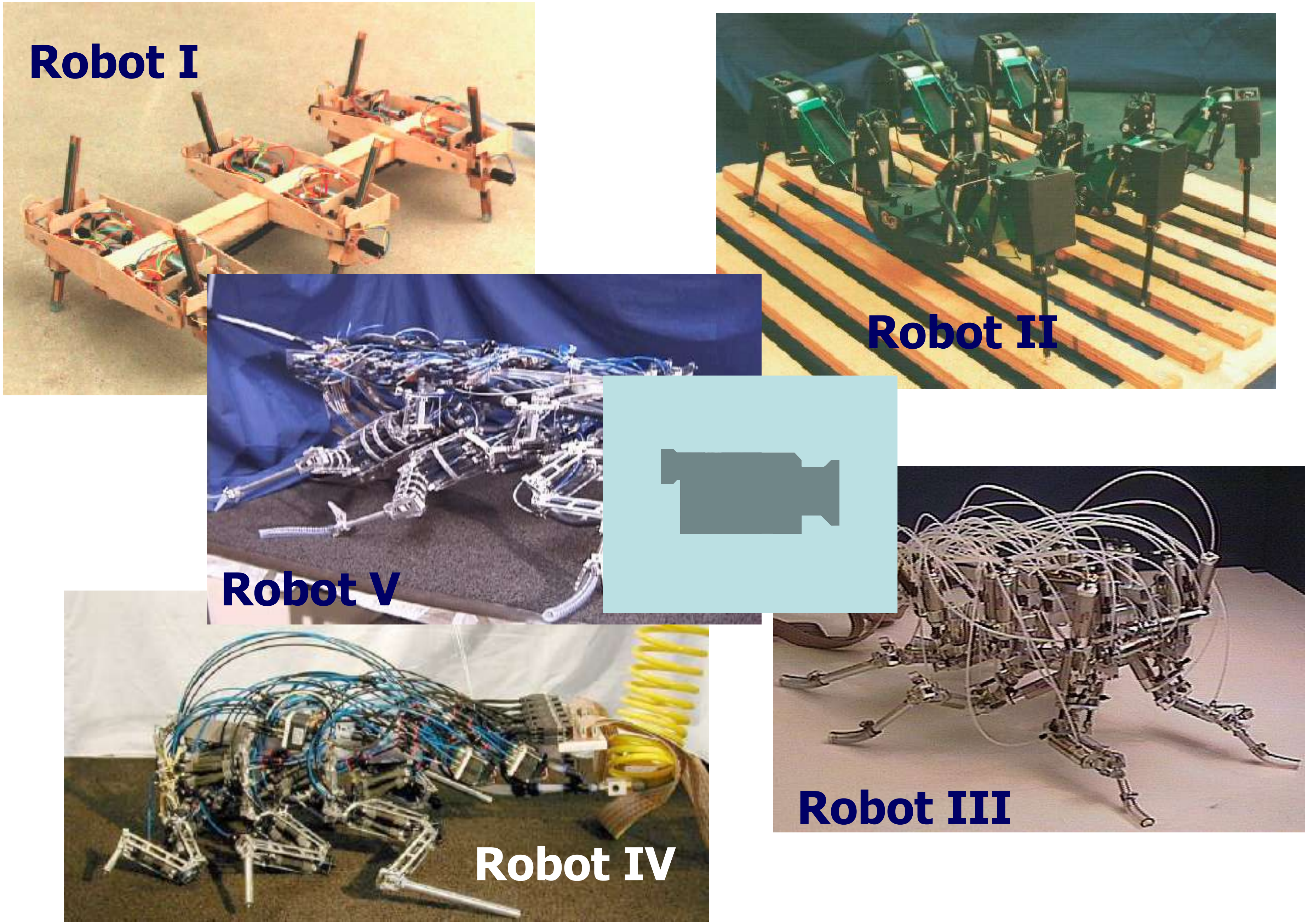
On **Robot V**, the **middle legs** have only **two degrees of freedom—α and β—** between the body and coxa, and retain the **single** joint between the **coxa and femur** and the **femur and tibia**.

Finally, the **rear legs** of the **robot** have **only one** joint between each of the segments. The body-coxa joint uses of only the **β joint**.



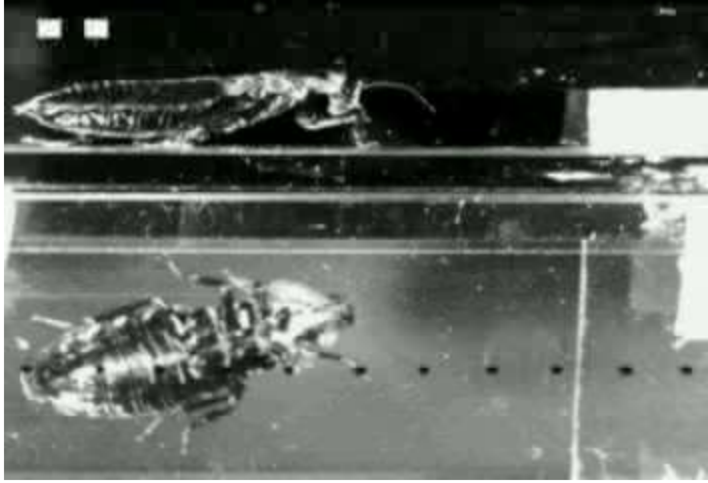


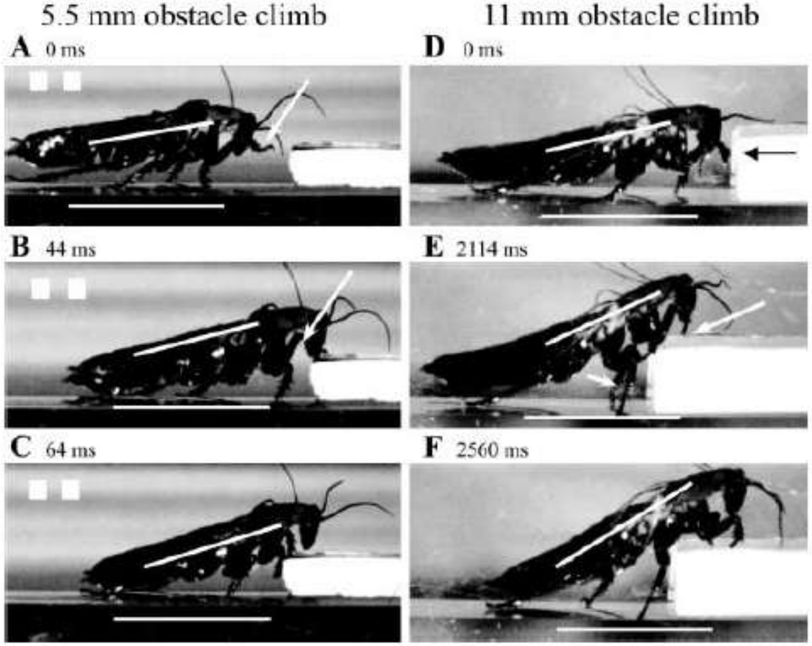
CWRU’s Robot serie



Control of obstacle climbing in the cockroach, *Blaberus discoidalis*

Case Western Reserve University –
Roger Quinn (engineer) – Roy Ritzmann (biologist)





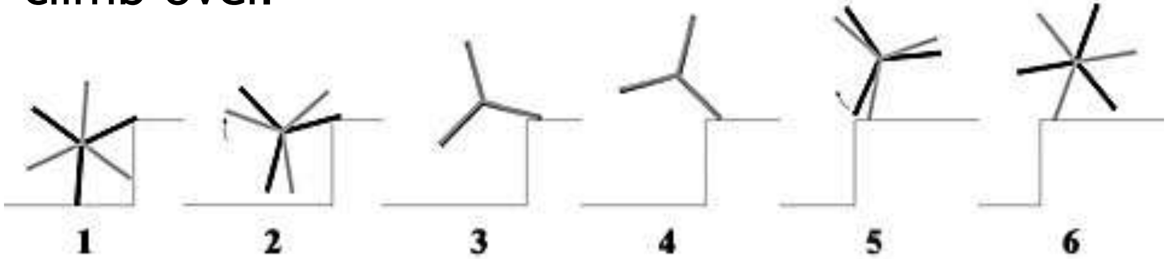
An insect that encounters an obstacle as it is walking could do one of the three things:

1. It could climb over the obstacle by making **little or no modifications of the tripod gait**.
2. It could **change to a completely** different set of leg movements.
3. It could use normal walking movements, coupled with **postural adjustments** to direct the movement of its body over the obstacle.

During horizontal running, the tarsi of the front legs are normally lifted higher than **6 mm**. Therefore, when the cockroach approaches a **5.5 mm block**, the front legs require no alteration in swing trajectory to reach the top of the obstacle. However, for **11-mm obstacles** the front tarsus would encounter the vertical surface of the barrier well below the top. The body angle increases *before* the tarsus of the front leg touches the top of the 11-mm obstacles, because of the middle leg extension. Then, the front leg contacts the top of the block.

Whegs Robot (CWRU)

The Whegs™ series robots utilize a method of locomotion that combines the advantages of **wheels and legs** (wheel-legs). Wheels are relatively simple, and allow a vehicle to move over terrain quickly. Legs allow robots to climb obstacles that are higher than what a wheeled vehicle would be able to climb over.



Bio-inspired working principle:

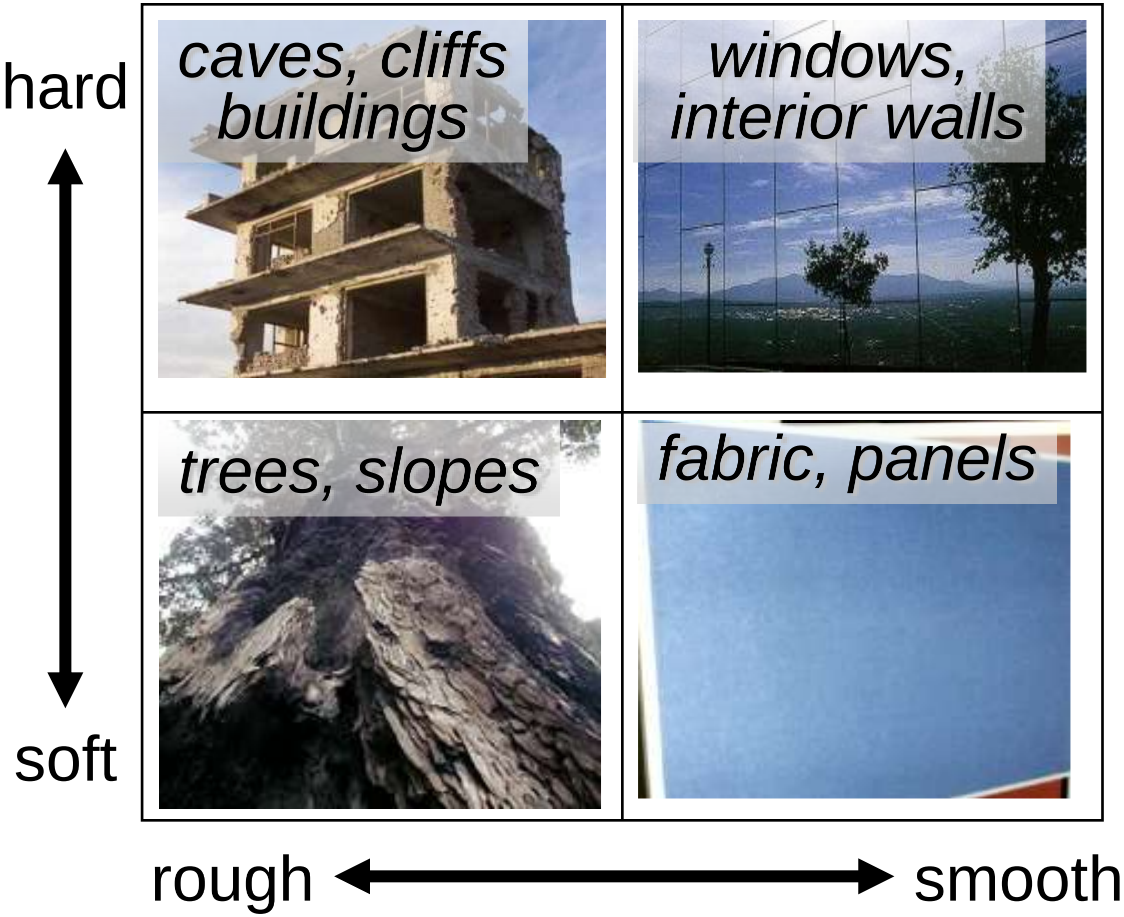
1. Locomotion
   - tripod gait

2. Climbing of obstacles
   - modification of leg’s movements
   - postural adjustment (body flexture)

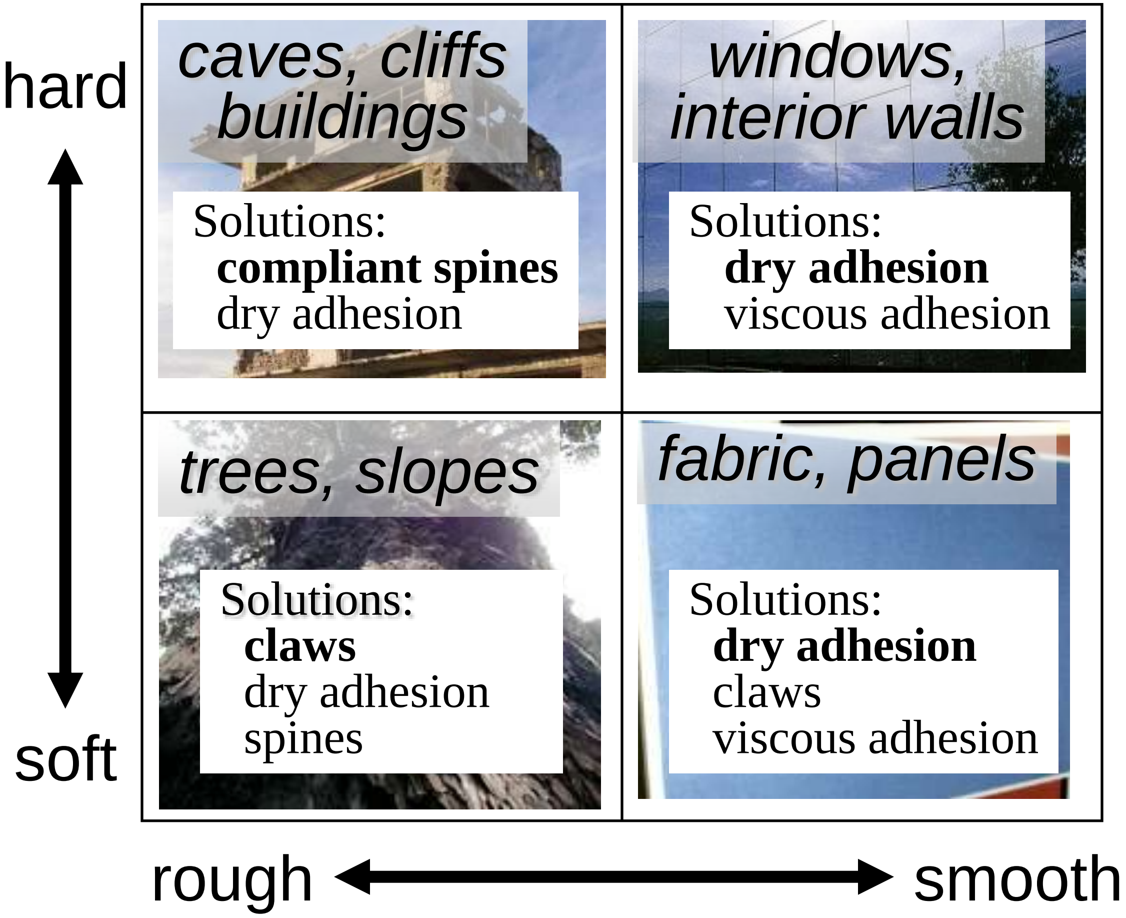
Bioinspired Climbing Robots

Topic - *Problem definition*

Scansorial Agility requires solutions that accommodate *a variety of surfaces*, which vary from hard to soft and from rough to smooth.



Scansorial Surfaces
which solutions excel on each surface type?



hard

soft

rough

smooth

caves, cliffs buildings

Solutions:
compliant spines
dry adhesion

windows, interior walls

Solutions:
dry adhesion
viscous adhesion

trees, slopes

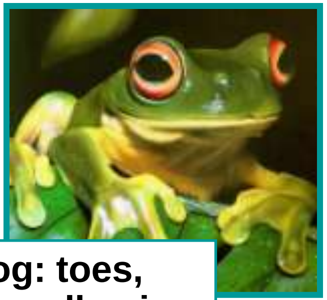
Solutions:
claws
dry adhesion
spines

fabric, panels

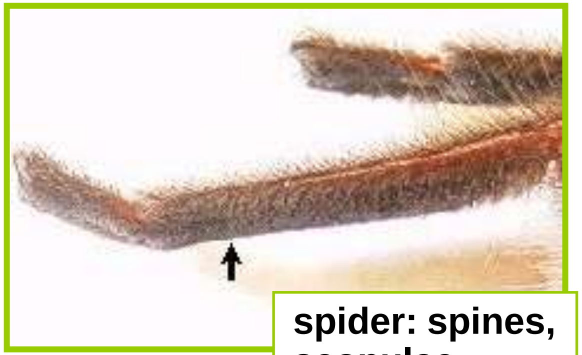
Solutions:
dry adhesion
claws
viscous adhesion

Bioinspiration - how do they do it?

insect: spines, adhesive pads and distal claws



tree frog: toes, viscous adhesion



spider: spines, scopulae

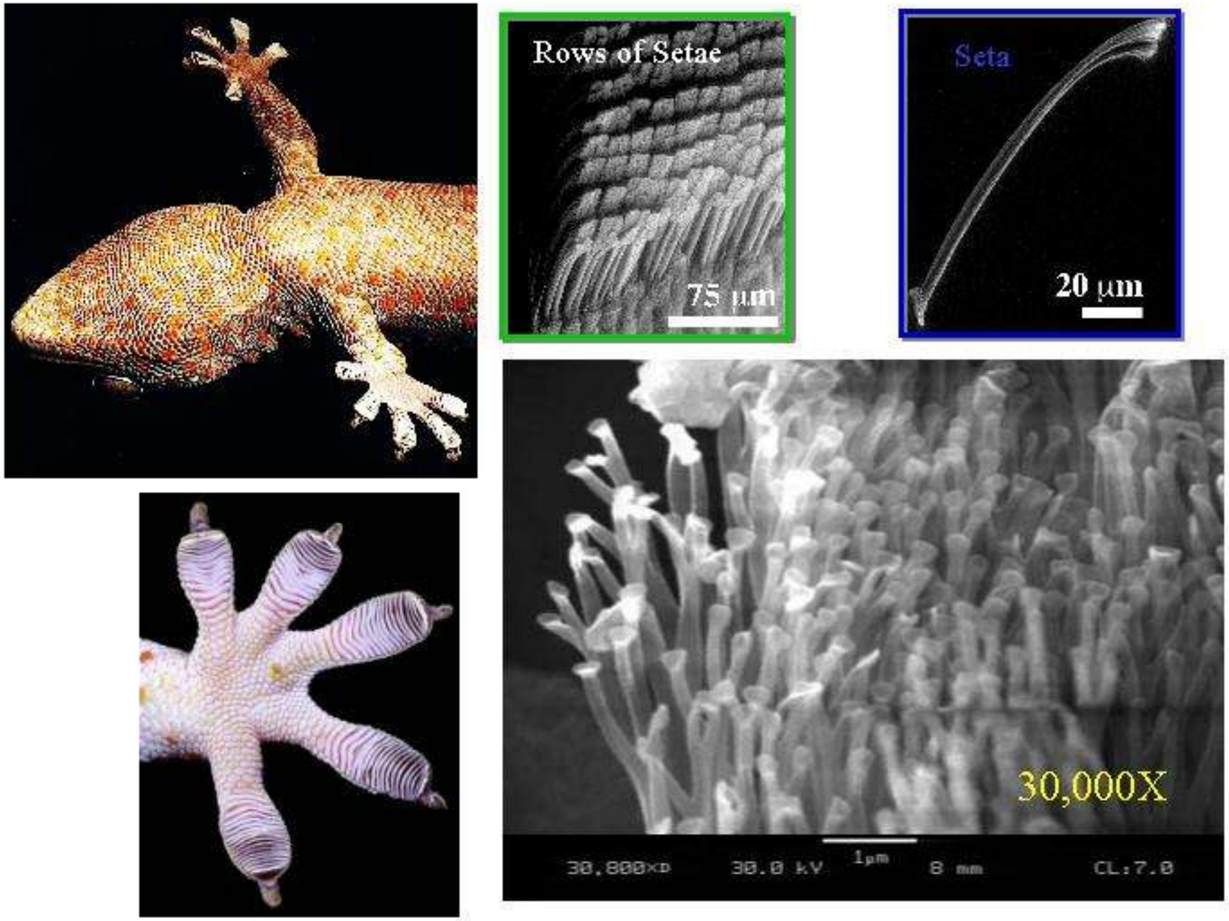
gecko: setae, lamellae, claws

squirrel: toes, claws

Creatures that exemplify **“scansorial agility”** always use multiple solutions.

