Lecture 2: Sensors And Actuators

Credits

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- Robert Stengel, Robotics and Intelligent Systems, Princeton University
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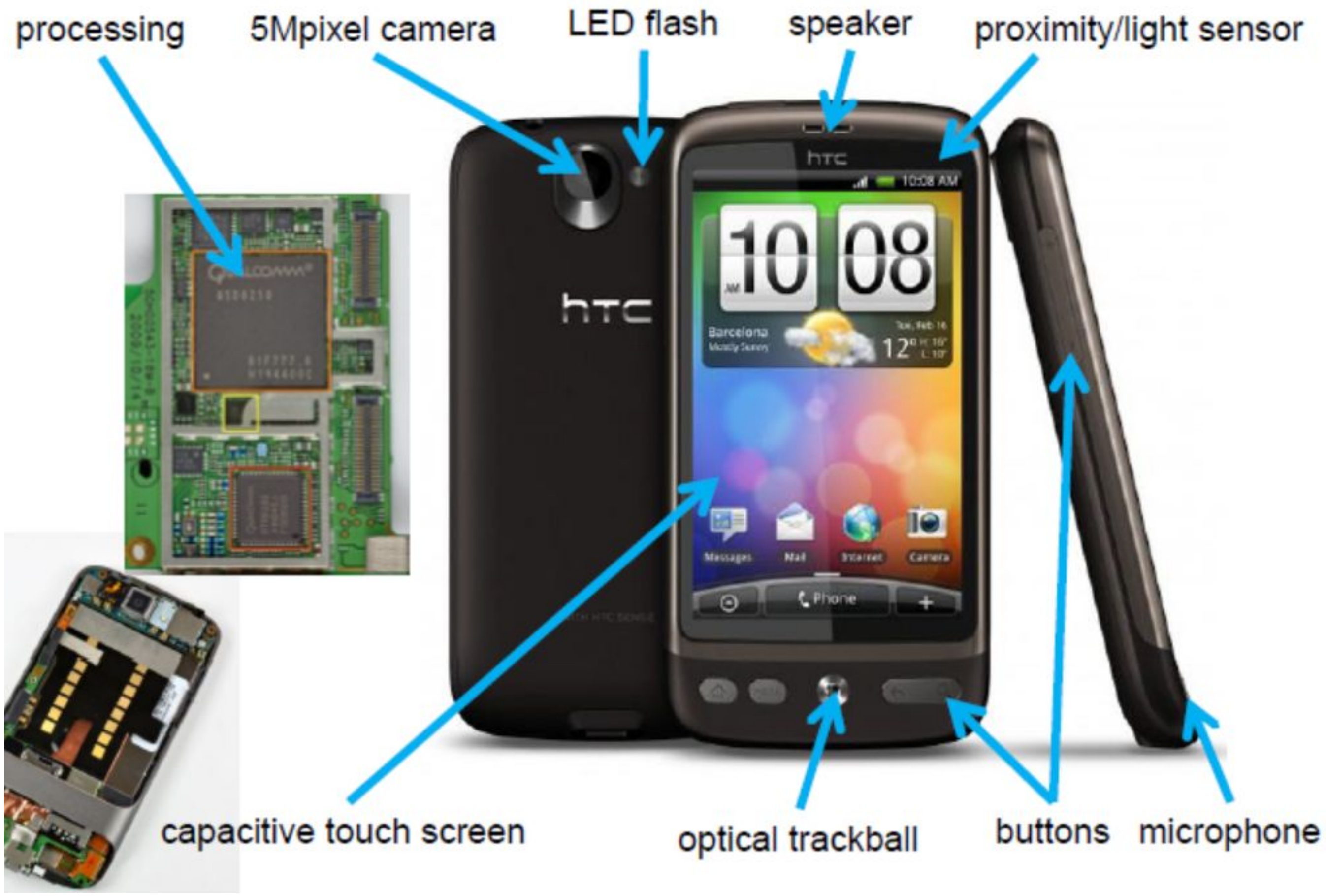
Sensors are everywhere...

TU/e

Example – Smartphone



Sensors and actuators

- sensors and actuators are common devices
- a system of any complexity cannot be designed without them


- **why can a system not perform its tasks without sensors?**
  - complexity
  - uncertainty
  - dynamic world
  - detection / correction of errors

Sensors and Actuators

- **Sensors:**
  - Capture physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - Typically generate a proportional electrical current
  - May require analog interface
- **Actuators**
  - Convert a command to a physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - May require analog interface

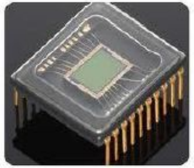
pressure

mic

speaker

radar

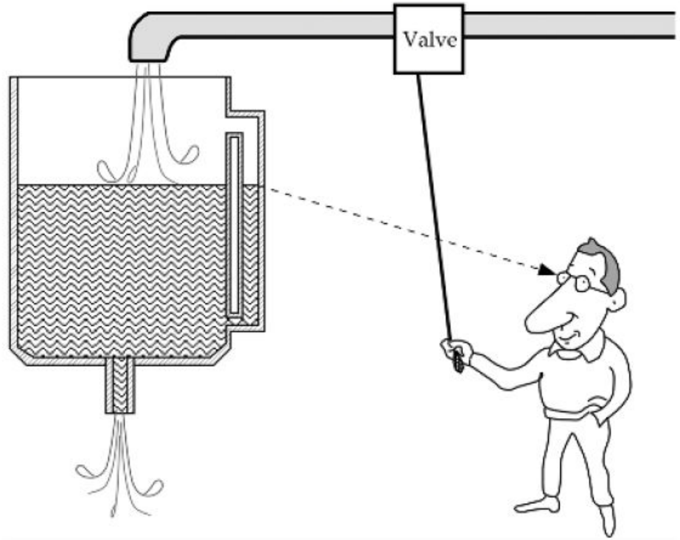
compass



camera

accelerometer

Example – Level control system

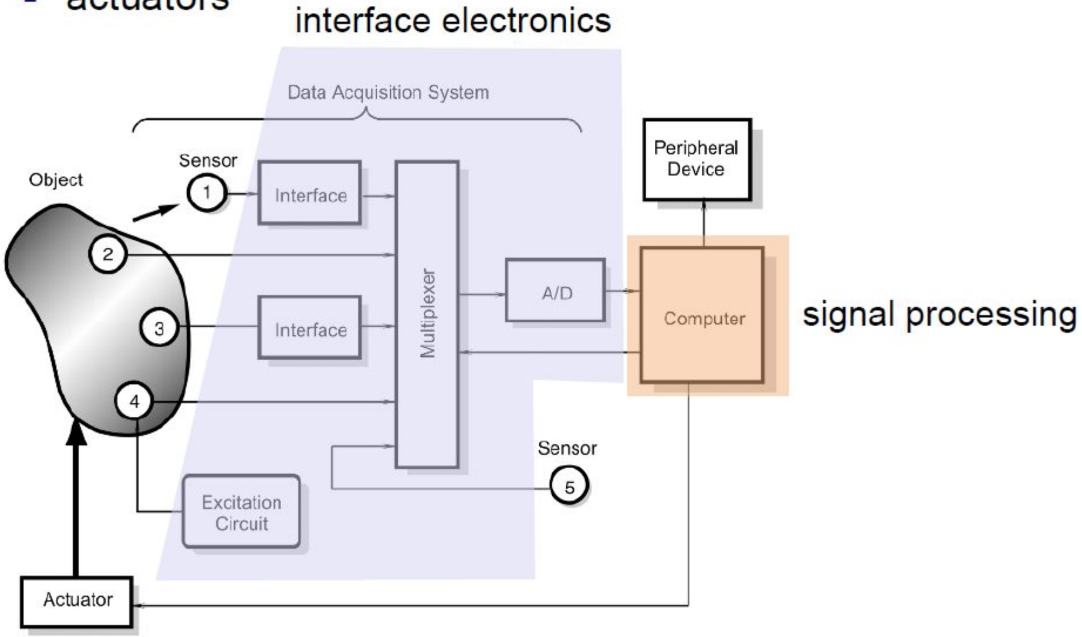


- information-processing system
  - sensor (sight tube + optic nerve)
  - processing (brain)
  - actuator (hand + valve)

- this sensor converts radiant energy to electrical energy

Information-processing systems

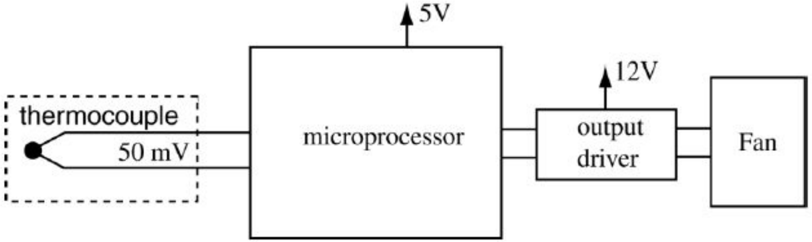
- information-processing system consist of
  - sensors
  - interface electronic circuits
  - processing elements
  - actuators



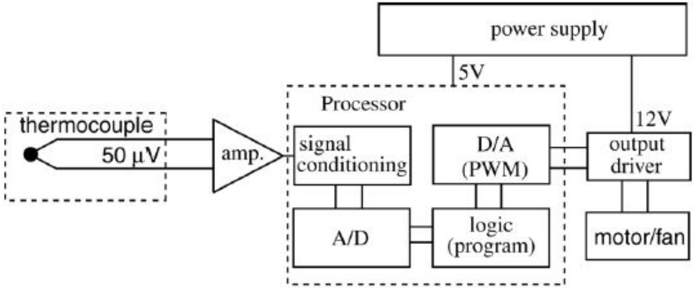
Sensors

- Processing of physical data starts with capturing data from sensors
- Sensors can be designed for virtually every physical stimulus
  - heat, light, sound, weight, velocity, acceleration, electrical current, voltage, pressure, ...
- Many physical effects used for constructing sensors.
  - law of induction
    - generation of voltages in an electric field
  - light-electric effects; magnetic effects; …

