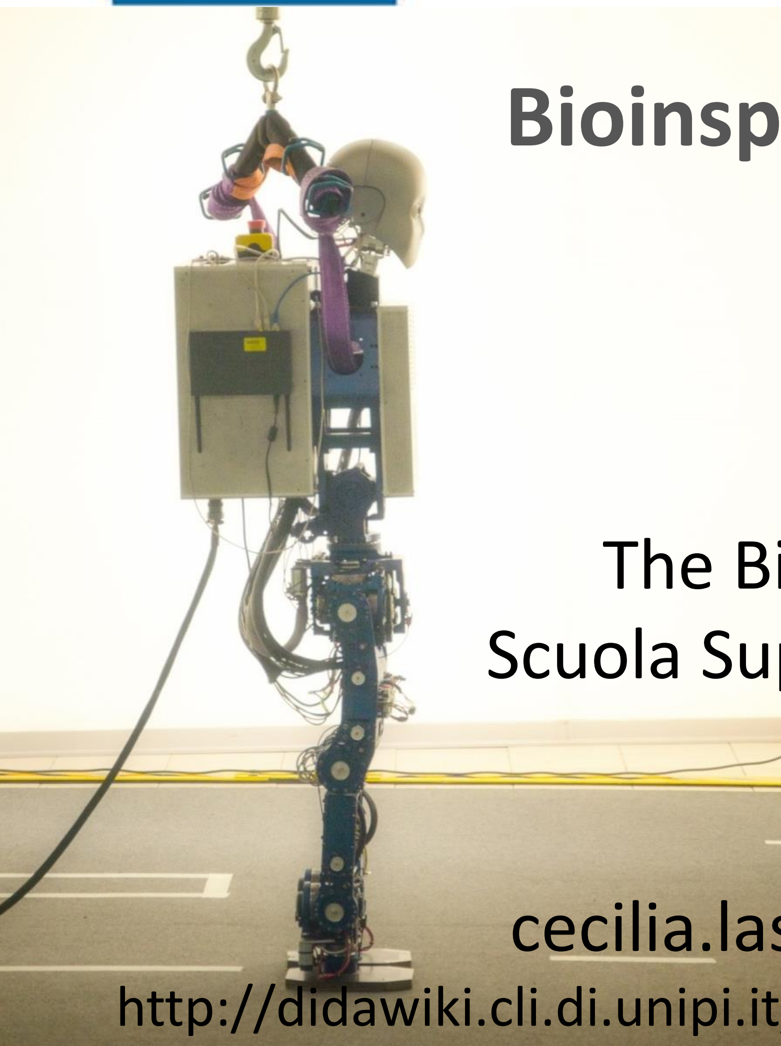
University of Pisa
Master of Science in Computer Science
Course of Robotics (ROB)
A.Y. 2017/18



Bioinspired robotics

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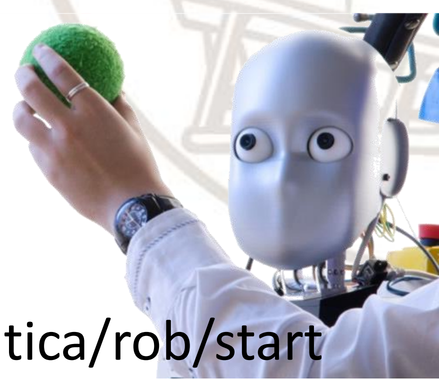

http://didawiki.cli.di.unipi.it/doku.php/magistraleinformatica/rob/start

Outline of the lesson

- Scientific motivations to bioinspired robotics
- Simplexity
- Simplifying principles in human vision
- The *sense of movement* and the vestibular system: simplifying principles in eye movements
- Predictive architectures
- Embodied Intelligence
- Simplifying principles in soft robots

Outline of the lesson

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Evolution of robot abilities

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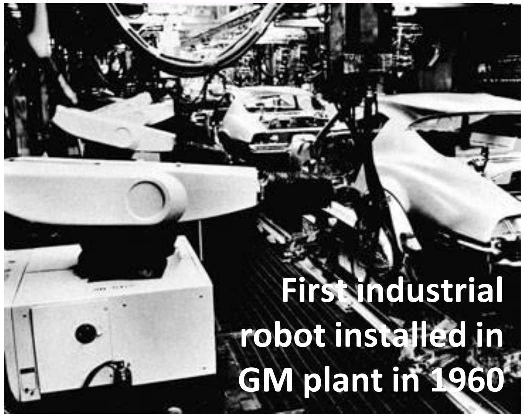
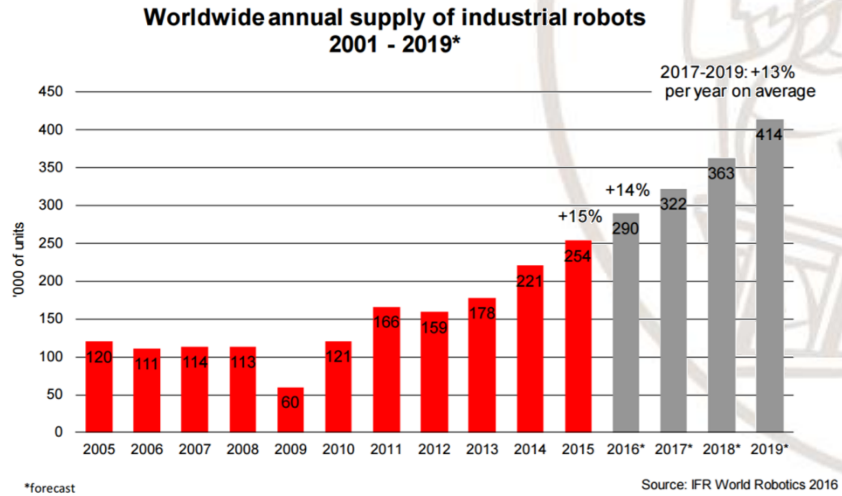
in industrial robotics



Video courtesy: COMAU

Reliability (minimal requested
Mean Time Before Failure = 40,000 hrs
Efficiency η > 99.99875% *(Source: COMAU)*



2.6 million industrial robots in operation in the world, with a growth rate of 15% per year *(Source: IFR)*

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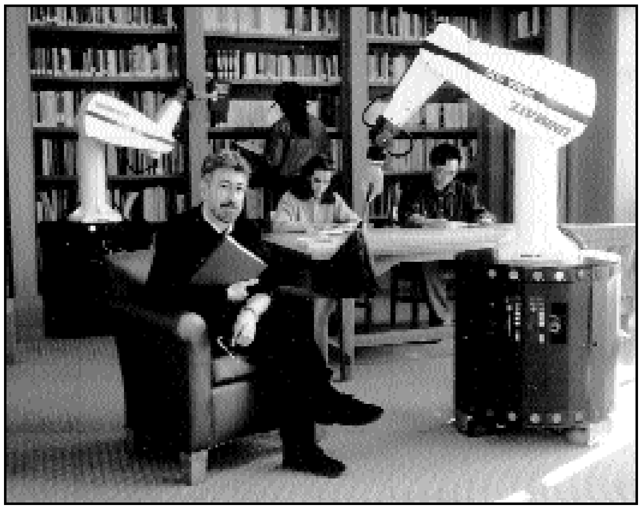
Evolution of robot abilities

in service robotics



Professional service

iRobot Roomba – 2.4M sold in 2015
double-digit growth of robot vacuum cleaner market

Autonomous cars

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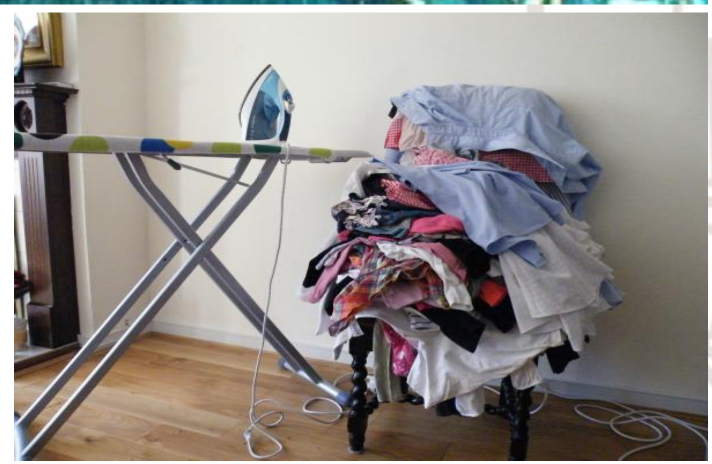
Evolution of robot abilities

Abilities not yet reached by robots

Poor working conditions result in a total of 300,000 work-related deaths and economic losses of 4% of the gross domestic product of the European Region every year (Source: WHO)



Up to 50 hours per household lost each week to work and family life

Lessons from Nature

Bioinspiration and biomimetics in robotics

Bioinspiration and biomimetics

Nevertheless...

…natural selection is not engineering

Organisms that are capable of surviving are not necessarily **optimal** for their performance.

They need to survive long enough to reproduce.

Models are never complete or correct: need to interpret with caution.

"**Simply copying** a biological system is either **not feasible** (even a single neuron is too complicated to be synthesized artificially in every detail) or is **of little interest** (animals have to satisfy multiple constraints that do not apply to robots, such as keeping their metabolism running and getting rid of parasites), or **the technological solution is superior** to the one found in nature (for example, the biological equivalent of the wheel has yet to be discovered).

Rather, the goal is to work out **principles** of biological systems and transfer those to robot design." *Rolf Pfeifer*

R. Pfeifer, M. Lungarella, F. Iida, "Self-Organization, Embodiment, and Biologically Inspired Robotics", *Science* 318, 1088 (2007)

Lessons from Nature: simplifying principles

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Mechatronic approach:
integration of subsystems that are often already very complex (e.g. complex humanoids)

Today, more functionality means:
- **more** complexity, energy, computation,
- **less** controllability, efficiency, robustness, safety

In robotics, we need **simplifying principles** for control and behavior

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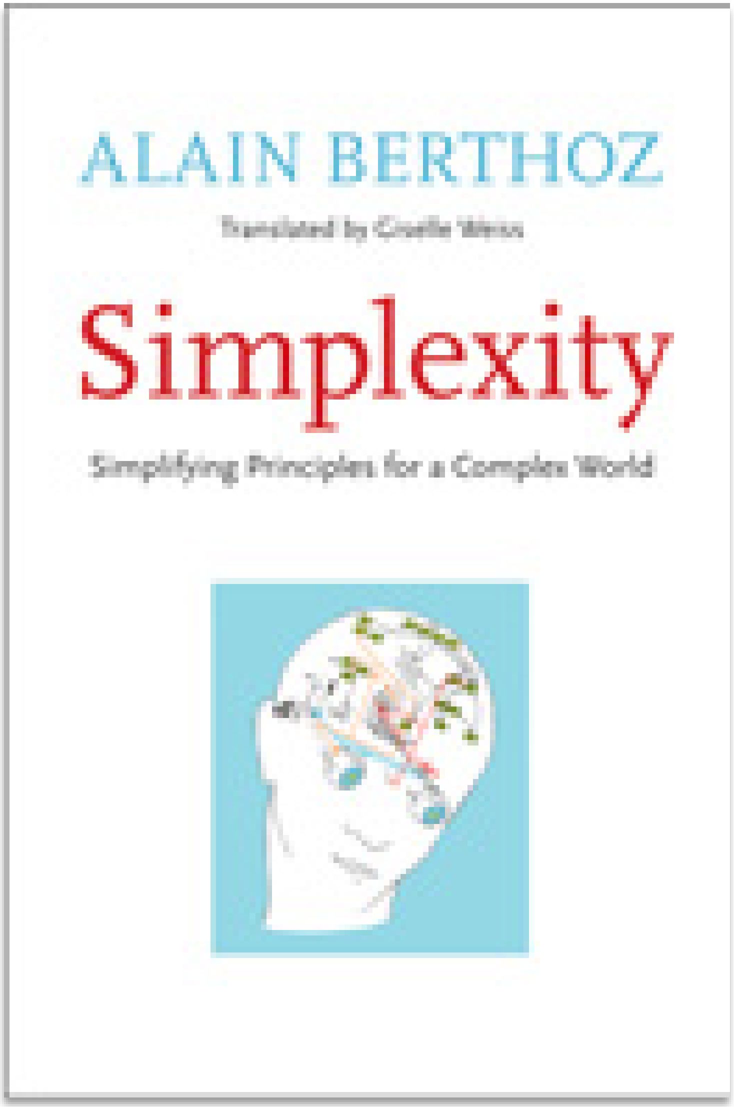
Simplexity

- **Simplexity** comprises a **collection of solutions** that can be observed in living organisms which, despite the complexity of the world in which they live, allows them to **act and project the consequences of their actions into the future.**
- It is **not** a matter of **simplified model** adoption, but rather an approach to **using simplifying principles**.



A. Berthoz (2012), *Simplexity: Simplifying principles for a Complex World*. Yale University Press.
U. Alon (2007), “Simplicity in Biology”, *Nature*, 446(7135):497

Simplexity principles

- Inhibition and principle of refusal
  - inhibition enables decision making
  - refusal is like ‘bracketing’ presumptions
- Principle of specialization and selection: *Umwelt*
  - sense only those aspects of the world that are relevant
- Principle of probabilistic anticipation
  - anticipation based on memory
  - prospective and perspective strategy
- Detour principle
  - Accessory complexity
- Principle of cooperation and redundancy
  - several values for the same variable
- Principle of meaning
  - actions responding to intentions, goals, functions

A. Berthoz (2012), *Simplexity: Simplifying principles for a Complex World*. Yale University Press.

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Image generation in the eye

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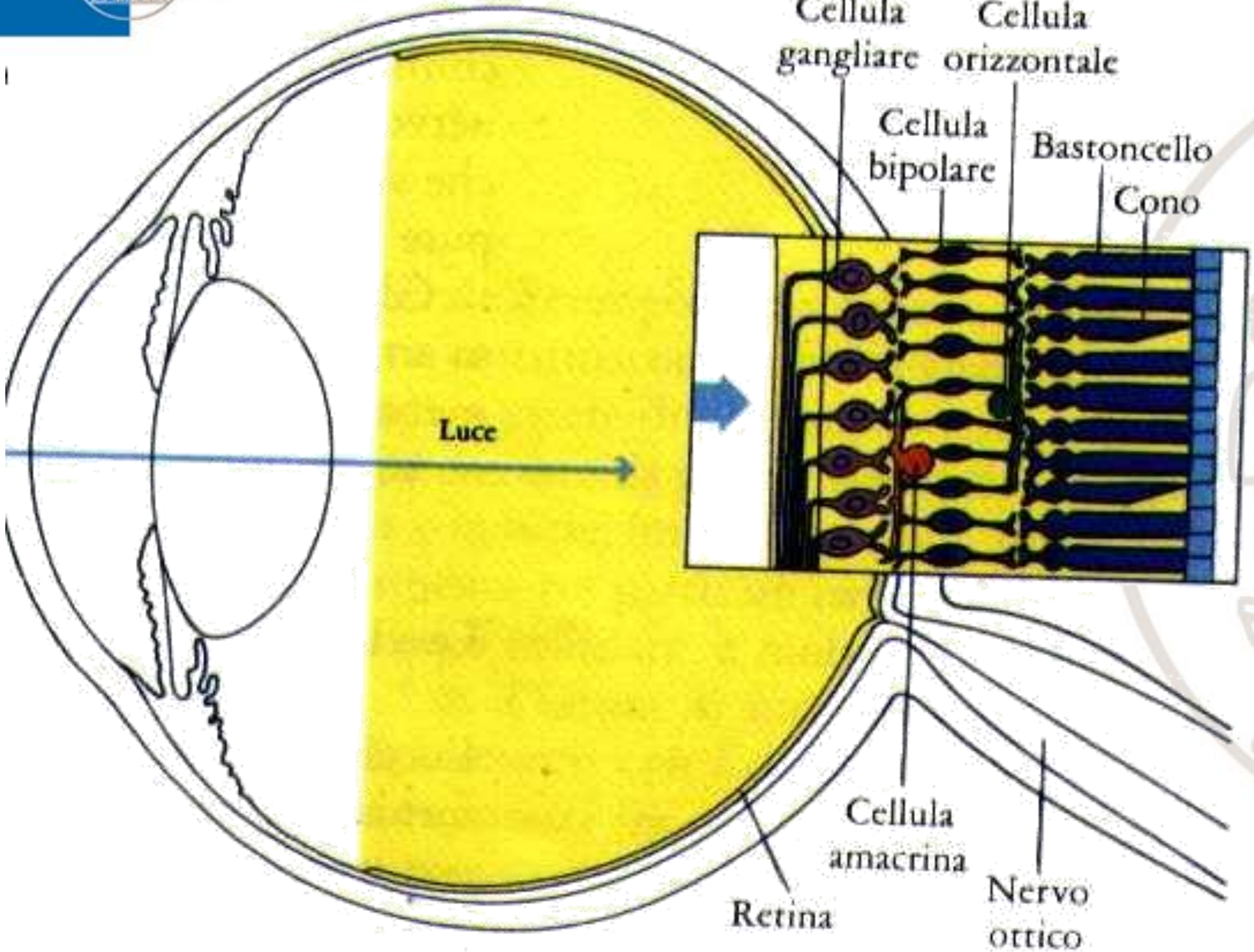

Photoreceptors: cones and rods

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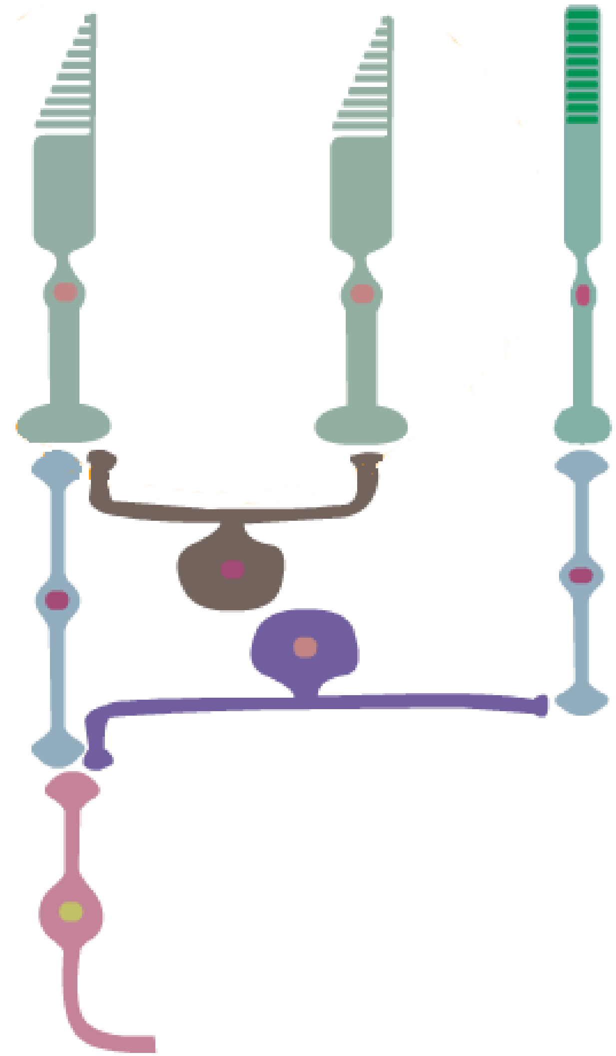
1. Light activates sensitive receptors
   Cones by different colors
   Rods by black and white
2. Ganglion cells are
   the only output from the eye.
3. Bipolar connect
   the receptors to the ganglion cells.
4. Horizontal cells
   converge signals from several cones.
   They determine how many receptors
   each ganglion cell sees.
5. Amacrine cells do the same
   from peripheral rods.



Distribution of photoreceptors in the retina

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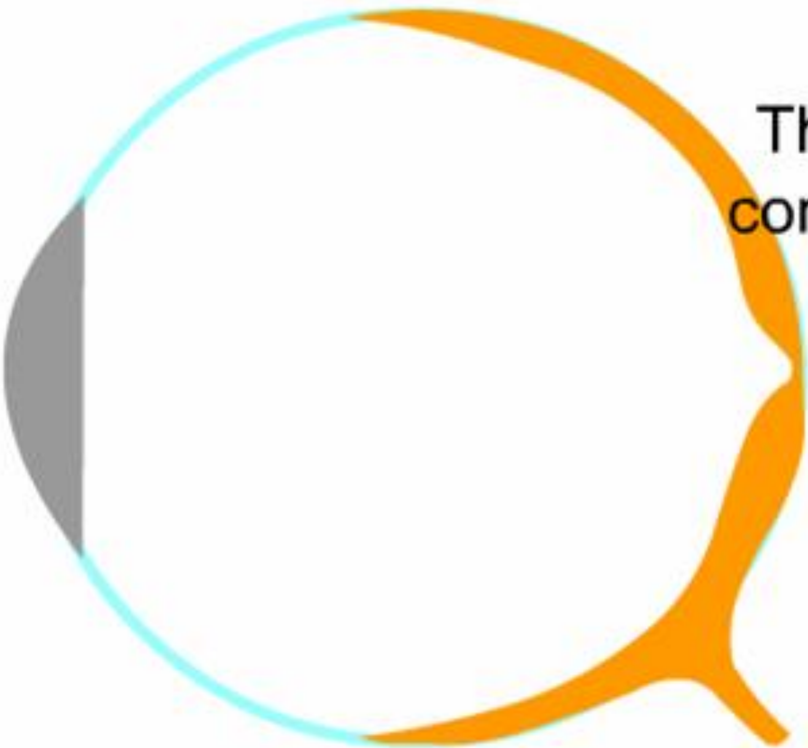
the retina is not uniform.



The **peripheral** retina contains primarily **rods**.

The **fovea**, in the center of the eye, contains only **cones**.

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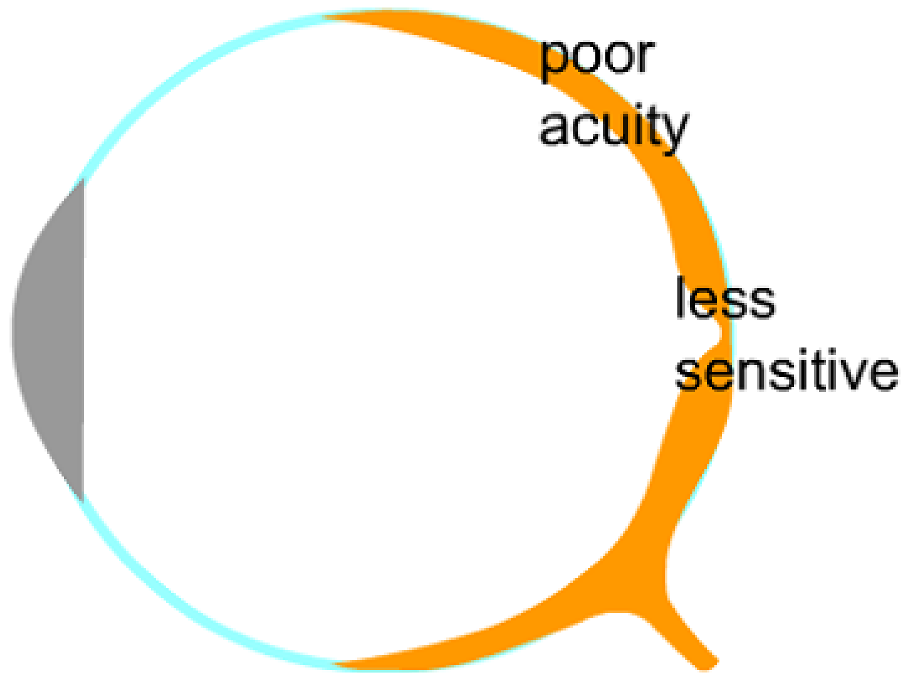
Sensitivity of photoreceptors in the retina

the rods and cones are not equally sensitive to low light levels.

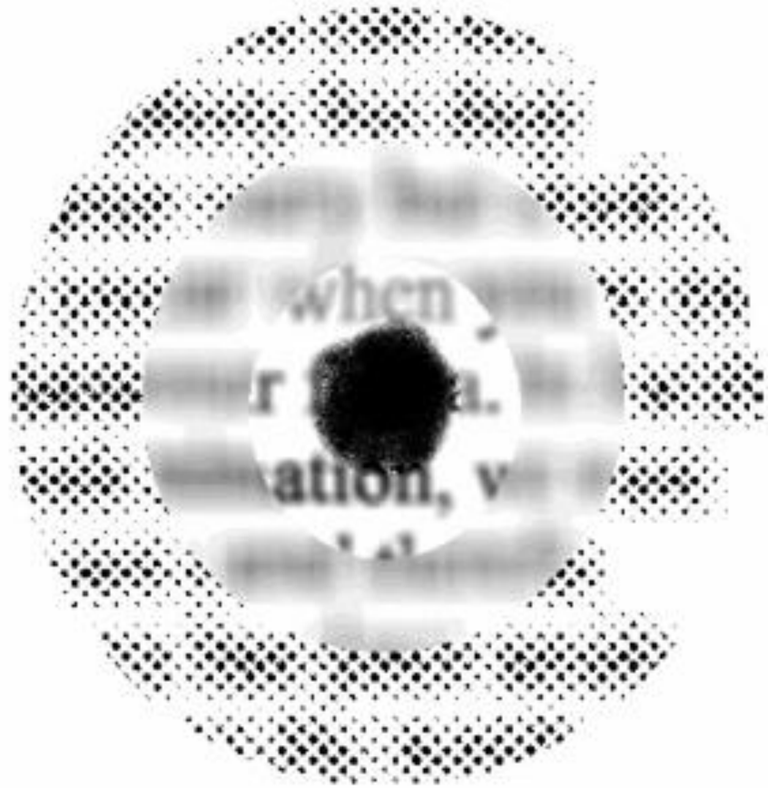
Cones are less sensitive to light.
e.g. Looking at dim stars,
one can see stars in the periphery
but they disappear when you
look at them with your fovea.
In very low levels of illumination,
we see only with our rods and
therefore see greys not colours.



the periphery has poor acuity.

What the eye sees

By daylight,
only the central fovea sees
clearly and in color



On a dark night,
only the periphery sees
only in
black & white,
and with poor resolution.
The fovea is blind

Receptive fields

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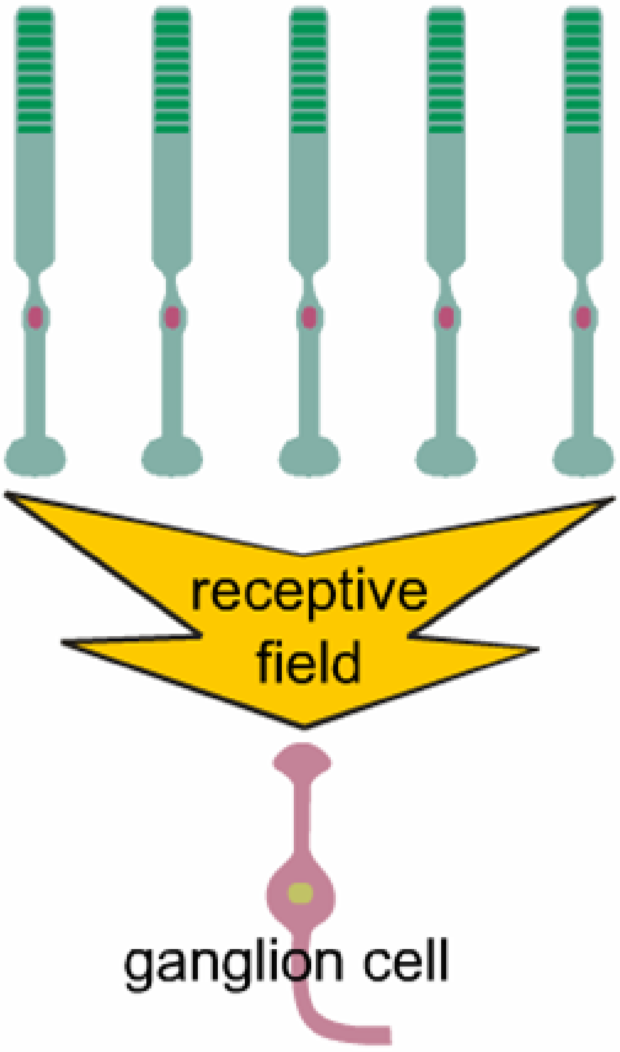
Definition of the receptive field of a ganglion cell:
"That area of retina over which light stimuli change the activity of a particular ganglion cell."

The receptive field shows which rods & cones are connected to the ganglion cell.



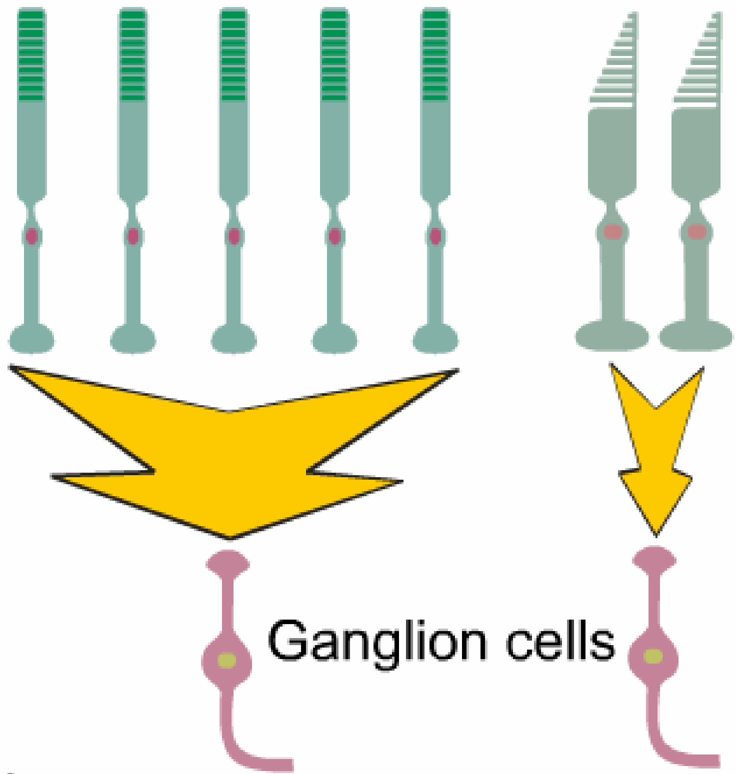
Distribution of photoreceptors in the retina

1) peripheral rods
large spacing
(lower density)

foveal cones
high density

2) large
convergence

small
convergence



integrate information
from a large area of retina (3 deg)

integrate information
from a small area of retina (.03 deg)

large spacing and large convergence
result in low acuity

small spacing and low convergence
result in high acuity.

Why is compression important?
There are 100 million rods and cones. Why not have the same number of ganglion cells instead of the actual 1 million?

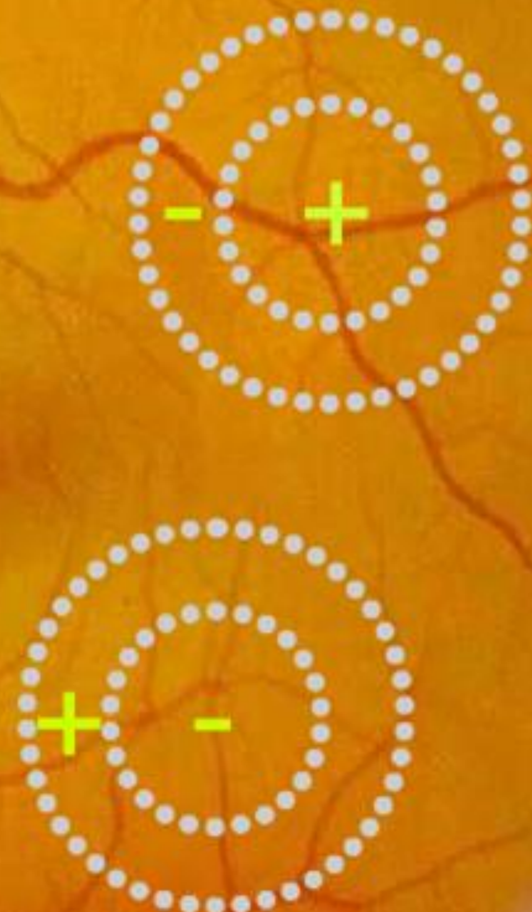
The answer is efficiency. Much of the information that the eyes sees is redundant. Through evolution the eye has been designed to remove this redundant information before sending it on to the brain. Why build and maintain a huge number of fibers when a much smaller number can convey the same information? When the eye sees a round image, it does not transmit the color and brightness of every point inside the image; only that at the edges.

This is similar to computer compression software used to transmit large images along the Internet. The ganglion cell sends compressed information down the optic nerve. The visual cortex then uncompresses this information. Suppose you were transmitting the color of a series of dots along the internet, each colour coded by a number from one to 2000000. The series uncompressed would look like: 1756333, 1756333, 1756333, 1756335, 1756335, 1756333 ...... Compressed, by coding only changes in color, it would look like: 1756333,0,0,2,0,-2.... a lot shorter.

Types of receptive fields of retinal ganglion cells

What are the two major types
of receptive fields
of retinal ganglion cells?

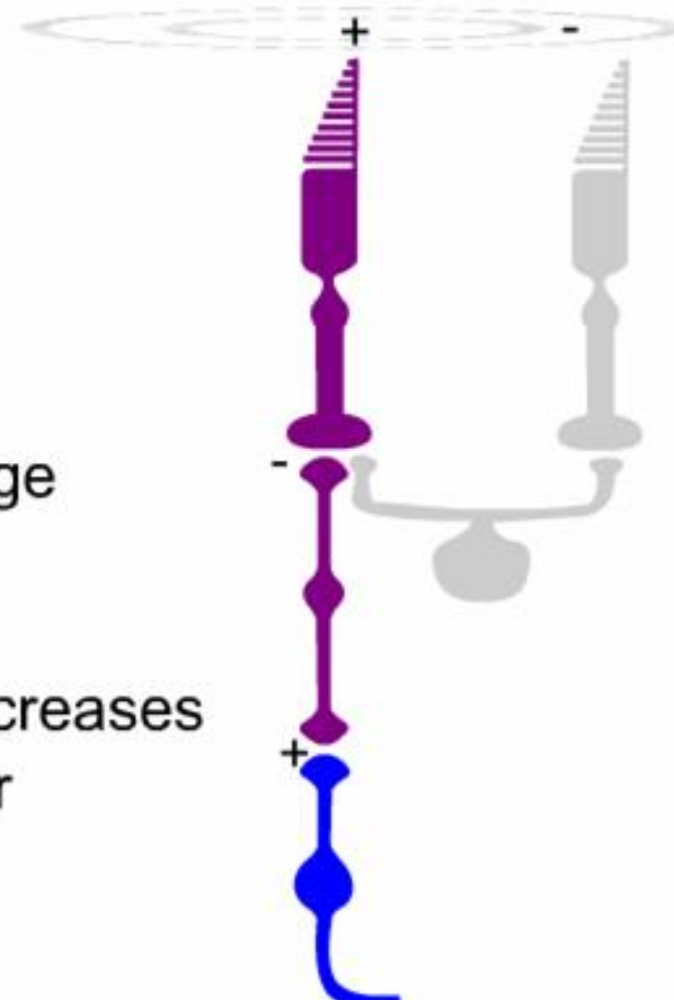
(a) ON center, OFF surround
which measure how much brighter
an object is than its background.
(b) OFF center, ON surround
which measure how much darker
an object is than its background.



ON centre, OFF surround ganglion cell

Light to a cone in the centre
produces
excitation of the ganglion cell.

This is because:
1) light decreases the cone voltage
and the cone releases
less inhibitory transmitter
2) the voltage inside the bipolar cell increases
and it releases more transmitter
3) the ganglion cell is excited
and it fires more often.



ON centre, OFF surround ganglion cell

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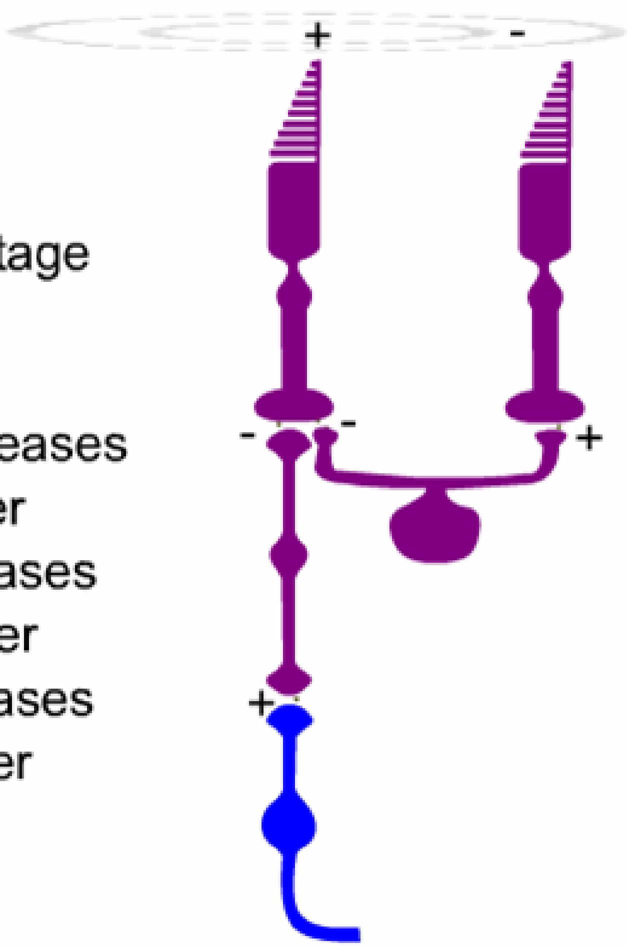
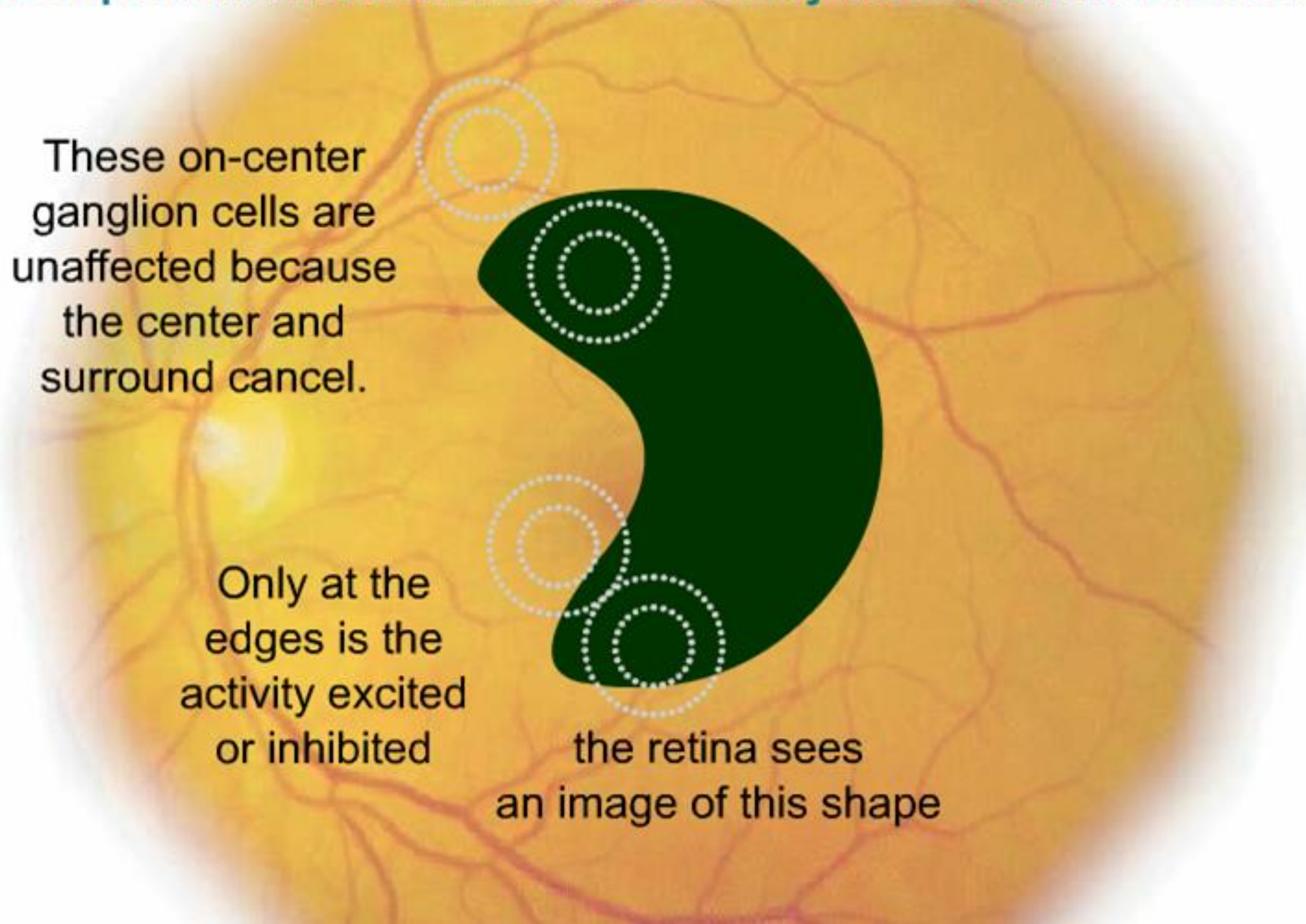
Light to a cone in the surround
produces
inhibition of the ganglion cell.