Biology - examine literature, work with biologists

e.g. Gecko hierarchical adhesion structures



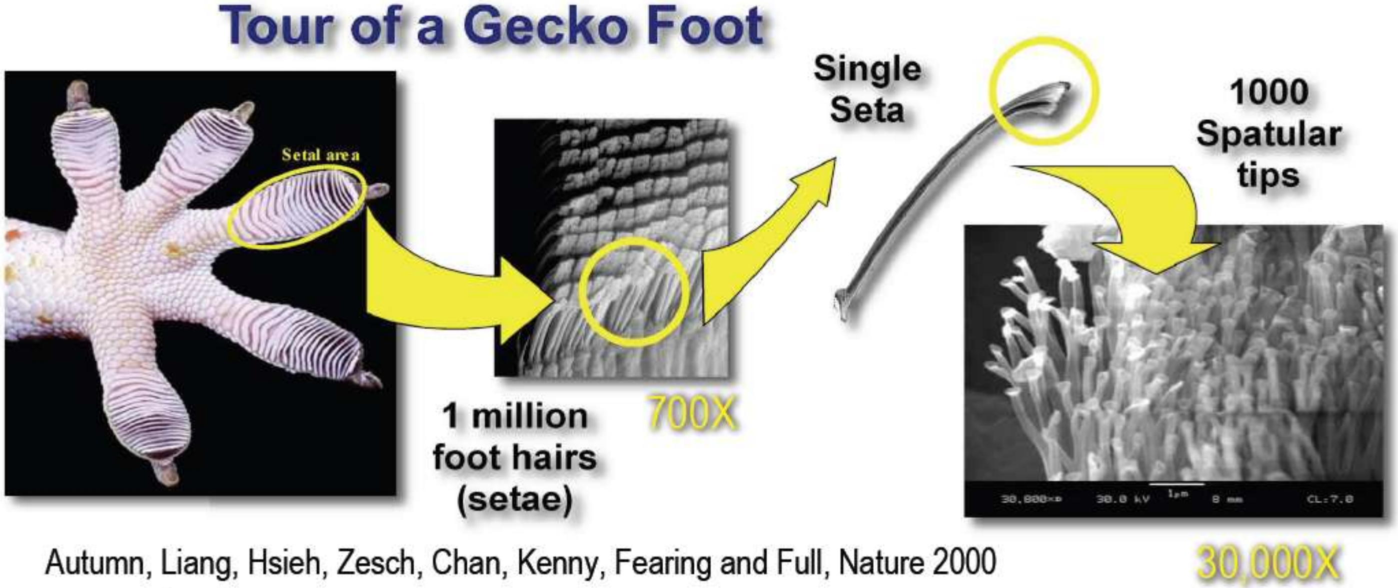
[Autumn et al. 2002 *PNAS*]

Hypotheses - regarding the principles at work

- What is dry adhesion?
  - What are the physical principles?
  - What rules must be followed for good results?
- How do geckos use dry adhesion?
  - What structures do they have?
  - What control do they exert?
- How can we create dry adhesive structures?
- How can we use dry adhesion in a climbing robot?

Hypotheses - regarding the principles at work

- **Foot** = **5 fingers**
- The bottom surfaces of toes are covered with **lamellae** (millimeter scale)
- **Lamellae** are composed of many individual **setae** (1-50 micrometer scale)
- The tips of the setae are divided into hundreds of **spatulae** (<500 nm scale)



Autumn, Liang, Hsieh, Zesch, Chan, Kenny, Fearing and Full, Nature 2000

The consequence of the gecko’s hierarchical system of compliances is that it can achieve **levels of adhesion** of over **500 KPa** on a wide variety of surfaces from glass to rough rock and can support its entire weight form just one toe.

Dynamics of Climbing Robots

Gecko

Rapid Wall Running

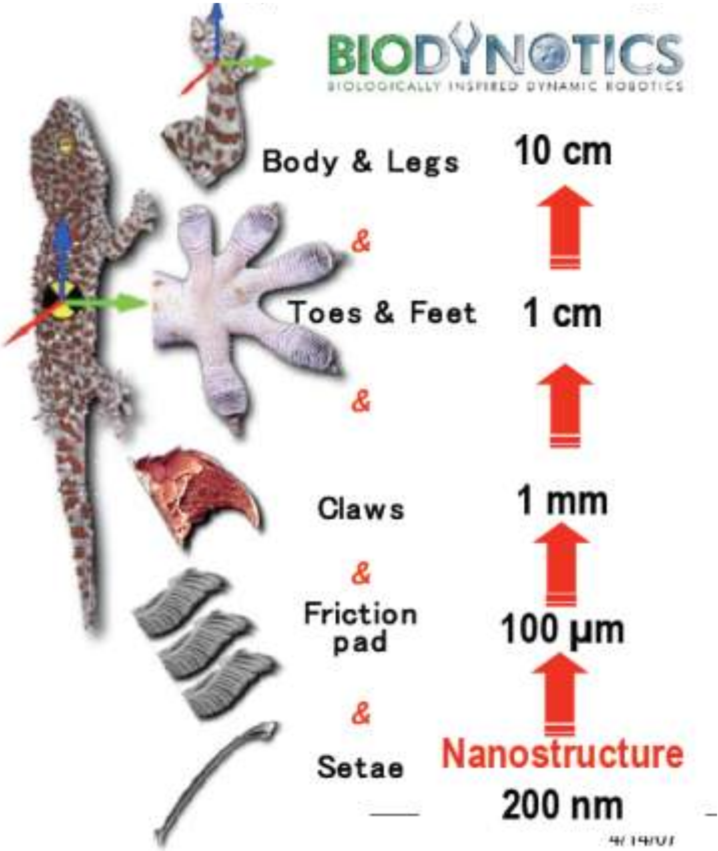
Vertical Climb
1 m/sec
30 steps per second
Attaches in 8 msec
Detaches in 16 msec

Requirements for climbing with dry adhesion

- **Hierarchical compliance** over scales from 10^{-2} to 10^{-7}m.
  ***Reason**:* obtain large contact areas and uniform loading on materials ranging from glass to bark.
  Consequence: need compliances at limb, toe, lamellar and setal scales; need integrated macro/micro fabrication solutions.

- **Anisotropic adhesion and friction**
  ***Reason**:* control adhesive stresses and attachment/detachment.
  ***Consequence**:* need asymmetric, fully 3D micro structures that are difficult to fabricate with current MEMS and nanofabrication technologies

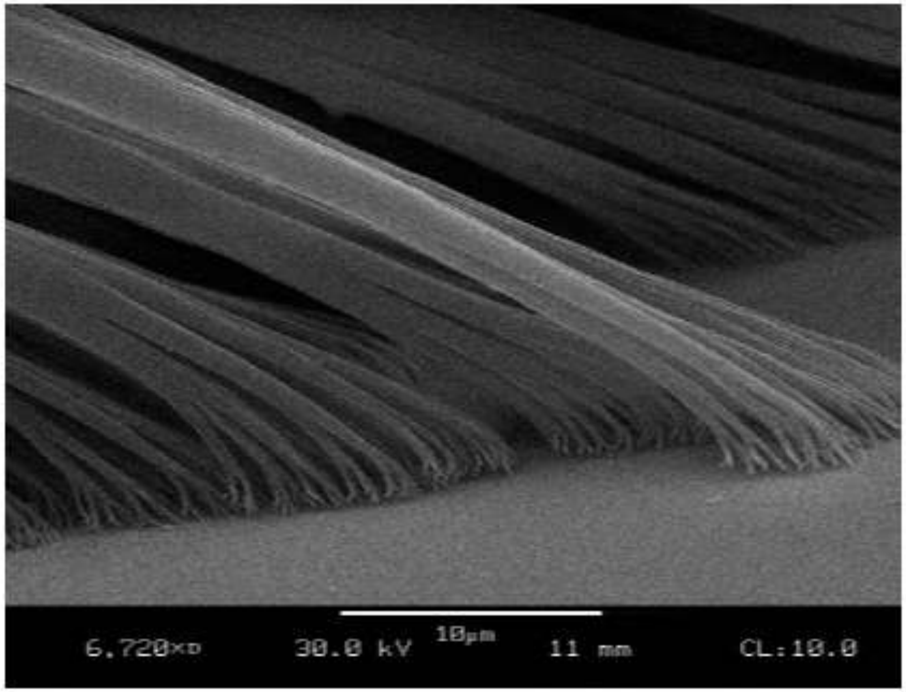
- **Distributed Control of Forces**
  ***Reason**:* increase stability, prevent contact stress concentrations ***Consequence**:* need heterogeneous and anisotropic structures behind the contact surface for shear load transfer; need compliant under-actuated mechanisms and feedback for internal force control.



[S. Kim et al 2006]

Detachment

A billion spatulae produce large forces.

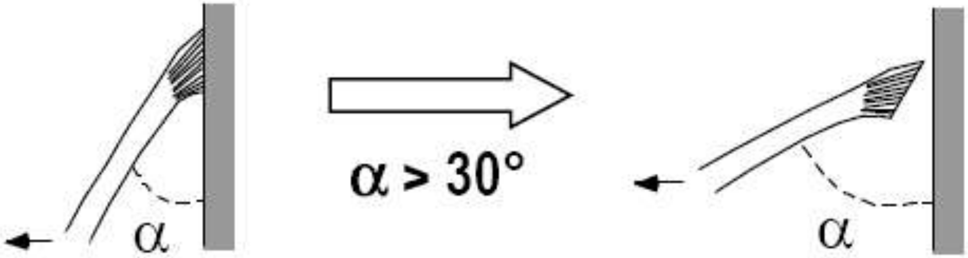


How do geckos *detach* if adhesion is so great?

Micro-Peeling

Peeling at micro and macro scale reduces detachment force

Micro scale



Macro scale

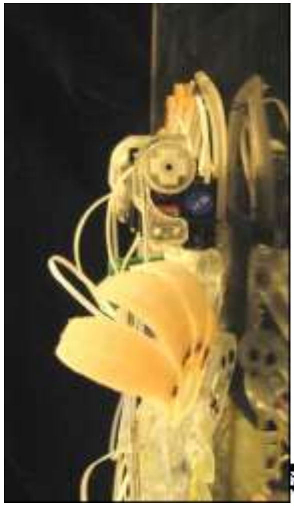
StickyBot Design

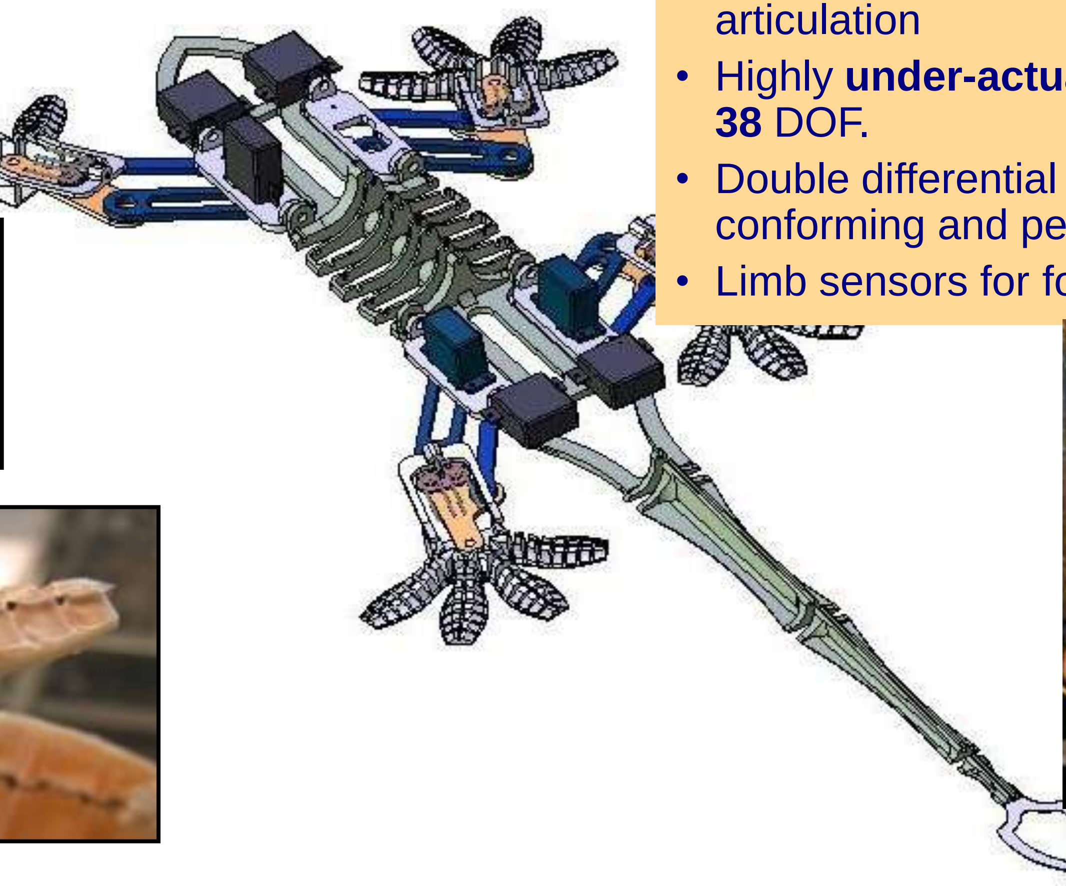
http://bdml.stanford.edu/twiki/bin/view/Main/StickyBot

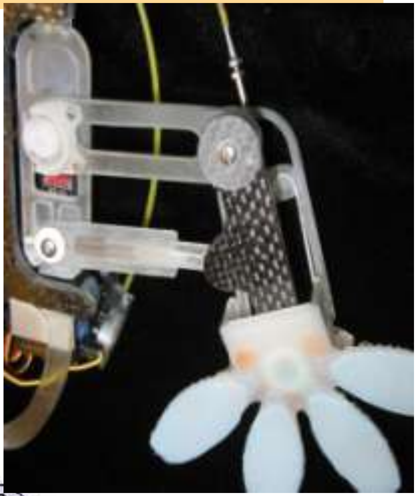
Robotics - Implementations of principles

StickyBot

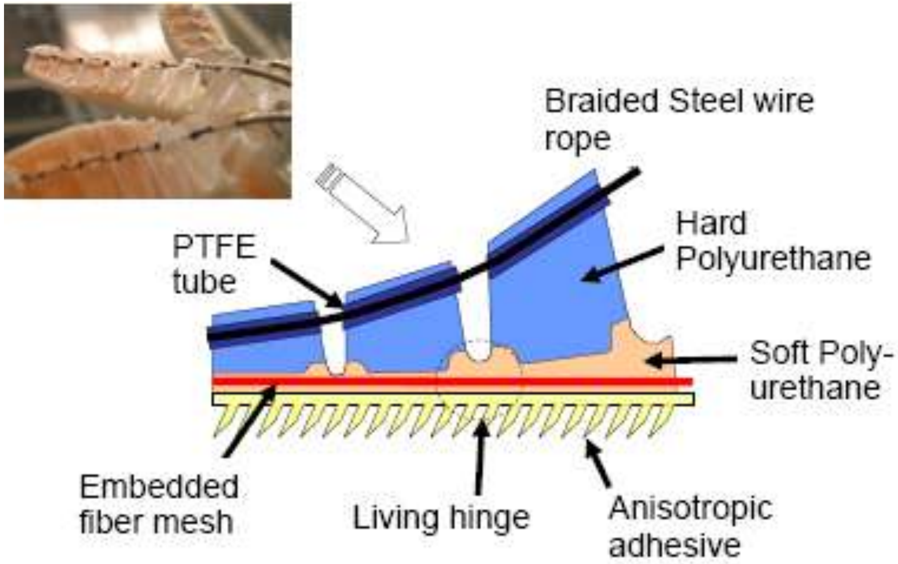
- The torso and limbs are created via **Shape Deposition Manufacturing** using two different grades of polyurethane
- Torso and forelimbs are reinforced with **carbon fiber**
- The **spine structure** at the center of body has the ability to provide body articulation
- Highly **under-actuated**: **12** servos, **38** DOF.
- Double differential toe mechanism for conforming and peeling
- Limb sensors for force control.

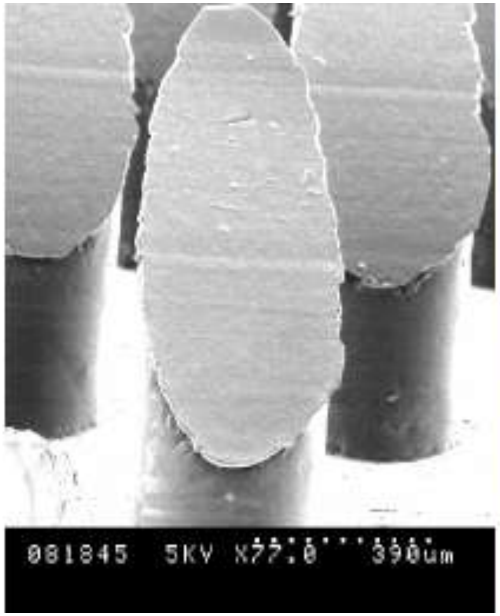


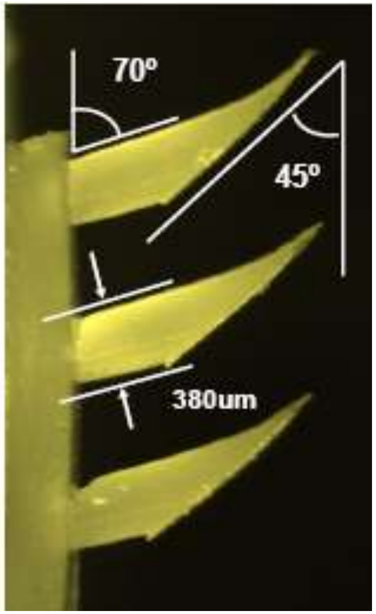




Hierarchical and anisotropic compliance





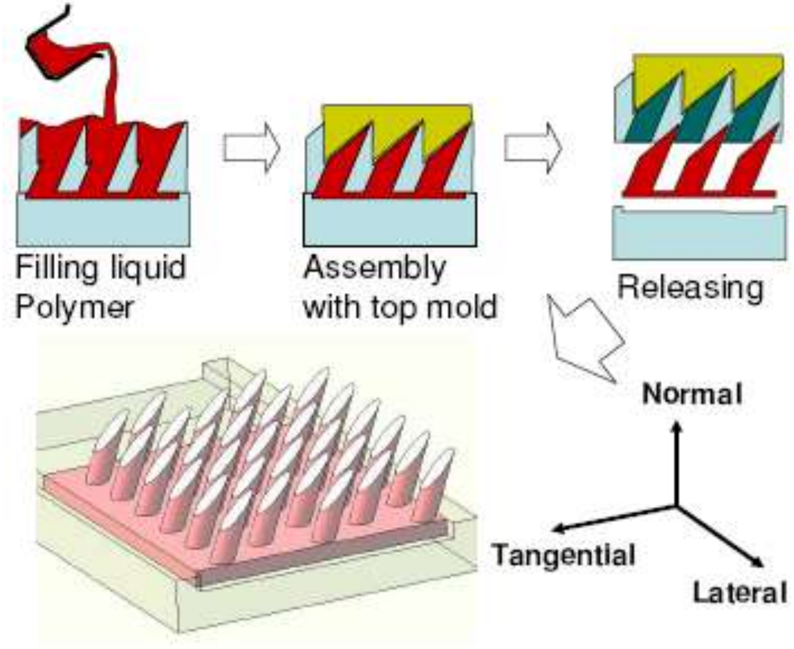


At the finest scale, the contact surfaces of the feet are equipped with **synthetic adhesive materials.** To date, the best results have been obtained with arrays of small, asymmetric elastomeric features. The arrays are made by micromolding with a soft (Shore 20-A) urethane polymer. This structure allows **anisotropic compliance** that is essential for the **directional adhesive behavior.**

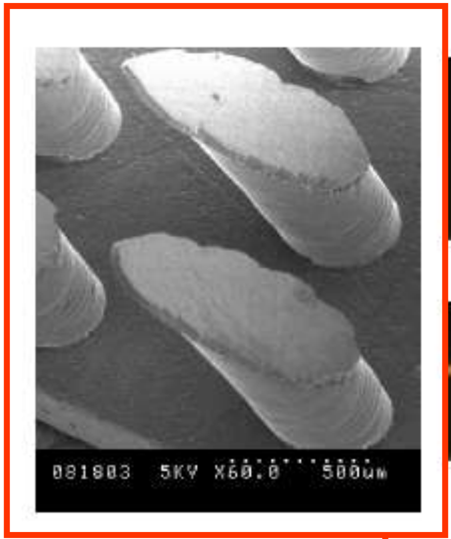
The adhesion only occurs if the lamellae and setae are loaded in the proper direction.