Example – Temperature control



- sense the temperature of a CPU
- control the speed of the fan to keep the temperature constant



- A/D and signal conditioner can be separated from the processor
- circuitry may be integrated into a "smart sensor"

Animal senses

bats
ultrasound (mechanical)

shark
electrical field

snake
thermal radiation

rats
touch (mechanical)

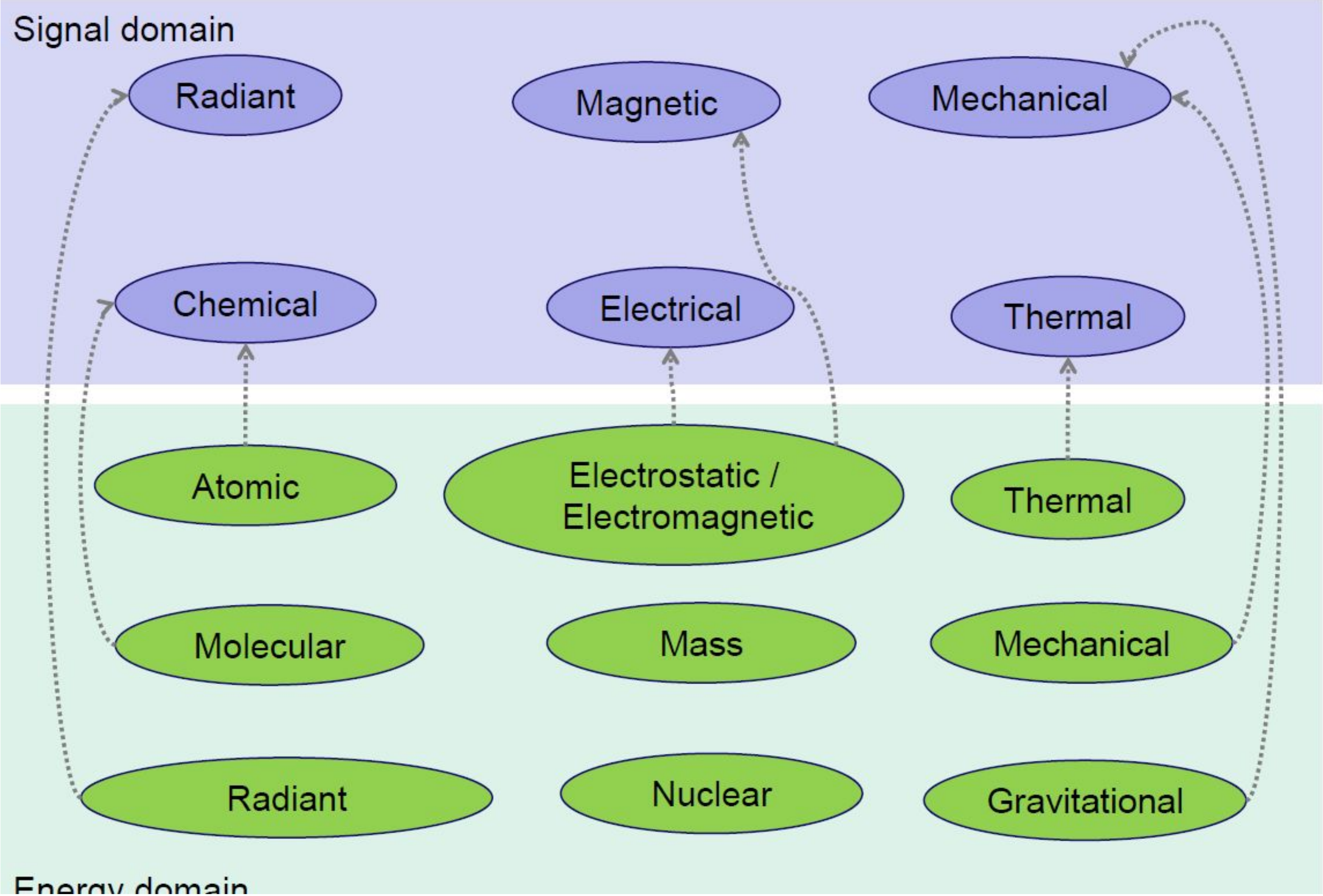
fish
sound vibrations (mechanical)

birds
magnetic field

Example: Artificial eyes (2)

- **Retinal implants (BRI Project)**
  - array of electrodes to stimulate light sensing cells that do not work
  - camera on pair of eyeglasses captures image
  - image processed by a microcontroller to produce a simplified picture
  - picture wirelessly beamed to the implant, which activates 15 electrodes inside the eye (to create a15-pixel image)
    - **Goal: 1000+ pixel images**
  - implant also receives power wirelessly from the microcontroller
  - electronics housed within a waterproof titanium case similar to those used for heart pacemakers

Signals-carrying energy



Sensors, transducers and actuators

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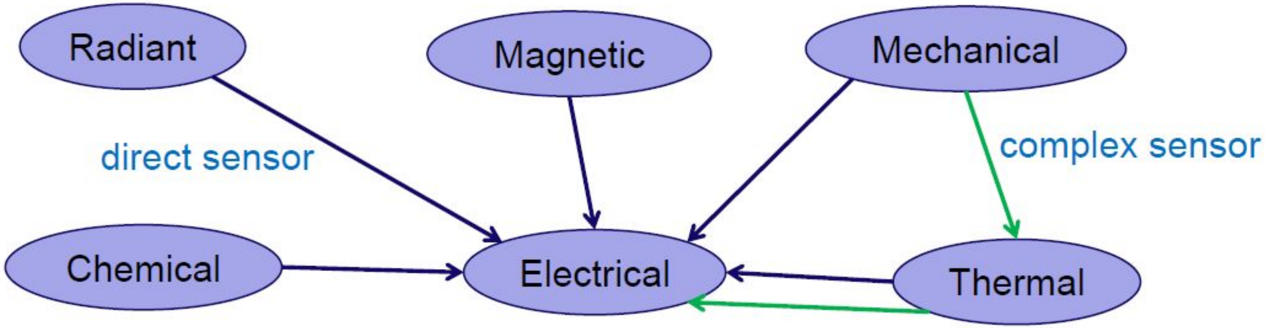
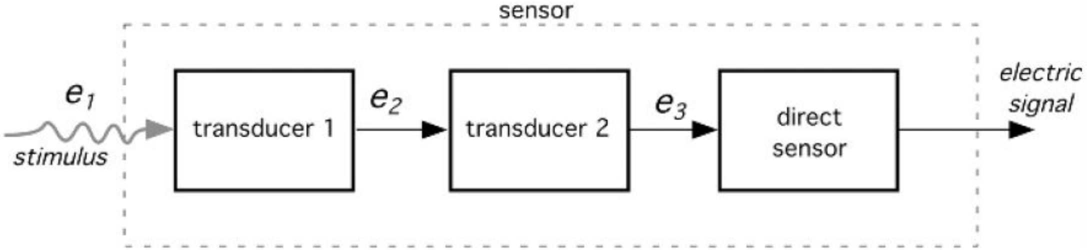
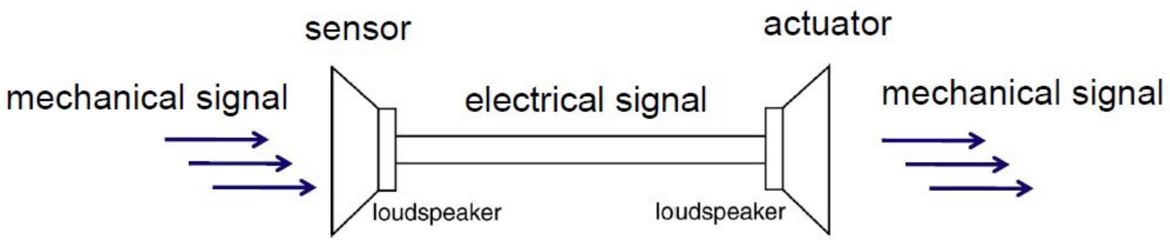


- a transducer converts a stimulus from a signal domain to another signal domain
- a sensor receives a stimulus and responds with an electrical signal

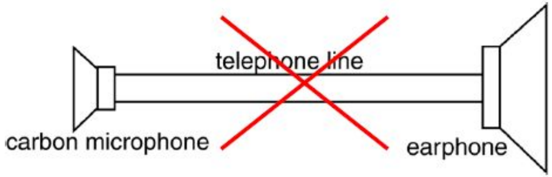


- an actuator converts an electrical signal to another signal domain

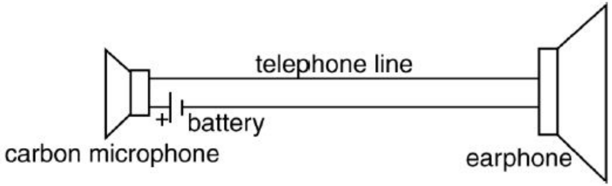
Example - telephone



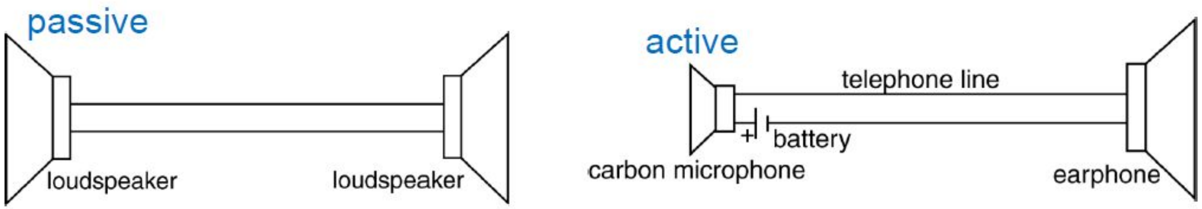
- a telephone works in a different way



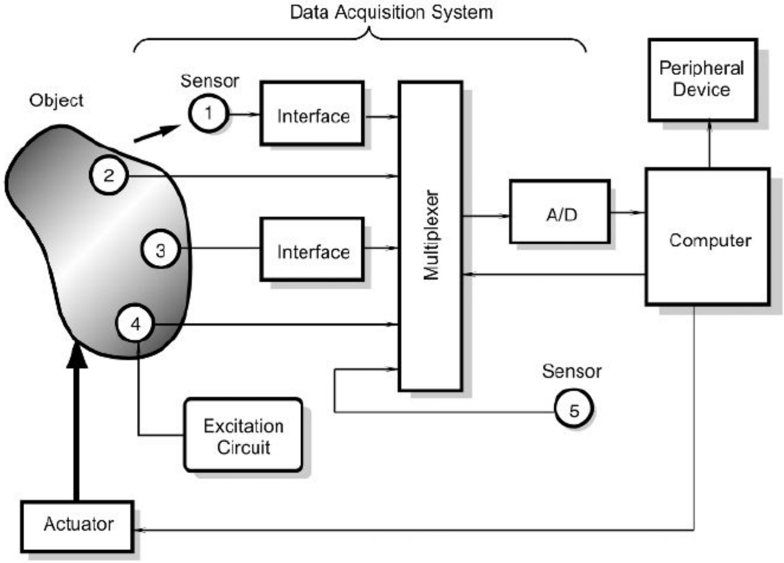
- microphone converts sound to change of resistance
- no transduction takes place (no change of energy)
- power source must be added to affect transduction



