Sensory robotics

Lecture 02.

i.) Introduction

ii.) Human sensing and sensors in biology

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02.15.2021.

Lecture 02.

- 1. Introduction - sensors
- Motivation and parallelism with biology; sensing categories, propriocepction, exteroception, exproprioception; reviewing the history of robotic sensors from the 70s, sensor revolution, state-of-the-art robotics, challenges and future of the sensors
- 2. Human sensing and sensors in biology
- Mechano-, termo-, and nociceptors; fast-slow adaptation; touch; pain; balancing; vision; visual-tactile-motori mechanisms; hearing; smell and taste; sensing the inner state; special sensors in biology: localisation (eg. birds, and salmon), distance measurement (eg. owl, bat, whale).

The sensor's age – Data's age

- The sensors revolution - a new approach
  - Small, inexpensive sensors, all measureable
  - More and more computing power is available (GPUs, FPGAs) – data processing in real time
  - Easy to use devices and tools
    - Person of Interest (TV series)
    - Mobile phones listen, traffic lights see and monitor, street cameras are everywhere
    - The interaction between human and machine changes, „gesture control”
  - Sensors will be everywhere - interactivity all
    - From games to vehicles, to smart homes and … with robots

Perception becomes part of the devices

- Sensors are easily available and easy to integrate into the devices
  - Cheap price, even high complexity, increasingly important to include the design
  - A significant change appears in the use of sensors. Instead of using one or two special purpose sensors, many general purpose sensors are integrated into our devices (later may evolve/develop/appear specific demands on request)

Modalities

- The sensing modalities appear collectively
- Physics help to connect a measured quantity with an unknown
  - From the temperature we can deduce wind speed (heat loss)
  - From displacement we can deduce
    - pressure (eg. In case of a spring: $F = kx$)
    - volume ($V = Ah$)
    - speed (based on measurements performed at two different times: $v = dx/dt$)
    - temperature (thermometer indicator)
    - vertical angle (based on the displacement of the bubble)
  - Additional parameters can be evaluated from the measurements using the appropriate mathematical models
    - Eg. using Kalman filter

Active and passive sensing

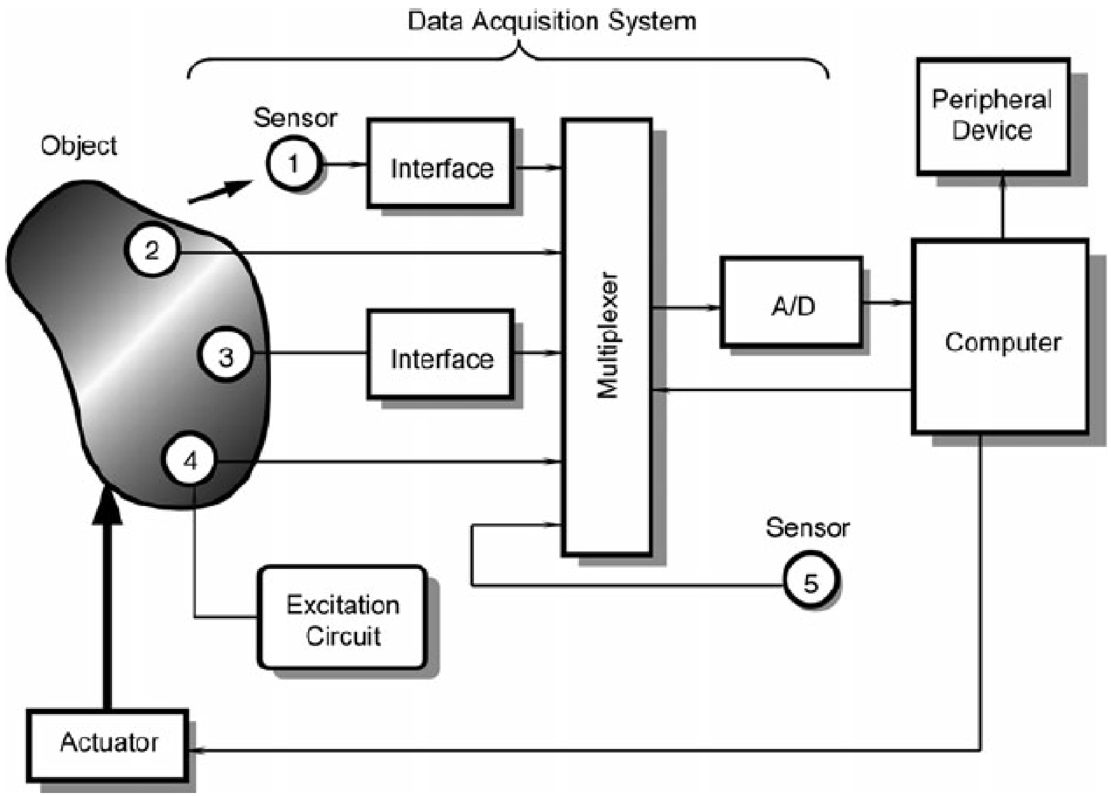


Fig. 1.3 Positions of sensors in a data acquisition system. Sensor 1 is noncontact, sensors 2 and 3 are passive, sensor 4 is active, and sensor 5 is internal to a data acquisition system

- Sensors (2,3,4), non-contact (1), and inner (calibration) sensing (5)
- Active sensor (4) requires a power source and generate responses by stimulating its environment – eg. termistor, FSR, radar
- A passive sensor (1,2,3,5) generates response using the received energy – eg. photodiode, piezo microphone
- Interventions to facilitate the perception

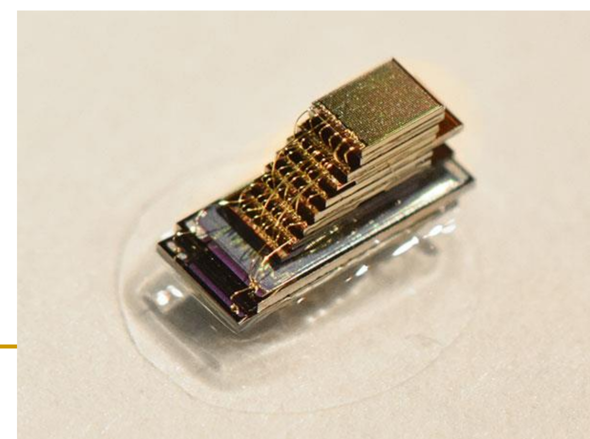
- Source: Fraden, J. Handbook of Modern Sensors

Motivation and parallelism with biology

- Nature vs. engineering solutions – muscle vs. engine, leg vs. wheel, human intelligence vs. artificial intelligence
- Robotics: human vs. humanoid, animals vs. mobile robots
- Biology shows solutions, but they may not be optimal
- We can get answers to our questions, moreover we may learn such functionalities and solutions, where even we did not know the question (eg. functions of vision, functions of hearing)

“Micromote” Computers Do Deep Learning

Many of the microphones, cameras, and other sensors featured on today’s smart devices are always on alert. What’s more, they frequently beam personal data into the cloud because they can’t analyze it themselves. But by 2035, when there will likely be close to a trillion such devices, we’d be drowning in data. Two University of Michigan computer scientists have been making steady improvements on so-called micromotes. Because these **millimeter-scale computing sensors can do analysis on board (using artificial intelligence)**, they make electronic gadgets more secure and energy efficient.



Sensing categories I.

- Proprioceptive sensing – self-monitoring
  - Measured displacement relativly to the robot’s own coordinate system. Measurement of signals that can be measured in the robot to control and maintenance the internal status.
  - Usually monitoring the state of the battery, current, and internal temperature.
- Proprioceptive sensors are:
  - GPS (Global Positioning System) – low refresh frequency rate, inaccurate, can not be used indoors
  - INS (Inertial Navigation System) –„slips” (drift) in time due to the cumulative error
  - Encoder – detects rotation and provides analog or digital signal proportional to the rotation
  - Compass – direction sensors
  - Inclinometer – tilt sensor

Sensing categories II.

- Exteroceptive sensing – environment monitoring
  - Measurement of the environment relativly to the robot's own coordinate system. These sensors are called as proximity sensors.
  - Proximity sensors measure the distance from the objects around the robot. One of its main applications is collision avoidance.
- There are three categories of exteroceptive sensors:
  - **Contact sensors:** Contact sensors are typically simple mechanical switches that send a signal when physical contact is made. Contact sensors measure the forces and torques of the interaction (eg. in case of a robot manipulator). Tactile sensors are also contact sensors, they can measure the parameters of the interaction with the surface on the touched object.

Sensing categories III.

- Exteroceptive sensing – environment monitoring
  - **Range Sensors:** Range sensors measure the distance to objects in robot's operation area. A sensor detecting an object in a given range with producing a binary signal is also a range sensor. Range sensors are used for robot navigation, obstacle avoidance, or estimating the third (depth) dimension of the vision. The principle measurement methods of range sensors can be TOF (time-of-flight) or triangulation.
  - It involves extracting, characterizing and interpreting information from images in order to identify or describe objects in environment.
  - **Vision Sensors:** Robot vision is a very complex sensing process. The identification, classification and characterization of the objects in the environment requires serious image processing, including feature extraction and processing the information content of the given image.

Sensing categories IV.

- Exproprioceptive sensing
  - These sensors measure the position of the robot relative to the environment.
  - Exproprioceptive sensors use a combination of proprioceptive and exteroceptive monitoring.
  - Sensing absolut direction and position instead of sensing relative distance to the coordinate system of the robot.
  - Determination of the position of the robot in a static or dynamic map.
  - Examples: SLAM (simultanous localization and mapping) techniques where displacement measurement of the internal sensors (encoders) is combined with the measurement of the range sensors, thus with continuous refinement the slide effect of the cumulative error can be eliminated. And even robot localization in a dynamic map can be implemented.

History of robot sensors I.

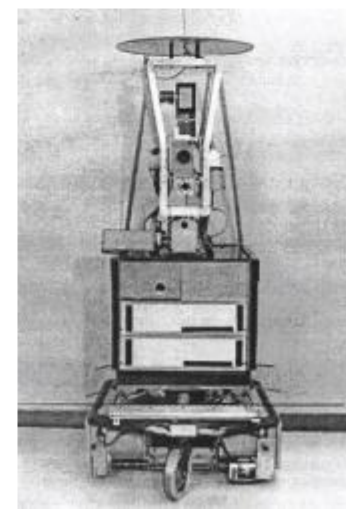
- Light Detection -> Hues -> using cameras -> higher resolution and more computation -> multi-camera usage -> stereo processing
- Contact / collision detection -> using piezo-electrical contacts the magnitude of the interaction can be measured -> detection of vibration and other effects -> tactile sensors, which can sense not only the size of the force, but also detect the direction of is -> number of sensors increases
- Fusion, example: IMU (Inertial Measurement Unit), tilt sensor, in which 3D accelerometer, gyroscope and compass is integrated.
- Distance measurement initially binary -> improved resolution -> differentiated according to price / performance -> 2D -> 3D

History of robot sensors II.