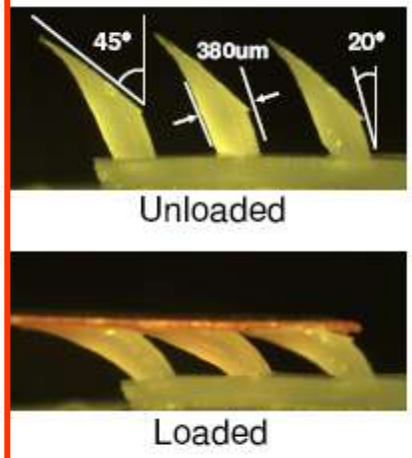
Anisotropic adhesion and friction

Fabrication of anisotropic adhesive pads for StickyBot



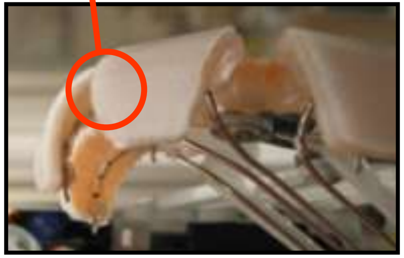
Fabricated anisotropic stalks oriented at 20° with stalk faces oriented at 45°, both with respect to normal.



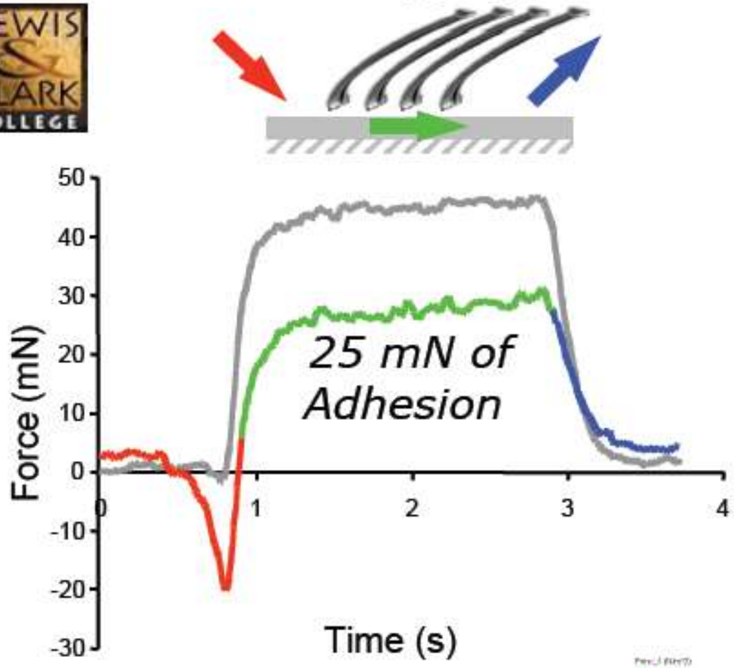


Molding process used to fabricate anisotropic patches.

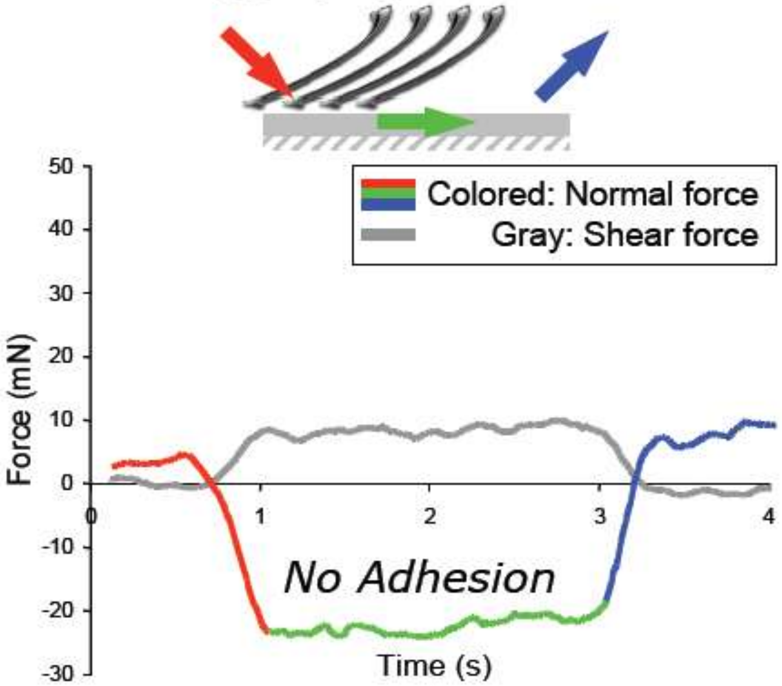
[D. Santos et al 2006]



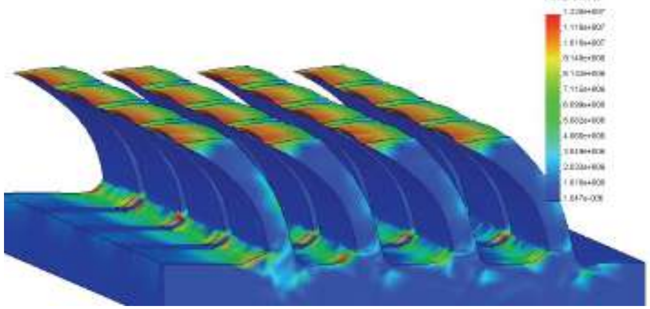
Anisotropic adhesion and friction



Gecko setae dragging with curvature



Dragging against curvature



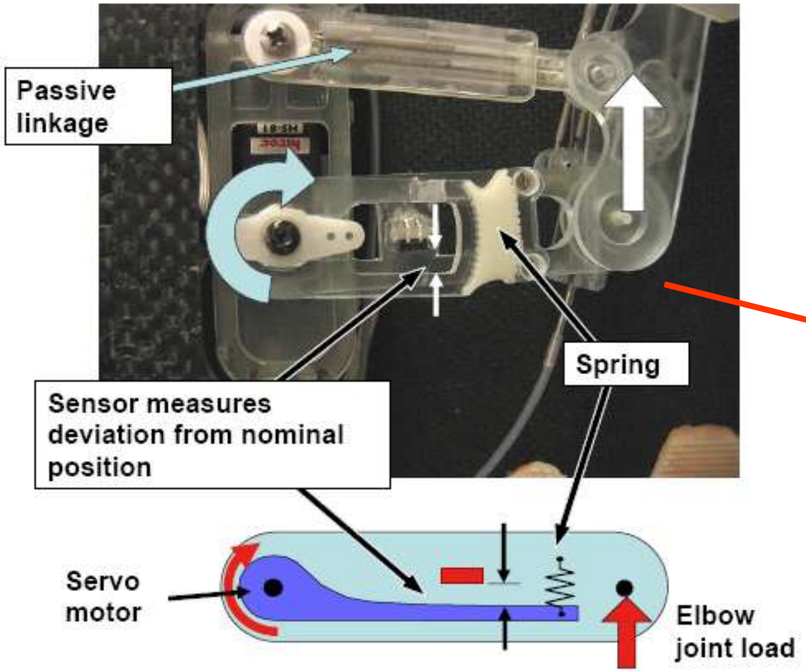
Synthetic elastomer μ-combs: optimize geometry for directional adhesion and uniform tip stress.

[Cutkosky et al. ICRA 2007]

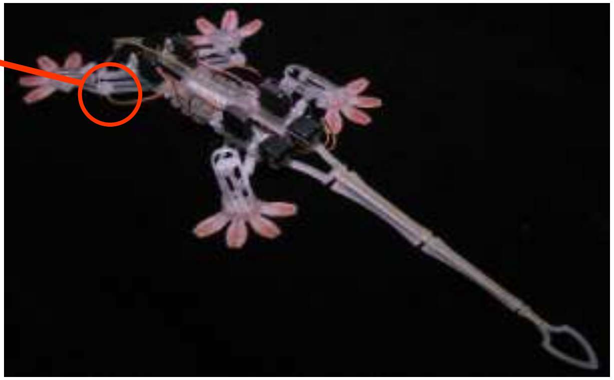
Distributed Control of Forces

Distributed force control ensures that stresses are uniformly distributed over the toes and that undesirable force transients are avoided.

In StickyBot, directional adhesion are used to minimize detachment forces. To achieve smooth engagement and disengagement and control its internal forces, **StickyBot uses force feedback coupled with a stiffness controller.**

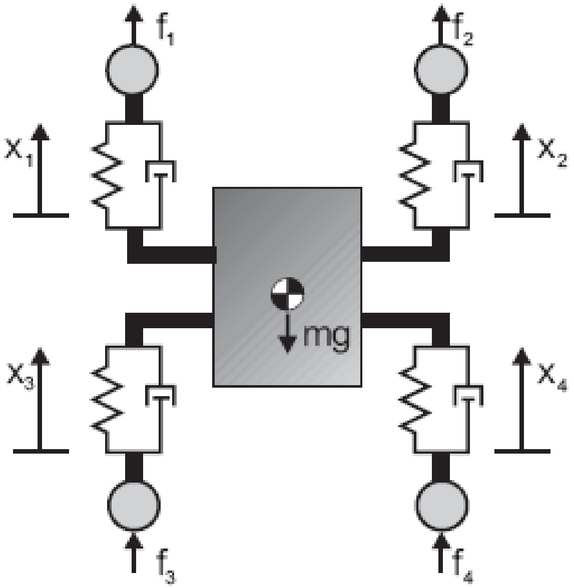


Force sensors located on StickyBot shoulder joints that measure the deflection of an elastomeric spring via a ratiometric Hall effect sensor

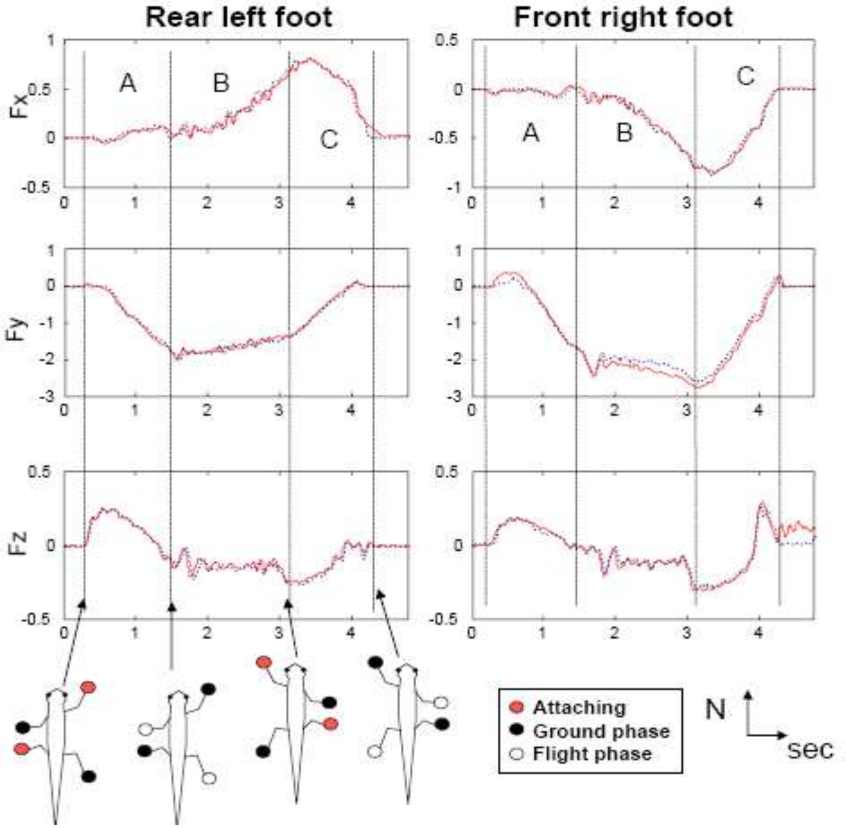


Distributed Control of Forces

Stickybot is capable of climbing a variety of surfaces at 90 deg including glass, glossy ceramic tile, acrylic, and polished granite at speeds up to **4.0 cm/s** (0.12 bodylengths/s)



Schematic of the body model used



Force plate data of rear left foot (L) and front right foot (R) of Stickybot climbing with a 6s period at a speed of 1.5 cm/s.

StickyBot at work!

The Gecko Product Line?

intel — Move wafers/computer chips

NORTEL — Move optic fibers

NASA — Robot inspection
of Space Shuttle
and satellites

3M *Innovations*

Great ideas that stick.

For about 75 years, people worldwide have relied on the quality, performance. and versatility of Scotch® brand tapes.

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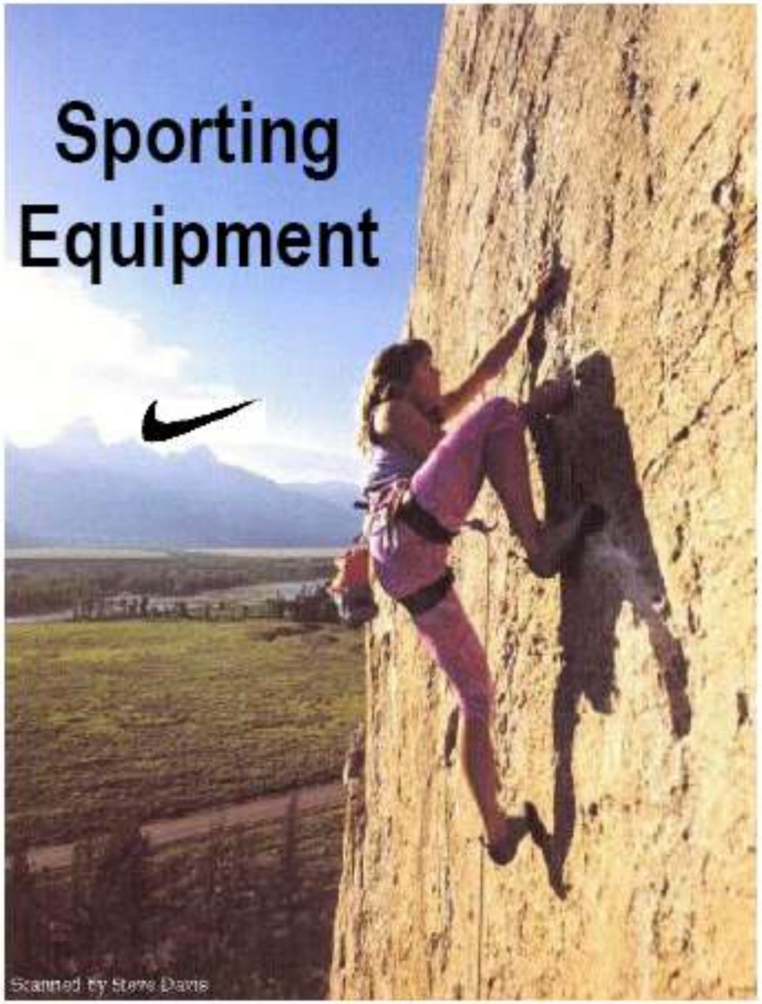
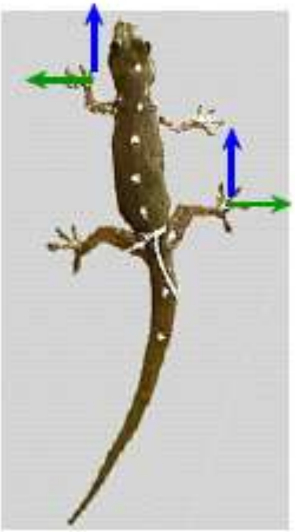


Sporting
Equipment

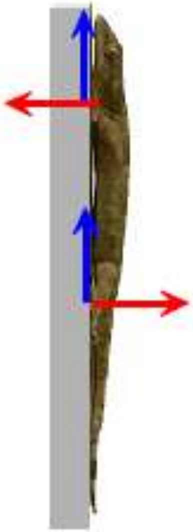
Template for Climbing

4 Legged
Vertebrate

Autumn, Hsieh, Dudek, Chen, Chitaphan & Full, 2006



Feet pull down and toward midline

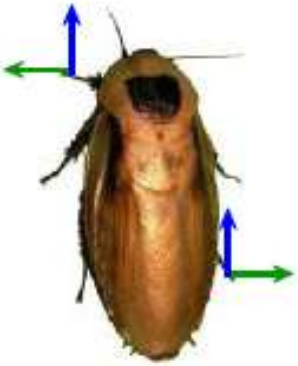


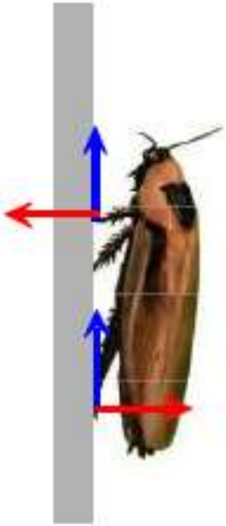
Front feet pull head toward wall. Hind push away.

van der Waals hairs

6 Legged
Invertebrate

Goldman, Chen & Full, 2006

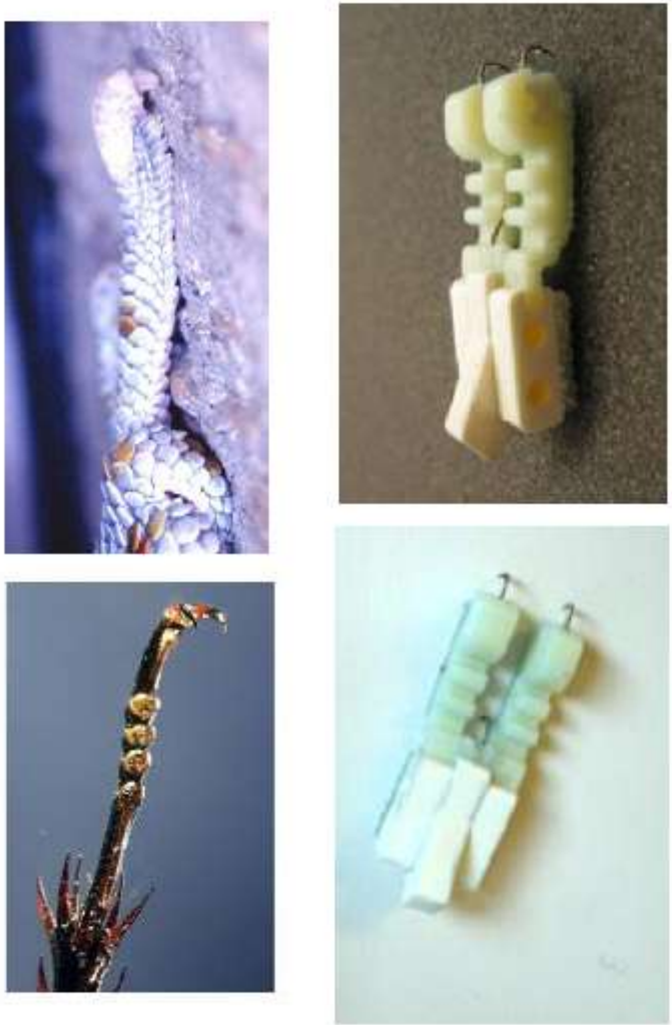




Claws, pads,spines

Designing Feet & Toes

Mark Cutkosky
STANFORD UNIVERSITY



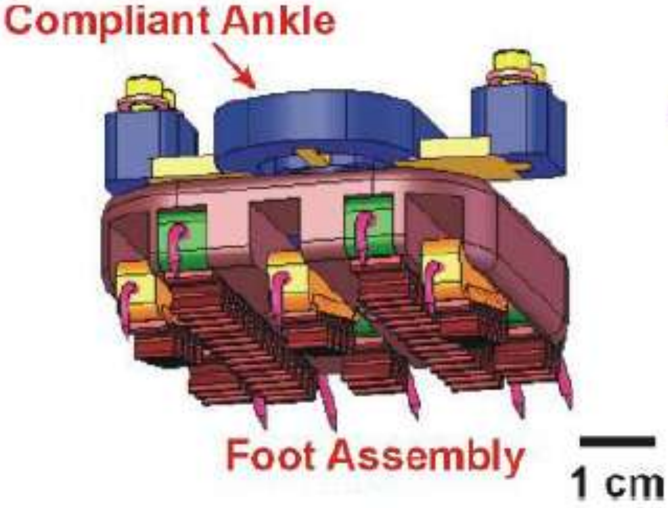
Shape Deposition Manufacturing
allows variable stiffness materials and simple embedding.

