# Frontiers of Virtual Reality - Widespread Usage in the Future

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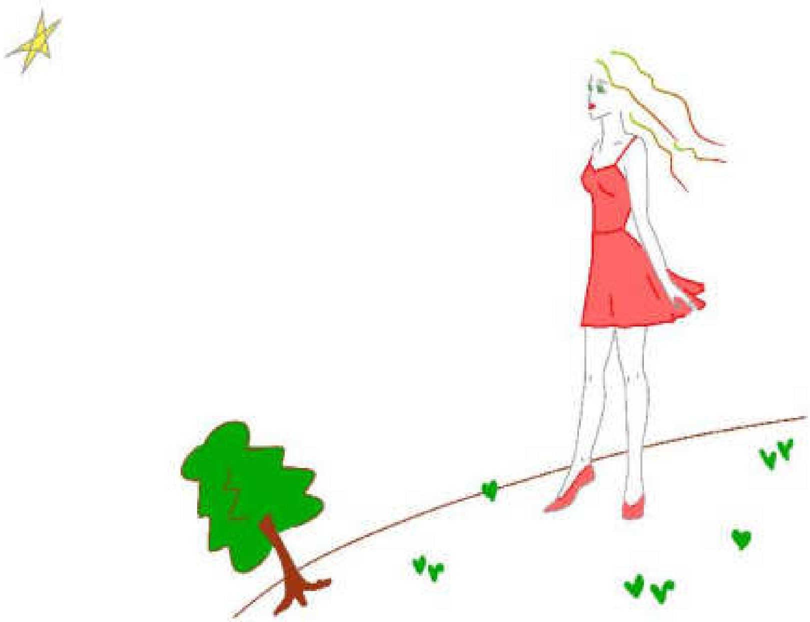
Source: VIRTUAL REALITY book, Steven M. LaValle. Cambridge University Press. 2017. http://vr.cs.uiuc.edu/

# Virtual reality

- **Virtual reality (VR) is a powerful technology that promises to change our lives unlike any other.**
- By artificially stimulating our senses, our bodies become tricked into accepting another version of reality.
- VR is like a waking dream that could take place in a magical cartoon-like world, or could transport us to another part of the Earth or universe.
- It is the next step along a path that includes many familiar media, from paintings to movies to video games.
- We can even socialize with people inside of new worlds, either of which could be real or artificial.

# VIRTUAL REALITY

Steven M. LaValle



# VIRTUAL REALITY

**Steven M. LaValle**

**University of Illinois**

CAMBRIDGE
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# Virtual reality

- The book is growing out of material for a popular undergraduate course on VR that author introduced at the University of Illinois in 2015 (with hardware support from Oculus/Facebook).

**The author:**

- „I have never in my life seen students so excited to take a Course.

  We cannot offer enough slots to come even close to meeting the demand“.

# Virtual reality

- Therefore, the primary target of the book is undergraduate students around the world.
- The book would be an ideal source for starting similar VR courses at other universities.
- Although most of the interested students have been **computer scientists**, the course at Illinois has attracted **students from many disciplines**, such as psychology, music, kinesiology, engineering, medicine, and economics.
- Students in these other fields come with the most exciting project ideas because they can see how VR has the potential to radically alter their discipline.

# Definition of VR

- Inducing **targeted behavior** in an **organism** by using **artificial sensory stimulation**, while the organism has little or no **awareness** of the interference.

aerial imagery provided by Pictometry International, 3D models provided by PLW Modelworks

# Definition of VR

- Four key components appear in the definition:
- **Targeted behavior**: The organism is having an “experience” that was designed by the creator. Examples include flying, walking, exploring, watching a movie, and socializing with other organisms.
- **Organism**: This could be you, someone else, or even another life form such as a fruit fly, cockroach, fish, rodent, or monkey (scientists have used VR technology on all of these!).
- **Artificial sensory stimulation:** Through the power of engineering, one or more senses of the organism become hijacked, and their ordinary inputs are replaced by artificial stimulation.

# Definition of VR

- **Awareness**: While having the experience, the organism seems unaware of the interference, thereby being “fooled” into feeling present in a virtual world.
- This unawareness leads to a sense of presence in an altered or another world.
- It is accepted as being natural.

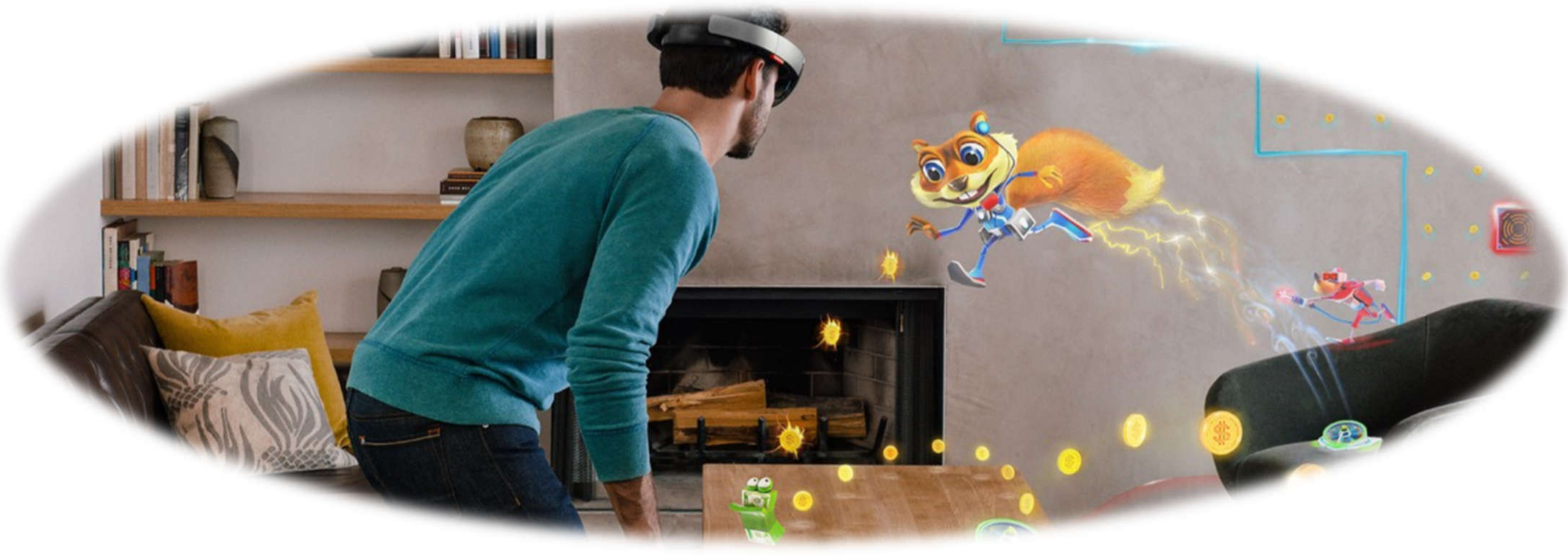
# Terminology regarding various “realit

- The term **virtual reality** dates back to German philosopher Immanuel Kant, although its use did not involve technology.
- Its modern use was popularized by Jaron Lanier

  in the 1980s.
- Although it is already quite encompassing, several competing terms related to VR are in common use at present.
- The term **virtual environments** predates widespread usage of VR and is presently preferred by most university researchers.
- **Augmented reality (AR)** refers to systems in which most of the visual stimuli are propagated directly through glass or cameras to the eyes, and some additional structures appear to be superimposed onto the user’s world.

# Terminology regarding various "realities"

- The term mixed reality (MR) - entire spectrum that encompasses VR, AR, and normal reality.
- More recently, the term VR/AR/MR has even been used to refer to all forms.

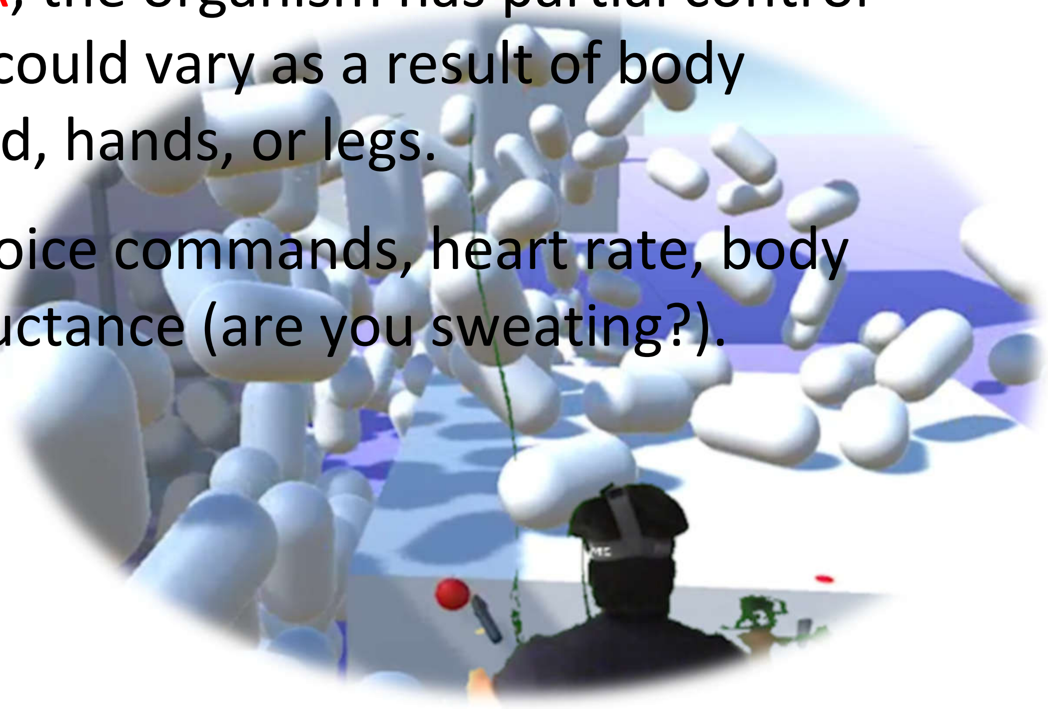


# Terminology regarding various "realities"

- Telepresence refers to systems that enable users to feel like they are somewhere else in the real world; if they are able to control anything, such as a flying drone, then teleoperation is an appropriate term.
- Virtual environments, AR, mixed reality, telepresence, and teleoperation will all be considered as perfect examples of VR.
- The most important idea of VR is that the user's perception of reality has been altered through engineering, rather than whether the environment they believe they are in seems more "real" or "virtual". Thus, perception engineering could be a reasonable term as well.

# Interactivity

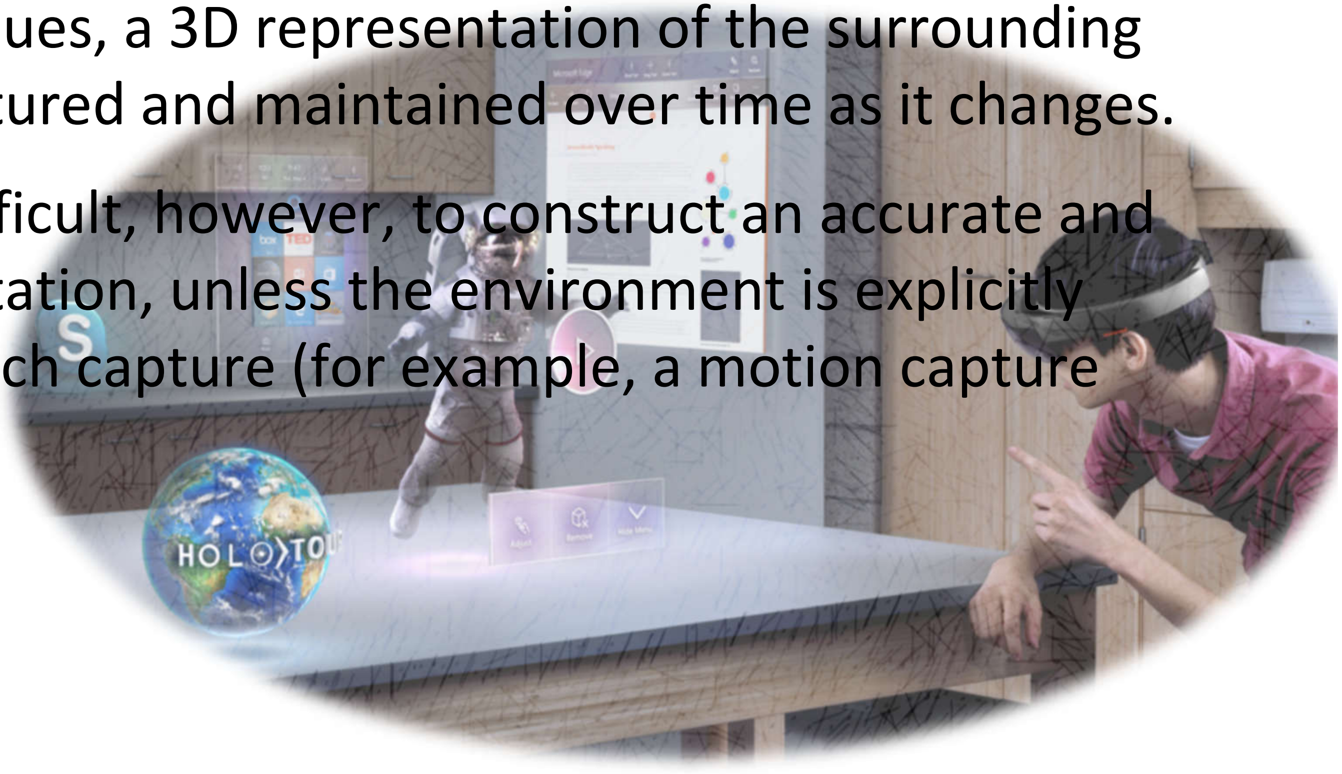
- Most VR experiences involve another crucial component: interaction. Does the sensory stimulation depend on actions taken by the organism?
- If the answer is “no”, then the VR system is called open-loop; otherwise, it is closed-loop.
- In the case of closed-loop VR, the organism has partial control over the stimulation, which could vary as a result of body motions, including eyes, head, hands, or legs.
- Other possibilities include voice commands, heart rate, body temperature, and skin conductance (are you sweating?).



## Synthetic vs. captured

- Two extremes exist when constructing a virtual world as part of a VR experience.
- At one end, we may program a ***synthetic world***, which is completely invented from geometric primitives and simulated physics. This is common in video games and such virtual environments were assumed to be the main way to experience VR in earlier decades.
- At the other end, the world may be ***captured*** using modern imaging techniques. For viewing on a screen, the video camera has served this purpose for over a century.
- Capturing panoramic images and videos and then seeing them from any viewpoint in a VR system is  a natural extension

# Synthetic vs. captured

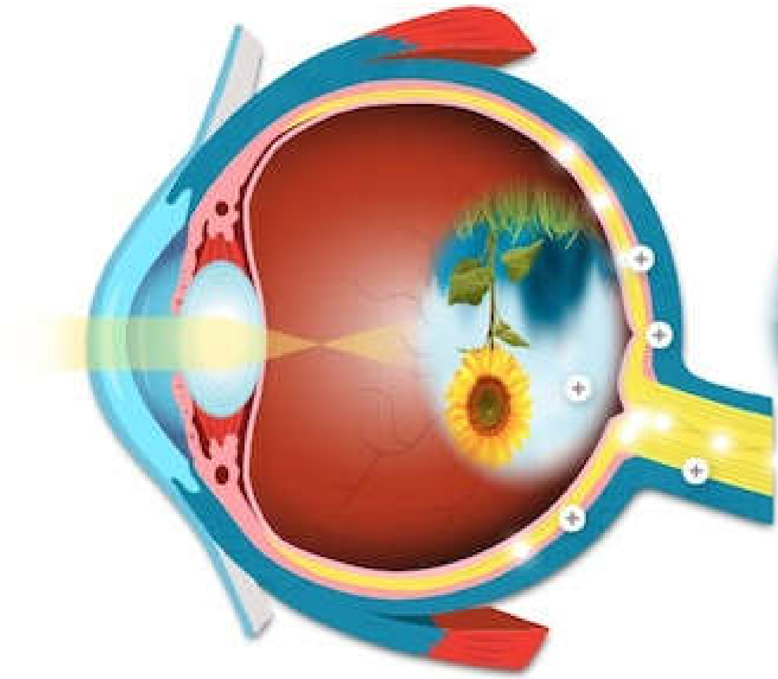


- In many settings, however, too much information is lost when projecting the real world onto the camera sensor.
- *What happens when the user changes her head position and viewpoint?* More information should be captured in this case.
- Using depth sensors and SLAM (Simultaneous Localization And Mapping) techniques, a 3D representation of the surrounding world can be captured and maintained over time as it changes.
- It is extremely difficult, however, to construct an accurate and reliable representation, unless the environment is explicitly engineered for such capture (for example, a motion capture studio).

# Synthetic vs. captured

- As humans interact, it becomes important to track their motions, which is an important form of capture.
- What are their facial expressions while wearing a VR headset?
- Do we need to know their hand gestures?
- What can we infer about their emotional state?
- Are their eyes focused on me?
- Synthetic representations of ourselves called avatars enable us to interact and provide a level of anonymity, if desired in some contexts.
- The attentiveness or emotional state can be generated synthetically.

# Frontiers



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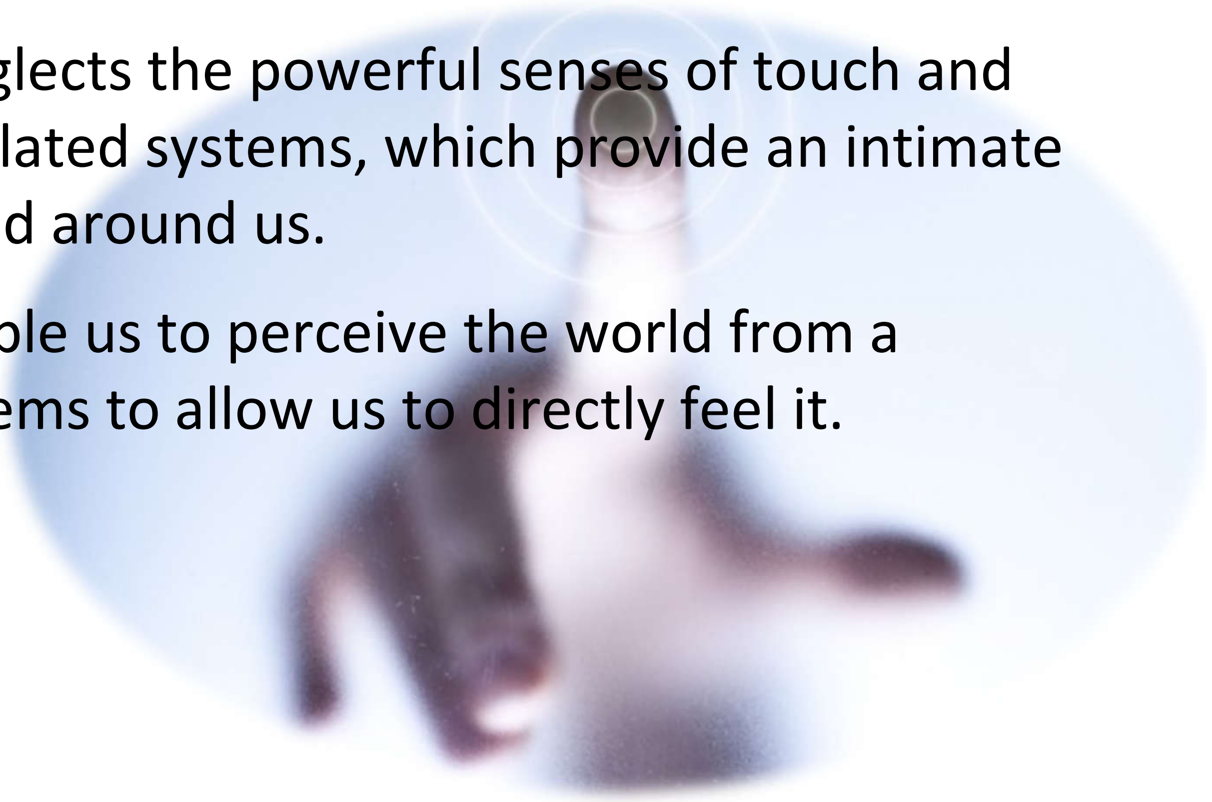
# Content

Topics that could influence widespread VR usage in the future, but are currently in a research and development stage.

- Touch and Proprioception
- Smell and Taste
- Robotic Interfaces
- Brain-Machine Interfaces

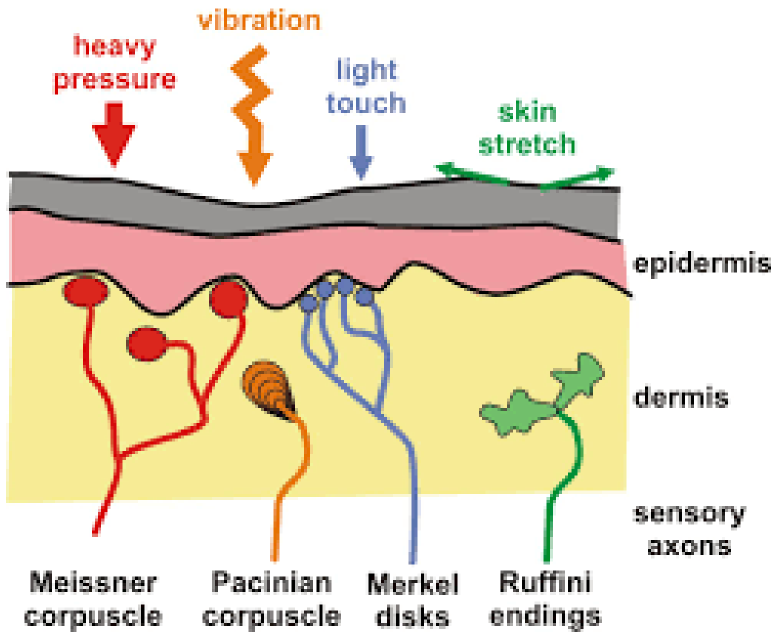
# Touch and Proprioception

- Visual and auditory senses are the main focus of VR systems because of their relative ease to co-opt using current technology.
- Their organs are concentrated in a small place on the head, and head tracking technology is cheap and accurate.
- Unfortunately, this neglects the powerful senses of touch and proprioception, and related systems, which provide an intimate connection to the world around us.
- Our eyes and ears enable us to perceive the world from a distance, but touch seems to allow us to directly feel it.