Sensor classification - excitation



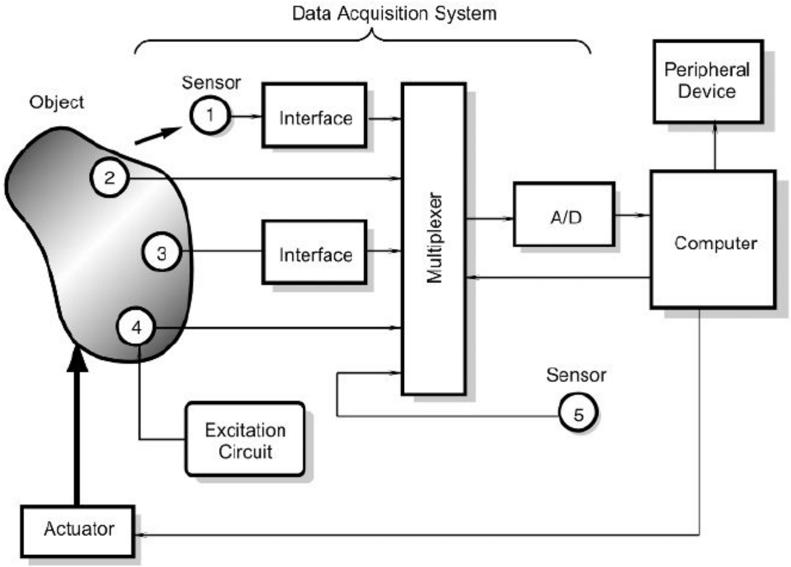
- an active sensor requires external power to operate
- a passive (self-generating) sensor generates its own electrical signal



sensor classification		
1	passive	
2	passive	
3	passive	
4	active	
5	passive	

Sensor classification – sensor placement

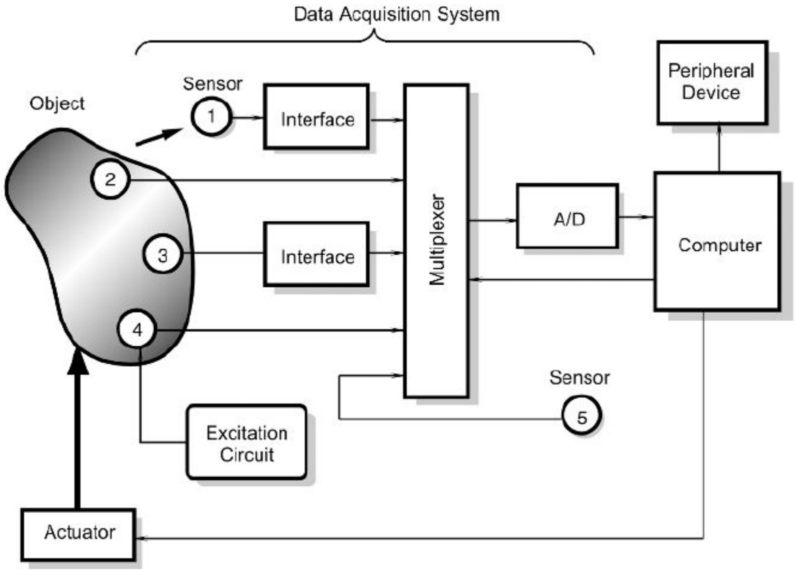
- a contact sensor requires physical contact with the object
- a non-contact requires no physical contact with the object
- an internal sensor is used within the data acquisition system itself



sensor classification		
1	passive	non-contact
2	passive	contact
3	passive	contact
4	active	contact
5	passive	internal

Sensor classification – reference point

- an absolute sensor reacts to a stimulus on an absolute scale
- a relative sensor senses the stimulus relative to a fixed or variable reference



sensor classification		
1	passive	non-contact
2	passive	contact
3	passive	contact
4	active	contact
5	passive	internal

Sensor classification – physical effect

- transducers (sensors) employ physical effects to convert a stimulus from a signal domain to another signal domain

in \ out	radiation	mechanical	thermal	electrical	magnetic	chemical
radiation	photo luminance	radiation pressure	radiation heating	photo-conduction	photo-magnetic	photo-chemical
mechanical	photo-elastic effect	conservation moment	friction heat	piezo-electric	magneto-strict.	pressure induced explosion
thermal	incandescen ce	thermal expansion	heat conduction	Seebeck effect	Curie-Weiss law	endothermic reaction
electrical	inject luminance	piezo-electric	Peltier effect	pn-junction effect	Ampere's law	electrolysis
magnetic	Faraday effect	Magneto-striction	Ettinghaus en effect	Hall effect	Magnetic induction	
chemical	Chemo-luminance	Explosive reaction	Exotherma l reaction	Volta effect		Chemical reaction

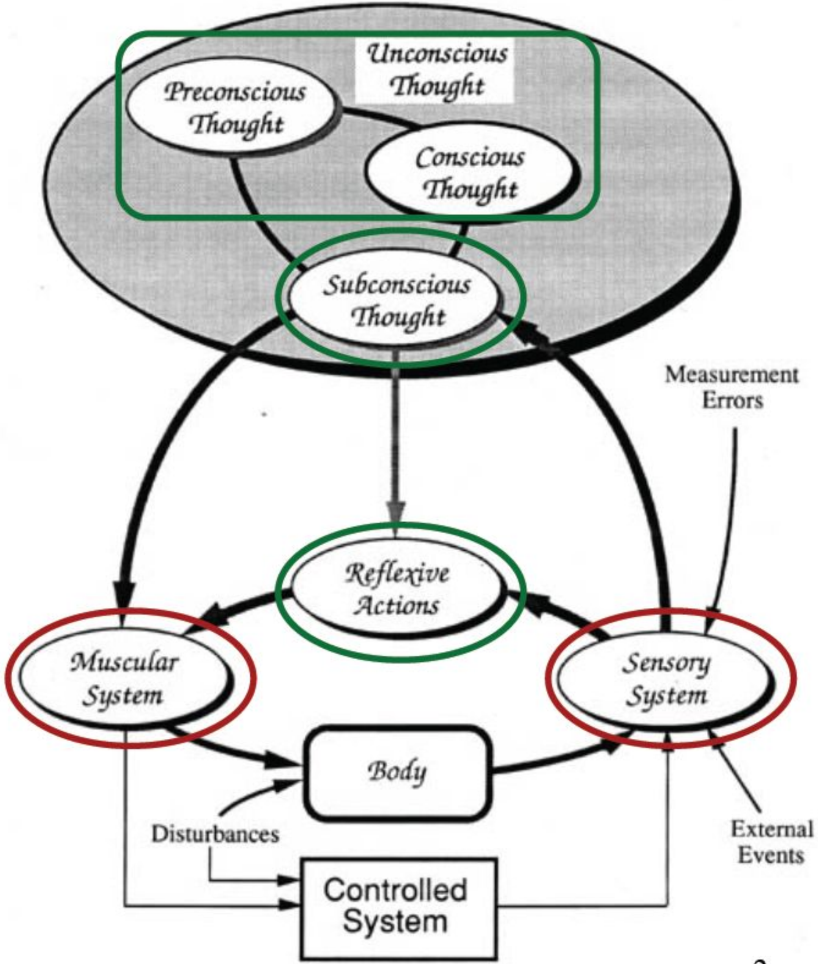
Sensor classification – type / quantity measured

Sensor type	Position, distance, displacement	Flow rate / Point velocity	Force	Temperature
Resistive	Magnetoresistor	Thermistor	Strain gage	RTD
	Potentiometer			Thermistor
Capacitive	Differential capacitor		Capacitive strain gage	
Inductive and electro-magnetic	Eddy currents	LVDT	Load cell + LVDT	
	Hall effect		Magnetostriction	
	LVDT			
	Magnetostriction			
Self-generating		Thermal transport + thermocouple	Piezoelectric sensor	Pyroelectric sensor
				Thermocouple
PN junction	Photoelectric sensor			Diode
				Bipolar transistor
Digital	Position encoder			Quartz oscillator
Optic				
Ultrasound	Travel time	Doppler effect		

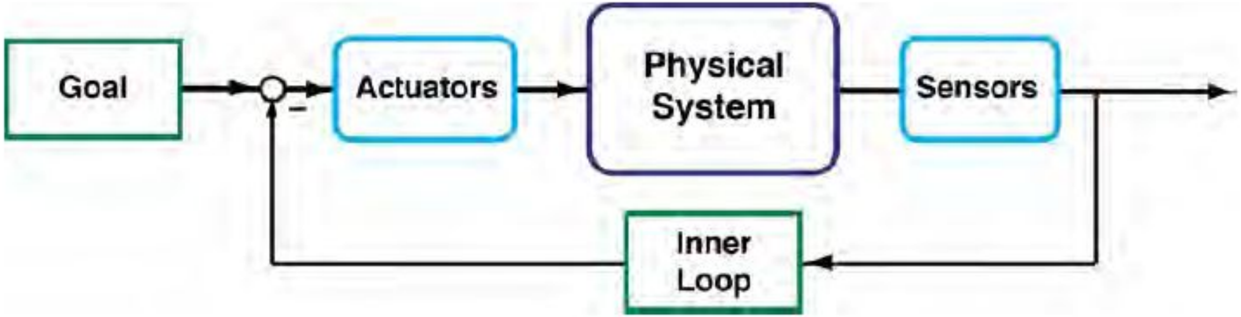
- there are many other interesting quantities: acceleration, vibration, humidity, level, pressure, velocity, ...