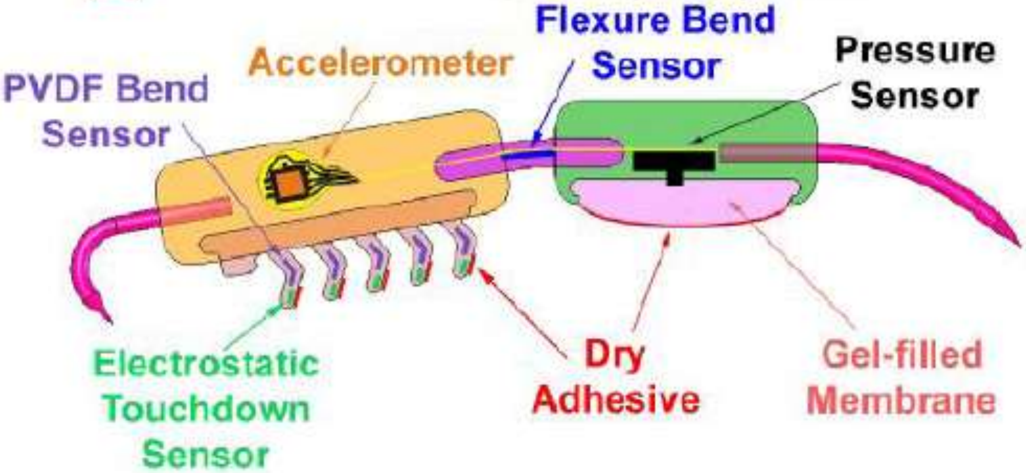
QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

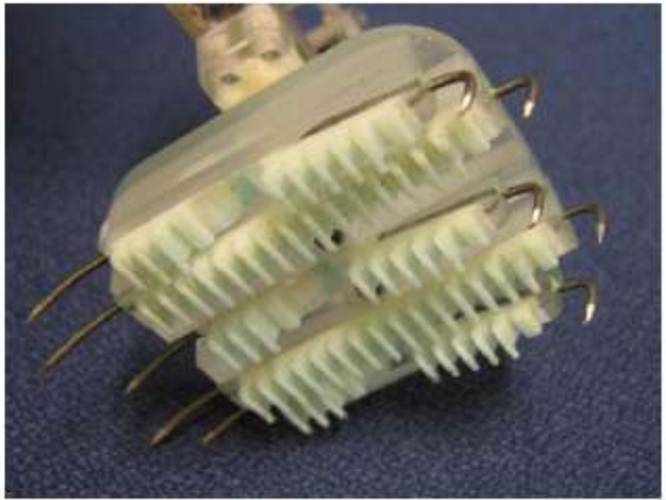
Feet - Inspired by Nature

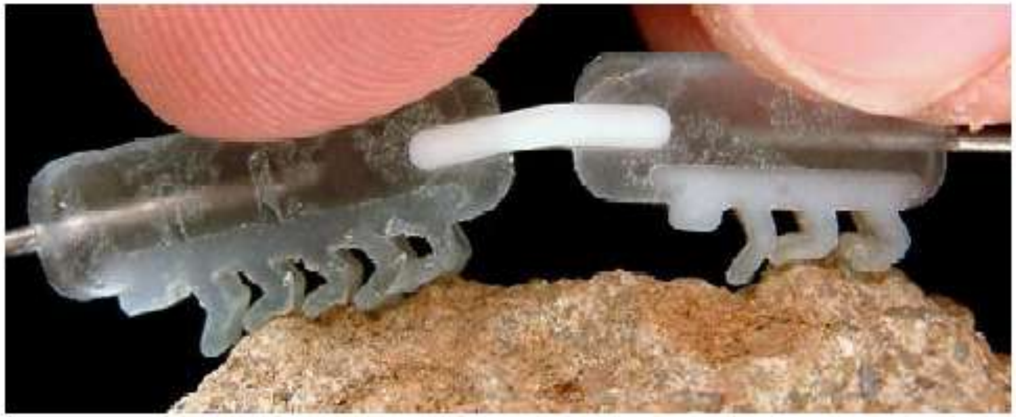
Cutkosky

Shape Deposition Manufacturing







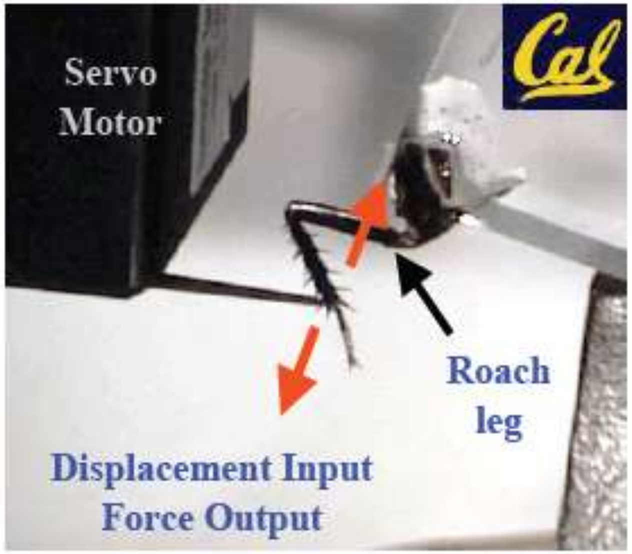


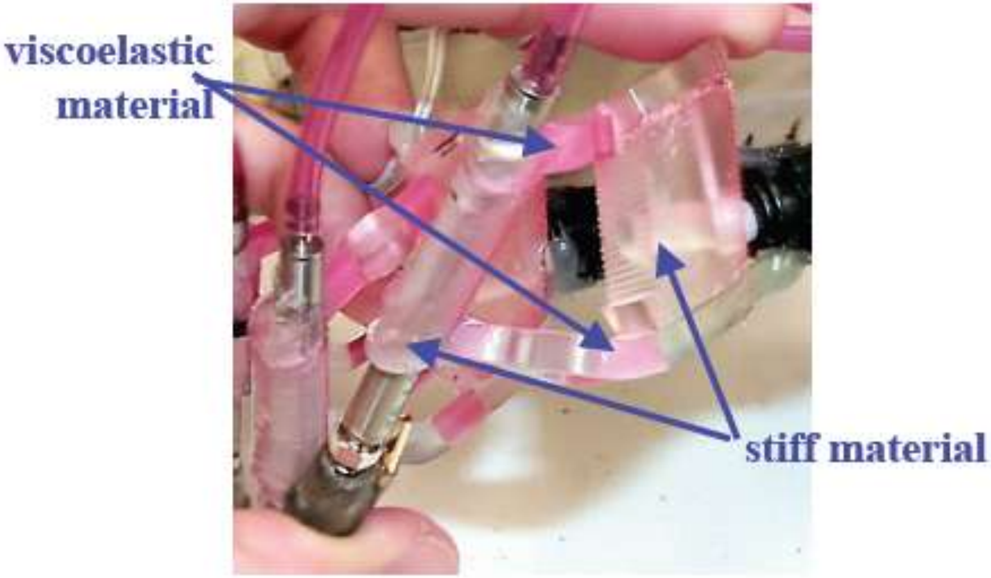
THE SHAPE DEPOSITION MANUFACTURING (SDM): TECHNOLOGY FOR BIOMIMETIC ROBOTICS

Biomimetic fabrication

Study biological materials, components, and their roles in locomotion.

Study Shape Deposition Manufacturing (SDM) materials and components.





Models of material behavior and design rules for creating SDM structures with desired properties

SDM - Shape Deposition Manufacturing

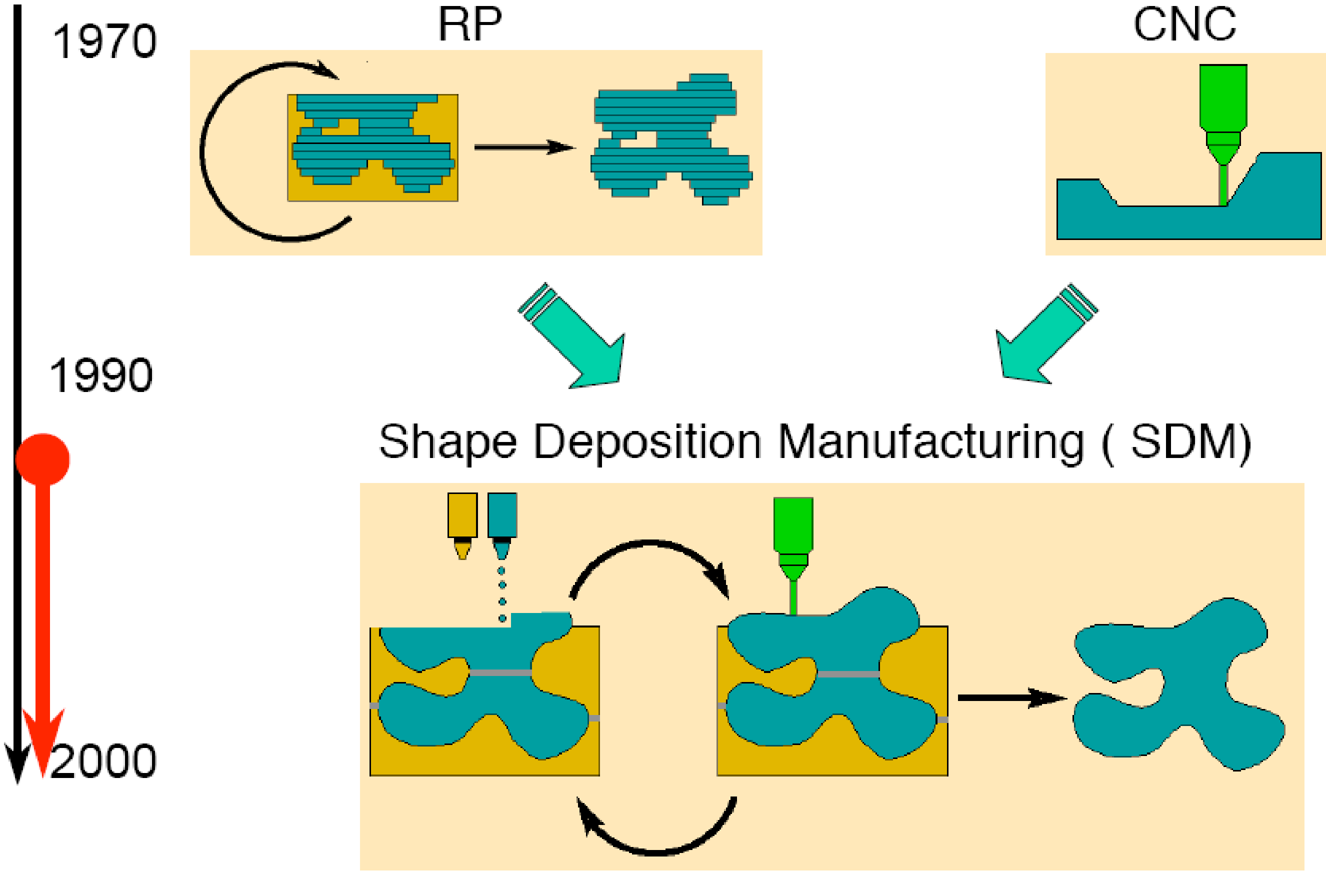
SDM integrates the concepts of two technologies: **Rapid Prototype (RP) and Computer Numerical Control (CNC) machines.**

RP allows to realize **moulds** in polymeric materials, following complex geometries not achievable by means of traditional machines (e.g. to realize a sphere able to move inside a square).

CNC, classic machines at **numerical control** (e.g. milling machine), realizes mechanical pieces in plastic and/or metallic materials, starting from CAD models.

SDM - Shape Deposition Manufacturing

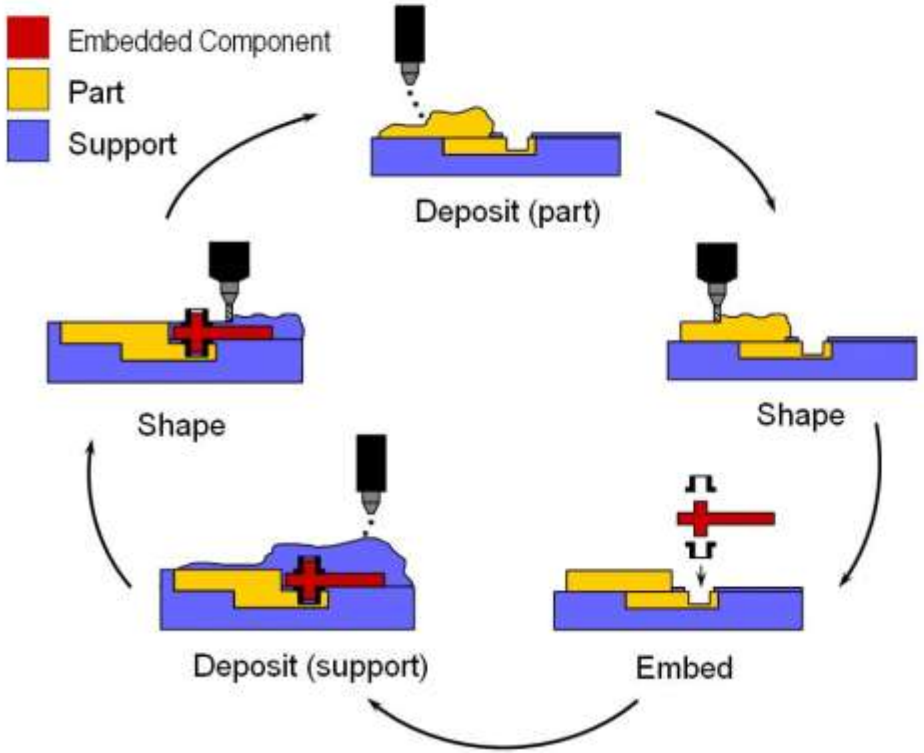
From Rapid Prototype (RP) and Computer Numerical Control (CNC) machining to . . .



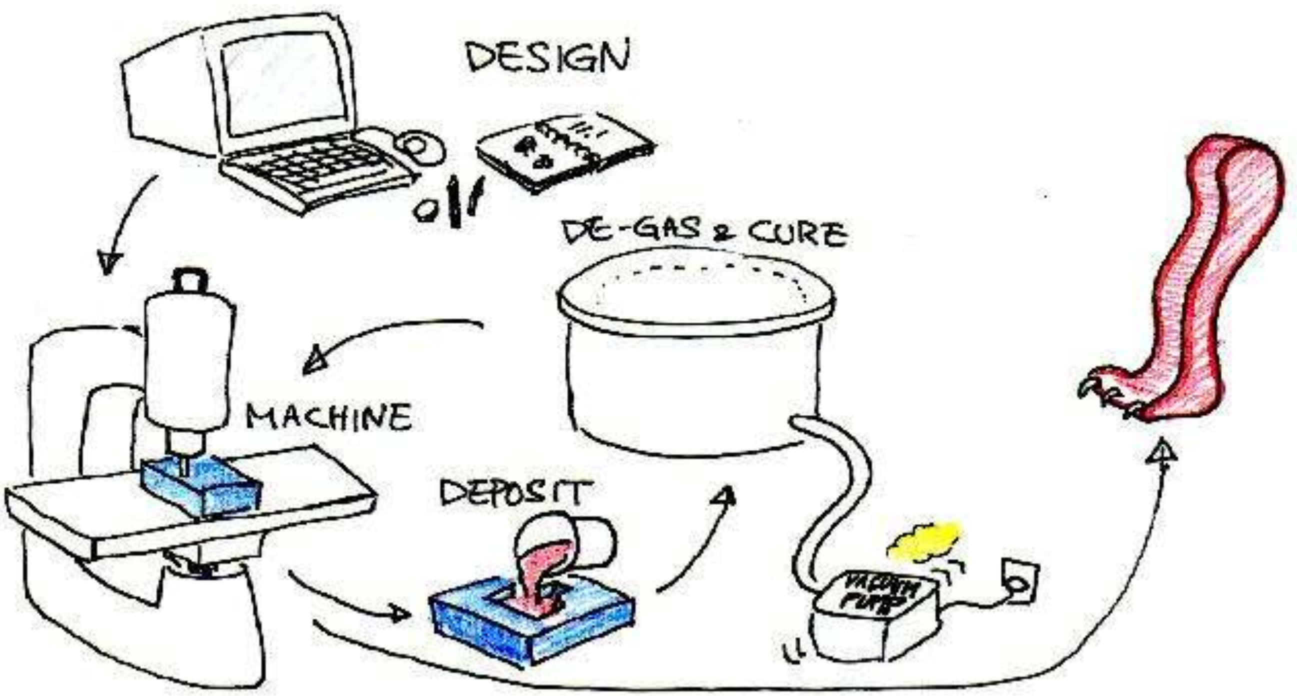
What is SDM?

Shape Deposition Manufacturing (SDM) Process directly produce functional prototypes from **CAD models.**

Shape Deposition Manufacturing (SDM) is a layered prototyping method where parts or assemblies are built up **through a cycle of alternating layers of structural and support material**. After a layer of material is added, it is **then shaped** to a precise contour **before the next layer is added**.



Steps of the SDM process



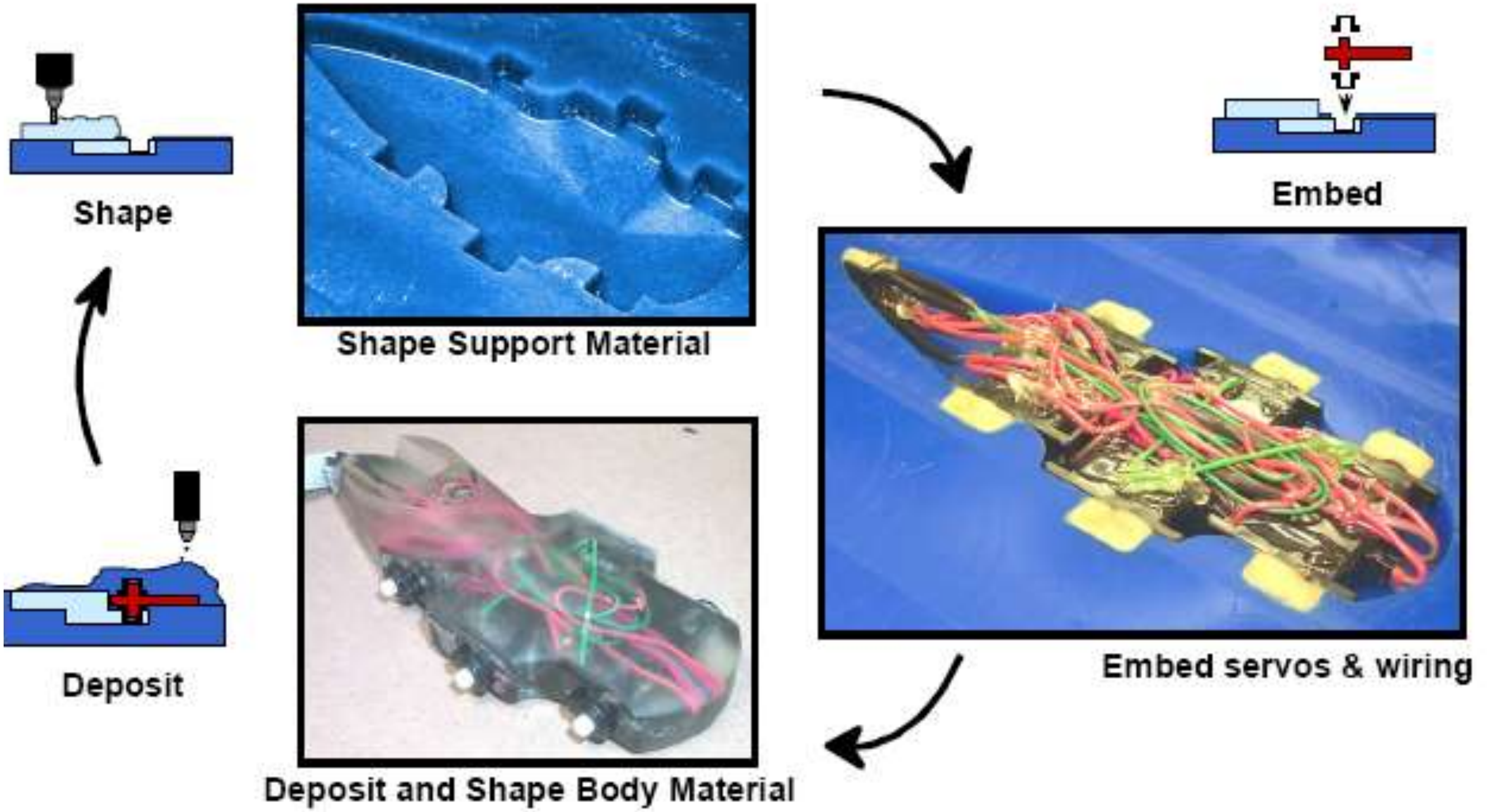
After deposition each layer is **shaped** using conventional CNC (Computer Numerical Control) technology, such as milling, grinding.