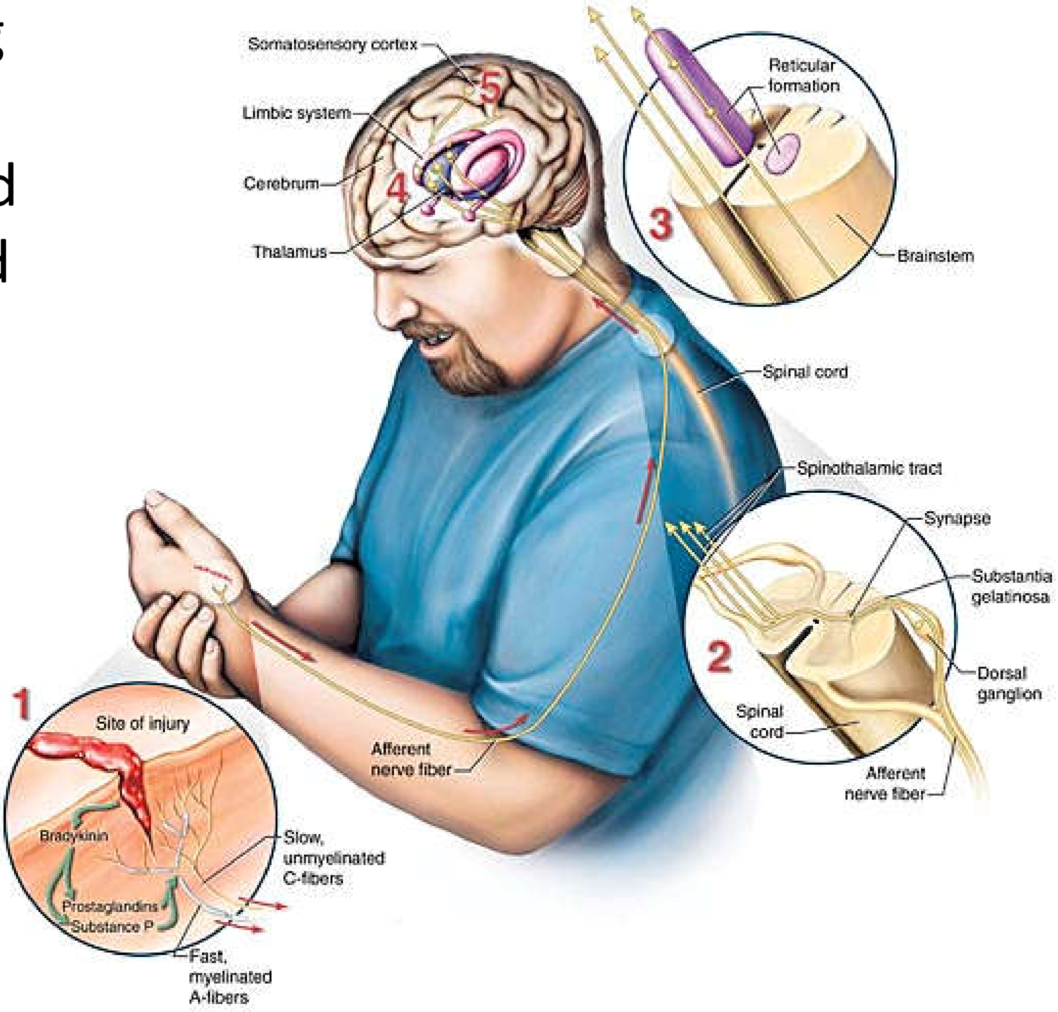
# Touch and Proprioception

- Furthermore, proprioception gives the body a sense of where it is any in the world with respect to gravity and the relative placement or configuration of limbs and other structures that can be moved by our muscles.
- We will therefore consider these neglected senses, from their receptors to perception, and then to engineering systems that try to overtake them.



# The somatosensory system

- The body senses provide signals to the brain about the human body itself, including direct contact with the skin, the body’s configuration and movement in the world, and the ambient temperature.
- Within this category, the vestibular system handles balance, and the somatosensory system handles touch, proprioception, and kinesthesis.

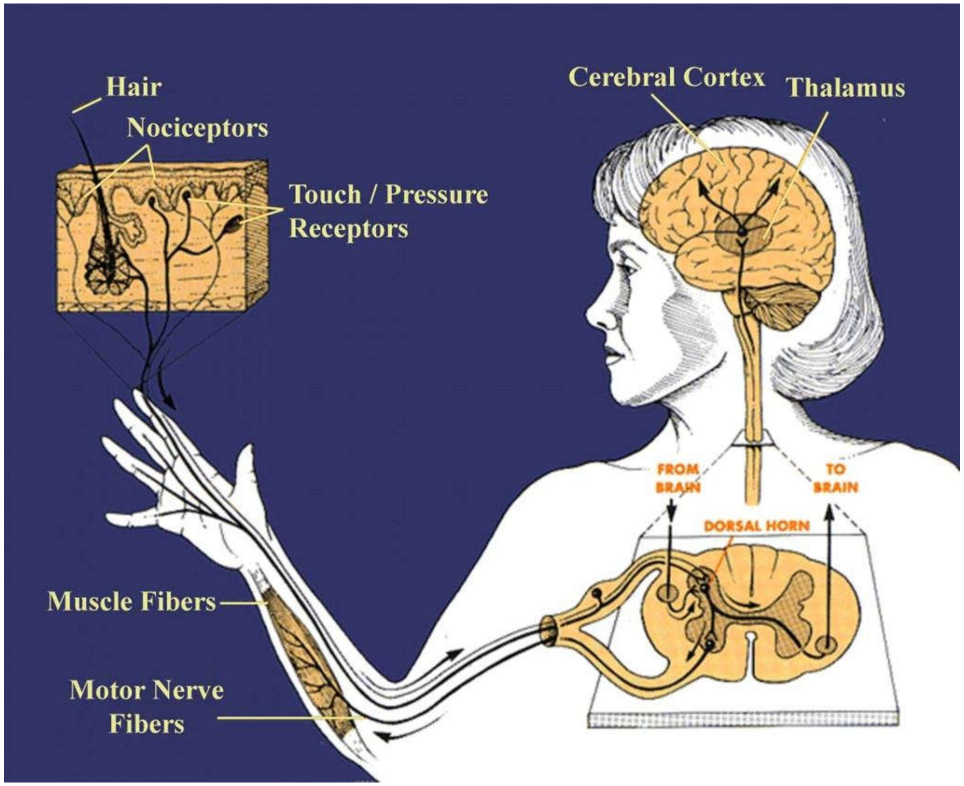


# The somatosensory system

- Consider the human body and all of its movable parts, such as the legs, arms, fingers, tongue, mouth, and lips.
- Proprioception corresponds to

the awareness of the pose of each part relative to others, whereas kinesthesis is the counterpart for the movement itself.

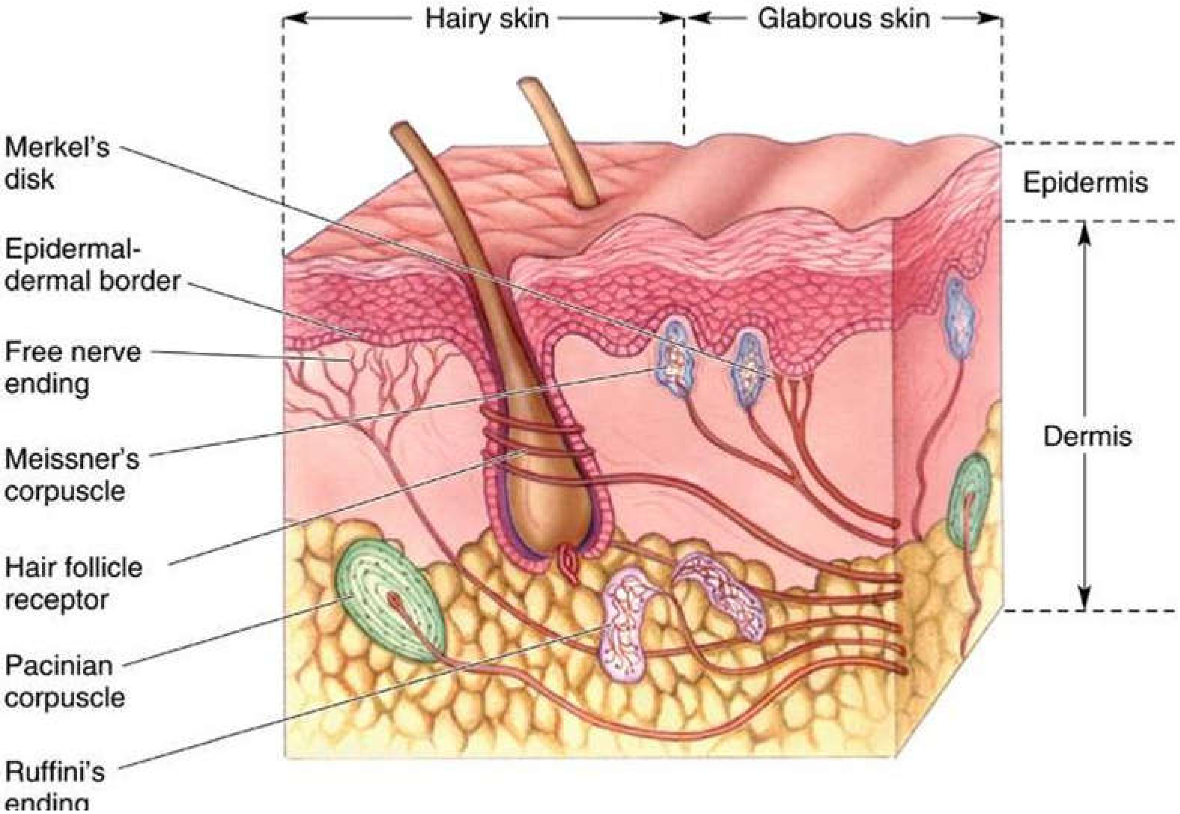
- In other words, kinesthesis provides information on velocities, accelerations, and forces.



# The somatosensory system

- The somatosensory system has at least nine major kinds of receptors, six of which are devoted to touch, and the remaining three are devoted to proprioception and kinesthesis.

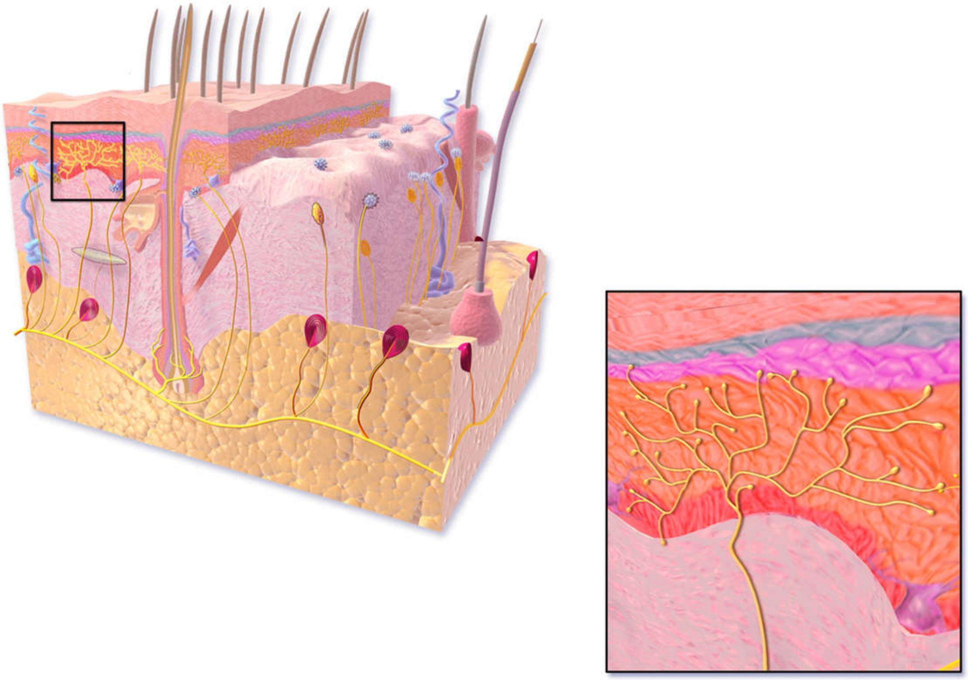
**Six main touch receptors**, which are embedded in the skin (dermis):



# The somatosensory system

**Six main touch receptors**, which are embedded in the skin (dermis):

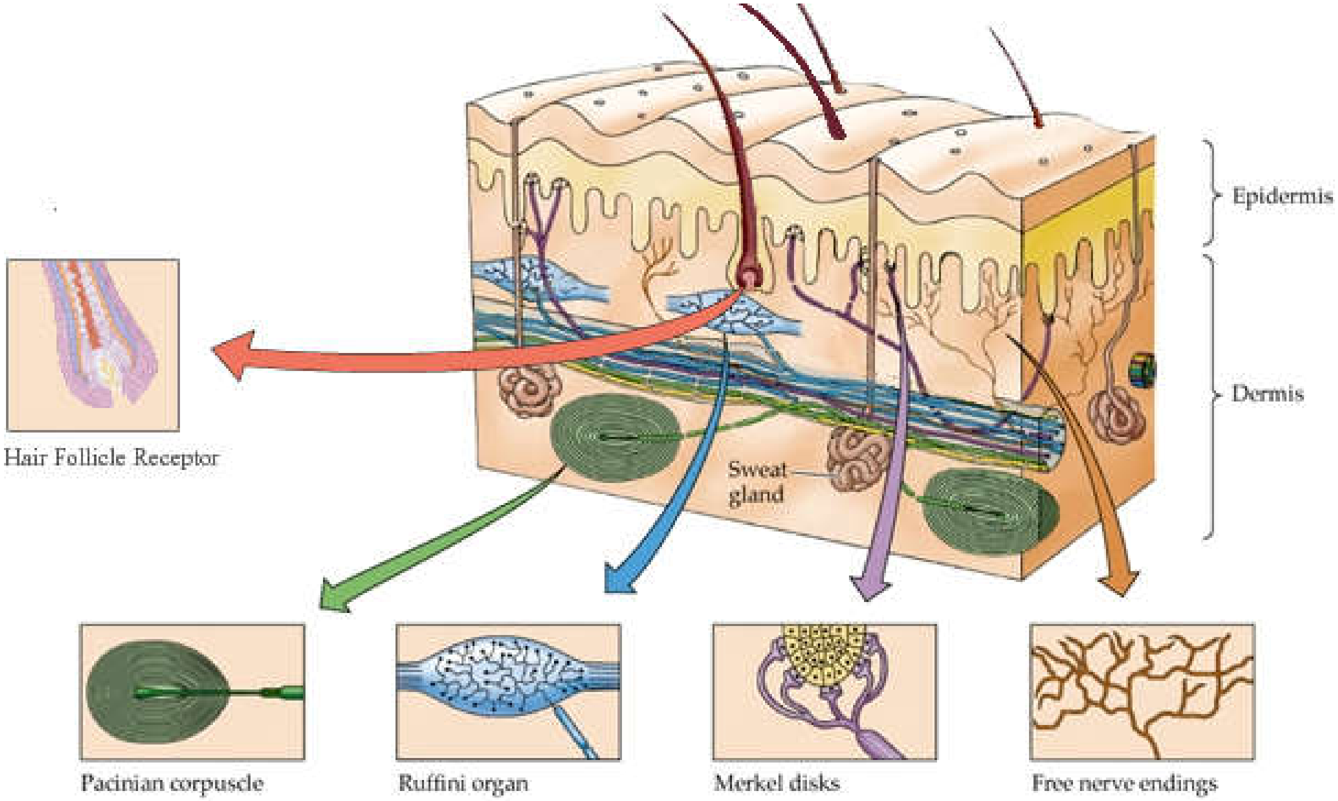
- **Free nerve endings.** These are neurons with no specialized structure.
- They have axons that extend up into the outer skin (epidermis), with the primary function of sensing temperature extremes (hot and cold), and pain from tissue damage.



# The somatosensory system

- **Ruffini's endings or corpuscles:** These are embedded deeply in the skin and signal the amount of stretching that is occurring at any moment.
- They have a sluggish temporal response.
- **Pacinian corpuscles:** These are small bodies filled with fluid and respond to pressure. Their response is fast, allowing them to sense vibrations (pressure variations) of up to 250 to 350 Hz.
- **Merkel's disks:** These structures appear just below the epidermis and respond to static pressure (little or no variation over time), with a slow temporal response.

# The somatosensory system

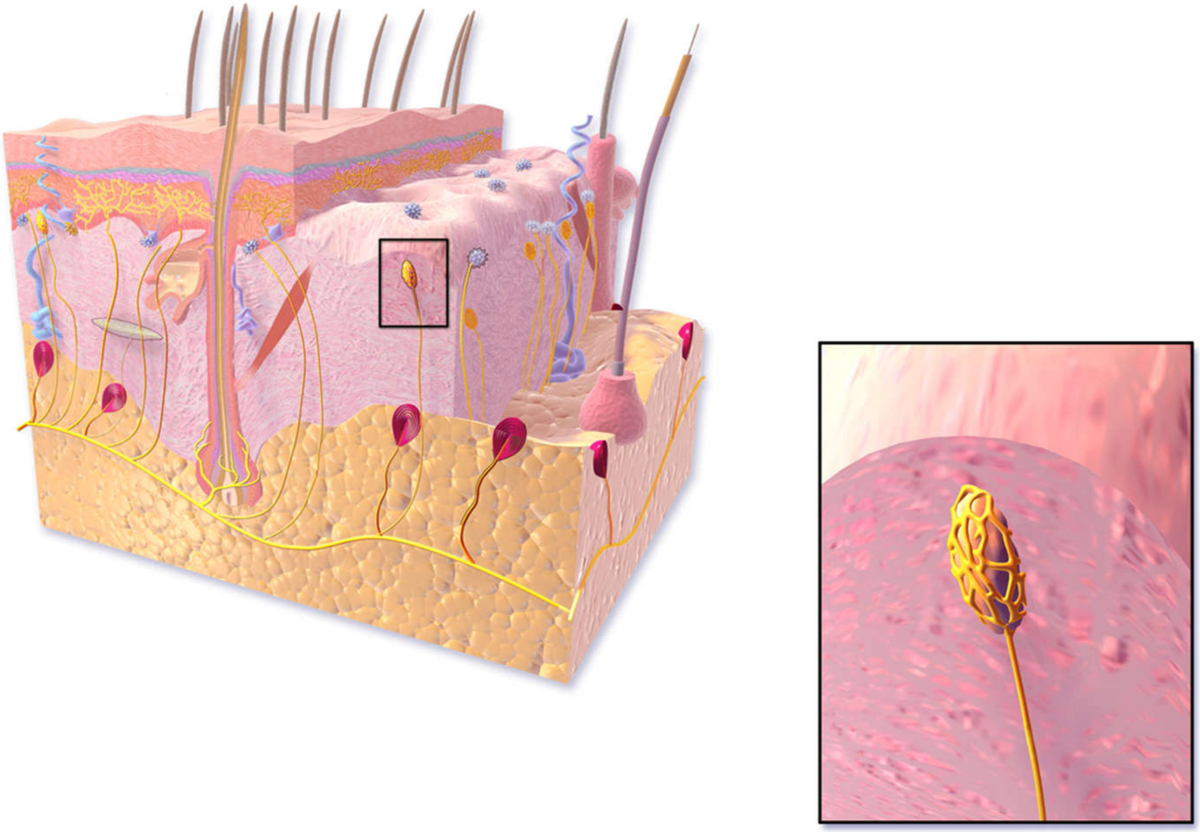


courtesy of http://www.hhp.uh.edu/clayne/6397/Unit4_files/image019.jpg

- **Hair follicle receptors:** These correspond to nerve endings that wrap closely around the hair root; they contribute to light touch sensation, and also pain if the hair is removed.

# The somatosensory system

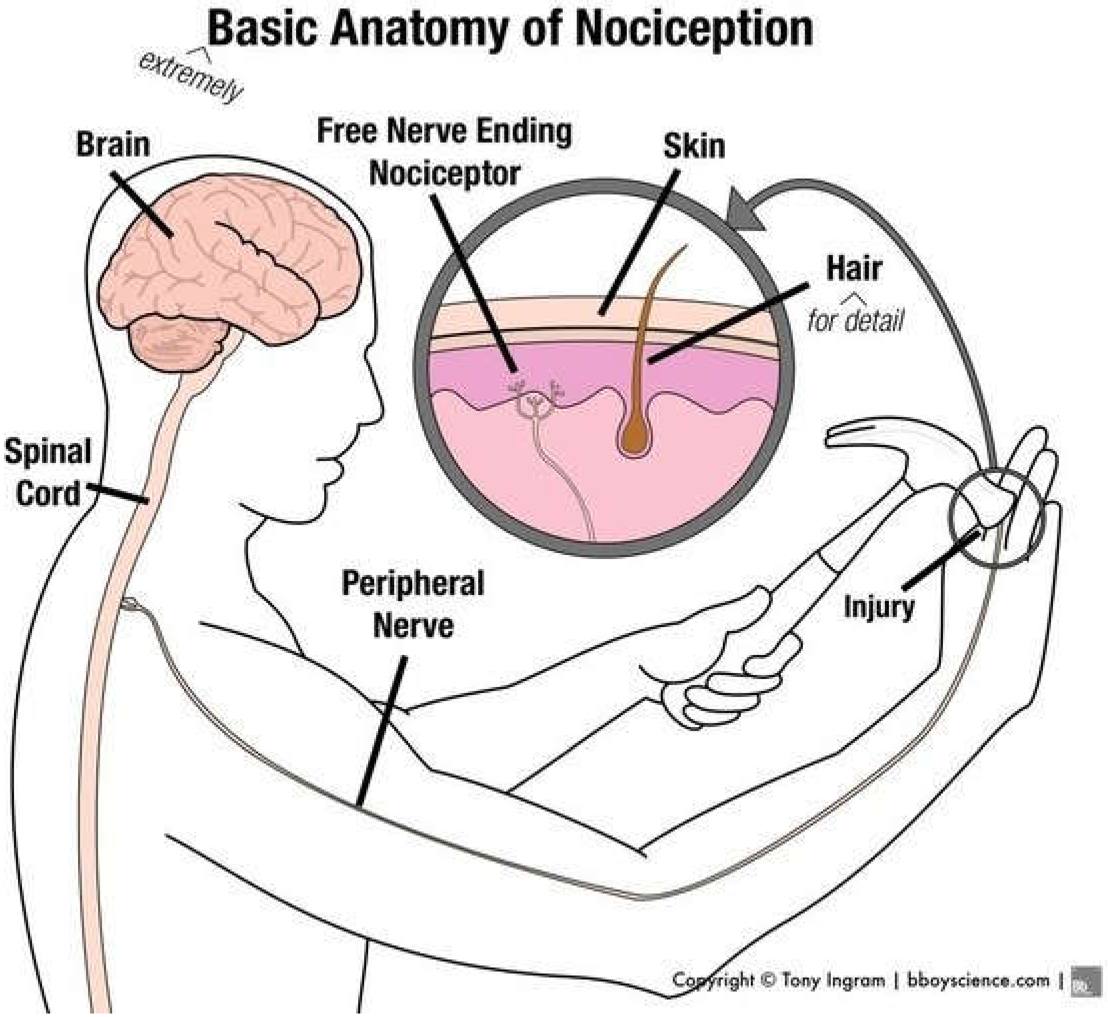
- **Meissner’s corpuscles:** These are also just below the epidermis, and respond to lighter touch. Their response is faster than Merkel’s discs and Ruffini’s corpuscles, allowing vibrations up to 30 to 50 Hz to be sensed; this is not as high as is possible as the Pacinian corpuscles.



## The somatosensory system

- The first four of these receptors appear in skin all over the body.
- Meissner’s corpuscles are only in parts where there are no hair follicles (glabrous skin), and the hair follicle receptors obviously appear only where there is hair.
- In some critical places, such as eyelids, lips, and tongue, thermoreceptors called the endbulbs of Krause also appear in the skin.
- Yet another class is **nocireceptors**, which appear in joint tissues and cause a pain sensation from overstretching, injury, or inflammation.