- Measurement data processing -> development of image processing methods -> increase in computing power -> development of methods and algorithms (SLAM, etc.)
- GPS -> resolution -> development of indoor positioning methods (wifi, GSM-based systems)
- Mobile robotics requires brain complex processing units, it is still not resolved, although there are encouraging results (SLAM, Deepmind) -> AI progress is expected
- Stereo vision -> 2D-3D LIDAR -> depth cameras (Kinect PMD) -> resolution is expected to grow, eg. Google Tango -> integration
- Sensor Networks -> better quality and more results

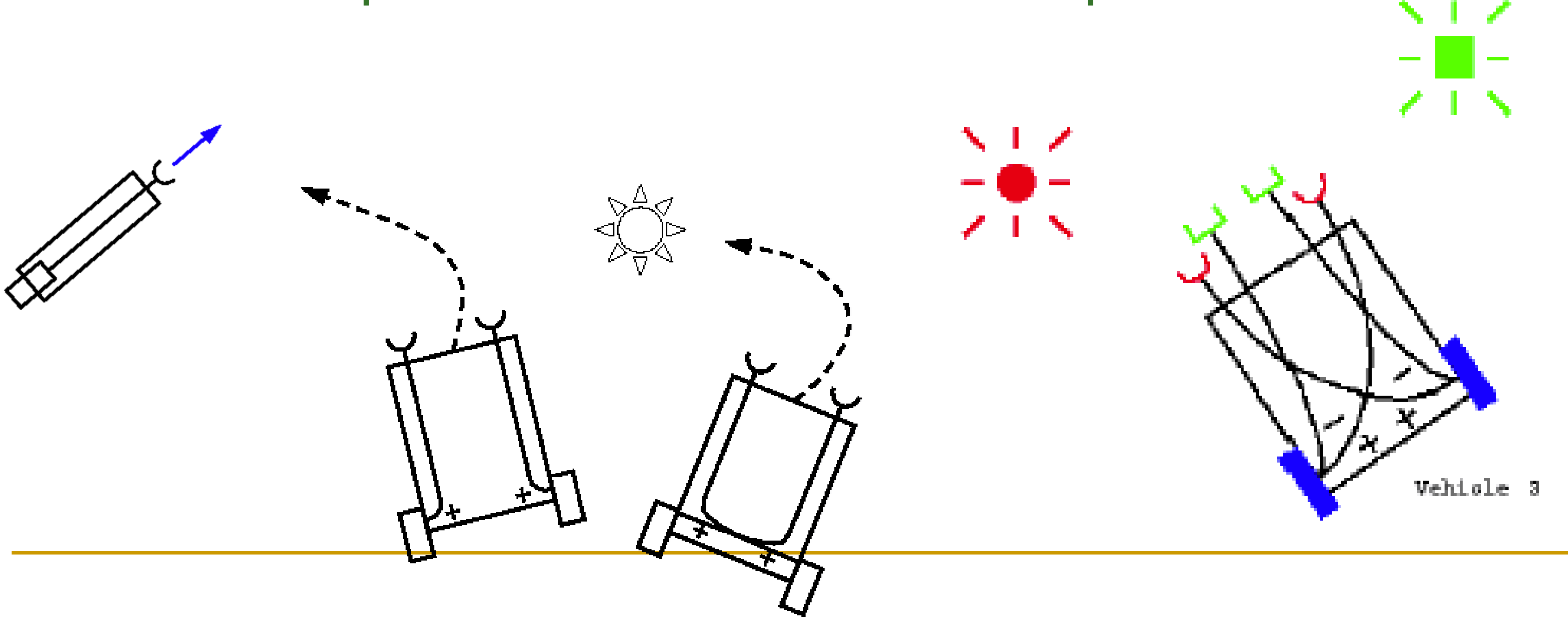
History of robot sensors III.

- 1966 Shakey
  - One of the first mobile robots
  - Sensors
    - camera
    - optical telemetry
    - bumpers
  - Wireless connection (optional)
  - Office environment
  - Planner modul (STRIPS): what to do to reach its goals
    - based on first-order logic
  - Low and high-level actions for simple movements and complex tasks
  - World model



History of robot sensors IV.

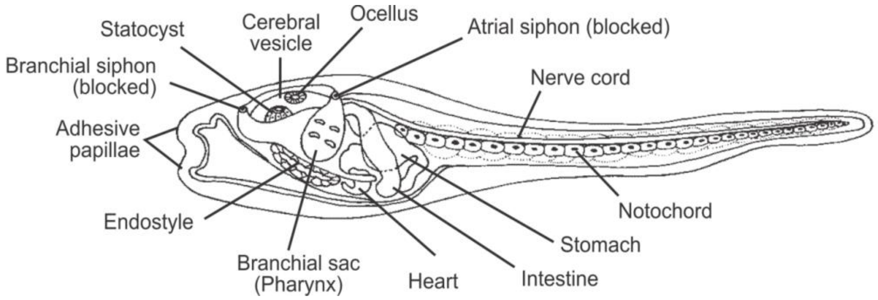
- 1984 Braitenberg
  - Vehicles
  - Excitatory and inhibitory inputs
  - Direct connections to the motors
  - Complex behavior based on simple structure



History of robot sensors V.

Motivation

- Sea sponge (Ascidiaceae)
  - two functional stages of life
  - in larval condition it has an eye-like sensor and a nerve-like processing center
- For a biologist, this means,
  - the evolution of the eye and brain is due to the appearance of locomotor movement.
- For an engineer, this means,
  - mobile robots require powerful sensors and brain complex processing units



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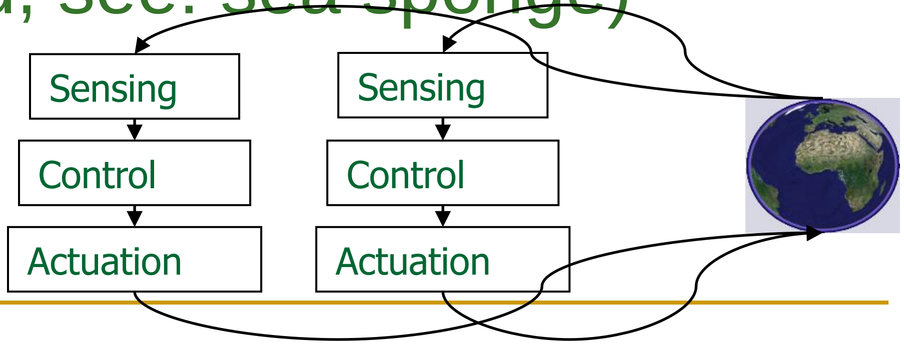
Why is mobile robotics interesting?

- Industrial robots vs. mobile robots
- You can not prepare for any event
- It is difficult to model the world in real-time
- The sensors and actuators are limited and inaccurate
- The environment changes dynamically
- We do locomotion and change place! (sensors and ‚brain' are required, see: sea sponge)
- There is no proper AI (yet)



Why is it so difficult to do robotics?

- The sensors are limited and inaccurate
- The actuators are limited and inaccurate
- The models are simplified and inaccurate
- The status (external and internal, but especially external) can be only partly observed
- The environment changes dynamically
- The environment is full of potentially useful information

Fundamental questions of robotics

- Where am I? (localization)
- How to interpret the sensory signals to define the current state of my position and parameters? (perception)
- How to combine the information from many sensors? (sensor fusion)
- What assumptions do I have to do about the environment? (a priori knowledge)
- What should I focus on? (attention)

Fundamental questions of robotics

- What control strategy should be applied?
- How to make decisions? (Reasoning, problem selection)
- Where do I want to go and how to get there? (navigation)
- How to adapt to the changing environment?
- How to work with other robots?
- AI? Machine learning? (At least low level automated tasks.)

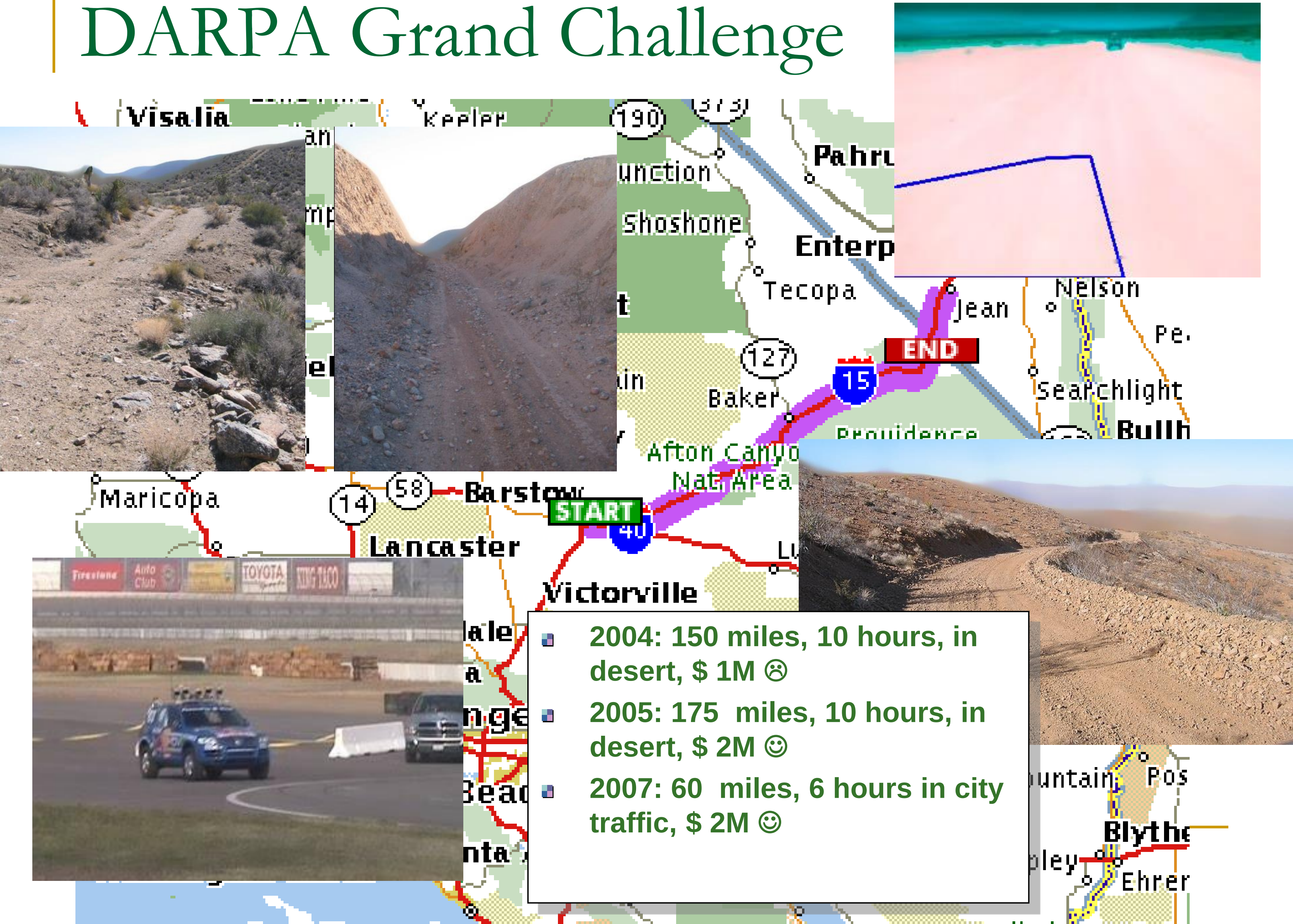
Autonomous vehicles - Motivations

- Military purposes
  - 2001 US congress:
    One third of the vehicles
    should be autonomous by 2015
  - More than $500 M was spent earlier
  - The future of military vehicles
- Social perspectives
  - Road accidents (USA): 42636 Dead (2004), 2.788 million injured (automatic transmission, smart phones, tablets)
  - Traveling to work (USA) 1.25 hours per day / working man
- Long-term benefits
  - Saving lives, cost-effectiveness
  - The optimization of traffic routes