Biologically Inspired Control

- Declarative Planning
- Procedural Formatting
- Reflexive Control
- Sensory input
- Motor output

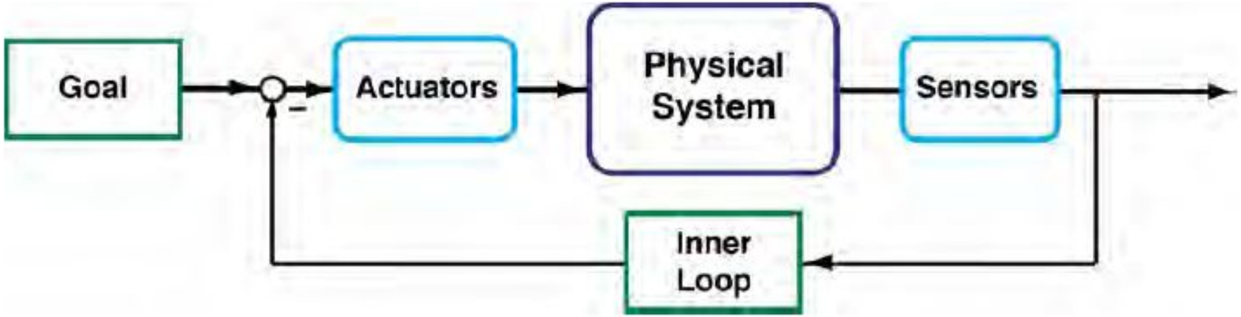


Feedback Control Requires Sensors and Actuators



- **Desirable properties of sensors and actuators**
  - High bandwidth ("faster" than system to be controlled)
  - Accuracy and Precision
  - Large dynamic range
  - Sufficient power for control
  - Reliability
  - Low cost

Feedback Control Requires Sensors and Actuators



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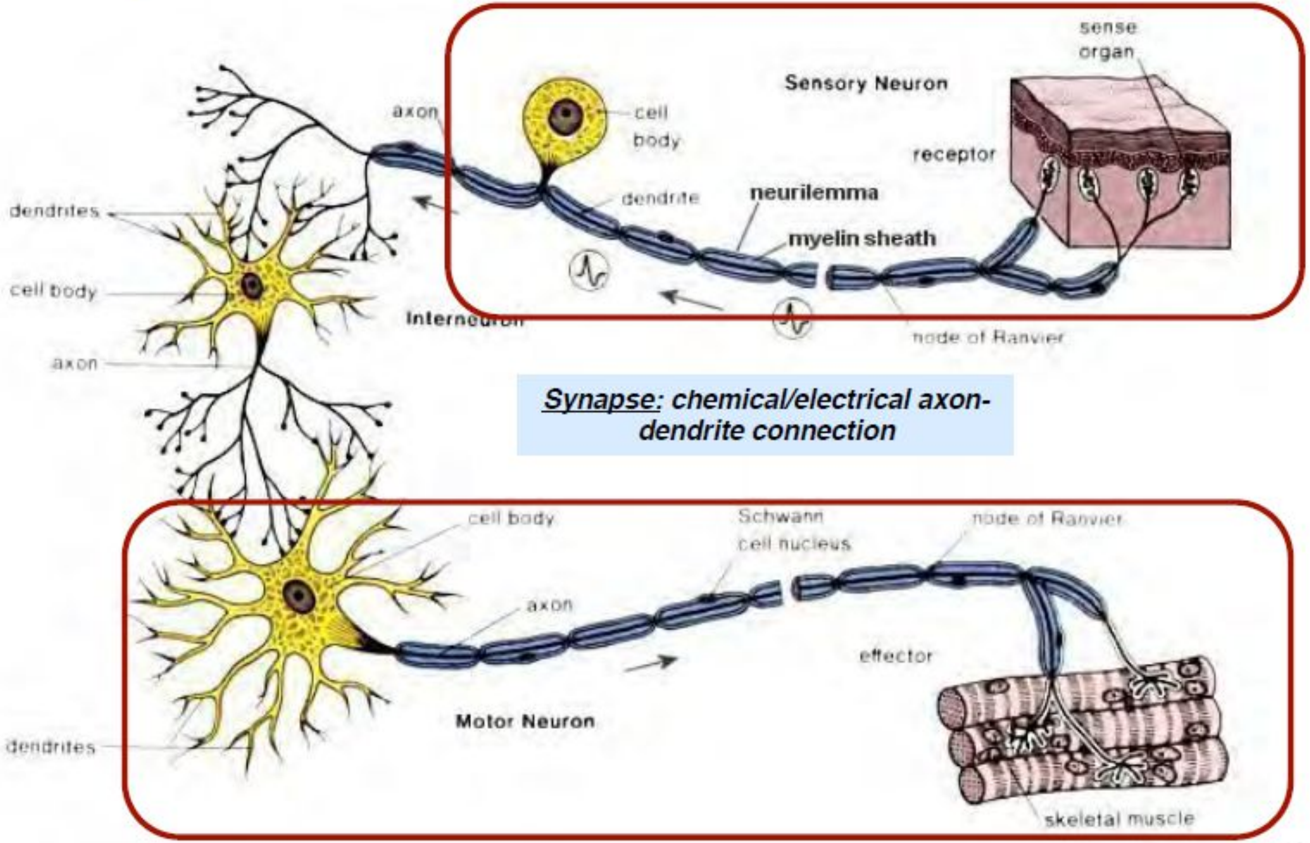
Peripheral Sensory and Motor Neurons

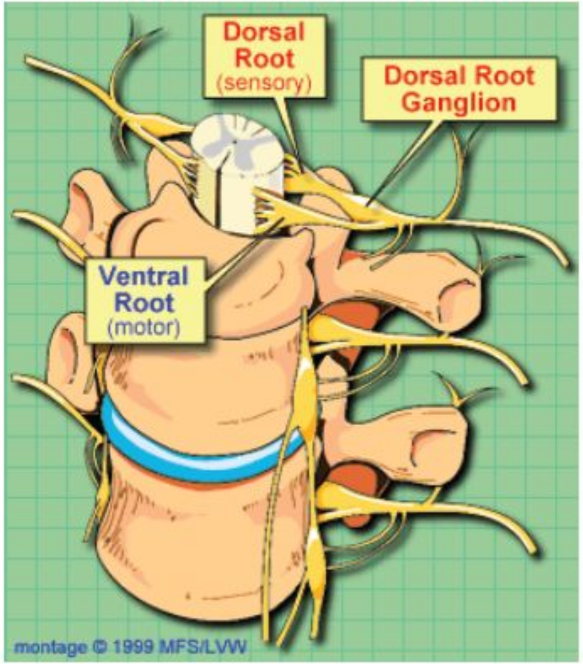


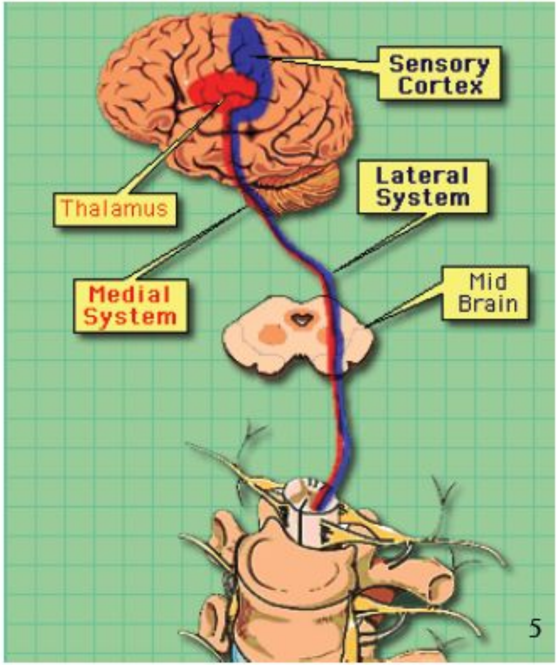
Synapse: ***chemical/electrical axon-dendrite connection***

Sensory and Motor Signal Paths to the Brain

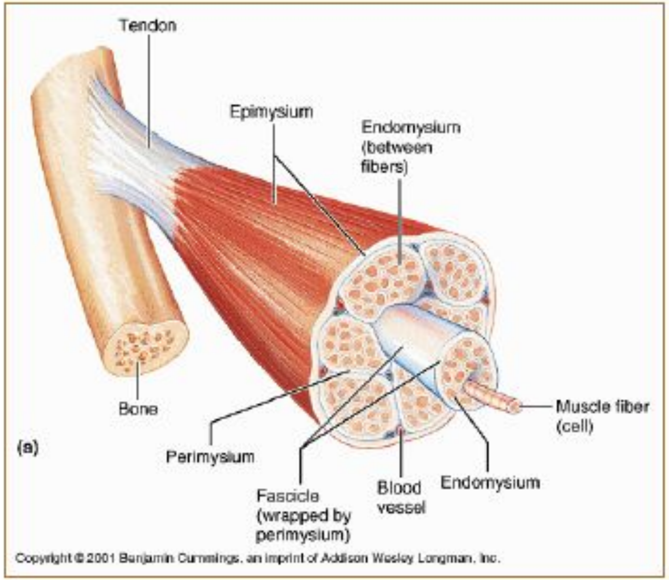
Reflexive response is processed in the spinal roots