# The somatosensory system



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# The somatosensory system

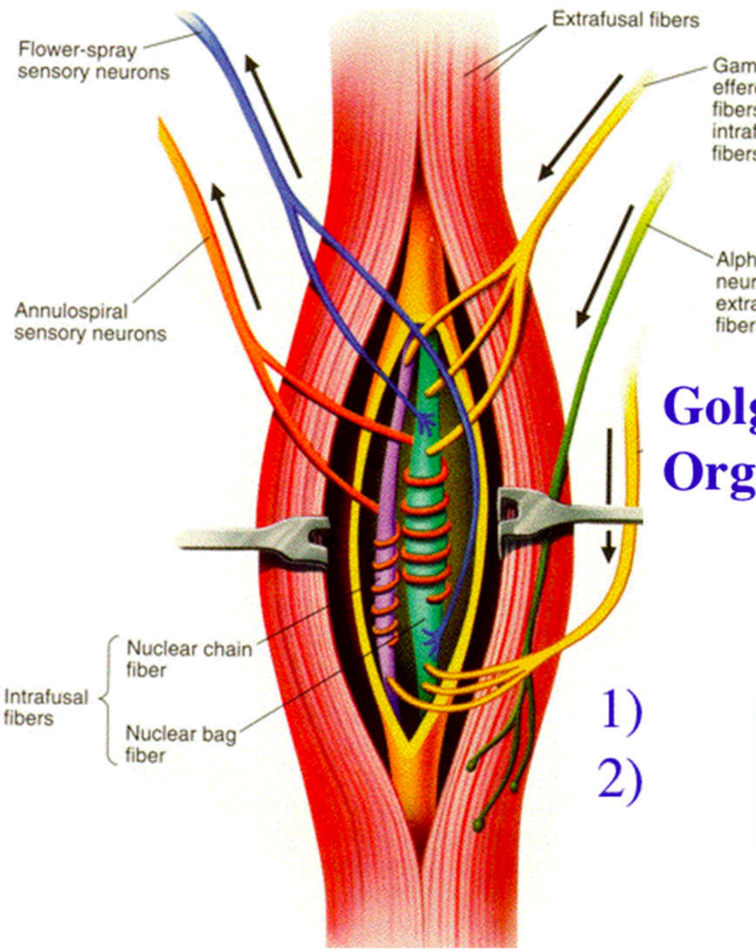
- Touch has both **spatial** and **temporal** resolutions.
- The spatial resolution or acuity corresponds to the density, or receptors per square area, which varies over the body.
- The density is high at the fingertips, and very low on the back.
- This has implications on touch perception, which will be covered shortly.
- The temporal resolution is not the same as for hearing, which extends up to 20,000 Hz; the Pacinian corpuscles allow vibrations up to a few hundred Hertz to be distinguished from a static pressure

# The somatosensory system

- Regarding proprioception (and kinesthesis), there are three kinds of receptors:
  - **Muscle spindles:** As the name suggests, these are embedded inside of each muscle so that changes in their length can be reported to the central nervous system (which includes the brain).
  - **Golgi tendon organs:** These are embedded in tendons, which are each a tough band of fibrous tissue that usually connects a muscle to bone. The organs report changes in muscle tension.
  - **Joint receptors:** These lie at the joints between bones and help coordinate muscle movement while also providing information to the central nervous system regarding relative bone positions. Through these receptors, the body is aware of the relative positions, orientations, and velocities of its various moving parts.

# The somatosensory system

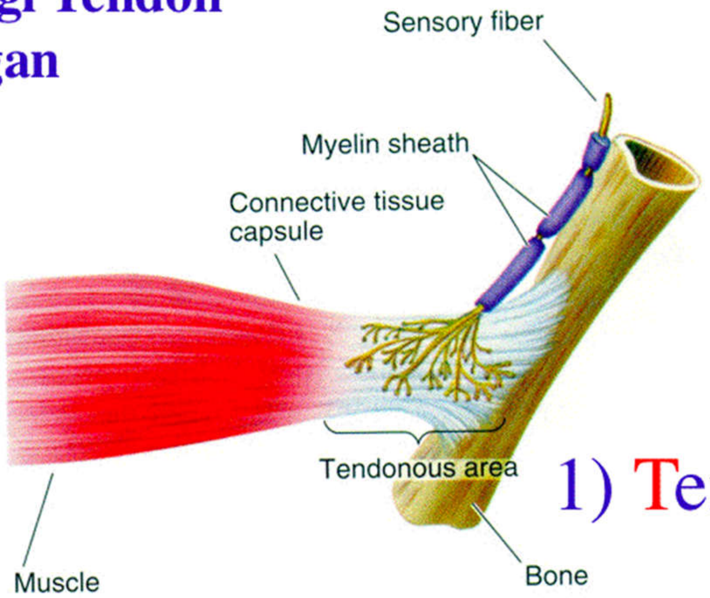
**Muscle Spindle**



**Golgi Tendon Organ**

1)

2)



1) Tension

# Texture perception

- By running fingers over a surface, texture perception results.
- The size, shape, arrangement, and density of small elements that protrude from, or indent into, the surface affect the resulting perceived texture.
- **The duplex theory** states that coarser textures (larger elements) are mainly perceived by spatial cues, whereas finer textures are mainly perceived through temporal cues.
  - **By spatial cue**, it means that the structure can be inferred by pressing the finger against the surface.
  - **By temporal cue**, the finger is slid across the surface, resulting in a pressure vibration that can be sensed by the Pacinian and Meissner corpuscles.

# Haptic perception

- For a larger object, its overall geometric shape can be inferred through haptic exploration, which involves handling the object.
- Imagine that someone hands you an unknown object, and you must determine its shape while blindfolded.

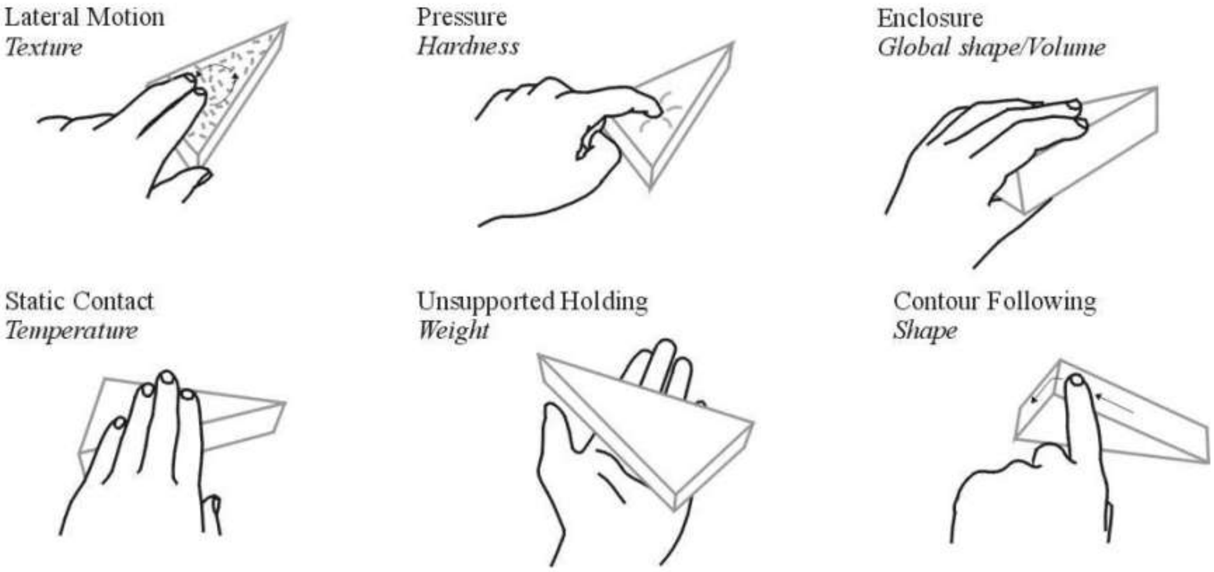
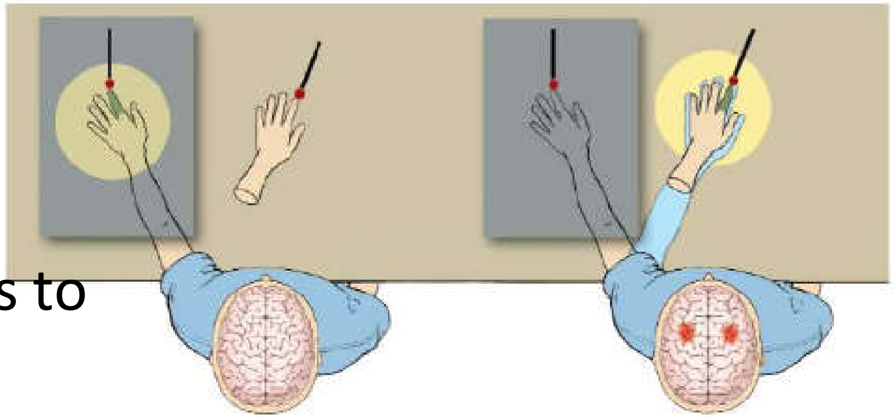


Figure 13.2: Haptic exploration involves several different kinds interaction between the hand and an object to learn the object properties, such as size, shape, weight, firmness, and surface texture. (Figure by Allison Okamura, adapted from Lederman and Klatzky.)

## Somatosensory illusions



- The brain combines signals across multiple sensing modalities to provide a perceptual experience.
- Just as the McGurk effect uses mismatches between visual and auditory cues, illusions have also been discovered by mismatching cues between vision and somatosensory systems.
- The **rubber hand illusion** is one of the most widely known.
- In this case, scientists conducted an experiment in which the subjects were seated at a table with both arms resting on it.
- The subjects’ left arm was covered but a substitute rubber forearm was placed nearby on the table and remained visible so that it appeared as if it were their own left arm.

# Somatosensory illusions

- The experimenter stroked both the real and fake forearms with a paint brush to help build up visual and touch association with the fake forearm.
- Using a functional MRI scanner, scientists determined that the same parts of the brain are activated whether it is the real or fake forearm.

Figure 13.3: The *rubber hand illusion*, in which a person reacts to a fake hand as if it were her own. (Figure from Guterstam, Petkova, and Ehrsson, 2011 [107])

# Somatosensory illusions

- More generally, this is called a **body transfer illusion**.

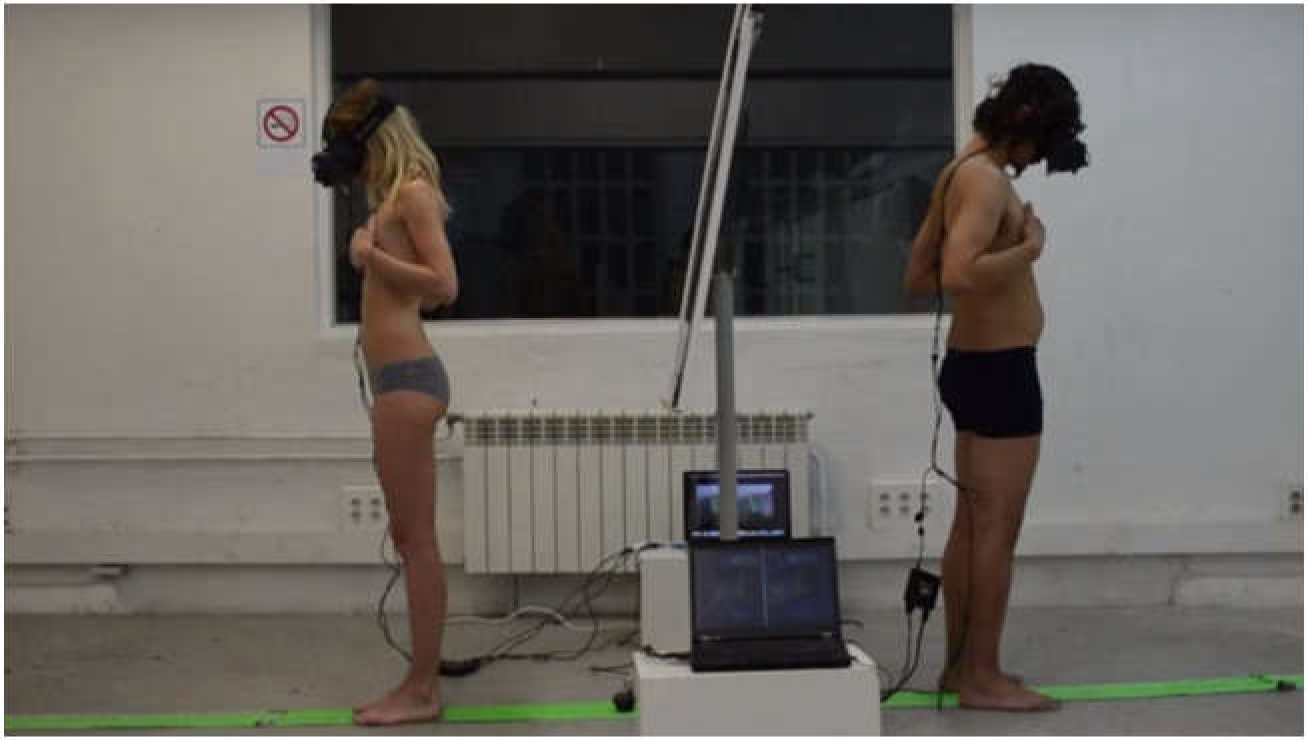


Figure 1.14: Students in Barcelona made an experience where you can swap bodies with the other gender. Each person wears a VR headset that has cameras mounted on its front. Each therefore sees the world from the approximate viewpoint of the other person. They were asked to move their hands in coordinated motions so that they see their new body moving appropriately.

# Somatosensory illusions

- Applications of this phenomenon include empathy and helping amputees to overcome phantom limb sensations.
- This illusion also gives insights into the kinds of motor programs that might be learnable, by controlling muscles while getting visual feedback from VR.
- It furthermore affects the perception of oneself in VR.

# Haptic interfaces

- Touch sensations through engineered devices are provided through many disparate systems.
- A system in which force feedback is provided by allowing the user to push mechanical wings to fly.

Figure 1.1: In the Birdly experience from the Zurich University of the Arts, the user, wearing a VR headset, flaps his wings while flying over virtual San Francisco. A motion platform and fan provide additional sensory stimulation. The figure on the right shows the stimulus presented to each eye.

# Haptic interfaces

(a) (b)

(c) (d)

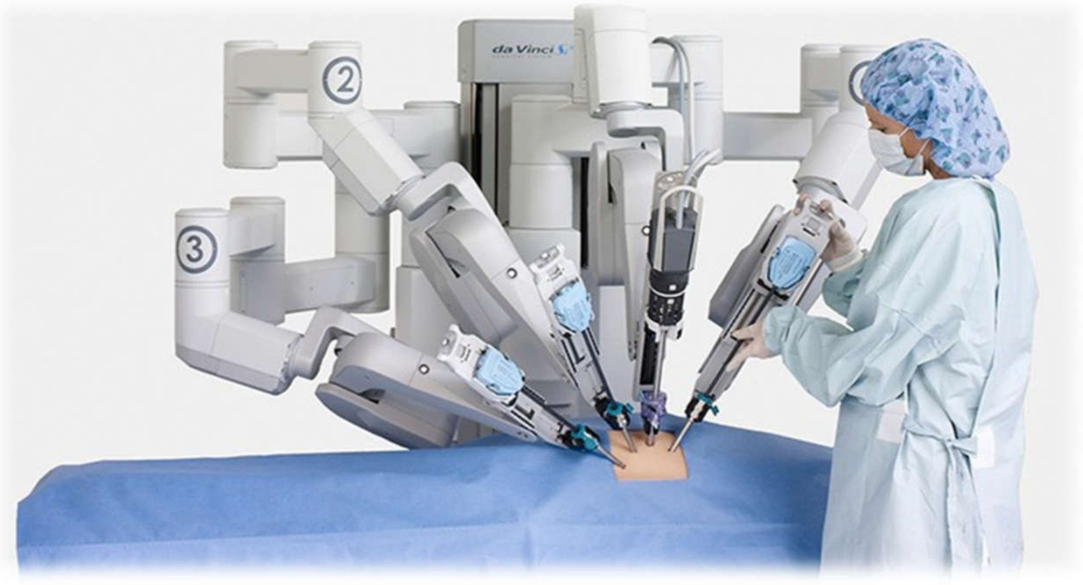
(a)The Logitech M325 wireless mouse with a scroll wheel that provides tactile feedback in the form of 72 bumps as the wheel performs a full revolution. (b) The Sega Dreamcast Jump Pack (1999), which attaches to a game controller and provides vibrations during game play. (c) Haptic Omni pen-guiding haptic device, which communicates pressure and vibrations through the pen to the fingers. (d) The KGS Dot View Model DV-2, which is a haptic pin array. The pins are forced upward to simulate various textures as the finger tip scans across its surface.

# Haptic interfaces

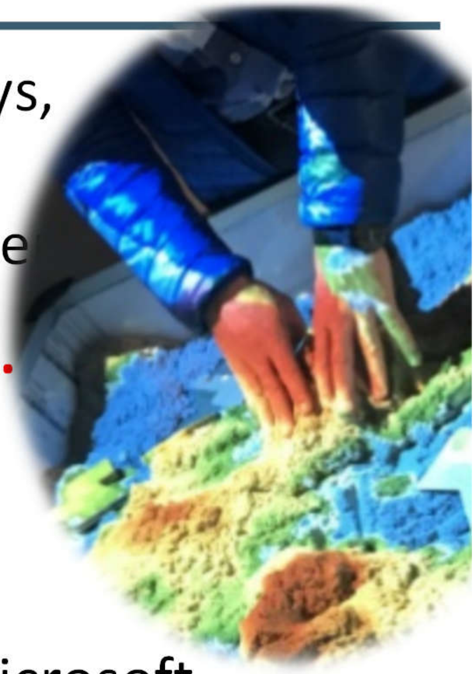
- Many haptic systems involve using a robot arm to apply force or pressure at precise locations and directions within a small region shows such a system in which the user holds a pen that is attached to the robot arm.
- Forces are communicated from the robot to the pen to the fingers.
- As the pen strikes a virtual surface, the robot provides force feedback to the user by blocking its motion.
- The pen could be dragged across the virtual surface to feel any kind of texture.

# Haptic interfaces

- Such force feedback is important in the development of medical devices that enable doctors to perform surgical procedures through an interface that is connected to a real device.
- Without accurate and timely haptic feedback, it is difficult for doctors to perform many procedures.
- Imagine cutting into layers of tissue without being able to feel the resistant forces on the scalpel. It would be easy to push a bit too far!



# Touch feedback via augmented reality



- Given the difficulties of engineering haptic displays, an alternative is to rely on real objects in the match zone to provide feedback to the somatosensory syste
- This is sometimes called a **tangible user interface.**
- A powerful experience is made by aligning the real and virtual worlds.
- At one extreme, a see-through display, such as Microsoft Hololens, enables users to see and interact with the physical world around them.
- The display simply adds virtual objects to the real world, or visually enhances real objects.
- Such systems are commonly included as part of augmented reality or mixed reality.

# Touch feedback via augmented reality

Figure 1.19: The Microsoft Hololens uses advanced see-through display technology to superimpose graphical images onto the ordinary physical world, as perceived by looking through the glasses.

# Smell and Taste

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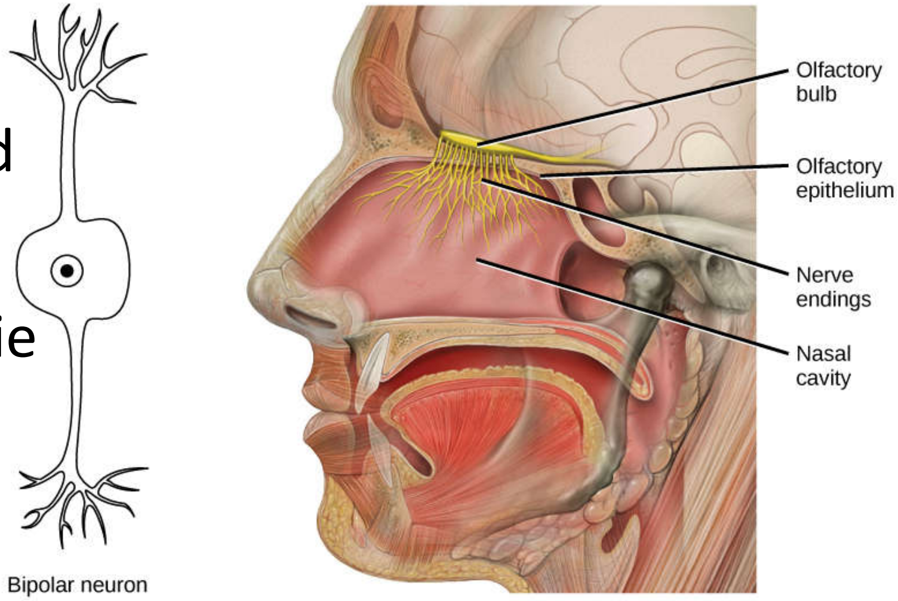
## Smell and taste

- The only human senses not considered so far are smell and taste.
- They are formally known as ***olfaction*** and ***gustation***.
- They are usually grouped together as the chemical senses because their receptors work by chemical interactions with molecules that arrive upon them.
- The resulting chemoreceptors respond to particular substances and sufficiently high levels of concentration.
- Compared to the other senses, **much less research has been done** about them and there are much fewer electronic devices that “display” stimuli to the nose and tongue.
- Nevertheless, these senses are extremely important.

# Smell physiology and perception

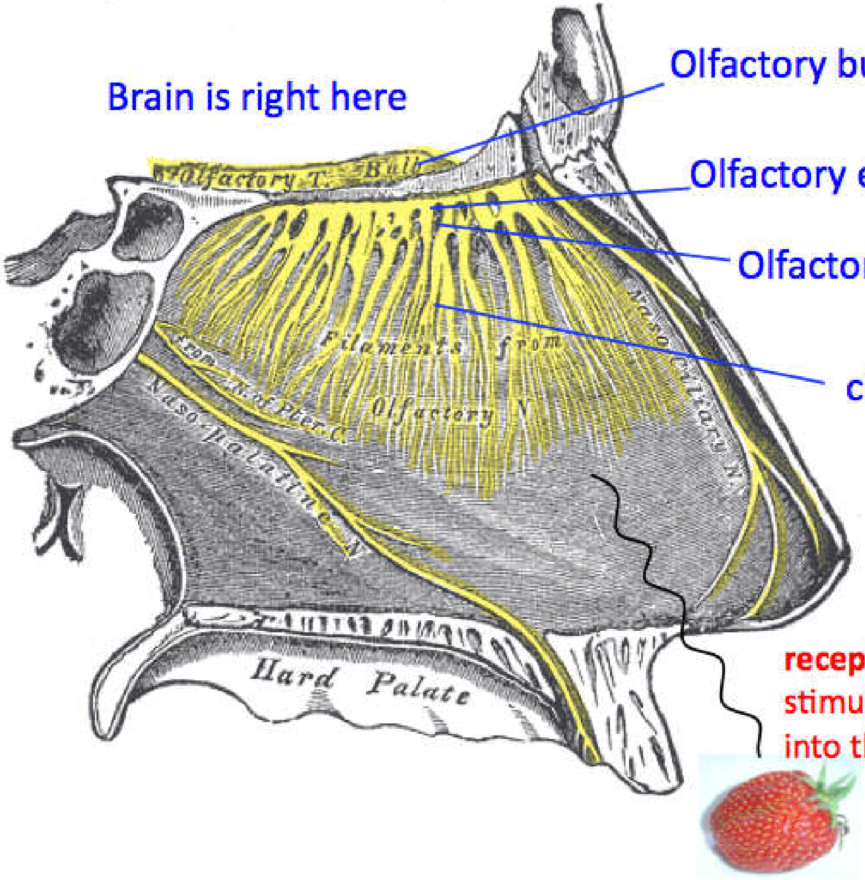
- Odors are important for several biological purposes, which includes detecting prey and predators, selecting potential mates, and judging whether food is safe to eat.
- The olfactory receptor neurons lie in the roof of the nasal cavity, covering an area of 2 to 4 $cm^2$.
- There are around 6 million receptors, which are believed to span 500 to 1000 different types depending on their responsiveness to specific chemical compositions.