Additional steps objects such as prebuilt **mechanical parts**, **electronic components or circuits and sensors can be embedded into each layer**.

Multi-material layers can be manufactured by repeating the cycle for each of the materials.

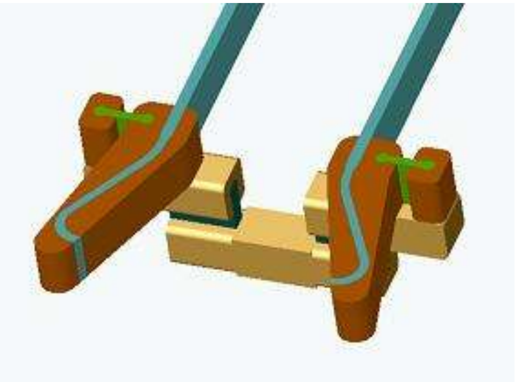
Biomimetic fabrication

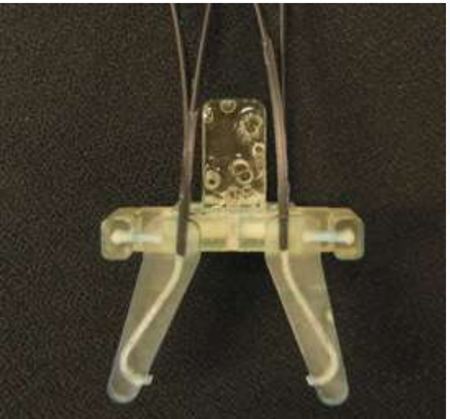
The construction of the multi-material compliant leg used in the robot takes advantage of SDM's capability **to vary the material properties** during construction of the part.



Main applications of SDM at BDML

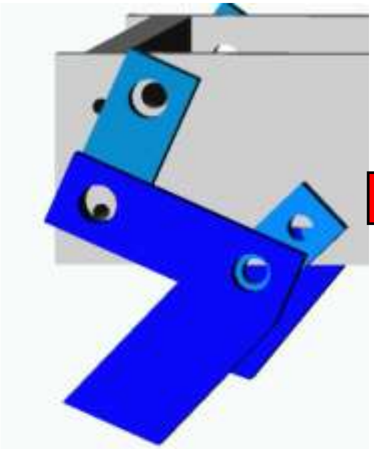
Current applications of the SDM process include the manufacture of custom tools (e.g. injection molds with internal cavities (cooling channels), multimaterial inserts (e.g. Cu pipes for heat distribution) and embedded sensors, functional prototype parts and shape-conformable embedded electronic structures.





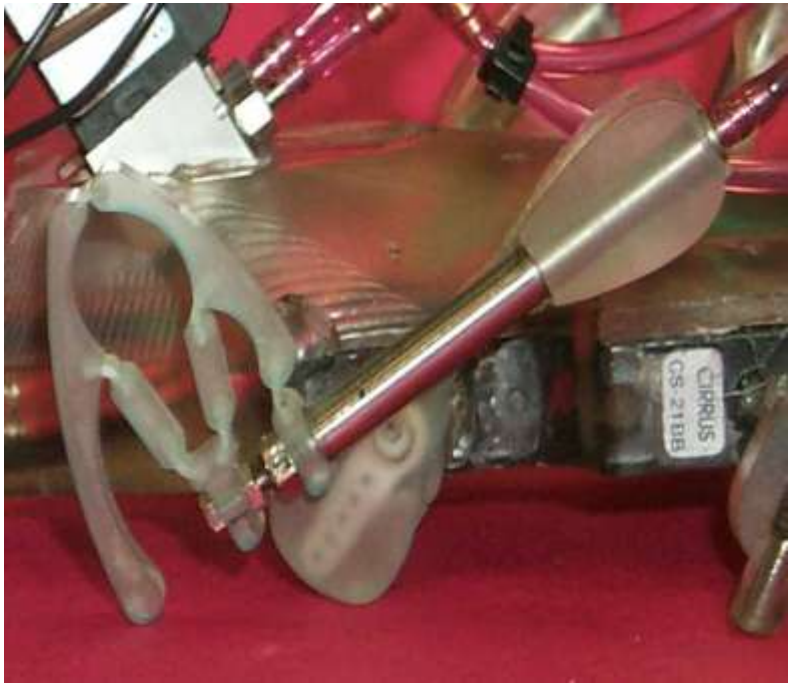
Graded Materials

- Pin Joints Replaced With Flexural Regions to Introduce locally tailored Compliance and Damping
- More robust than a pin joint...
- More robust than using a single homogeneous material and varying flexure thickness

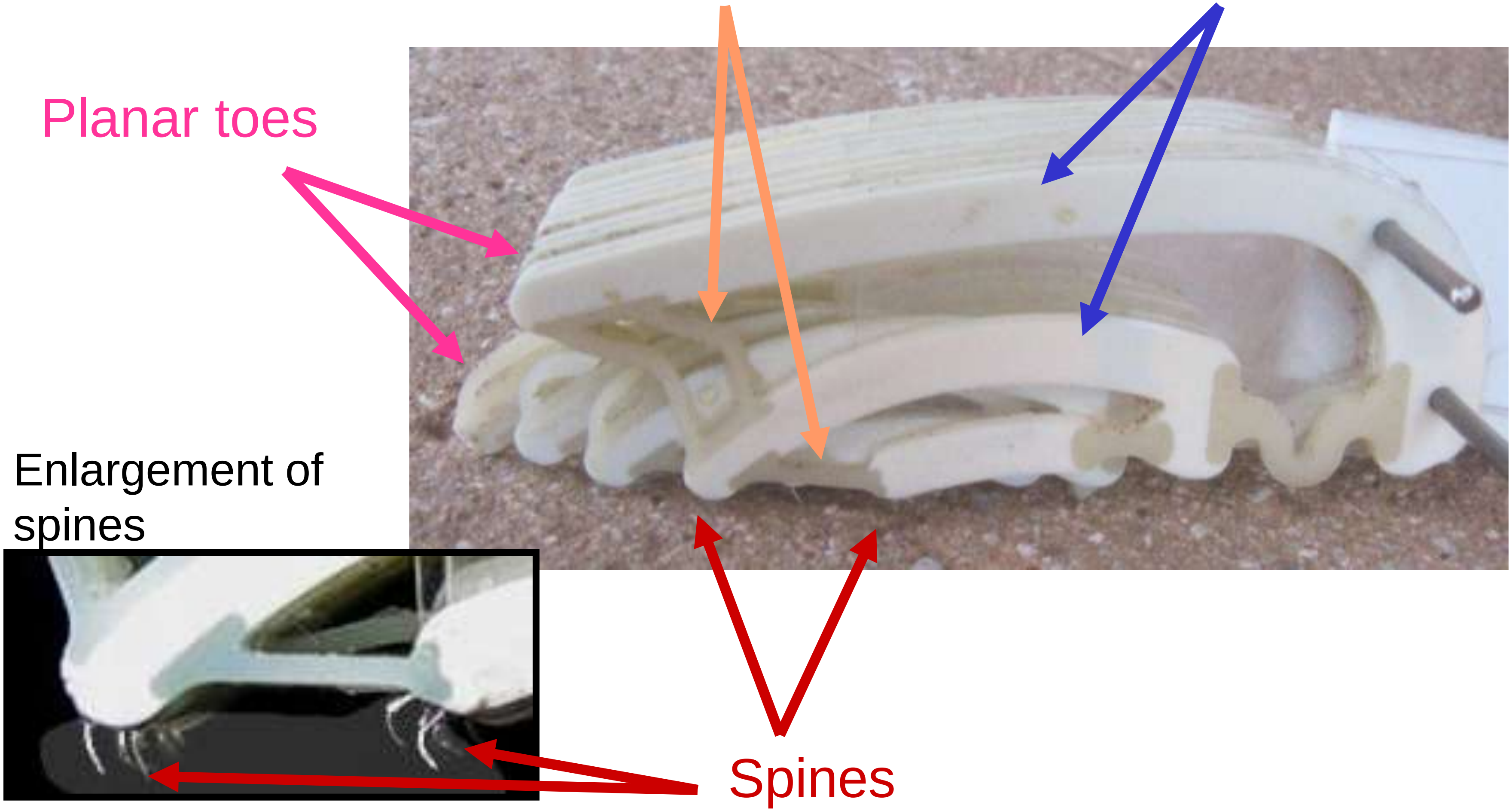


Original Design

SDM Re-Design



SpinyBot foot



Soft Polyurethane

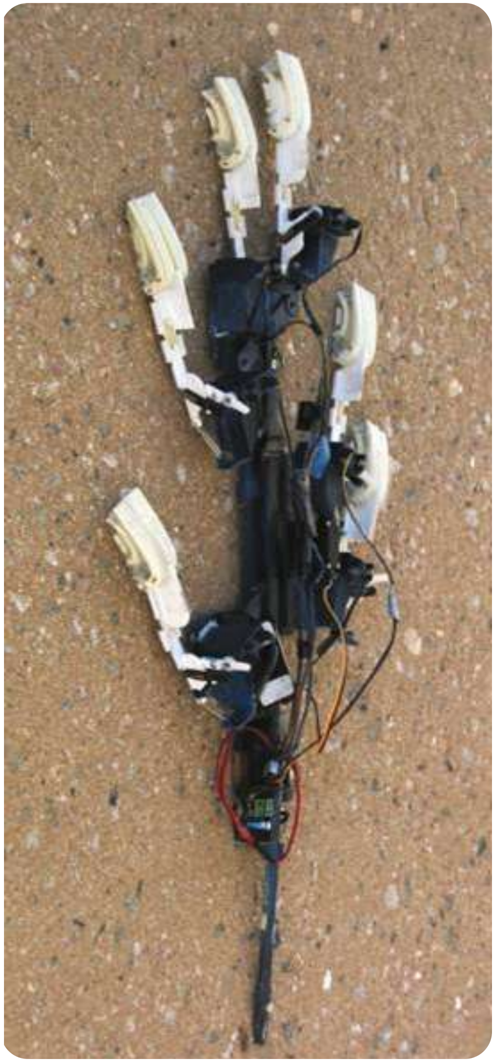
Hard Polyurethane

Planar toes

Enlargement of spines

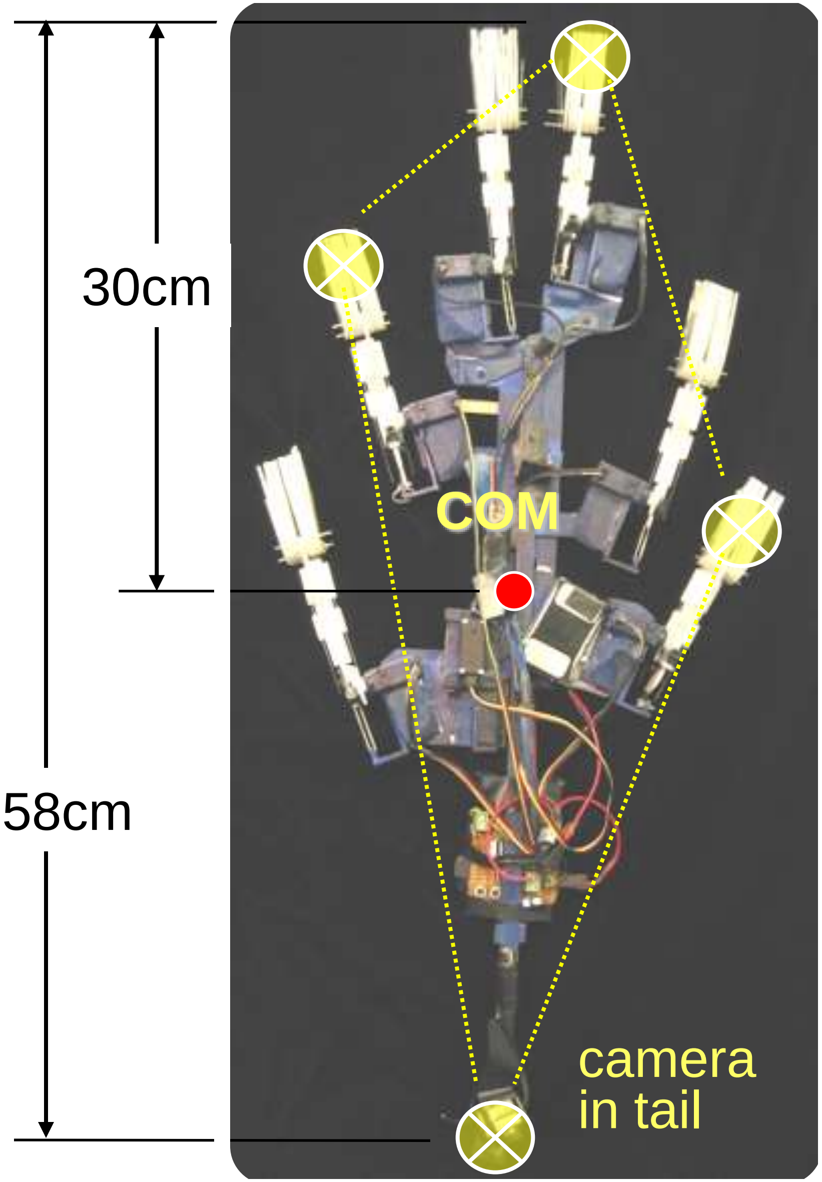
Spines

Spinybot II

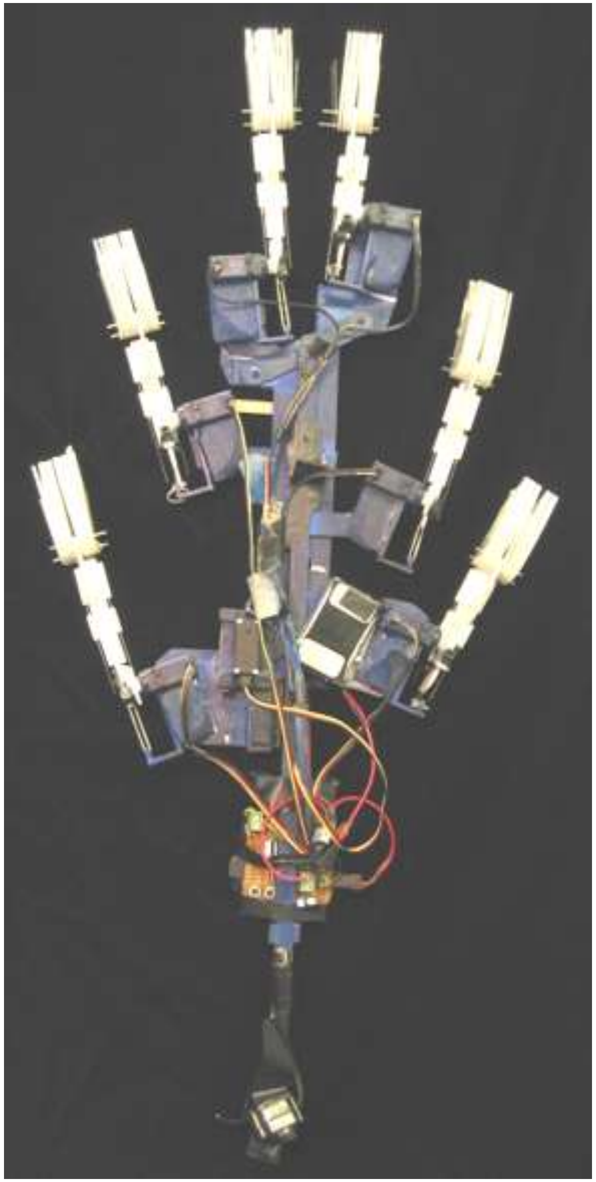


SpinyBot body

- Totally rote—just fixed servo movement pattern
- COM well within polygon of wall contacts—very stable
- 400g bodyweight



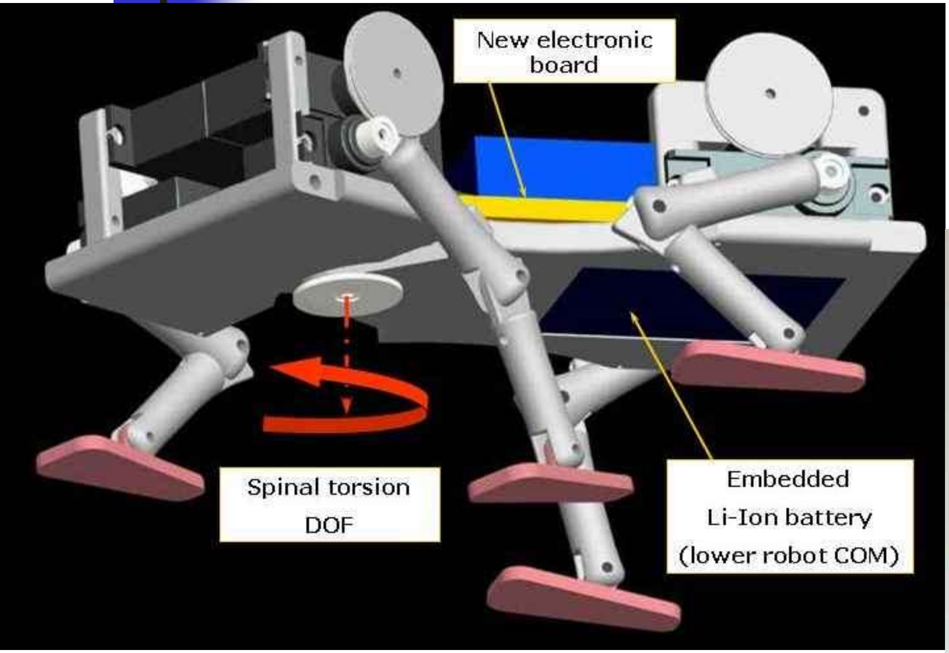
SpinyBot Stats



- Mass: 400g
- Max. payload: 400g
- Speed: 2.3 cm/sec
- Controlled DOF: 3
- 20 spines/foot

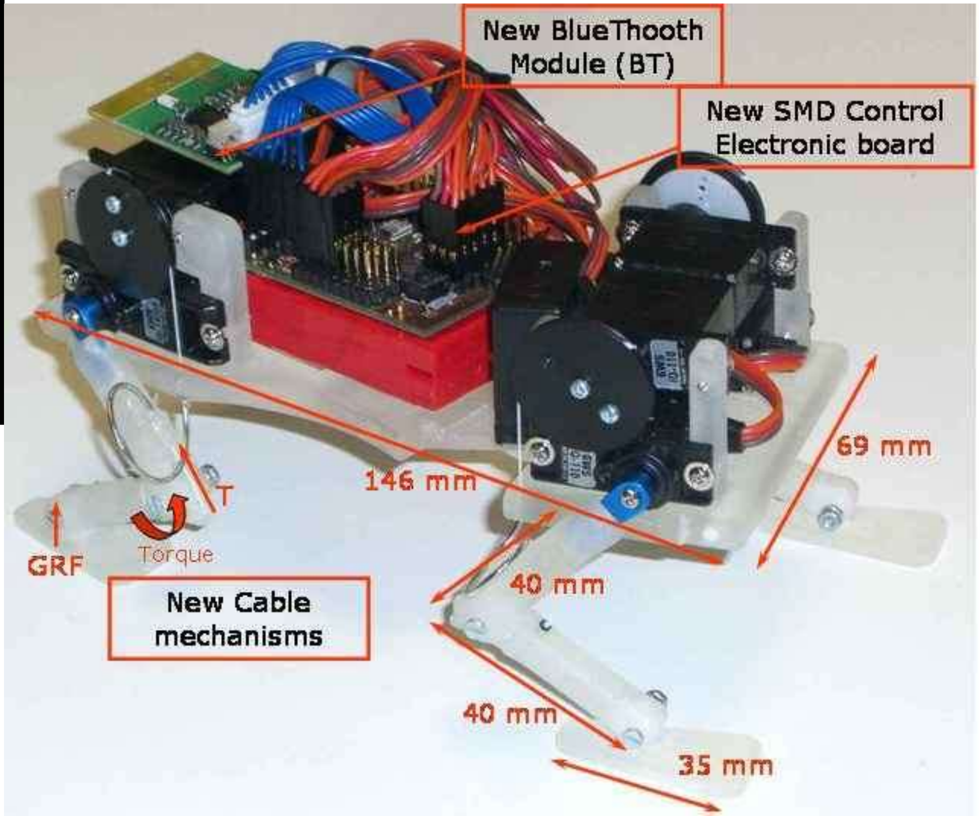
Foot Manufacturing:
Shape Deposition Manufacturing

From the original design of the rat-robot....