This is because:
1) light decreases the surround cone's voltage and the cone releases less excitatory transmitter
2) the voltage inside the horizontal cell decreases and it releases less inhibitory transmitter
3) the voltage inside the center cone increases and it releases more inhibitory transmitter
4) the voltage inside the bipolar cell decreases and it releases less excitatory transmitter
5) the ganglion cell is inhibited and it fires less often.



What important information is extracted by the retinal neural network?



What important information is extracted by the retinal neural network?

Ganglion cells exaggerate the contrast at borders (i.e. like a cartoon).

Why? By sending only the information on contours, the changes in brightness, less redundant information is sent along the small optic nerve to the CNS.

ganglion cells see an edge

Color perception

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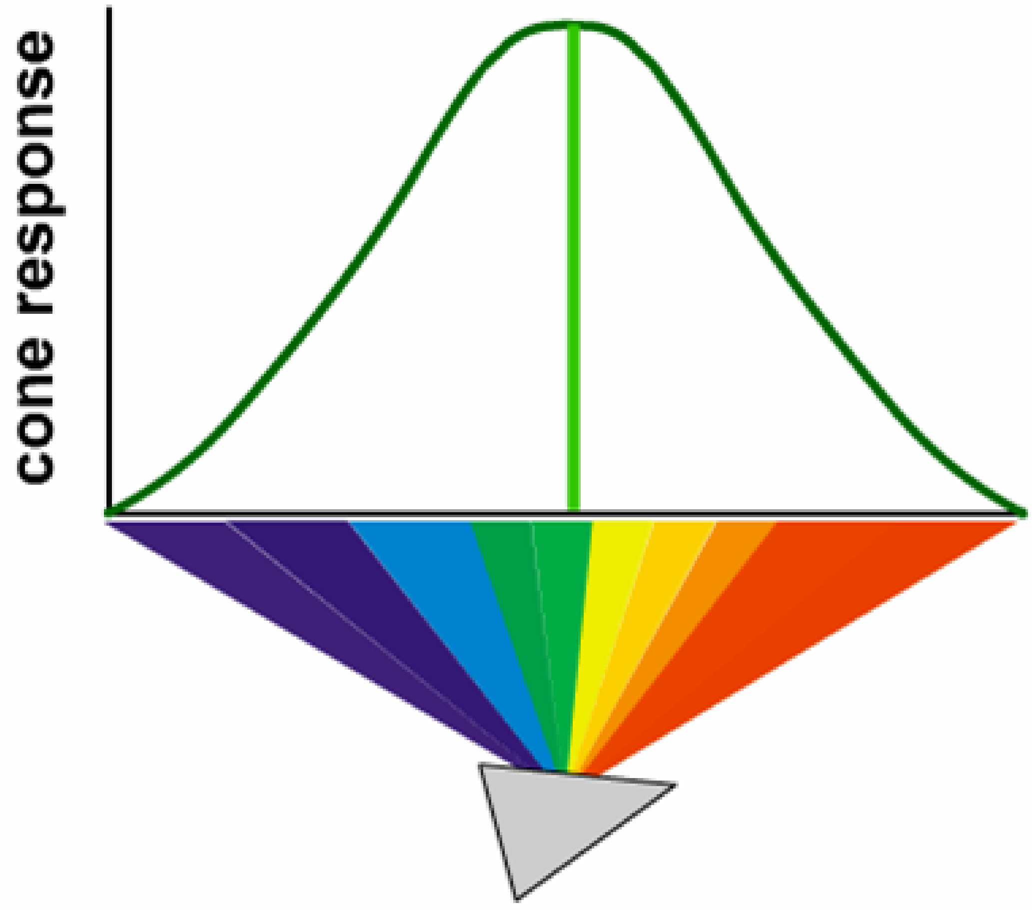
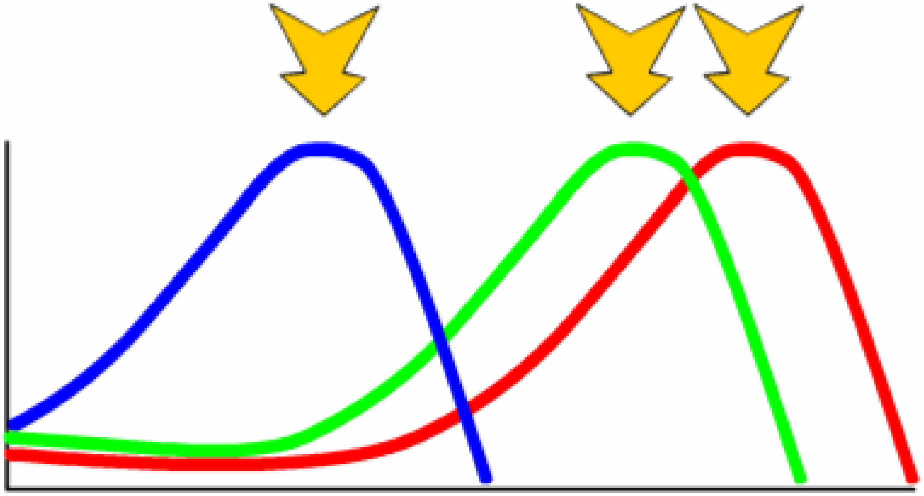
Cones responds best to a particular wavelength of light
and less to others.

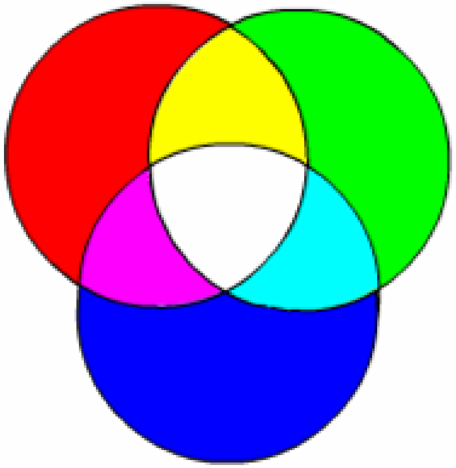
Note that this one reponds best to green light.



We have 3 cone types.



Mixing light is **not** like mixing paint.

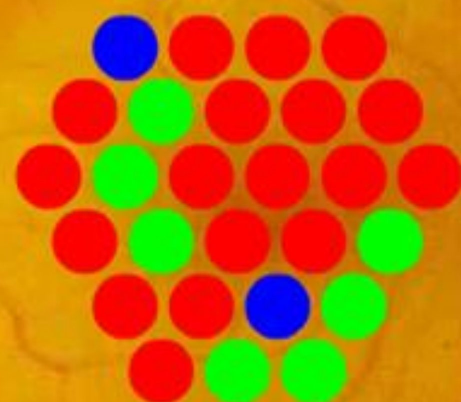


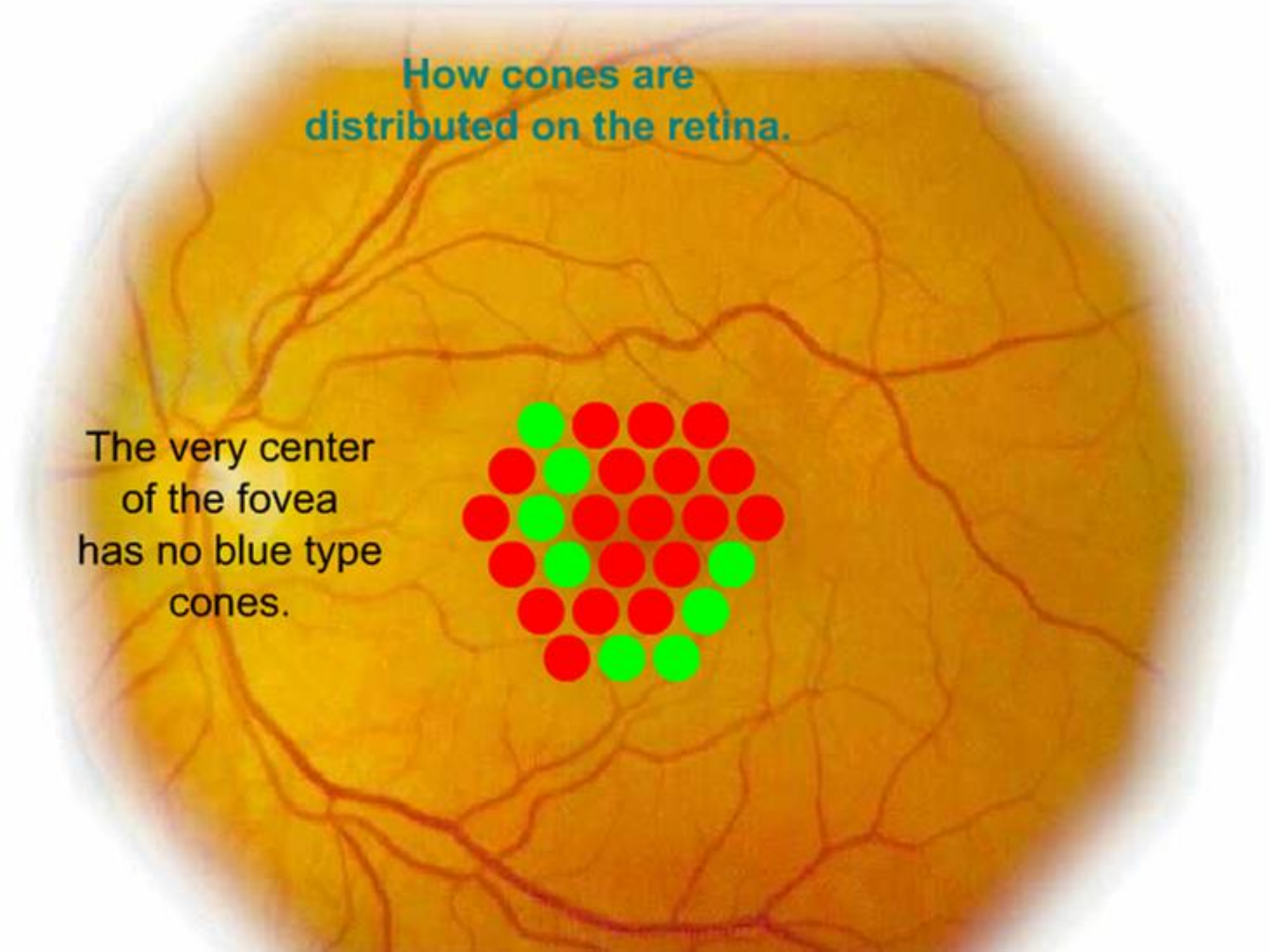
When red & green cones are stimulated one sees yellow

When all three cone types are stimulated one sees white.

How cones are distributed on the retina.

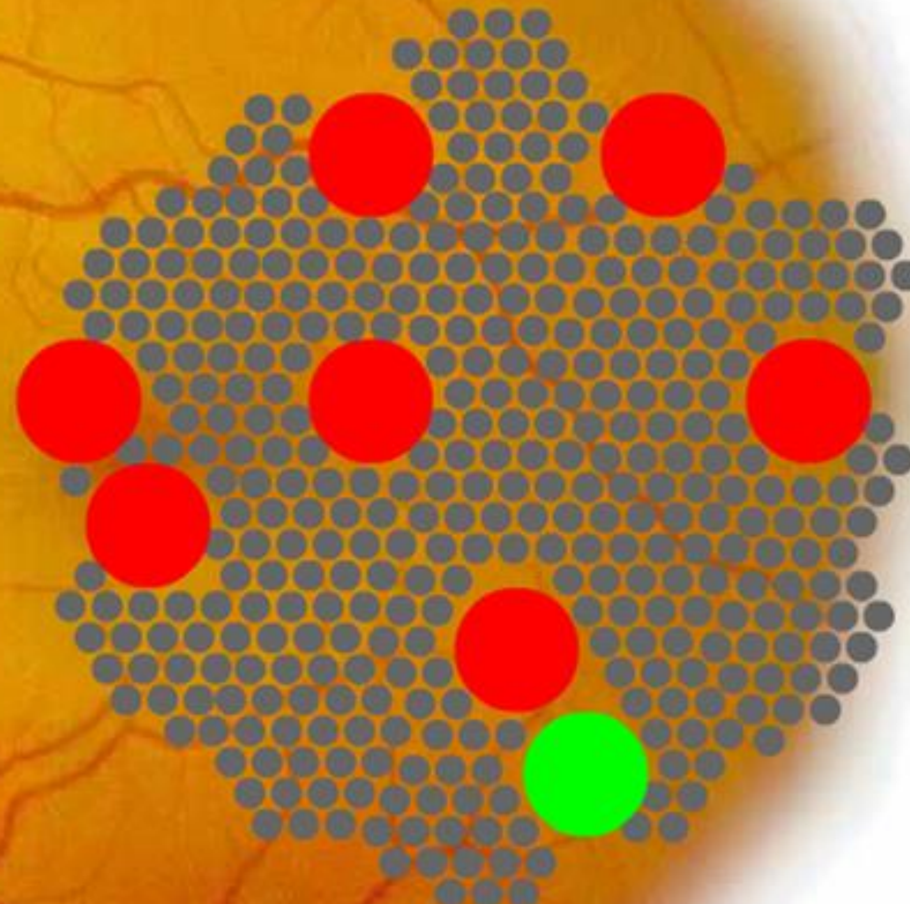
In the fovea
1) the # of each cone type is not equal. Usually red cones are most numerous and blue cones least numerous
2) the relative #'s vary from person to person
3) the cones of the same type form clusters




How cones are
distributed on the retina.
The very center
of the fovea
has no blue type
cones.

How cones are distributed on the retina.

As one moves
away from the fovea
1) the #'s of cones drops and
the #'s of rods increases
2) the size of both rods and
cones increases and thus
their density (# per square
mm) decreases
3) cones become larger than
rods.



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Color perception

a) **200 hues**

The brain transforms the single wavelengths of light seen in rainbow into a color circle. Hues on opposite sides of the circle are complementary.

b) **20 levels of saturation**

Combinations of two more wavelengths. When complementary wavelengths are combine equally one gets white.

c) **500 brightness levels**

Any color on the circle can be made brighter or darker. But because brighter or darker colors are more difficult to distinguish, the circle becomes narrower.

500x200x20 = 2,000,000 gradations of color

Basic principles of retina-like vision

Standard image

Retina-like image

Log-polar image (magnified to 200% for display)

Log-polar projection

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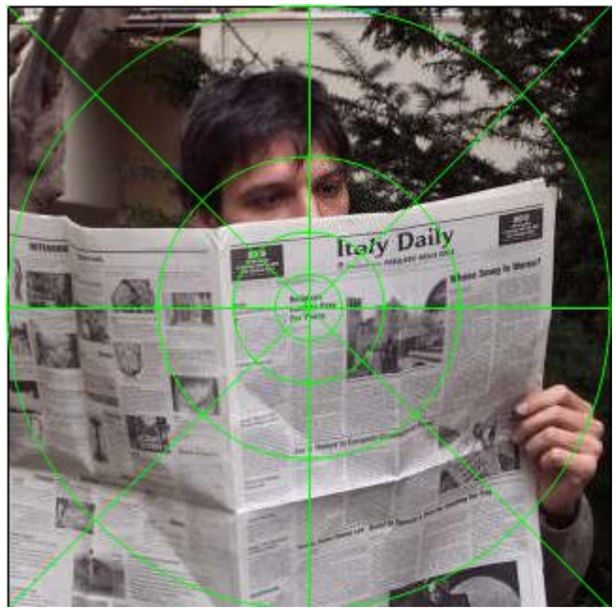
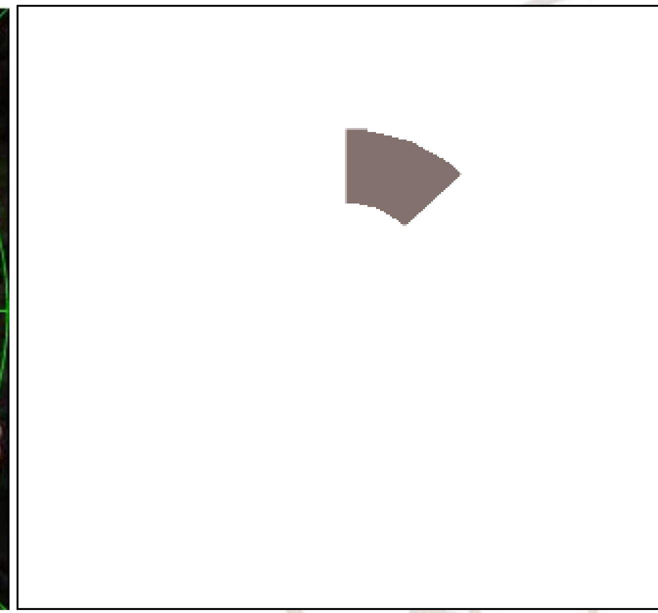
Building a retina-like image

Cartesian image



Cutting in circles and slices



Computing the average value in each sector

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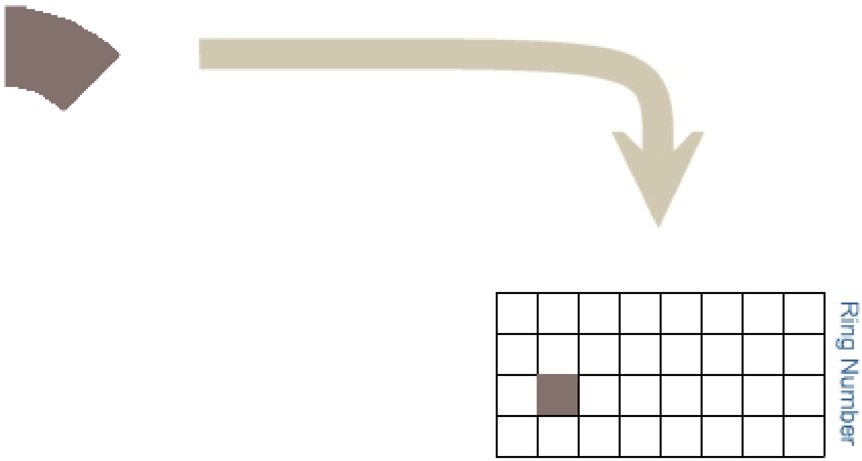
Building a retina-like image



Copying the average value of a sector in a polar image

Resulting polar image

Cartesian image re-built from the polar image

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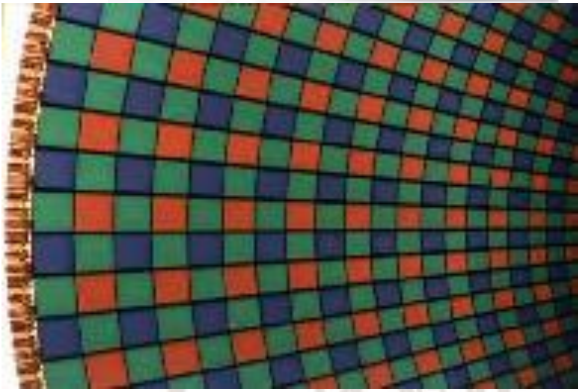
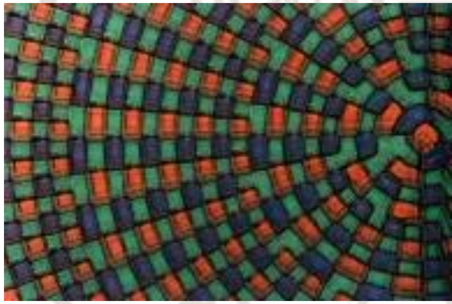
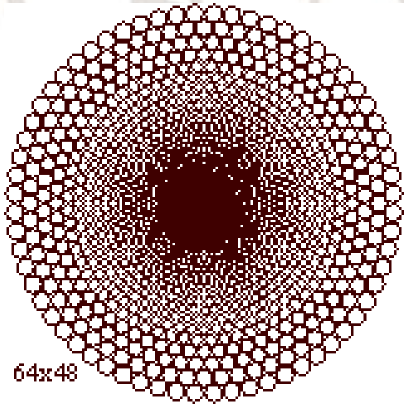
The Retina-like Giotto cameras







- Technology: 0.35 micrometer CMOS
- Total Pixels: 33193
- Geometry:
  - 110 rings with 252 pixels
  - 42 rings with a number of pixels decreasing toward the center with a "sunflower" arrangement
- Tessellation: pseudo-triangular
- Pixels: direct read-out with logarithmic response
- Size of photosensitive area: 7.1mm diameter
- Constant resolution equivalent: 1090x1090
- On-chip processing: addressing, A/D, output amplifier

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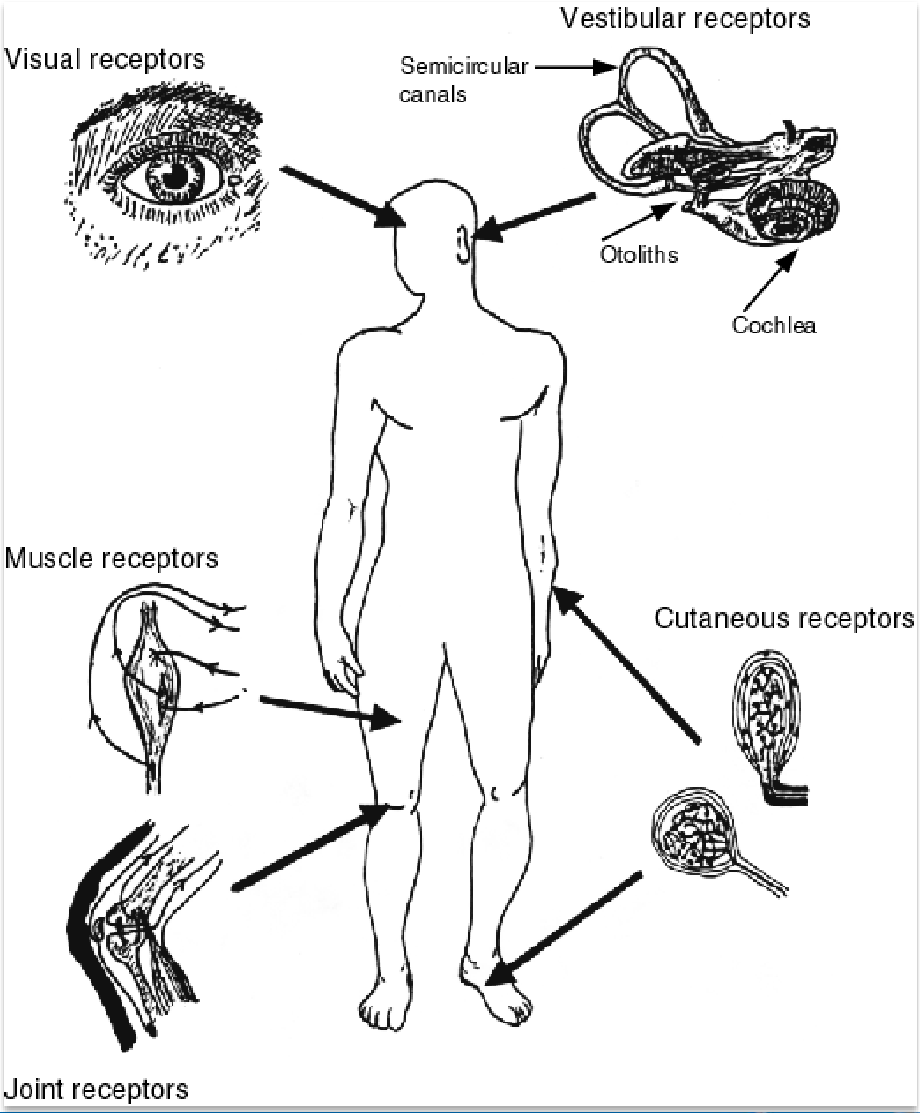
- **The *sense of movement* and the vestibular system: simplifying principles in eye movements**
- Predictive architectures
- Embodied Intelligence
- Simplifying principles in soft robots

The human “sense of movement”

In humans the **sense of movement** is given by the integration of a variety of sensory signals, mostly proprioceptive.

The **vestibular system** that provides perception of the head movements and postures relative to space plays a key role.



Berthoz A.(2002),*The sense of movement*. Harvard University Press

The human vestibular system

- "Organ of balance"
- Sensitive to:
  - head movements
  - head position in space
- Measures:
  - Angular velocities
  - Linear accelerations
- Fundamental role in several motor functions:
  - control of posture
  - coordination of movements
  - control of eye movements

The human vestibular system

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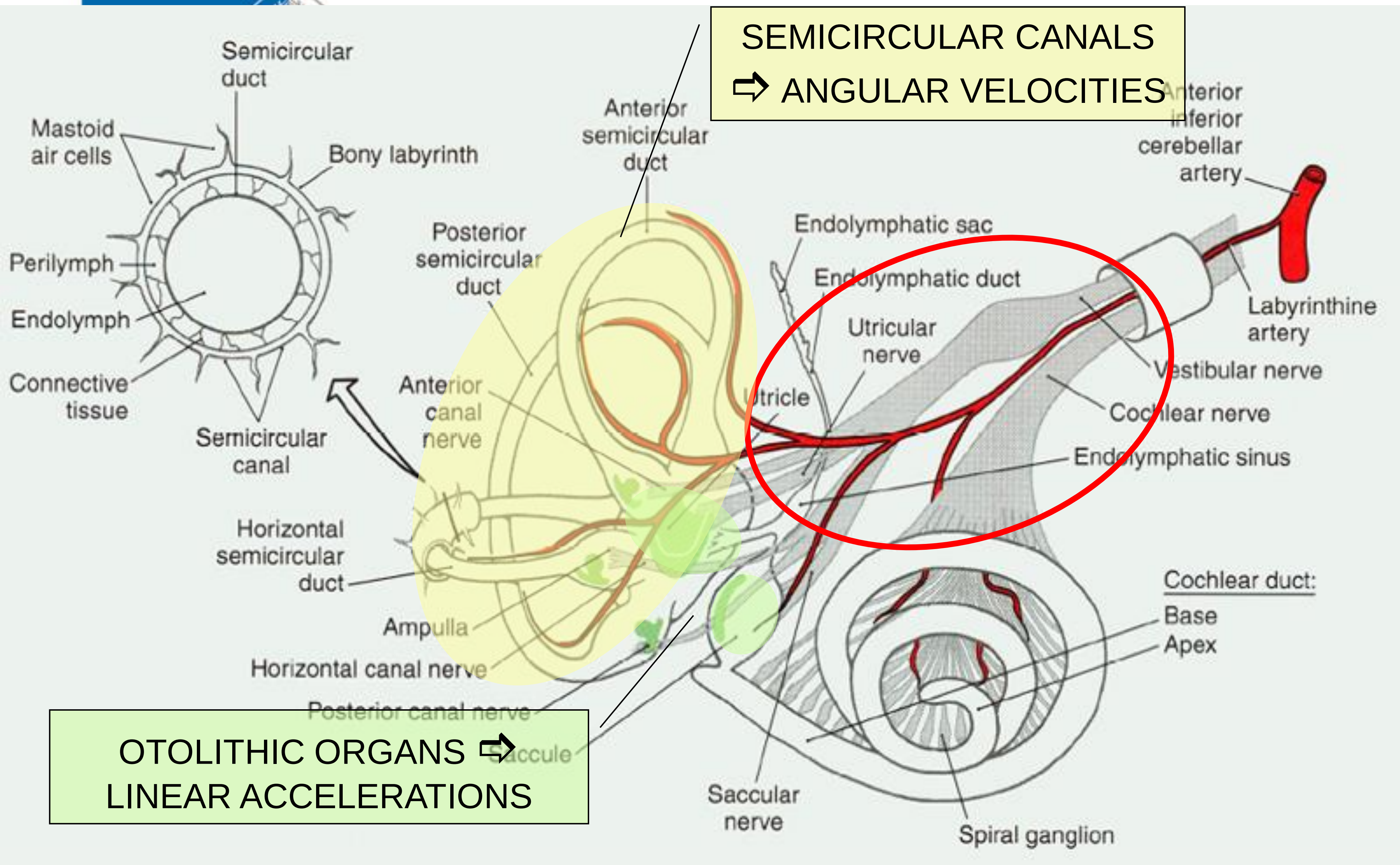

Semicircular canals

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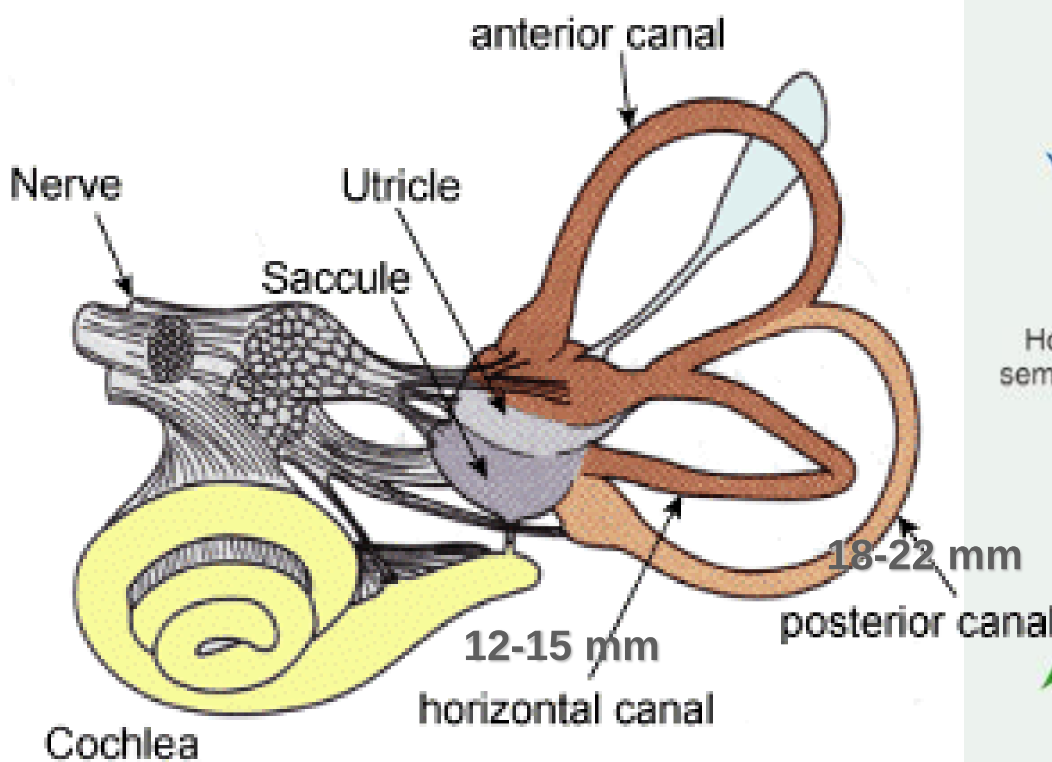
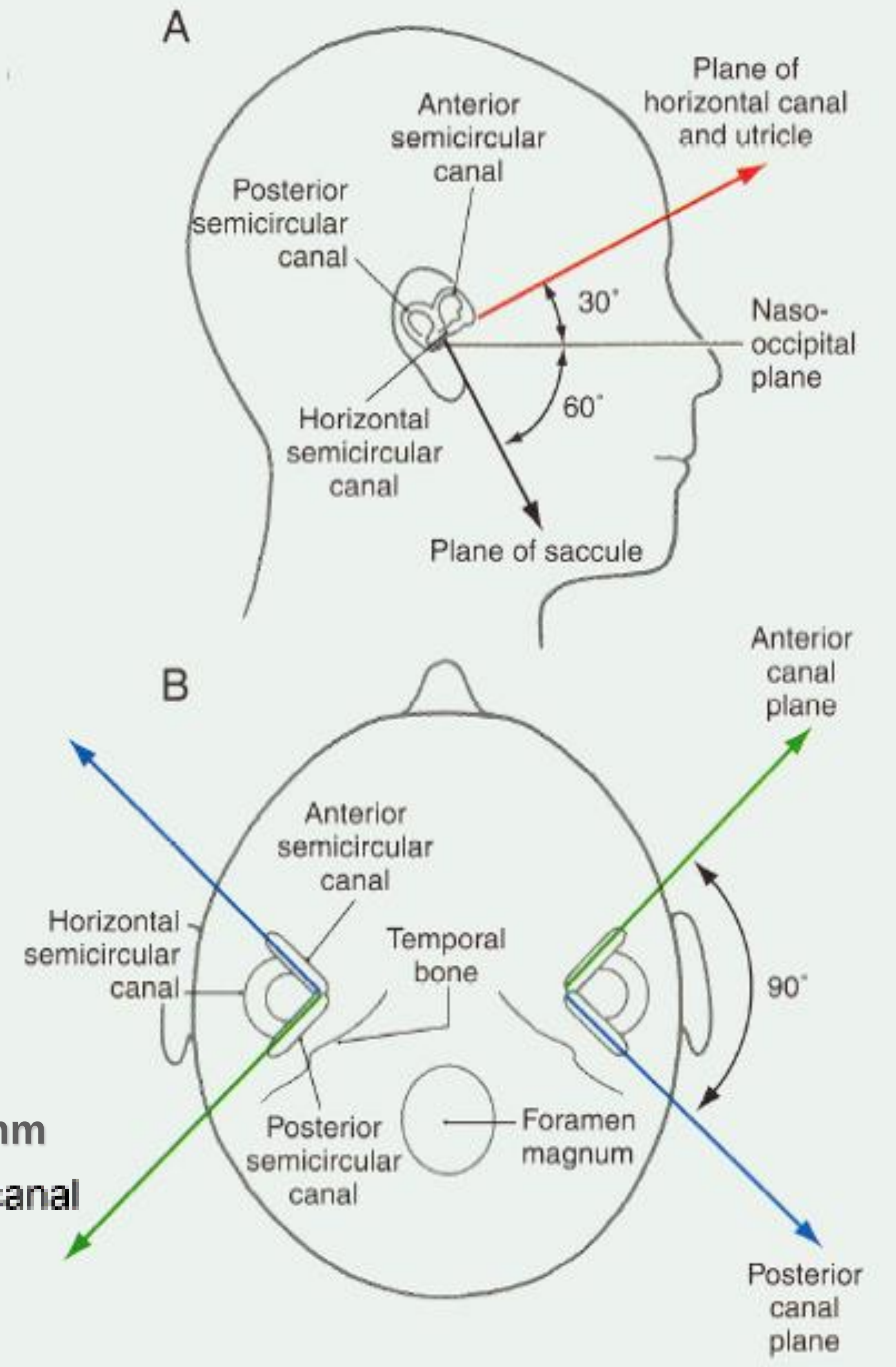
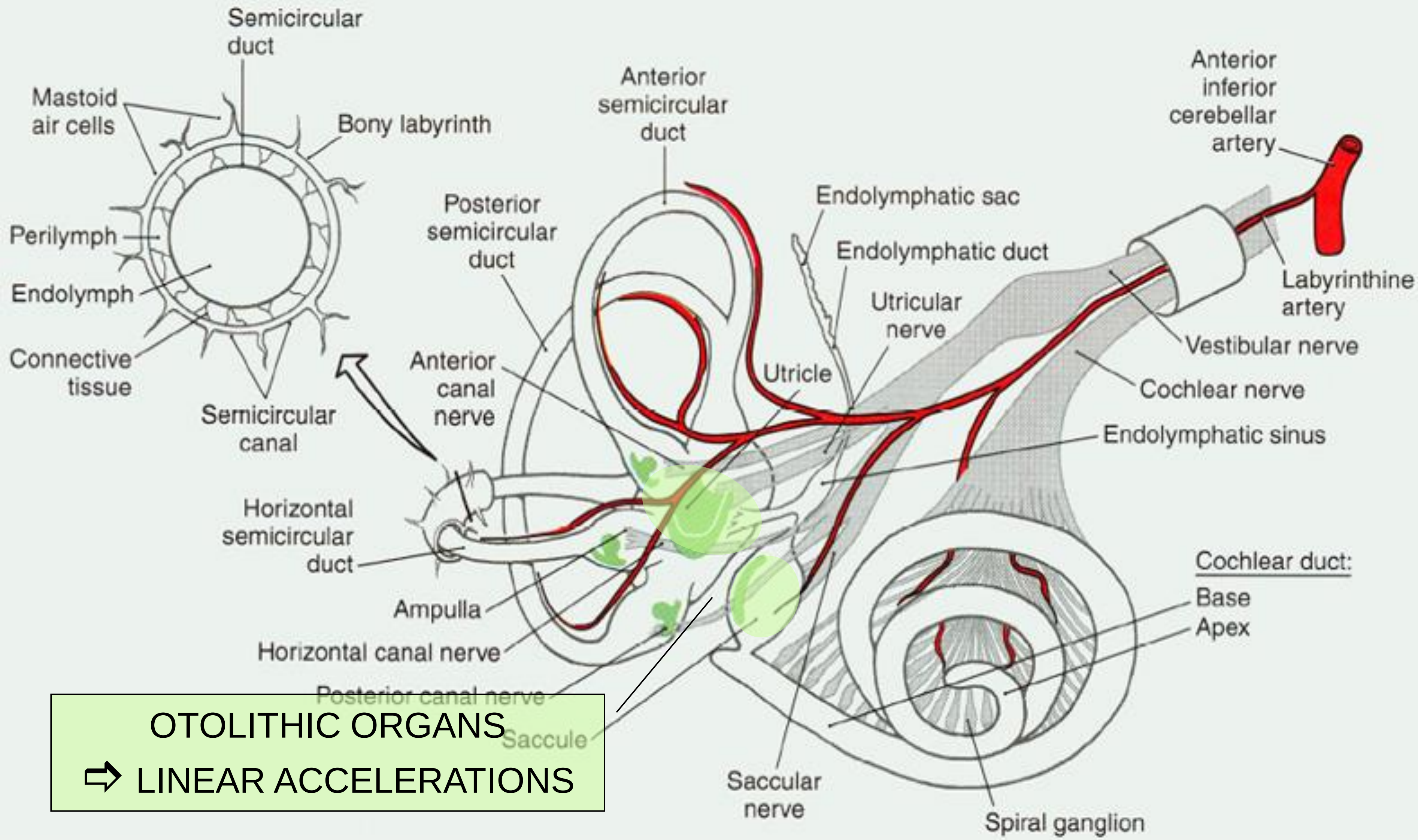
2/3 of a circle with 6.5-mm diameter
Inner diameter: 0.4 mm