(a) (b)

# Smell physiology and perception

- Airborne molecules dissolve into the olfactory mucus, which triggers detection by cilia (small hairs) that are part of the receptor.



Brain is right here

Olfactory bulb

Olfactory epithelium

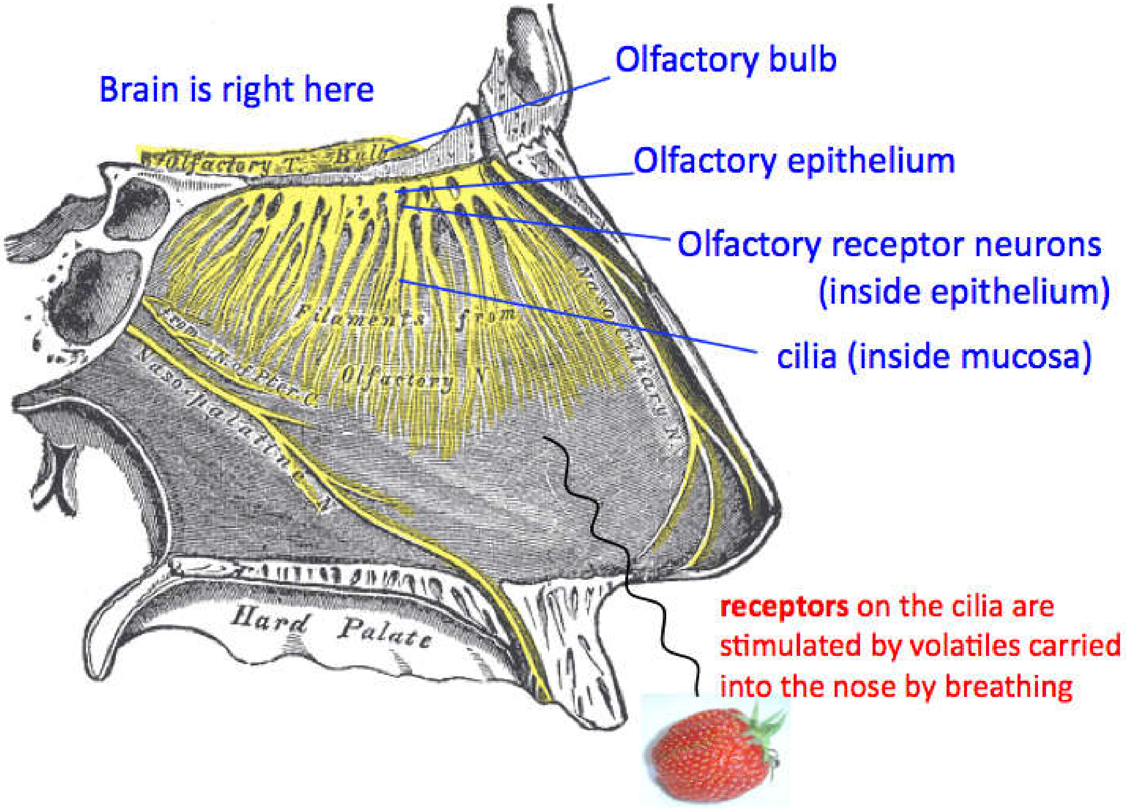
Olfactory receptor neurons (inside epithelium)

cilia (inside mucosa)

**receptors** on the cilia are stimulated by volatiles carried into the nose by breathing

# Smell physiology and perception

- The olfactory receptors are constantly regenerating, with an average lifespan of about 60 days.
- In addition to receptors, some free nerve endings lie in the olfactory mucus as well.



Brain is right here

Olfactory bulb

Olfactory epithelium

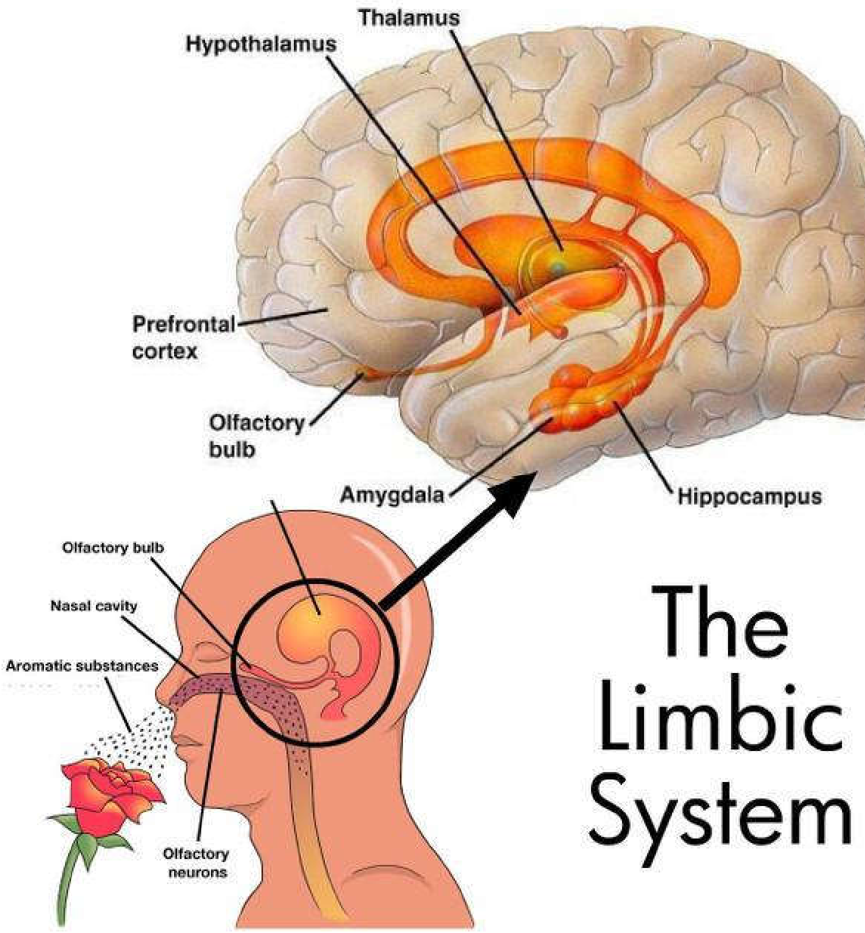
Olfactory receptor neurons (inside epithelium)

cilia (inside mucosa)

**receptors** on the cilia are stimulated by volatiles carried into the nose by breathing

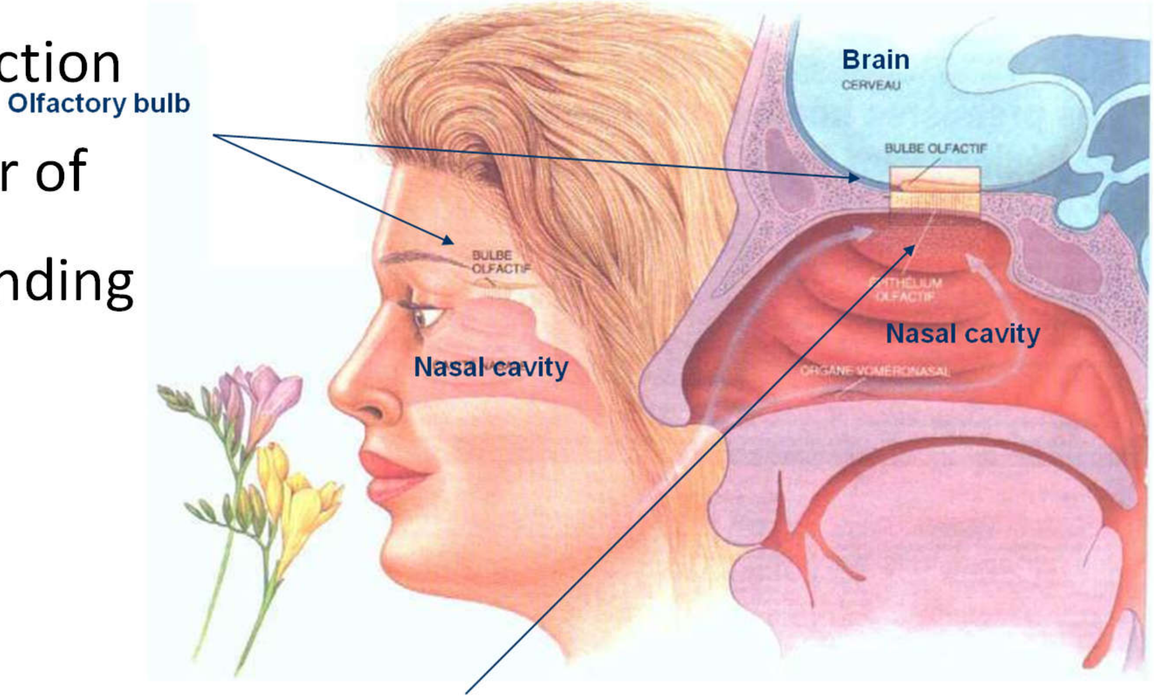
# Smell physiology and perception

- The sensory pathways are unusual in that they do not connect through the thalamus before reaching their highest level destination, which for smell is the primary olfactory cortex.
- There is also a direct route from the receptors to the amygdala, which is associated with emotional response.
- This may help explain the close connection between smell and emotional reactions.



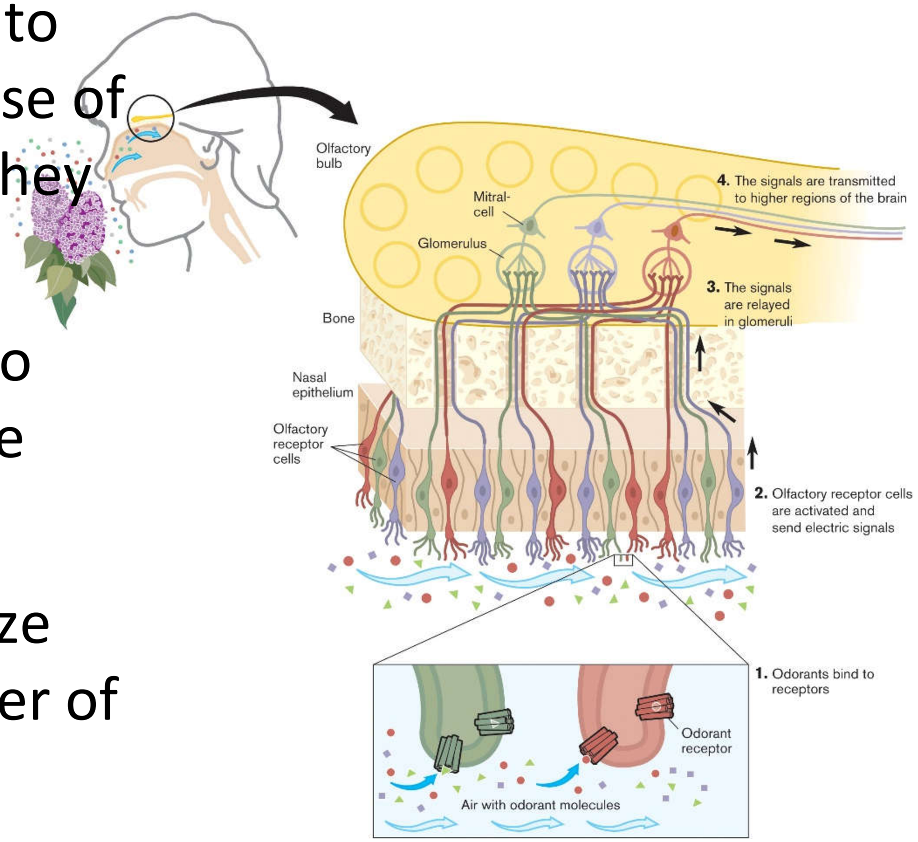
# Smell physiology and perception

- In terms of perception, humans can recognize thousands of different smells, and women generally perform better than men.
- The discrimination ability depends on the concentration of the smell (in terms of molecules per cubic area).
- What is considered to be a high concentration for one odor may be barely detectable for another.
- Consequently, the detection thresholds vary by a factor of a thousand or more, depending on the substance.



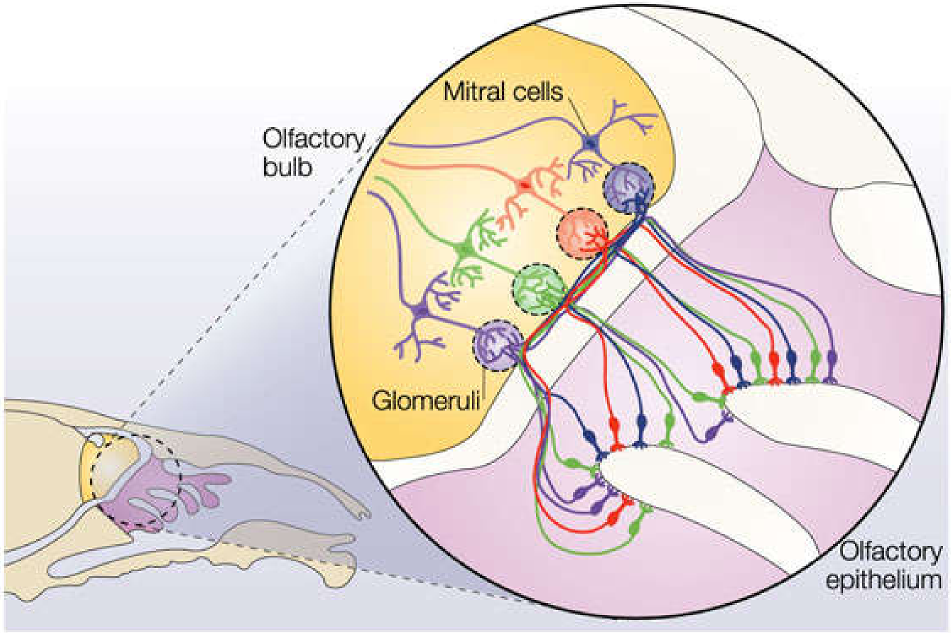
# Smell physiology and perception

- **Adaptation** is also important for smell.
- People are continuously adapting to surrounding smells, especially those of their own body or home, so that they become unnoticeable.
- Smokers also adapt so that they do not perceive the polluted air in the way that non-smokers can.
- It seems that humans can recognize many more smells than the number of olfactory receptors.
- This is possible because of combinatorial encoding.



## Smell physiology and perception

- Any single odor (or chemical compound) may trigger multiple kinds of receptors.
- Likewise, each receptor may be triggered by multiple odors.
- Thus, a many-to-many mapping exists between odors and receptors. This enables far more odors to be distinguished based on the distinct subsets of receptor types that become activated.



# Olfactory interfaces

- Adding scent to films can be traced back to the early 20th century.
- One system 1960, was called Smell-O-Vision and injected 30 different odors into the movie theater seats at different points during the film.
- The Sensorama system also included smells. In 1957, Morton Heilig's Sensorama added motion pictures, sound, vibration, and even smells to the experience.
- In addition, the military has used smells as part of simulators for many decades.

sensorama

The Revolutionary Motion Picture System that takes you into another world with

- 3-D
- WIDE VISION
- MOTION
- COLOR
- STEREO-SOUND

# Olfactory interfaces

- It is generally believed that smell is powerful in its ability to increase immersion in VR.
- It also offers advantages in some forms of medical treatments that involve cravings and emotional responses.
- Surprisingly, there is even recent evidence that pleasant odors help reduce visually induced motion sickness.

# Olfactory interfaces

- Olfactory displays usually involve air pumps that can spray chemical compounds into air.
- The presentation of such engineered odors could be delivered close to the nose for a personal experience. In this case, the canisters and distribution system could be worn on the body.

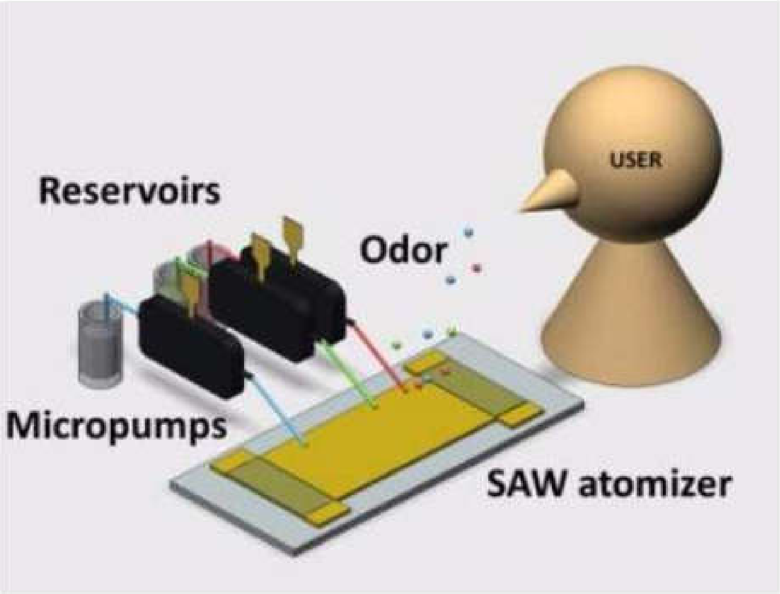
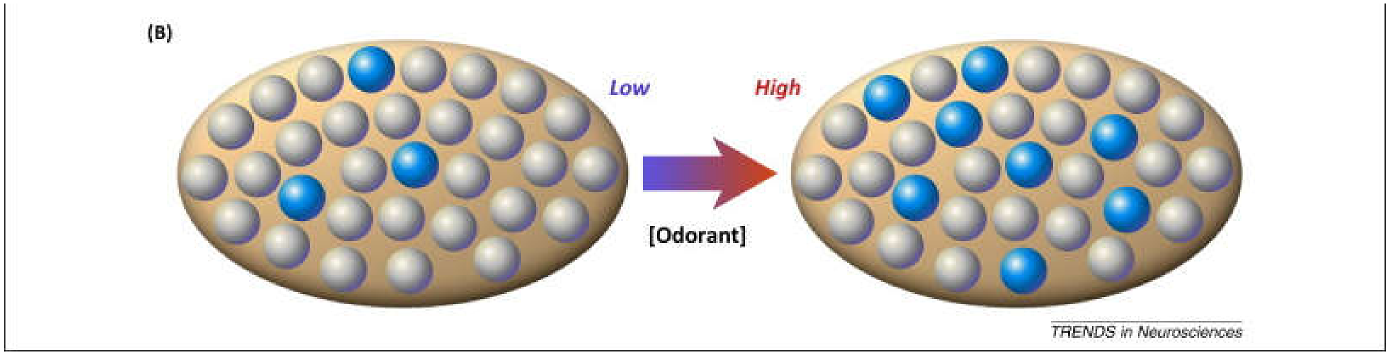


Figure 13.5: A depiction of a wearable olfactory display from [114]. Micropumps force bits of liquid from small reservoirs. The SAW atomizer is an surface acoustic wave device that converts droplets into an atomized odor.

# Olfactory interfaces

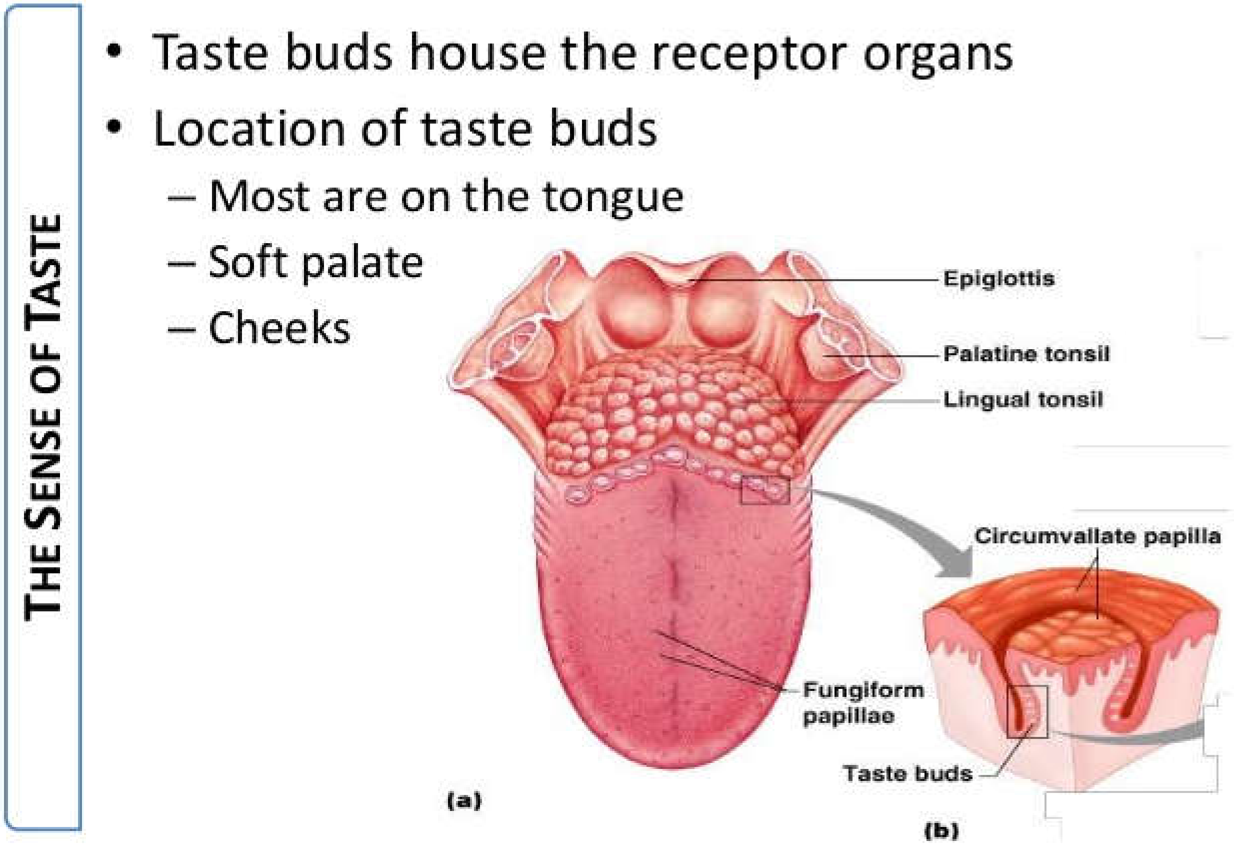
- Alternatively, the smells could be delivered on the scale of a room.
- It is generally hard to control the intensity and uniformity of the odor, especially in light of air flow that occurs from open windows and air vents.
- It might also be desirable to vary the concentration of odors over a large area so that localization can be performed, but this is again difficult to achieve with accuracy.



TRENDS in Neurosciences

# Taste physiology and perception

- On the human tongue lie about 10,000 taste buds, which each contains a group of about 50 to 150 taste receptors.
- The receptors live for an average of 10 days, with regeneration constantly occurring.



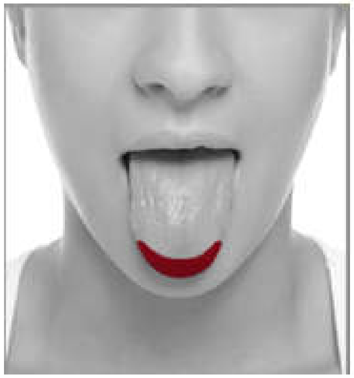
THE SENSE OF TASTE

- Taste buds house the receptor organs
- Location of taste buds
  - Most are on the tongue
  - Soft palate
  - Cheeks

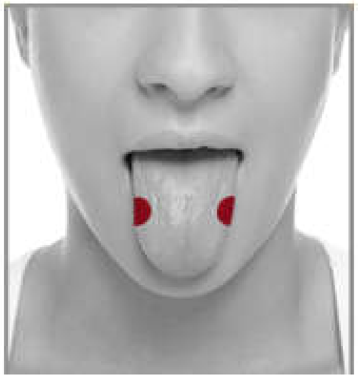
# Taste physiology and perception

- Five basic types of taste receptors have been identified:
  - **Umami:** This one is sensitive to amino acids, such as monosodium glutamate (MSG), and is responsible for an overall sense of tastiness.
  - This enables food manufacturers to cheaply add chemicals that made food seem to taste better.
  - The biological motivation is likely to be that amino acids are important building blocks for proteins.