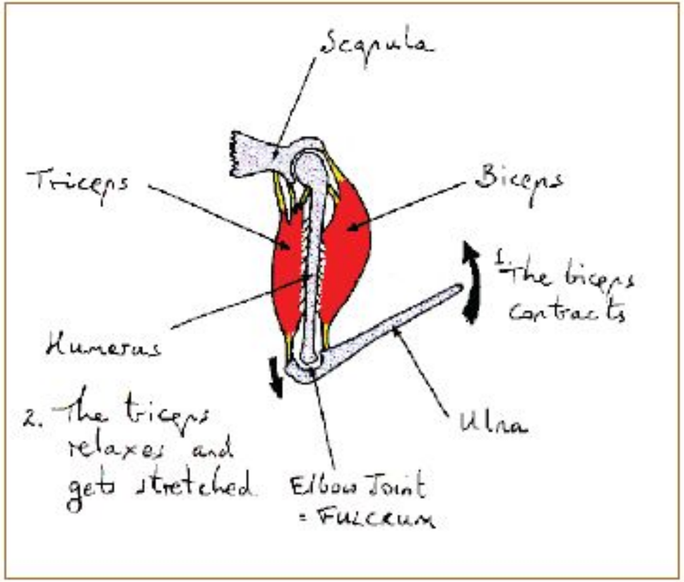
Declarative and procedural response is processed in the brain





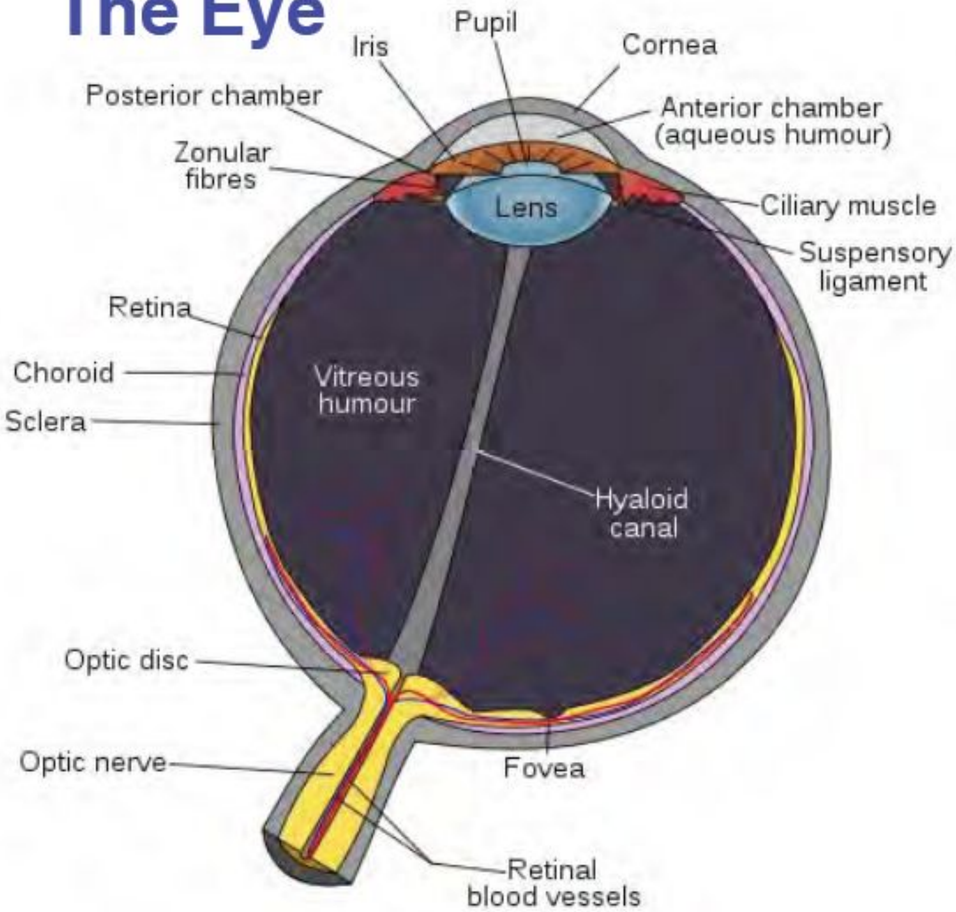
Skeletal Muscle





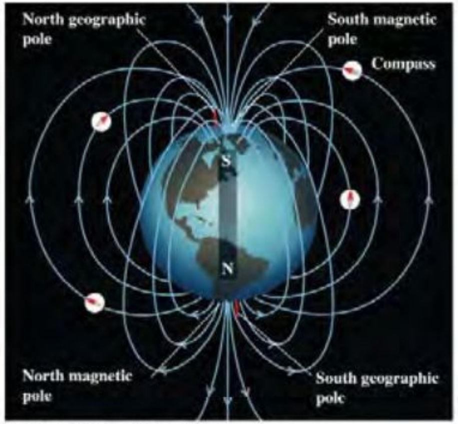
- **Attached to the skeleton to produce motion of limbs, torso, neck, and head**
- **Agonist-antagonist muscle pairs produce opposing motion (flexion and extension)**
- **End-effecter strength depends on lever arm and varies with joint angle**
- **Voluntary (declarative) commands from somatic central nervous system**

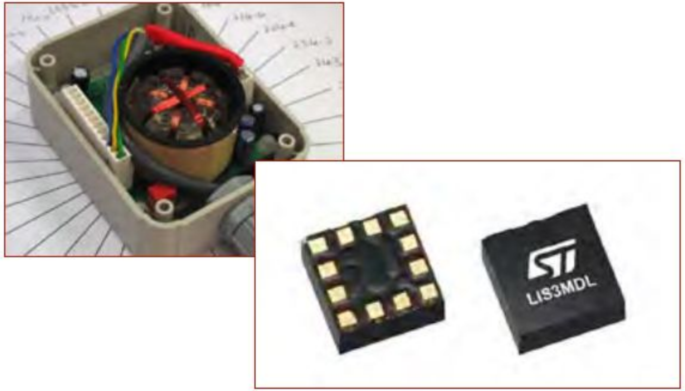
The Eye


Iris
Pupil
Cornea
Posterior chamber
Anterior chamber
(aqueous humour)
Zonular
fibres
Lens
Ciliary muscle
Suspensory
ligament
Retina
Choroid
Vitreous
humour
Sclera
Hyaloid
canal
Optic disc
Optic nerve
Fovea
Retinal
blood vessels

Magnetometer

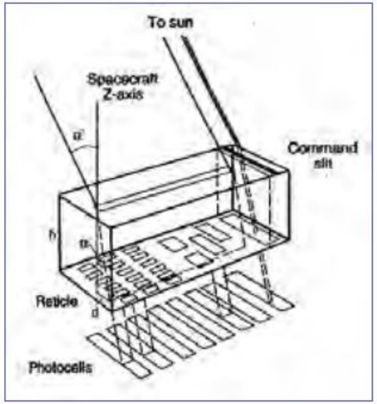
- **Flux gate “compass”**
  - Alternating current passed through one coil
  - Permalloy core alternately magnetized by electromagnetic field
  - Corresponding magnetic field sensed by second coil
  - Distortion of oscillating field is a measure of one component of the Earth’s magnetic field
- **Three magnetometers required to determine Earth’s magnetic field vector**

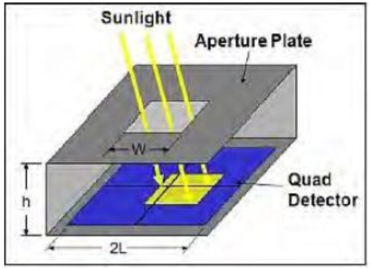




Sun Angle Sensor

- Distance from centerline measured by sensed pattern, which determines angle, α
- With index of refraction, *n*, angle to sun, α', is determined
- Reticle digitizes slit of light in 1st example
- Photodetectors may provide digital (coarse) or analog (fine) outputs





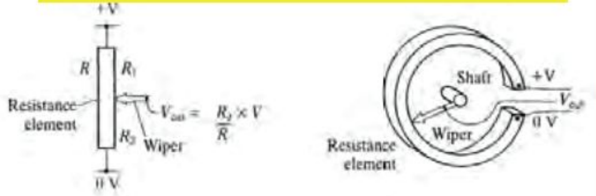
$$\tan\alpha = d / h$$

$$\sin\alpha' = n\sin\alpha \quad (Snell's\ law)$$

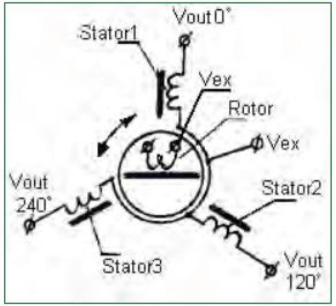
$$n = index\ of\ refraction$$

Potentiometer, Synchro, and Tachometer

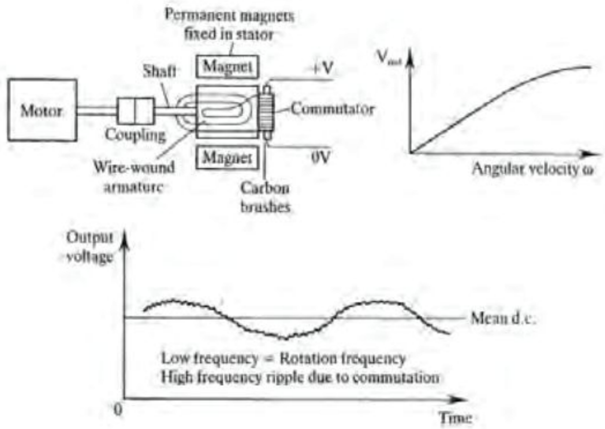
Potentiometer (displacement)



Synchro (angle)

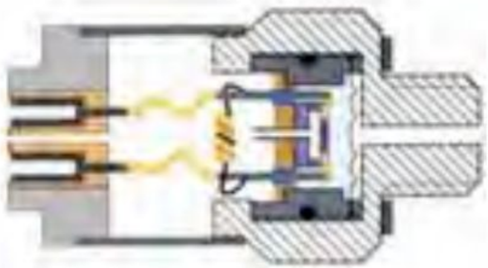


Tachometer (rate)