DARPA challenges

- 2004:
  - Autonomous vehicle (no human driver and no remote control), 142 miles in less than 10 hours $ 1M in the desert, Mojave desert, rocky mountain roads
- 2005:
  - Autonomous vehicle, 175 miles in less than 10 hours in the desert, $ 2M, Mojave desert, rocky mountain roads
- 2007:
  - Autonomous vehicle, 60 miles in less than 6 hours of the city, $ 2M, $ 1M, $ 0.5M, traffic, buildings, pedestrian detection and avoidance, traffic signals and lights, parking, in some places GPS is completely blocked

DARPA Grand Challenge

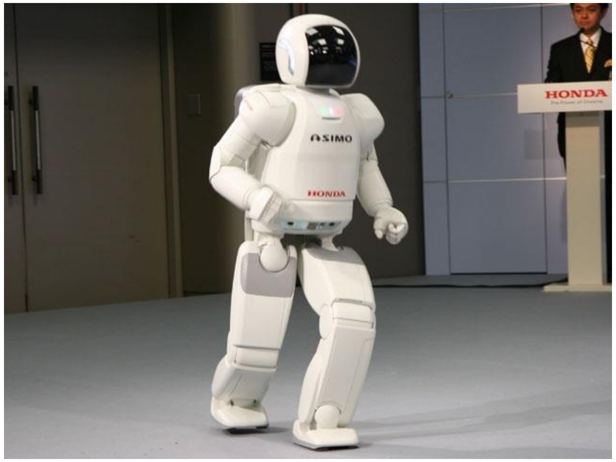


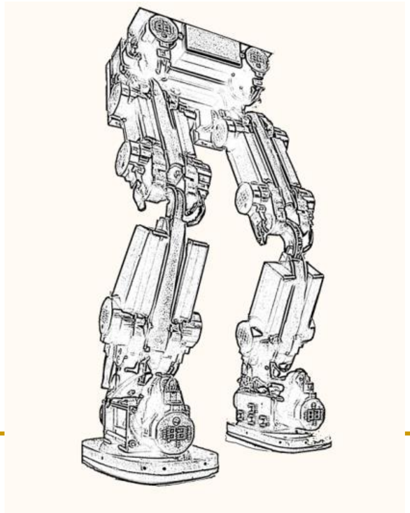
- 2004: 150 miles, 10 hours, in desert, $ 1M ☹
- 2005: 175 miles, 10 hours, in desert, $ 2M ☺
- 2007: 60 miles, 6 hours in city traffic, $ 2M ☺

Results and impacts

- Already integrated auxiliary functions in the automotive industry (parking, Tracking, overtaking, etc.).
- Efficient SLAM – simultanous localization and mapping algorithms (read Thrun et al: Probabilistic robotics)
- Google autonomous car - mapping without a driver
- In the US, three states gave permission for driverless cars
- Autonomous aerial and other vehicles (UAV, UGV, USV)
- Household appliances, military industry ...
- Unresolved problem?
  Specify the problem
  in a midterm... (or competition)

Humanoid robots





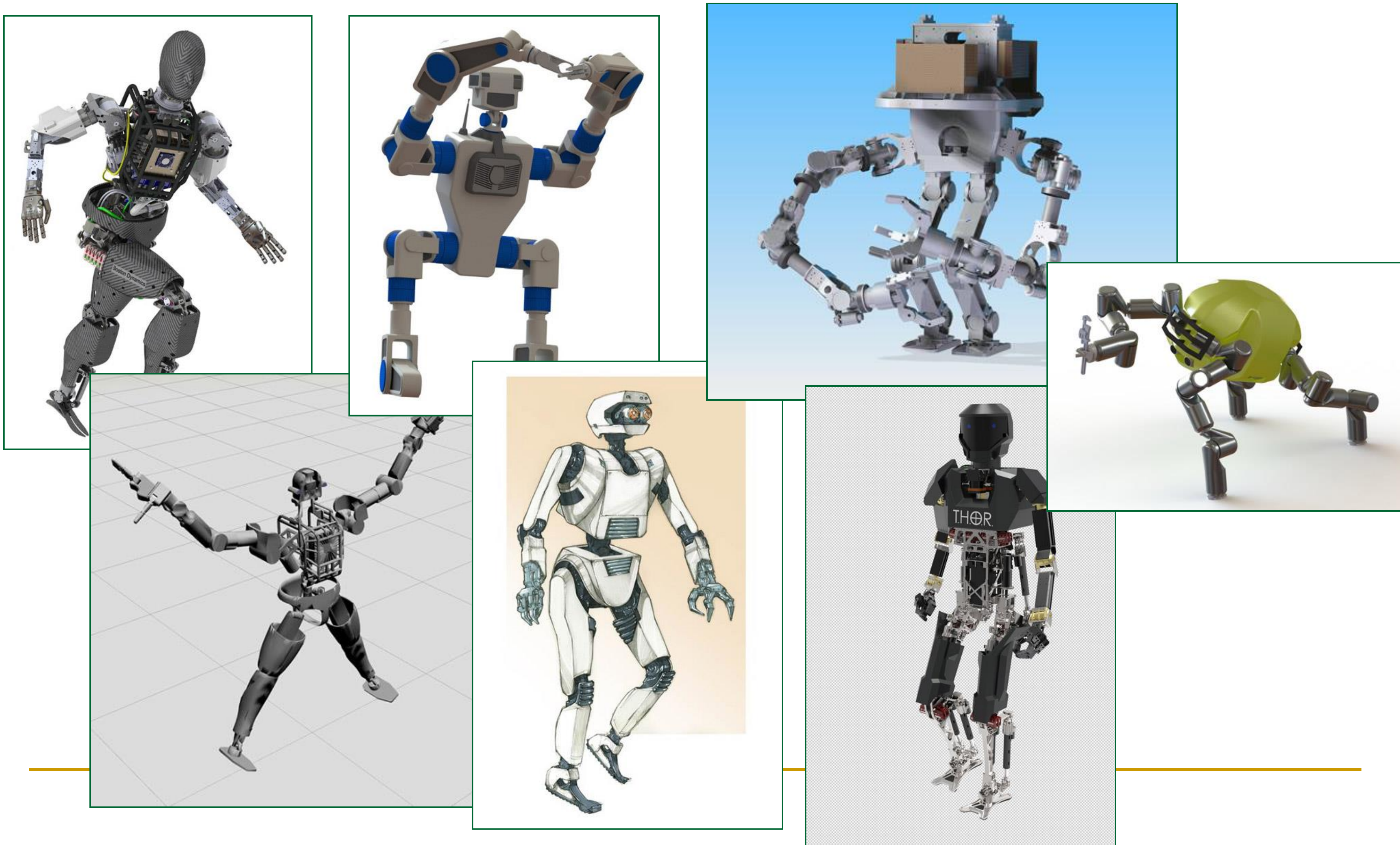
DARPA Robotics Challenge 2012

- Robotics competition with three stages
  - 2013 June – tasks in simulation environment
  - 2013 December – tasks in real environmnet
  - 2015 June - tasks in disaster environment (task details are not known)
- Motivated by the Fukushima disaster
- Humanoid-like robot must carry out complex tasks in disaster zone
- Different categories, 7 teams: hardware design, 11+n teams develop software and use Atlas humanoid from Boston Dynamics, m teams develop software and do not take part in the simulation challenge
- Semi-autonomous mode

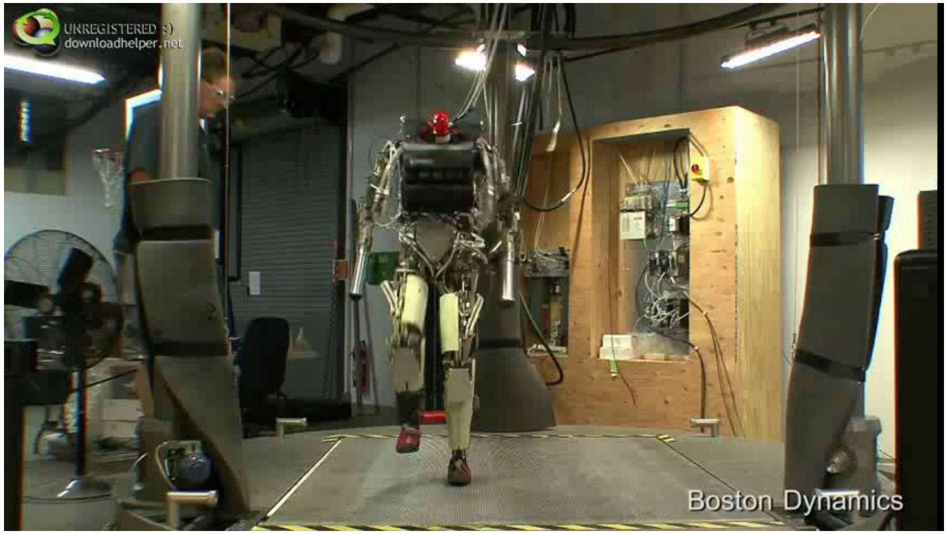
DARPA Robotics Challenge 2012

- „The new Grand Challenge is for a humanoid robot (with a bias toward bipedal designs) that can be used in **rough terrain** and for industrial disasters. The robot will be required to maneuver into and **drive an open-frame vehicle** (eg. tractor), proceed to a building and **dismount, ingress through a locked door using a key**, traverse a 100 meter rubble-strewn hallway**, climb a ladder**, locate a leaking pipe and seal it by **closing off a nearby valve**, and then **replace a faulty pump** to resume normal operations -- all semi-autonomously with just **"supervisory teleoperation"**."