Sweet

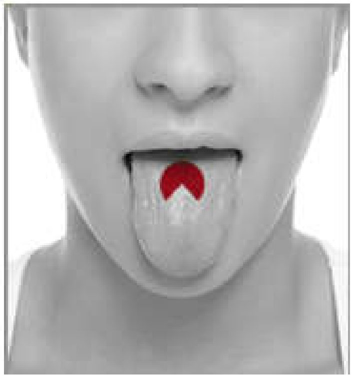


Sour



Salty

Bitter



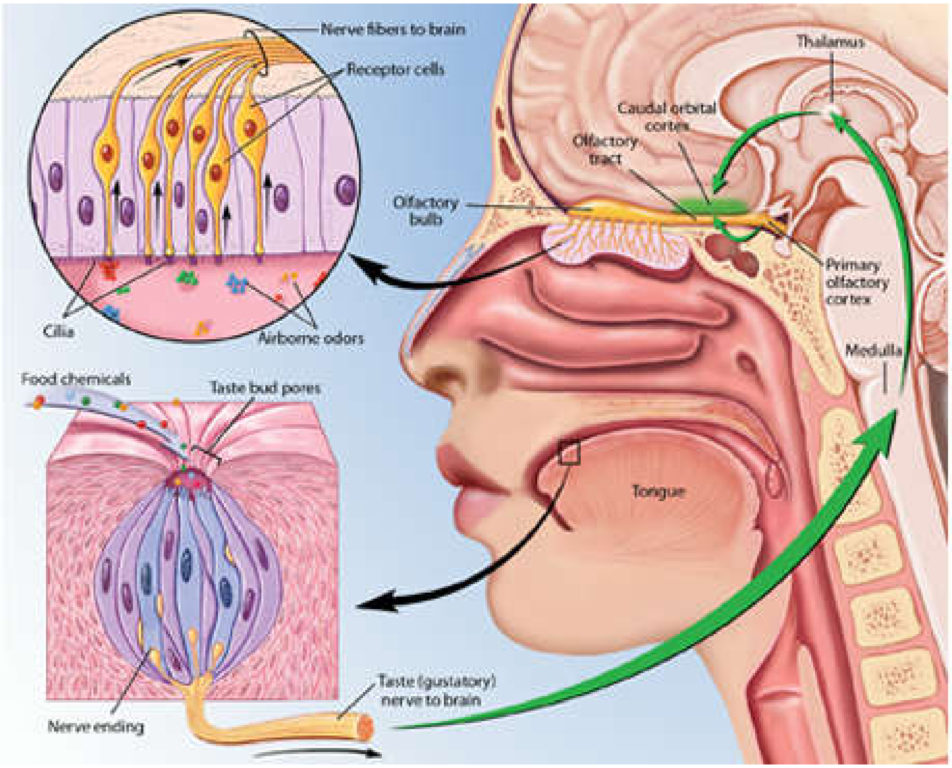
UMAMI !

# Taste physiology and perception

- **Sweet** : This is useful for identifying a food source in terms of its valuable sugar content.
- **Salty**: This is useful for determining whether a food source has sufficient salt content, which is required for normal neural functions.
- **Sour**: This is useful for determining the amount of acidity in a food, which could imply useful vitamins, unripens, or even bacteria in spoiled food.
- **Bitter**: This is often associated with toxic plants, which may trigger a natural aversion to them.

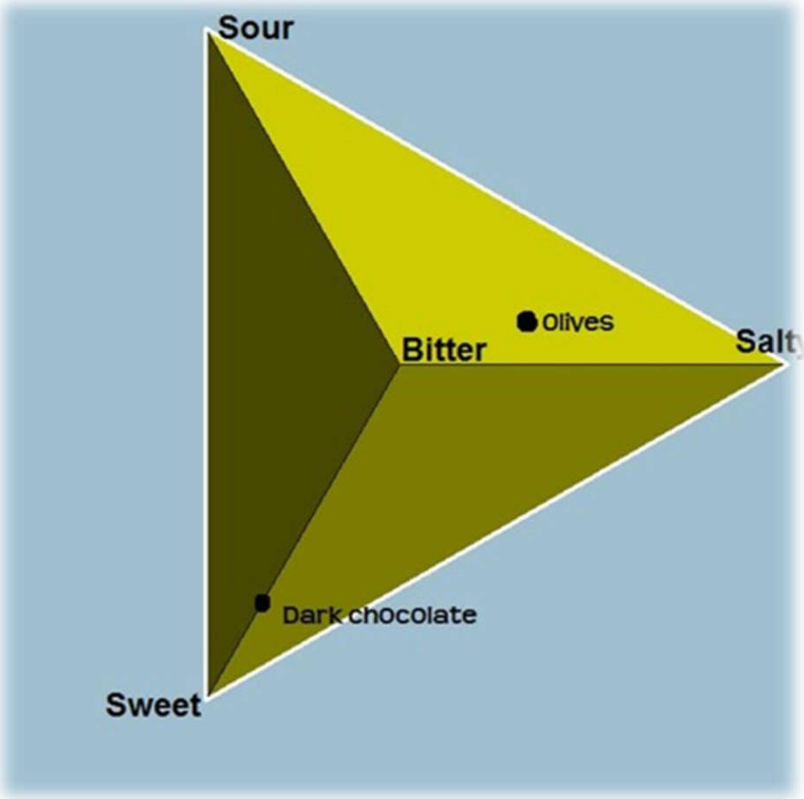
# Taste physiology and perception

- All of these work by dissolving food and generating a response based on chemical decomposition.
- The sensory pathways connect to through the thalamus to the ***gustatory cortex*** and to the amygdala, which affects emotional responses. Taste perception is closely related to the taste receptor types.



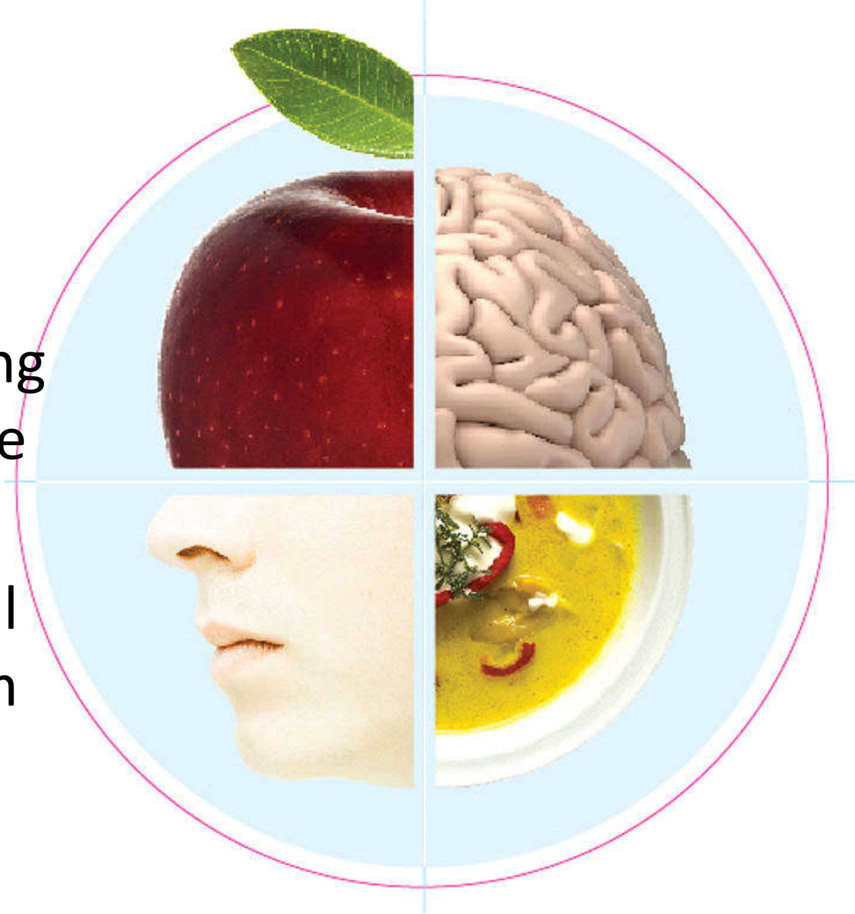
# Taste physiology and perception

- One of the most widely known models is Henning's tetrahedron from 1927, which is a 3D space of tastes that is generated using barycentric coordinates over four extreme vertices that each represent pure sweet, salty, sour, or bitter.



# Taste physiology and perception

- Thus, each taste is a linear interpolation the four components.
- This of course, neglects umami, which was added to the list of receptor types very recently.
- Adaptation occurs for taste, including an aversion to foods that might have been coincident with sickness.
- The concept of flavor is a perceptual experience that combines cues from taste, smell, temperature, touch, vision, and sound.
- Therefore, it is challenging to understand the mechanisms that create a flavor experience.



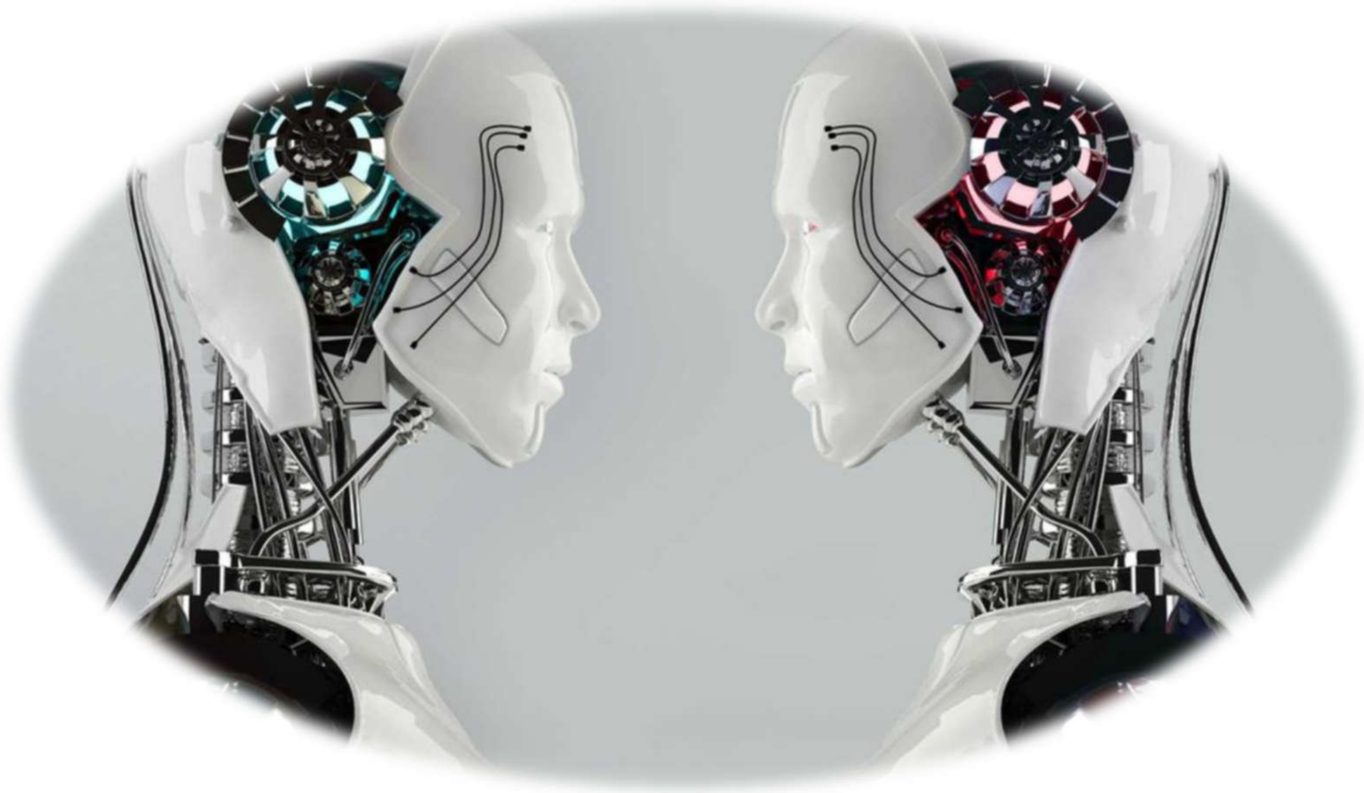
# Gustatory interfaces

- Relatively little has been done to date on simulating taste electronically.
- One recent example, in which electrodes are placed over and under the tongue to provide stimulation that simulates the main taste types.

# Gustatory interfaces

- In another work, taste illusions are formed by accompanying eating with incorrect visual and olfactory cues.
- It is generally difficult to develop gustatory interfaces for VR without actually causing people to eat food during the experience.
- There are clearly health and hygienic issues as well.

# Robotic Interfaces



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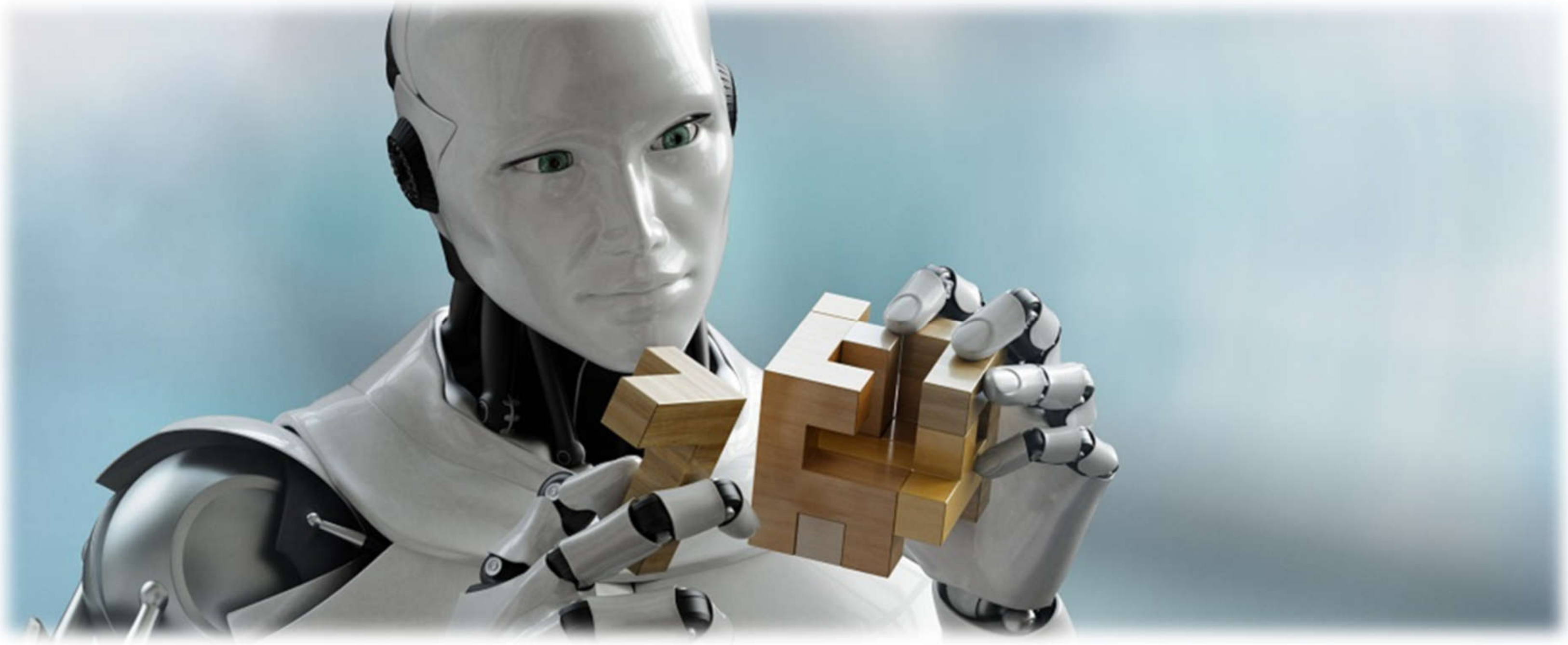
**Department of Mathematics and Informatics**

# Robotic Interfaces

- **Robots are programmable devices** that involve a mixture of sensors, actuators (motors), and computational devices.
- They are usually expected to interpret highlevel commands, use sensors to learn about the world around them, and plan and execute actions that move them safely to accomplish the goals set out by their commanders.

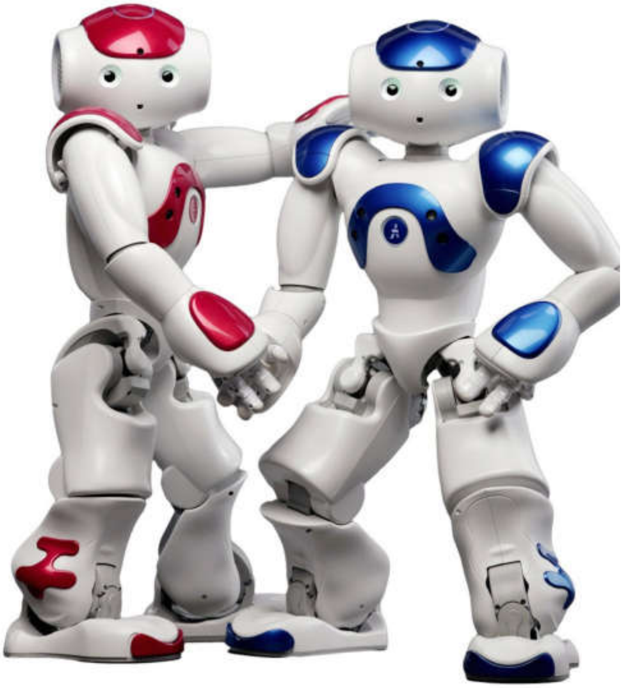
# Robotic Interfaces

- Their components mimic those of humans in many ways.
- Robots have sensors and humans have senses.
- For some specific correspondences, robots have cameras, IMUs, and joint encoders, whereas humans measure the same quantities via vision, vestibular, and proprioceptive senses.



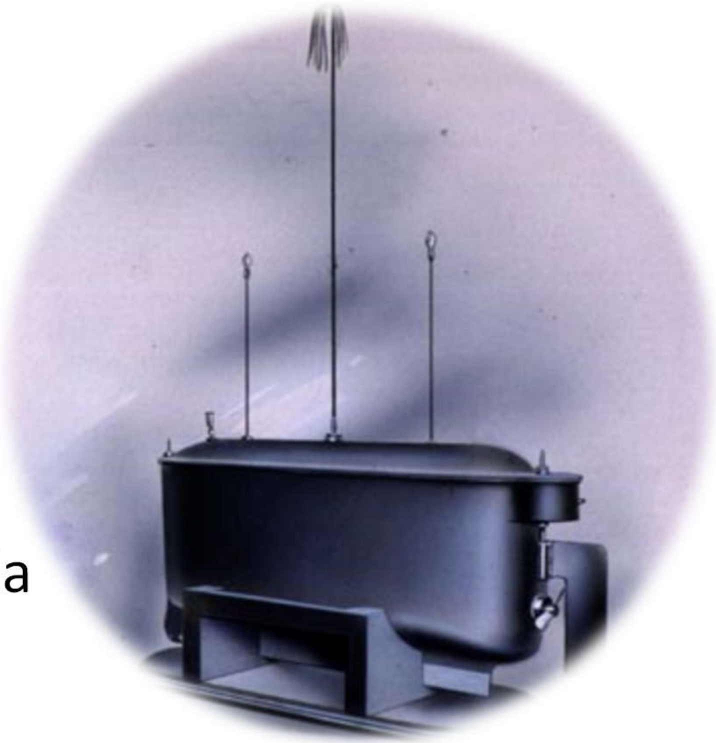
# Robotic Interfaces

- Most robots have motors and humans have muscles, both of which serve the same purpose.
- Robots perform computations to relate high-level goals to low-level motor commands while interpreting data from sensors.
- Humans reason about high-level goals as well, while sending motor signals to muscles and turning stimuli from senses into perceptual phenomena.
- After making so many parallels between robots and humans, a natural question is: Why not use VR technology to allow a human to inhabit the body of a robot?
- We could use robots as our ***surrogate selves***.



# Teleoperation

- The first step toward this vision is to interact with robots over large distances.
- Vehicles have been operated by remote control for well over a century.
- One of the earliest examples is a radio-controlled boat that was publicly demonstrated in New York by Nicola Tesla in 1898.



- Space agencies (such as NASA) and militaries have conducted extensive research and development of remote controlled vehicles.

# Teleoperation

- Another intriguing example of teleoperation is the **TeleGarden** from 1995, which was a robot arm hovering over a real garden, at the University of Southern California, that was connected to the Internet.
- Remote visitors could plant seeds and generally take care of the garden. In 2001, teleoperated robots were deployed to the World Trade Center bombing Site to search for victims.

# Teleoperation

- In current times, remote controlled vehicles of all kinds are widely available to hobbyists, including cars, fixed-wing aircraft, quadrotors (drones), boats, and submarines.
- Operation is often difficult because the user must control the vehicle from a third-person view while handling the controller.
- Therefore, many vehicles have been equipped with wireless cameras so that the user obtains a first-person view (FPV) on a screen.

# Teleoperation

- Teleoperation need not be limited to vehicles.
- Health care is one of the largest and growing fields for teleoperation, which usually involves fixed-based robot arm that manipulates medical instruments.

# Modern robots

- Thousands of different robots have been designed and built, some with very special purposes, such as cleaning windows outside of a building, and others for more general purposes, such as assisted living.

**The HRP-4 humanoid robots**

# Modern robots

- Thousands of different robots have been designed and built, some with very special purposes, such as cleaning windows outside of a building, and others for more general purposes, such as assisted living.

(a) (b)

Figure 13.8: A sampling of commercial and university robots: (a) Neato XV vacuum cleaning robot. (b) Kuka YouBot, which is an omnidirectional mobile base with a manipulator arm on top. (c) Aqua, an underwater robot from McGill University [64]. (d) A flying microrobot from Harvard University [190].