15-20 mm





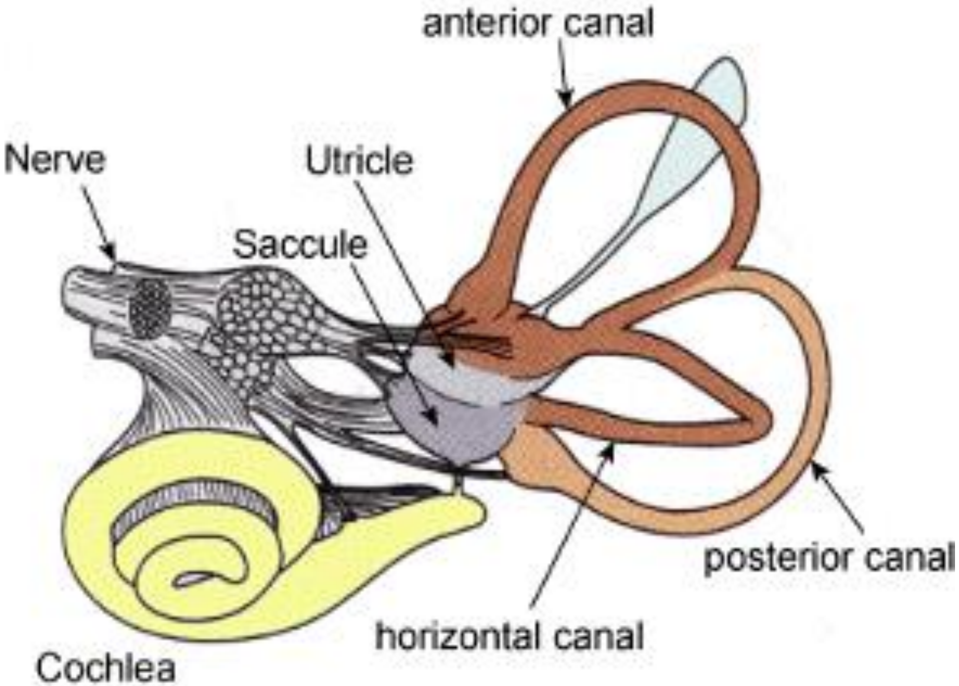
Otolithic organs

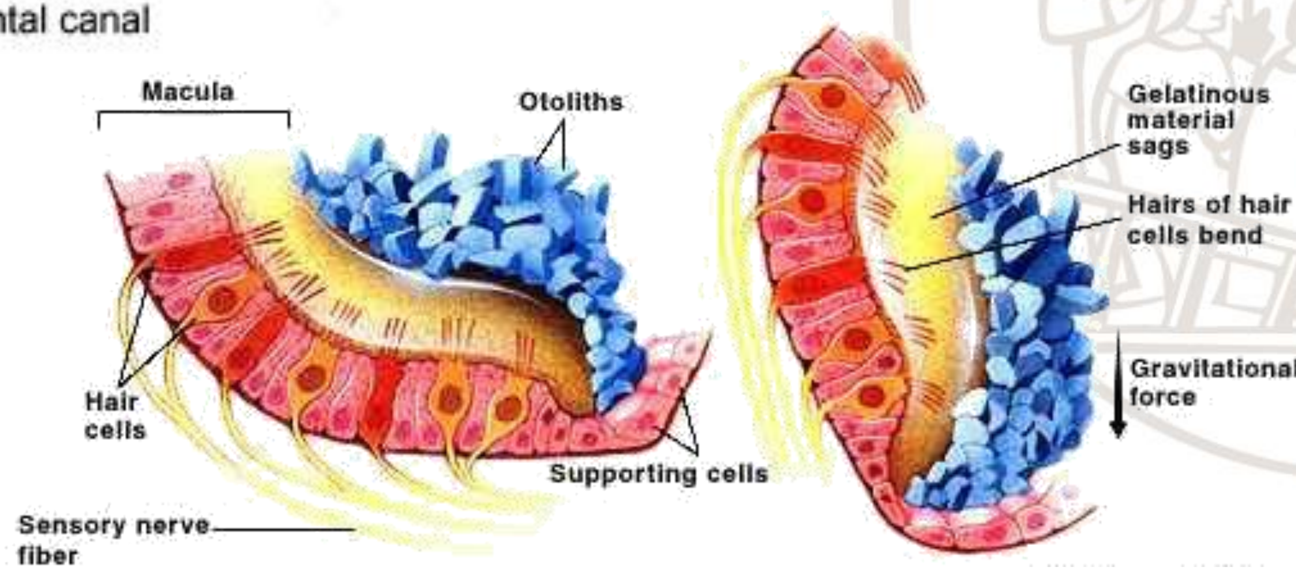


OTOLITHIC ORGANS

⇨ LINEAR ACCELERATIONS

Otolithic organs





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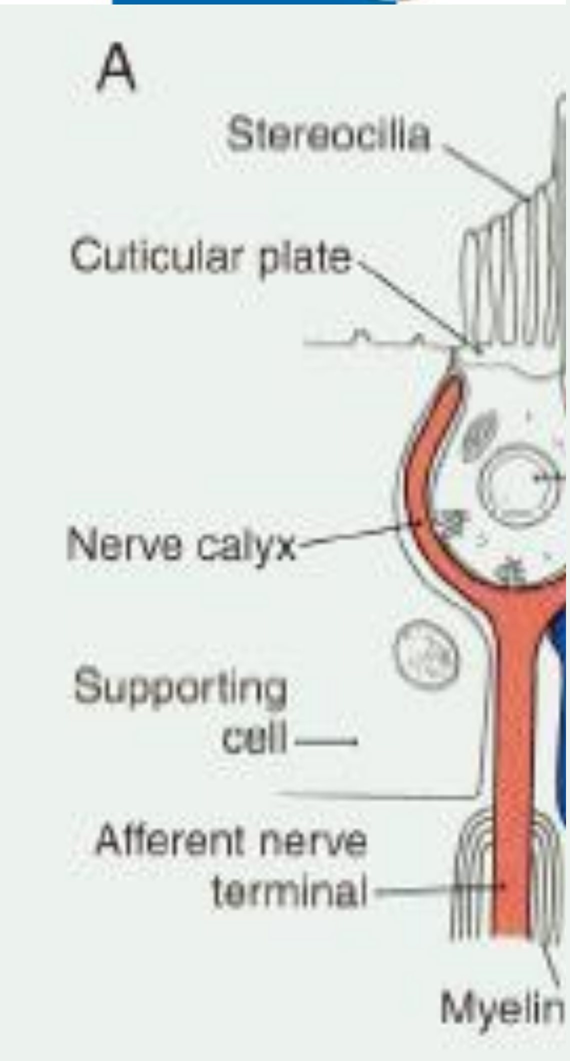
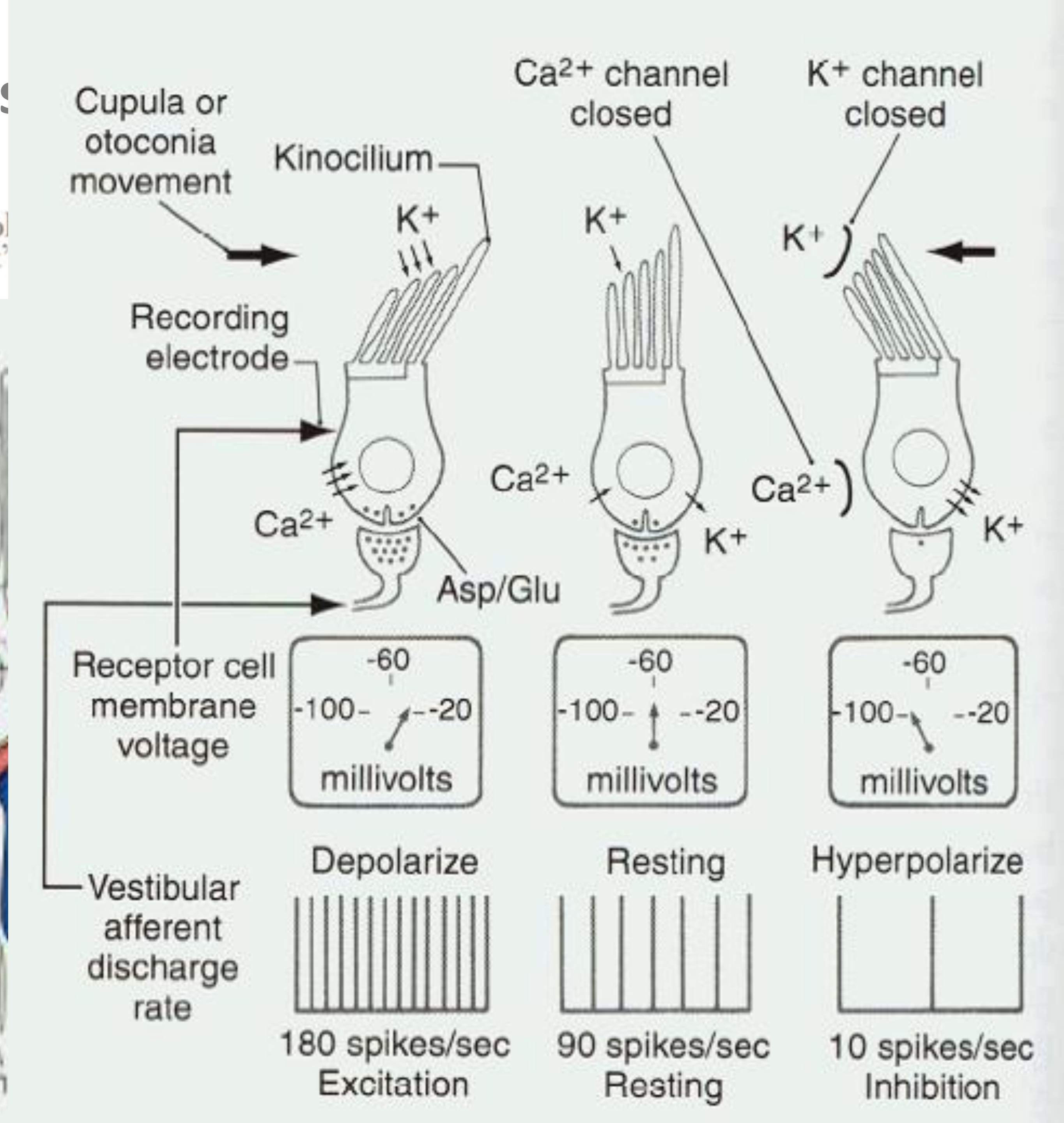
Ves





Vestibular receptors

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How is motion transduced into neural firing?

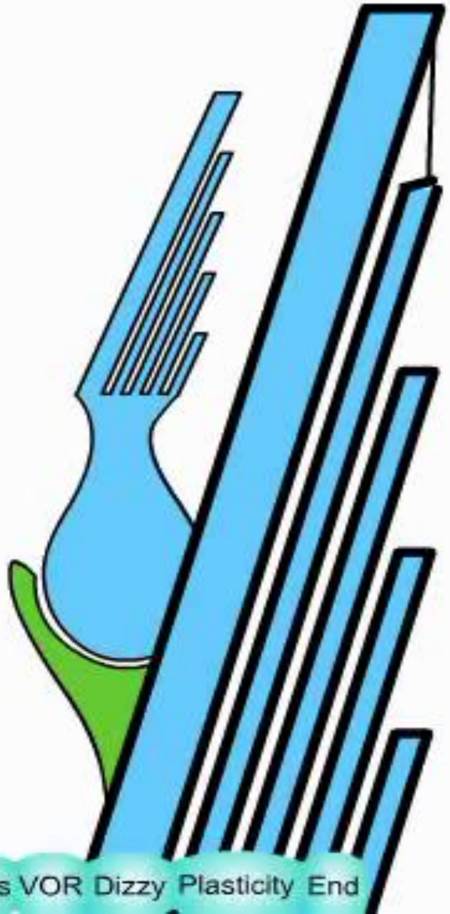
The steps are.

1) As in auditory hair cells, motion bends the hairs.

2) The filament between adjacent hairs opens ion channels allowing K+ to enter the hair cell.

3) The hair cell depolarizes, releasing neurotransmitter.

4) There is an increase in the frequency of AP's in the bipolar 8th nerve afferent.



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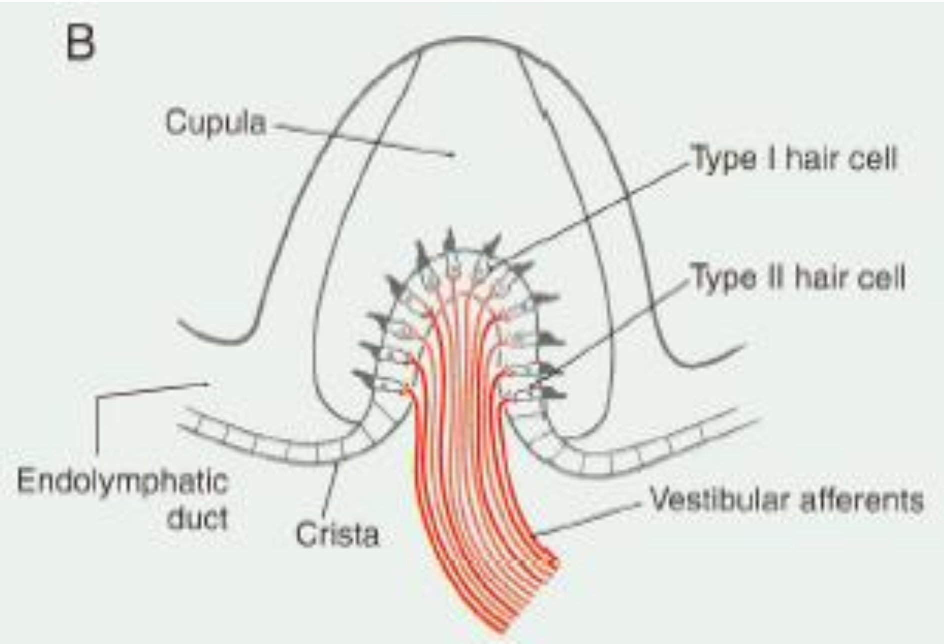
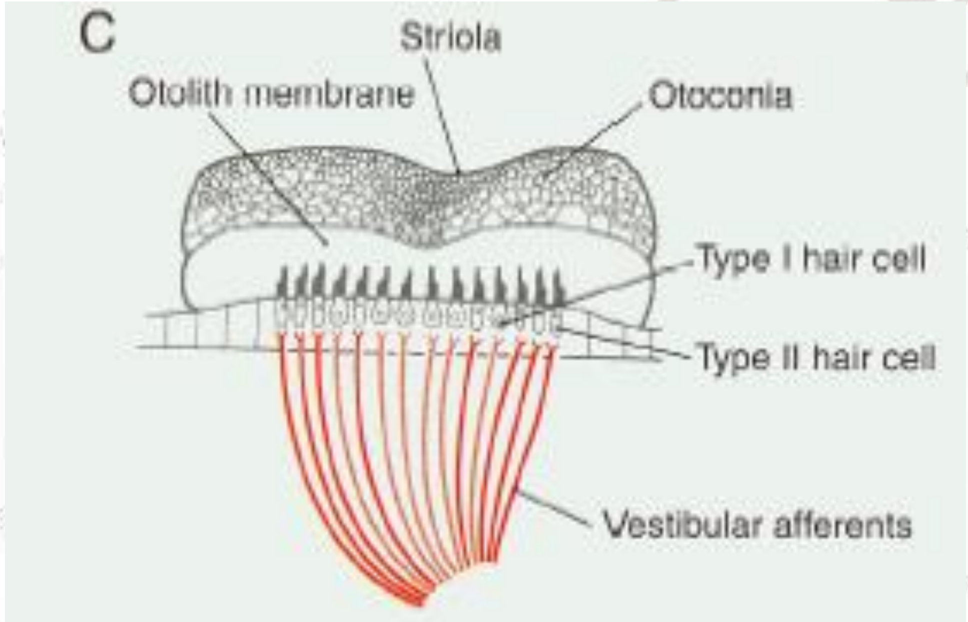
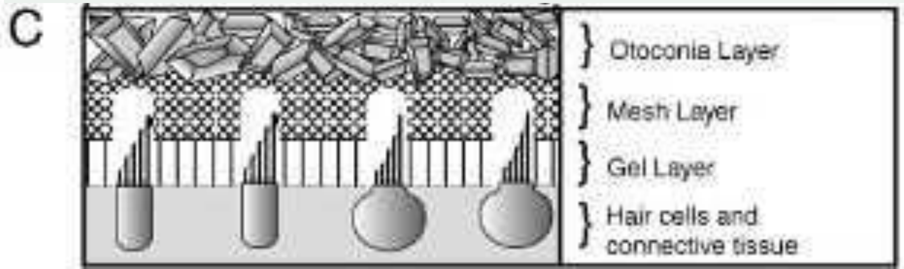
Vestibular receptors in the semicircular canals and in the otolithic organs

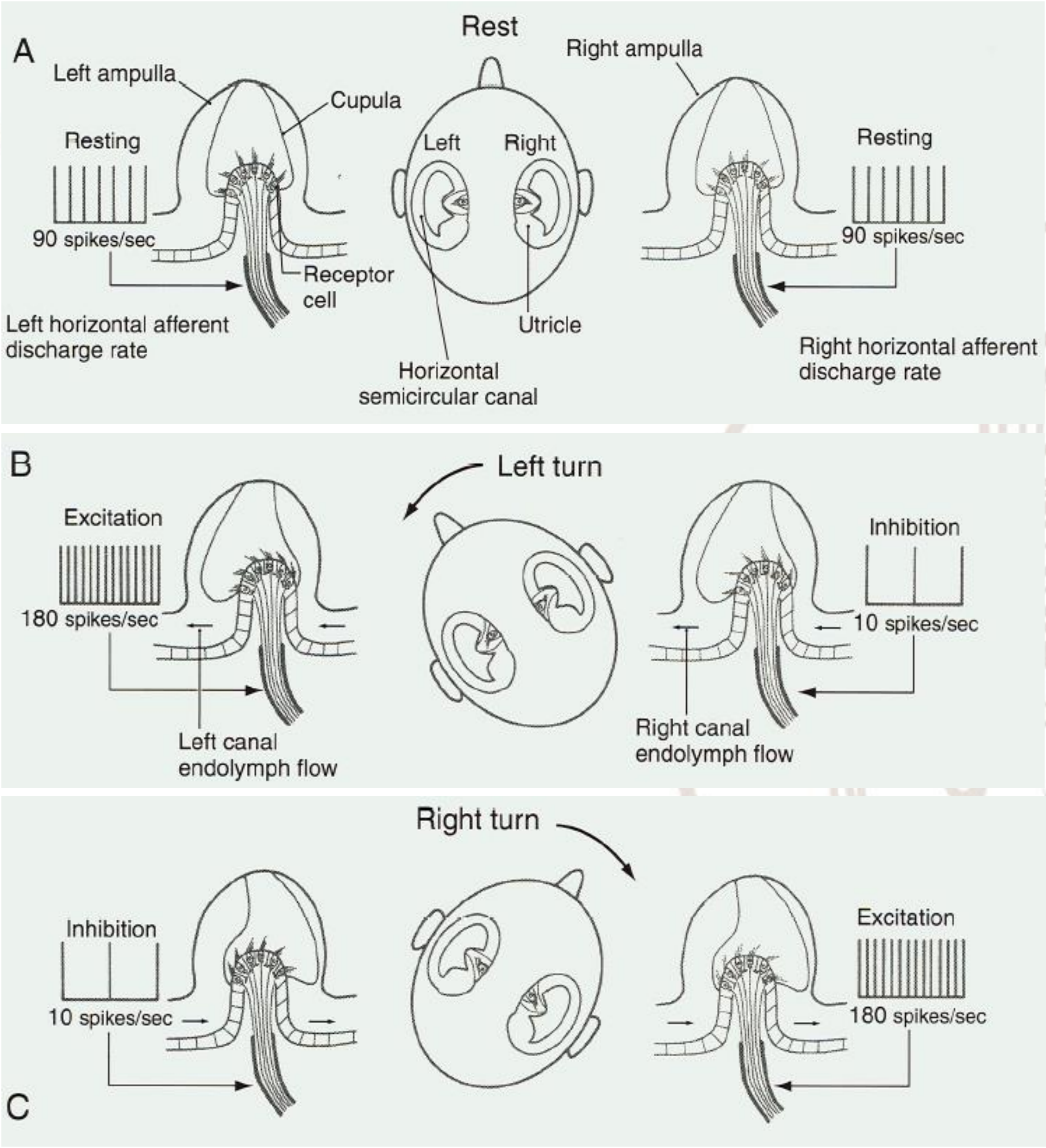
- Semicircular canals
- Otolithic organs







Response mechanism of semicircular canals to head rotations



Human Vestibular System

What is the functional anatomy of the semicircular canals?

There are three canals in each side.
One is approximately horizontal (h), and the other two, the anterior (a) and posterior (p), are aligned vertically and are about perpendicular to each other.

Within the canals are endolymph-filled semicircular ducts which open at both ends onto the utricle.

Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End

Human Vestibular System

What is the functional anatomy of the semicircular canals?

Each duct has a swelling called the ampulla.

The crista, a crest covered with sensory hair cells, projects into the cavity of the ampulla.

The cilia of the hair cells are embedded in a pliable membrane called the cupula which spans the inner diameter of the ampulla.

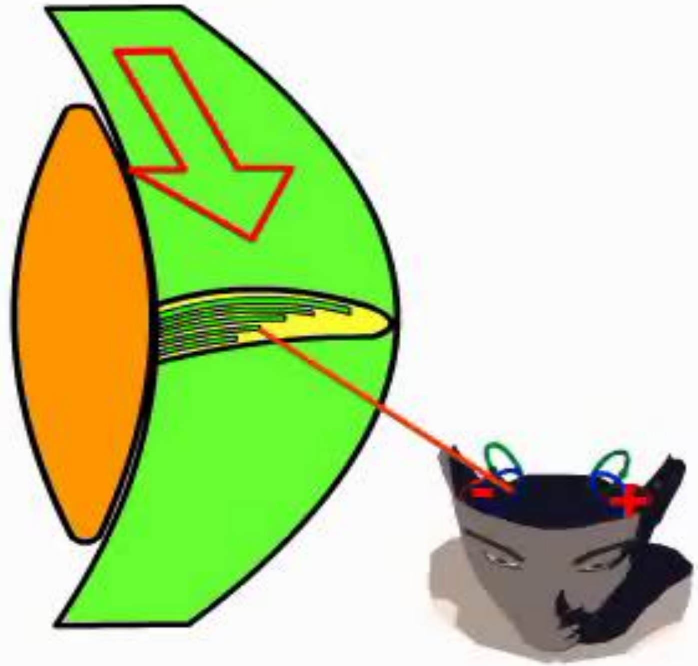
Human Vestibular System

How does this structure detect angular acceleration of the head?

When there is a change in speed of head rotation, the endolymph fluid lags behind because of inertia, pushing on and distorting the cupula.

Bending of the stereocilia **towards** the kinocilium causes **increased** excitation of the hair cell.

Bending occuring **away** from the kinocilium causes **less** excitation of the hair cell.



Response mechanism of otolithic organs to head tilts

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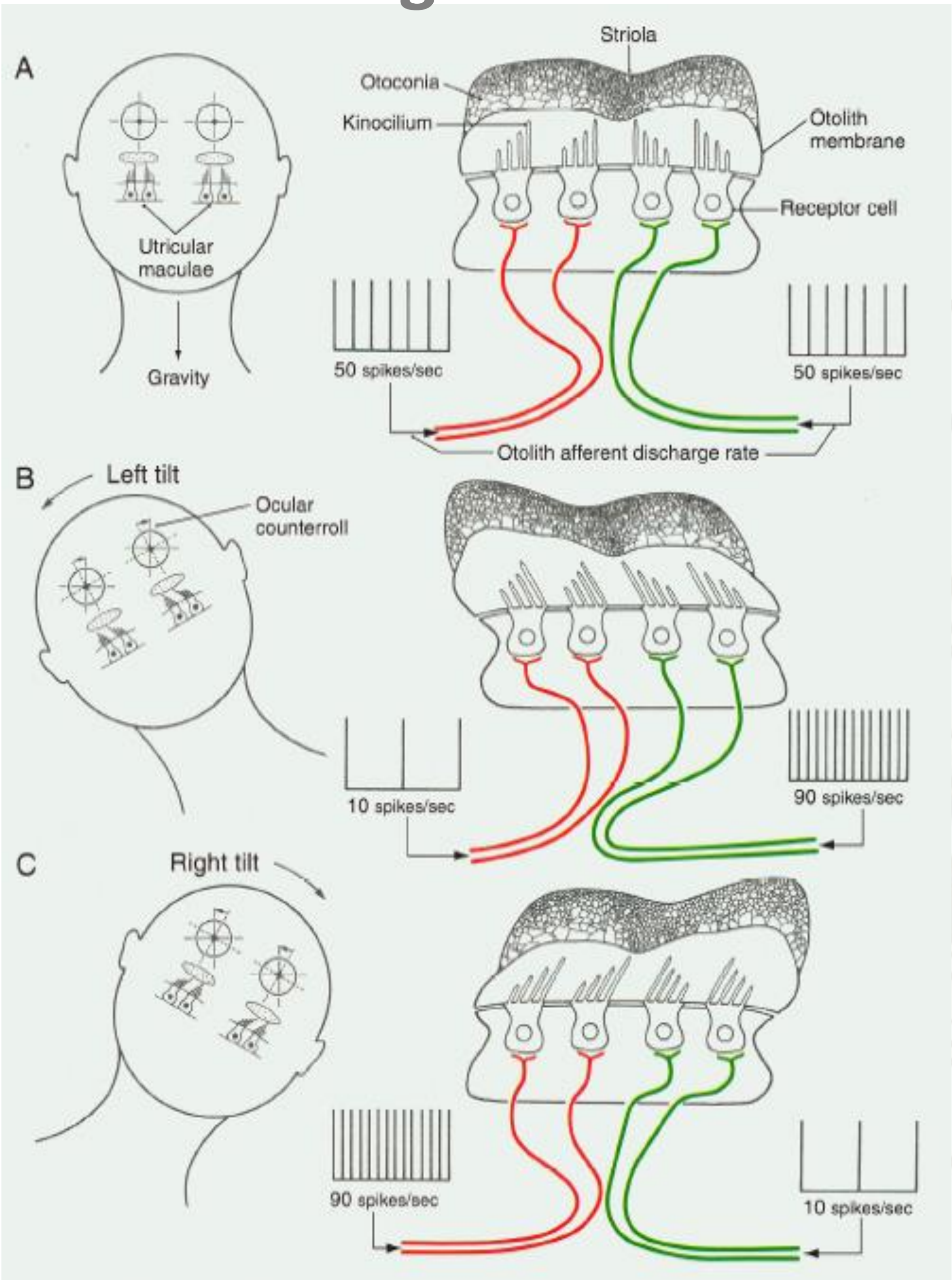

Eye movements

1. Saccades
2. Vergence
3. Smooth pursuit
4. Vestibulo-Ocular Reflex (VOR)
5. Opto-Kinetic Response (OKR)

Eye movements

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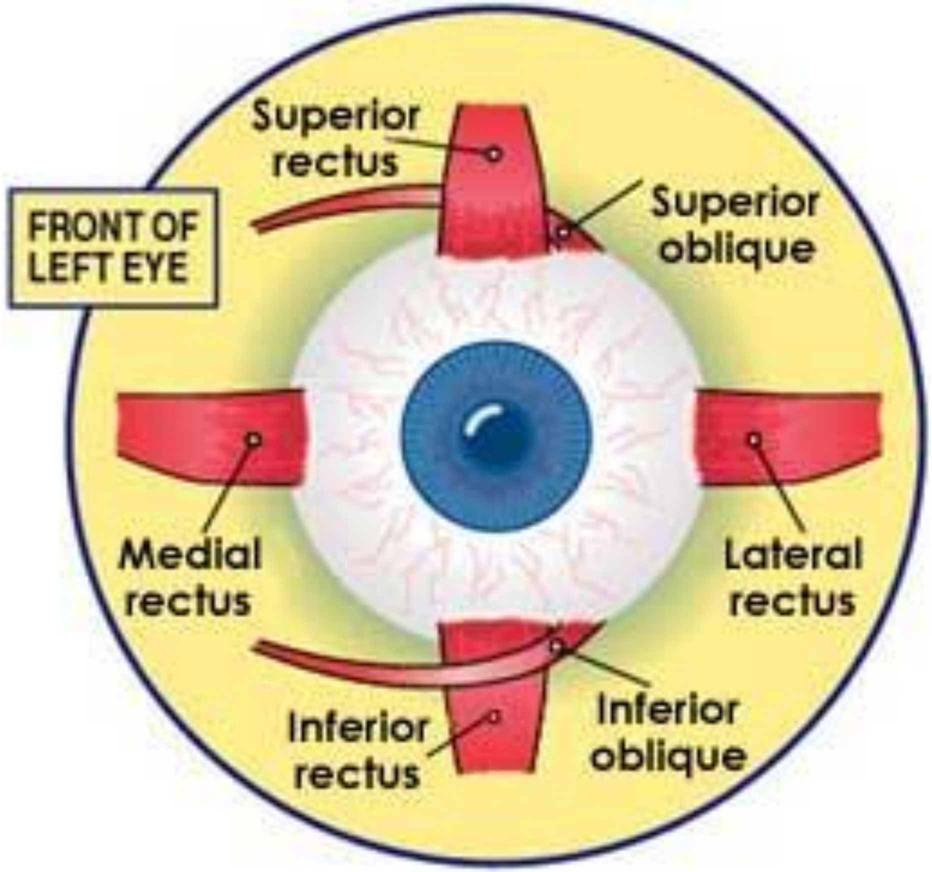


Eye Muscles

Saccades

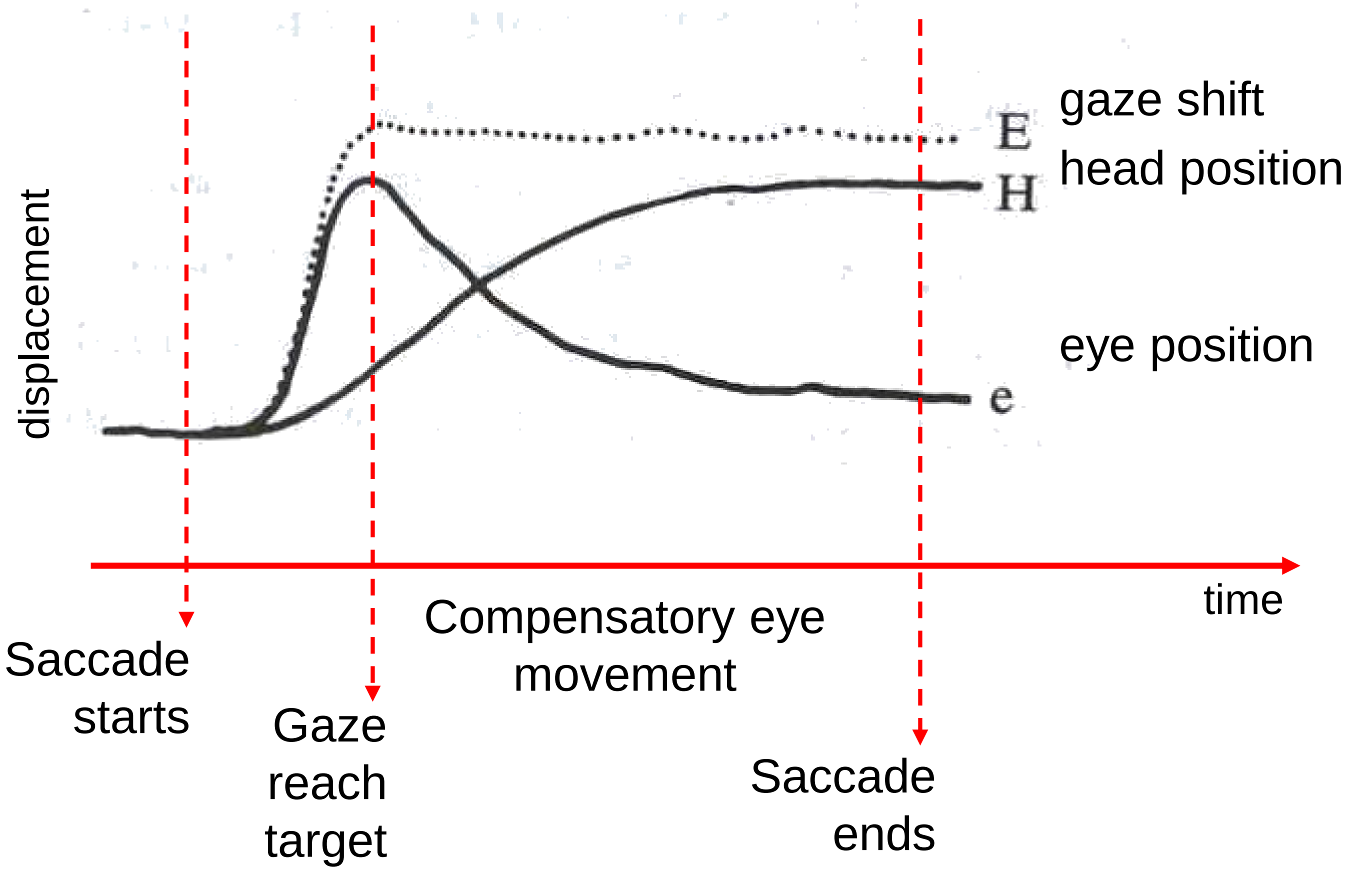
If an image appears to the side,
eye movements called saccades rotate both eyes
so that the image now falls on the fovea.
Saccades are what you are using now
to point the fovea at each word in this sentence.

Because vision is poor during saccades,
saccades are very fast, up to 500 degrees per second.

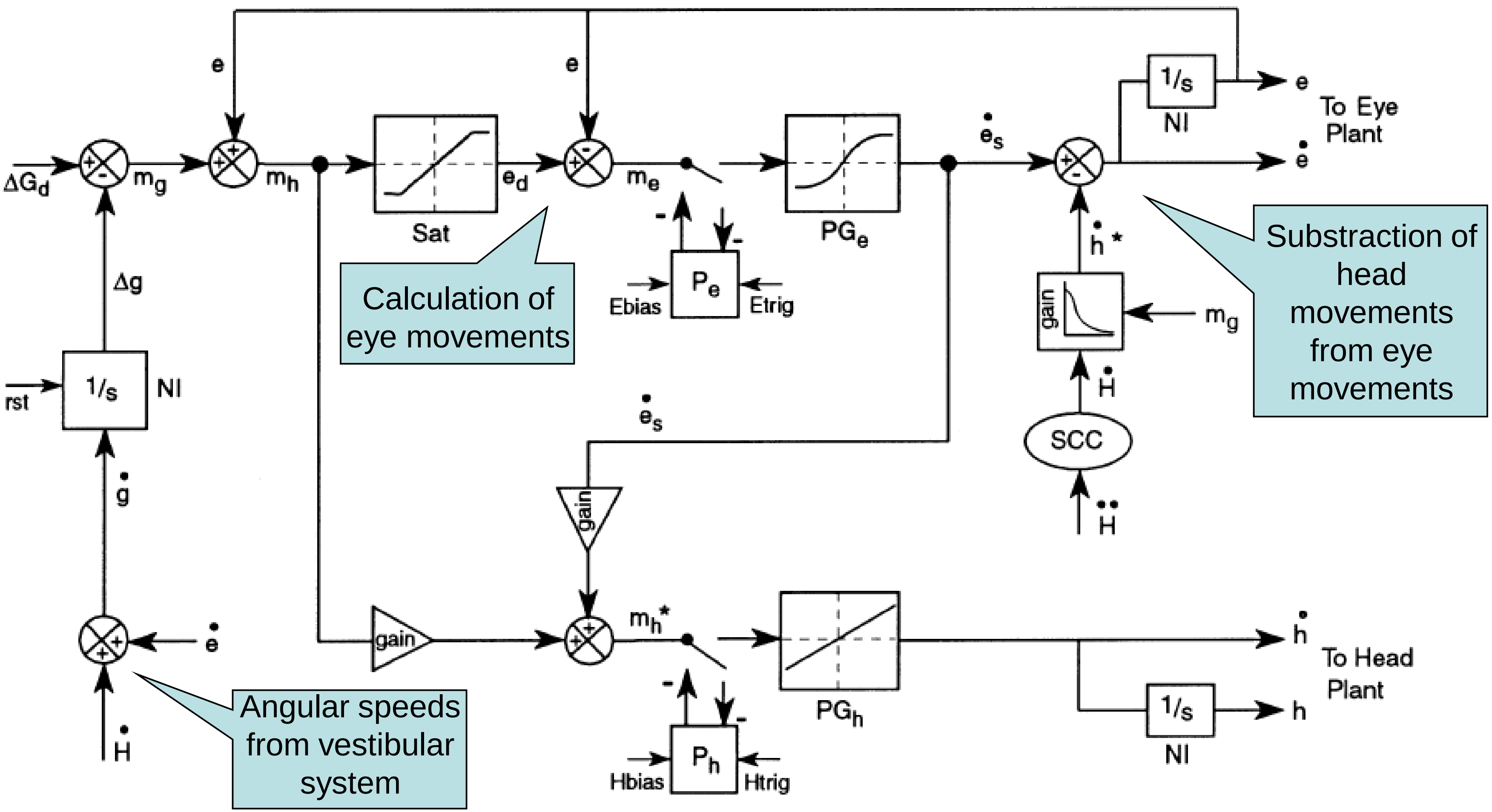
Saccades

- Quick “jumps” that connect fixations
- Duration is typically between 30 and 120 ms
- Very fast (up to 700 degrees/second)
- Saccades are ballistic, i.e., the target of a saccade cannot be changed during the movement
- Vision is suppressed during saccades to allow stable perception of surroundings
- Saccades are used to move the fovea to the next object/region of interest

Coordination of eye and head movements in fast gaze shifts



A model of fast gaze shift, coordinating eye and head movements



Goossens H.H. and Van Opstal A.J., "Human eye-head coordination in two dimensions under different sensorimotor conditions", *Exp. Brain Res.* 1997, Vol. 114, pp. 542–560

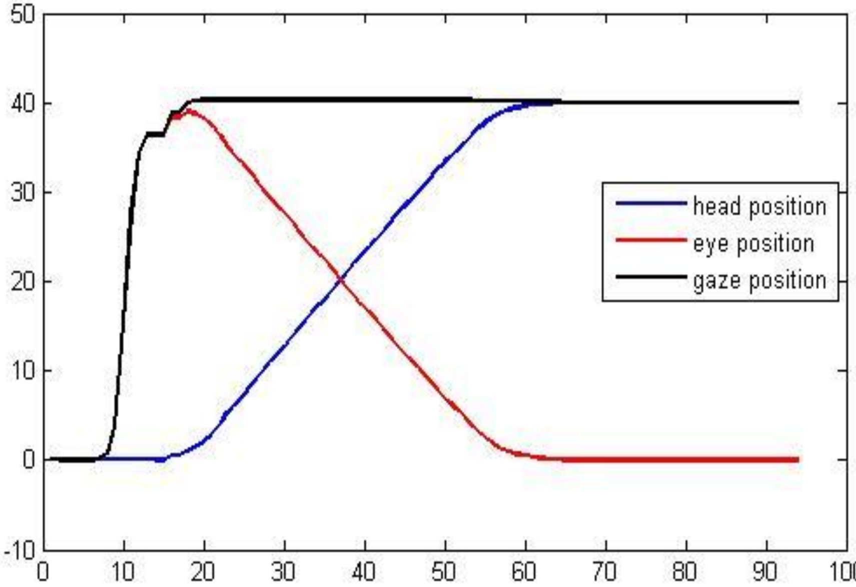
Model of fast gaze shift

The saccade starts and the eye joint moves at his **highest velocity** thus realizing the initial phase of the saccade.

