# Clarke's Prediction "Laws"

- Any sufficiently advanced technology is indistinguishable from magic

Arthur Clarke

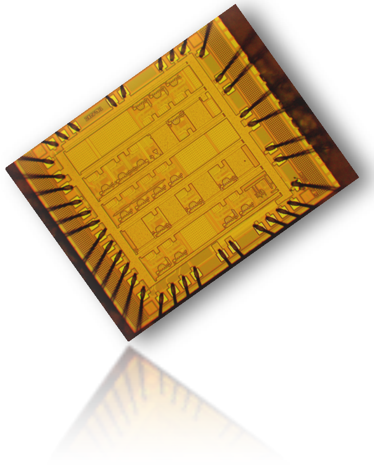
# Implantable Telemetry Systems: the State of the Art and Challenges

Robert Sobot

# Overview

- The short history of technology development
- Implantable technology
- RF Telemetry System
- Technology and the human body
- Closing comments

# The short history of technology development



# Technology waves

- **20??-20??** → Neurotechnology: biochip, brain imaging
- **1960-20??** → Information technology: microchip
- **1910-1960** → Motorization: oil
- **1870-1920** → Electrification: electricity, copper, steel
- **1820-1880** → Steam mechanization: coal, iron, steam engine
- **1770-1830** → Water mechanization: canals, water wheels

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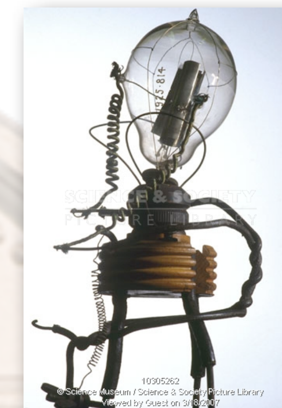
# From the tube to IC

1904

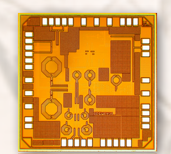


Fleming's valve

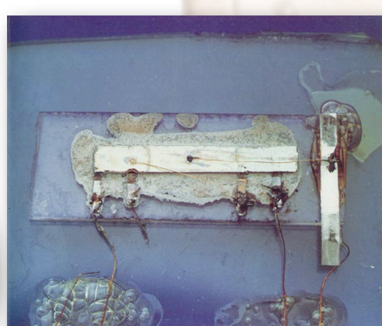
2006


IBM Co. Itanium 2

2011

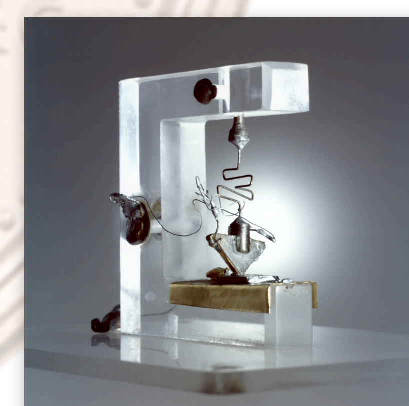


1958



TI Inc. the first IC

1947



Bell Labs the first transistor

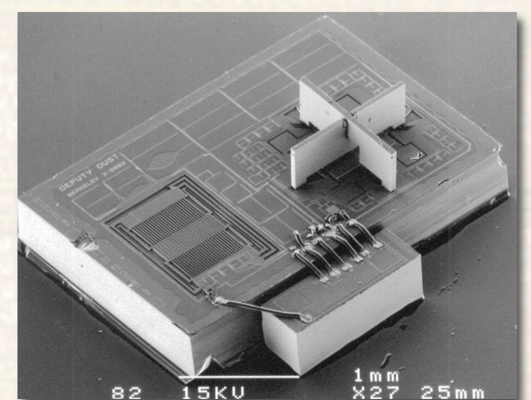
# Evolution of the radio

*>10cm$^3$*


*~36mm$^3$*

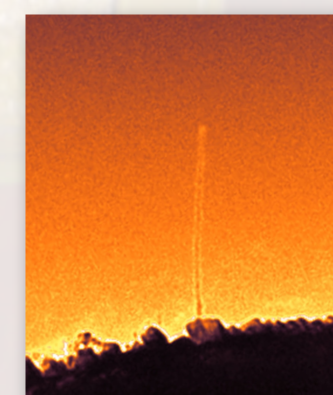
Commercial

Research




*~6.6mm$^3$*

*Courtesy Zettl Research Group, Lawrence Berkeley National Laboratory and University of California at Berkeley*



*~µm$^3$*

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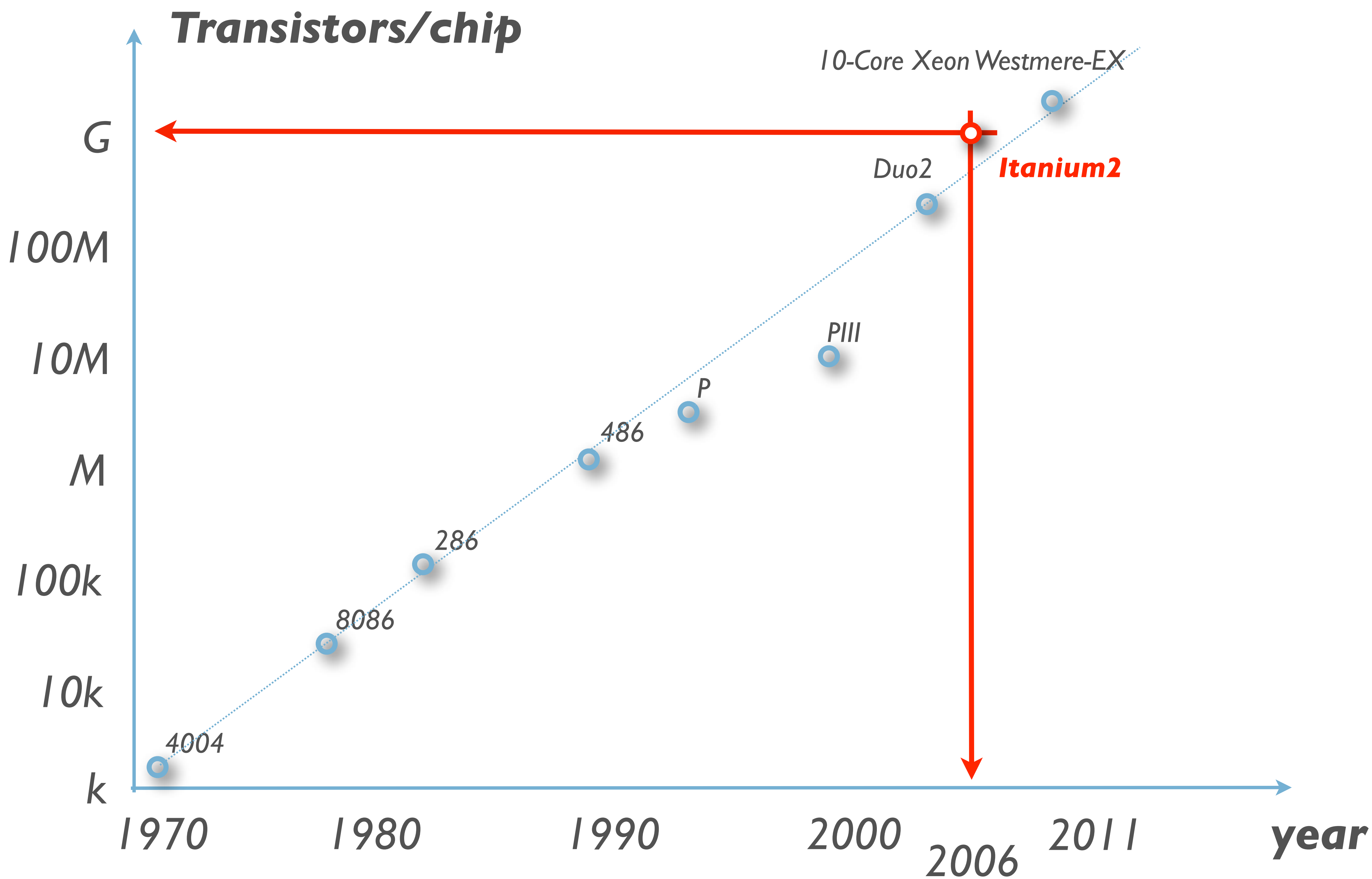
# Moore's law