# Modern robots

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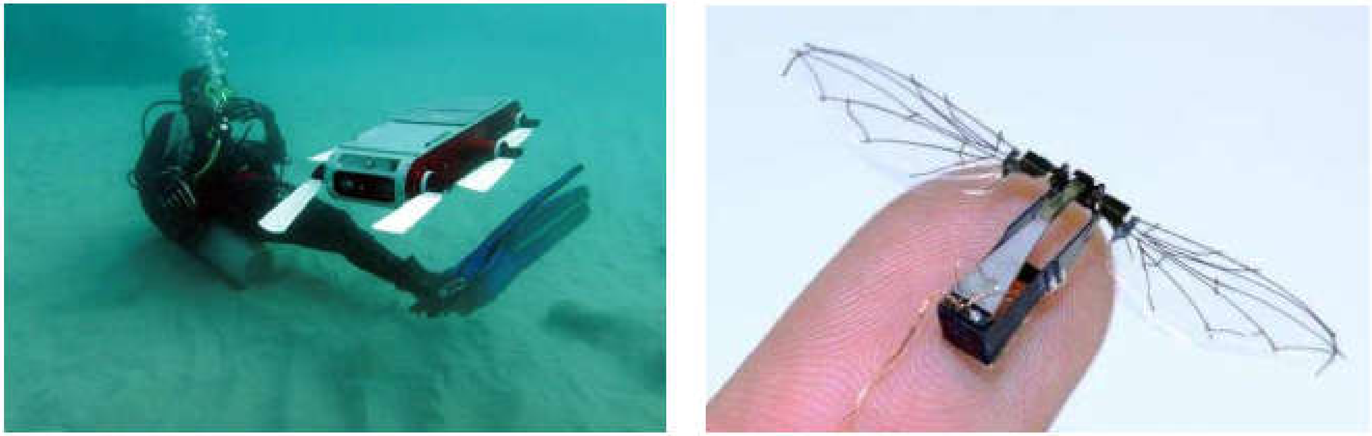
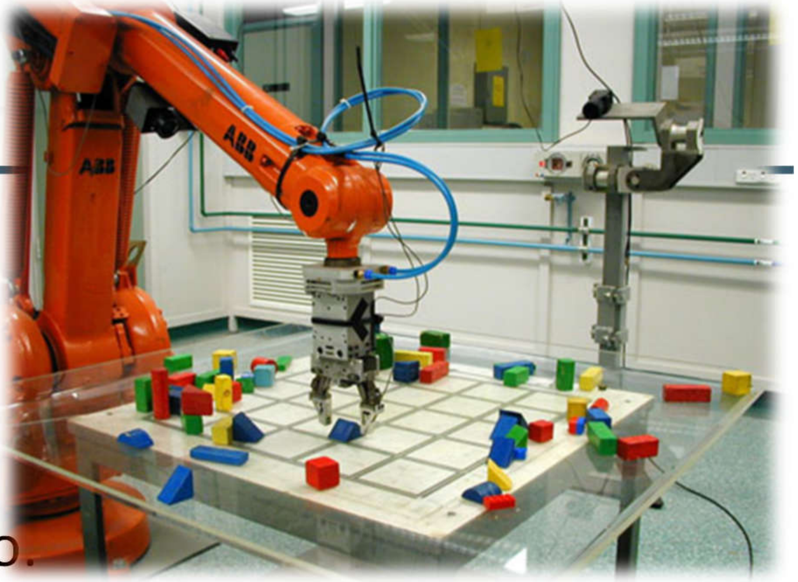


(c) (d)

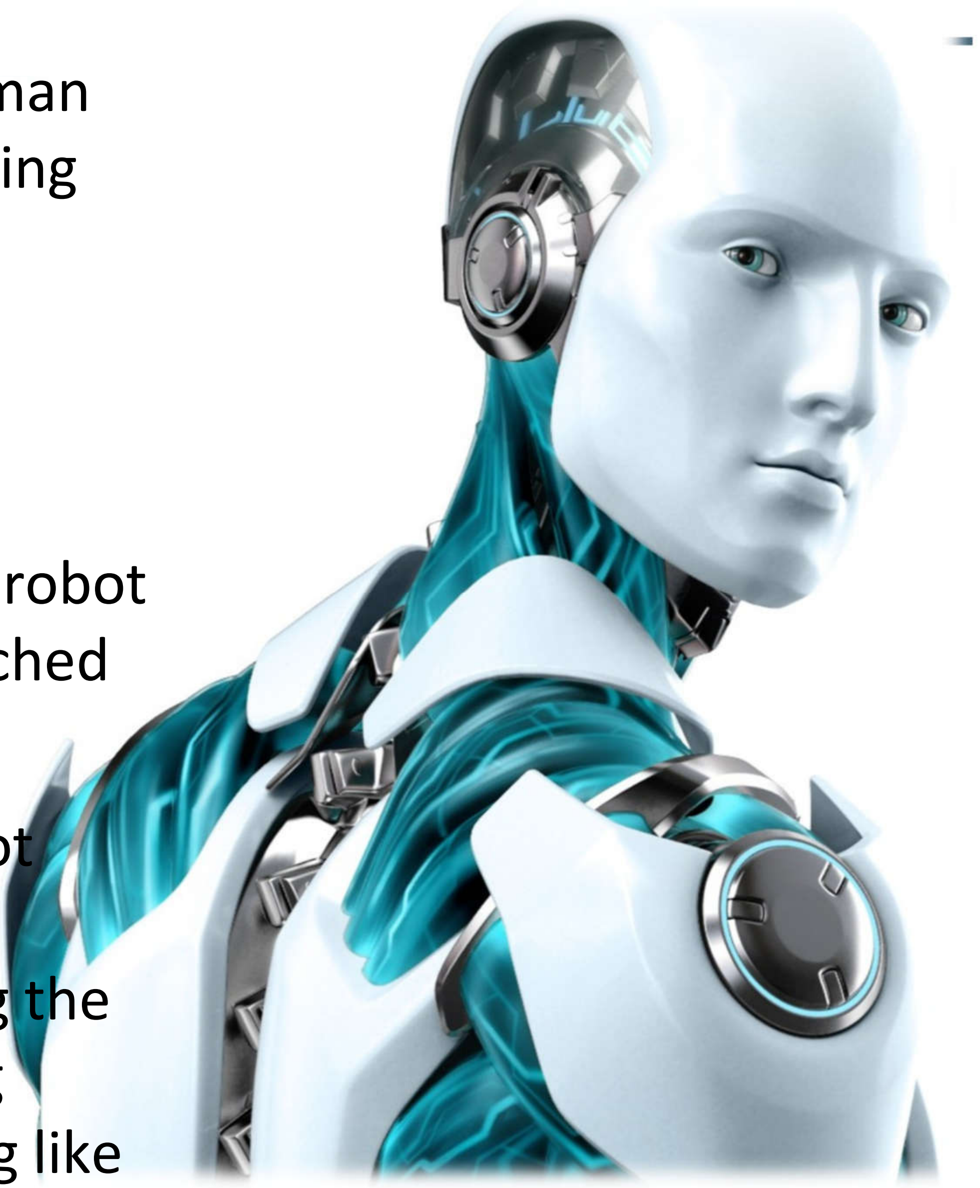
Figure 13.8: A sampling of commercial and university robots: (a) Neato XV vacuum cleaning robot. (b) Kuka YouBot, which is an omnidirectional mobile base with a manipulator arm on top. (c) Aqua, an underwater robot from McGill University [64]. (d) A flying microrobot from Harvard University [190].

## Modern robots



- In addition to hardware, substantial software infrastructure exists to help developers, such ROS (Robot Operating System) and Gazebo.
- Almost any robot is a candidate platform from which a telerobotic VR interface could be attached.
- Cameras and microphones serve as the surrogate eyes and ears of the user.
- A gripper (also called end-effector) could serve as remote hands, if feasible and important for the application.
- The user can command the robot’s motions and actions via keyboards, controllers, voice, or body motions.

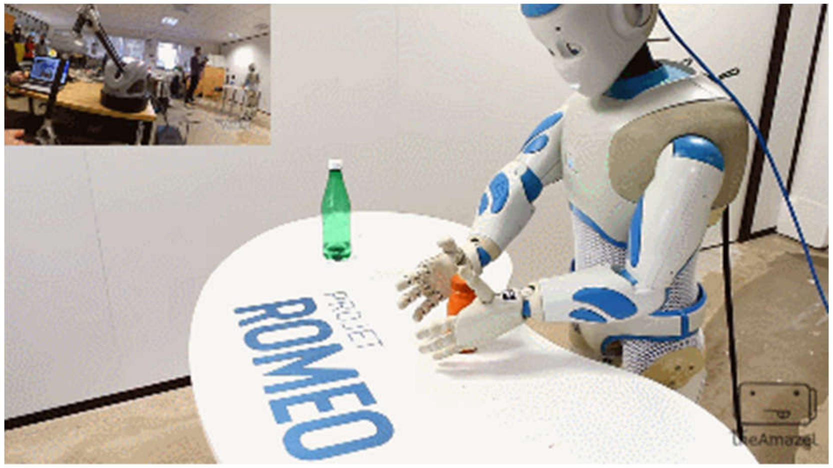
# Modern robots



- For a humanoid robot, the human body could even be tracked using motion capture and mapped directly onto motions of the humanoid.
- More generally, any anthropomorphic aspects of a robot could become part of the matched zone.
- At the other extreme, the robot allows many non-human experiences, such as becoming the size of a small insect and flying around the room, or swimming like a fish in the sea.

# Modern robots - Telepresence

- The term and concept of telepresence is attributed to Marvin Minsky, pioneer of artificial intelligence.
- In the most idealized case, which we are far from achieving with current technology, it could completely eliminate the need to physically travel.
- It could also revolutionize the lives of people who have limited mobility due to disabilities or advanced age.
- In terms of technical challenges, telepresence involves the integration of two components: **teleoperation and VR.**

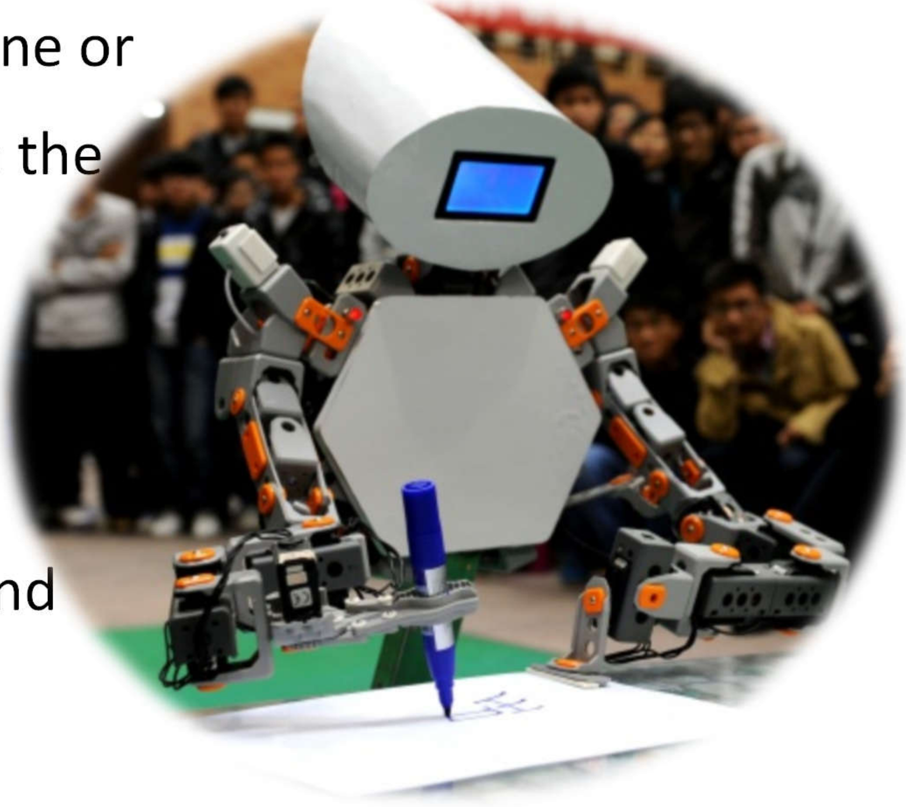


# Modern robots - Telepresence

Figure 13.9: The Double telepresence robot is a screen and camera on a stick. The robot costs around $2500, and the screen is a tablet, such as an iPad. The height can even be adjusted remotely so that the person may appear to be sitting or standing.

# Modern robots - Telepresence

- **Several aspects come to mind regarding a telepresence robot:**
- **Sensory input**: What will it sense from the remote physical world? For visual input, it could contain cameras that directly map the eye viewpoints and are even matched to user head motions.
- Auditory input is captured using one or more microphones, depending on the importance of localization.
- Some other possible inputs for telepresence are: temperature, contact forces, humidity, odors, and the robot's remaining battery life.



# Modern robots - Telepresence

- **Mobility**: Where can the robot go?
- With no mobility, telepresence is reduced to a stationary camera and microphone.
- If the task is to interact with people, then it should be able to move into the same places that people are capable of entering.
- In other settings, many modes of mobility may be desirable, such as flying, swimming, or even crawling through pipes.

# Modern robots - Telepresence

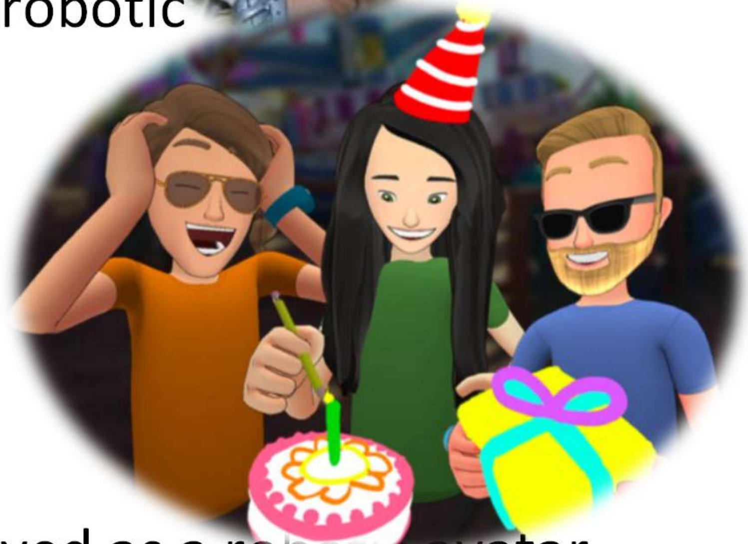
- **Audiovisual output:** telepresence system could seem like a "fly on the wall" and not disrupt life at the remote site.
- More commonly, it is designed to interact with people, which could be accomplished by a screen and a speaker.
- If the robot has some anthropomorphic characteristics, then it may also be able to make gestures that communicate emotion or intent with other people.

# Modern robots - Telepresence

- **Manipulation**: The telepresence system targets face-to-face interaction, and therefore neglects being able to manipulate objects at the remote site.

- A telepresence robot is much more powerful if it can grasp, manipulate, carry, and ungrasp objects.
- It could then open doors, operate elevators, go grocery shopping, and so on.

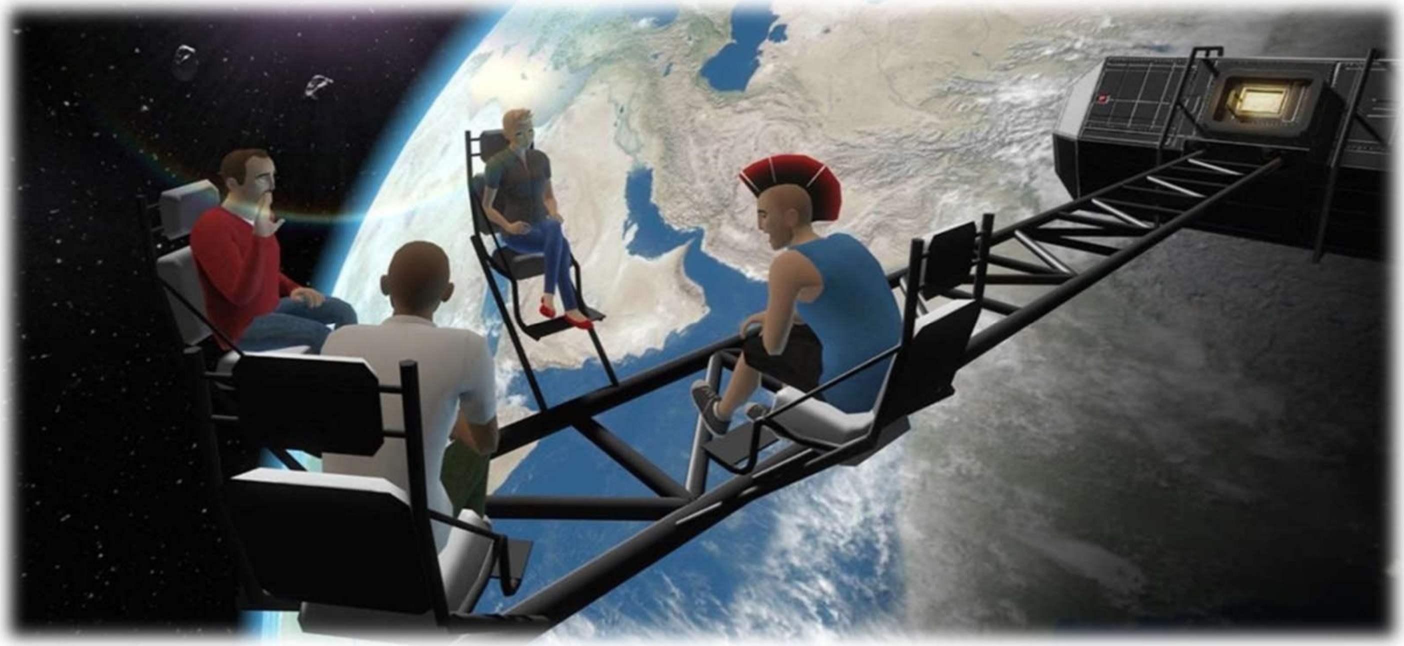
# Development of better telepresence syste
Challenges



- **Tele-embodiment issues**
- Imagine how people would react to the robotic surrogate version of yourself.
- Social interaction in VR depends on the avatars that people chose to represent themselves.
- With telepresence, you would be perceived as a robotic avatar, which leads to the same kinds of social issues.
- Unfortunately, there is much less freedom to chose how you want to look in comparison to interaction in a purely virtual world.

# Development of better telepresence systems - Challenges

- **Tele-embodiment issues**
- You may have to be perceived by everyone as an awkward screen on a stick if that is the platform.
- Research in social robotics and human-robot interaction may be useful in helping improve social interactions through such a robotic avatar.

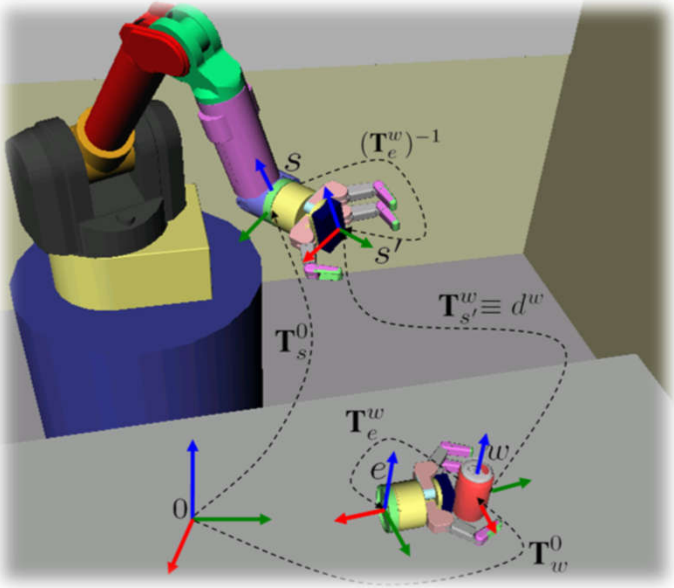


# Development of better telepresence systems - Challenges

- **Remote-control versus autonomy**
- Assuming that the robot may roam over a larger area than the matched zone, a locomotion method is needed.
- That the user controls the robot motion through an interface.
- A spectrum of choices exists for the user who teleoperates the robot.
- At one extreme, the user may continuously control the movements, in the way that a radio-controlled car is driven using the remote.

# Development of better telepresence systems - Challenges

- **Remote-control versus autonomy**
- Latency becomes critical some applications, especially telesurgery.
- At the other extreme, the user may simply point out the location on a map or use a virtual laser pointer to point to a visible location.
- In this case, the robot could execute all of the motions by itself and take the user along for the ride.
- This requires a higher degree of autonomy for the robot because it must plan its own route that accomplishes the goals without running into obstacles; this is known in robotics as ***motion planning***.



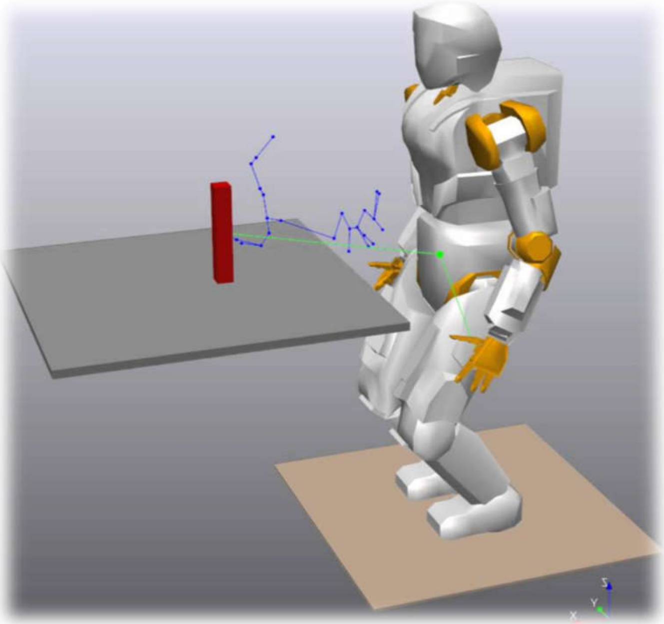
# Development of better telepresence systems - Challenges

## VR sickness issues

- Because of the connection to locomotion, vection arises.
- Users may be more comfortable controlling the robot themselves rather than a higher level of autonomy, even though it involves tedious concentration.
- Furthermore, the path itself determined by a motion planning algorithm could be optimized to reduce sickness by shortening times over which accelerations occur.

# Development of better telepresence systems - Challenges

- Another idea is to show the motion on a 2D or 3D map while the robot is moving, from a third-person perspective.
- The user could conceivably be shown anything, such as news feeds, while the robot is moving.
- As in the case of locomotion for virtual worlds, one must be careful not to disorient the user by failing to provide enough information to easily infer the new position and orientation relative to the old one by the time the user has arrived.



# Development of better telepresence systems - Challenges

## Latency issues

- As expected, time delays threaten the performance and comfort of telepresence systems.
- A networked system causes new latency to be added to the VR system because information must travel from the client to the server and back again.
- Furthermore, bandwidth (bits per second) is limited, which might cause further delays or degradation in quality.

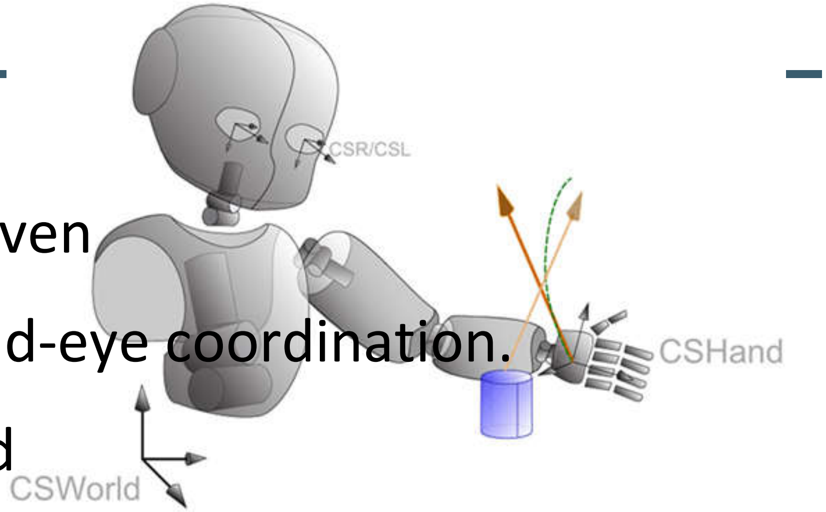
# Development of better telepresence systems - Challenges

## Latency issues

- By transmitting an entire panoramic view to the user, the network latency should not contribute to head tracking and rendering latencies.
- However, latency has a dramatic impact on interactivity, which is a well-known problem to networked gamers.
- On the other hand, it has been found that people generally tolerate latencies in phone calls of up to 200 ms before complaining of difficulty conversing;
- However, they may become frustrated if they expect the robot to immediately respond to their movement commands.