Rapid prototyping:

3D printer; discrete DOF

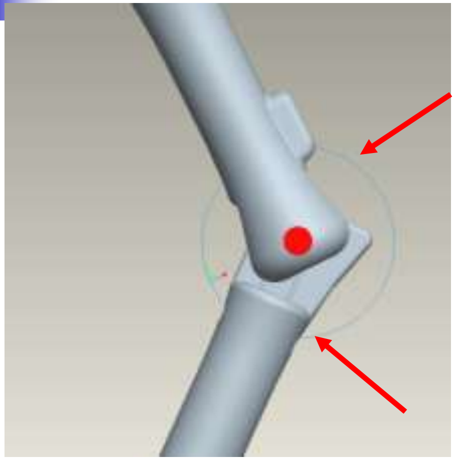


Traditional link joints:

Pin joints, internal springs, screws, bolts…

…to the SDM re-design of the Rat-Robot joints

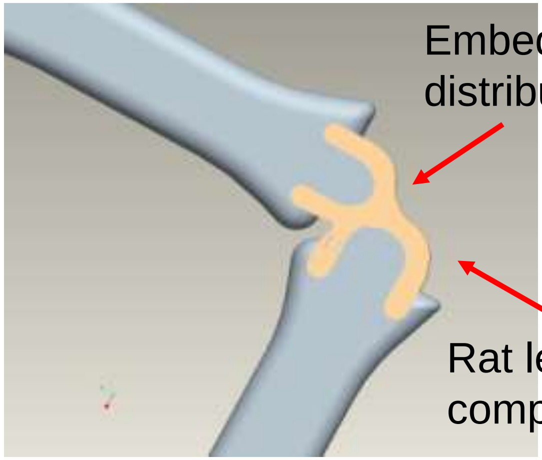
Knee Joint



Traditional discrete rotational joint

Rat leg: 2 connected links

Original Design

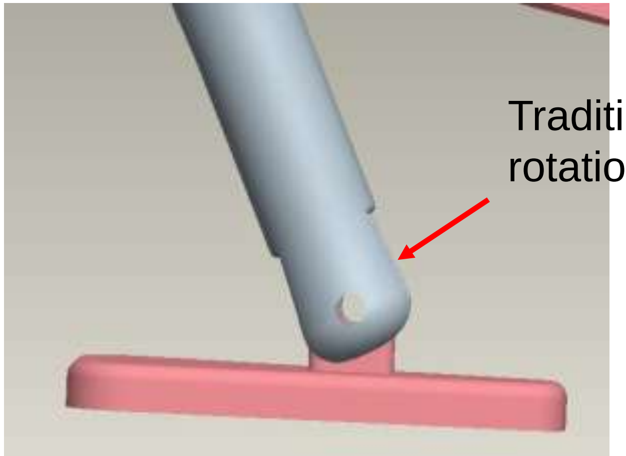


Embedded knee distributed joint

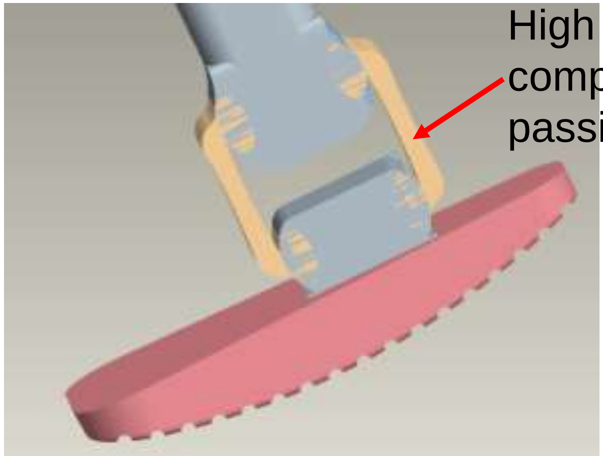
Rat leg: single component

SDM Re-Design

Ankle Joint

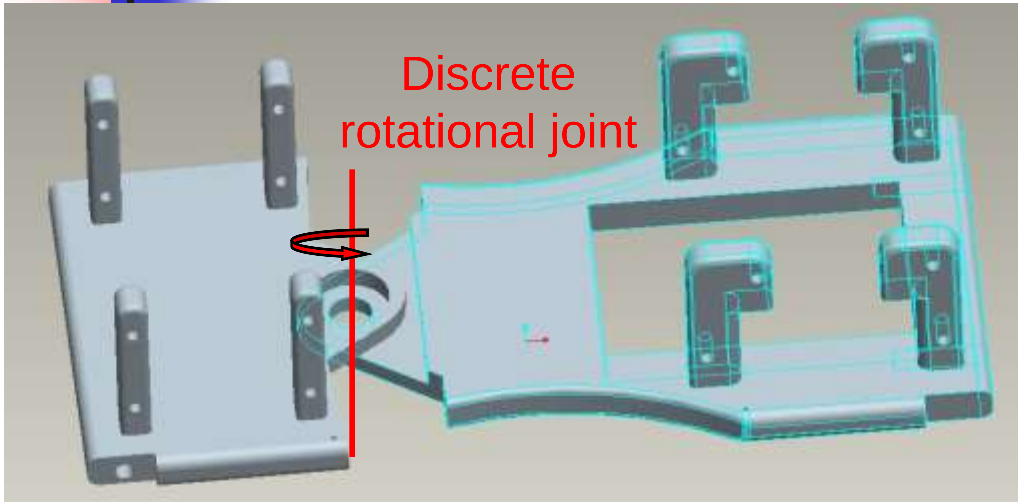


Traditional rotational joint



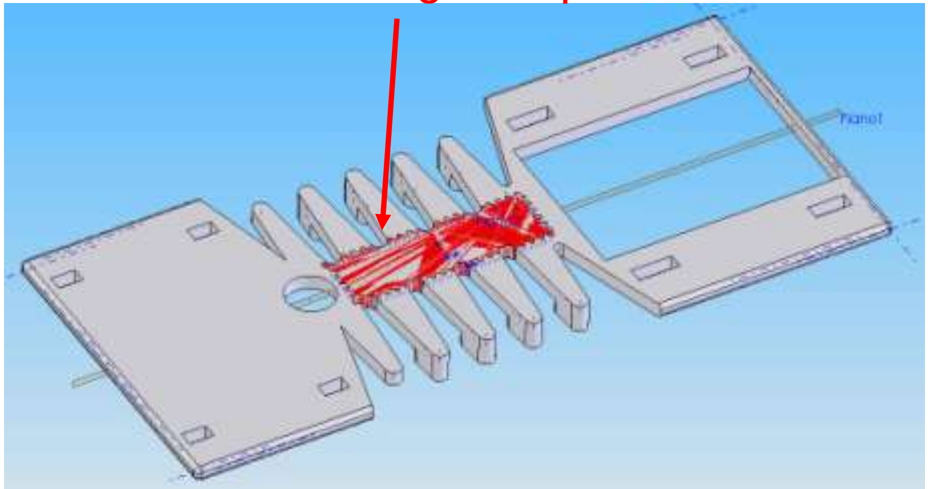
High compliant passive joint

…to the SDM re-design of the Rat-Robot joints



Original Design

Flexible spines: the flexion is distributed all along the spine

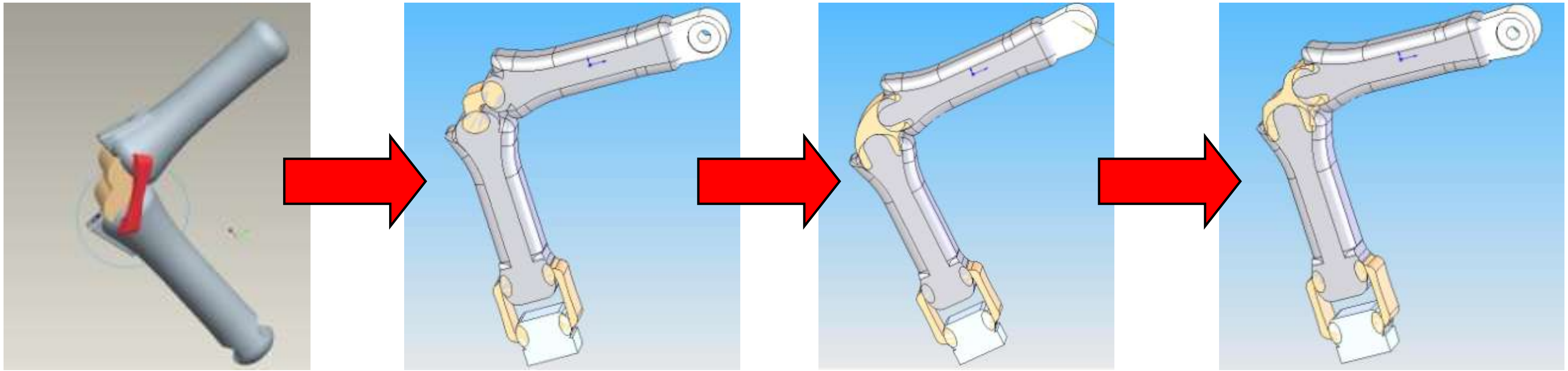


SDM Re-Design

Parametric design of the Knee Joint

2 possible variables on the design of the SDM compliant joints

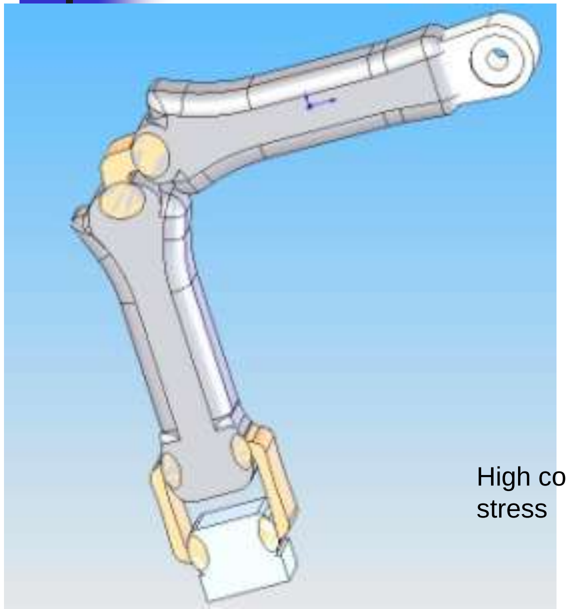
- Intrinsic material characteristic: Young modulus, demold time, shore hardness, tensile strength, elongation at break…
- Joint geometry: thickness, shape, contact surface…



1st 2nd … … last

Drawback: from the 1st prototype to the last one…..empiric process: trails and errors. There is not an automatic method and rules that allow to build the desired mechanical parts starting from the design.

Parametric design of the Knee Joint (continue)



First prototype:
Hard material surrounding soft material

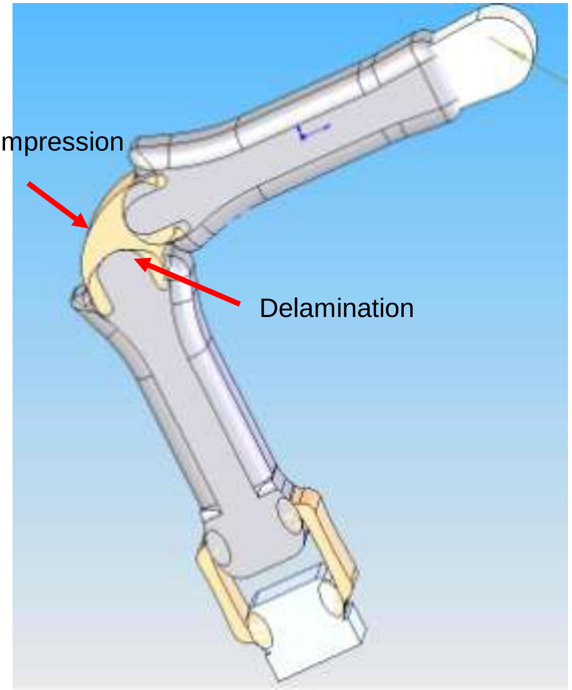
↓

Big Range of Motion, very high compliance of the knee joint. Unstable structure in torsion

Second prototype:
Soft material surrounding hard material

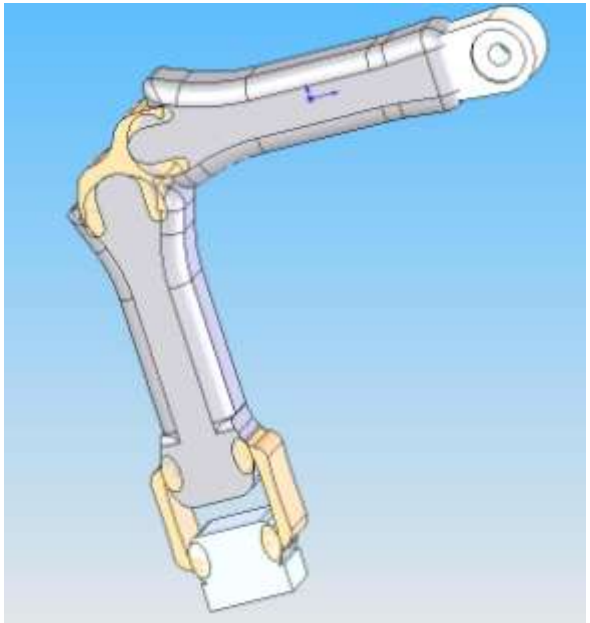
↓

Small Range of Motion, stiff knee joint. High stress concentration, delamination



High compression stress

Delamination

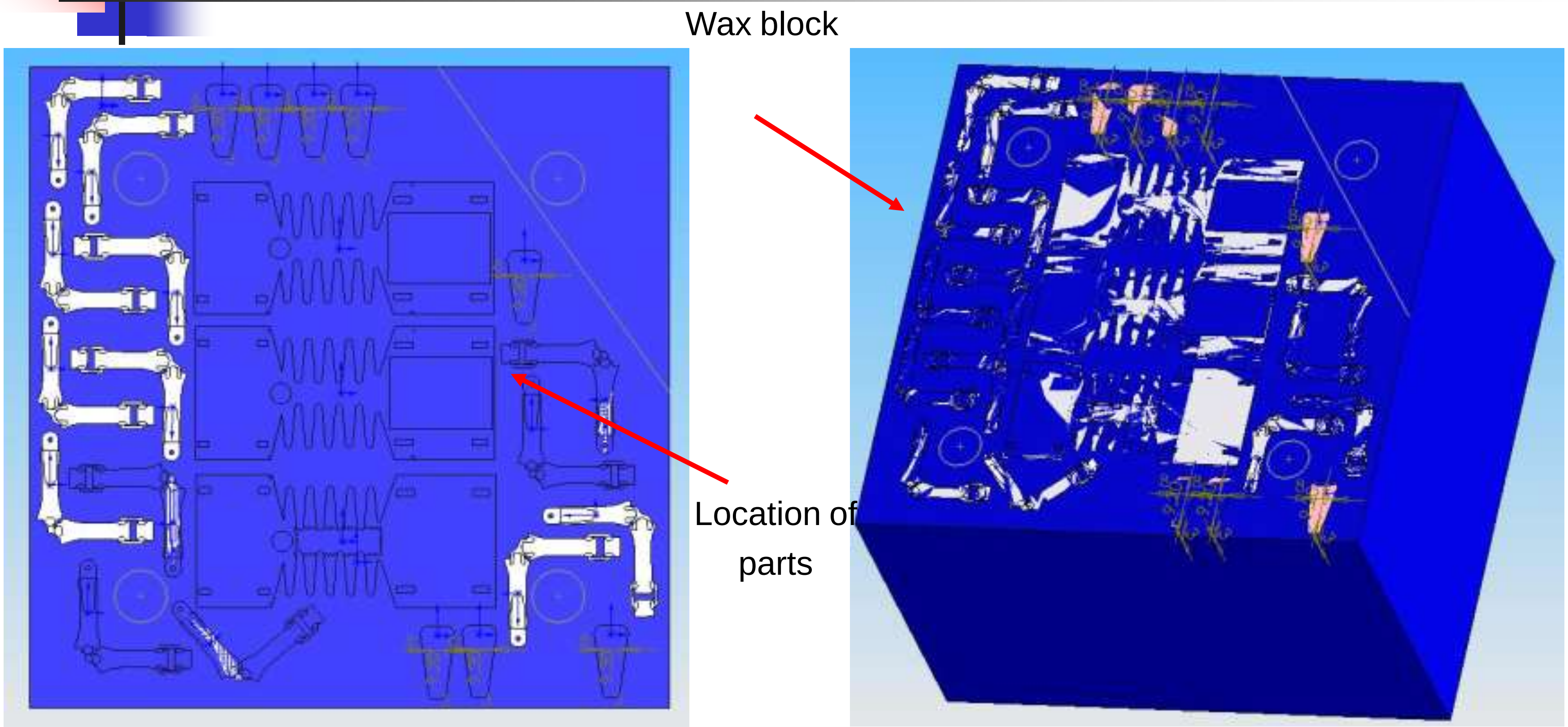


Final prototype:
Hard material surrounding soft material; reshaping of the soft material

↓

Better distribution of stress and strain

Manufacturing of the Prototypes CAD models

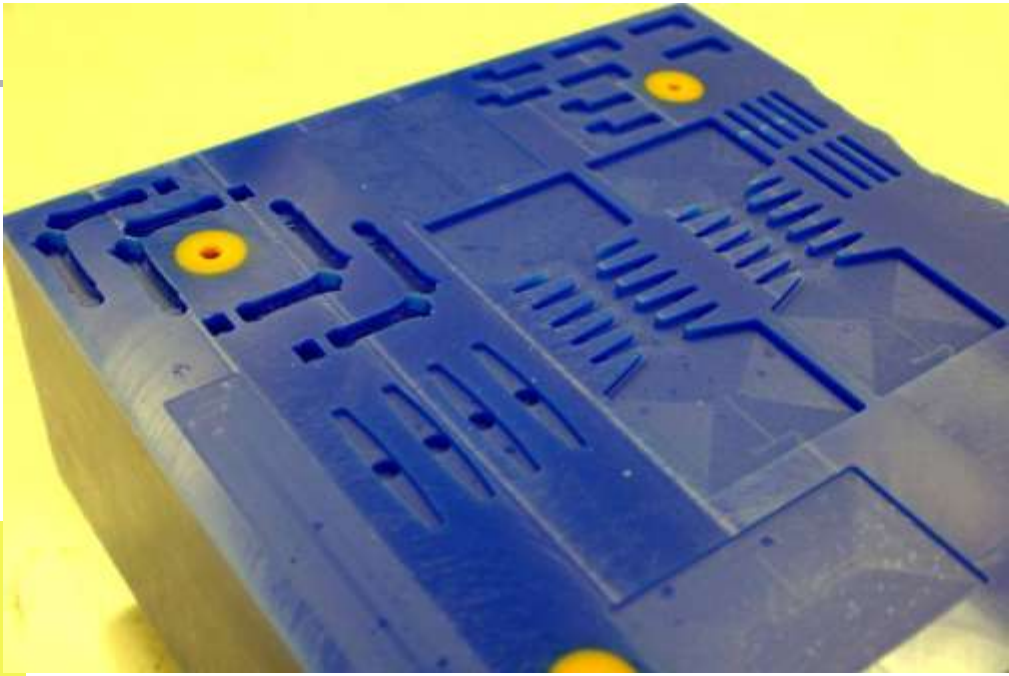


Wax block

Location of parts

CAD model: all the parts and assemblies are placed on the wax block for creating the cavities