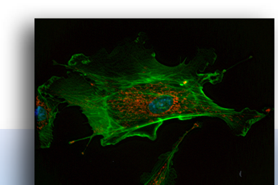
Transistors/chip
10-Core Xeon Westmere-EX
G
Itanium2
Duo2
100M
10M
PIII
P
486
M
286
100k
8086
10k
4004
k
1970
1980
1990
2000
2006
2011
year

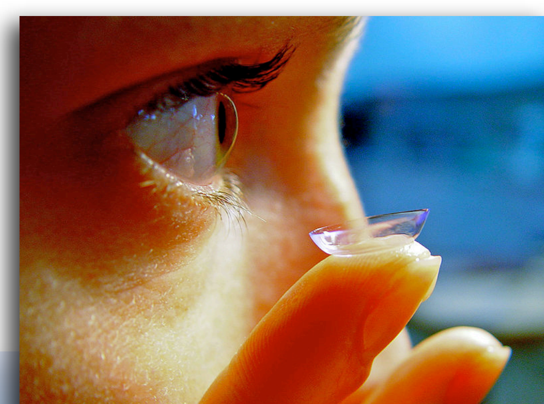
# Moore's law

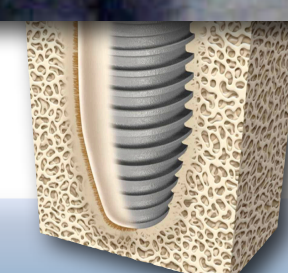
- 24th century: Cpt. Picard's iPad mini must have...
  ...CPU with ~1e60 transistors
- the human brain: ~ 1e10 neurones
- the human body: ~1e27 atoms
- the Universe: ~1e80 atoms

# Augmented technology distance

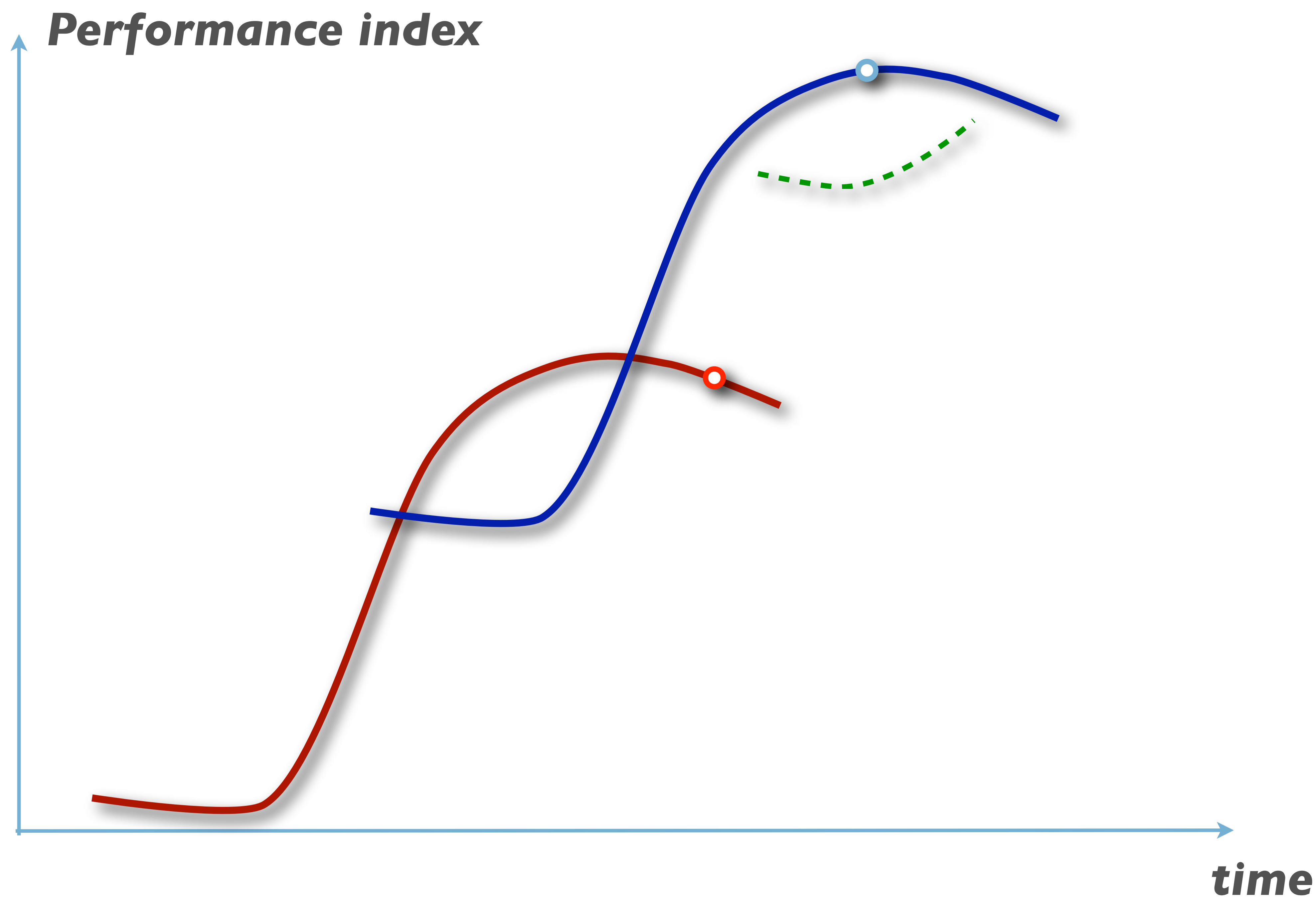
- infinite
- external (shared)
- external (personal)
- internal (temporarily)
- internal (permanently)
- iCyborg ?