DARPA Robotics Challenge 2012



DARPA Robotics Challenge 2012



DRC 2012 – 2015 results

DRC 2012 – 2015 results

Some related references

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- Torricelli D. et al. (2020) **Benchmarking Human Likeness of Bipedal Robot Locomotion: State of the Art and Future Trends**. Cognitive Systems Monographs, vol 36. Springer, Cham
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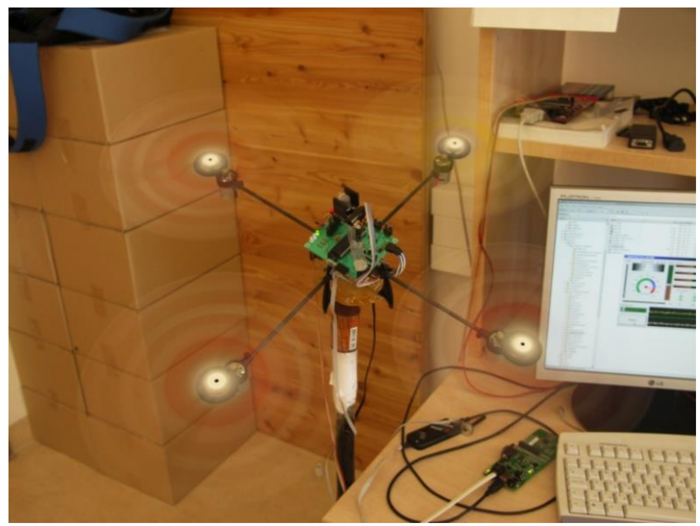
- Izquierdo-Córdoba, Luis Miguel, João Maurício Rosário, and Darío Amaya Hurtado. "**Hybrid Dynamic Modelling and Bioinspired Control Based on Central Pattern Generator of Biped Robotic Gait.**" In *Advanced Robotics and Intelligent Automation in Manufacturing*, pp. 233-268. IGI Global, 2020.
- Giraud, Kevin, Pierre Fernbach, Gabriele Buondonno, Carlos Mastalli, and Olivier Stasse. "**Motion Planning with Multi-Contact and Visual Servoing on Humanoid Robots.**" 2020.