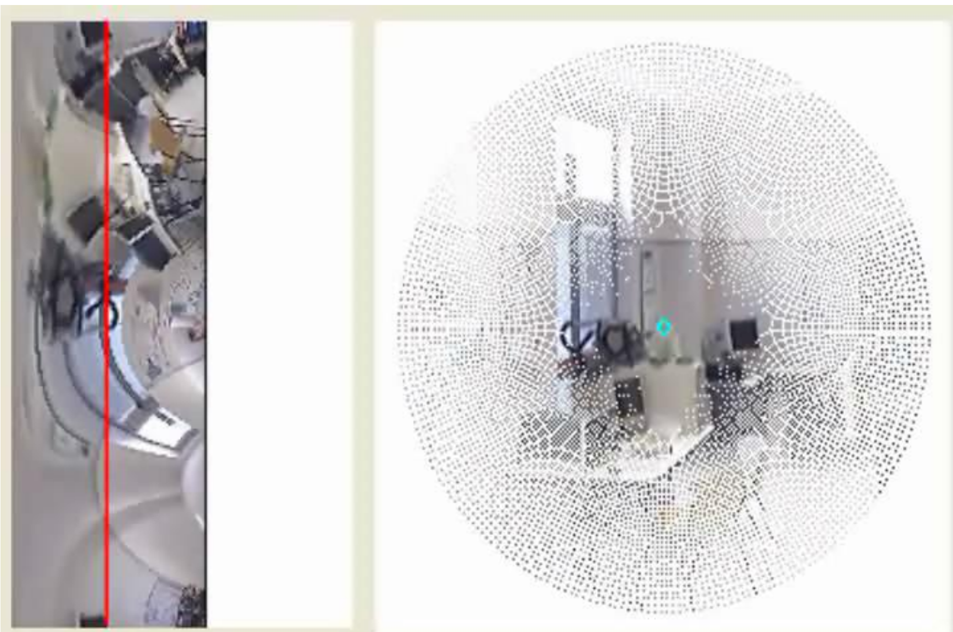
At the same time the head does not move, but it will start moving only after the head delay time is passed.

Given that the speed of the eye is much higher than the speed of the head, the *eye reaches the target position well before the head.*

Time course of head, eye and gaze position of a saccade of 40 degrees



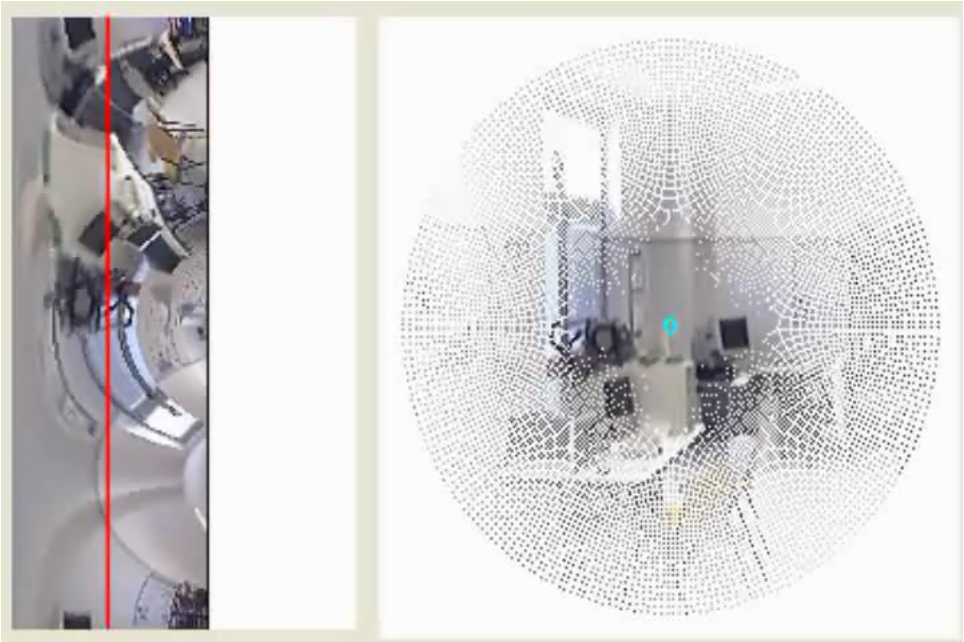
Robotic implementation: horizontal saccades



Left eye only **Camera View**

E.S. Maini, L. Manfredi, C. Laschi, P. Dario, "A bio-inspired velocity control of fast gaze shifts on a robotic anthropomorphic head", *Autonomous Robots*, Vol.5, 2008, pp.37-58

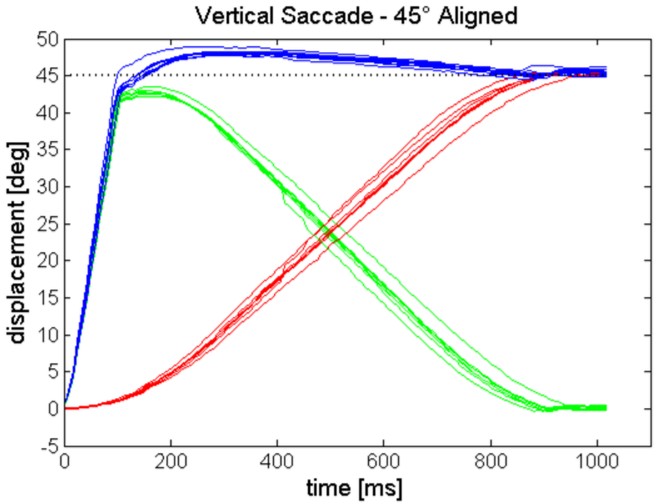
Robotic implementation: vertical saccades

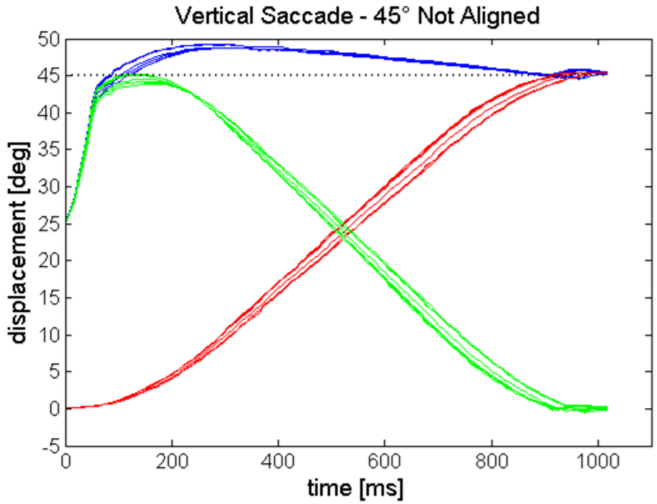


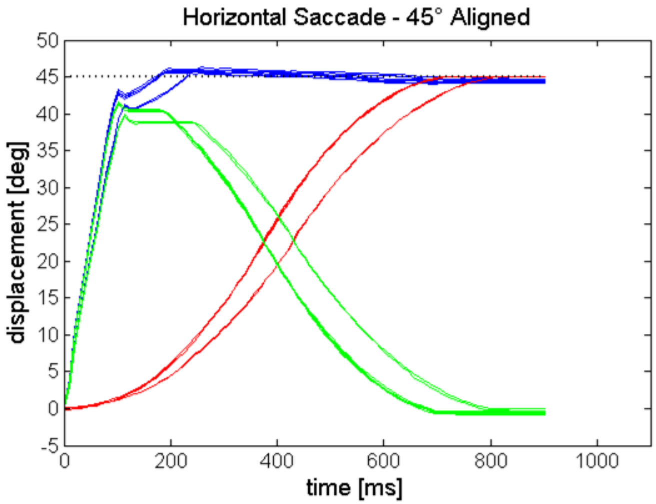
Camera View

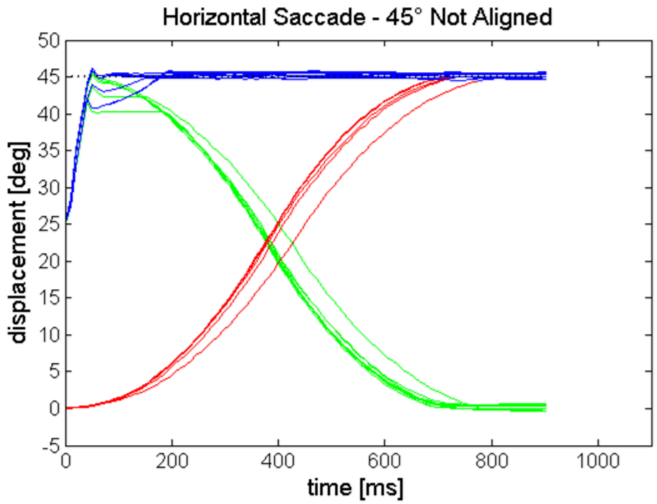
E.S. Maini, L. Manfredi, C. Laschi, P. Dario, “A bio-inspired velocity control of fast gaze shifts on a robotic anthropomorphic head”, *Autonomous Robots*, Vol.5, 2008, pp.37-58

Experimental Results









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Vergence

If you look (i.e. direct the foveas) from a far object to a near one, vergence eye movements are generated, convergence when looked from far to near and divergence when looking from near to far.

How do saccadic and vergence eye movements differ?

Notice that vergence movements are much slower than saccades. Also during saccades both eyes rotate in the same direction. During vergence, they rotate in opposite dirctions.

Vergence

- Slow, smooth movements changing the vergence angle (the angle between the two viewing axes)
- Used for changing gaze from a near to a far object or vice versa
- Can take up to 1 second
- Execution is often interrupted if no thorough inspection of the object is required

Smooth pursuit

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When an object moves,
the image is kept still on the retina by means of a pursuit eye movement
(e.g. tracking a moving ball or your finger).

- Smooth movement of the eyes for visually tracking a moving object
- Cannot be performed in static scenes (fixation/saccade behavior instead)

→ *prediction*

VOR (Vestibulo-Ocular Reflex)

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If we move our head, an eye movement very similar to pursuit is elicited whose function is also to keep the image still on the retina. However, in spite of the fact that the movement looks similar, it is generated by a different neural circuit, the vestibular ocular reflex (VOR).

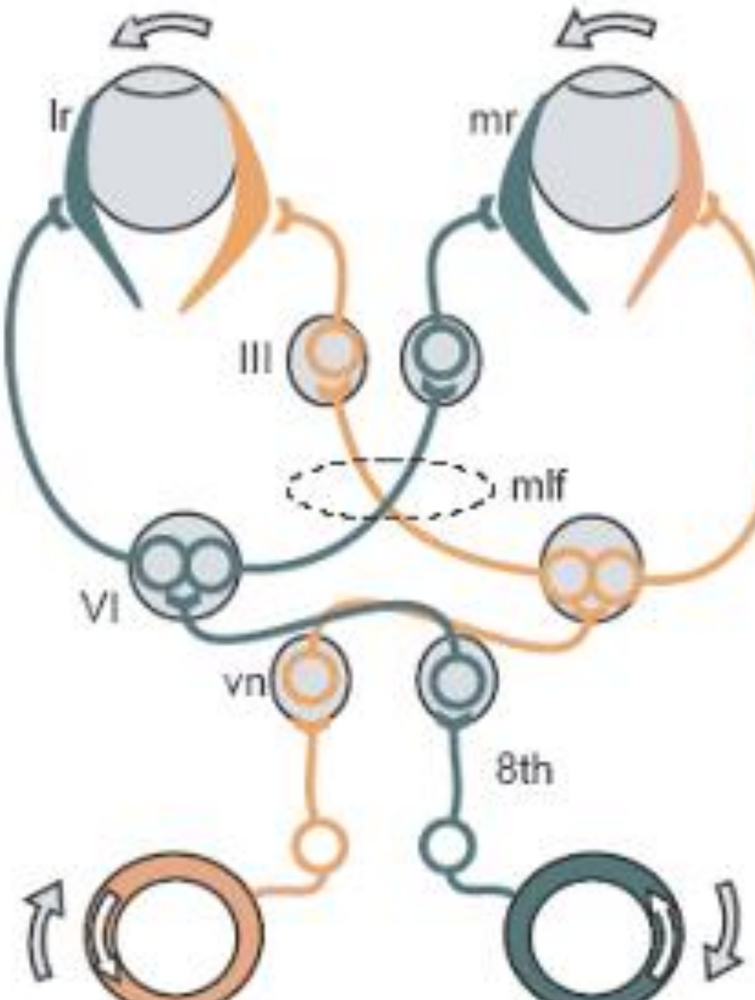
The VOR responds much faster than the pursuit system. Notice that you can read a page of text while you shake your head quickly from side to side. To activate the pursuit system, take a page of text and try reading it while you shake the page quickly from side to side.

Also unlike the pursuit system, the VOR does not need a visual stimulus. It works in the dark. Rotate your head with your eyes closed. Feel your eyes move with your finger tips.

VOR (Vestibulo-Ocular Reflex)

- Reflex eye movement that stabilizes images on the retina during head movement by producing an eye movement in the direction opposite to head movement, thus preserving the image on the center of the visual field.
- Since slight head movements are present all the time, the VOR is very important for stabilizing vision: patients whose VOR is impaired cannot read, because they cannot stabilize the eyes during small head tremors
- The VOR reflex does not depend on visual input and works even in total darkness or when the eyes are closed
- Latency of 14 ms (time between the head and the eye movement)

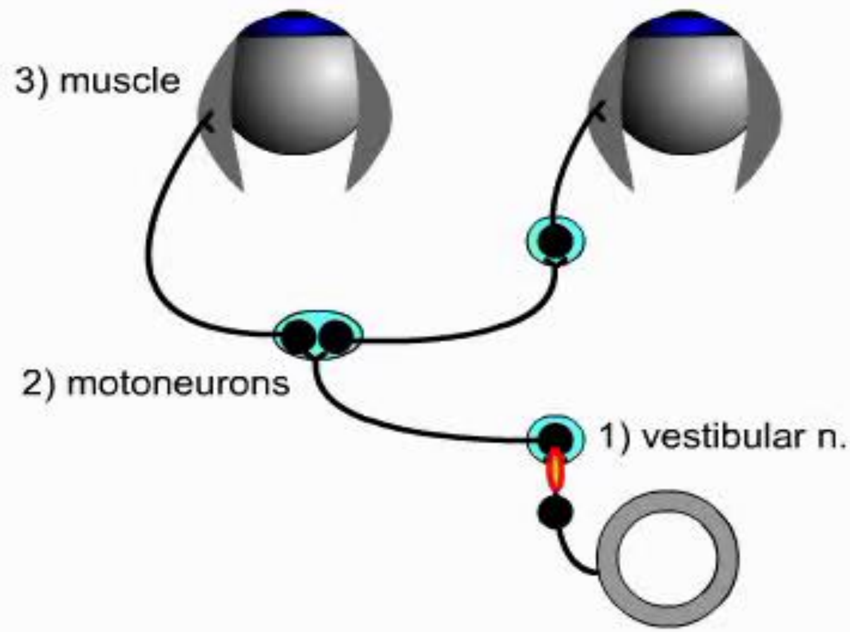
The Vestibulo-Ocular Reflex (VOR)



Vestibulo-ocular Reflex (VOR)

Explain the neural mechanism for a horizontal VOR.

The direct path is a short reflex with 3 synapses.



Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End

Vestibulo-ocular Reflex (VOR)

Explain the neural mechanism for a horizontal VOR.

When the **head rotates rightward** the following occurs.

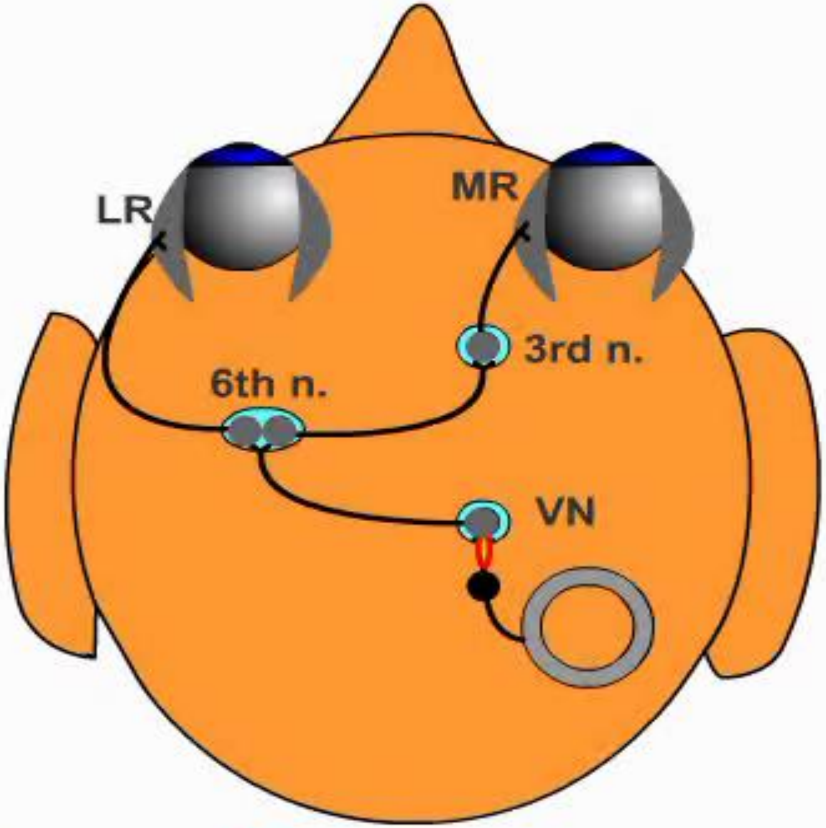
The right horizontal canal hair cells depolarize.

The right vestibular nucleus (VN) firing rate increases.

The motoneurons (in the right 3rd and left 6th nuclei) fire at a higher frequency.

The left lateral rectus (LR) extraocular muscle and the right medial rectus (MR) contract.

Both **eyes rotate leftward**.



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Vestibulo-ocular Reflex (VOR)

Explain the neural mechanism for a horizontal VOR.

The VOR is a push-pull reflex.
Neurons on other side do the opposite.

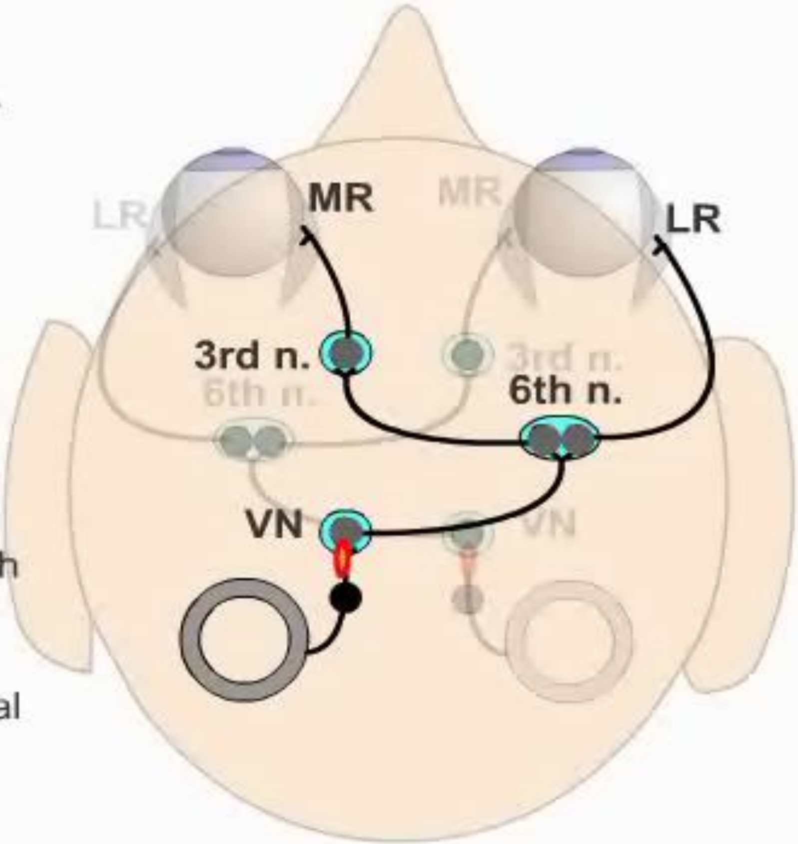
When the **head rotates rightward** the following occurs.
The left horizontal canal hair cells hyperpolarize.

The left vestibular nucleus firing rate decreases.

Motor neurons in the left 3rd and right 6th nuclei fire at a lower frequency.

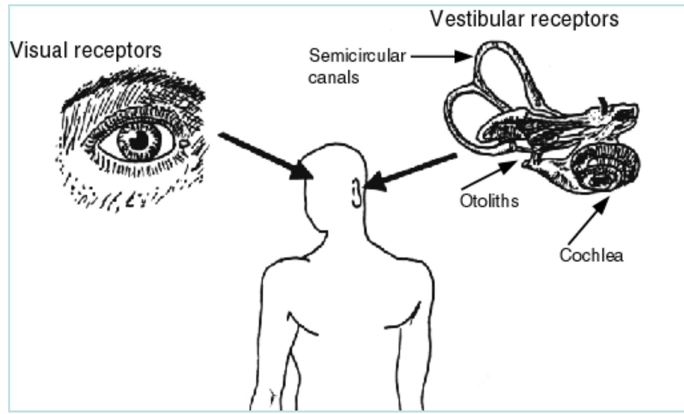
The left medial rectus and the right lateral rectus relax.

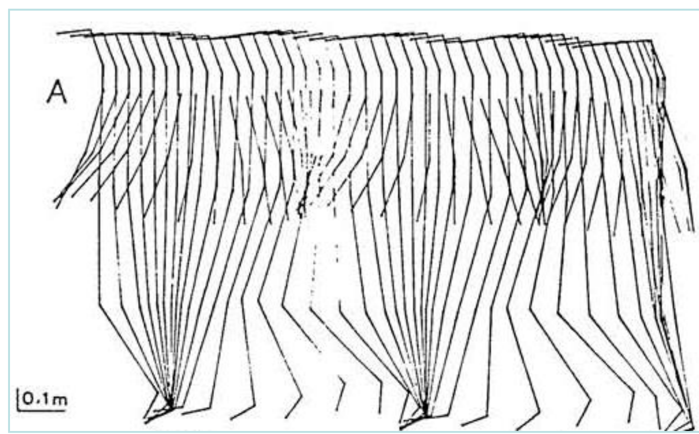
This helps the **eyes rotate leftward.**



Head stabilization in biped locomotion

The brain uses the information coming from vestibular system to generate a ***unified inertial reference frame***, centred in the head, that allows whole-body coordinated movements and head-oriented locomotion.





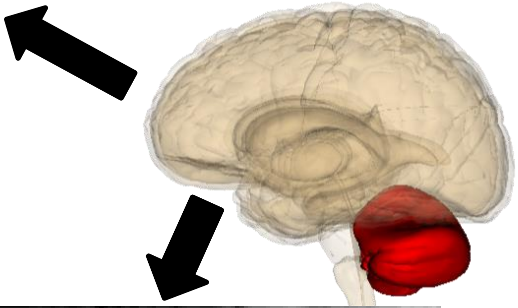
✓Vertical and lateral **translations** are **not** stabilized
✓ Head **orientation** is **stabilized**
✓ Head **yaw** counteracts body (trunk) yaw
✓The same for the **pitch**

Berthoz A., 2002, *The sense of movement*. Harvard University Press
Pozzo T. et al. (1990)

Gaze stabilization

- generation of a unified inertial reference frame
- head is kept stable by the **Vestibulo-Collic Reflex**.

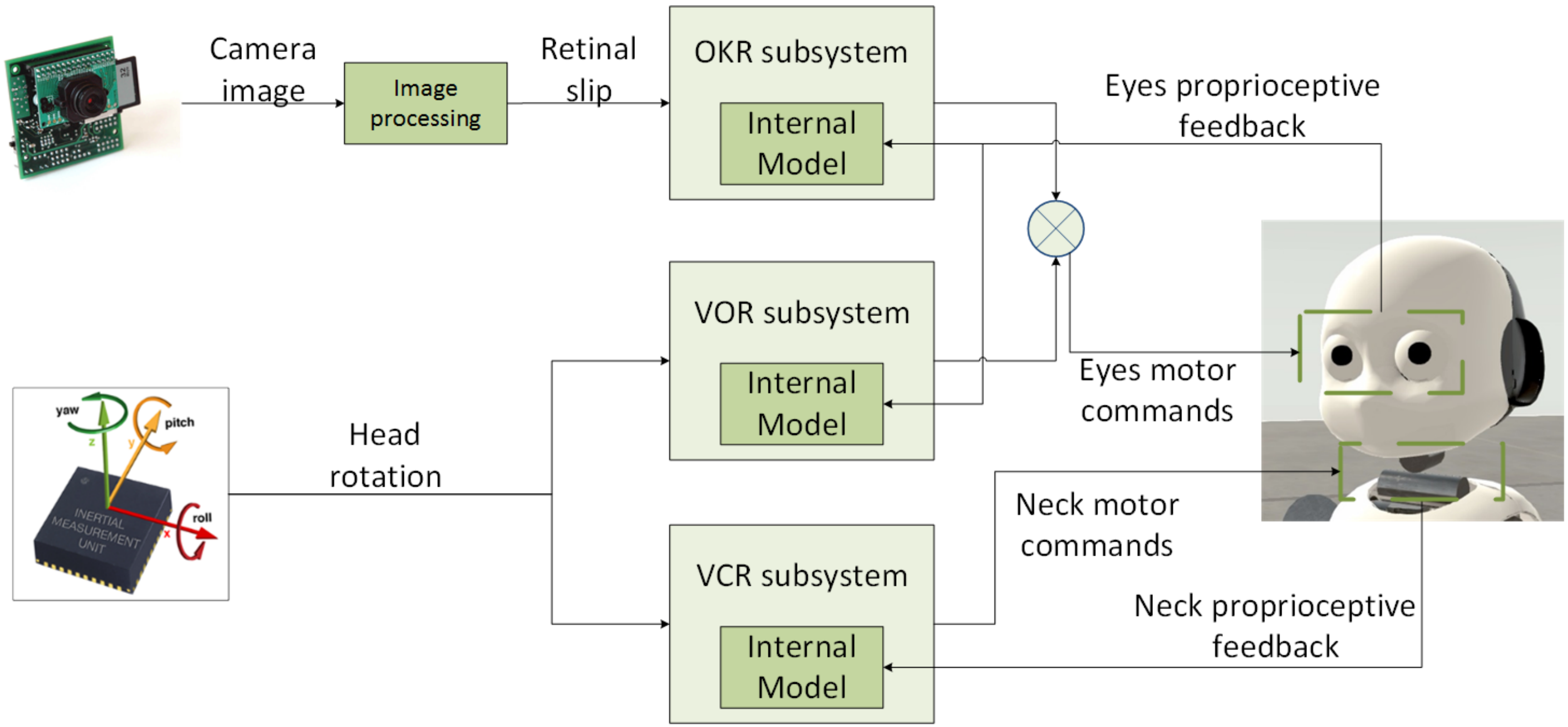
- the **Vestibulo-Ocular Reflex** stabilizes the image on the retina by moving the eyes in the opposite direction of the head



- the **Opto-Kinetic Reflex** compensates for drifts in the retinal images due to external motions.

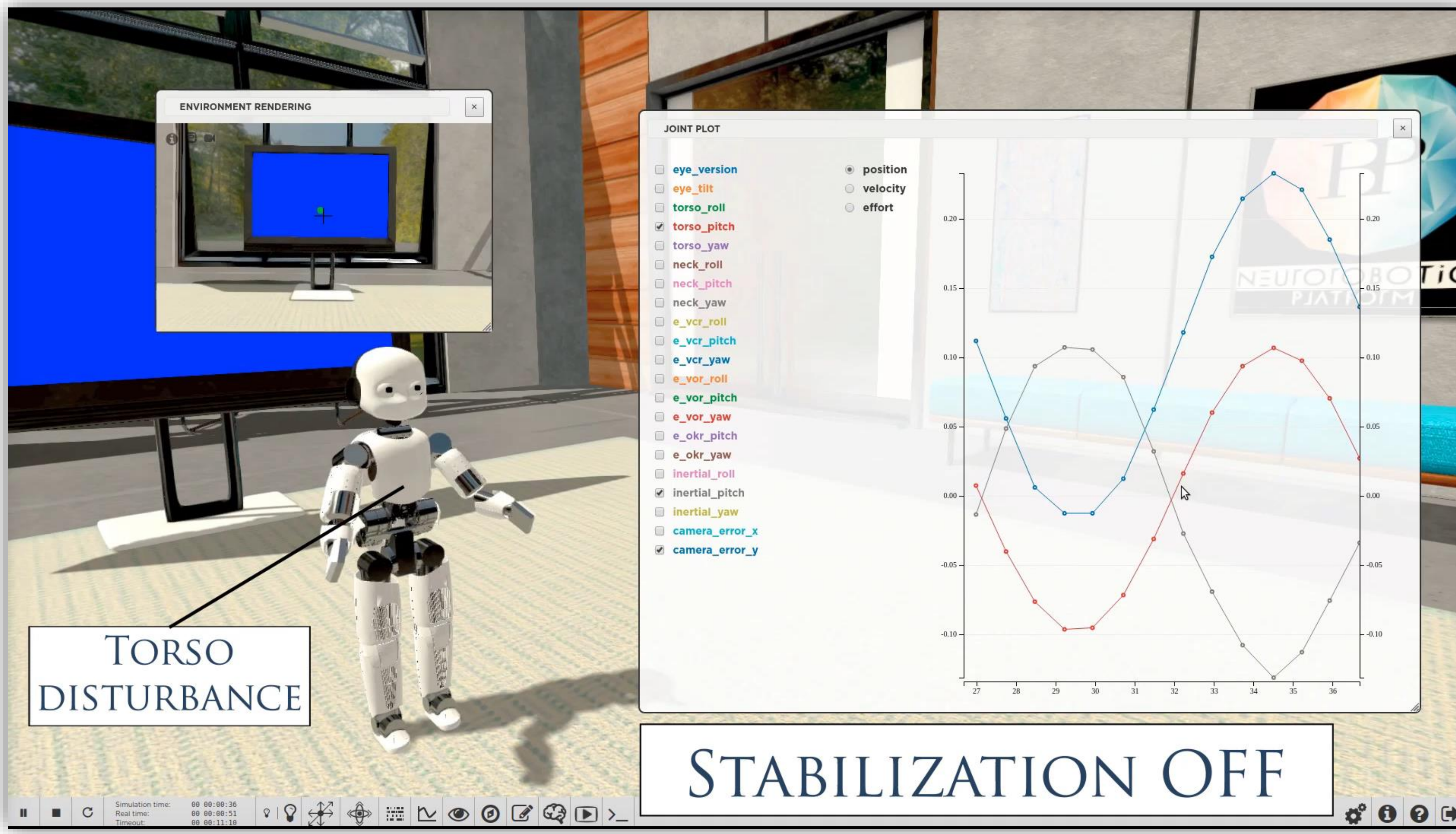
- the **cerebellum** provides **internal models** that generate corrective motor signals for the three reflexes.

Gaze stabilization



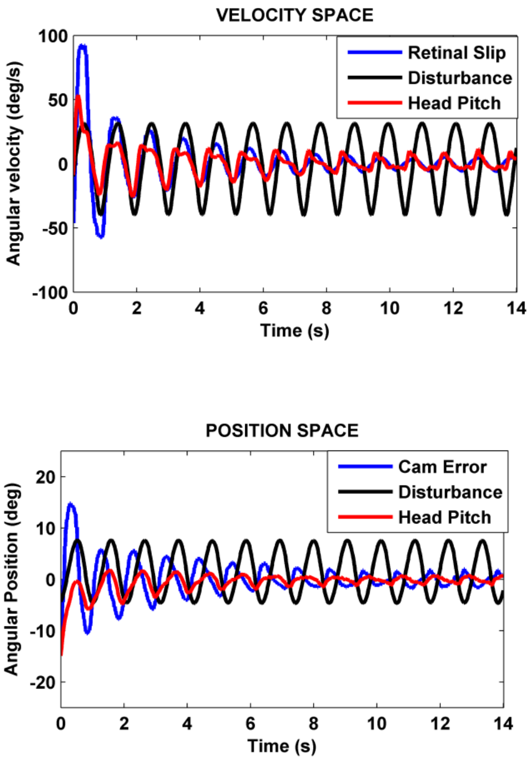
Vannucci, L., Falotico, E., Tolu, S., Cacucciolo, V., Dario, P., Lund, H. H., & Laschi, C. (2017). "A comprehensive gaze stabilization controller based on cerebellar internal models", *Bioinspiration & Biomimetics*, 12(6).

Gaze stabilization



Vannucci, L., Falotico, E., Tolu, S., Cacucciolo, V., Dario, P., Lund, H. H., & Laschi, C. (2017). "A comprehensive gaze stabilization controller based on cerebellar internal models", *Bioinspiration & Biomimetics*, 12(6).

Gaze stabilization



Vannucci, L., Falotico, E., Tolu, S., Cacucciolo, V., Dario, P., Lund, H. H., & Laschi, C. (2017). "A comprehensive gaze stabilization controller based on cerebellar internal models", *Bioinspiration & Biomimetics*, 12(6).