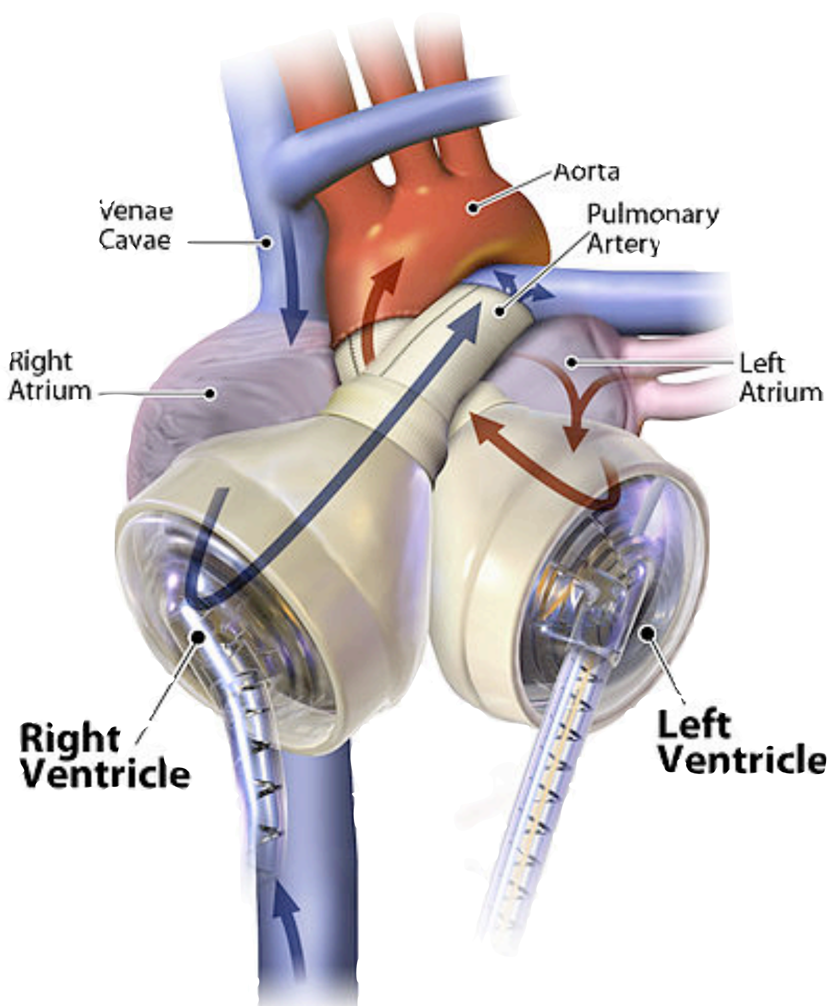


# S-curves

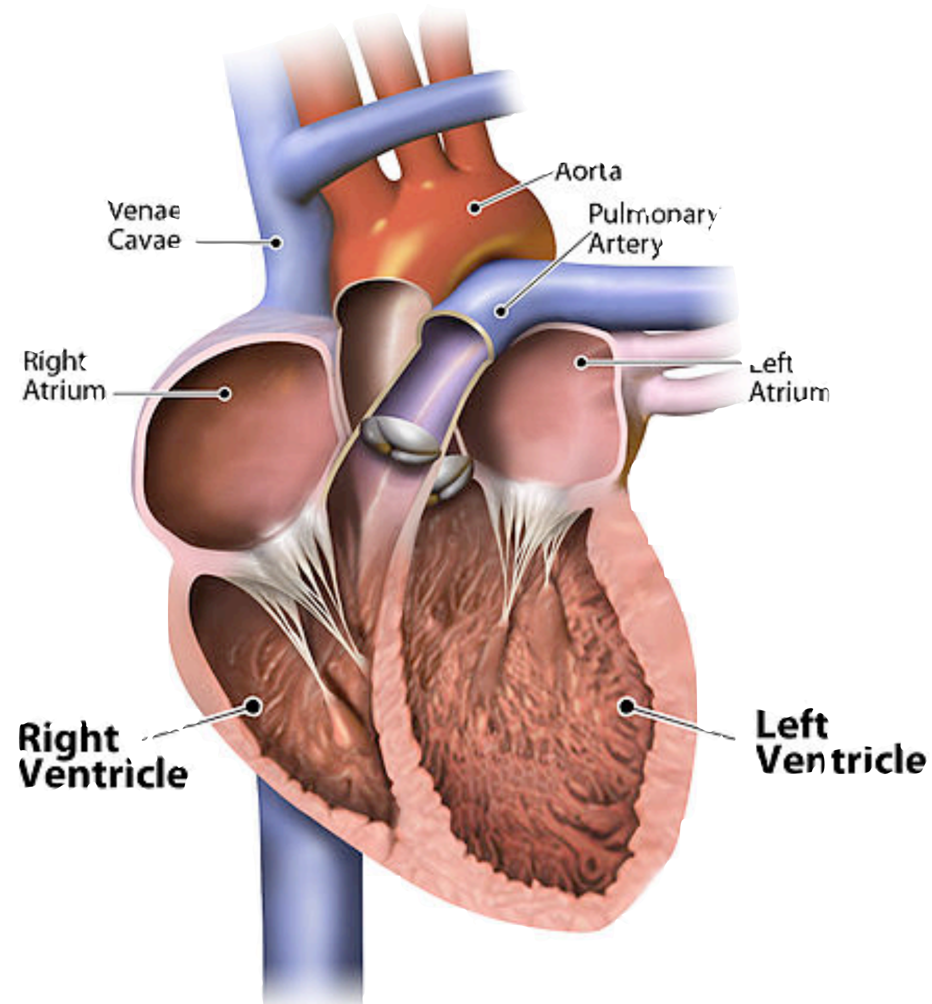


# Implantable Technology

# Why the implants ?



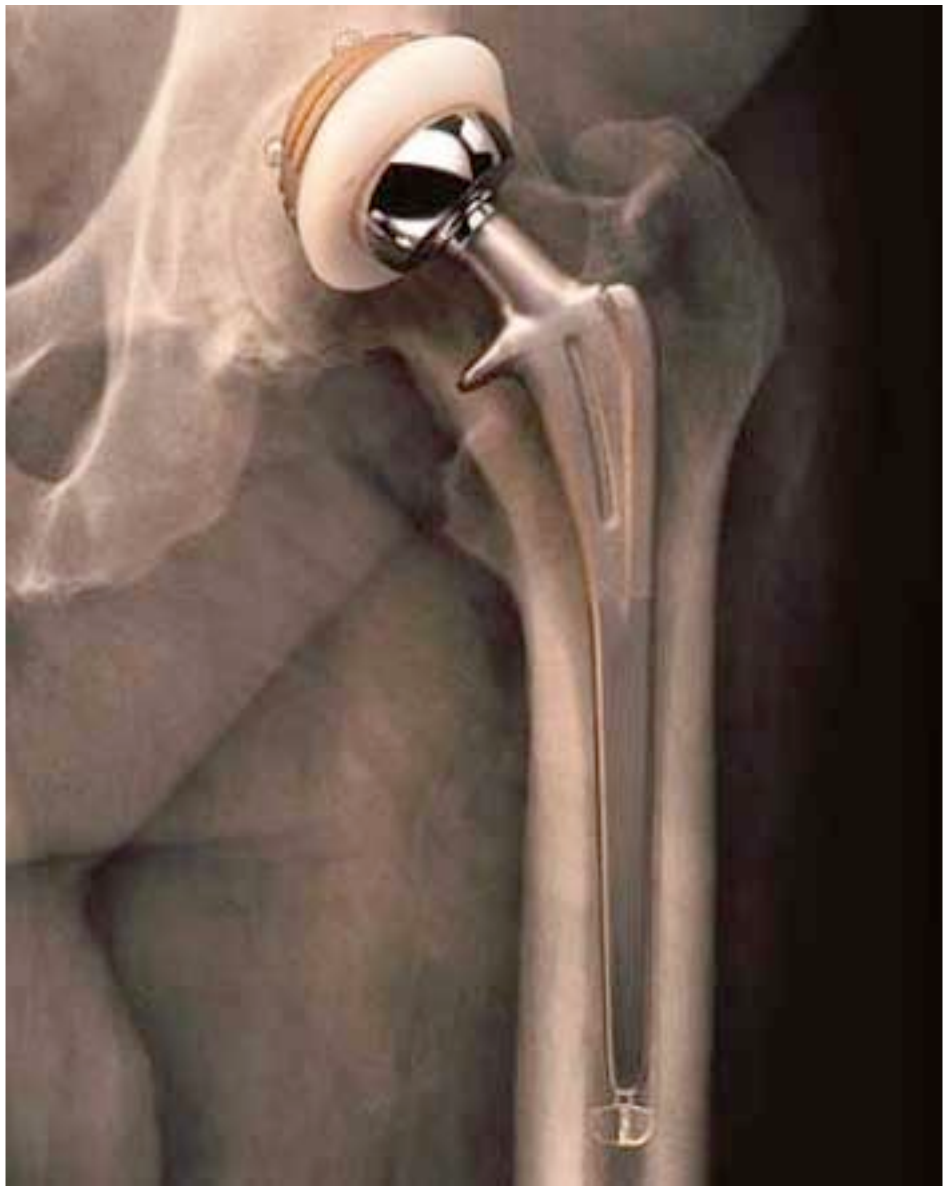

Total Artificial Heart




Human Heart