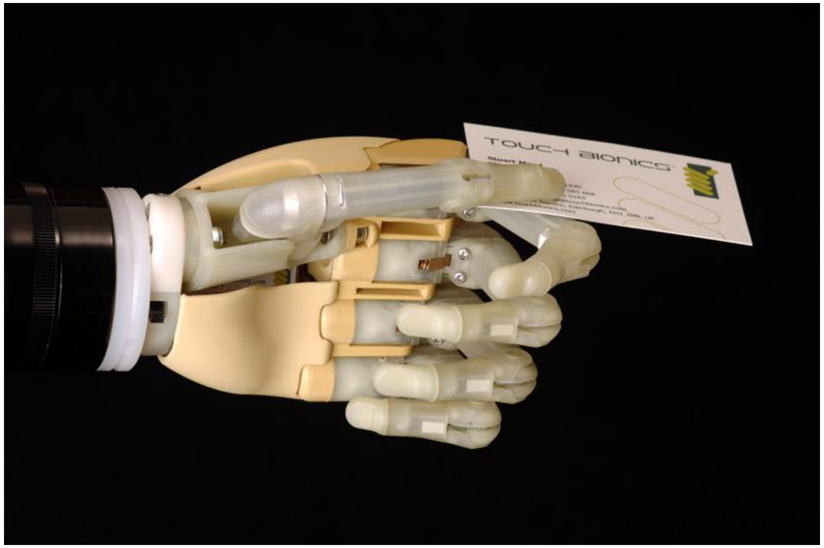
Robotarms – industrial robotics

UAVs - Unmanned Aerial Vehicles



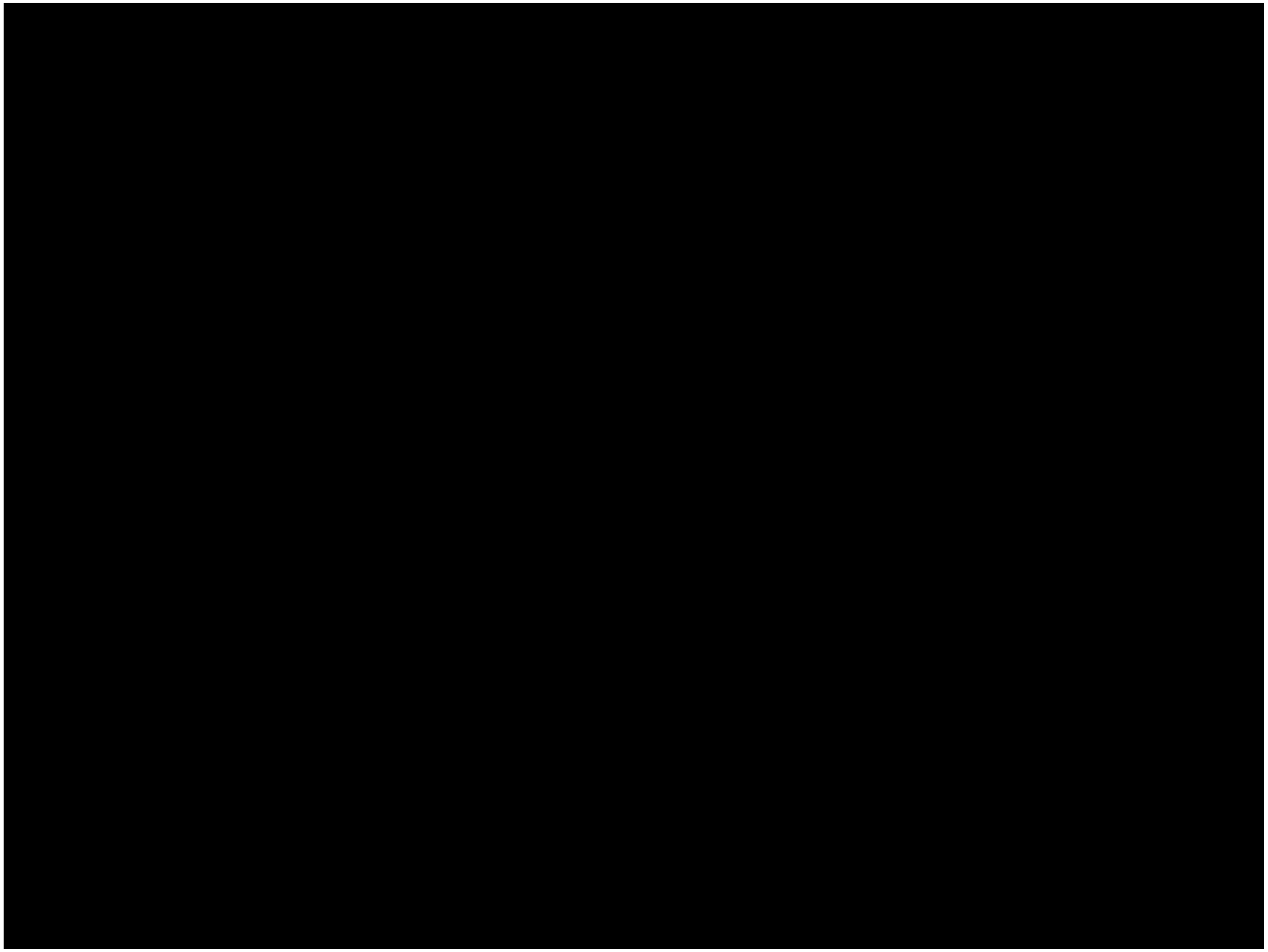
www.youtube.com

Robotic hands - prosthetics

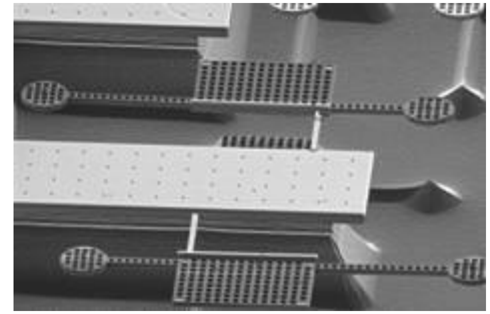


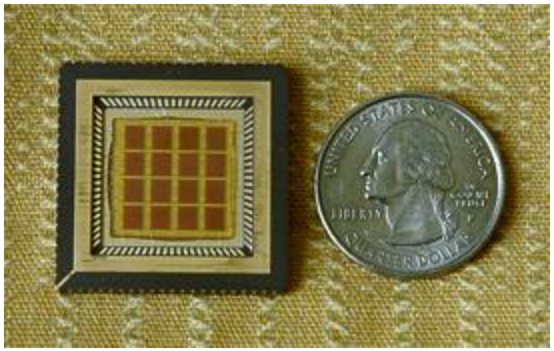
Swarm intelligence

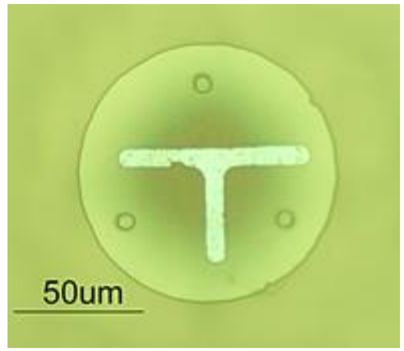
Swarm intelligence

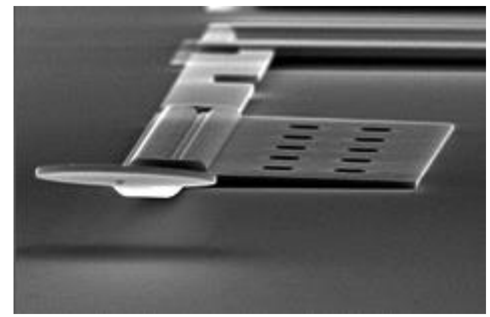


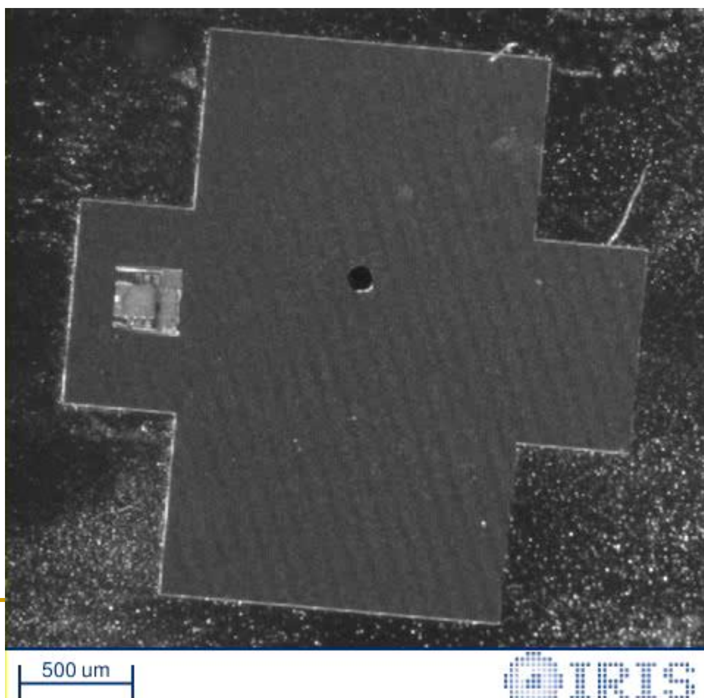
Nano-robotics

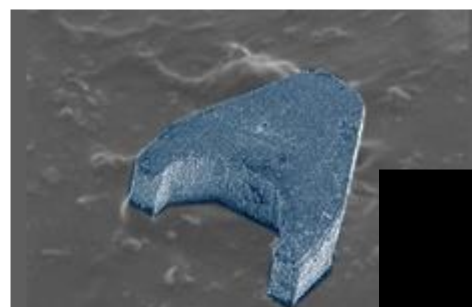


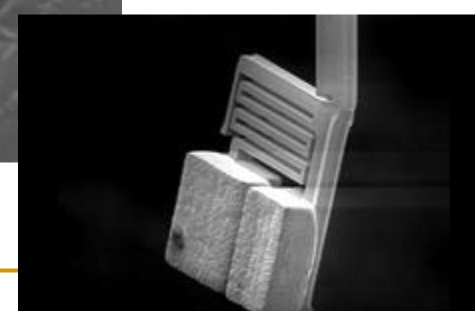






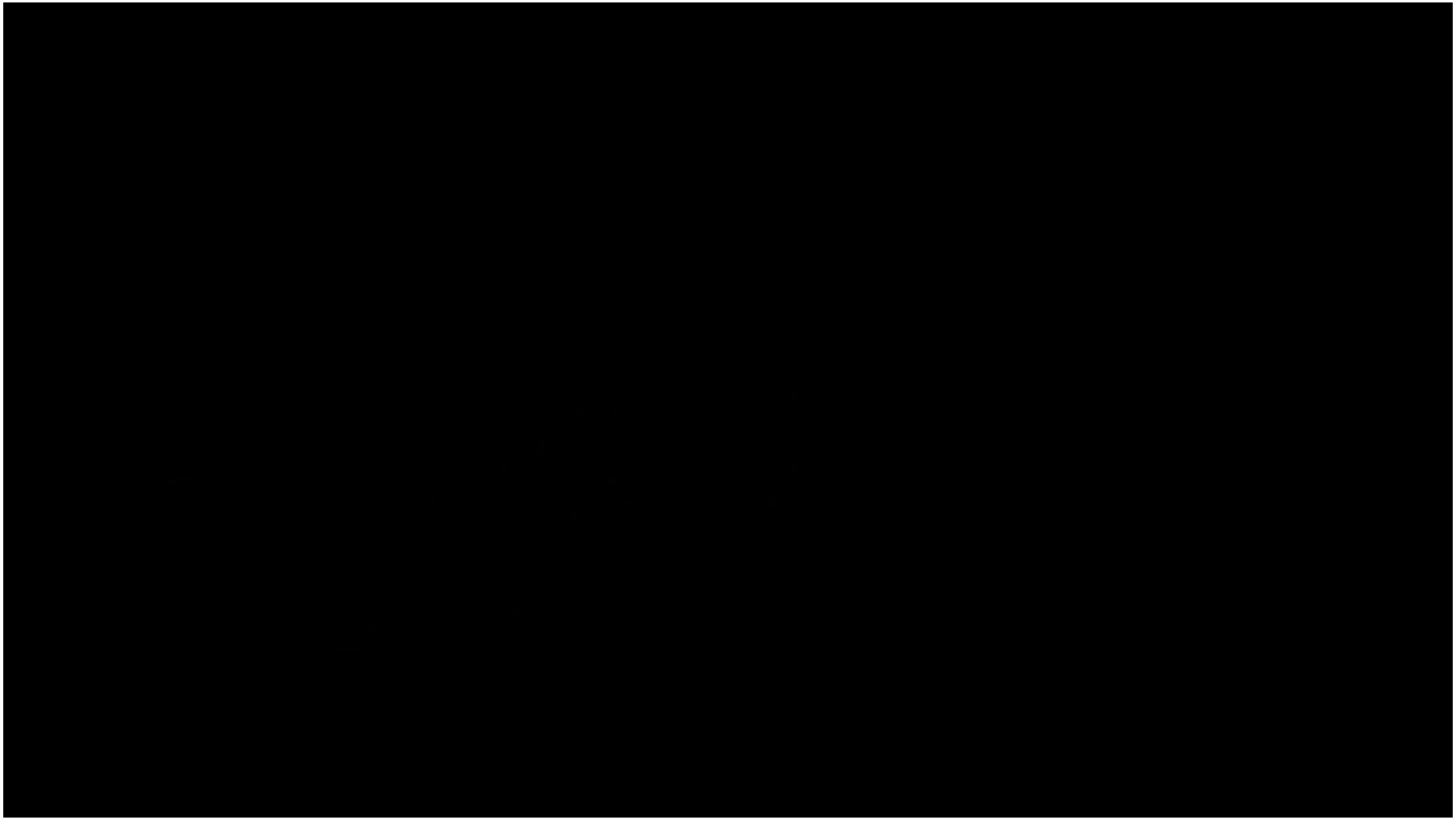






State-of-the-art robotics

State of the art



Future (?)

- DARPA Robotics Challenge, possible effects on daily life (eg. jobs)
- The classical robotic problems
  - power supply – autonomous vehicles
  - Human-computer interface/interaction
  - Actuation - artificial muscle
- Molecular self-assembly
- Bio-robotics

The source and impact of uncertainty

- The source of sensor noise:
  - The sensors are limited in resolution
  - Reflection, absorption
  - Poor condition for sensing (eg., low light conditions)
- The source of actuator noise:
  - Friction: fixed or variable (carpet, PVC, asphalt, clean and dirty)
  - Sliding
  - Battery current is changing (consumption)
- Impact:
  - It is difficult to interpret the sensor signals
  - In case of repetation the same action has different effect
  - Missing information while making decisions

The sensors revolution

- The size is decreasing
- Reduced price, sensors are available for everybody
- The resolution is increasing
- More and more computing power is available
- New sensors
- Some important new results and breakghroughs, such as autonomous cars
- New methods
- Sensor networks

Challenges and future of the sensors

- „Internet of things” – miniaturization, cost effectiveness
- Medical diagnostics
- New sensors, principals, robustness
- Smart and autonomous multy-sensoral systems (eg. New speedcams)
- Autonomous cars, smart and auxiliary functions
- Smart, mobile world
- Space exploration

Human sensing

- Vision, hearing, touch, smell, taste
- Detection of balance, heat, pain, internal state
- Detection, conversion and processing of a physical stimuli or impact
- Information: which modality, what area (receptive field), Value of amplitude (value of frequency) and how long
- Receptors (work as a filter):
  - Photo or electromagnetic receptors (vision)
  - Chemical or Chemoreceptor (taste, smell, itching, pain)
  - Mechanical or mechanoreceptors (touch, hearing, balance, proprioception)
  - Thermoreceptor or thermal (heat sensation, feeling cold, body temperature)
  - Pain (tissue injury)

Sensors in biology

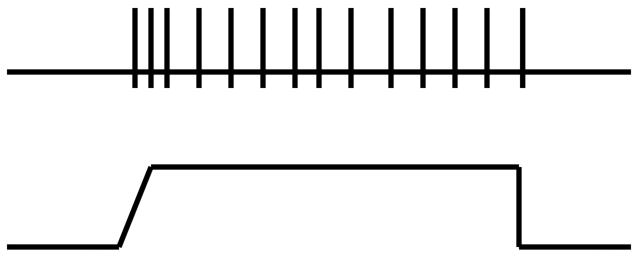
- Eye (mops eyes, compound eyes)
- Color detection, infrared and ultraviolet detection
- Temperature sensing, thermal imaging, temperature, fever
- Touch, vibration, earthquake ...
- Hearing, directional hearing, ultrasonic detection
- Odour detection, communication
- Taste, hunger, thirst
- Pain perception
- Balance detection
- Electricity detection
- Magnetic field detection

Fast-slow adaptation

- In case of persistent simuli, adaptations can be:
  - slow adaptation – persistent stimulus causes continuous firing line

firing line

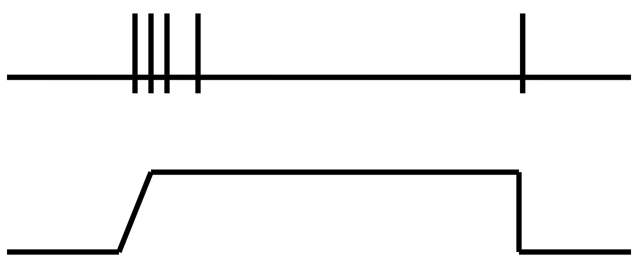
stimulus



  - fast adaptation – disappear after a short answer

firing line

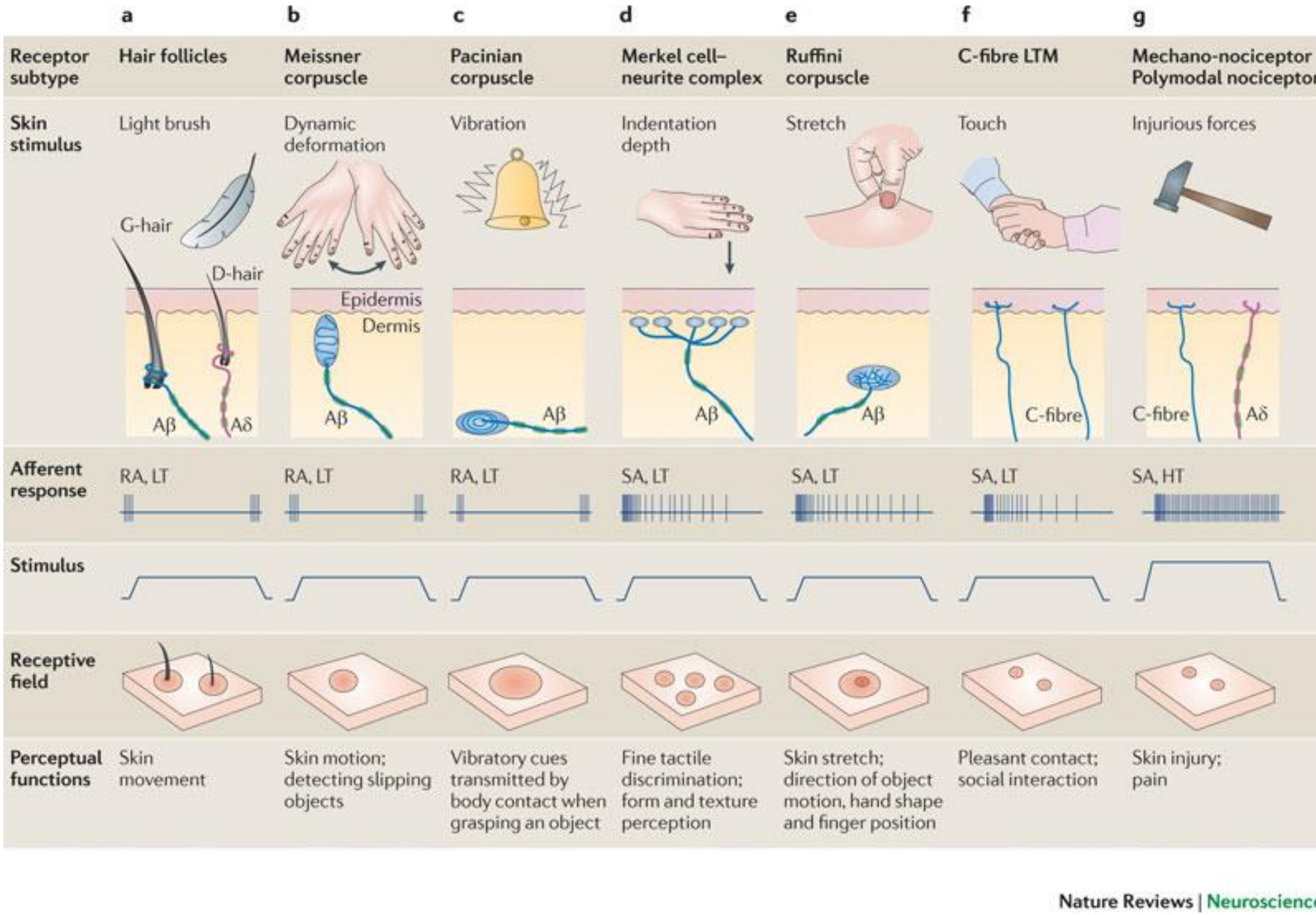
stimulus



Mechano-, termo-, and nociceptors

- The skin receptors can be categorized into three groups based on their modalities: mechano-, thermo- and nociceptors.
- The tactile perception is basically the sensing of mechanical effects.
- The thermal sensing is related to the detection of thermal energy transfer. The heat sensing receptors are Ruffini corpuscles/végtestek (warm receptors) and Krause's end bulbs/végbunkók (cold receptors).
- The pain receptors (nociceptors) of the skin are partially mechano and / or partially thermo-receptors, their activity generates the feeling pain.