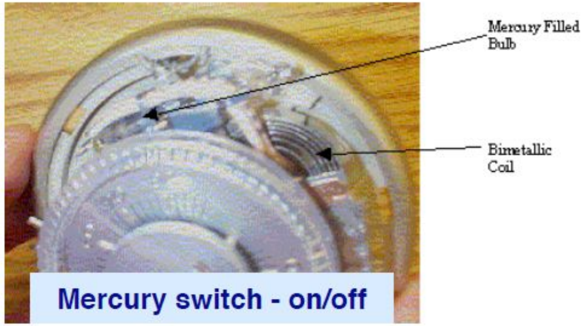
Pressure and Temperature Sensors

Deflection of Diaphragm Between Chambers at Different Pressure



Variation in Capacitance or Resistance

Deflection of Bi-Metallic Element

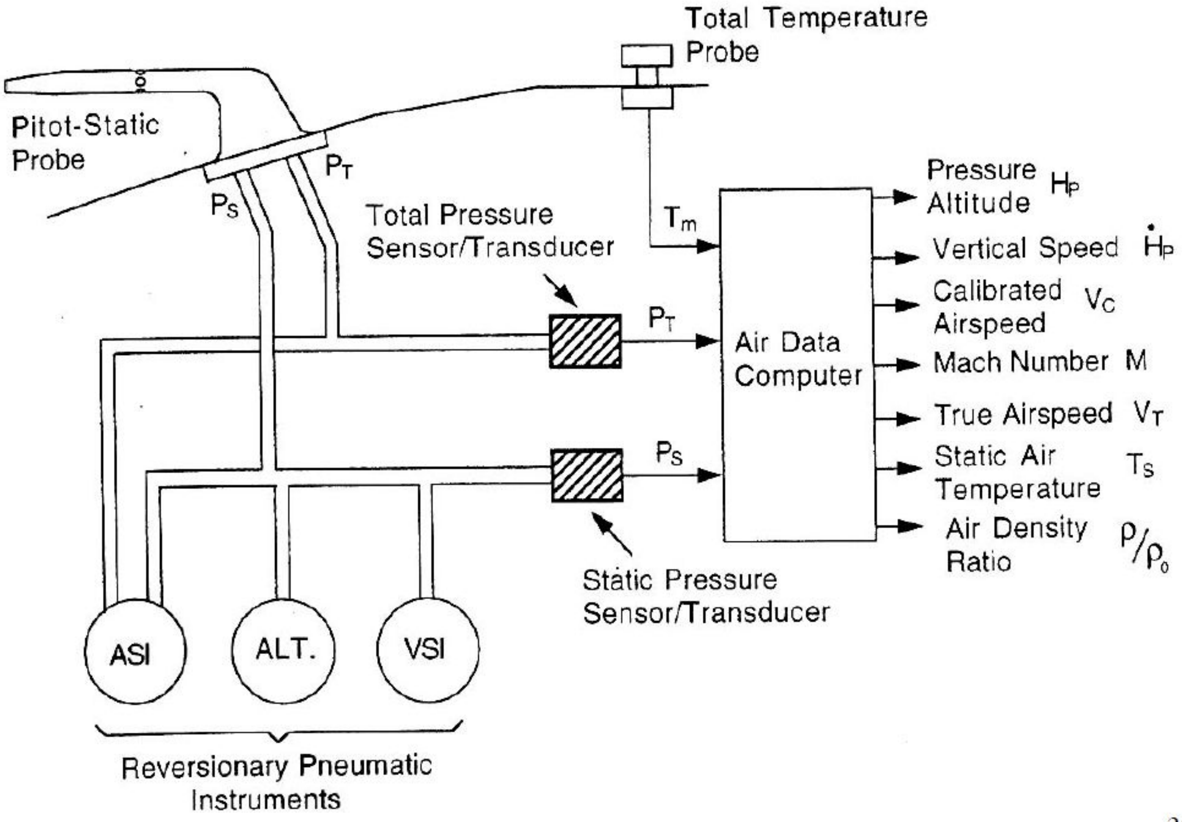


Mercury switch - on/off

Thermistors

Variation in Resistance

Air Data Sensors



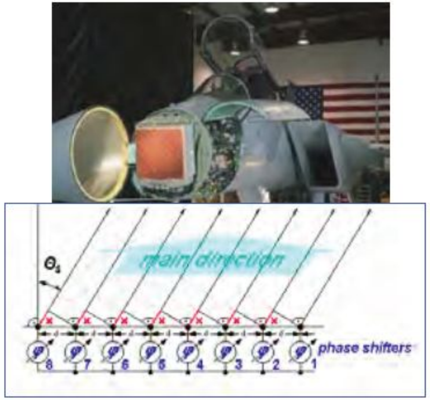
Radar and Sonar

Tracking (Pulse) RADAR

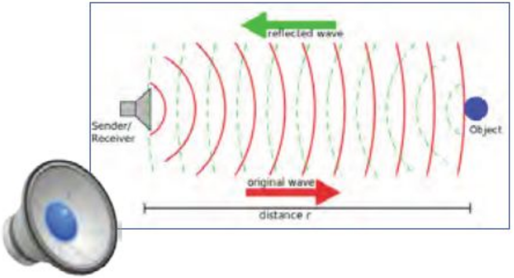
http://www.youtube.com/watch?v=LOqRBtbEulq

(Doppler) Radar Gun

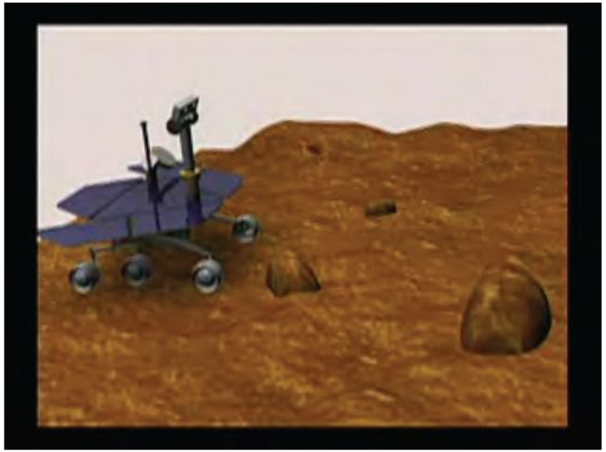
Electronically Steered Array Tracking Radar



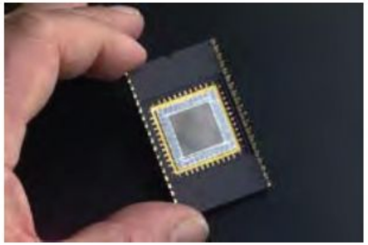
SONAR (SOund NAvigation and Ranging)



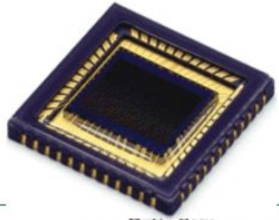
Video and Computer Vision



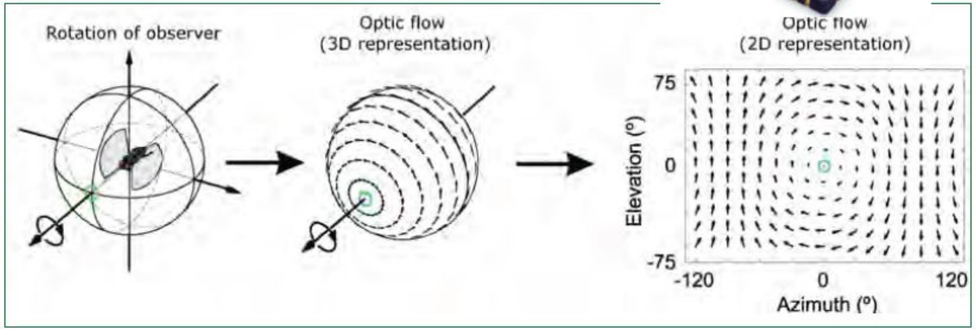
CCD Sensor



CMOS Device

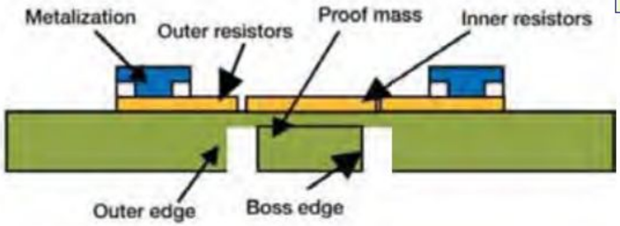


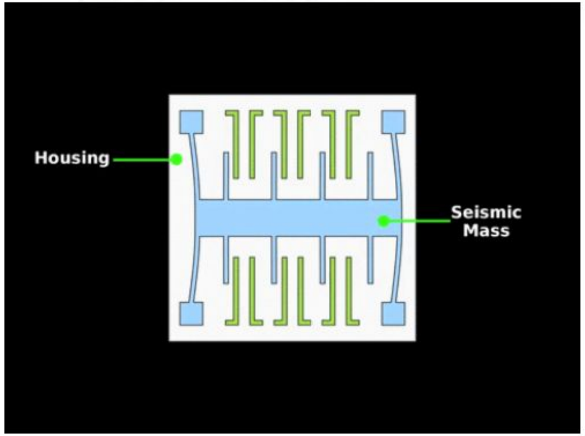
Optic Flow



MicroElectroMechanical System (MEMS) Accelerometer

3-DOF MEMS Accelerometer





Vibrating Piezoelectric Crystal Angular Rate Sensor

- “Tuning fork” principle
- 4 piezoelectric crystals
  - 2 active, oscillating out of phase with each other
  - 2 sensors, mounted perpendicular to the active crystals
- With zero rate along the long axis, sensors do not detect vibration
- Differential output of the sensors is proportional to angular rate

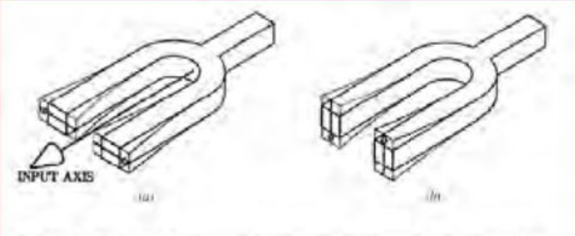
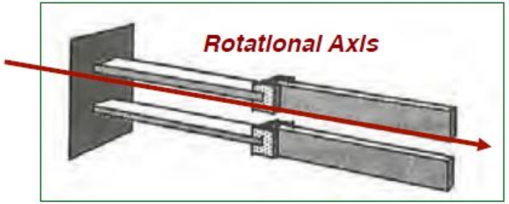
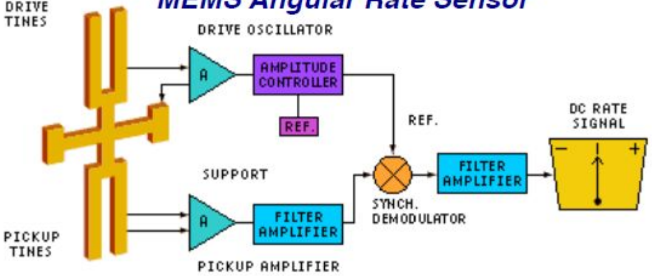


Fig. 9.11 Vibration modes of tuning fork gyroscope: (a) input mode; (b) output mode.