File source: wikipedia.org

# Why the implants ?

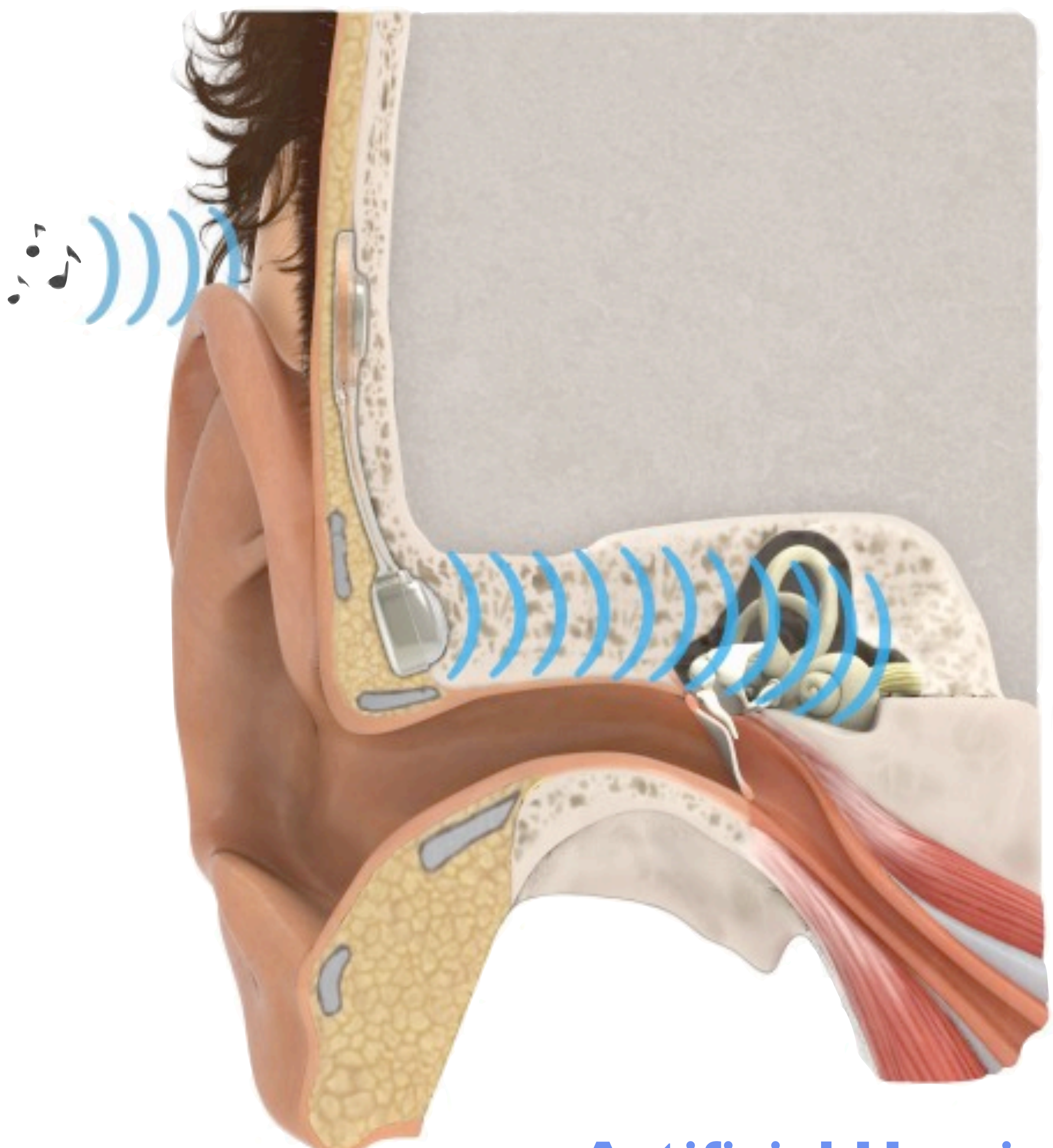


File source: wikipedia.org

**Artificial Hip**

- Human population is living longer
- We need medical care
- Technology integration is inevitable