Touch

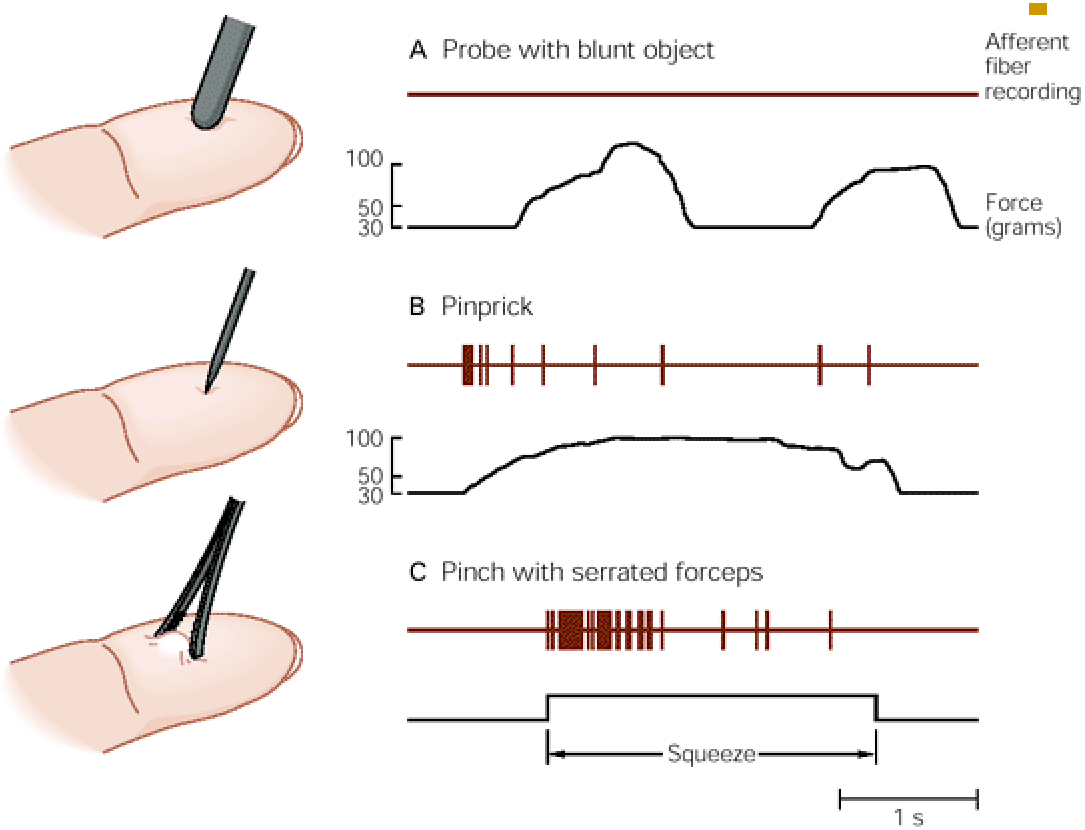


a
b
c
d
e
f
g
Receptor subtype
Hair follicles
Meissner corpuscle
Pacinian corpuscle
Merkel cell–neurite complex
Ruffini corpuscle
C-fibre LTM
Mechano-nociceptor Polymodal nociceptor
Skin stimulus
Light brush
Dynamic deformation
Vibration
Indentation depth
Stretch
Touch
Injurious forces
G-hair
D-hair
Epidermis
Dermis
Aβ
Aδ
Aβ
Aβ
Aβ
Aβ
C-fibre
C-fibre
Aδ
Afferent response
RA, LT
RA, LT
RA, LT
SA, LT
SA, LT
SA, LT
SA, HT
Stimulus
Receptive field
Perceptual functions
Skin movement
Skin motion; detecting slipping objects
Vibratory cues transmitted by body contact when grasping an object
Fine tactile discrimination; form and texture perception
Skin stretch; direction of object motion, hand shape and finger position
Pleasant contact; social interaction
Skin injury; pain
Nature Reviews | Neuroscience

Pain

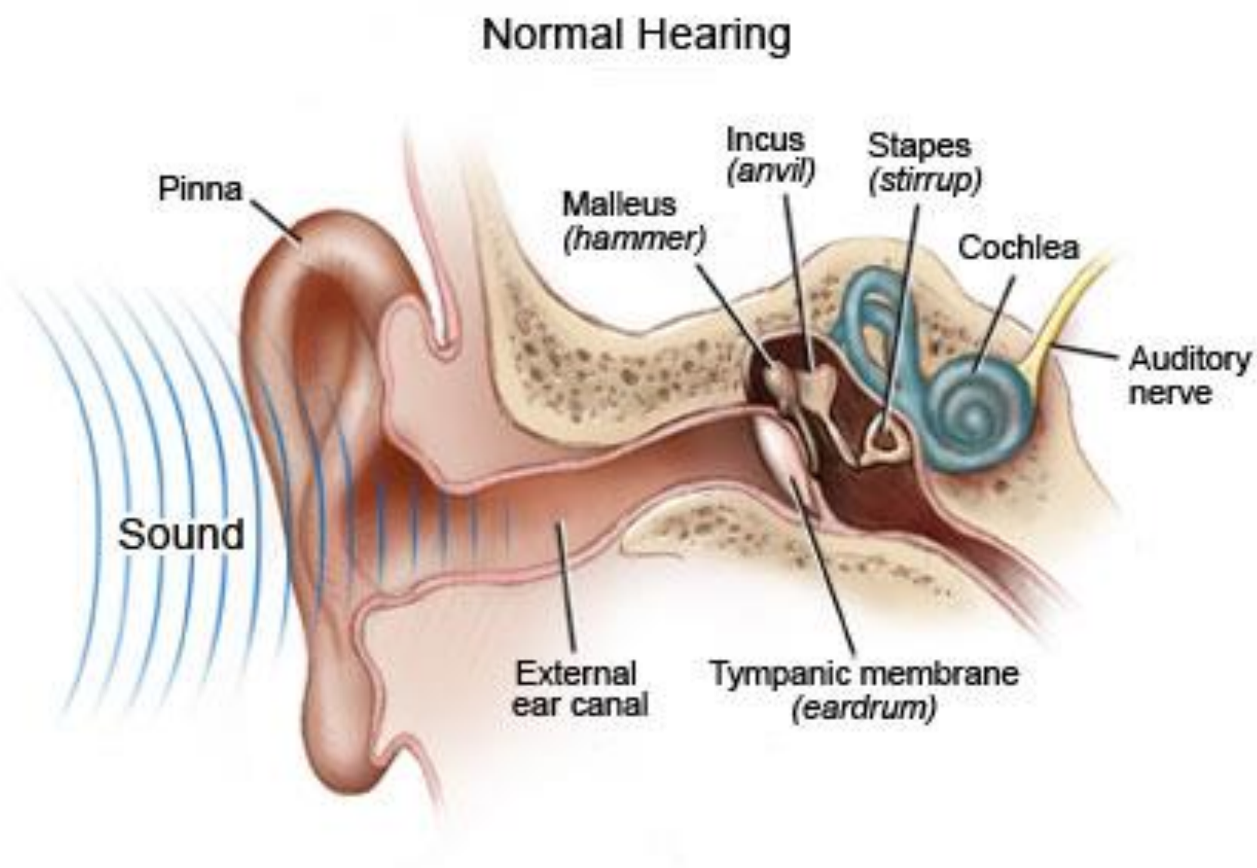
- Aim: to avoid and manage injuries.
- The intensity of pain is influenced by the actual environment. The same stimulus may have different response in different people.
- Nociceptors – receptors that are activated in the case of harmful impacts. It does not always coincide with the feeling of pain.
- Two types: acute and chronic.
- Three classes of nociceptors: thermal (extreme temperature), mechanical (intensive pressure on the skin) and polymodal (responds to very intensive sensations of mechanical, chemical and termal stimuli).
- Two sections of pain: first: sharp pain; second: blunt pain
- The outer and inner receptors both stimulate the same neurons – the higher levels of the nervous system cannot identify the source of the pain

Pain



- **Mechanical nociceptors are activated by strong stimuli and mediate sharp, pricking sensations.** Pressure on the cell's receptive field with a blunt-tipped probe elicits no response even if the skin is indented by 2 mm (**A**), but the tip of a needle that punctures the skin produces a clear response (**B**). The bottom traces in parts A and B are the output of a force transducer coupled to the stimulator. Pinching the skin with serrated forceps (**C**), which is more traumatic than a pin prick, produces the strongest response. (Adapted from Perl 1968.)