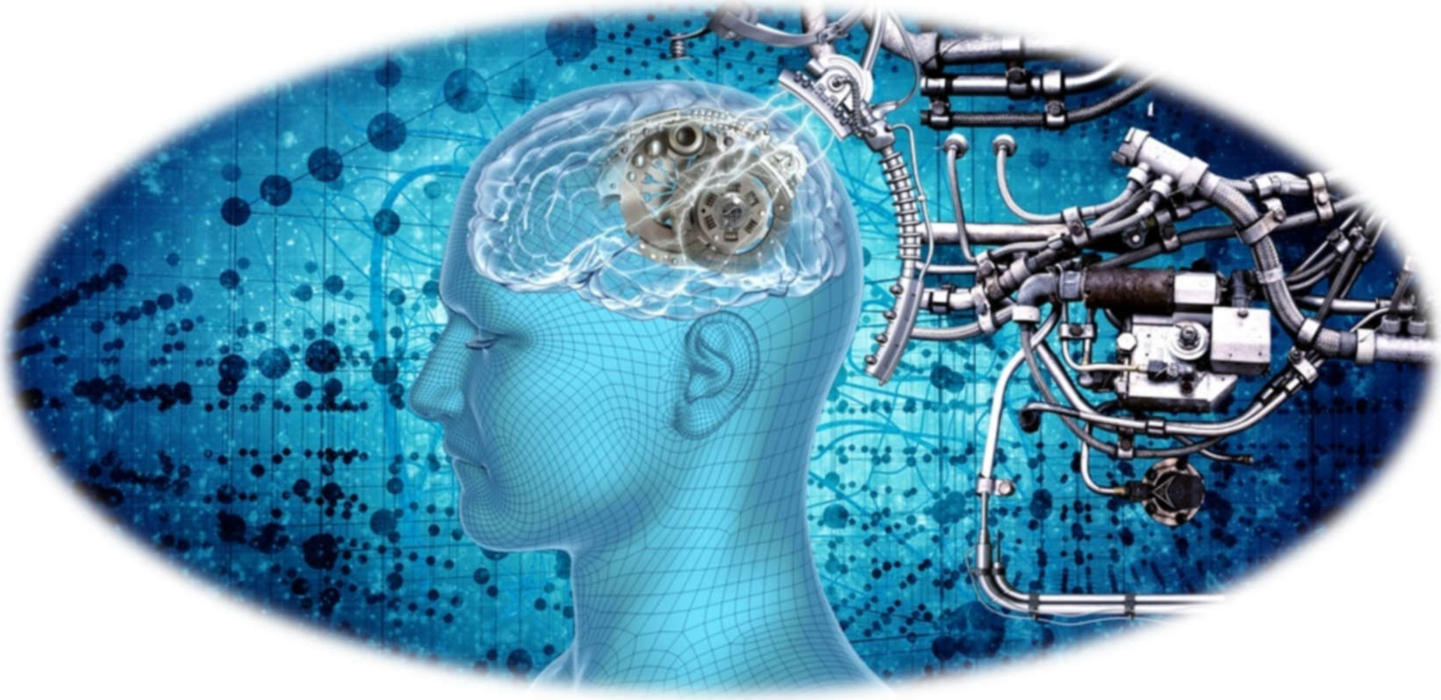
# Development of better telepresence systems - Challenges

## Latency issues



- Completing a manipulation task is even more difficult because of delays in hand-eye coordination.
- In some cases people can be trained to overcome high latencies through adaptation, assuming the latencies do not substantially vary during and across the trials.
- The latency poses a considerable challenge for medical applications of telepresence.
- Imagine if you were a doctor pushing on a scalpel via a telepresence system, but could not see or feel that it is time to stop cutting until 500 ms later.
- This might be too late!

# Brain machine interfaces



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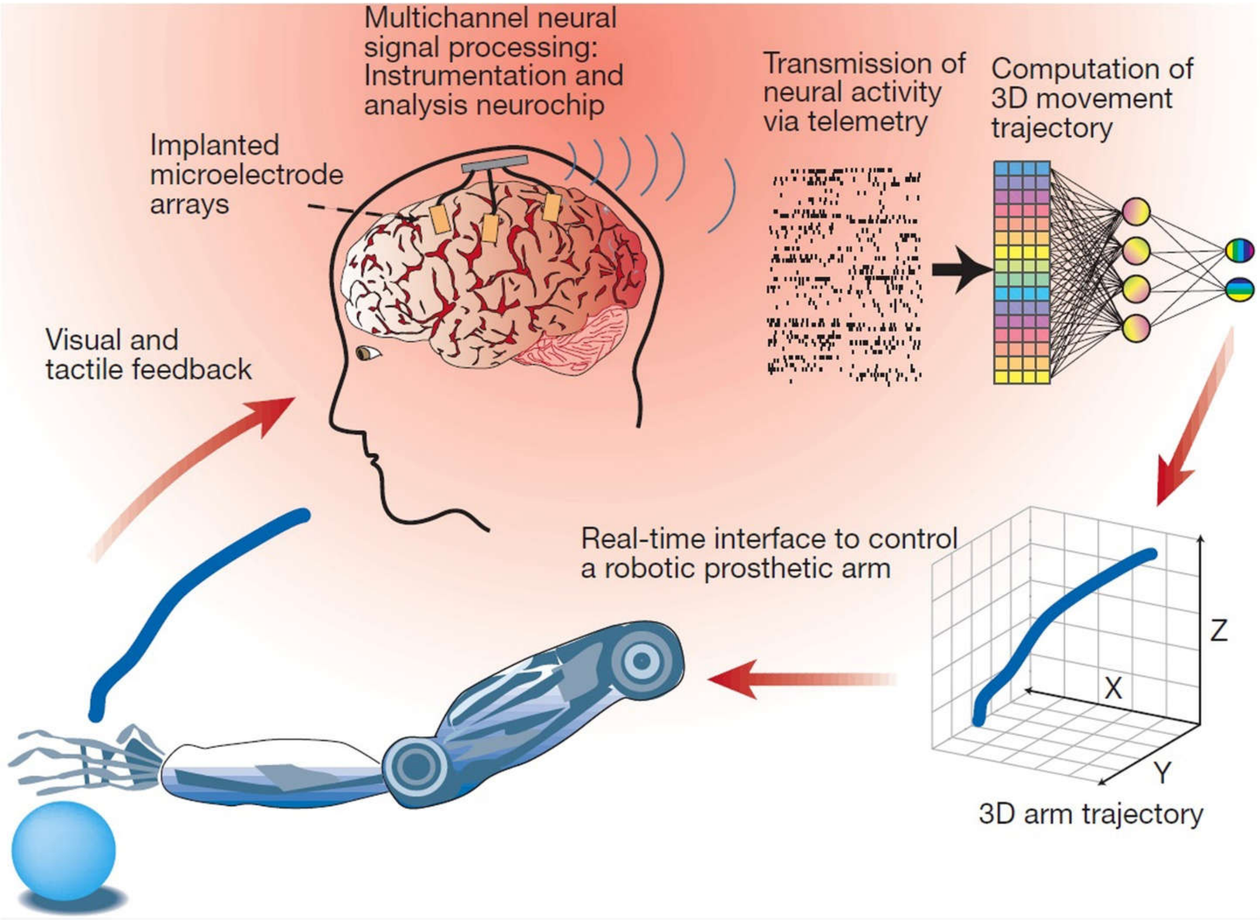
Department of Mathematics and Informatics

# Brain-Machine Interfaces

- The ultimate interface between humans and machines could be through direct sensing and stimulation of neurons.
- One step in this direction is to extract physiological measures.



# Brain-Machine Interfaces

- Rather than using them to study VR sickness, we could apply measures such as heart rate, galvanic skin response, and pallor to adjust the VR experience dynamically.
- Various goals would be optimized, such as excitement, fear, comfort, or relaxation.
- Continuing further, we could apply technology that is designed to read the firings of neurons so that the VR system responds to it by altering the visual and auditory displays.

# Brain-Machine Interfaces

- The users can learn that certain thoughts have an associated effect in VR, resulting in mind control.
- The powers of neuroplasticity and perceptual learning could enable them to comfortably and efficiently move their avatar bodies in the virtual world.
- This might sound like pure science fiction, but substantial progress has been made.

# Brain-Machine Interfaces

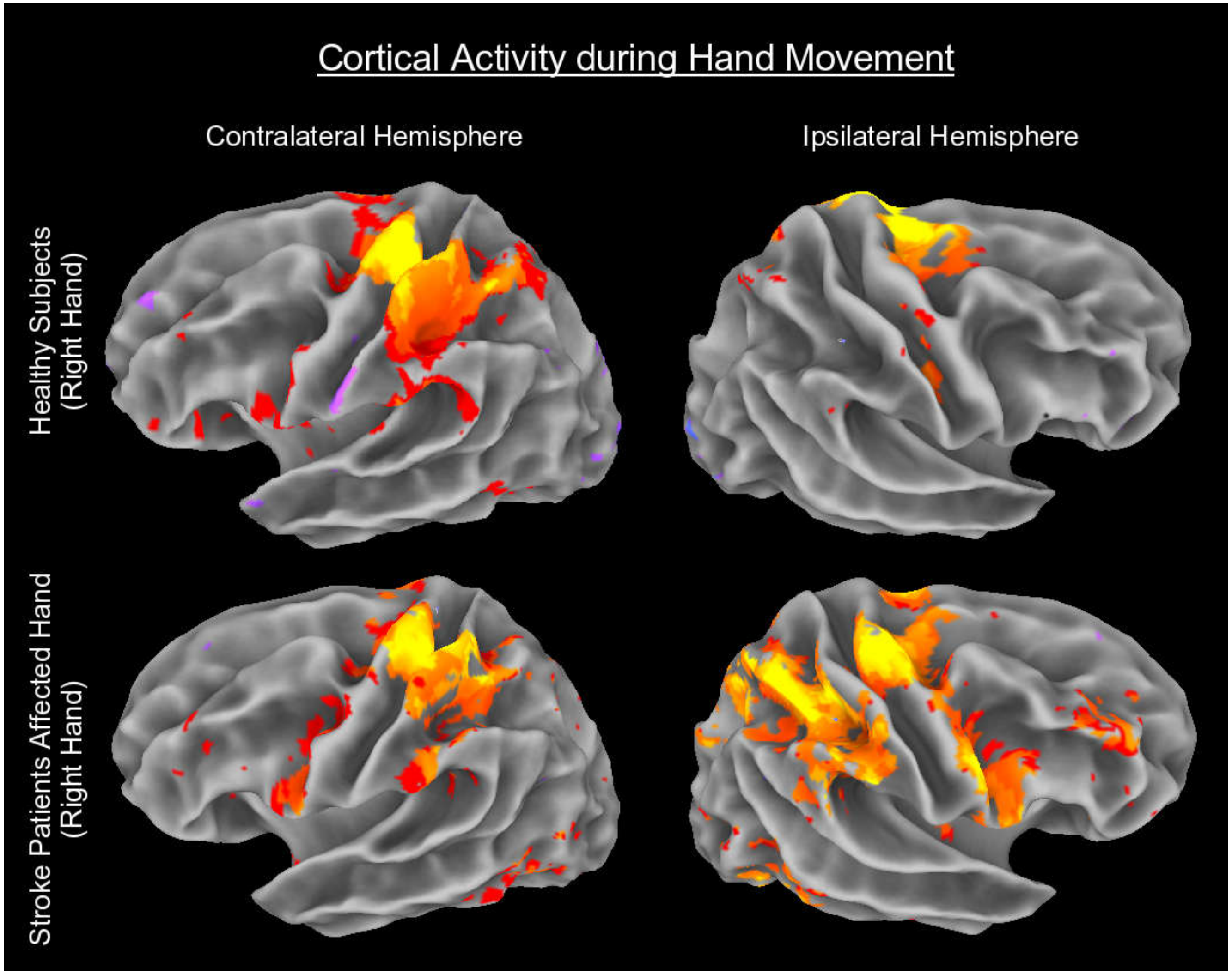
- For example, monkeys have been recently trained by neuroscientists at Duke University to drive wheelchairs using only their thoughts.
- In the field of brain-machine interfaces (alternatively, BMI, brain-computer interfaces, or BCI), numerous other experiments have been performed, which connect humans and animals to mechanical systems and VR experiences via their thoughts.

# Brain-Machine Interfaces

- Measurement methods
- The goal of devices that measure neural activity is to decipher the voluntary intentions and decisions of the user.
- They are usually divided into two categories:
  - non-invasive (attaching sensors to the skin is allowed) and
  - invasive (drilling into the skull is allowed).
- First consider the non-invasive case, which is by far the most appropriate for humans.
- The most accurate way to measure full brain activity to date is by functional magnetic resonance imaging (fMRI).

# Brain-Machine Interfaces

- The most accurate way to measure full brain activity to date is by functional magnetic resonance imaging (fMRI).



# Brain-Machine Interfaces

- Measurement methods

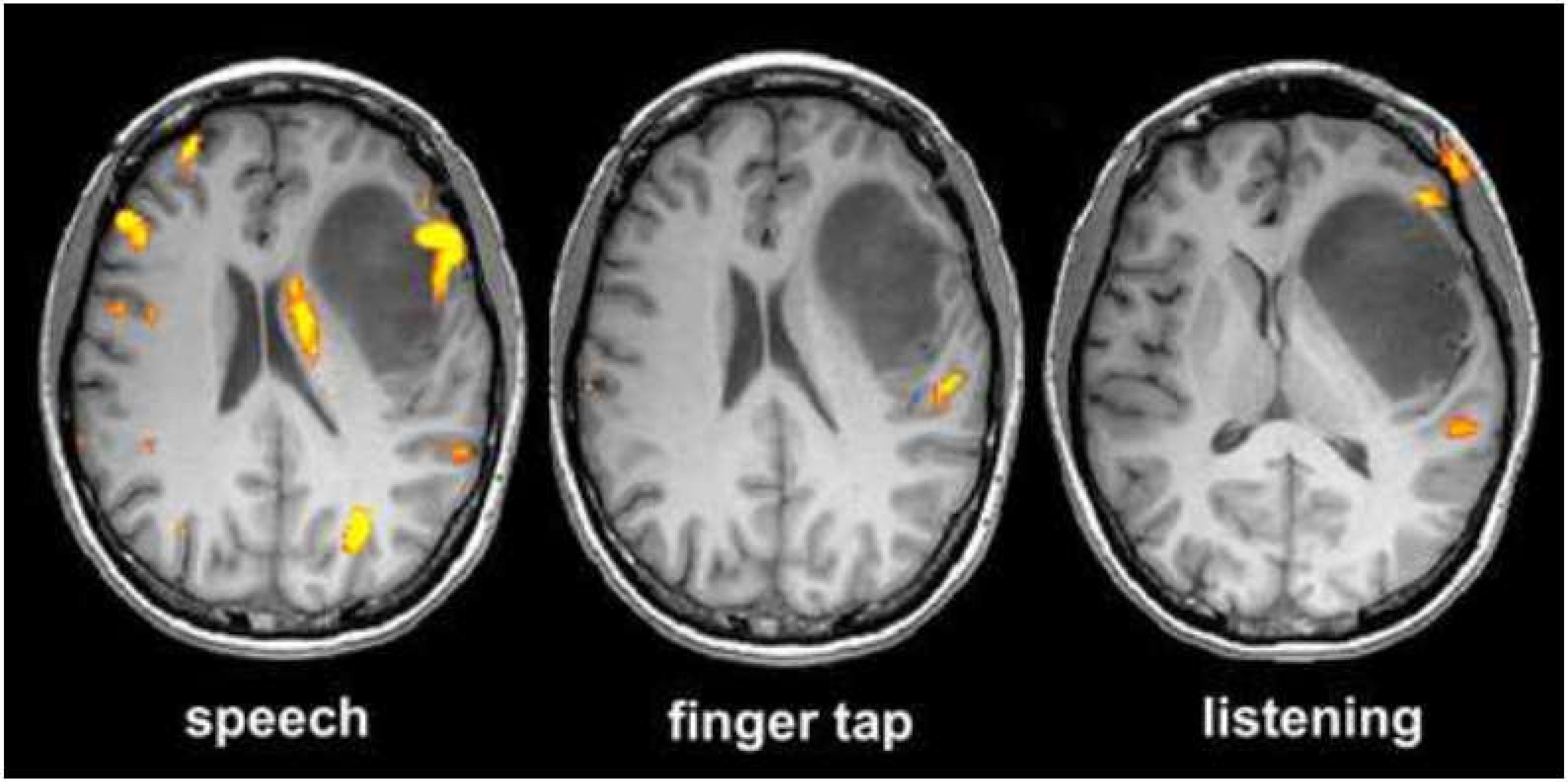


Figure 13.10: fMRI scans based on various activities. (Figure from Mayfield Brain and Spine)

# Brain-Machine Interfaces

- Measurement methods
- Ordinary MRI differs in that it provides an image of the static structures to identify abnormalities, whereas an fMRI provides images that show activities of parts of the brain over time.
- Unfortunately, fMRI is too slow, expensive, and weighty for everyday use as a VR interface.

# Brain-Machine Interfaces

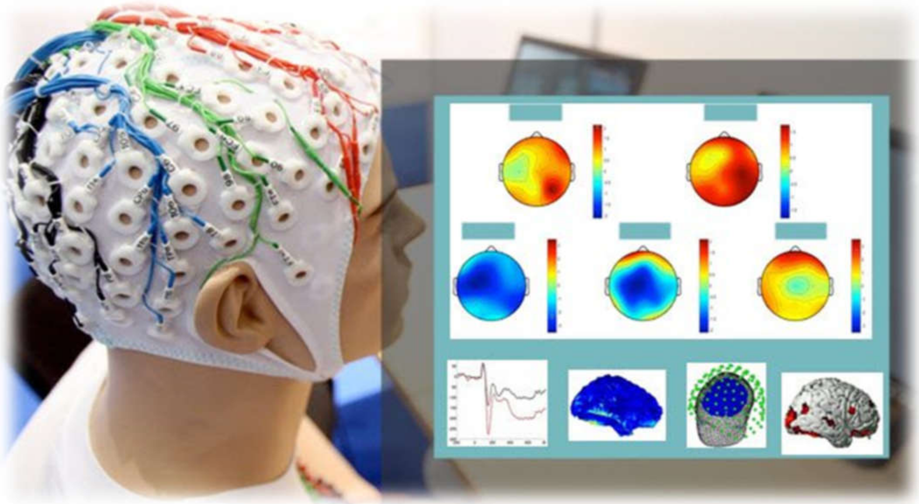
- Measurement methods
- Thus, the most common way to measure brain activity for BMI is via **electroencephalogram** (EEG), which involves placing electrodes along the scalp to measure electrical field fluctuations that emanate from neural activity.

(a) (b)

Figure 13.11: EEG systems place electrodes around the skull: (a) A skull cap that allows up to a few dozen signals to be measured. (b) Emotive wireless EEG device.

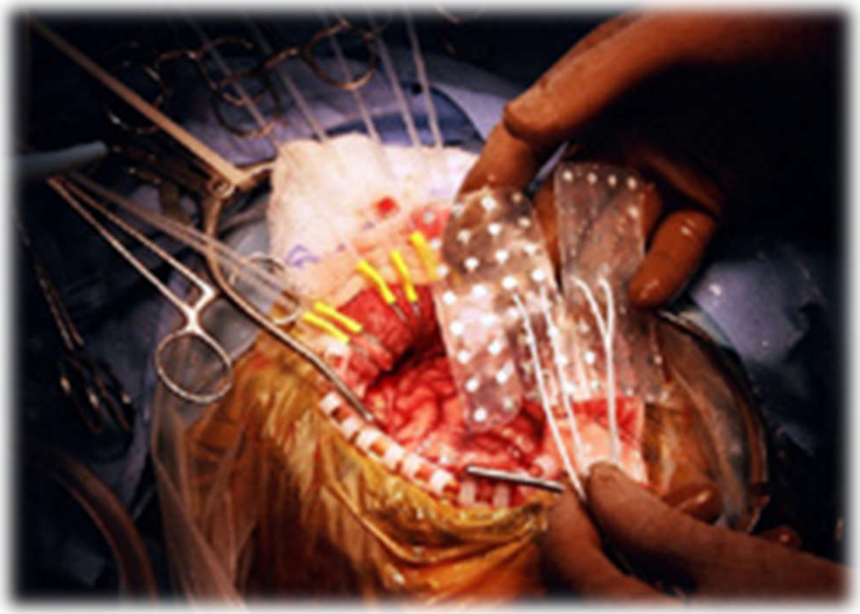
# Brain-Machine Interfaces

- There is also significant attenuation and interference with other neural structures.
- The transfer rate of information via EEG is between 5 and 25 bits per second.
- This is roughly equivalent to one to a few characters per second, which is two orders of magnitude slower than the average typing rate.
- Extracting the information from EEG signals involves difficult signal processing; open-source libraries exist, such as OpenVibe from INRIA Rennes.



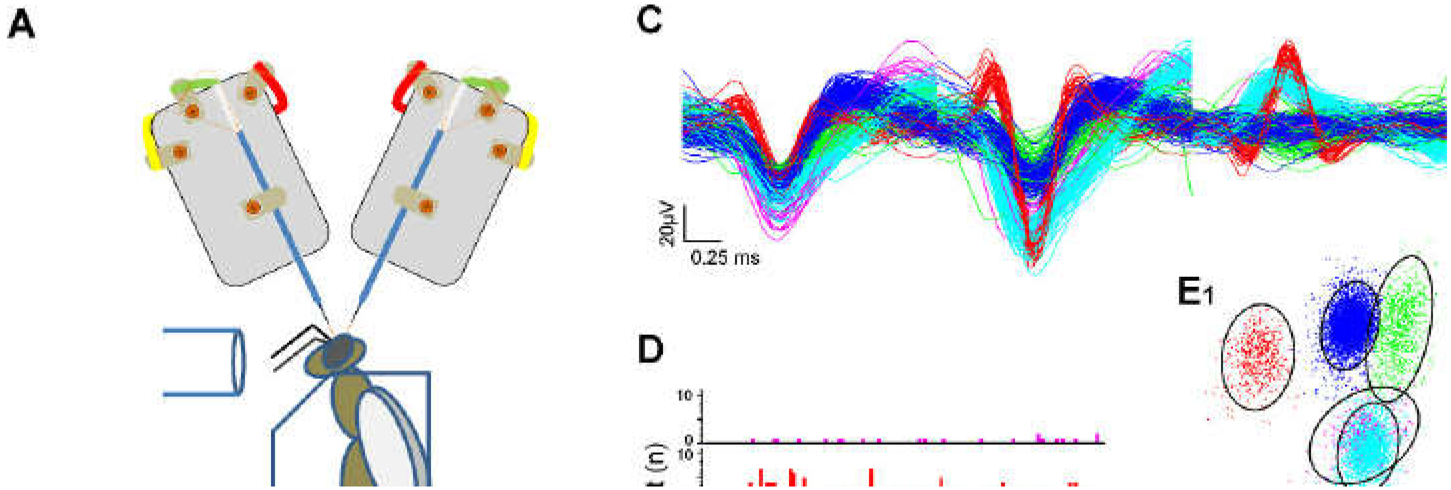
# Brain-Machine Interfaces - Measurement methods

- For the invasive case, electrodes are implanted inside of the skull.
- This provides much more information for scientists, but is limited to studies on animals (and some humans suffering from neural disorders such as Parkinson's disease).
- Thus, invasive methods are not suitable for the vast majority of people as a VR interface.