Developing the moulds with the CNC tool machine

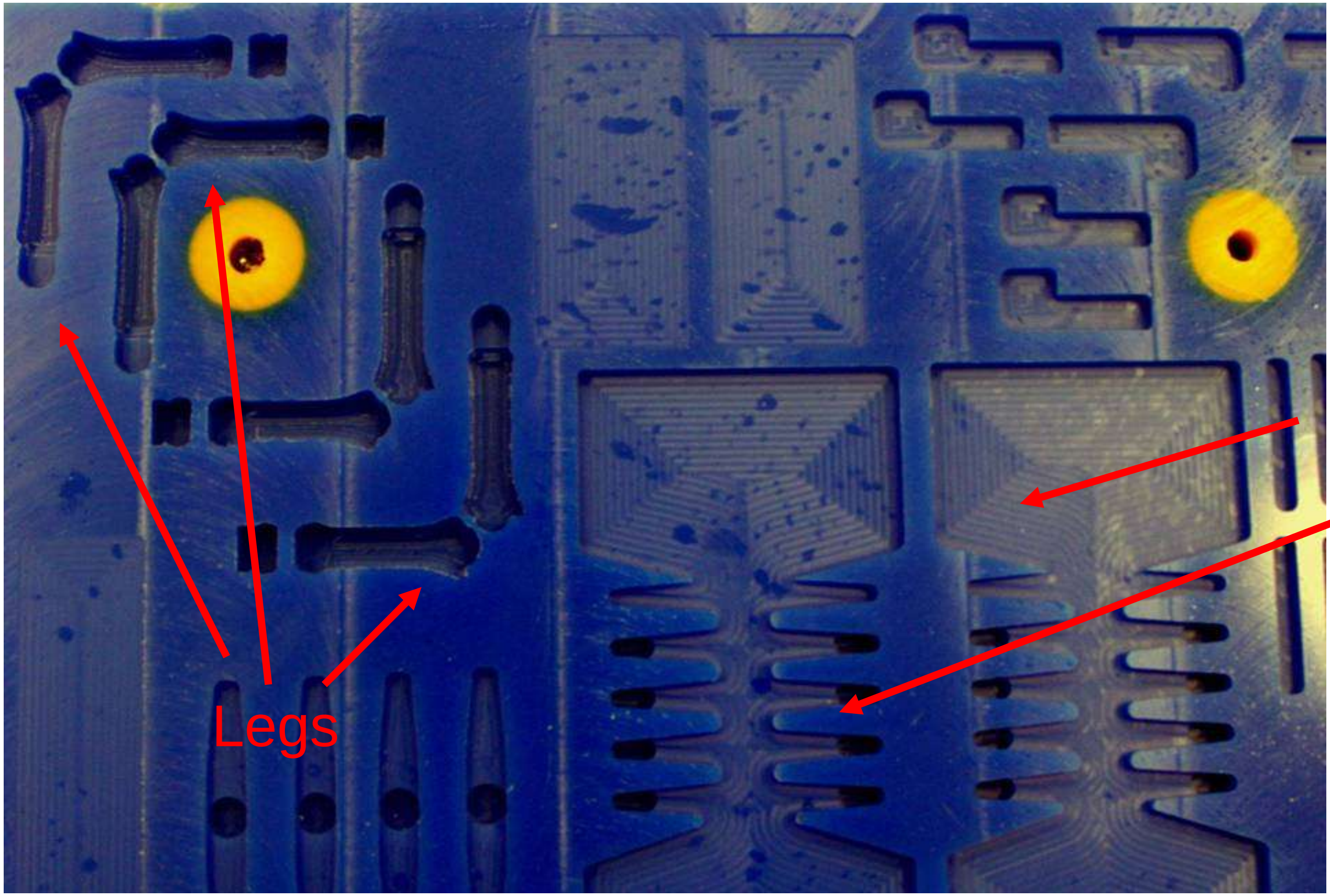


The tool paths are created layer by layer according to the different material to be machined

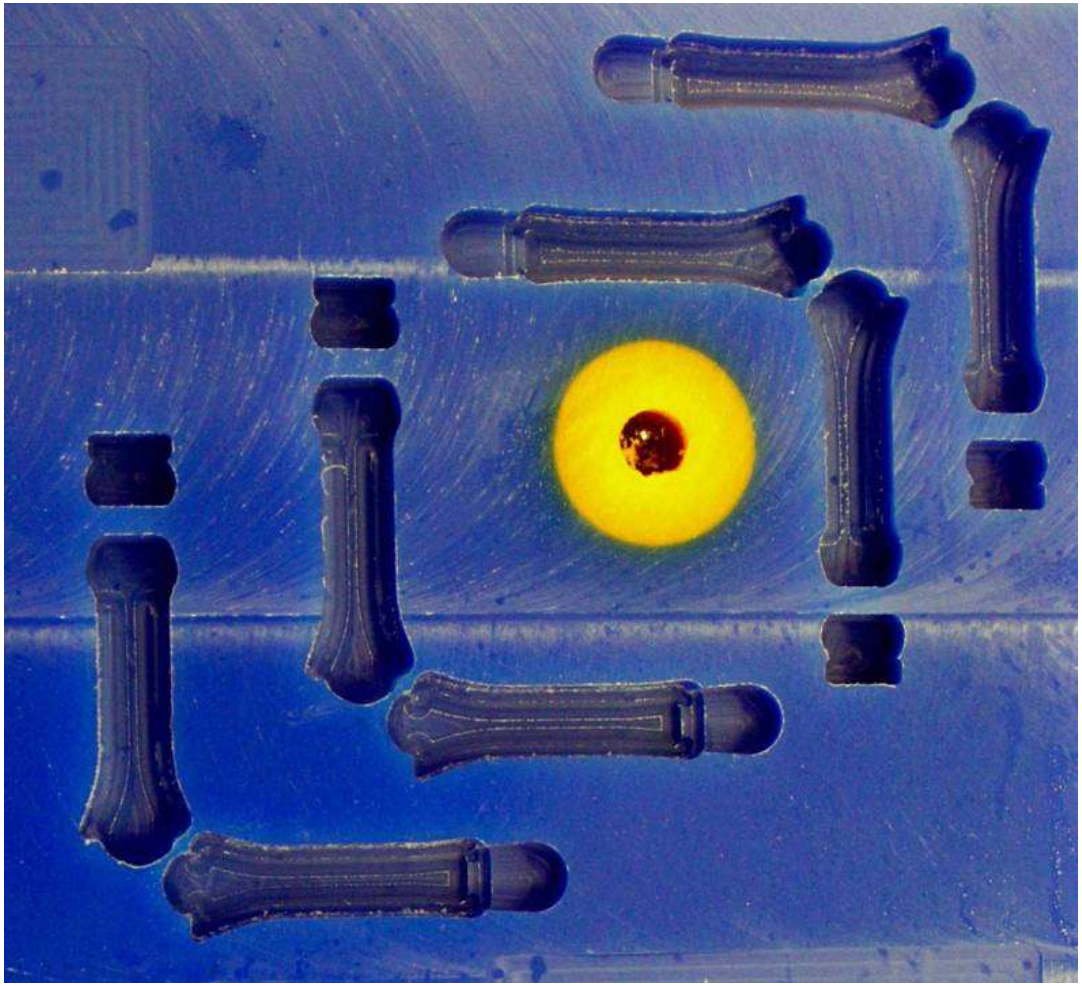
The hard material cavities are created.

Second step: pouring the polyurethane

Developing the moulds with the CNC tool machine (2)



Developing the moulds with the CNC tool machine (2)



Hard material (72 DC) developing caves:

Mix Ratio Resin to Hardner by wt.: 100/50

Gel Time (min) 17-20

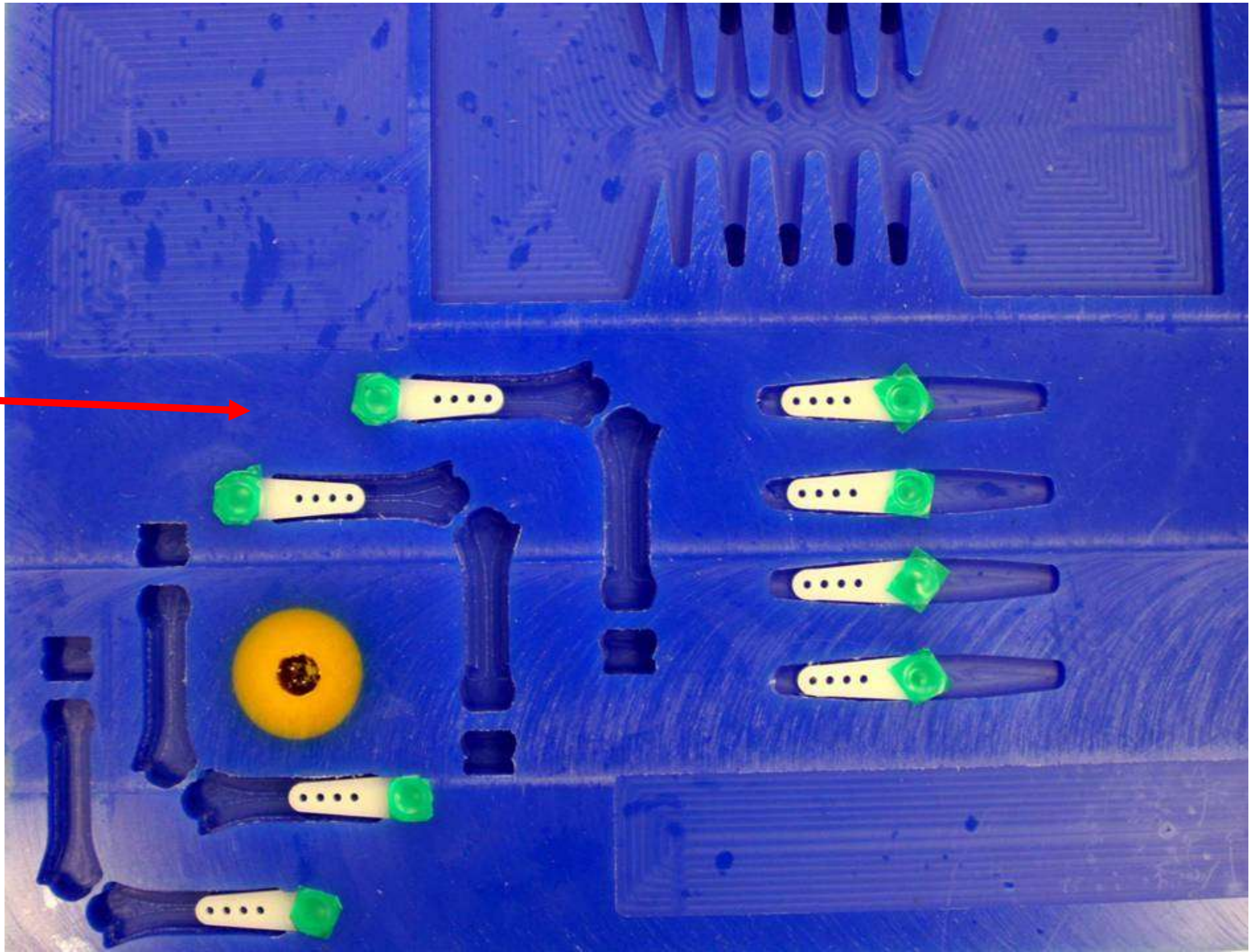
Demold Time 10 Hrs

Hardness 65-75 D

Tensile Strength ASTM D-638 4000 psi

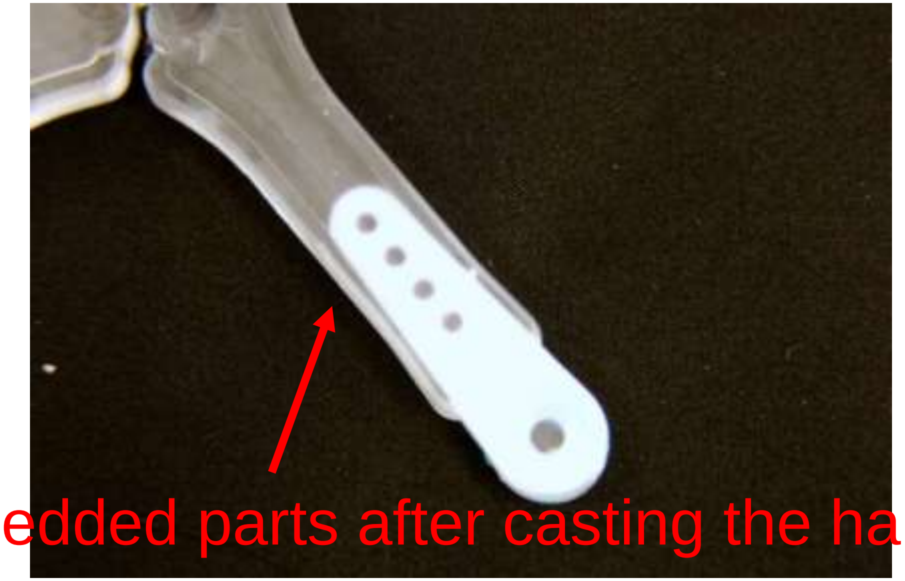
Elongation at Break 60%

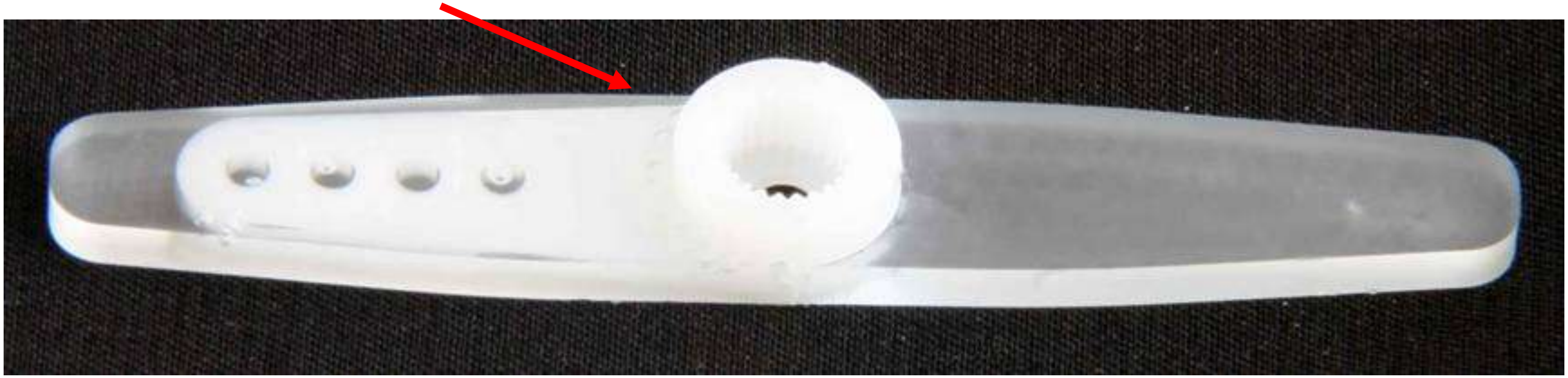
Placing the embedded parts



Connecting rod to servos are placed before casting the hard material

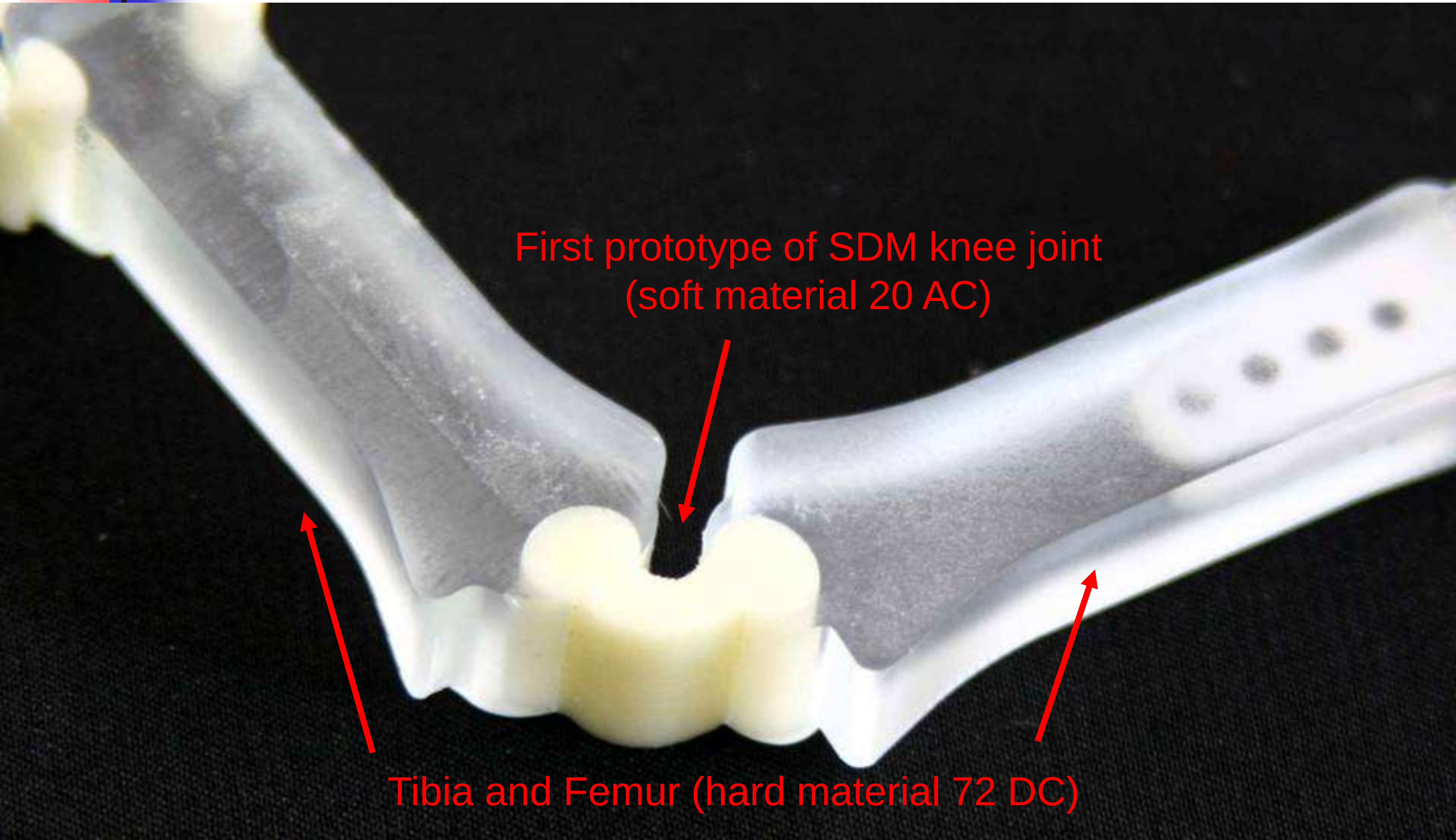
Realization of the first prototypes





Embedded parts after casting the hard material

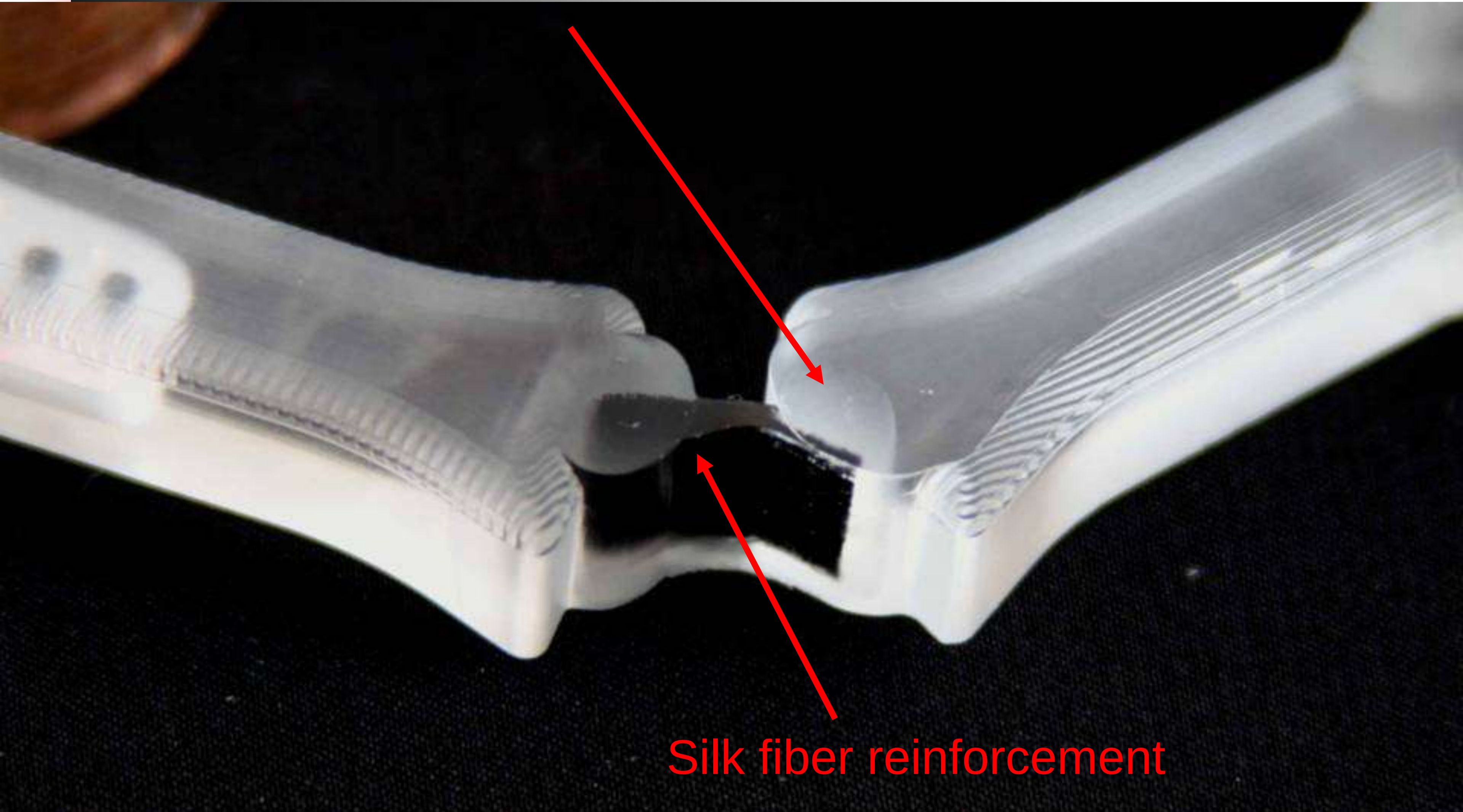
Realization of the first prototypes (2)