# Why the implants ?



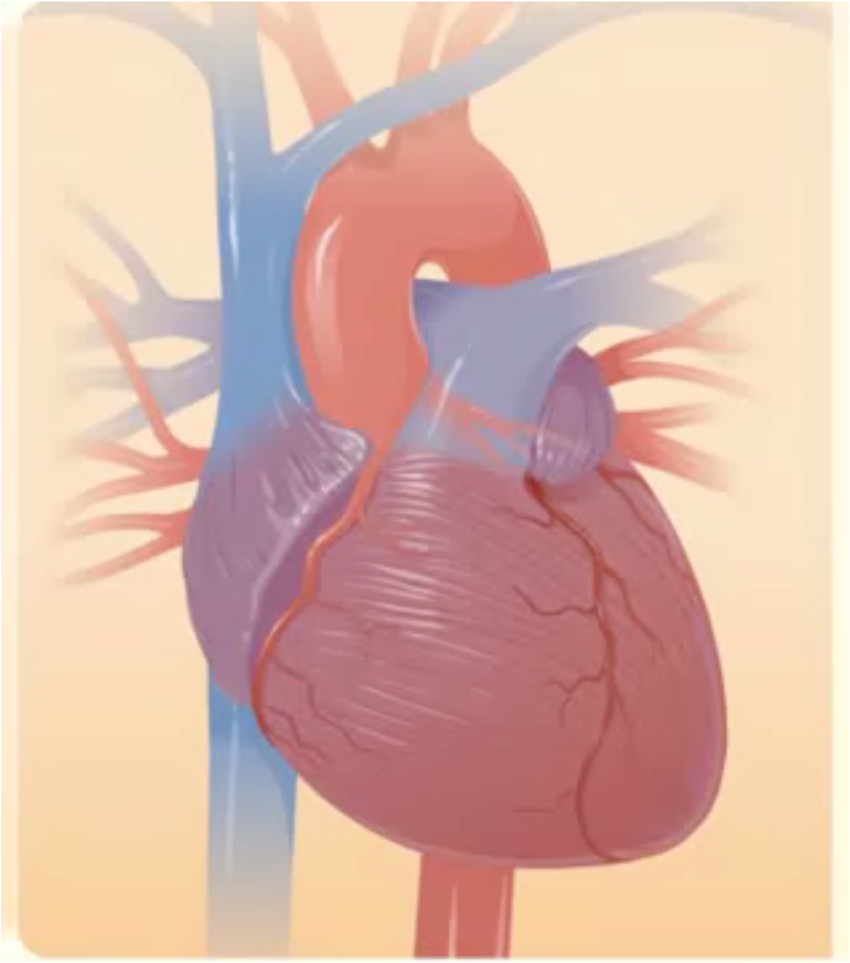
File source: wikipedia.org

**Artificial Hearing**

- Human population is living longer
- We need medical care
- Technology integration is inevitable

# Heart pump

- In 2008, 29% of ALL deaths in Canada caused by cardiovascular diseases
- A heart works similar to a piston engine
- Genetically modified animal subjects are essential for research