Hearing



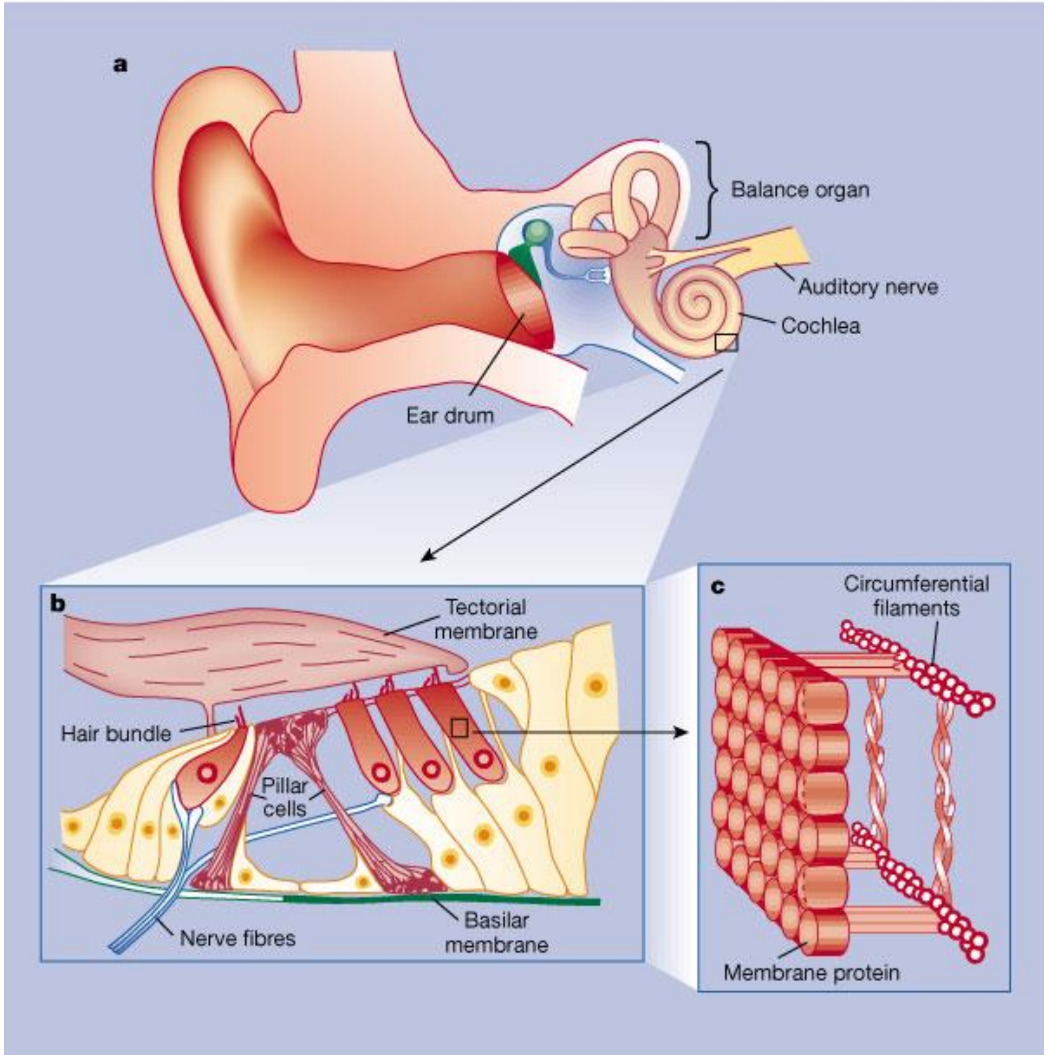
- Source: http://kidshealth.org/

Hearing

- The sound wave and the change of air pressure makes an impact on the eardrum –> The three ossicles bones move –> the stapes/stirrup pushes the oval window –> the fluid in the cochlea moves –> the secondary tympanic membrane/round window membrane moves
- Topographic encoding of frequency: Each and every frequency component of the sound creates a travelling wave on the secondary tympanic membrane/round window membrane. The place of the greatest deflection is found on the part of the secondary tympanic membrane/round window membrane that corresponds to the relevant frequency component. The receptors at the top of the travelling wave will fire the most.
- Coding intensity: The more intense the sound is, the more the hair cells will deflect –>more receptor activity (faster firing)

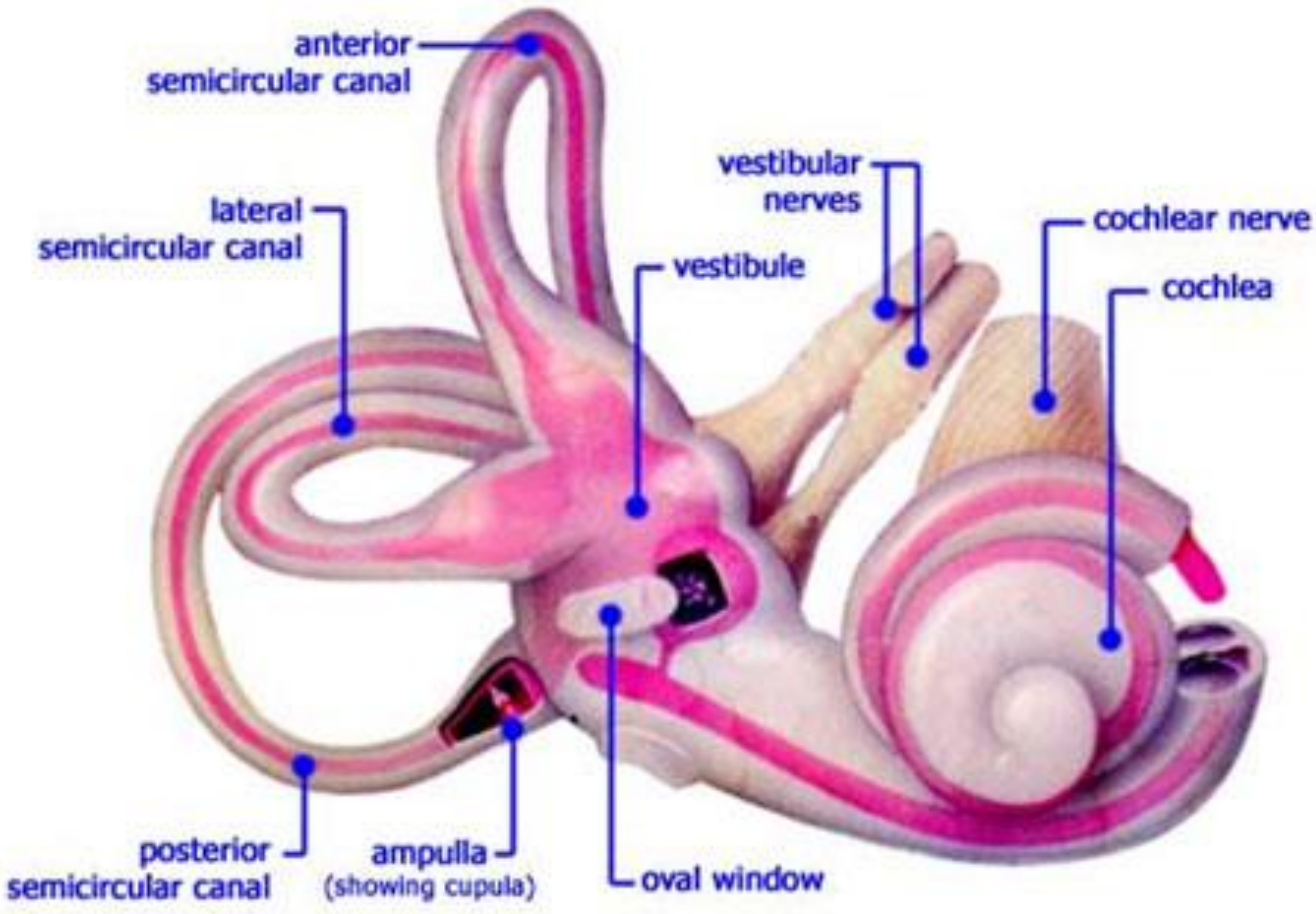
Hearing

- Organ of Corti, contains the hair cell receptors in the cochlea, on the secondary tympanic membrane/round window membrane
- Auricle!



- Forrás: http://pixshark.com/

Balancing



- Source: http://neurochangers.com

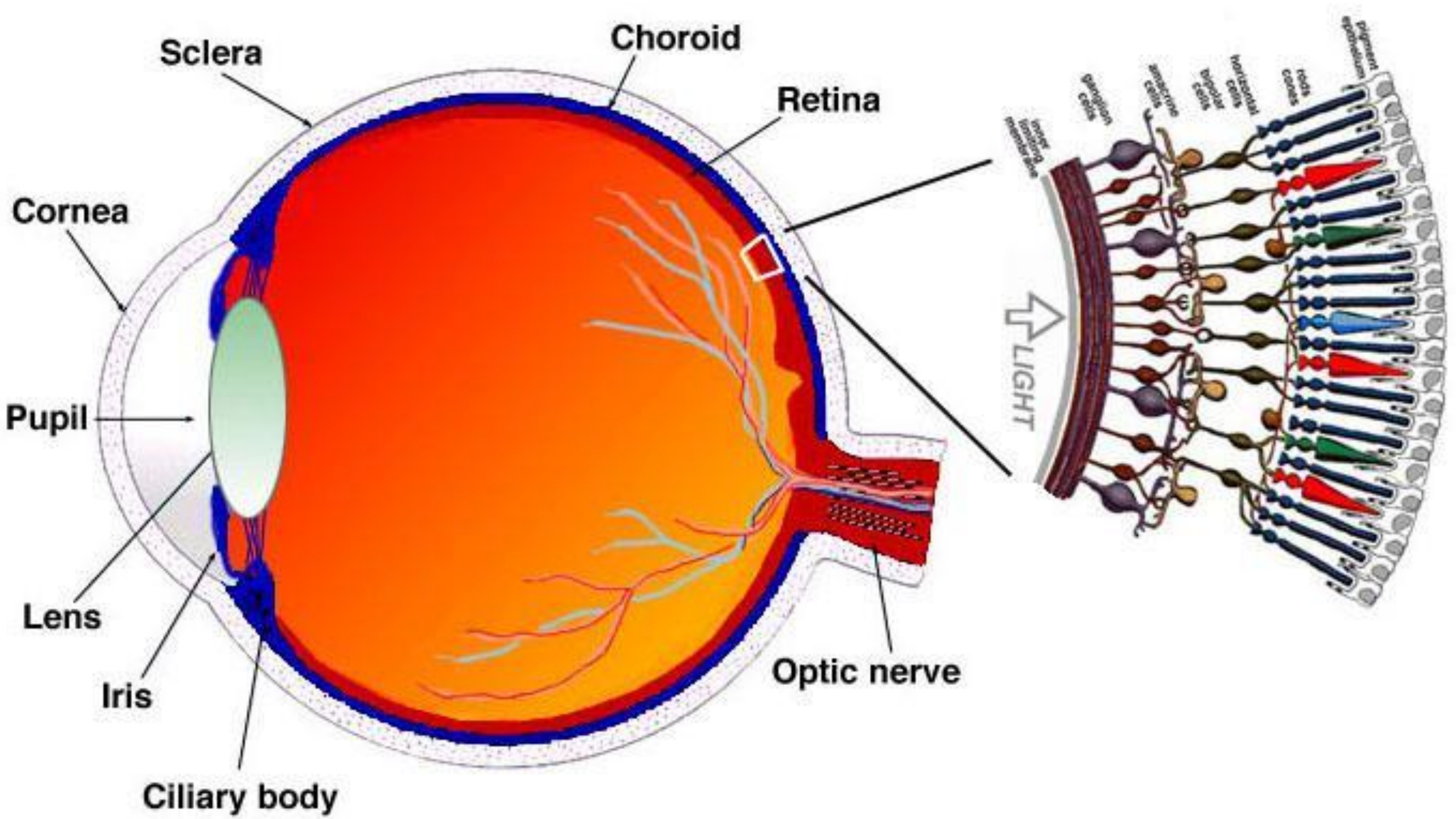
Balancing

- To define the **orientation of the body**, we need certain information that is supplied by labyrinth of the inner ear. This is also supported by the central nervous system.
- In the inner ear we find the bony labyrinth, which contains **the three semicircular canals, the utricle and the saccule (**a három félkörös ívjárat, a tömlőcske és a zsákocska**)**. These two senses the spatial orientation of the head. They are filled with fluid. They contain a stretch of receptors, with hair cells covered in a jelly-like matter. The semicircular canals are also filled with fluid, the movement of these produces the stimulus of the movement of the head.