First prototype of SDM knee joint
(soft material 20 AC)

Tibia and Femur (hard material 72 DC)

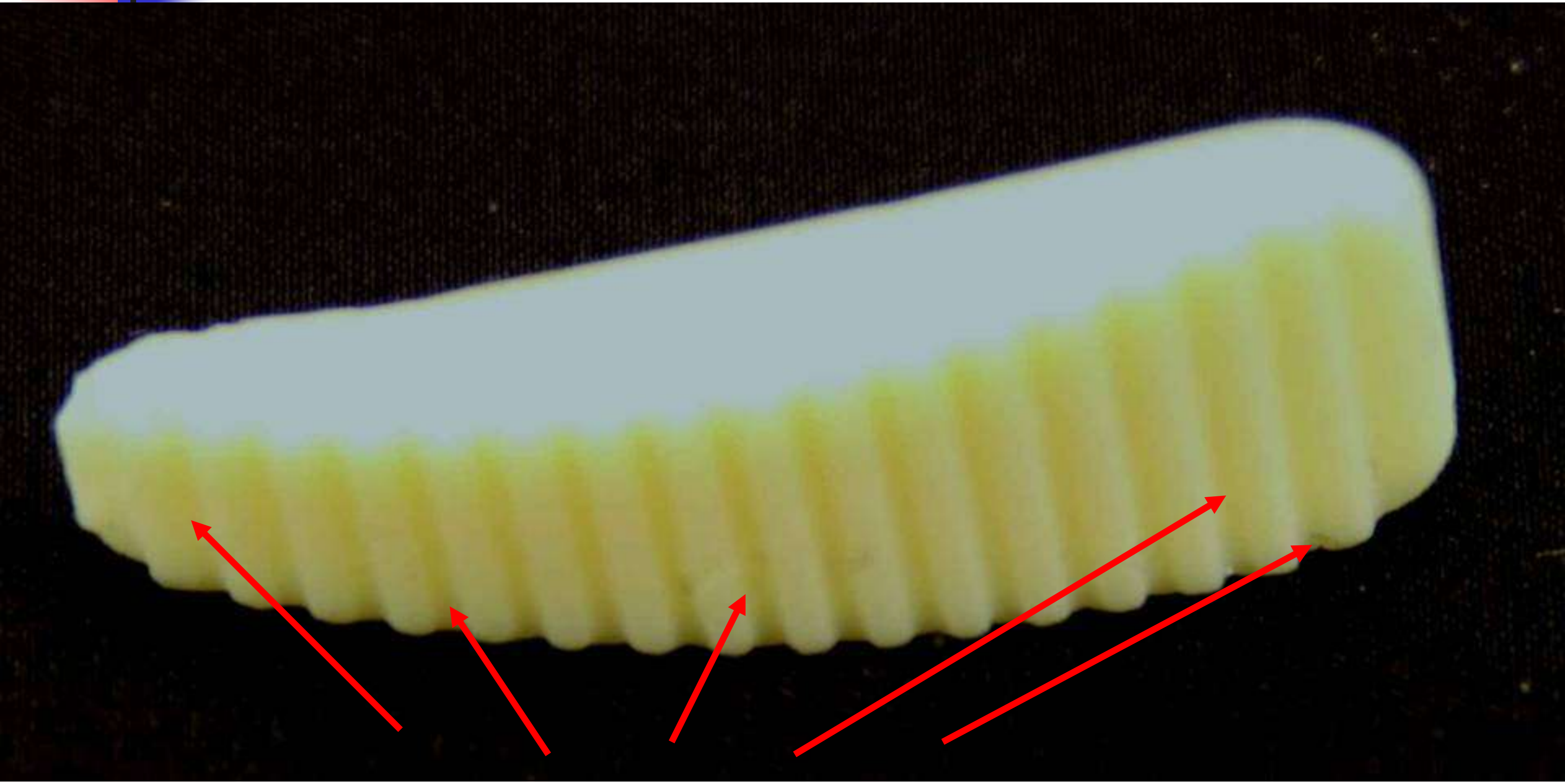
Silk reinforced prototype of SDM knee joint (soft material 20 AC + silk fiber)



Silk fiber reinforcement

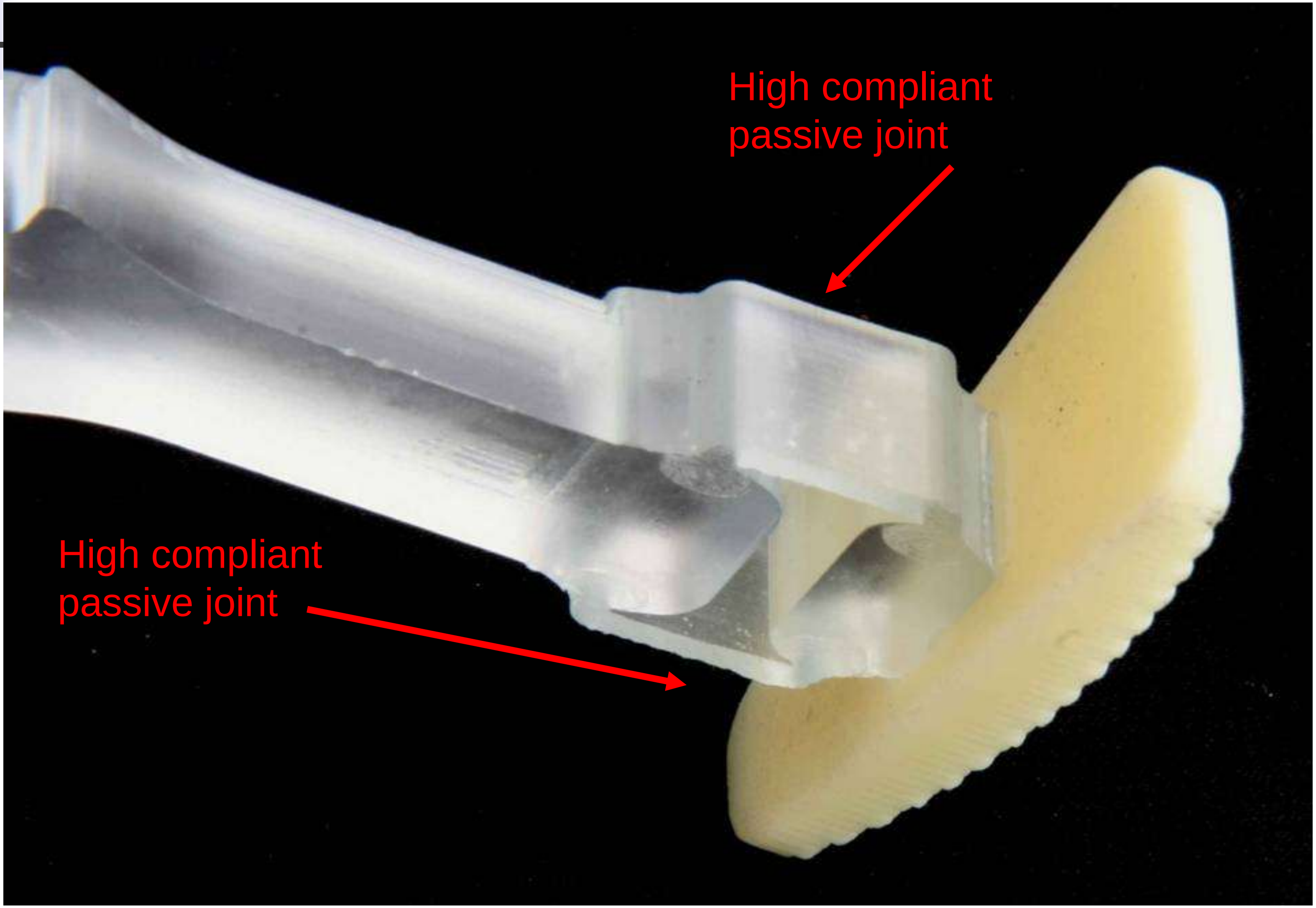
Developing of compliant foot

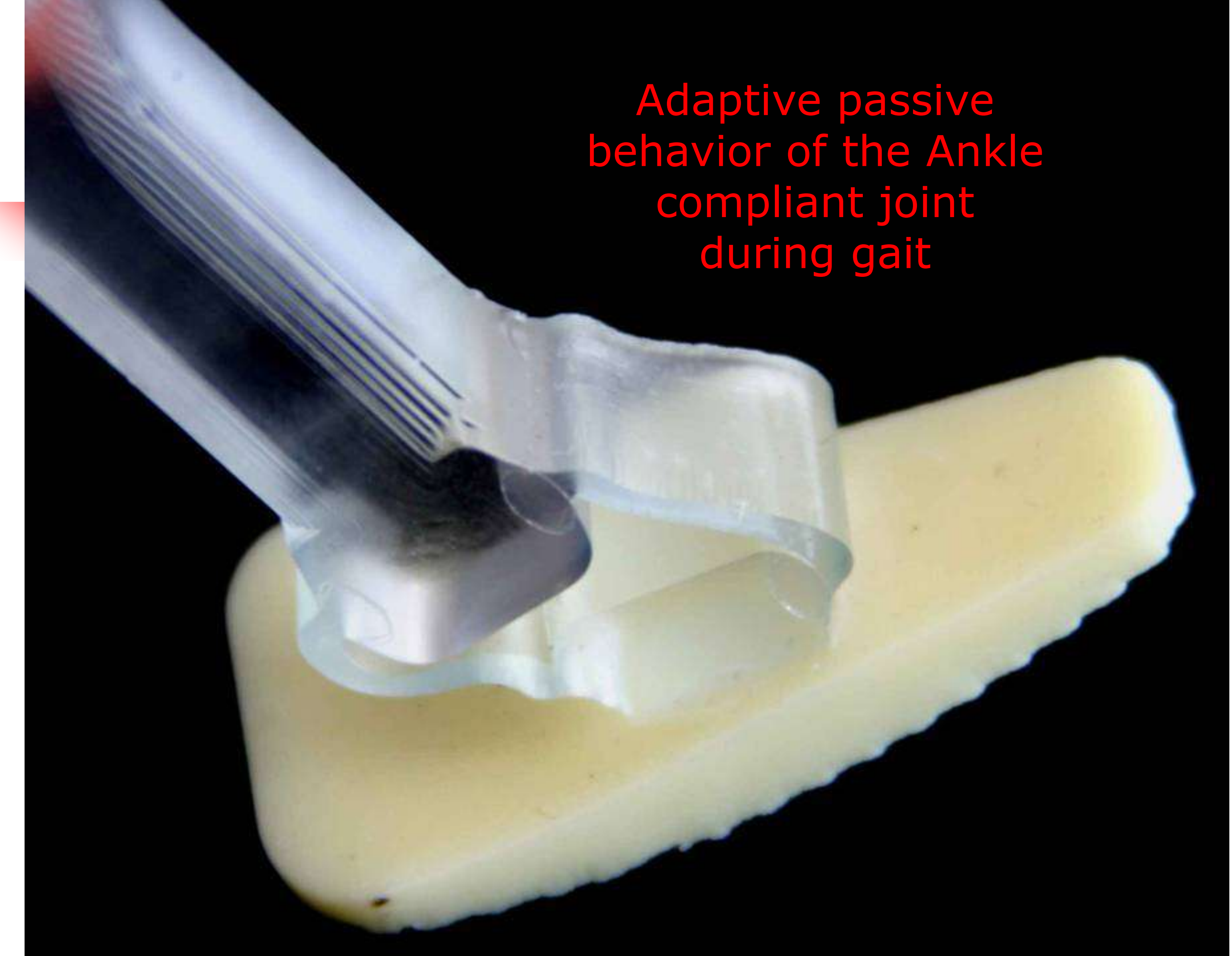
(soft material 20 AC)



Grooves for a better grip during gait

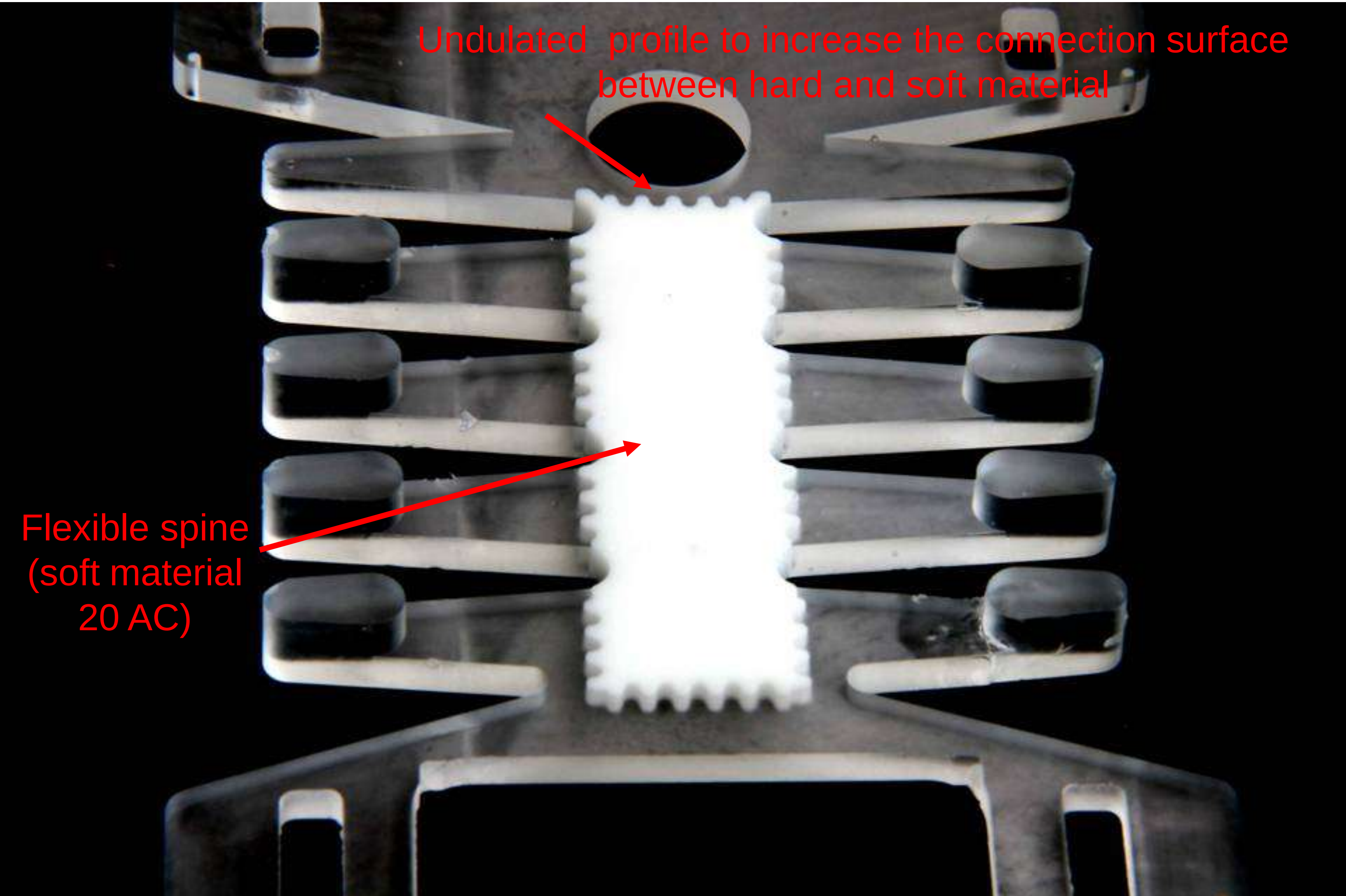
First prototype of high compliant ankle joint (soft material 50 AC)





Adaptive passive
behavior of the Ankle
compliant joint
during gait

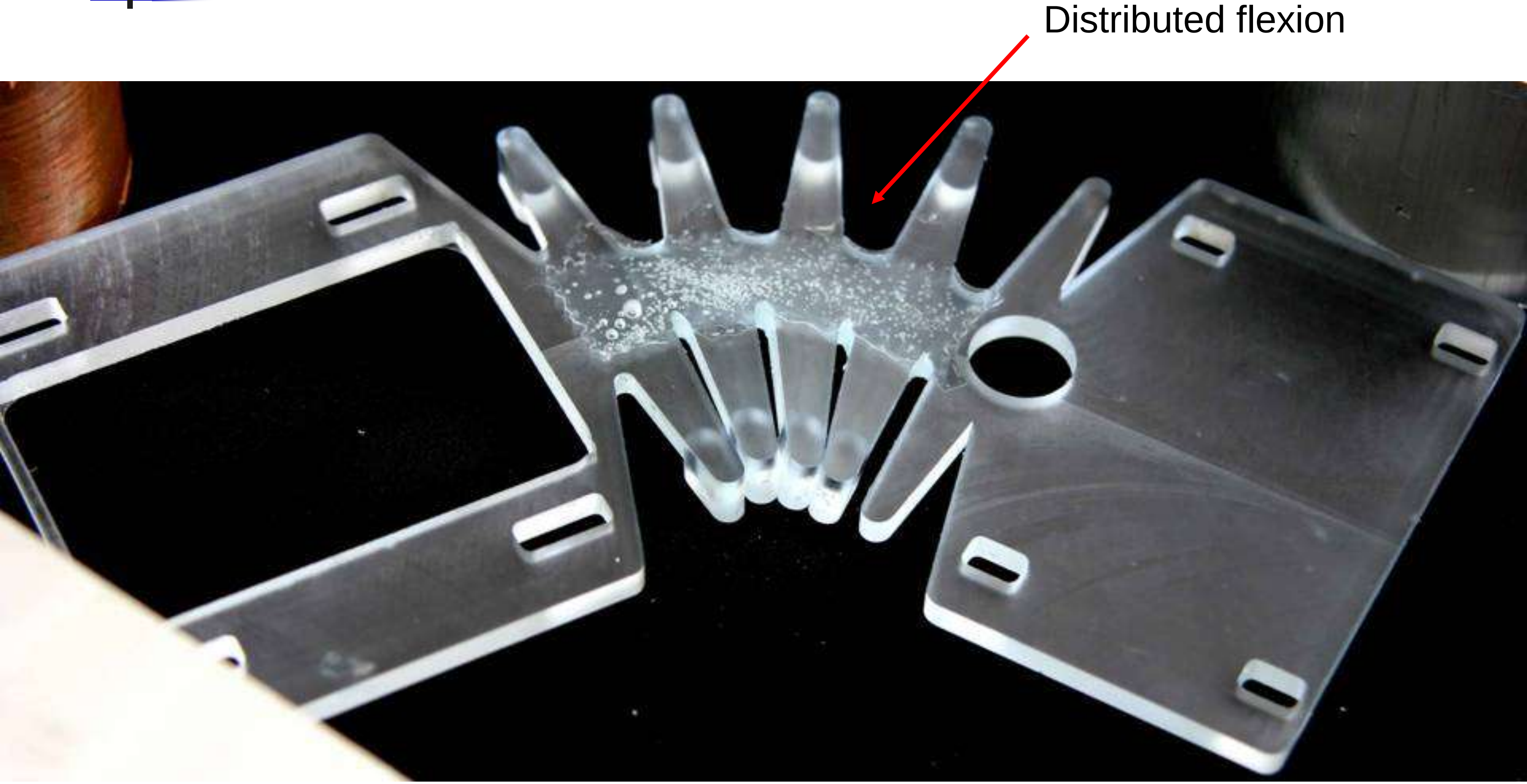
On the design of the flexible spine



Undulated profile to increase the connection surface between hard and soft material

Flexible spine (soft material 20 AC)

On the design of the flexible spine



Distributed flexion

Advantages and limits of the SDM Technology

Advantages:

- multi-material process
- no screws and bolts
- embedded mechanical and electronic components
- low cost
- almost any kind of shaping

Limits:

- layered design and process
- no algorithms for developing
- bubbling during polymerization
- long process as rapid prototyping