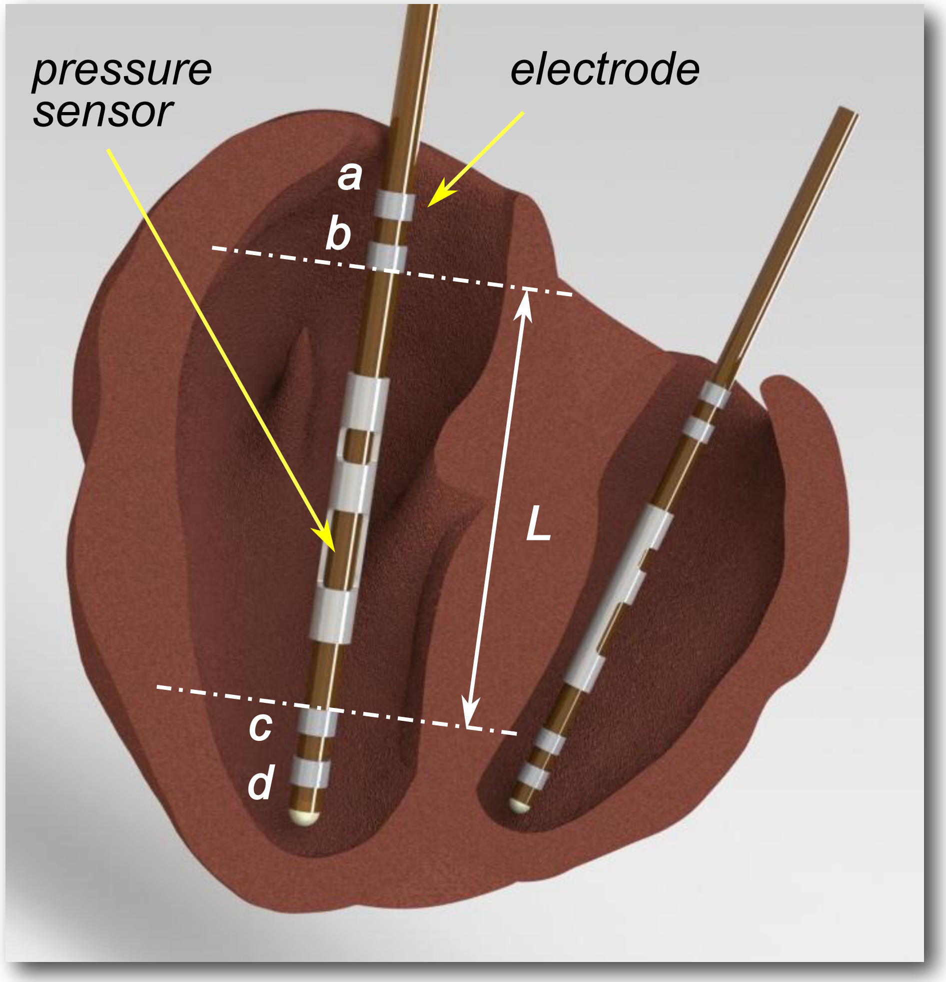


File source: wikipedia.org

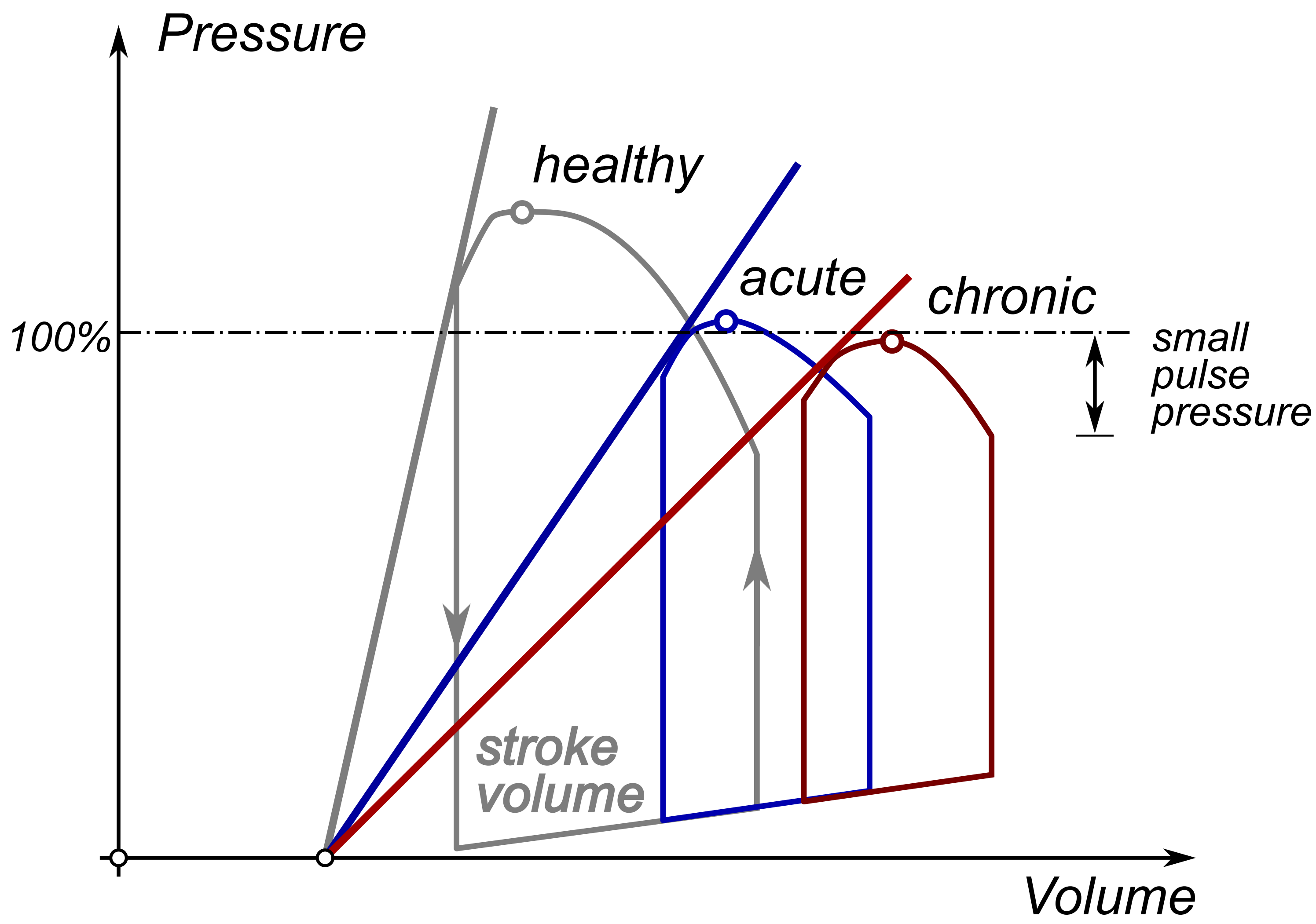
# Heart pump

- PV conductance based sensor
- Small enough to fit in a ...

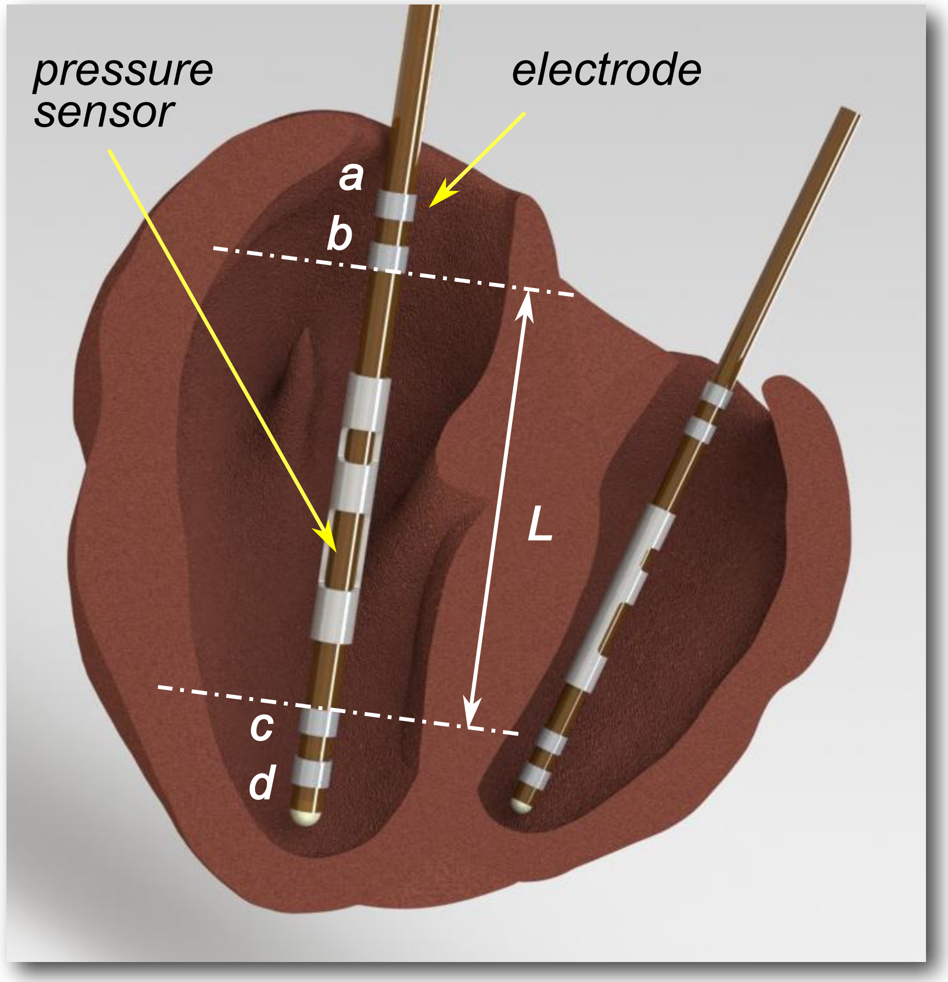
  ... mouse heart !
- Commercially available