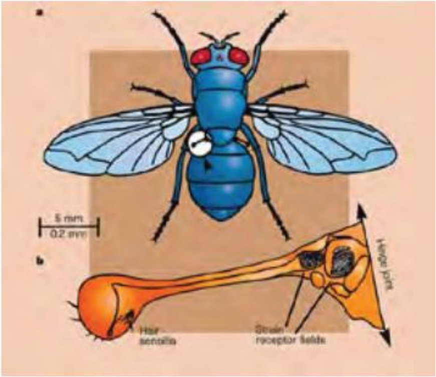
MEMS Angular Rate Sensor

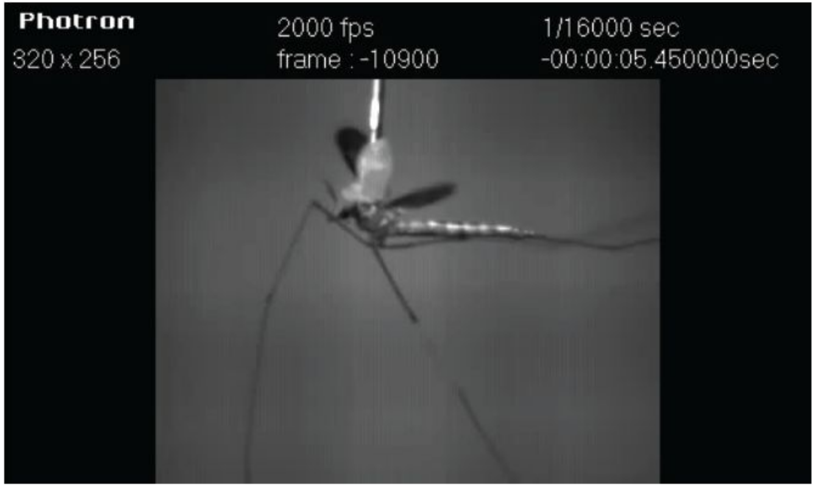


Halteres:

Biological Angular Rate Sensors

Vestigal second pair of wings





All in Your Pocket

iPhone 6s

- 3-axis accelerometer
- 3-axis angular rate
- 2-axis magnetometer compass
- GPS position measurement
- 64-bit, 1.8 GHz processor
- 2 GB RAM
- 128 GB flash memory
- 2 cameras, mic, speakers

$$\mathbf{z} = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ p \\ q \\ r \\ \varepsilon_{horizontal} \\ \varepsilon_{vertical} \\ L \\ \lambda \\ h \end{bmatrix}$$

Parrot AR.Drone 2.0

- 1GHz 32 bit ARM Cortex A8 processor with 800MHz video DSP TMS320DMC64x
- Linux 2.6.32
- 1Gbit DDR2 RAM at 200MHz
- USB 2.0 high speed for extensions
- Wi-Fi b,g,n
- 3 axis gyroscope 2000°/second precision
- 3 axis accelerometer +-50mg precision
- 3 axis magnetometer 6° precision
- Pressure sensor +/- 10 Pa precision
- Ultrasound sensors for ground altitude measur
- 60 fps vertical ground speed m

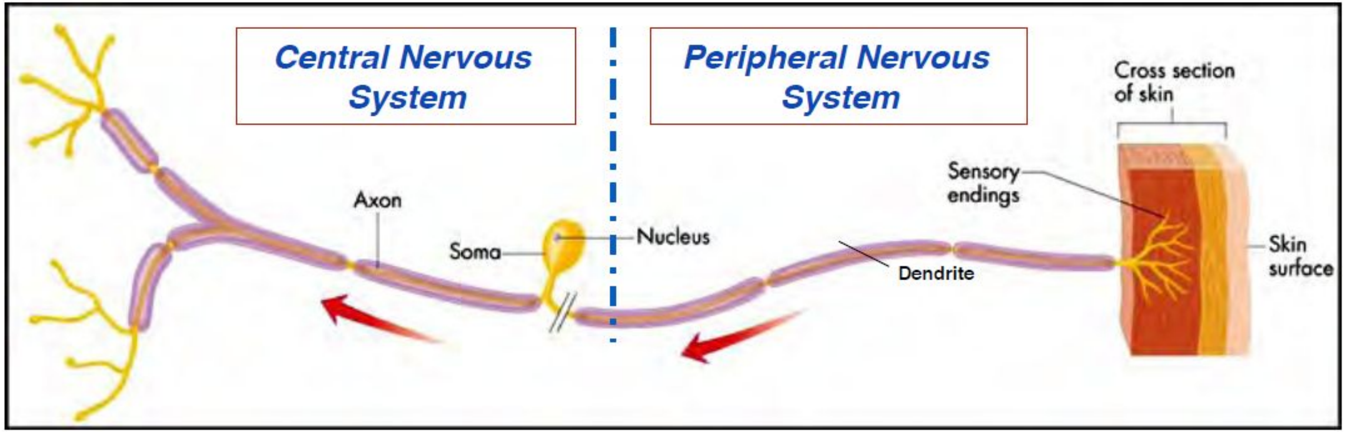
- 4 brushless inrunner motors. 14.5W 28,500 RMP
- Micro ball bearing
- Low noise Nylatron gears for 1/8.75 propeller reductor
- Tempered steel propeller shaft
- Self-lubrificating bronze bearing
- Specific high propelled drag for great maneuverability
- 8 MIPS AVR CPU per motor controller
- 3 elements 1000 mA/H LiPo rechargeable battery (Autonomy: 12 minutes)
- Emergency stop controlled by software
- Fully reprogrammable motor controller
- Water resistant motor's electronic controller

- HD Camera. 720p 30fps
- Wide angle lens : 92° diagonal
- H264 encoding base profile
- Low latency streaming
- Video storage on the fly with the remote device
- JPEG photo
- Video storage on the fly with Wi-Fi directly on your remote device or on a USB key

Global Positioning System (GPS)

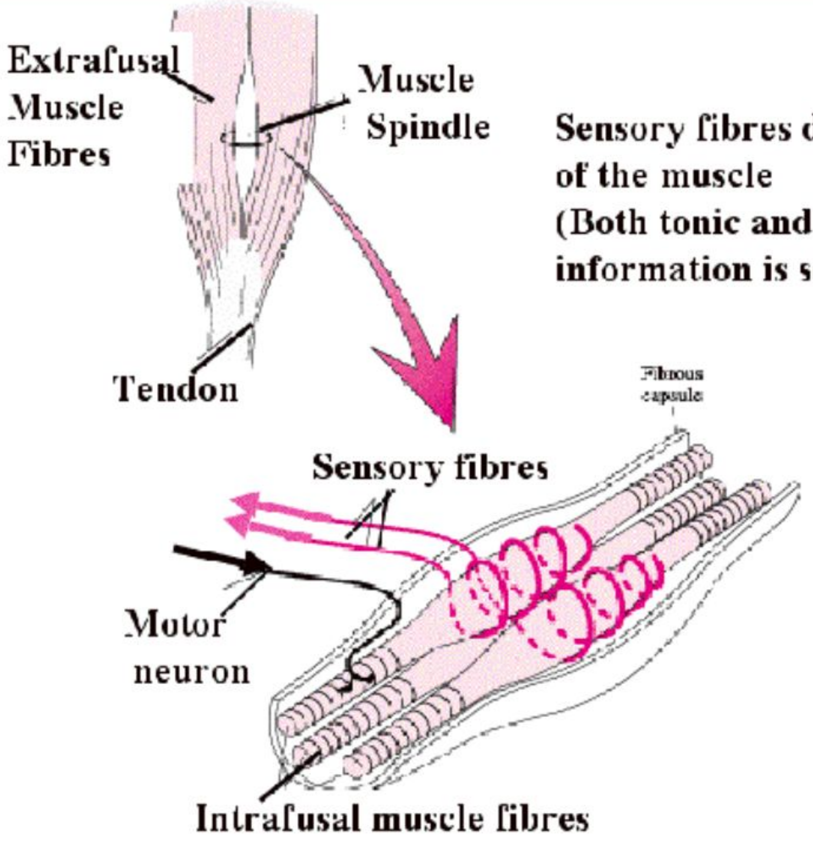
- **Six orbital planes with four satellites each**
  - Altitude: 20,200 km (10,900 nm)
  - Inclination : 55 deg
  - Constellation planes separated by 60 deg
- **Each satellite contains an atomic clock and broadcasts a 30-sec message at 50 bps**
  - Ephemeris
  - ID
  - Clock data
- **Details of satellite signal at** *http://en.wikipedia.org/wiki/Gps*
- *https://www.youtube.com/watch?v=FU_pY2sTwTA*

Sensory (*Afferent*) Neurons



- Components of the peripheral nervous system that measure *pressure*, *temperature*, *vibration*, etc.
- Neuron Soma located in the dorsal root at the base of the spine
- The sensory neuron is pseudo-unipolar
  - Input from a single receptor's axon
  - Output to a single axon to synapses in the spinal column

Motor Neuron Receptors



Sensory fibres detect stretching of the muscle
(Both tonic and phasic information is sent to the CNS)

Sensors and Actuators

- **Sensors:**
  - Capture physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - Typical generate a proportional electrical current
  - May require analog interface

- **Actuators**
  - Convert a command to a physical stimulus (e.g., heat, light, sound, pressure, magnetism, or other mechanical motion)
  - May require analog interface

solenoid

speaker

laser diode/transistor

dc motor

LED display

Actuators

- **Output physical stimulus varies in range and modality**
  - Large (industrial) control actuators
    - Pneumatic systems: physical motion
  - Optical output
    - IR, LEDs, displays, etc.
  - Motor controllers
    - DC, stepper, servo, …
  - Sound
    - Loudspeakers, etc.
  - List goes on…..