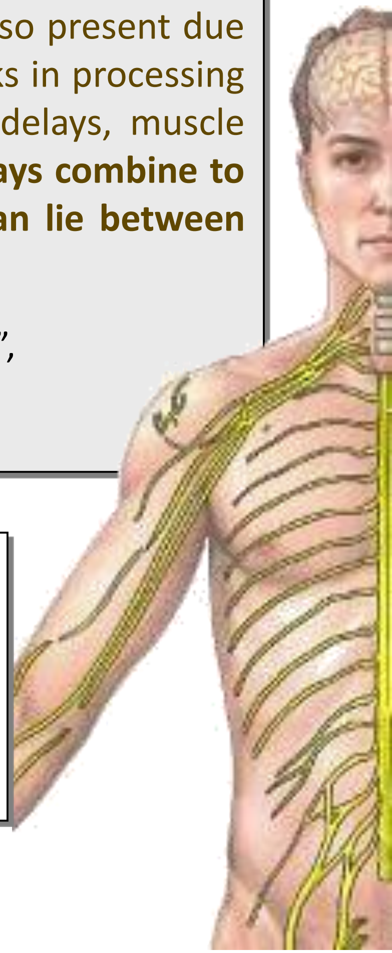
Outline of the lesson

- Scientific motivations to bioinspired robotics
- Simplexity
- Simplifying principles in human vision
- The *sense of movement* and the vestibular system: simplifying principles in eye movements
- **Predictive architectures**
- Embodied Intelligence
- Simplifying principles in soft robots

Delays in the human nervous system

"In motor control **delays** arise in **sensory transduction**, **central processing**, and in the **motor output**. Sensor transduction latencies are most noticeable in the visual system where the retina introduces a delay of 30-60 ms, but sensory conduction delays can also be appreciable. Central delays are also present due to such ill-defined events such as neural computation, decision making and the bottlenecks in processing command. Delays in the motor output result from motorneuronal axonal conduction delays, muscle exictation-contraction delays, and phase lags due to the intertia of the system. **These delays combine to give an unavoidable feedback delay within the negative feedback control loop, and can lie between about 30 ms for a spinal reflex up to 200-300 ms for a visually guided response.**"

R.C. Miall, D.J. Weir, D.M. Wolpert, J.F. Stein, "Is the cerebellum a Smith predictor?", *Journal of Motor Behavior*, vol. 25, no. 3, pp. 203-216, 1993



"Fast and coordinated arm movements **cannot be executed under pure feedback control** because biological feedback loops are both too slow and have small gains"

M. Kawato, Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9, 718-727(1999). Elsevier Science Ltd.

A. Berthoz, *Le sens du mouvement*. Odile Jacob, Paris, 1997

R.S. Johansson, "Sensory input and control of grip", in M. Glickstein (Ed.), *Sensory Guidance of Movements*. John Wiley, Chichester, UK, pp. 45-59,1998

From hierarchical to reactive architectures in robotics

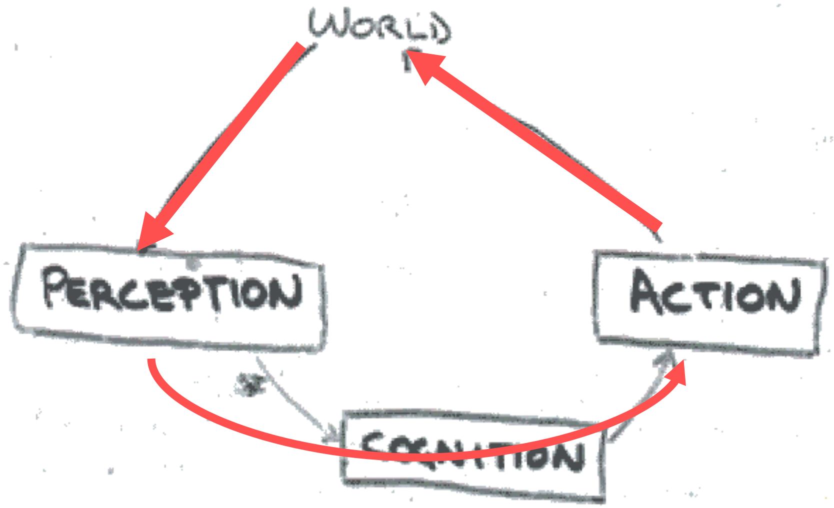


Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

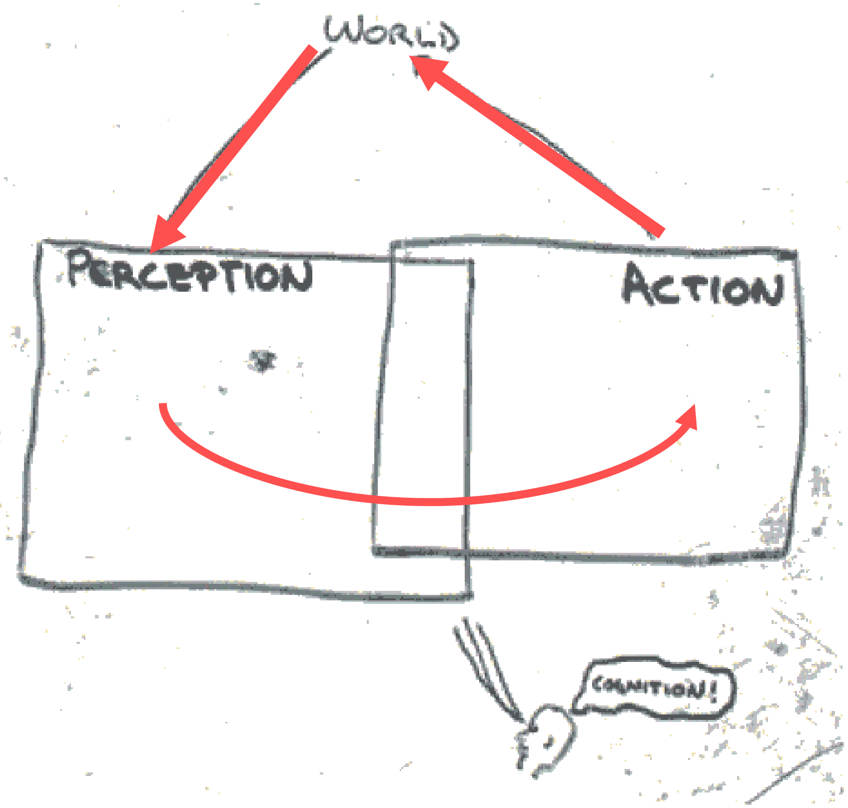


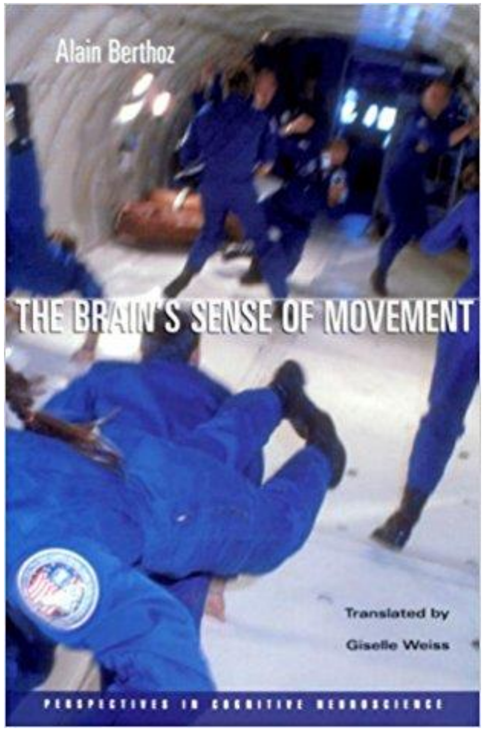
Figure 2: The new model, where the perceptual and action subsystems are all there really is. Cognition is only in the eye of an observer.

R. Brooks, *Cambrian Intelligence"*
MIT Press, 2000

Prediction and anticipation strategies in the human brain

In humans, perception is not just the interpretation of sensory signals, but a prediction of consequences of actions

“Perception can be defined as a ***simulated action***: perceptual activity is not confined to the interpretation of sensory information but it **anticipates** the consequences of action, so it is an internal simulation of action.
Each time it is engaged in an **action**, the brain constructs hypotheses about the state of a variegated group of **sensory** parameters throughout the movement.”



Berthoz A. (2002), *The brain’s sense of movement*. Harvard University Press

Anticipation and Internal models

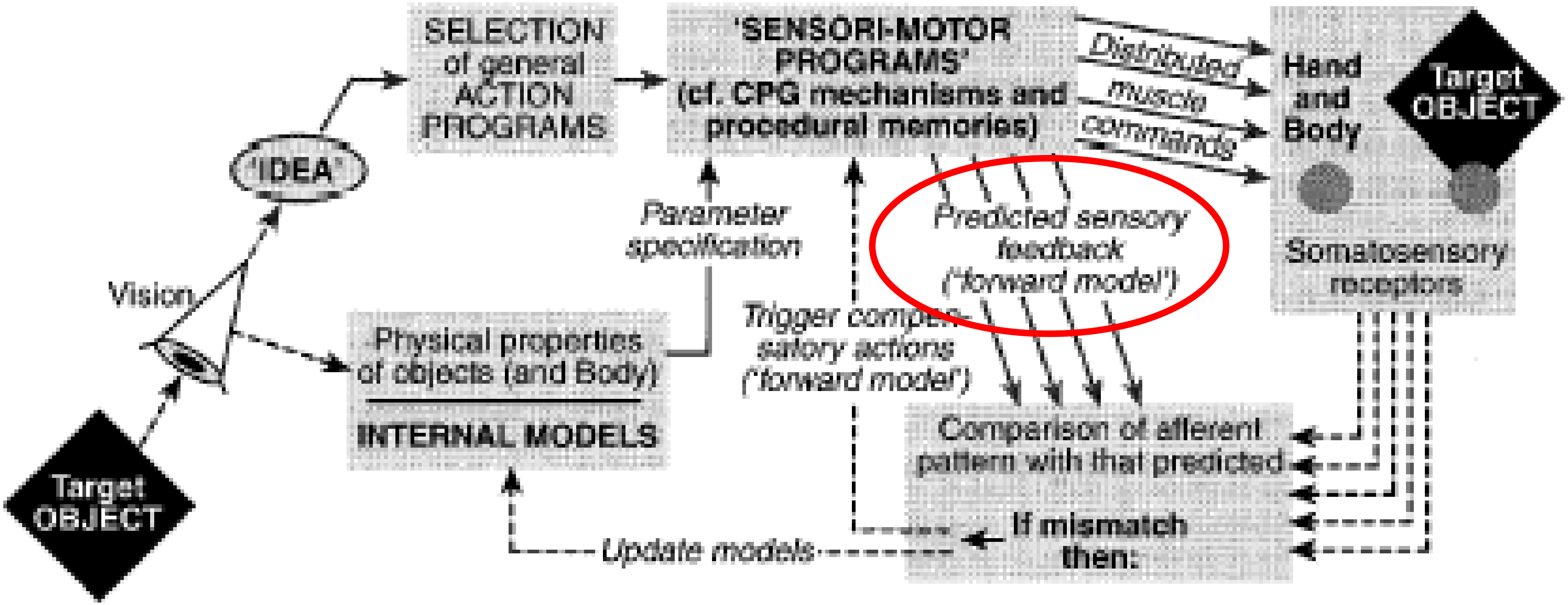
- Anticipatory mechanisms guide human behavior, i.e., predictions about future states, allowing to perform accurate movements

- The bases of human anticipation mechanisms are the ***internal models*** of the body and the world
- Internal models can be classified in two conceptually distinct groups:
  - Forward Models: causal representations of the motor apparatus
  - Inverse models: inversion of the causal relation, they give the causal event

R.C. Miall and D.M. Wolpert, Forward Models for Physiological Motor Control. *Neural Networks*, vol. 9, no. 8, pp. 1265-1279, 1996

Sensory prediction proposed by R. Johansson

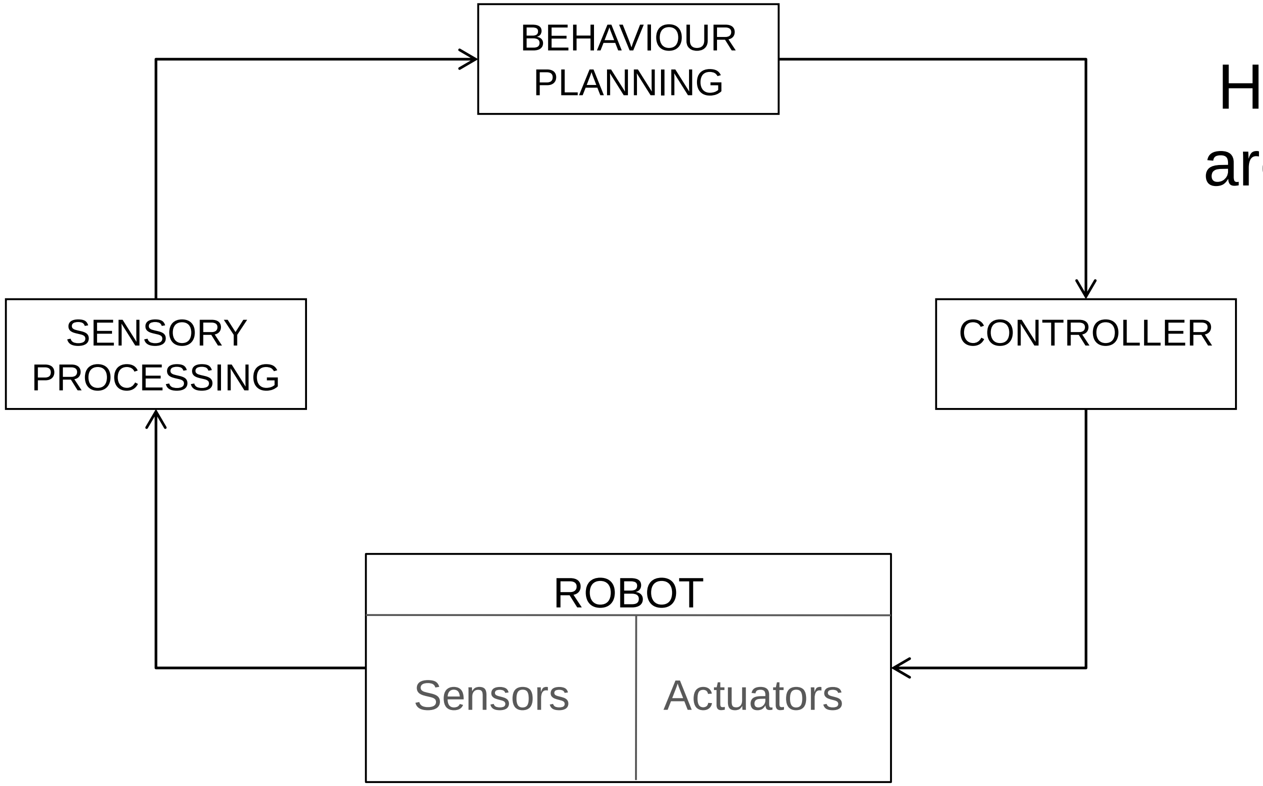
“Because of the long time delays with feedback control the swift coordination of fingertip forces during self-paced everyday manipulation of ordinary ‘passive’ objects must be explained by other mechanisms. **Indeed, the brain relies on feedforward control mechanisms and takes advantage of the stable and predictable physical properties of these objects by parametrically adapting force motor commands to the relevant physical properties of the target object**.”



Corrections are generated when expected sensory inputs do not match the actual ones

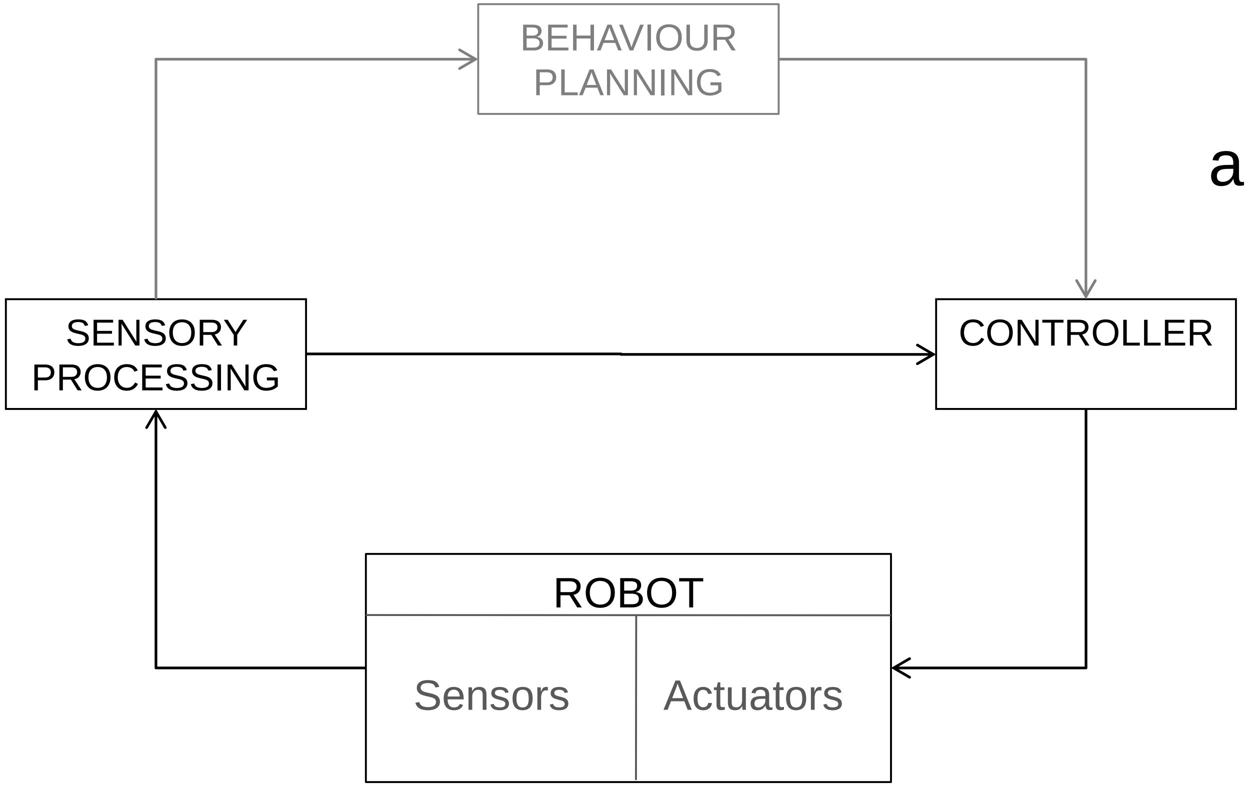
R.S. Johansson, “Sensory input and control of grip”. In *Sensory Guidance of Movements*, John Wiley, Chichester, UK, pp. 45-59, 1998

Basic scheme for robot behaviour control



Hierarchical architectures

Basic scheme for robot behaviour control

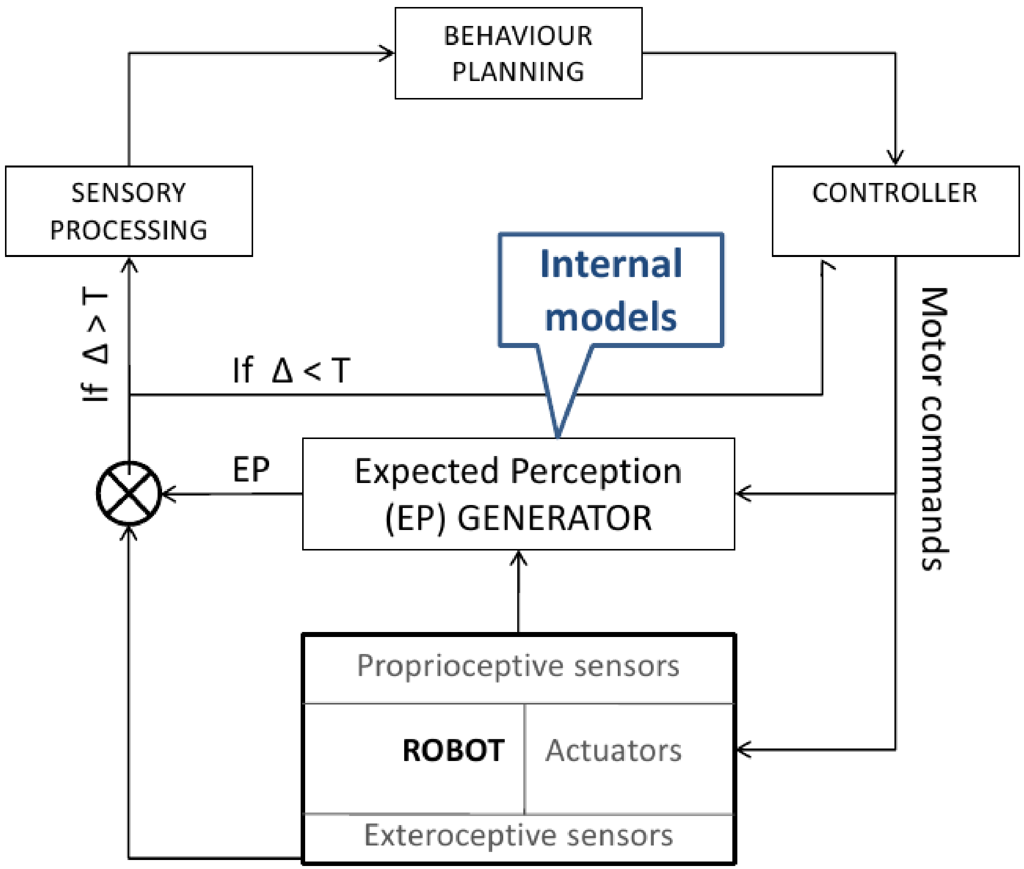


Reactive architectures

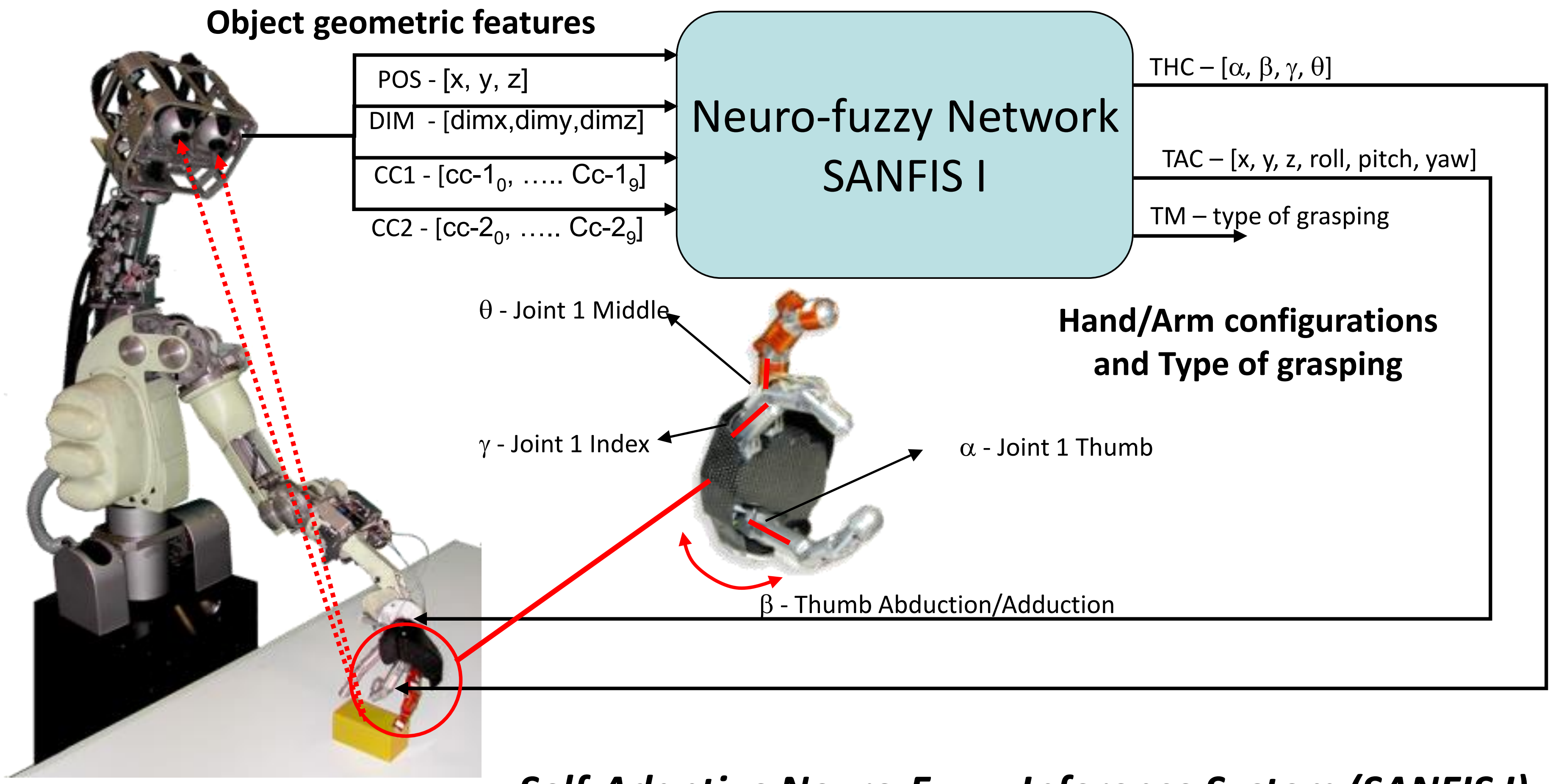
Expected Perception (EP) System

Expected Perception:

- Internal Model to predict the robot perceptions
- Comparison between actual and predicted perception
- ***Open loop*** controller if the prediction error is low
- ***Closed loop*** controller if the prediction error is high



Preshaping Module



Self-Adaptive Neuro-Fuzzy Inference System (SANFIS I)

- *Combine advantages NN and Fuzzy Logic*
- *Learning, adaptation, and connectionist structure*
- *Ability to exact explicit IF-THEN rules from training data*

EP Generator (preshaping) Module

Object geometric features

POS - [x, y, z]

DIM - [dimx,dimy,dimz]

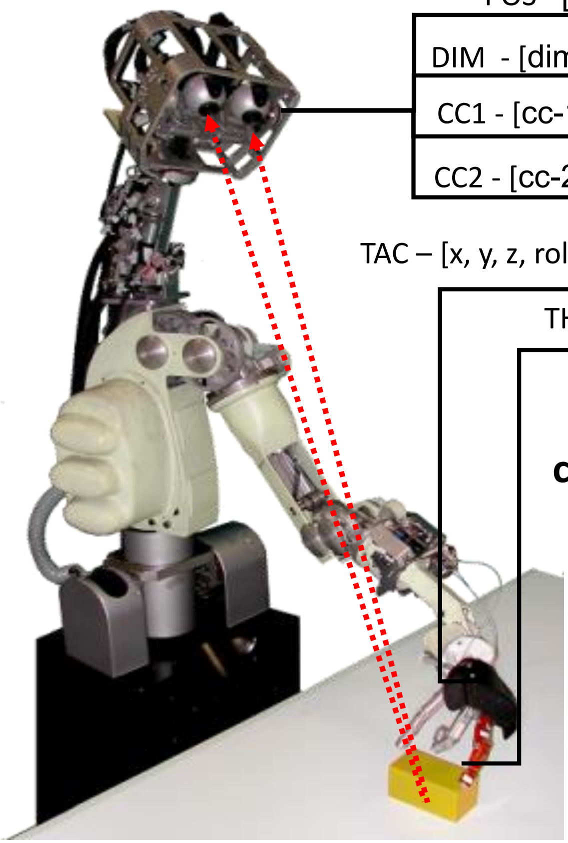
CC1 - [$cc\text{-}1_0$, ….. $Cc\text{-}1_9$]

CC2 - [$cc\text{-}2_0$, ….. $Cc\text{-}2_9$]

TAC – [x, y, z, roll, pitch, yaw]

THC – [α, β, γ, θ]

Hand/Arm configurations



Neuro-fuzzy Network SANFIS II

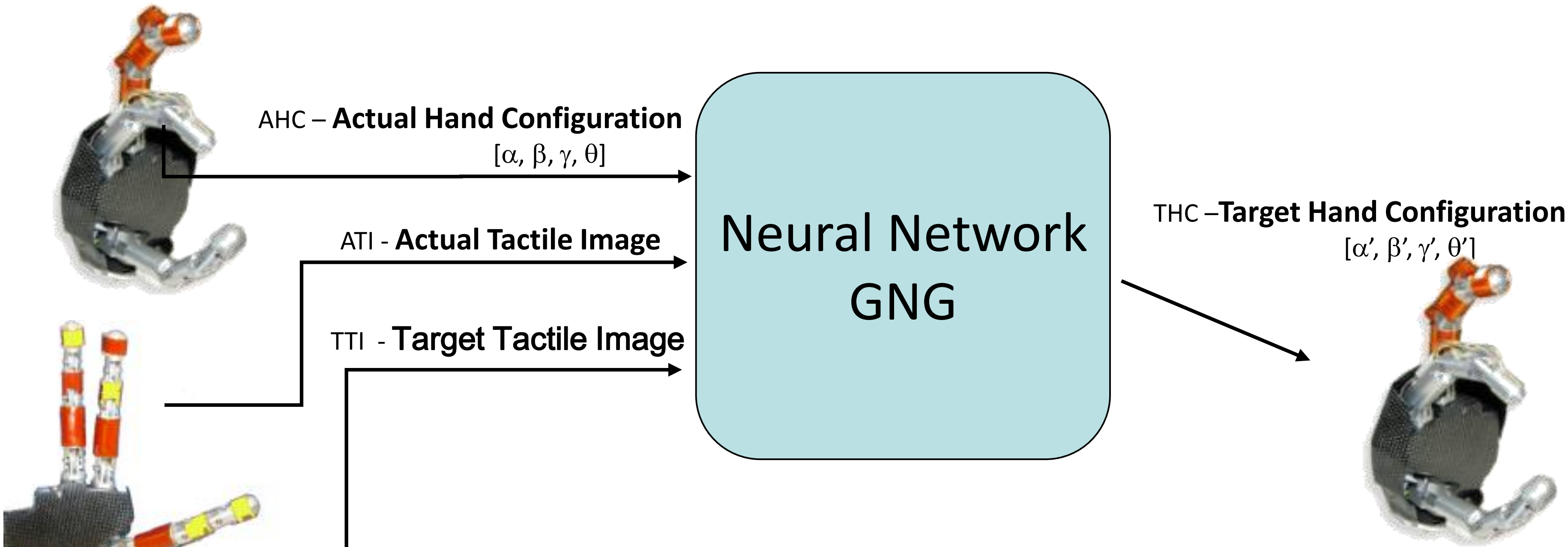
TTI - **Target Tactile Image**

[tt_1, tt_2, …, tt_m]
where:
m=9
tt_i = i-th value for the tactile sensor $\in$ {0,1}

SANFIS II

- *Combine advantages NN and Fuzzy Logic*
- *Learning, adaptation, and connectionist structure*
- *Ability to exact explicit IF-THEN rules from training data*
- *Output space not very complex*

EP-based Grasping Module



Growing Neural Gas + Grossberg's Outstars

- *Unsupervised learning paradigm*
- *Competitive learning methods (winner-takes-all)*
- *Generation of a topology-preserving mapping from the input space onto a topological structure of equal or lower dimension*
- *Network topology is unconstrained*
- *Uses growth mechanism (the network size does not need be predefined)*

Building the Preshaping Module and the EP Generator Module

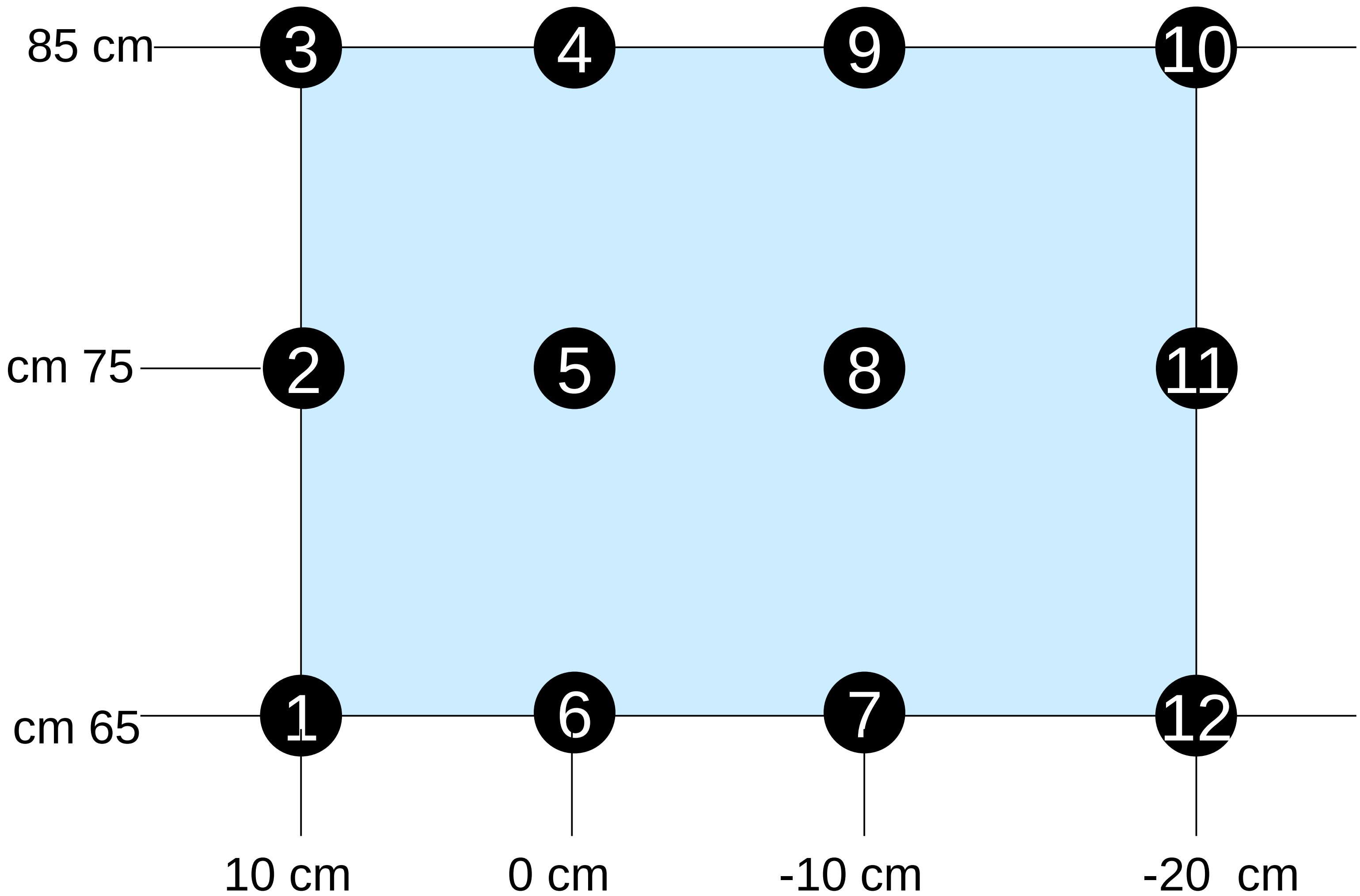
Three objects:

a ball: diameter of 80 mm 

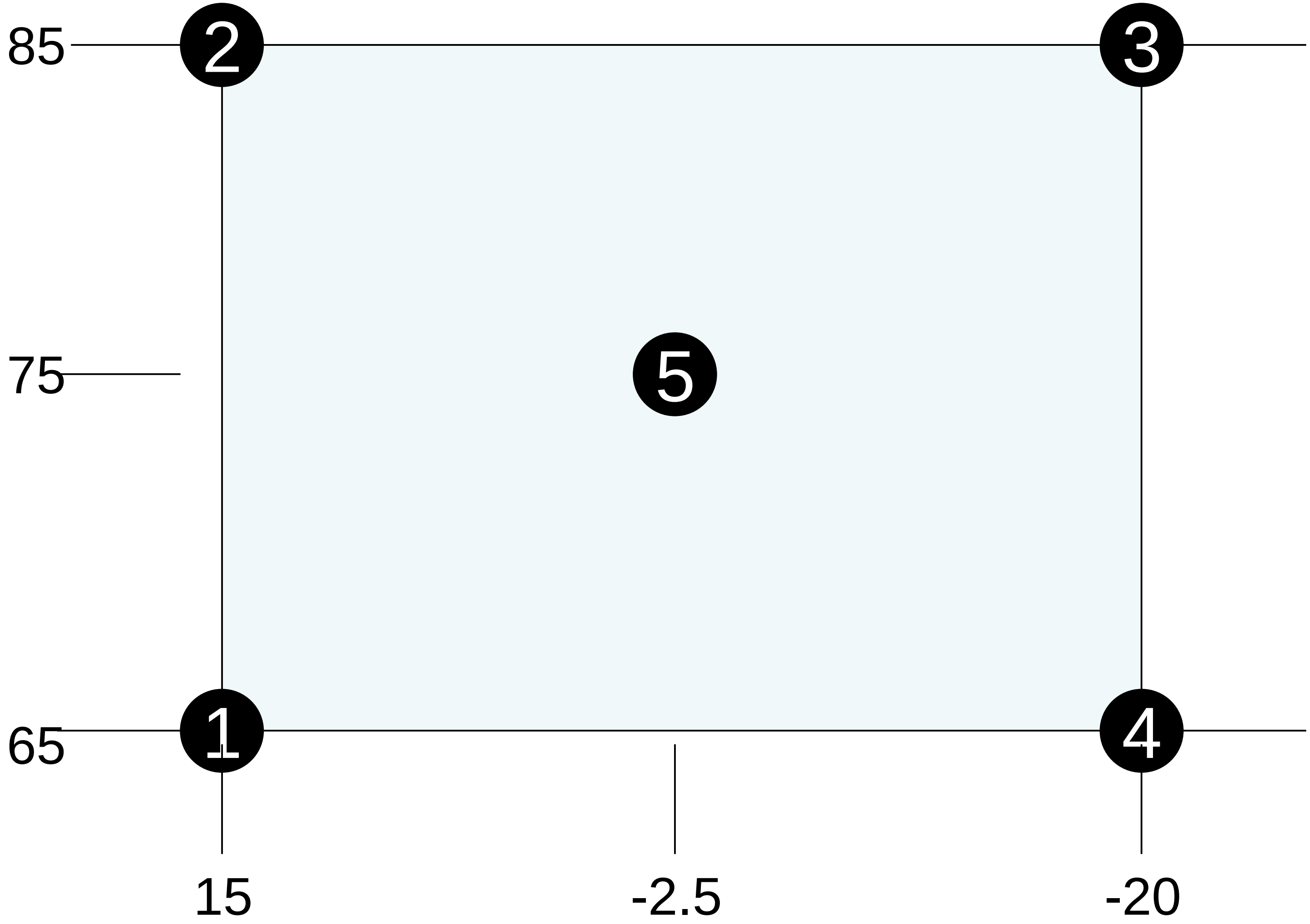
a bottle: diameter of 60 mm, height of 200 mm 