# Heart pump

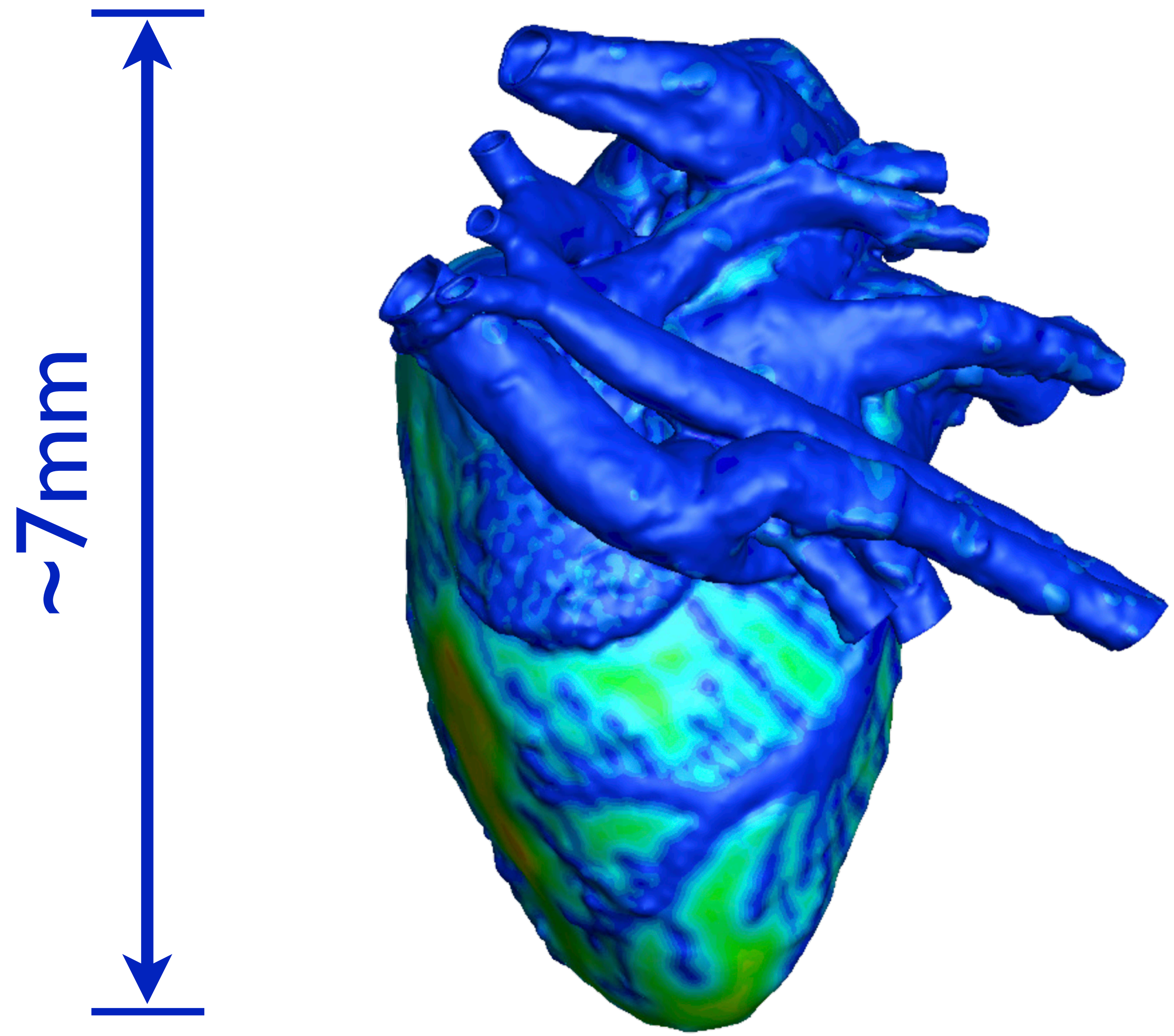



Pressure - Volume curves



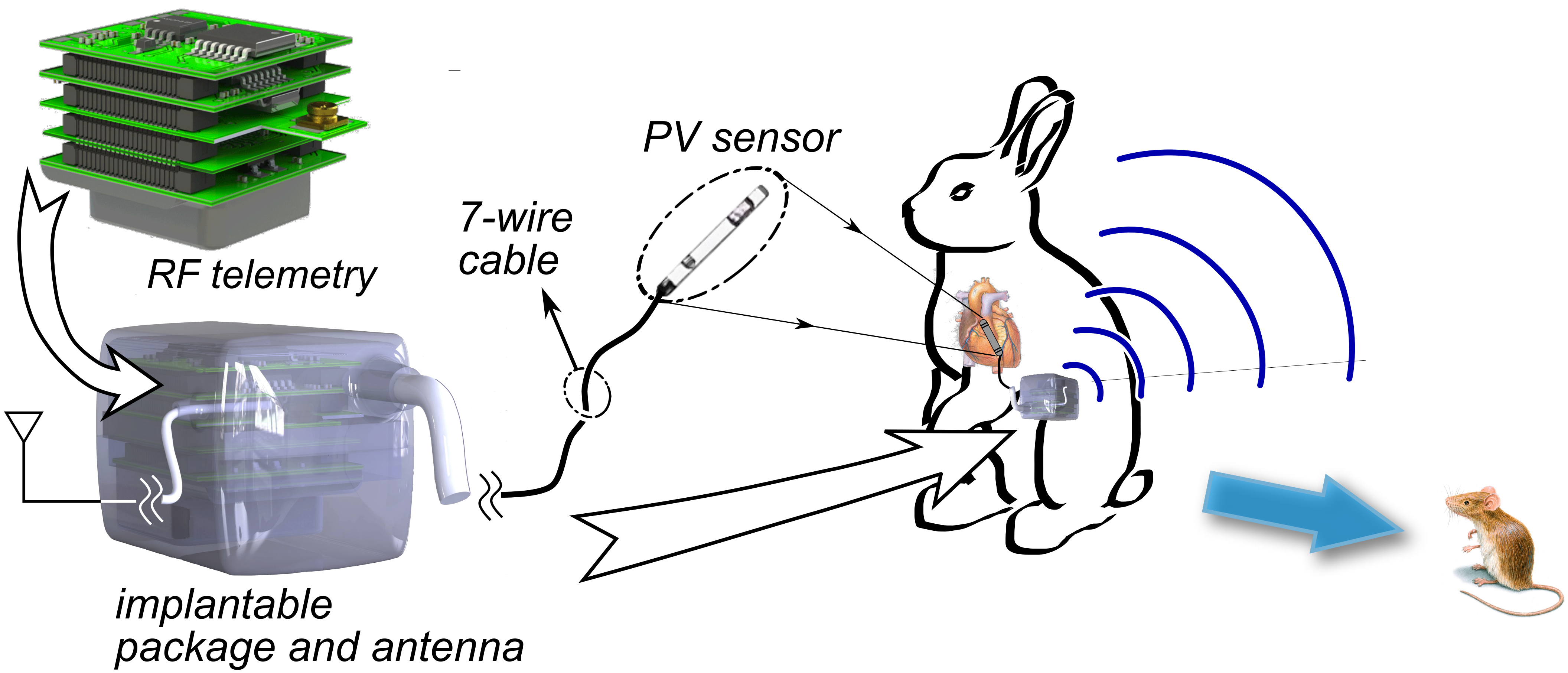
# Mouse heart

- ~1mL blood volume
- ~1/1000 of a human heart
- ~7mm long
- ~630±50 beats/min



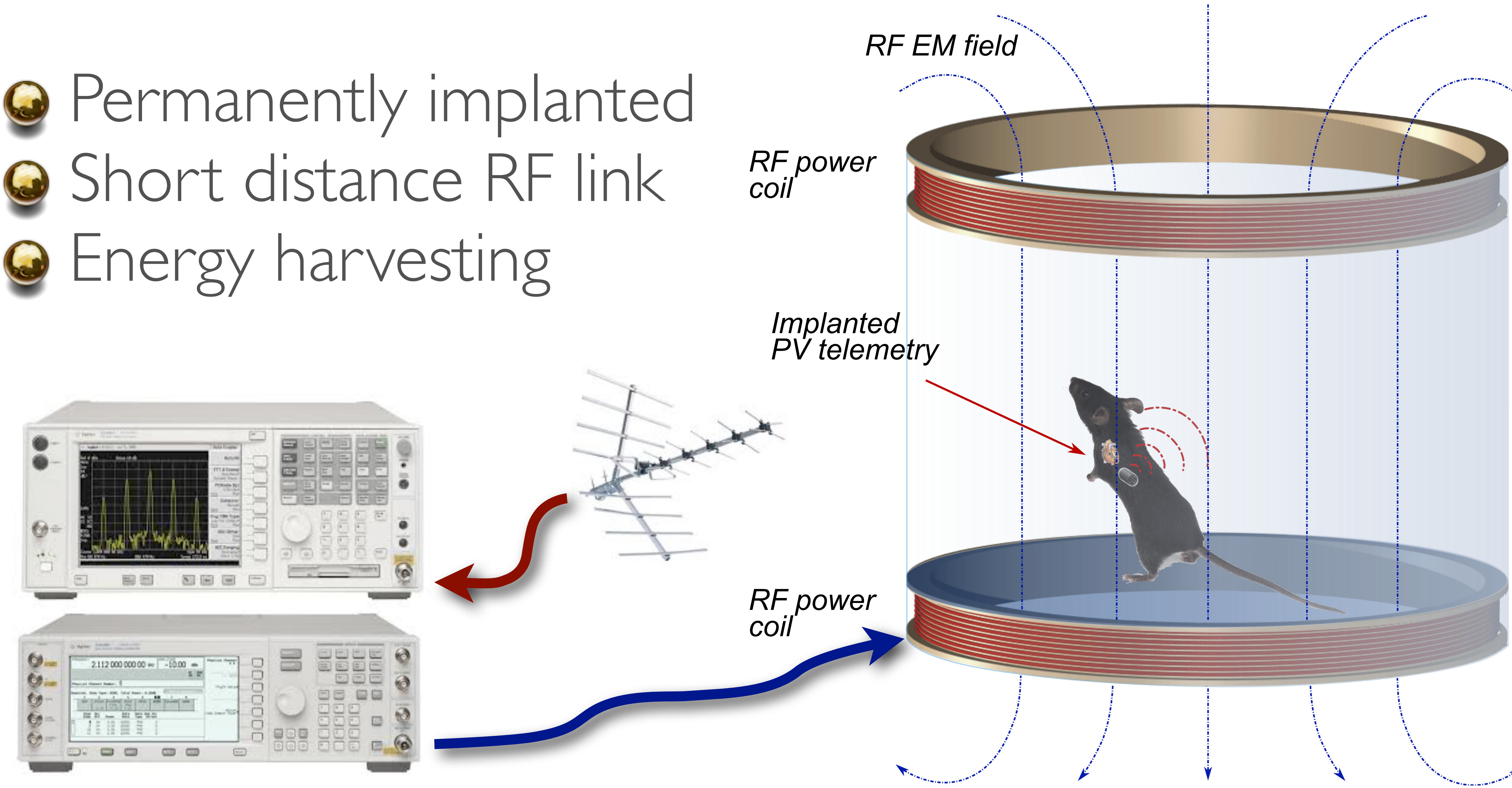

Courtesy of Dr. James P. Carson.

# Cardiac telemetry



# Telemetry system

- Permanently implanted
- Short distance RF link
- Energy harvesting