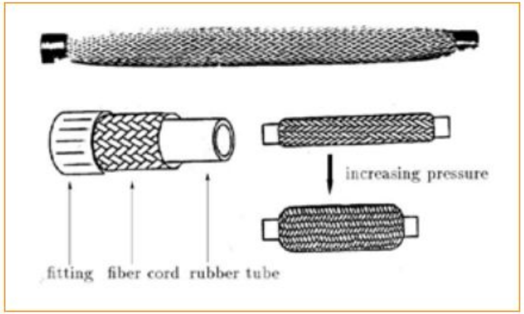
Stepper Motor Controller

- **Stepper motor: rotates fixed number of degrees when given a "step" signal**
  - In contrast, DC motor simply rotates when power applied, and coasts to stop
- **Rotation achieved by applying specific voltage sequence to coils**
  - Controller greatly simplifies this
- **Stepper motors used commonly in hard drives (traditionally)**
  - Head motor (stepper), spindle motor (DC)

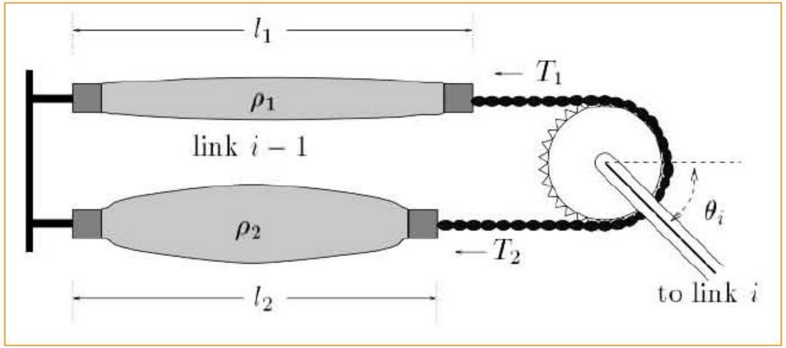
Rubbertuator

Pneumatic analog of muscle

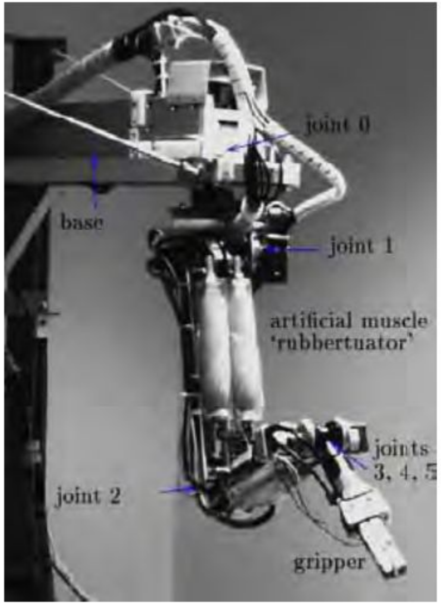
Contraction under pressure



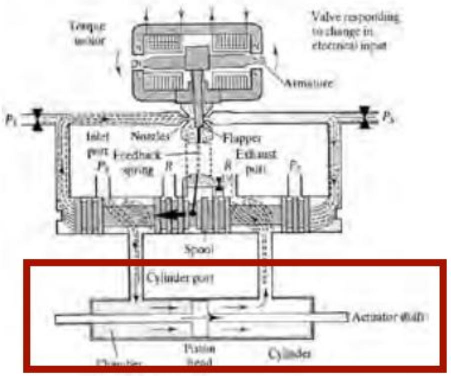
Agonist-antagonist action produces rotation



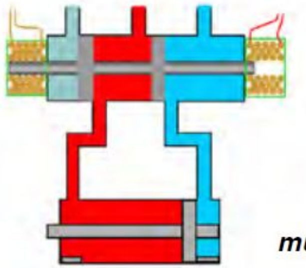
Robot arm



Linear Hydraulic Actuator

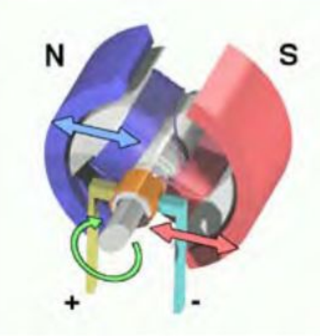


Electro/ mechanical transduction via small piston

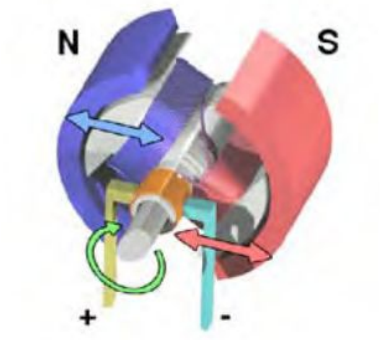


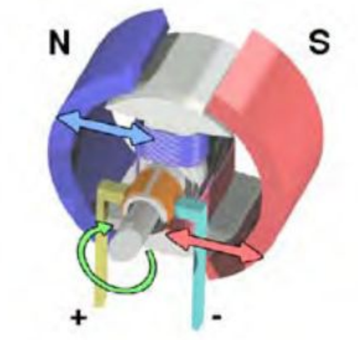
Force multiplication by large piston

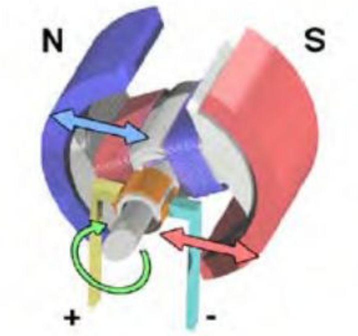
Electric Actuator
Brushed DC Motor



Two-pole DC Motor







Current flowing through armature generates a magnetic field

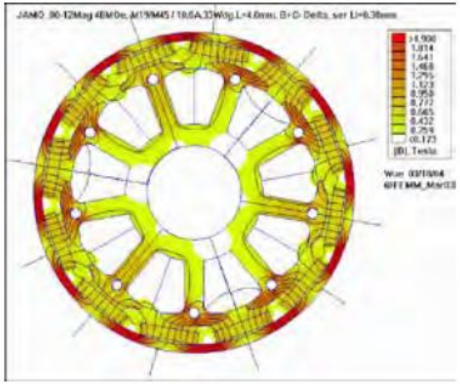
Permanent magnets torque the armature

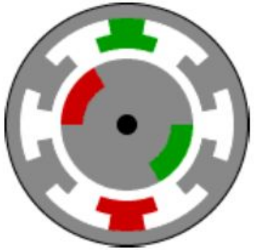
When armature is aligned with magnets, commutator ("brush") reverses current and magnetic field

Multiple poles added to allow motor to smooth output torque and to start from any position

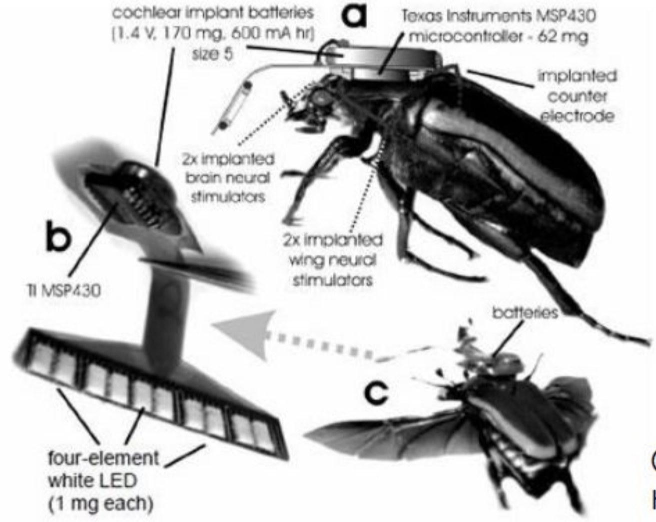
Electric Actuator
Brushless DC Motor

- **Armature is fixed, and permanent magnets rotate**
- **Electronic controller commutates the electromagnetic force, providing a rotating field**
- **Advantages**
  - Efficiency
  - Noise
  - Lifetime
  - Reduced EMI
  - Cooling
  - Water-resistant





Actuators: The Future?



- **Cyborg Beetle**
  - giant flower beetle with implanted processor , microbattery, electrodes
  - electrodes deliver electrical jolts to its brain and wing muscles
  - flight can be wirelessly controlled
    - e.g. take off, turn, stop midflight.

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http://www.technologyreview.com/computing/22039/?a=f

Touch Bionics iLIMB Actuator

It's got an embedded computer, a rechargeable battery, and five small dc motors. It costs US $18 500. And it can do things most other prosthetic hands just can't, like grabbing a paper cup without crushing it, turning a key in a lock, and pressing buttons on a cellphone.

The fingers of Touch Bionics' iLIMB Hand are controlled by the nerve impulses of the user's arm, and they operate independently, adapting to the shape of whatever they're grasping. The hand can also do superhuman tricks, like holding a very hot plate or gripping an object tirelessly for days. A skin-tone covering gives the bionic hand a lifelike look, but some customers refer semitransparent models, to proudly flaunt their robotic hands. "They like the Terminator look," says Touch Bionics CEO Stuart Mead. IEEE Spectrum, Oct. 2007.