a cassette: dimension of 110X13X13 mm 

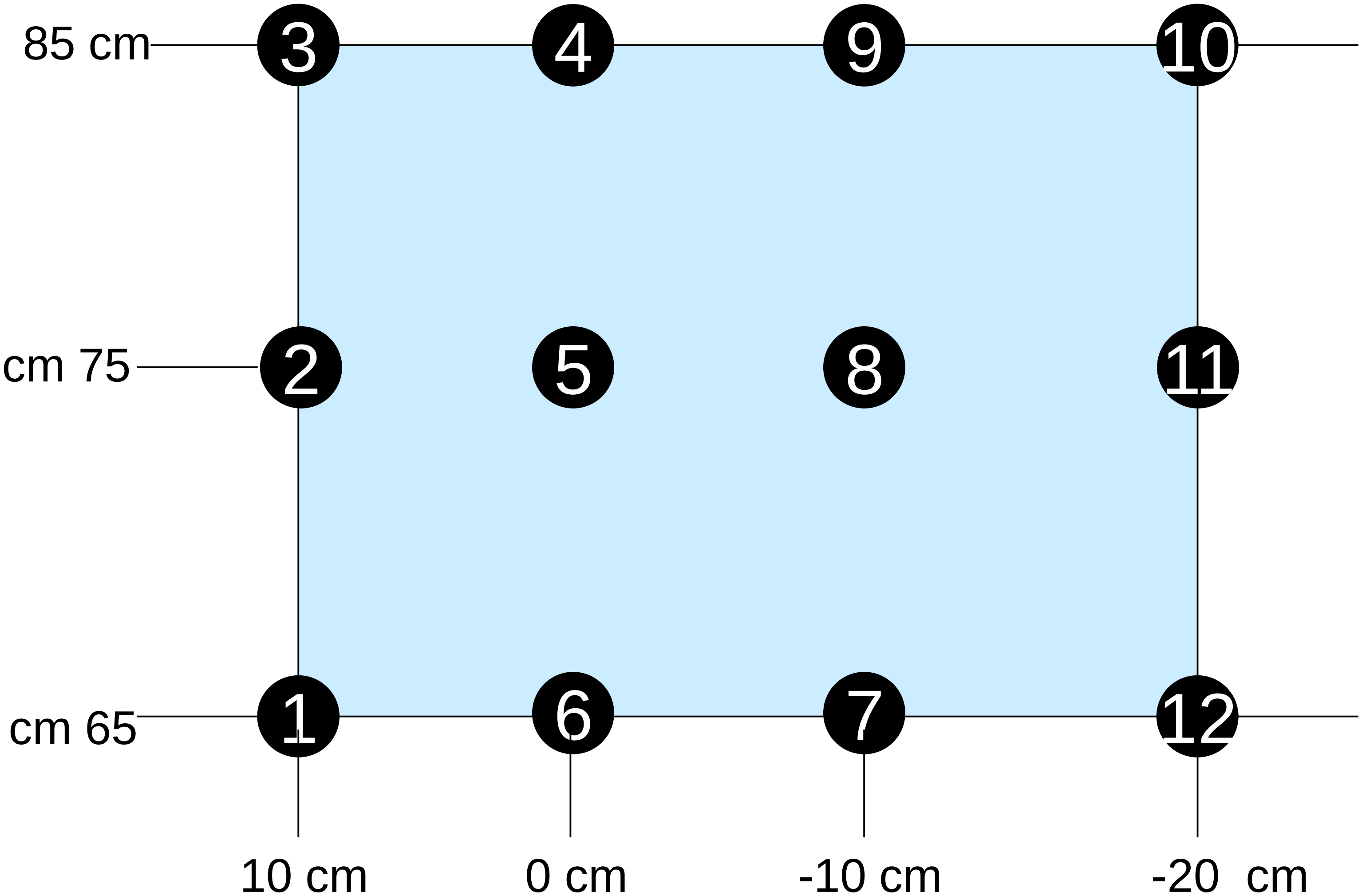
Ball



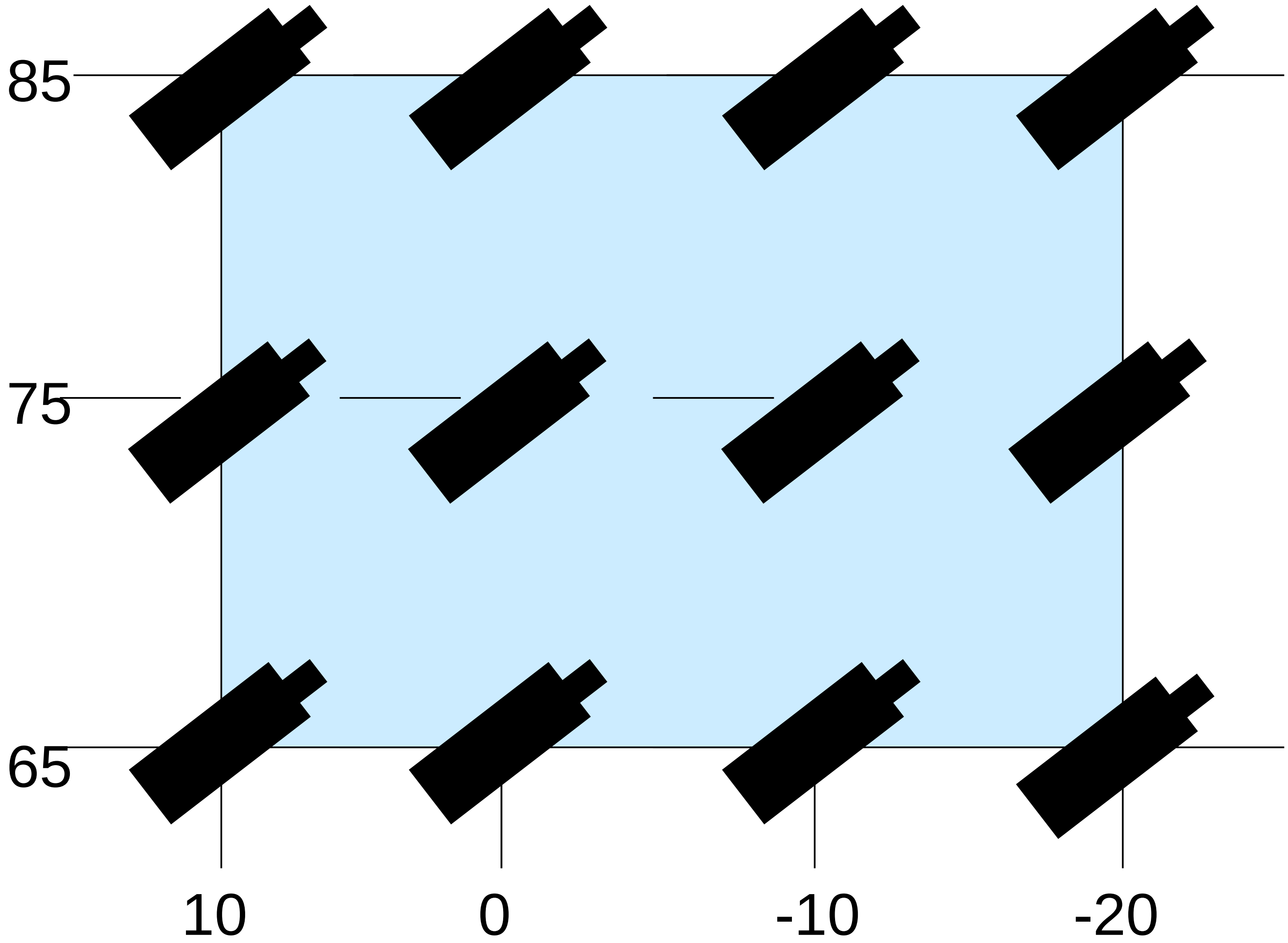
Small Ball



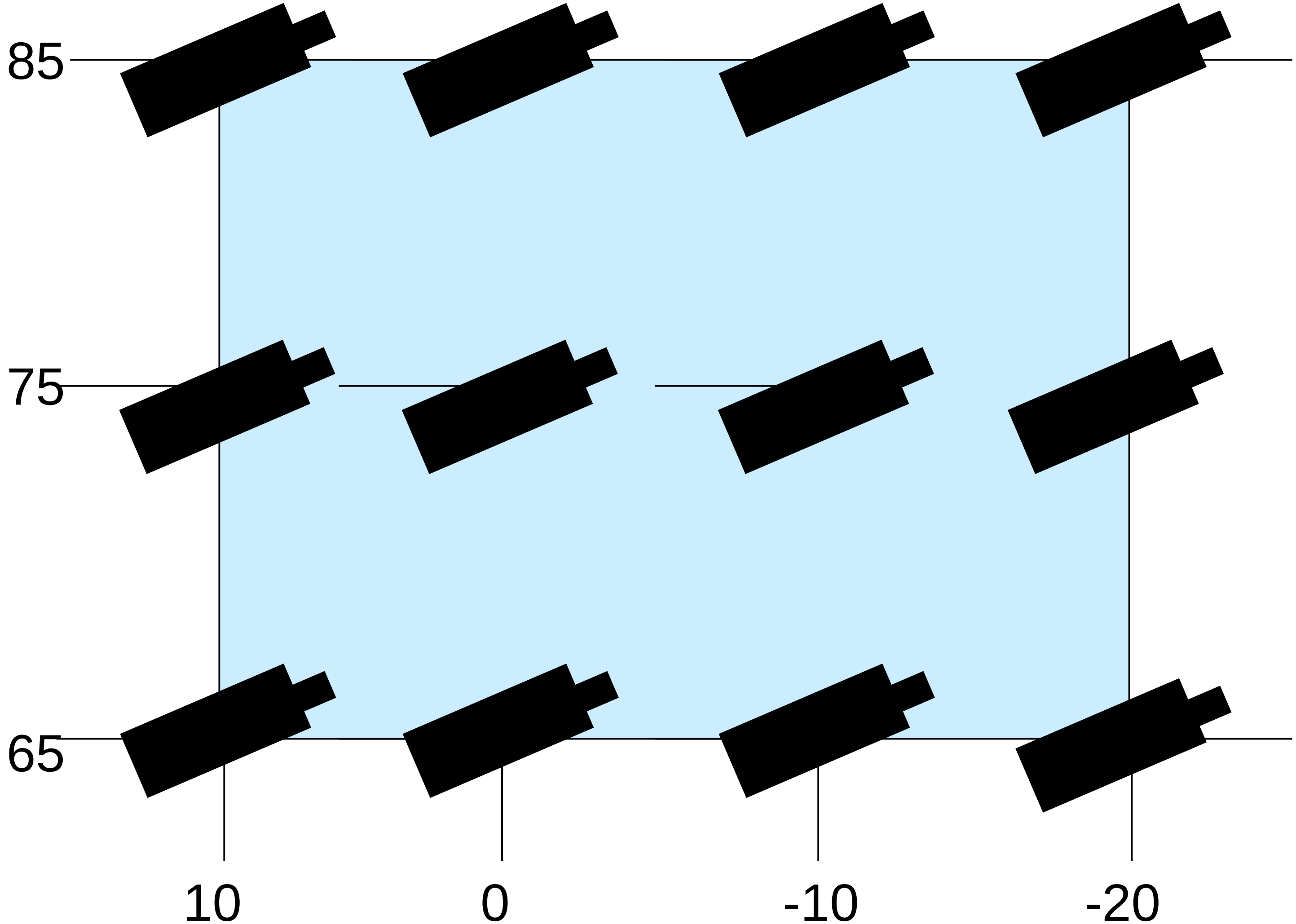
Bottle in standing position



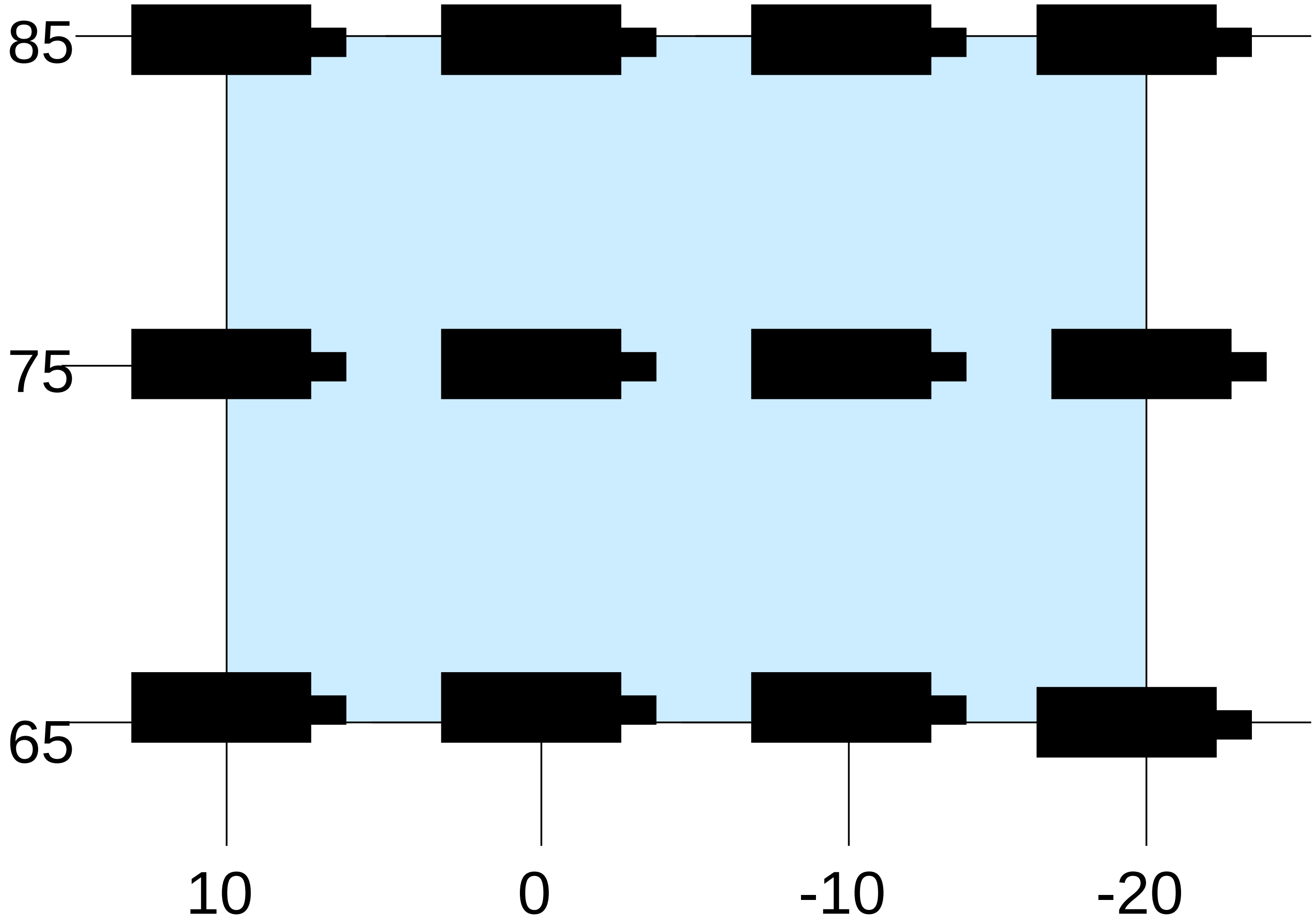
Bottle lying at +40°



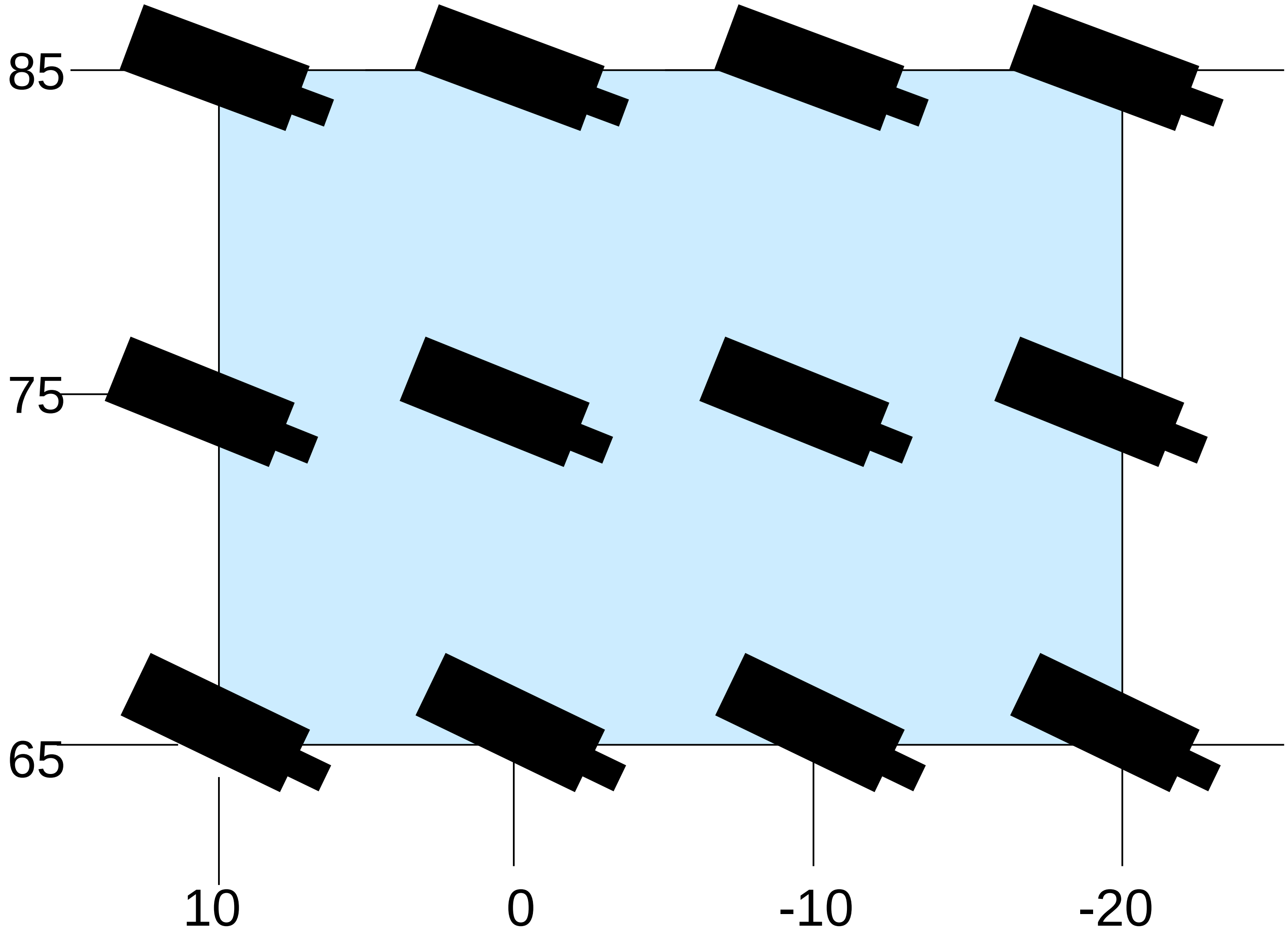
Bottle lying at +20°



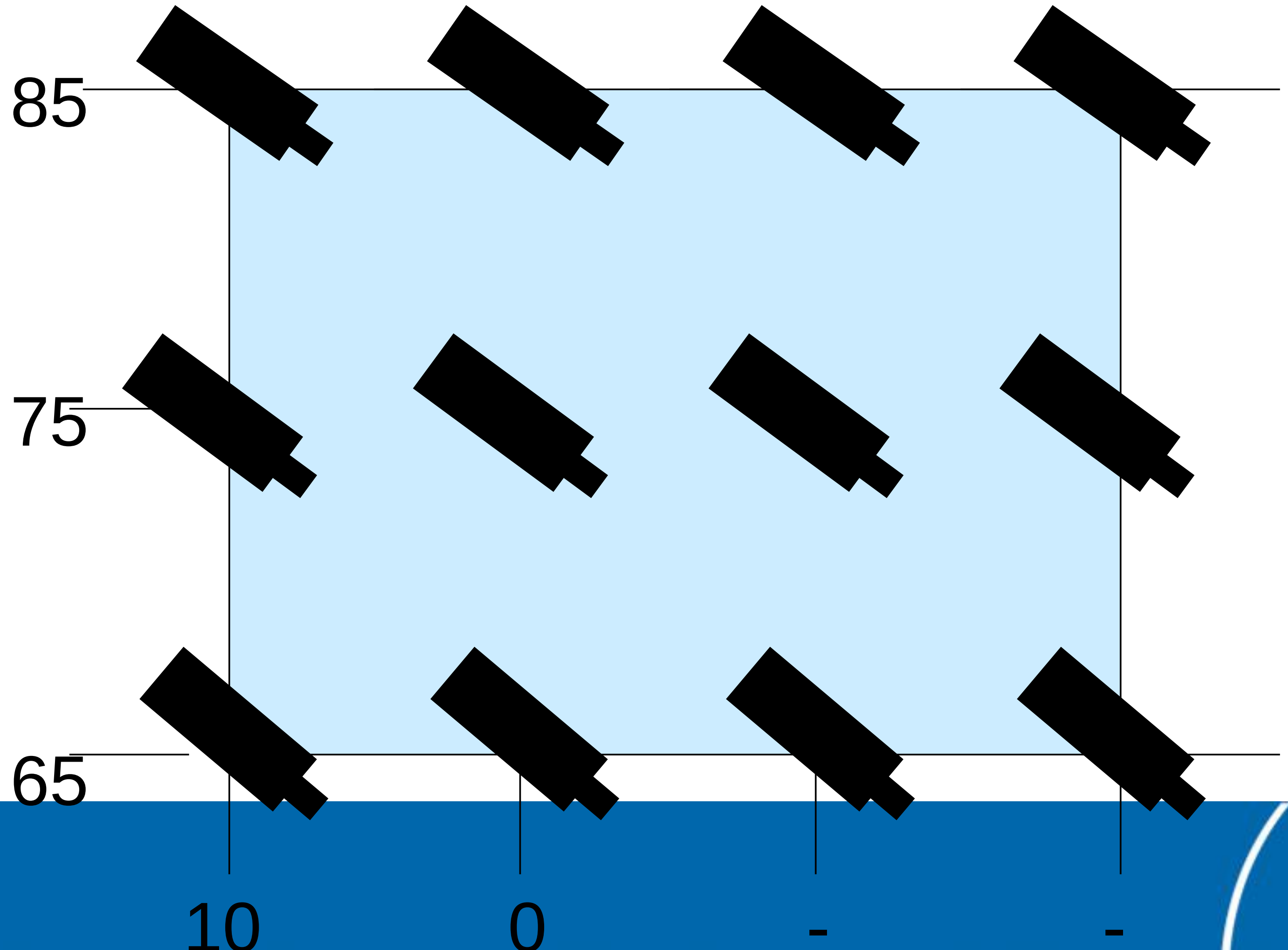
Bottle lying at 0°



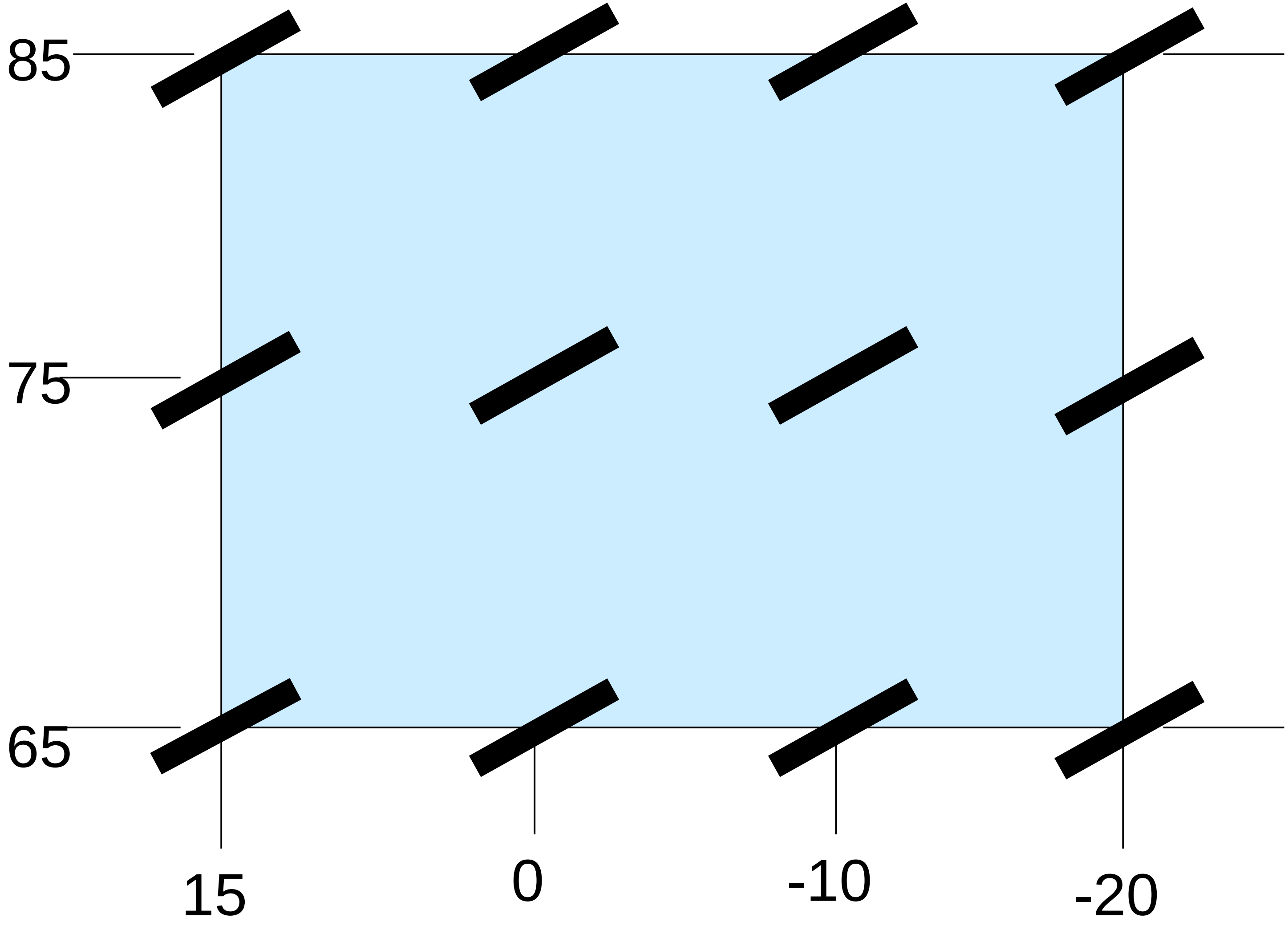
Bottle lying at -20°



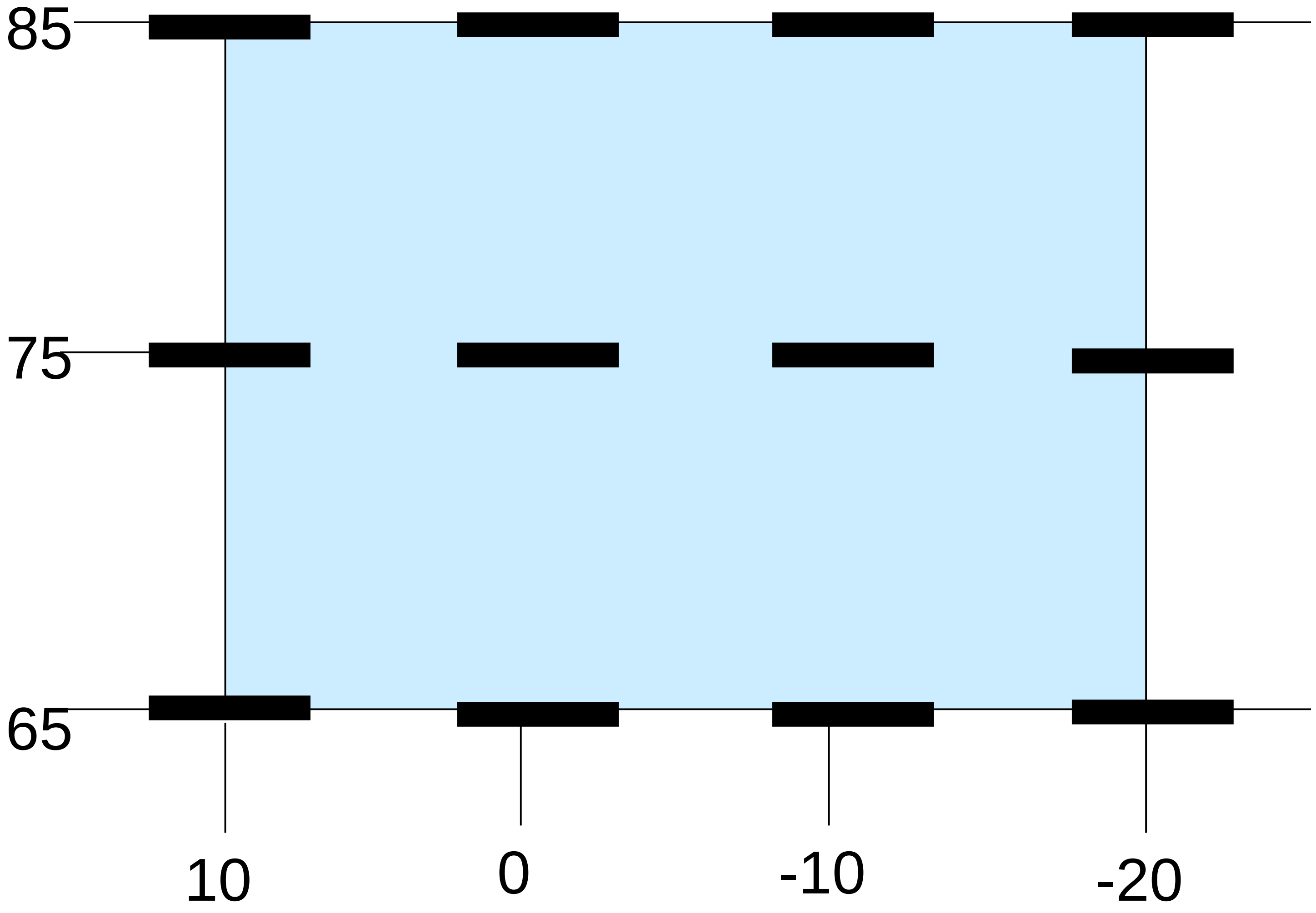
Bottle lying at -40°



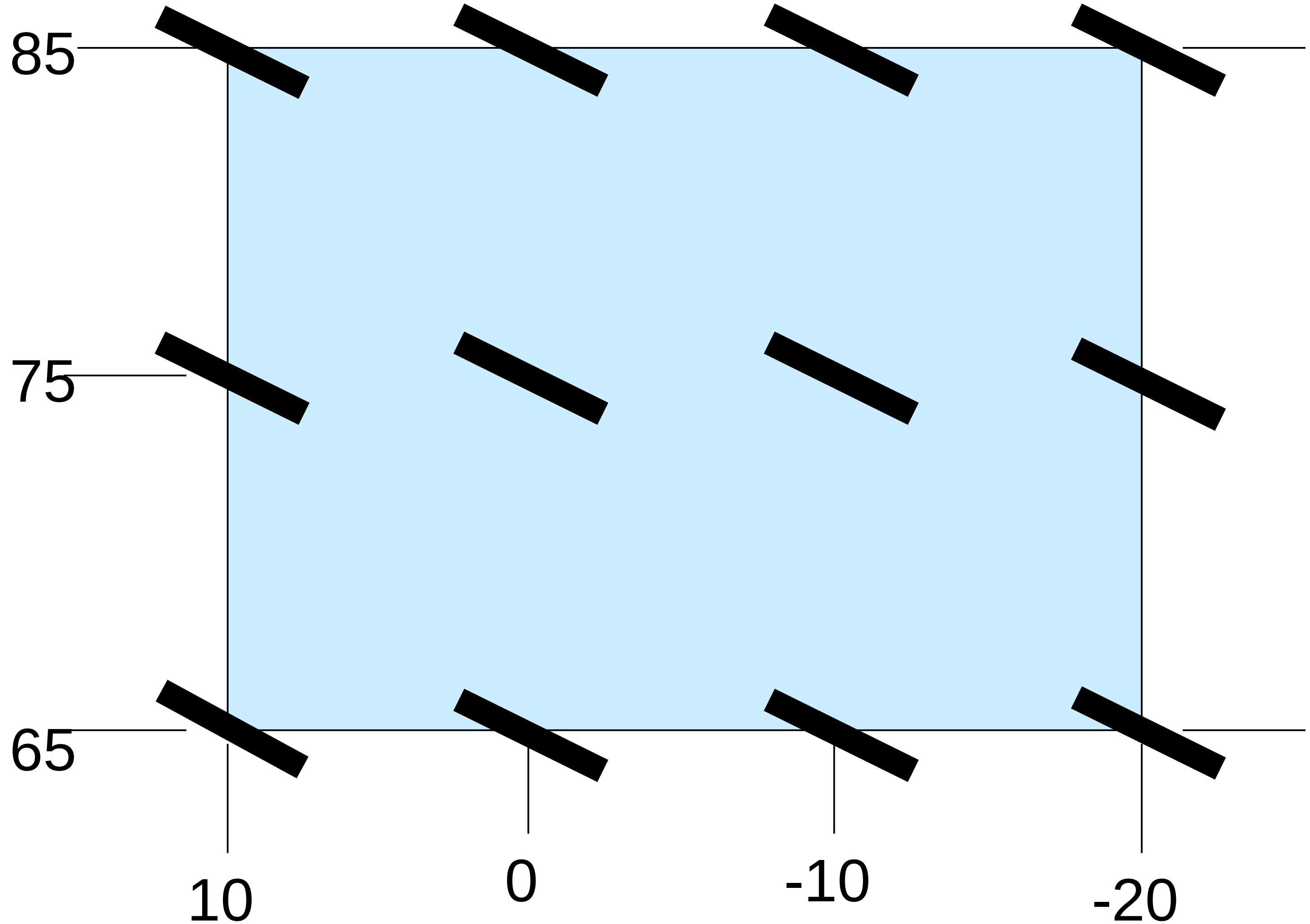
Cassette +35°



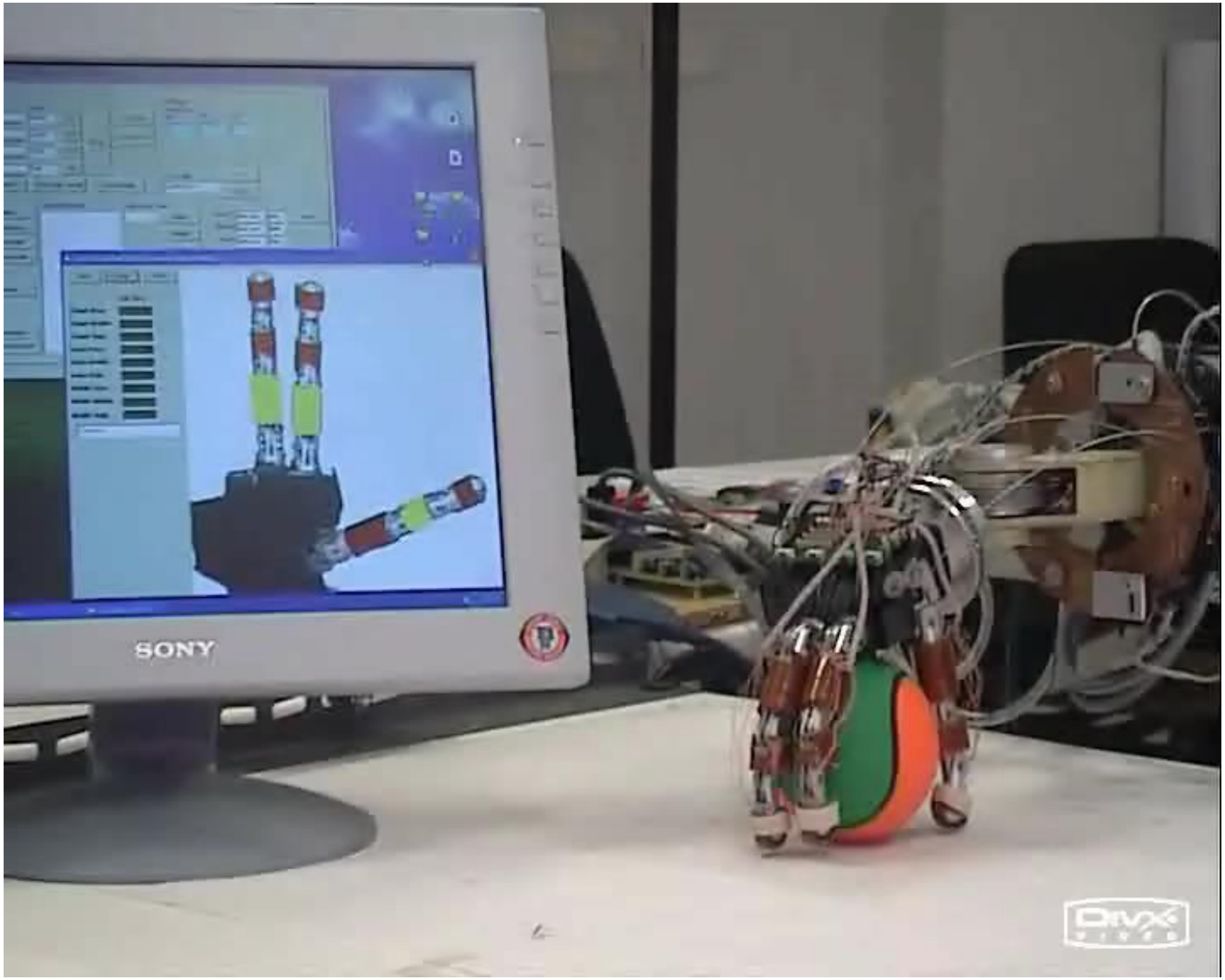
Cassette 0°



Cassette -35°

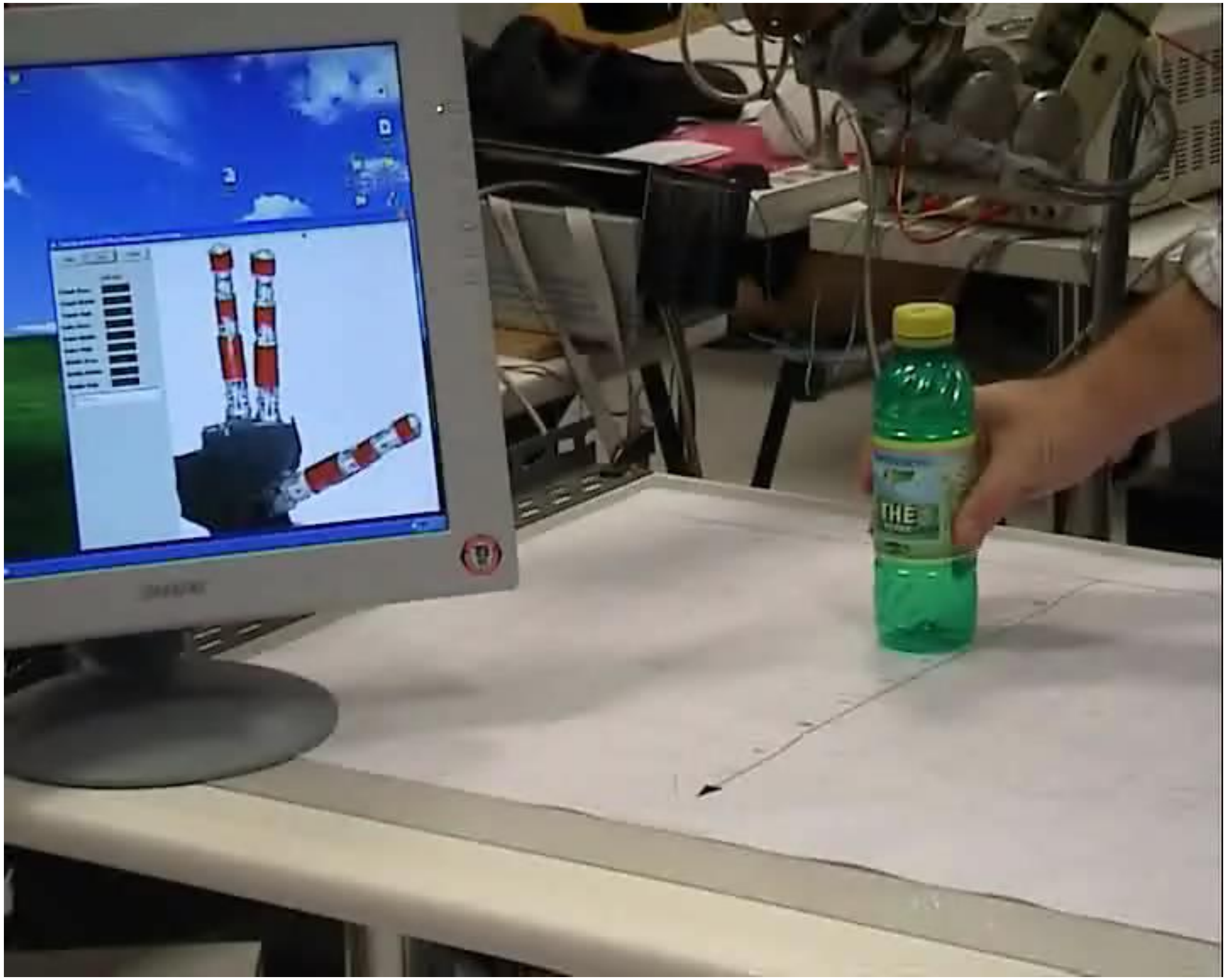


Learning of grasping module



Learning phase:
About 40000 random movements

Grasping the bottle



C. Laschi, G. Asuni, E. Guglielmelli, G. Teti, R. Johansson, M.C. Carrozza, P. Dario, "A Bio-inspired Neural Sensory-Motor Coordination Scheme for Robot Reaching and Preshaping", *Autonomous Robots*, Vol.5, 2008, pp.85-101.