Balancing

- Static balance (the spatial position of the head): The hair cells in the utricle and the saccule (tömlőcskében és zsákocskában) are covered with formations of calcium carbonate ($CaCO_3$). The epithelial cells sense the dislocation of these formations by the pressure taking place due to gravitation.
- Dynamic balance (the movement of the head): the three semicircular canals are placed perpendicular to each other, in three different planes of space. During movement, due to the inertia, the fluid flows in the opposite direction, which in turn effect the sensory hairs of the receptor cells.

Vision



- Source: Pedro Tomas

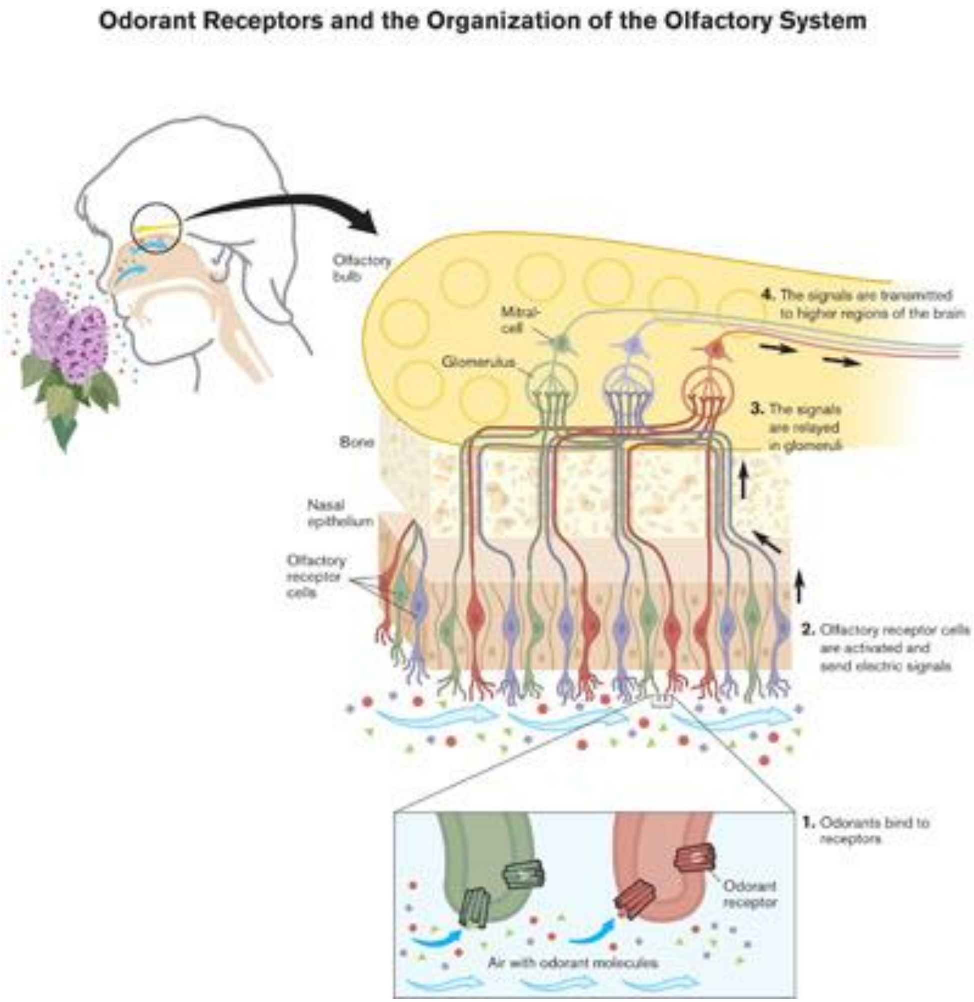
Vision

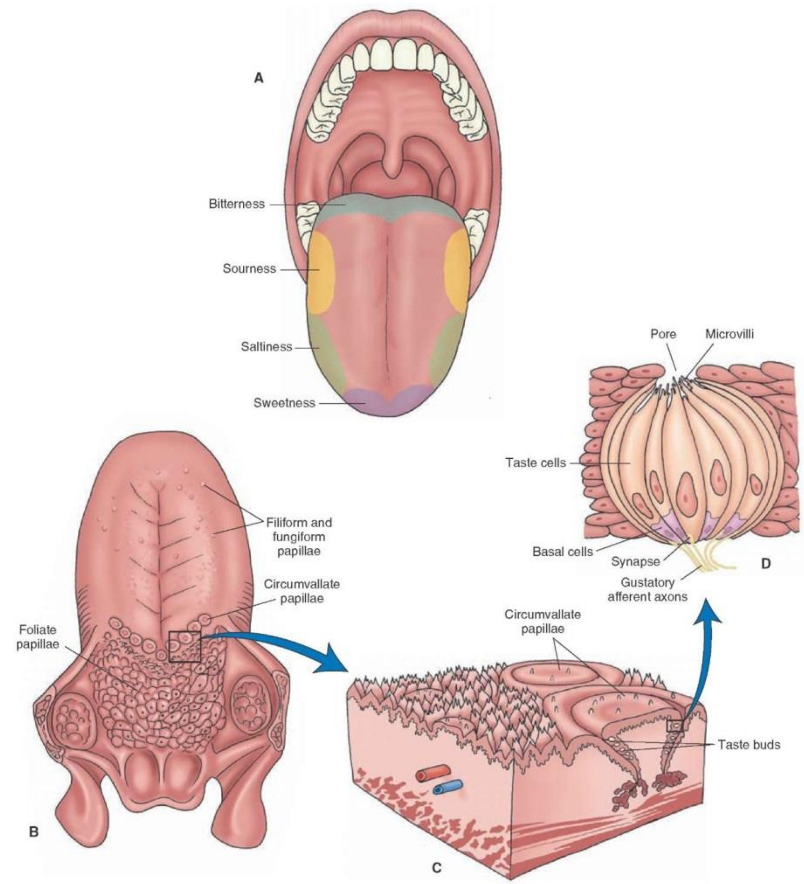
- Sensation of visible light – between the range of 400 and 700 nm of the electromagnetic radiation.
- 3D -> 2D -> 3D
- Optical system and the retina: the retina contains the sensors (photoreceptors), and performs some processing as well (eg. saccade).
- Photoreceptors and their neural connections are part of the central nervous system (CNS).
- The reality is projected on the retina upside down and reversed, in miniature.
- The eye operates under the steady inner pressure of about 16 Hgmm, due to the balance of the production and absorption of the fluid. The whole fluid is regenerated every 2-3 hours.

Vision

- Mechanical defence: eyelids and tears
- Pupil – can handle 20x changes of amount of light
- Absorption of photons -> hyperpolarization (change of +/-) -> lower transmitter release -> through chemical synapses, other cells change their signs (e.g. bipolar and ganglion cells)
- Photoreceptors: rods (pálcikák) (are able to sense very small intensity; periphery) and cones (csapok) (smaller sensitivity to light, high range of sensation, better spatial resolution, in the center of the retina called the fovea).
- Membrane potential: in the dark: -40mV, in light -70mV
- Sensation of color: three cone types (blue, green, red)
- Saccades: 900 °/s

Smell and taste





- Source: Nobelprize.org
- Source: http://what-when-how.com/

Smell and taste

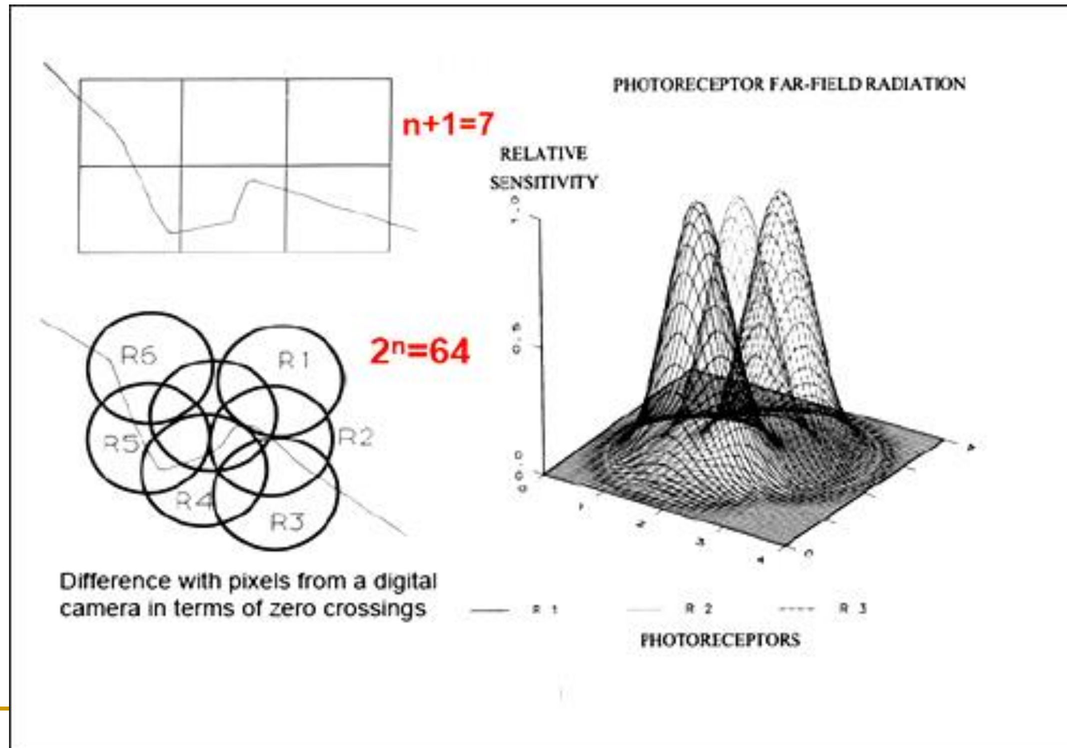
- Chemoreceptors: the sensation of molecules
- Olfactory epithelium: 4-5 cm2, the life span of sensory neurons is 30-60 days
- In humans: 1000/3 types of receptor genes, every sensory neuron is specific to one receptor gene, it connects to the epitope of the smell. More than one epitope can connect to a receptor. A type of smell may have more epitopes, therefore the smell can be recognized on the basis of the pattern of the activated neurons. This way, we can distinguish more types of smells than the number of receptors we have.
- Adaptation

Smell and taste

- Our sense of taste is only capable of distinguishing between a few flavours: sweet, salty, sour, bitter, and umami. (dangerous, spoilt or rich in nutrients)
- Taste buds (ízlelőbimbók), up to 100 sensory cells
- Sensory stimulus
- Specific taste receptors (open question), we cannot distinguish between different matters having the same
- Thermal receptors in the mouth

Special sensors in biology

- Salmon's localisation method
- Bird's vision while migration
- Owl's hearing
- Whale, bat's distance measurement
- Hyperacuity:



- Source: 19 June 2007, SPIE Newsroom

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End of Lecture 02.

i.) Introduction
ii.) Human sensing and sensors in biology

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02.15.2021.