# Brain-Machine Interfaces - Measurement methods

- The simplest case is to perform a single-unit recording for a particular neuron; however, this often increases the number of required trials because the neural response typically switches between different neurons across trials.
- As the number of neurons increases, the problem of deciphering the thoughts becomes more reliable.
- Numerous recordings could be from a single site that performs a known function, or could come from multiple sites to help understand the distributed processing performed by the brain.



# Brain-Machine Interfaces

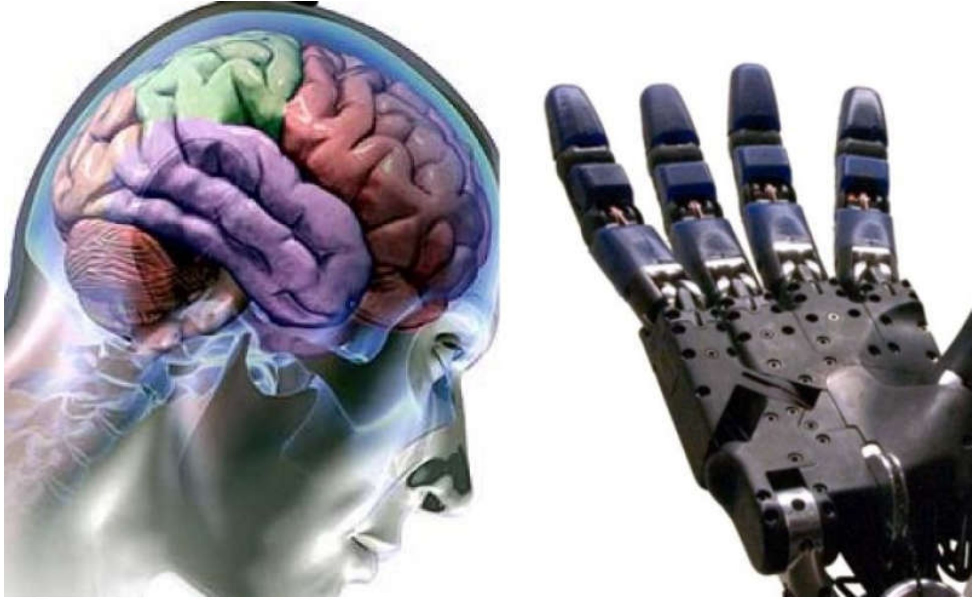
- Medical motivation
- It is important to understand the difference between VR users and the main targeted community for BMI.
- The field of BMI has rapidly developed because it may give mobility to people who suffer from neuromuscular disabilities.
- Examples include driving a wheelchair and moving a prosthetic limb by using thoughts alone.
- The first **mental control system** was built by Jacques Vidal in the 1970s, and since that time many systems have been built using several kinds of neural signals.
- In all cases, it takes a significant amount of training and skill to operate these interfaces.

# Brain-Machine Interfaces

- Medical motivation
- People with motor disabilities may be highly motivated to include hours of daily practice as part of their therapy routine, but this would not be the case for the majority of VR users.
- One interesting problem in training is that trainees require feedback, which is a perfect application of VR.

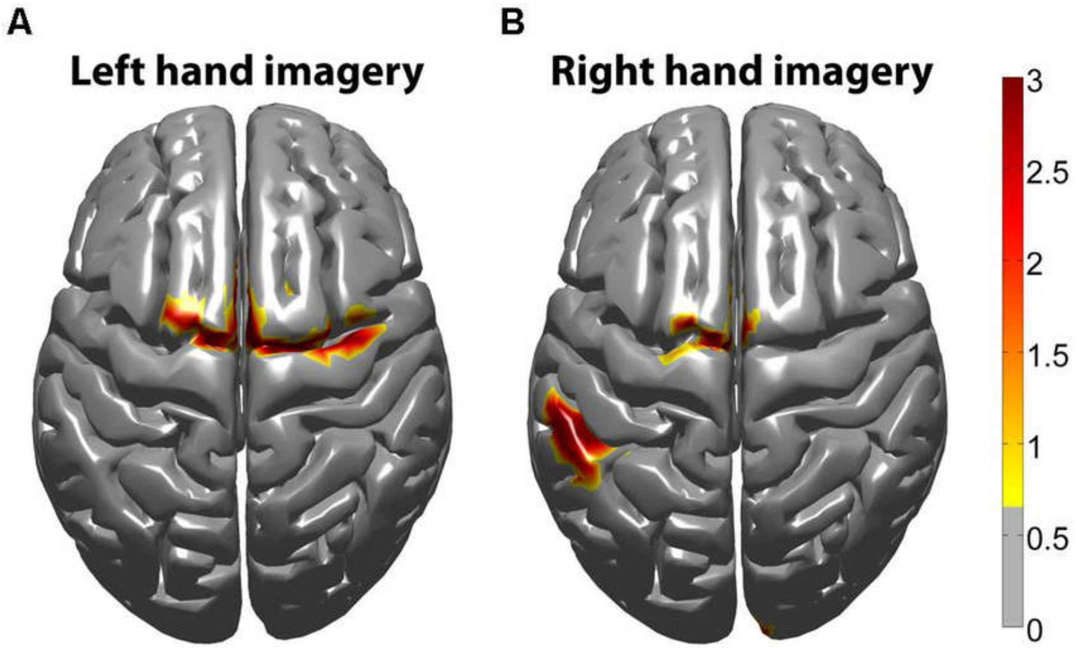
# Brain-Machine Interfaces - Medical motivation

- The controller in the VR system is essentially replaced by the output of the signal processing system that analyzes the neural signals.
- The user can thus practice moving a virtual wheelchair or prosthetic limb while receiving visual feedback from a VR system.
- This prevents them from injuring themselves or damaging equipment or furnishings while practicing.



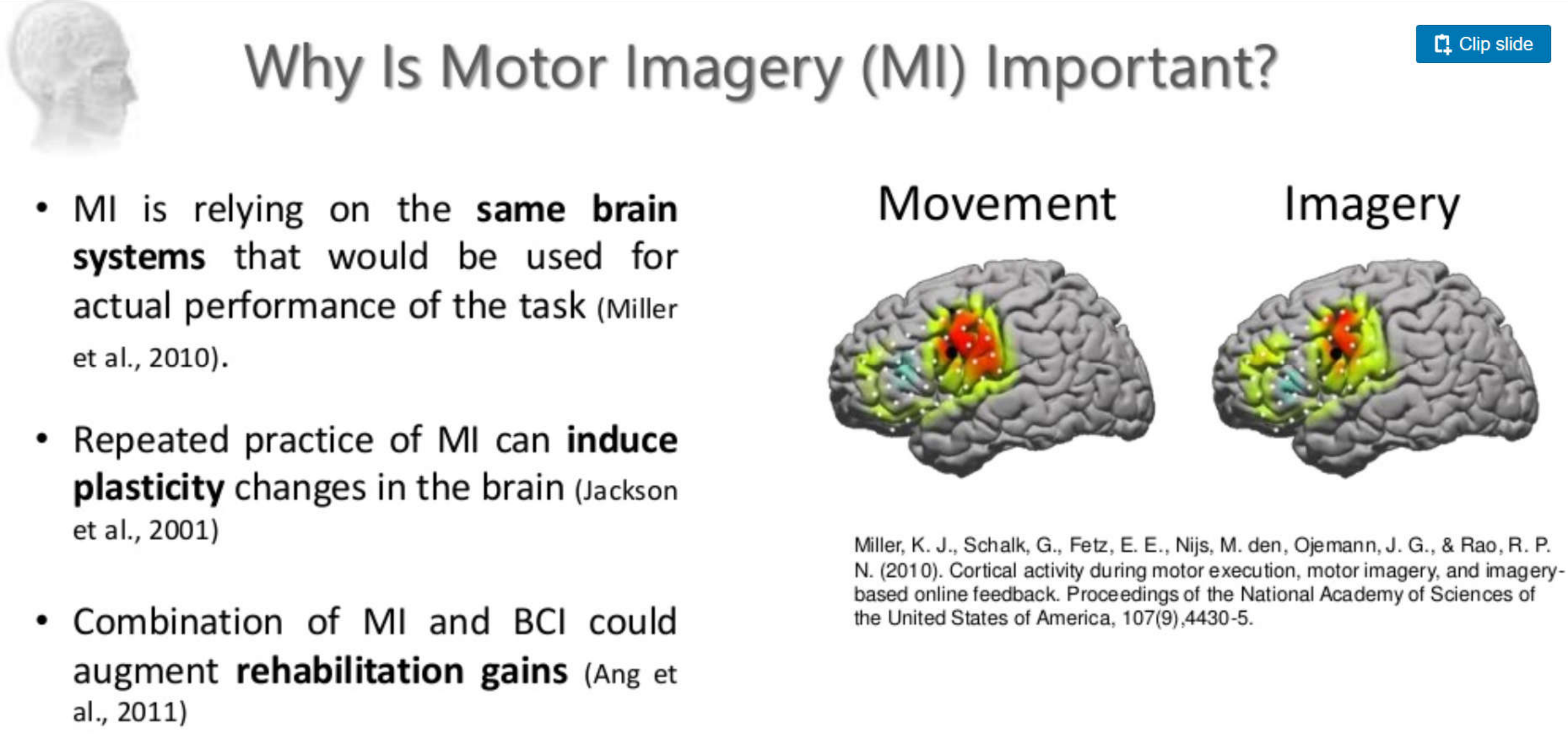
# Brain-Machine Interfaces - BMI in VR

- Medical motivation
- In the context of VR, most systems have used one of three different kinds of EEG signals:
  - motor imagery,
  - SSVEP, and
  - P300.



- The most common is motor imagery, which is a mental process that a person performs before executing an action.

# Brain-Machine Interfaces - BMI in VR



## Why Is Motor Imagery (MI) Important?

- MI is relying on the **same brain systems** that would be used for actual performance of the task (Miller et al., 2010).
- Repeated practice of MI can **induce plasticity** changes in the brain (Jackson et al., 2001)
- Combination of MI and BCI could augment **rehabilitation gains** (Ang et al., 2011)

Miller, K. J., Schalk, G., Fetz, E. E., Nijs, M. den, Ojemann, J. G., & Rao, R. P. N. (2010). Cortical activity during motor execution, motor imagery, and imagery-based online feedback. Proceedings of the National Academy of Sciences of the United States of America, 107(9),4430-5.

# Brain-Machine Interfaces - BMI in VR

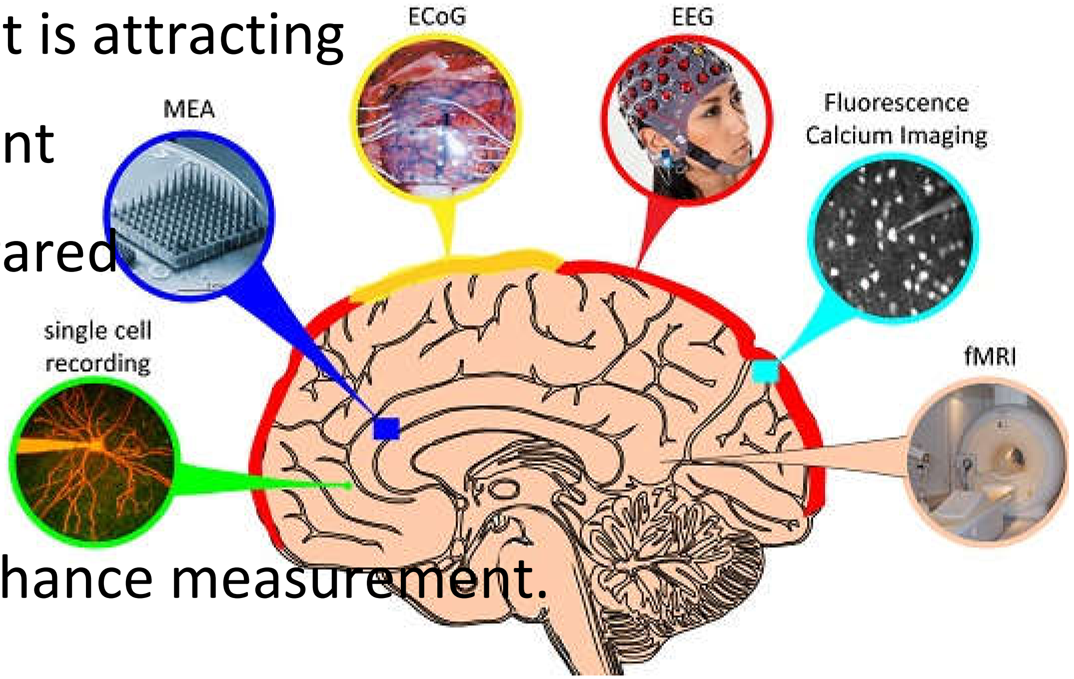
- During this time, the person rehearses or simulates the motion in the brain, which leads to measurable activations in the primary motor cortex.

- Users imagine rotating in place or making footsteps to achieve locomotion in the virtual world.
- Unfortunately, most successful systems are limited to a couple of simple commands, such as starting and stopping walking.
- Nevertheless, users have been able to explore maze-like environments by simply imagining the motions.

# Brain-Machine Interfaces - Research challenges

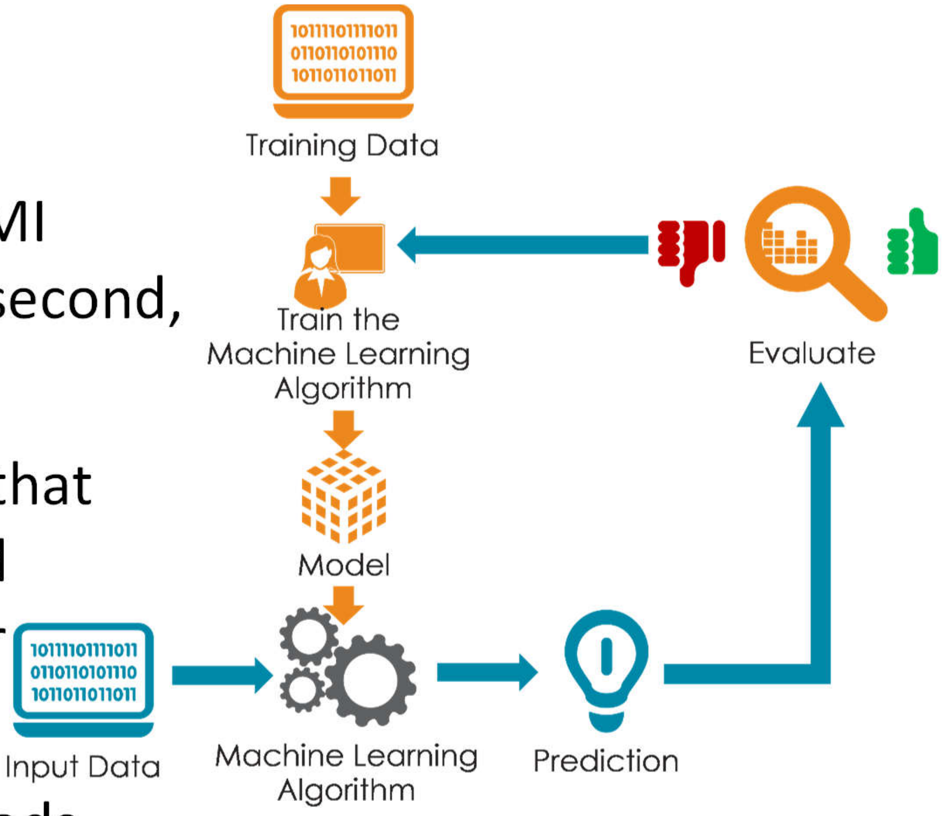
- Although BMIs are rapidly maturing, several challenges remain before they could come into widespread use:
- **Better technologies for measuring neural signals** while remaining non-invasive.
- Ideally, one would like to measure outputs of thousands of neurons with a high signal-to-noise ratio.
- One alternative to fMRI that is attracting significant attention in recent years is functional near-infrared spectroscopy (fNIRS).

Such signals can be used in combination with EEG to enhance measurement.



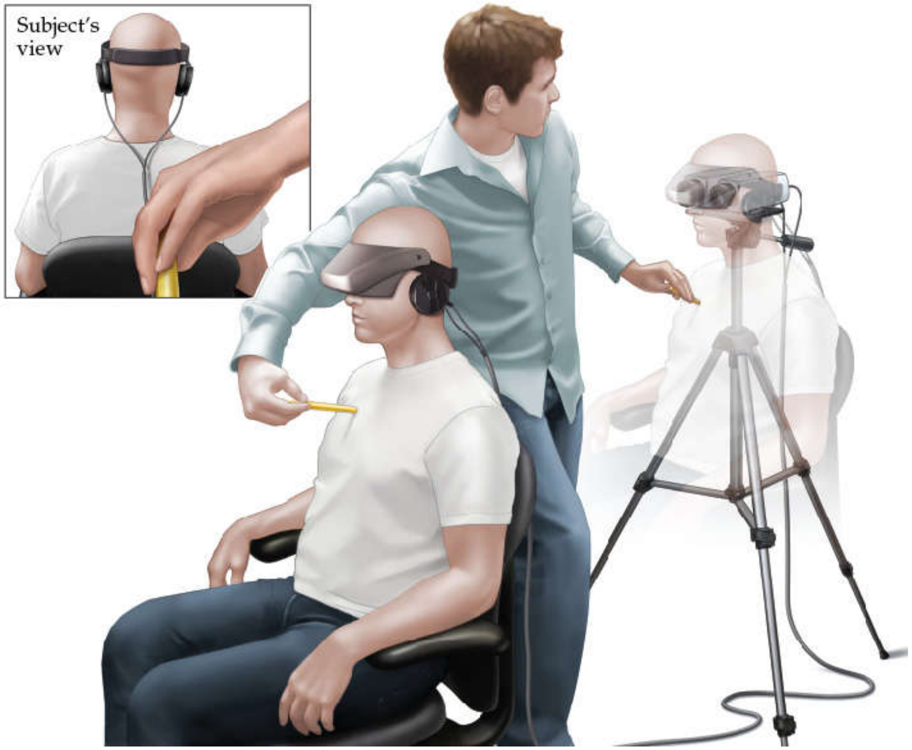
# Brain-Machine Interfaces - Research challenges

- **Improved bandwidth in terms of bits-per-second** that can be commanded by the user so that there are clear advantages over using body movements or controllers.
- VR systems with non-invasive BMI typically offer up to one bit per second, which is fully inadequate.
- Better classification techniques that can recognize the intentions and decisions of the user with higher accuracy and detail.
- Modern machine learning methods may help advance this.



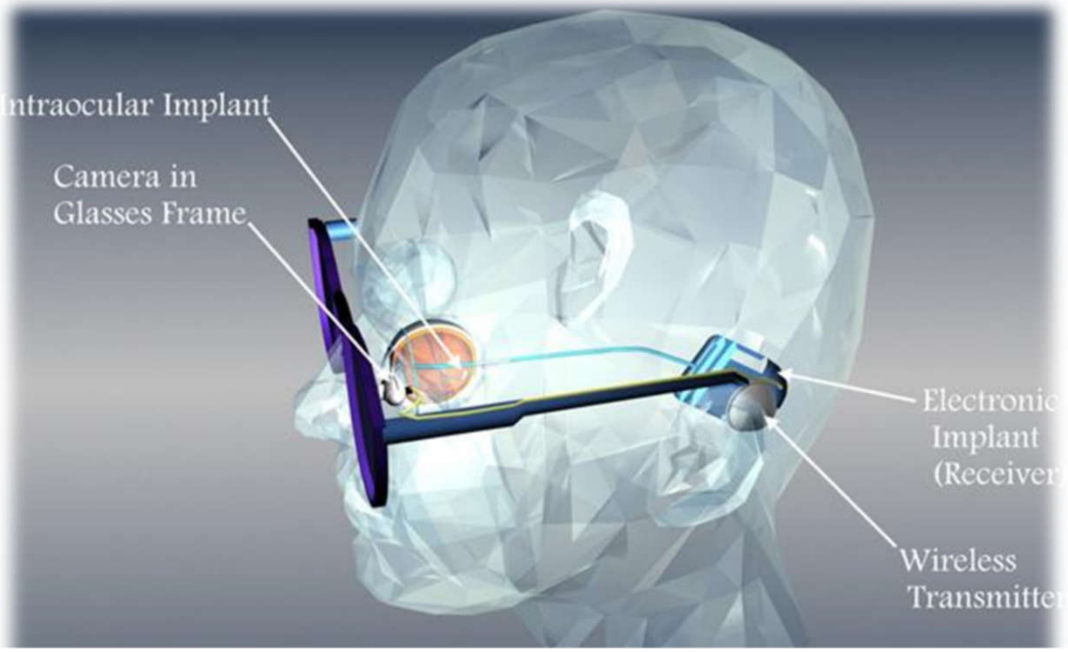
# Brain-Machine Interfaces - Research challenges

- **Dramatic reduction in the amount of training** that is required before using an interface.
- If it requires more work than learning how to type, then widespread adoption would be unlikely.
- **A better understanding what kinds of body schemas** can be learned through the feedback provided by VR systems so that the brain accepts the virtual body as being natural.



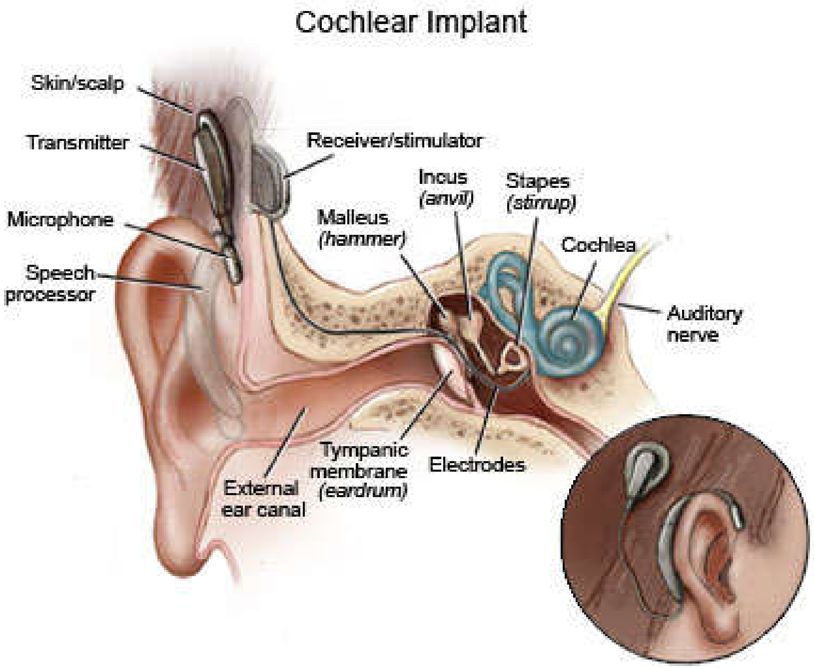
# Brain-Machine Interfaces - Toward a brain in a vat

- Suppose that in addition to measuring neural outputs, direct neural stimulation were also used.
- This would forgo the need to place displays in front of senses.
- For the eye, signals could be sent directly to the photoreceptors.
- This technology is called **retinal implants**, and already exists for the purpose of helping the blind to see.



# Brain-Machine Interfaces - Toward a brain in a vat

- Similarly, cochlear implants help the deaf to hear.



- Neuroscientists, such as David Eagleman from Stanford, have even proposed that we could learn to develop completely new senses.
- An example is perceiving infrared or radio signals by remapping their frequencies, amplitudes, and spatial arrangements to other collections of receptors on the body, such as the back.

# Brain-Machine Interfaces - Toward a brain in a vat

- To build a widespread, networked VR society, it is tempting to consider invasive BMI possibilities in a distant future.
- Before proceeding, recall the discussion of ethical standards and consider whether such a future is preferable.