Expected Perception in the visual space

EP architecture applied to 3D reconstruction of the environment

09ar0078cl [RF] © www.visualphotos.com

Task: free walking in an unknown room with obstacles

Classical approach:

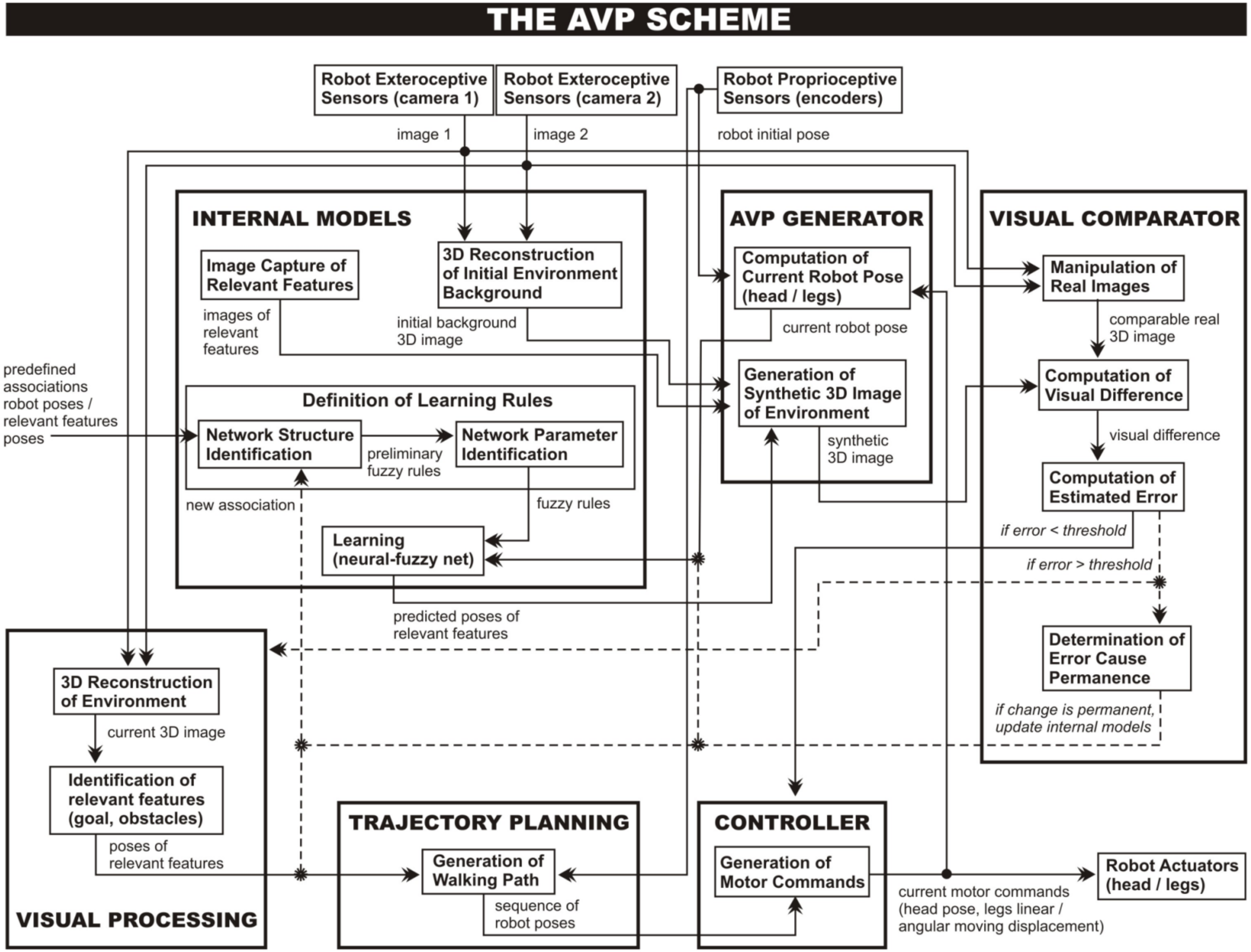
- 3D reconstruction of the environment
- path planning for collision-free walking

-> large computational burden

In a Visual EP architecture, after a first 3D reconstruction of the environment, images can be predicted, based on internal models and on the ongoing movement.

Predicted images are compared with actual ones and in case of unexpected obstacles a mismatch occurs and the motor action is re-planned

Visual EP scheme



Barrera, A. & Laschi, C. "Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion ", *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

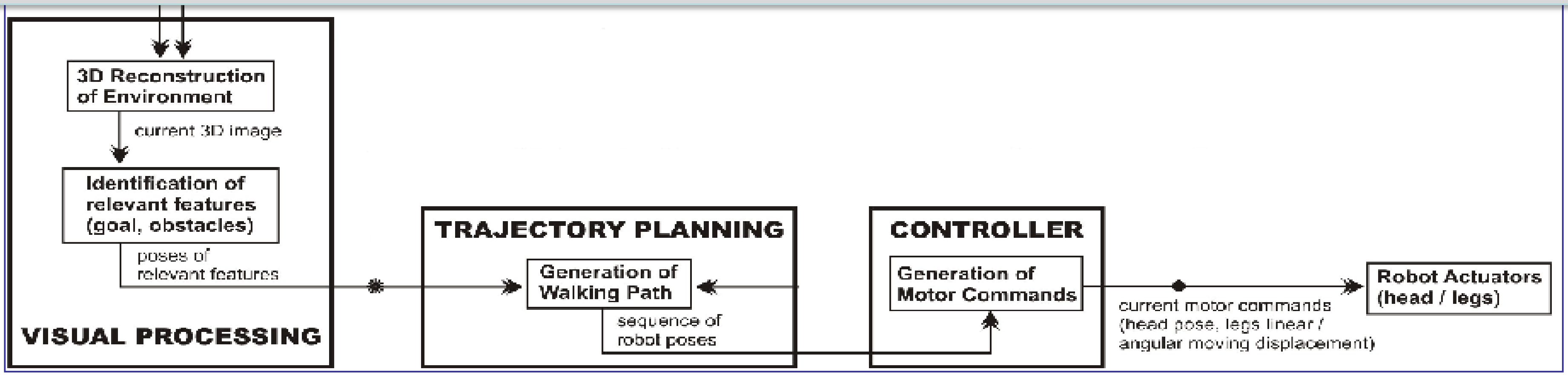
AVP architecture (I)

- **Visual Processing** module takes as input current images from both robot cameras to reconstruct the environment producing the **relevant feature position.**

- The poses of relevant features are sent to a **Trajectory Planning** module to generate the walking path

- The **Controller** module then takes the first robot pose from the sequence of poses planned by the Trajectory Planning module and produces the corresponding motor commands

-This cycle continues until the robot reaches the target.

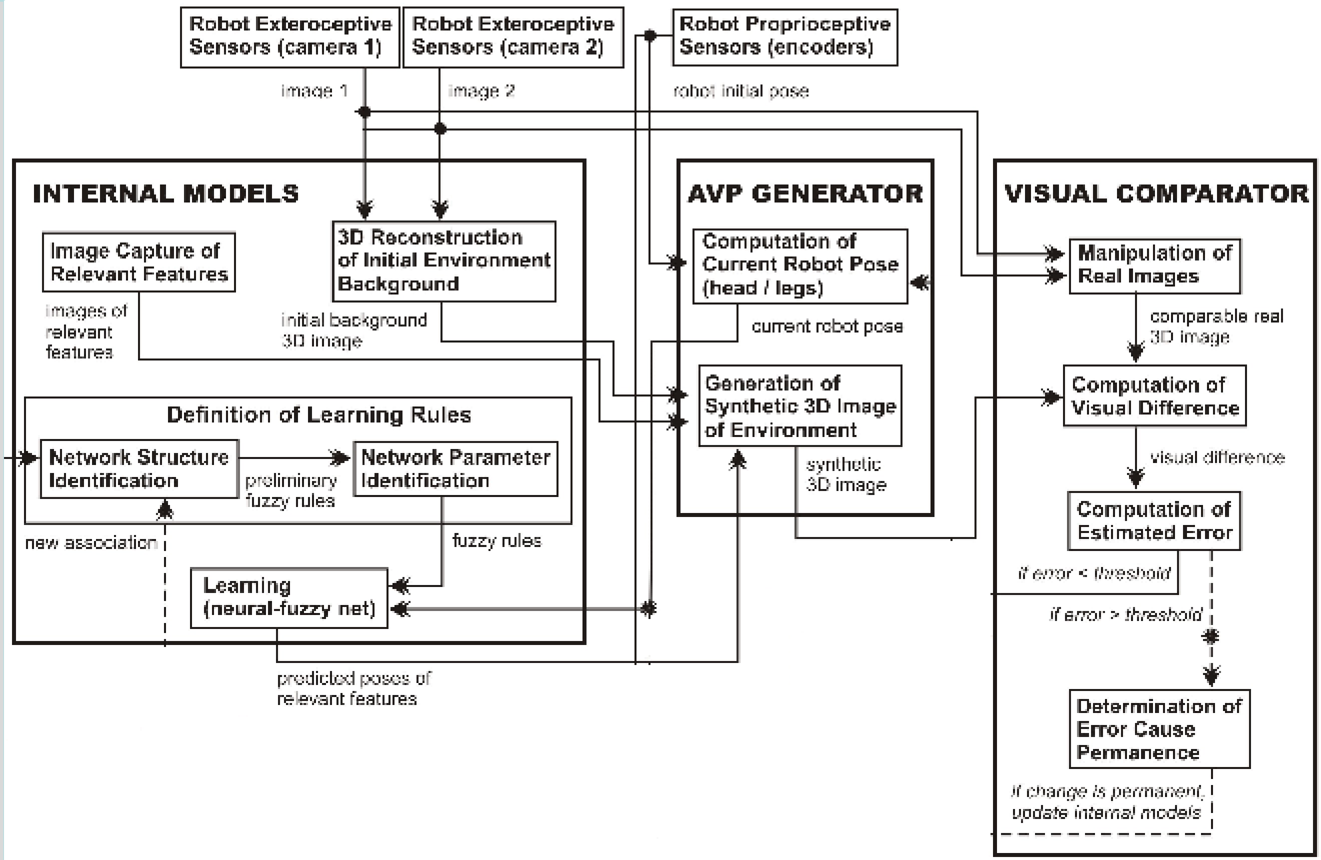


Barrera, A. & Laschi, C. "Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion ", *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

AVP architecture (II)

- **Internal Models** of the environment and of the task to be performed are necessary to *predict future visual perceptions*.

- Images of different features relevant to the locomotion task are captured and memorized



Barrera, A. & Laschi, C. “Anticipatory visual perception as a bio-inspired mechanism underlying robot locomotion “, *IEEE Int. Conf. on Engineering in Medicine and Biology Society (EMBC)*, Minneapolis, MN, USA, September 2010, pp.3206-3209

Visual EP System (implementation)

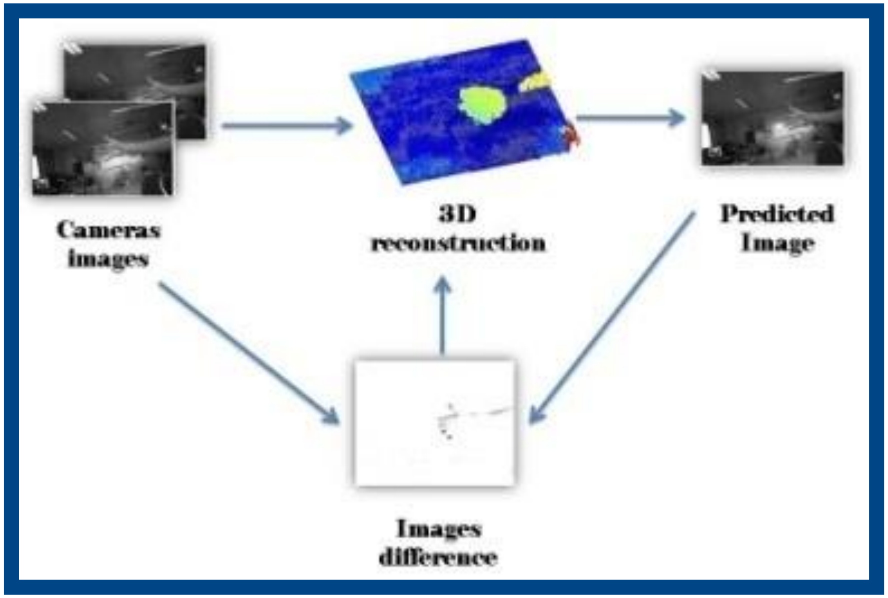
The system performs a real time 3D reconstruction of the environment (30fps) used to generate an **expected synthetic camera image**. The cloud of 3D points is updated using an image sensory-motor prediction.

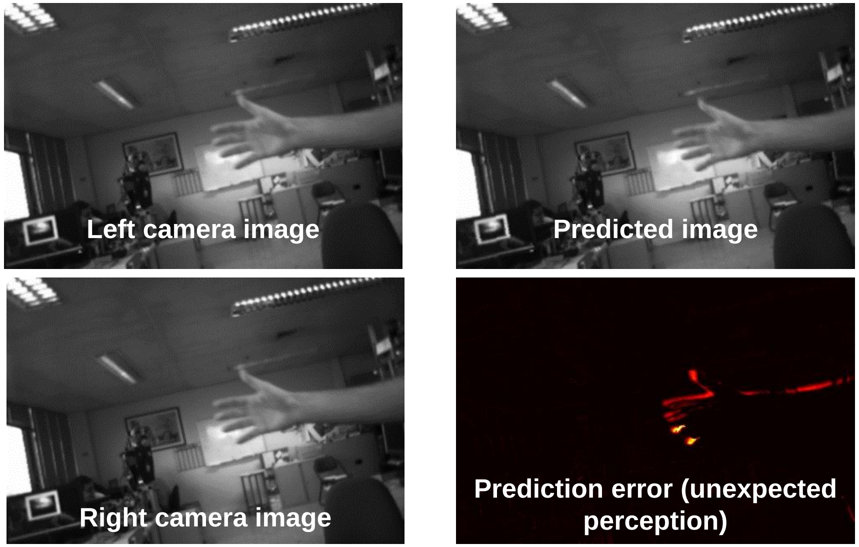
At each step:

- the next predicted image (EP) is calculated.
- the predicted and actual cameras images are compared.
- the 3D reconstruction of the visible environment is updated based on the prediction error

The system has 2 advantages:

- A faster real-time 3D reconstruction
- Recognition of the unexpected objects in the scene





Moutinho, N.; Cauli, N.; Falotico, E.; Ferreira, R.; Gaspar, J.; Bernardino, A.; Santos-Victor, J.; Dario, P.; Laschi, C.; 2011. "An expected perception architecture using visual 3D reconstruction for a humanoid robot," *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, San Francisco, CA, USA, 25-30 Sept. 2011 , pp.4826-4831.

EP of external moving objects
Prediction of movements of other agents

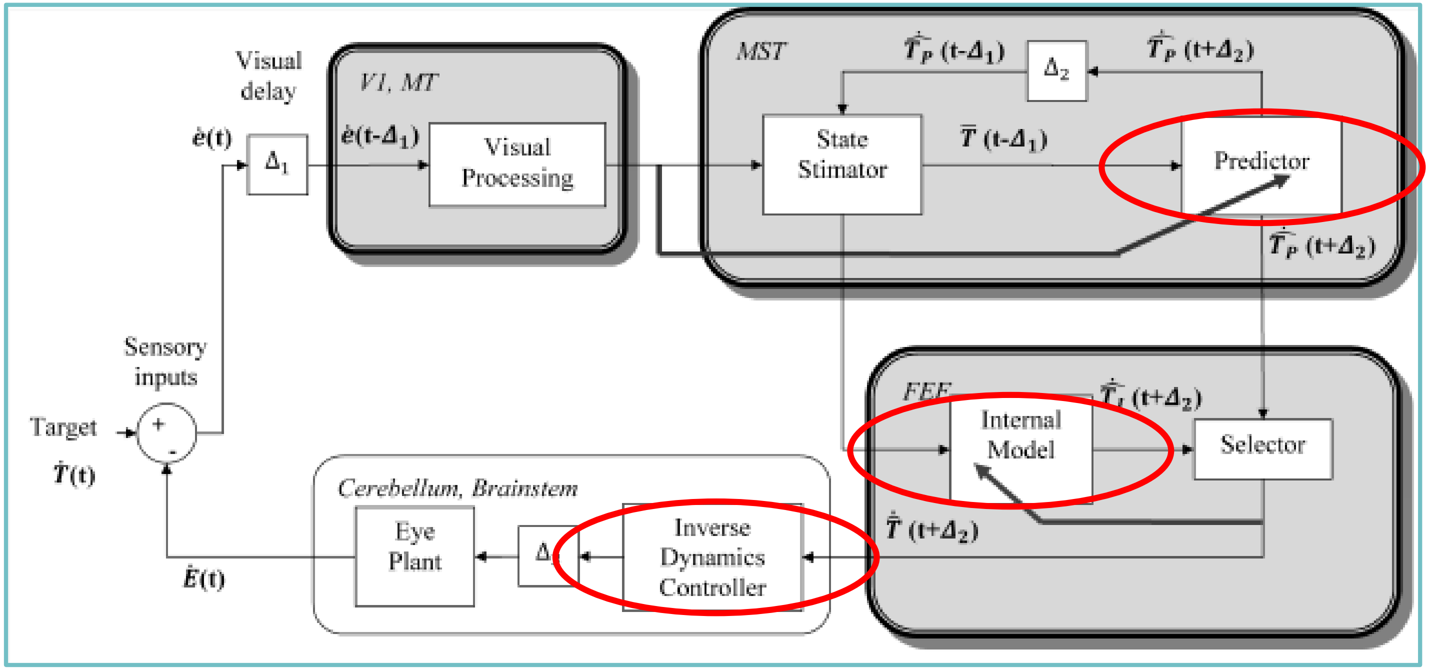
Applications: avoiding, reaching, hitting or caching moving objects

- The Expected Perception is not only generated by self motion

- Movements of other agents can be predicted, when their motion dynamics follows rules that can be learnt
  (e.g. laws of physics)

- In this case the planning is based on a long term prediction (more than one step ahead) of the object trajectory

A predictive model for smooth pursuit

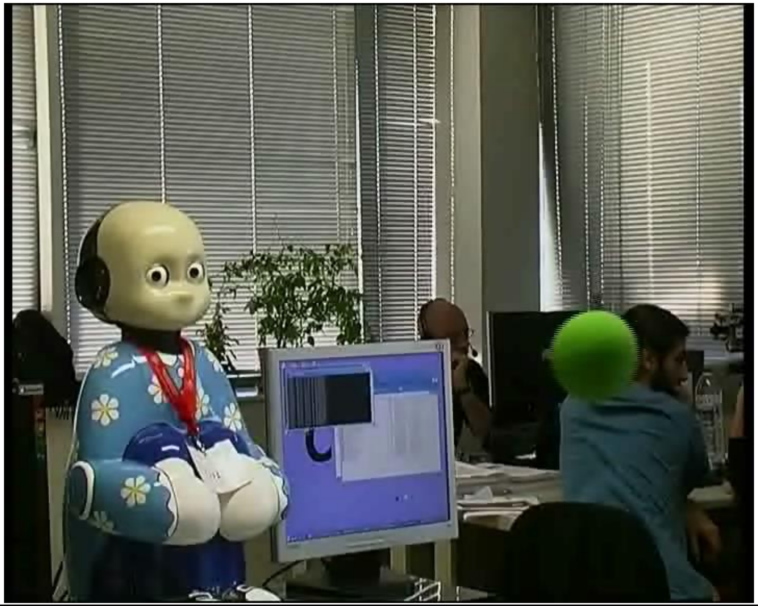


This circuit is based on Shibata and Schaal's model (*Shibata 2005*) of smooth pursuit and consists of **three subsystems**:

1. a **recurrent neural network** (RNN) mapped onto medial superior temporal area (MST), which receives the retinal slip with delays and ***predicts*** the current target motion,
2. an **inverse dynamics controller** (IDC) of the oculomotor system, mapped onto the cerebellum and the brainstem,
3. and **a memory block** that recognizes the target dynamics and provides the correct weights values before the RNN.

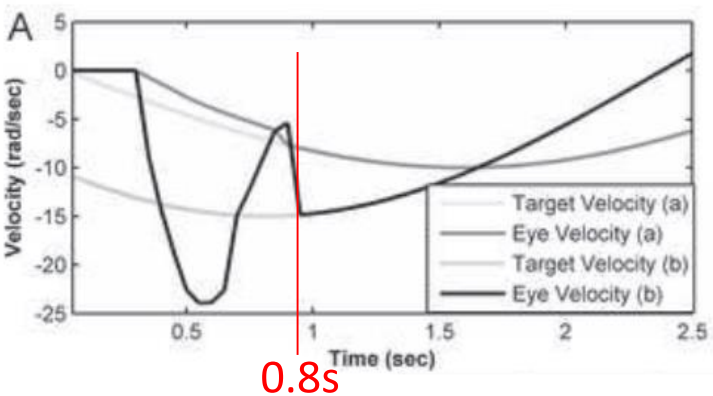
Zambrano D, Falotico E, Manfredi L, and Laschi C. (2010). "A model of the smooth pursuit eye movement with prediction and learning". *Applied Bionics and Biomechanics*

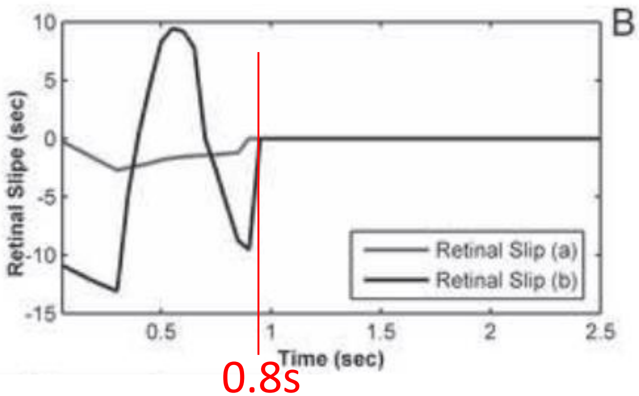
Predictive smooth pursuit on a robot head



iCub platform
head, 6 dof:
3 for the eyes
3 for the neck

The *retinal slip* (target velocity onto the retina) reaches zero after that the algorithm converges.
When the target is unexpectedly stopped, the system goes on tracking the target for a short time.



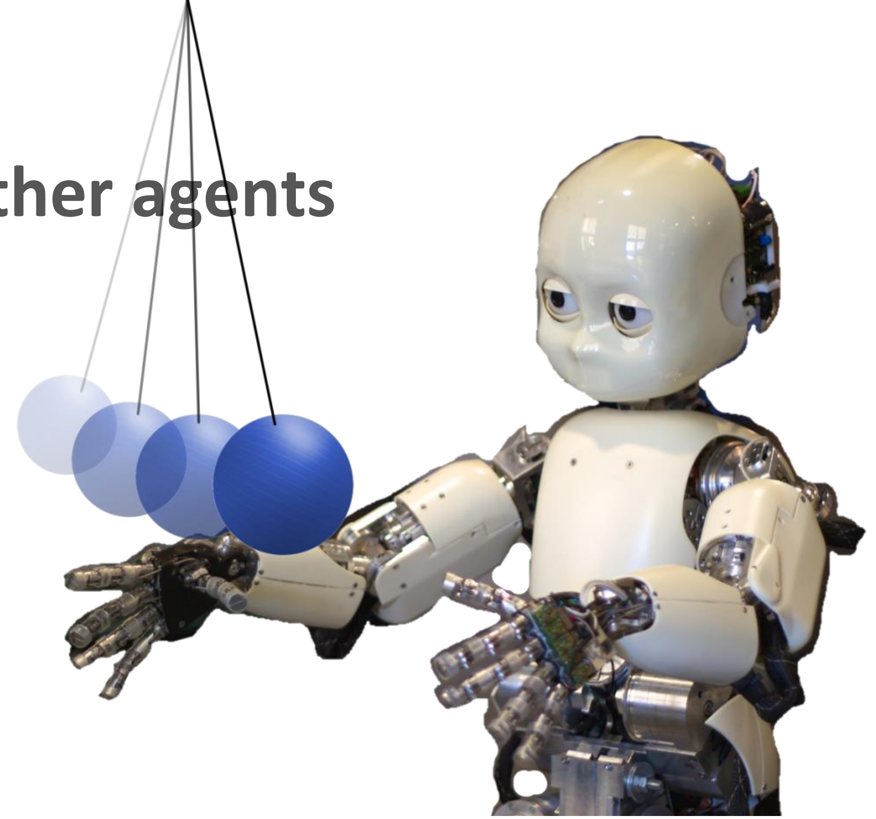


Sinusoidal dynamics:

a) angular frequency: 1 rad/s, amplitude: 10 rad, phase: π/2
b) angular frequency: 1 rad/s, amplitude: 15 rad, phase of ¾ π

EP of external moving objects
Prediction of movements of other agents

Punching a moving target

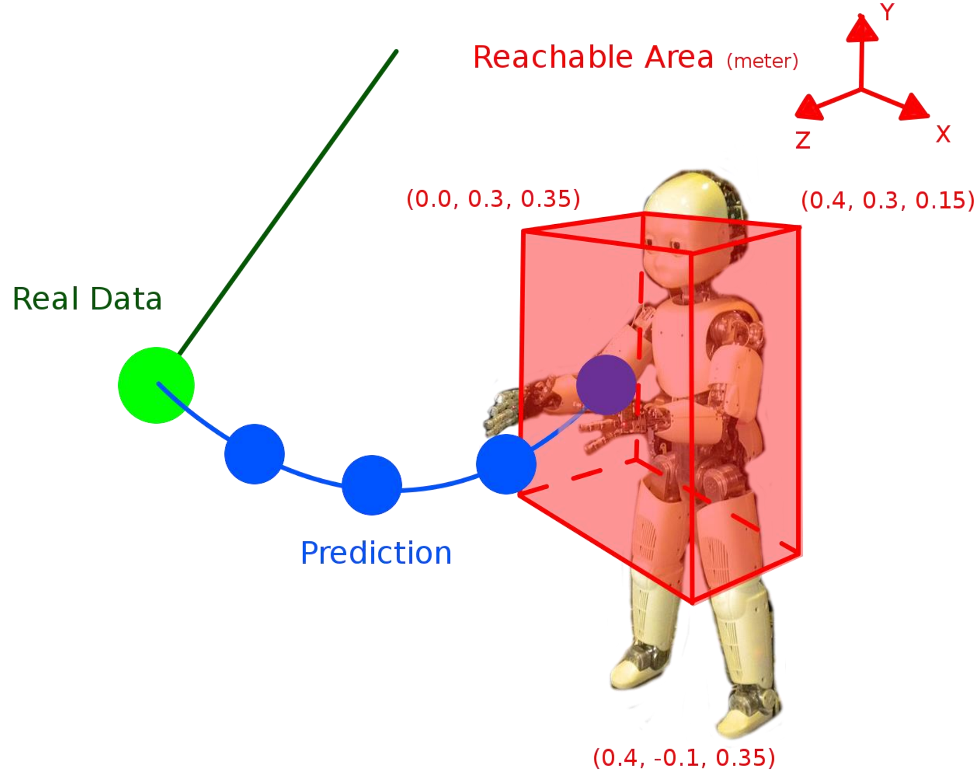


The robot punches a target oscillating in front of it with a predictable dynamics (pendulum)

An internal model is used to predict the dynamics of the moving target

The prediction allows to anticipate the movement of the arm and hit the ball

Punching a moving target
Experiment on Simulation/Robot



Experiment environment:

- A pendulum oscillates in front of the robot

Goal:

- Punching a predictable moving target when it reaches the robot arm workspace

Solution:

- *External model* used to predict the trajectory of the target (position through time) using a *Kalman Filter*
- Arm controller used to move the hand towards the desired position with a fixed time delay

Punching a moving target - robot experiments

The prediction is iterated ahead 0.5 seconds
As the predicted target is inside the arm workspace, the robot executes a movement to punch the ball in the ***predicted position***

N. Cauli, E. Falotico, A. Bernardino, J. Santos-Victor, C. Laschi, "Correcting for Changes: Expected Perception-Based Control for Reaching a Moving Target", *IEEE Robotics and Automation Magazine*, 23 (1), pp.63-70, 2016.

Outline of the lesson

- Scientific motivations to bioinspired robotics
- Simplexity
- Simplifying principles in human vision
- The *sense of movement* and the vestibular system: simplifying principles in eye movements
- Predictive architectures
- **Embodied Intelligence**
- Simplifying principles in soft robots

Embodied Intelligence: the modern view of Artificial Intelligence

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Classical approach
The focus is on the brain and central processing

Modern approach
The focus is on interaction with the environment. Cognition is emergent from system-environment interaction

Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

1. *They are subject to the laws of physics* (energy dissipation, friction, gravity).
2. *They generate sensory stimulation* through motion and generally through interaction with the real world.
3. *They affect the environment* through behavior.
4. *They are complex dynamical systems* which, when they interact with the environment, have *attractor states*.
5. *They perform morphological computation.*

These properties are simply unavoidable consequences of **embodiment**.

These are also the properties that can be exploited for generating behavior, and how this can be done is specified in the design principles.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

1. *A complete agent is subject to the laws of physics.*

Walking requires energy, friction, and gravity in order to work. Because the agent is embodied, it is a physical system (biological or not) and thus subject to the laws of physics from which it cannot possibly escape; it must comply with them. If an agent jumps up in the air, gravity will inevitably pull it back to the ground.

Properties of complete agents

2. *A complete agent generates sensory stimulation.*
When we walk, we generate sensory stimulation, whether we like it or not: when we move, objects seem to flow past us (this is known as optic flow);
by moving we induce wind that we then sense with our skin and our hair;
walking also produces pressure patterns on our feet;
and we can feel the regular flexing and relaxing of our muscles as our legs move.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

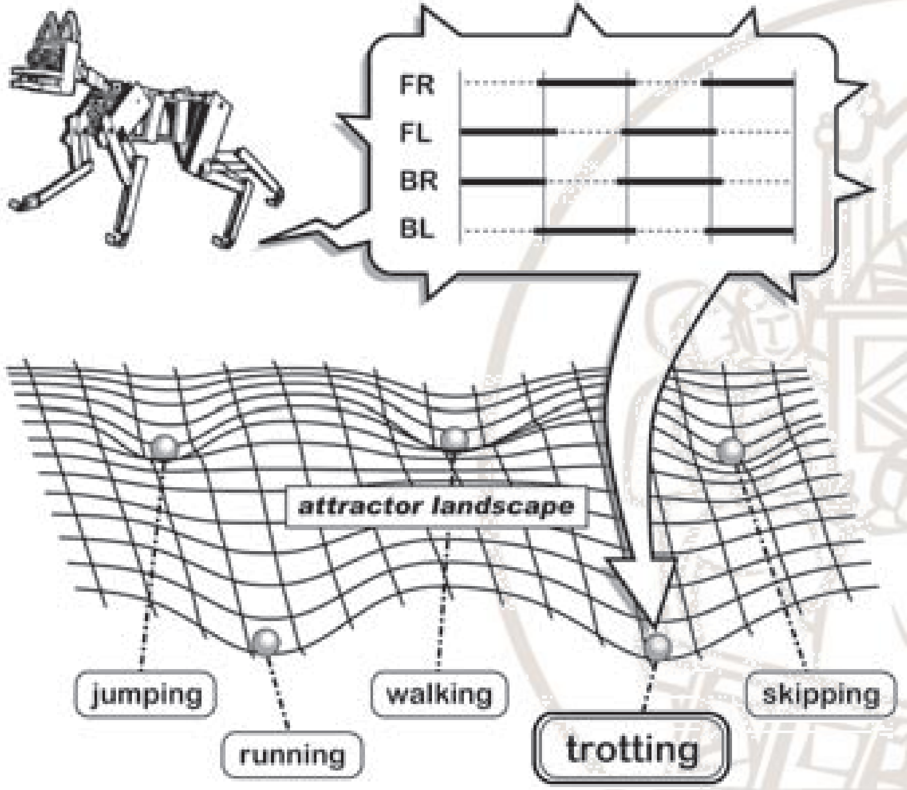
Properties of complete agents

3. *A complete agent affects its environment.*
When we walk across a lawn, the grass is crushed underfoot;
when we breathe, we blow air into the environment;
when we walk and burn energy, we heat the environment;
when we drink from a cup, we reduce the amount of liquid in the glass;
when we drop a cup it breaks;
when we talk we put pressure waves out into the air;
when we sit down in a chair it squeaks and the cushion is squashed.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

4. *Agents tend to settle into attractor states.*
Agents are dynamical systems, and as such they have a tendency to settle into so-called attractor states. Horses, for example, can walk, trot, canter, and gallop, and we—or at least experts—can clearly identify when the horse is in one of these walking modes, or gaits, the more technical word for these behaviors.
These gaits can be viewed as **attractor states**. The horse is always in one of these states, except for short periods of time when it transitions between two of them, for example from canter to gallop. We should point out here that the attractor states into which an agent settles are always the result of the interaction of three systems: the agent's body, its brain (or control system), and its environment.



Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Properties of complete agents

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5. *Complete agents perform morphological computation.*

By "morphological computation" we mean that certain processes are performed by the body that otherwise would have to be performed by the brain.

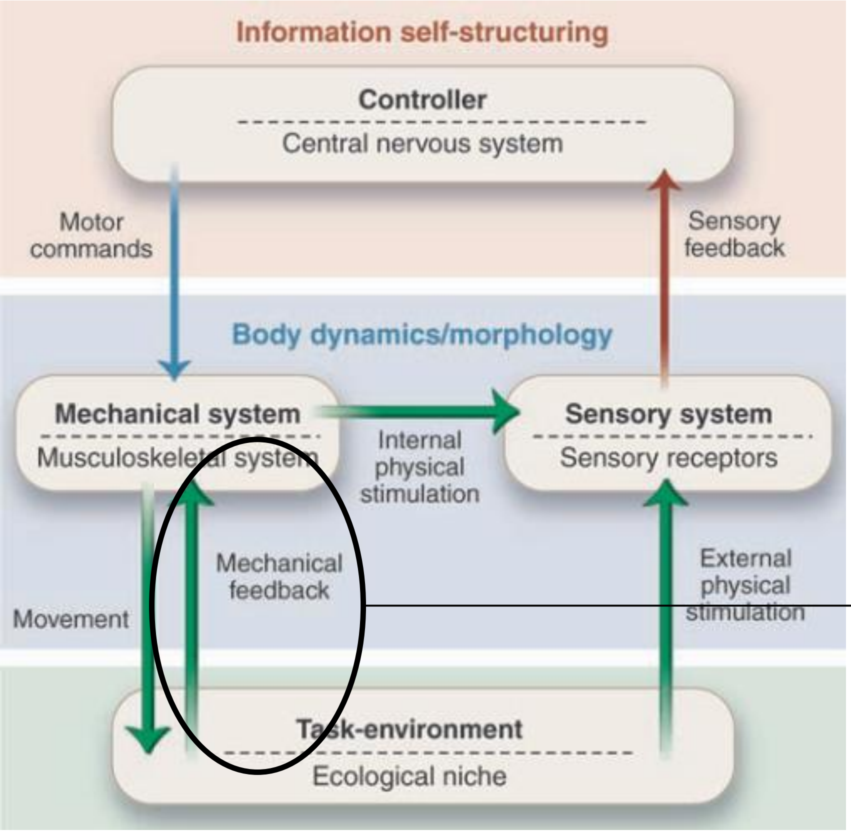
An example is the fact that the human leg's muscles and tendons are elastic so that the knee, when the leg impacts the ground while running, performs small adaptive movements without neural control.

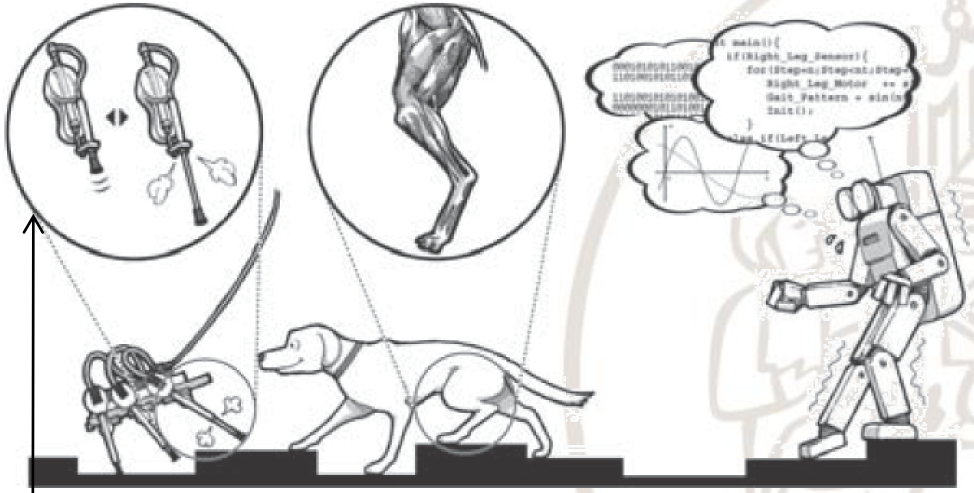
The control is supplied by the muscle-tendon system itself, which is part of the morphology of the agent.

It is interesting to note that systems that are not complete, in the sense of the word used here, hardly ever possess all of these properties. For example, a vision system consisting of a fixed camera and a desktop computer does not generate sensory stimulation because it cannot produce behavior, and it influences the environment only by emitting heat and light from the computer screen. Moreover, it does not perform morphological computation and does not have physical attractor states that could be useful to the system.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Morphological computation

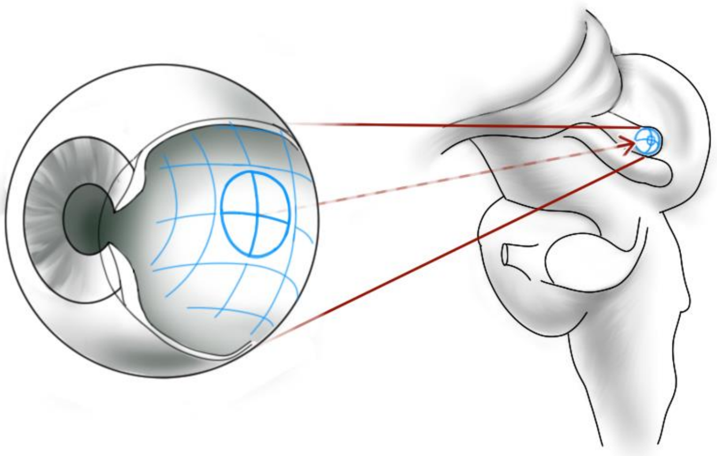


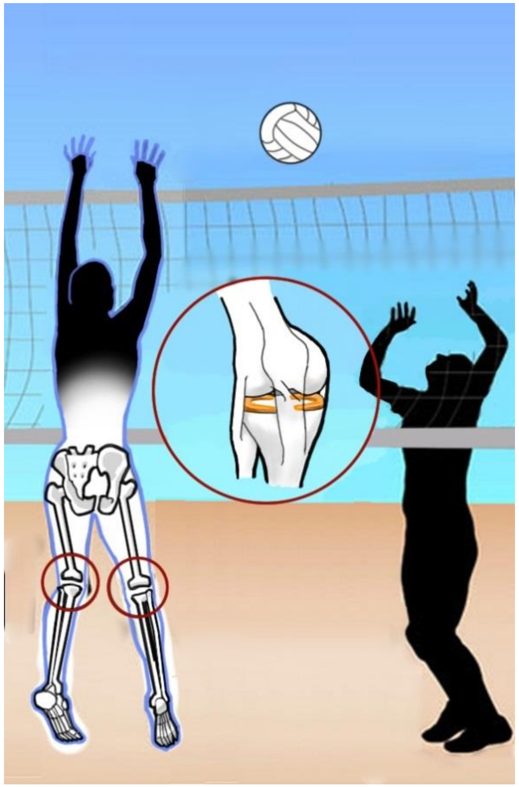


Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Morphological Computation

As any transformation of information can be named as *computing*, *Morphological Computation* endows all those behaviours where computing is mediated by the mechanical properties of the physical body





The arrangement
of the motor, perceptive and processing units

The shape
as body structure, specifies the behavioral response of the agent

The mechanical properties
allow emergent behaviors and highly adaptive interaction with the environment

Zambrano D, Cianchetti M, Laschi C (2014) "The Morphological Computation Principles as a New Paradigm for Robotic Design" in *Opinions and Outlooks on Morphological Computation*, H. Hauser, R. M. Füchslin, R. Pfeifer (Ed.s), pp. 214-225.

Agent Design Principle 1

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The **three-costituents** principle:

- define the ecological niche — ENVIRONMENT
- define the desired behaviour and tasks — TASK
- design the agent — BODY

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 2

The **complete-agent** principle:

- think about the complete agent behaving in the real world

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 3

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Cheap design:

- If agents are built to exploit the properties of the ecological niche and the characteristics of the interaction with the environment, their design and construction will be much easier, or 'cheaper'

Passive walker

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 4

Redundancy:

- Intelligent agents must be designed in such a way that
  - (a) their different sub-systems function on the basis of different physical processes, and
  - (b) there is partial overlap of functionality between the different sub-systems

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

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Agent Design Principle 5

Sensory-Motor Coordination:

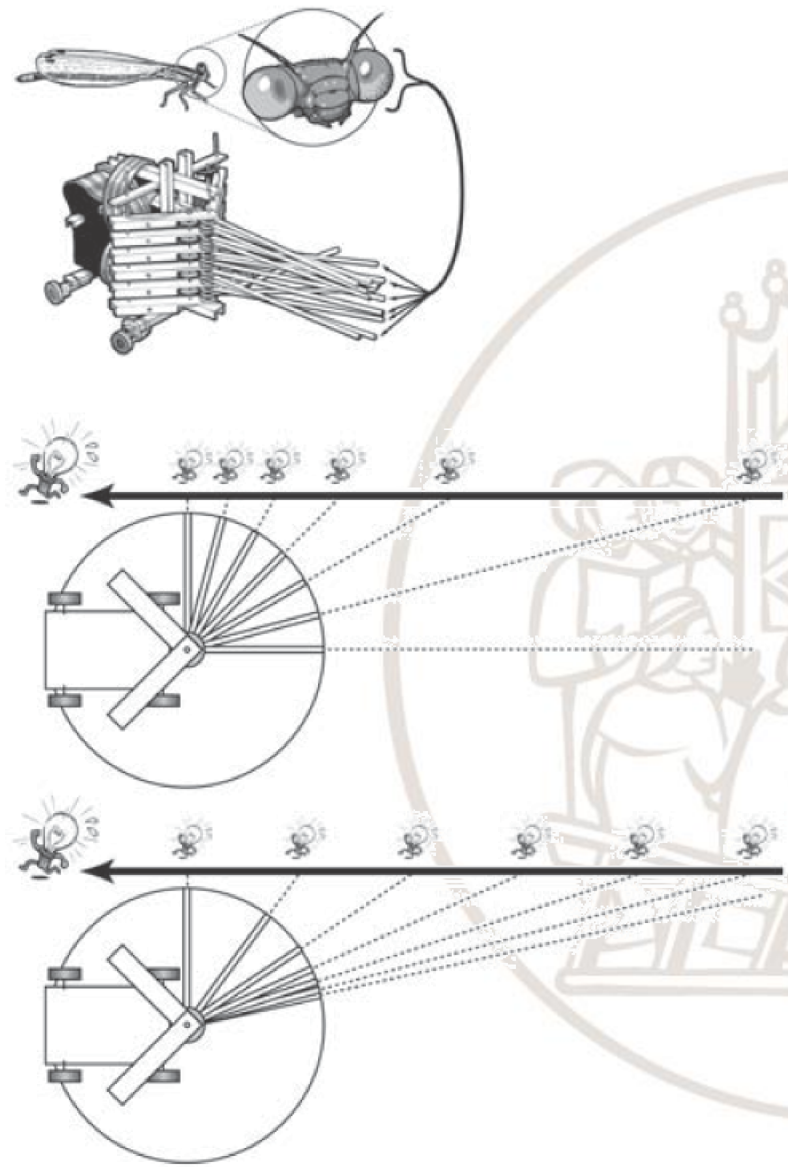
- through sensory-motor coordination, structured sensory stimulation is induced.

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 6

Ecological balance:

1. given a certain task environment, there has to be a match between the complexities of the agent's sensory, motor, and neural systems
2. there is a certain balance or task distribution between morphology, materials, control, and environment.



Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 7

Parallel, loosely coupled processes: intelligence is emergent from a large number of parallel processes that are often coordinated through embodiment, in particular via the embodied interaction with the environment

Reactive architectures

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Agent Design Principle 8

Value:
agents are equipped with a value system which constitutes a basic set of assumptions about what is good for the agent

Rolf Pfeifer & Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Embodied Intelligence and soft robotics

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Any cognitive activity arises from the ***interaction*** between the body, the brain and the environment.

Adaptive behaviour is not just control and computation, but it emerges from the complex and dynamic interaction between the morphology of the body, sensory-motor control, and environment.

<u>Many tasks become much easier if morphological computation is taken into account.</u>

=> A new soft bodyware is needed

Modern approach

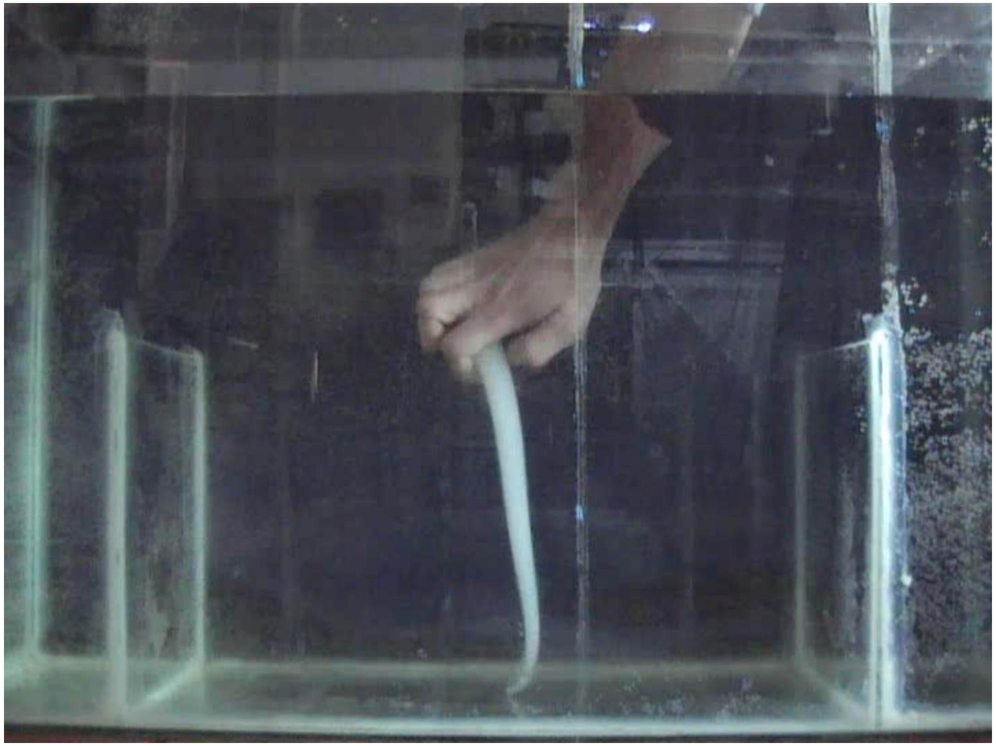
The focus is on interaction with the environment. Cognition is emergent from system-environment interaction

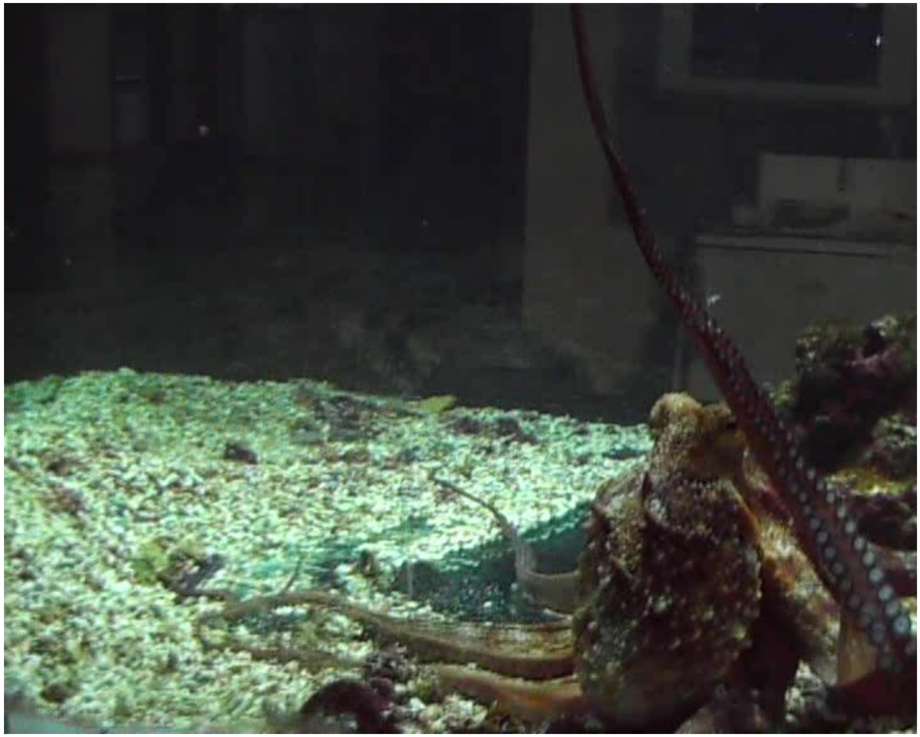
Rolf Pfeifer and Josh C. Bongard, *How the body shapes the way we think: a new view of intelligence*, The MIT Press, Cambridge, MA, 2007

Outline of the lesson

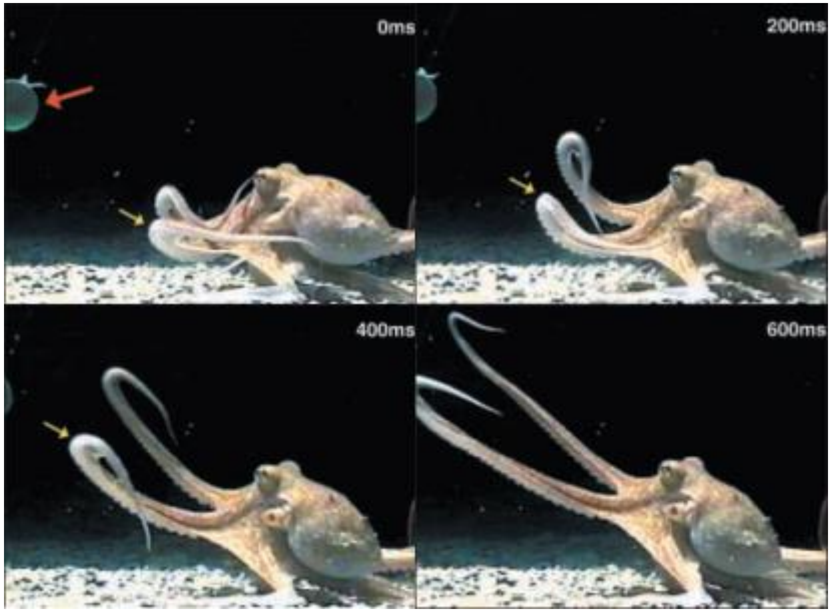
- Scientific motivations to bioinspired robotics
- Simplexity
- Simplifying principles in human vision
- The *sense of movement* and the vestibular system: simplifying principles in eye movements
- Predictive architectures
- Embodied Intelligence
- **Simplifying principles in soft robots**

The octopus arm embodied intelligence





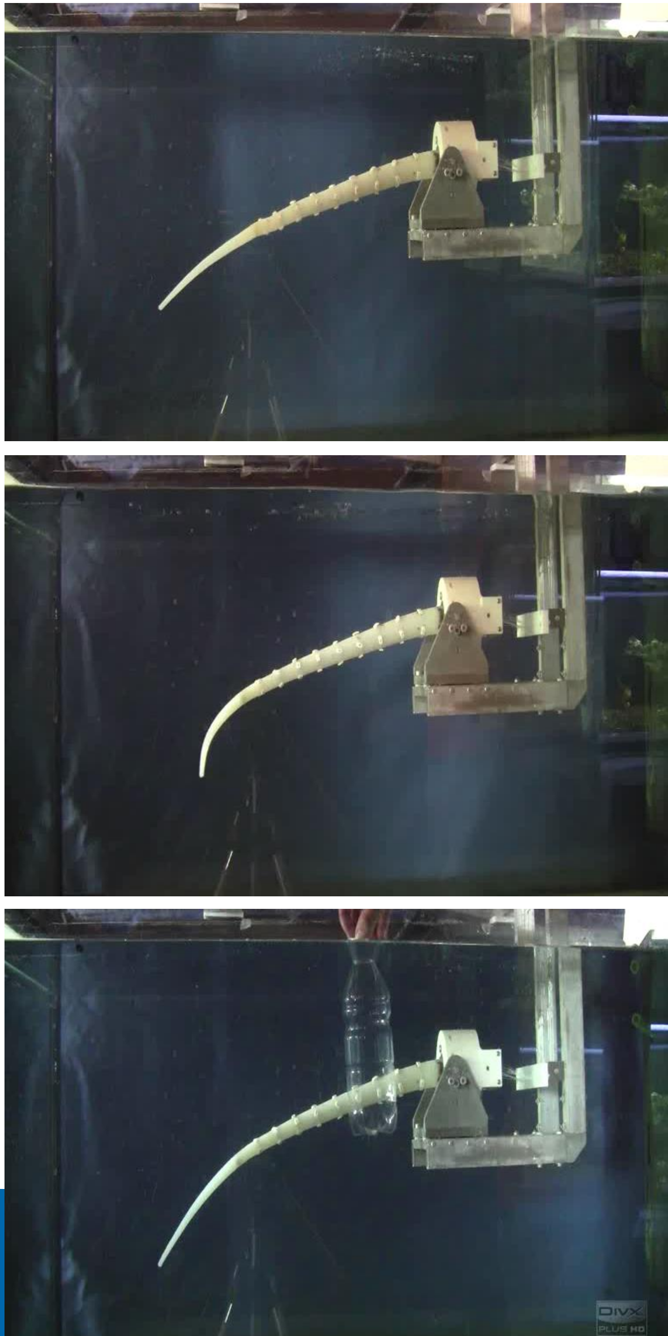
Reaching movement of the octopus arm



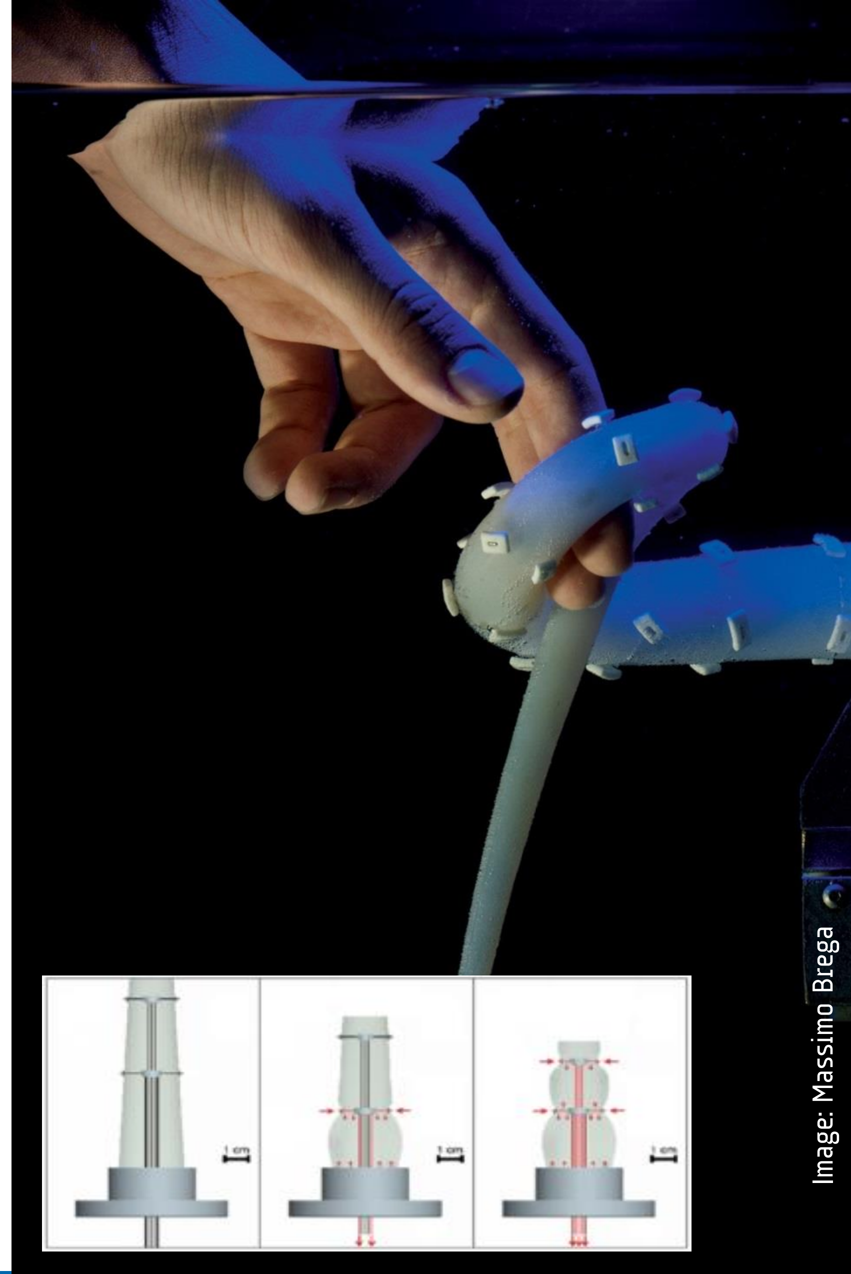
- stiffening wave from base to distal part, that can start from any part of the arm;
- co-contraction of antagonistic muscles, with no diameter reduction or elongation
- movement executed in about 1 second;
- velocities in the range of 20–60 cm/s;
- control divided between central and peripheral: from brain: **3 parameters** (yaw and pitch of arm base and peak velocity of bend-point); locally: propagation of stiffness

I. Zelman, M. Galun, A. Akselrod-Ballin, Y. Yekutieli, B. Hochner, and T. Flash (2009) Nearly automatic motion capture system for tracking octopus arm movements in 3D space, *Journal of Neuroscience Methods, Volume 182: 97-109*
L. Zullo, G. Sumbre, C. Agnisola, T. Flash, B. Hochner (2009) Nonsomatotopic Organization of the Higher Motor Centers in Octopus, *Current Biology, 19:1632-1636.*

Simplifying principles in reaching



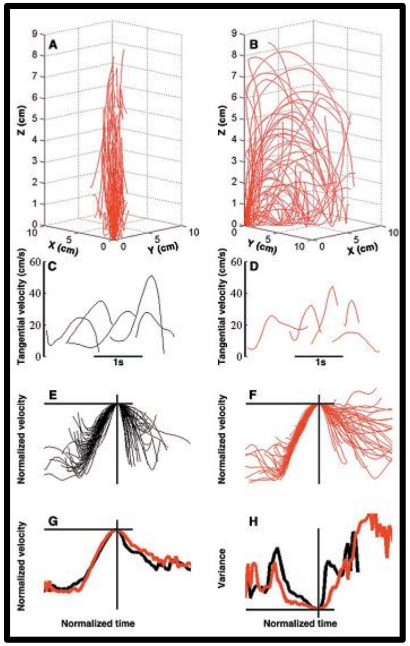
- Silicone
- 9 sections of transverse and longitudinal cables (coupled)
- Simple activation pattern: sequential activation of sections, with equal activation of 4 longi-transverse cables per section



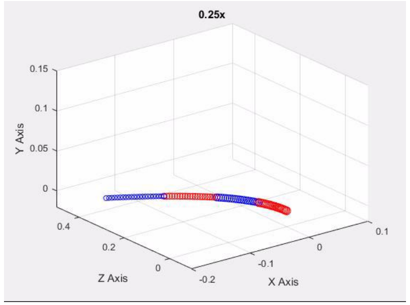
Cianchetti, M., Arienti, A., Follador, M., Mazzolai, B., Dario, P., Laschi, C. "Design concept and validation of a robotic arm inspired by the octopus", *Materials Science and Engineering C*, Vol.31, 2011, pp.1230-1239.

Simplifying principles in reaching

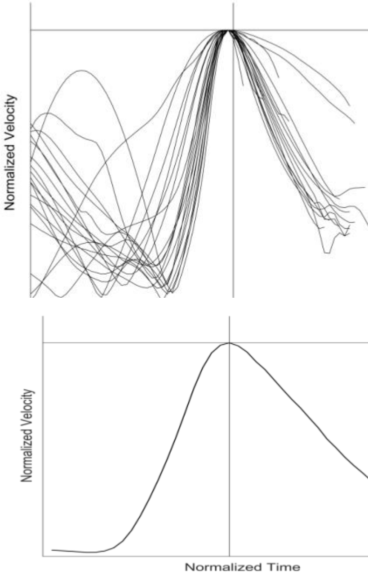
Biological behaviour



Robot behaviour



- Soft robot
- Passive distal part
- Water
- Neural controller (not octopus-like)



TIP TANGENTIAL VELOCITY PROFILE

morphological and environmental properties *are the factors that affects the invariant velocity profile observed*

Configuration	Learnable	Invariant Profile Observed
Lower Environment Density (0.1x)	No	
Lower Environment Density (0.1x) + Higher Body Stiffness + Higher Body Viscosity	Yes	No
Actuators at Tip (4th Section)	No	
Actuators at 3rd Section	No	
Only two actuators at the base	Yes	Yes
Four Actuators at the base	Yes	Yes
Three Actuators at base + One at the tip	Yes	Yes*
Shorter Manipulator (Only two sections)	Yes	No

Self-Stabilizing Open Loop Control in soft robots

Sumbre, G., Gutfreund, Y., Fiorito, G., Flash, T., & Hochner, B. (2001). "Control of octopus arm extension by a peripheral motor program", *Science*, *293*(5536), 1845-1848.

Unpublished

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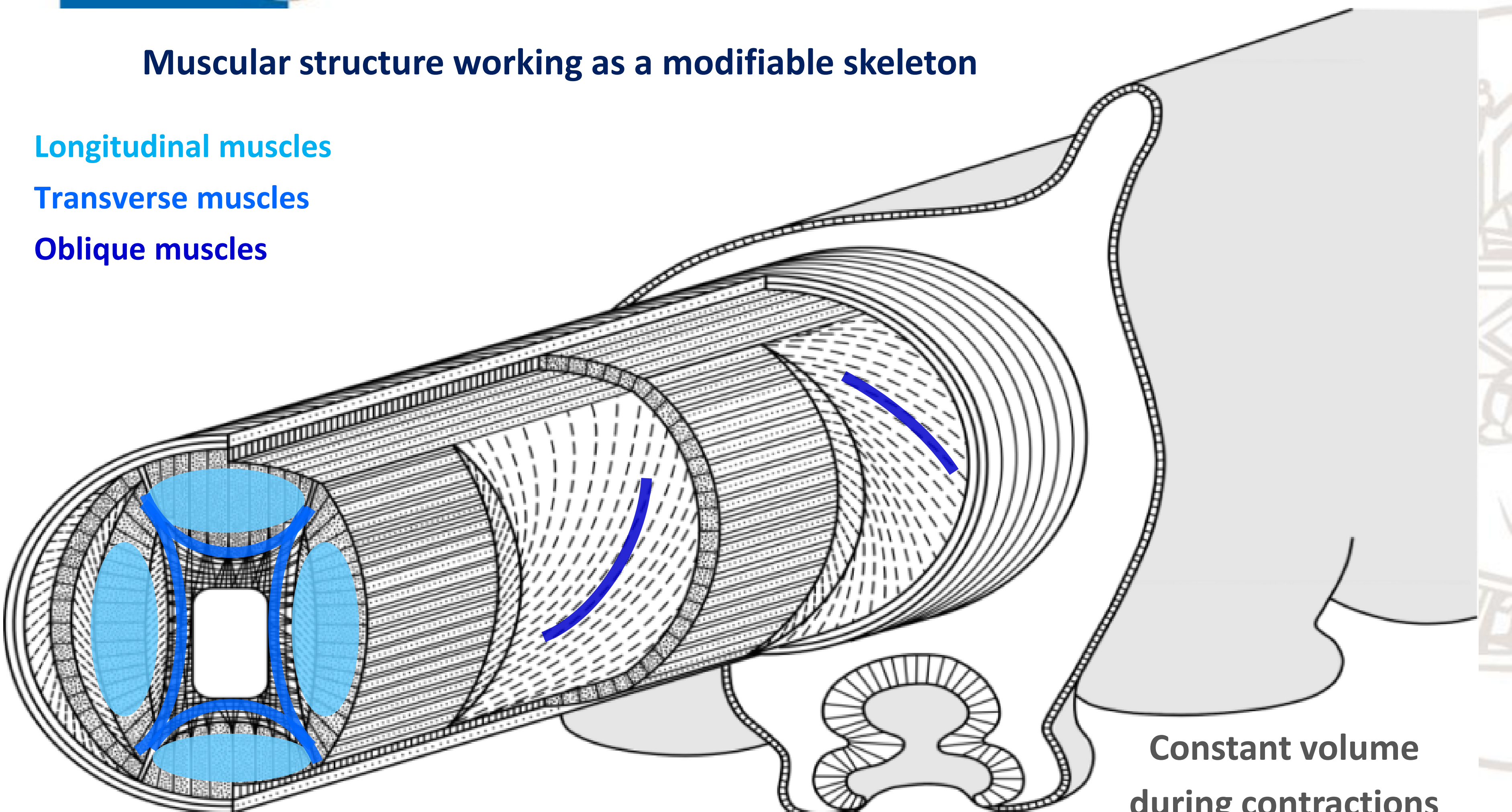
Octopus muscular hydrostat

Muscular structure working as a modifiable skeleton

Longitudinal muscles

Transverse muscles

Oblique muscles



Constant volume during contractions

Simplifying principles in elongation and stiffening

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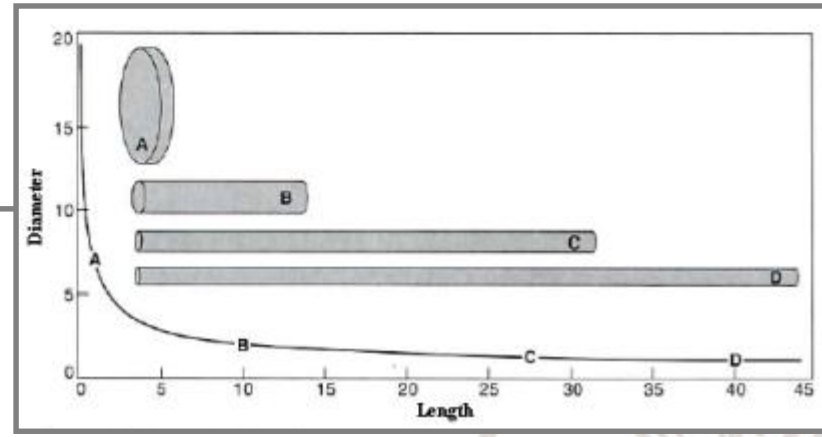
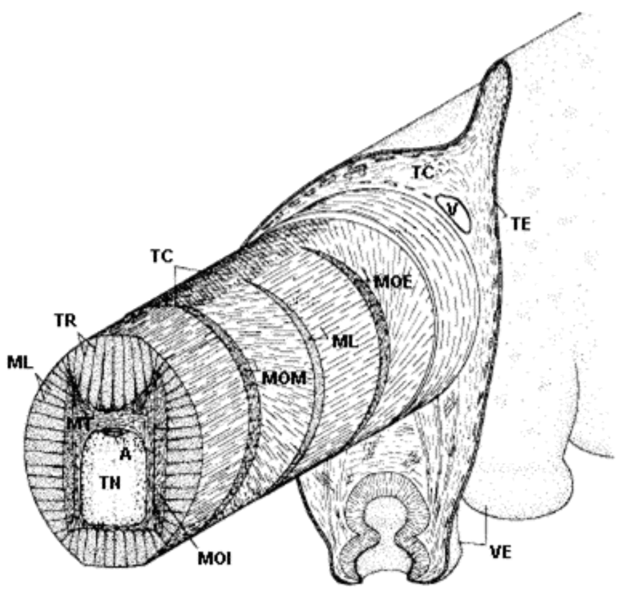
Octopus muscular hydrostat

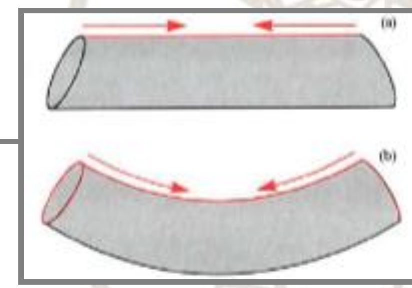
- ELONGATION
- SHORTENING



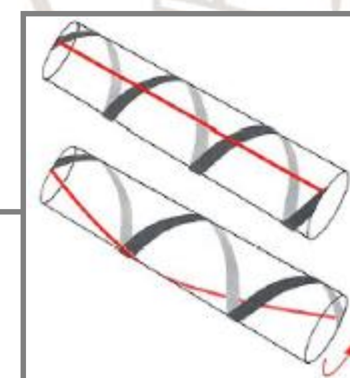
- STIFFENING – co-contractions



- BENDING

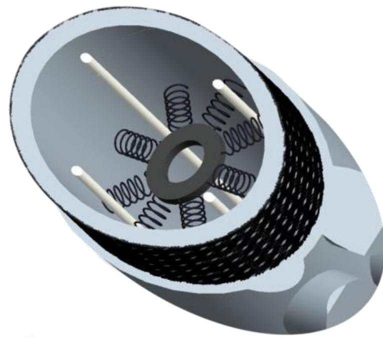


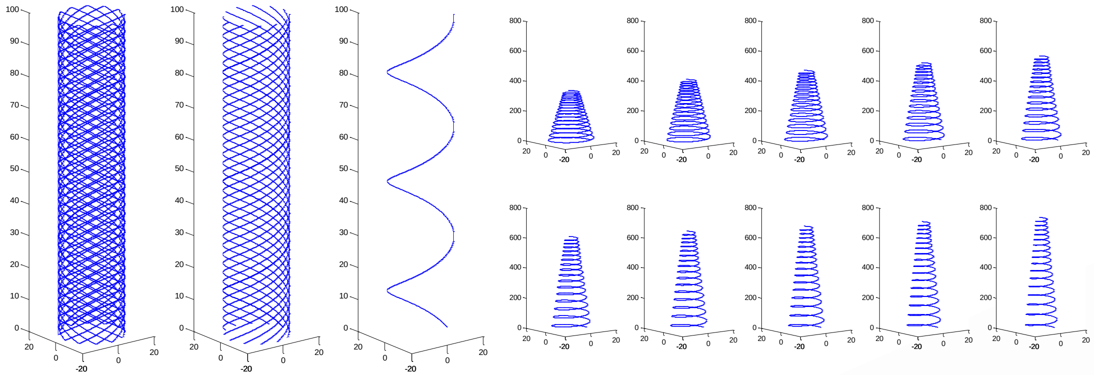
- TORSION



Kier W. "The arrangement and function of Molluscan muscle", *The Molluscа*, Vol. II, 1988

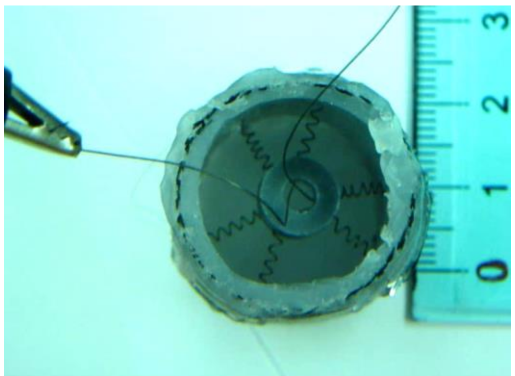
Octopus-like muscular hydrostat

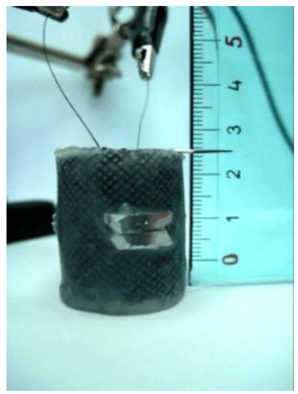




20% of diameter reduction

89% of elongation





Diameter reduction by 25%,
elongation by 41.3%

PATENT

1 second of 600 mA direct current and then 50% duty cycle pulse current

6 SMA springs:

- 0.2 mm Flexinol® wire diameter
- <D>/d = 6 (cycle life parameter)
- Spring internal diameter = 1 mm

Silicone / braided sleeve:

- External diameter = 28mm
- Internal diameter = 20mm

Follador M., Cianchetti M., Arienti A., Laschi C., "A general method for the design and fabrication of shape memory alloy active spring actuators", *Smart Materials and Structures* 21(1), 2012

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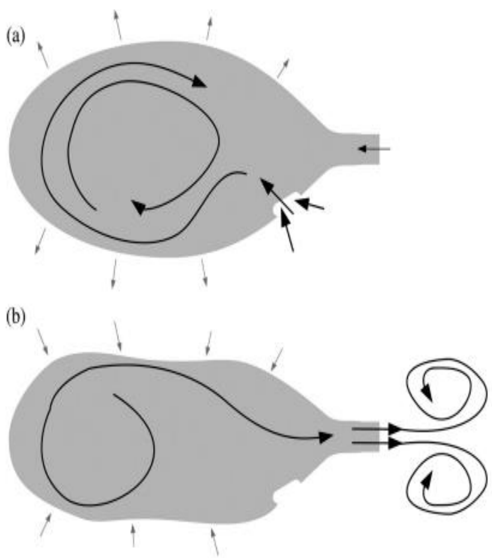
Sant'Anna School of Advanced Studies – Pisa

Pulsed-jet swimming in cephalopods

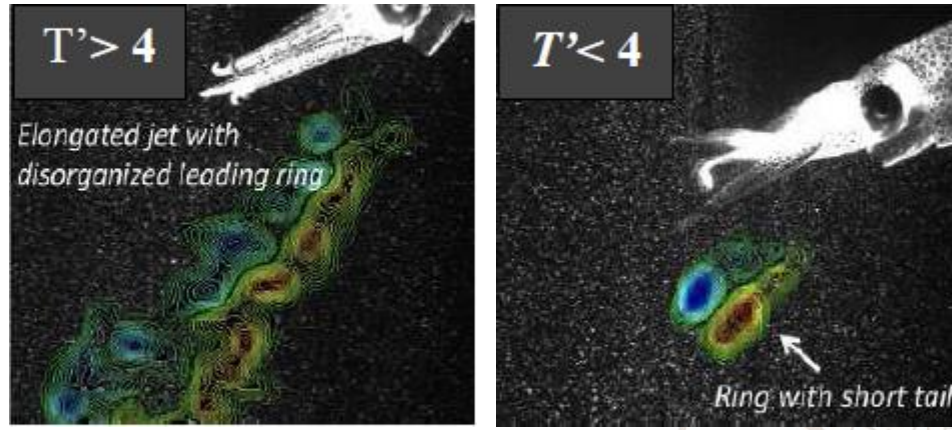


REFILL PHASE

- mantle expansion
- refilling of the mantle cavity through water inlets

JET PHASE

- mantle contraction
- expulsion of a fluid slug through the funnel (siphon)

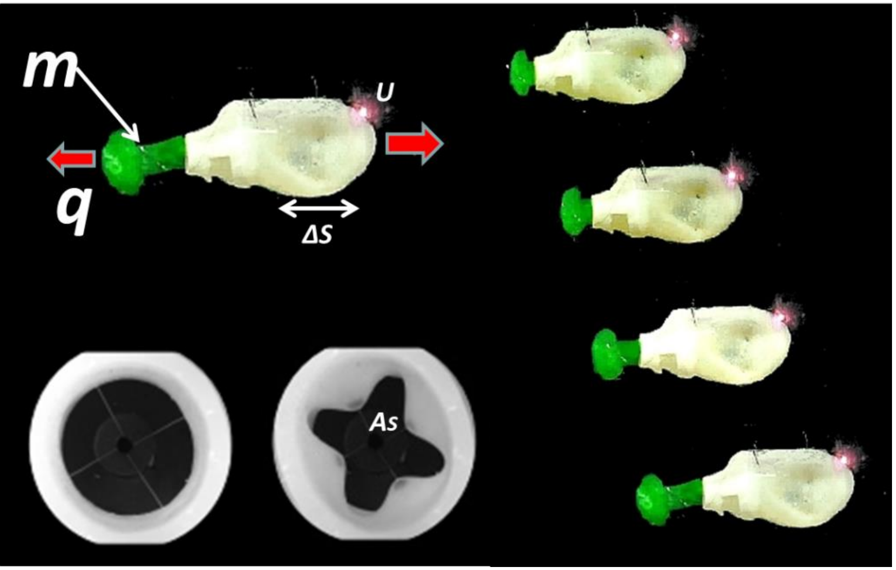


Ejection of a discontinuos stream of fluid through a nozzle that produces **ring vortexes**.
The generation of ring vortexes provides an additional thrust to the one generated by a continuous jet, by generating an additional pressure at the nozzle orifice

The mantle and siphon **morphology** and the pulsed jet **frequency** optimize propulsion, producing **ring vortexes**

Giorgio Serchi F., Arienti A. and Laschi C. (2013) "Biomimetic Vortex Propulsion: Toward the New Paradigm of Soft Unmanned Underwater Vehicles", *IEEE/ASME Transactions on Mechatronics*, 18(**2**), pp. 484-493

Pulsed-jet swimming soft robot



Silicone and cables, 1 DOF

PoseiDrone

The mantle and siphon **morphology** and the pulsed jet **frequency** optimize propulsion, producing ring vortexes (in green)

Giorgio-Serchi F., Arienti A., Laschi C. (2016), "Underwater Soft-bodied Pulsed-Jet Thrusters: actuator, modelling and performance profiling", *International Journal of Robotics Research,* 35 (11), 1308-1329

Summary
Bioinspired simplifying principles

- Simplexity
- Retina-like vision
- Sense of movement
- Predictive architectures
- Embodied Intelligence
- Neuro-controllers