# Telemetry system

## Main challenges:

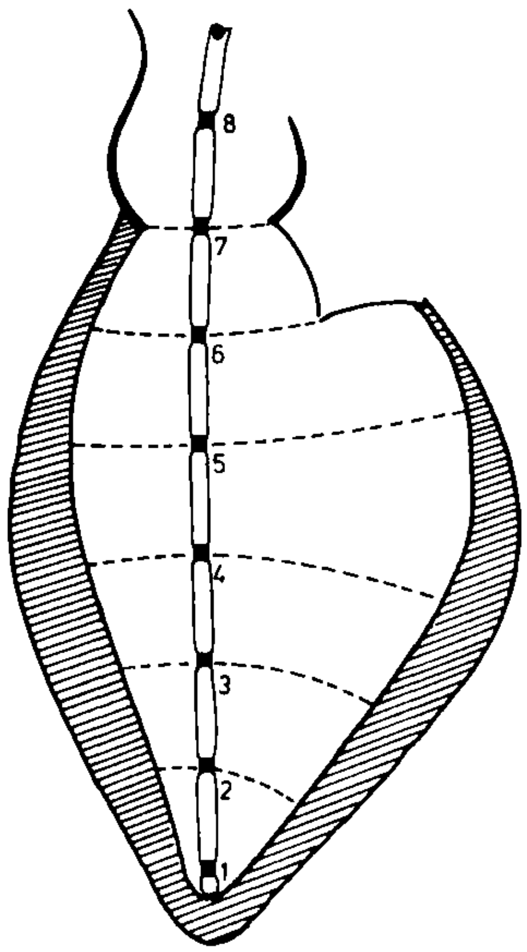
- Power consumption
- The system's size
- Hostile environment
- Multidisciplinary design
- Ethical and legal issues
- ...

# PV Sensor

# PV sensor model

- Linear model
- Wei's nonlinear model
- Dubois model
- Sensor calibration

# Baan's model




$$g(t)' = \frac{1}{R(t)} = \frac{\sigma}{L} A(t) + \frac{\epsilon}{L}\frac{dA(t)}{dt}$$

$$g(t)'' = \omega \frac{\epsilon}{L} A(t)$$

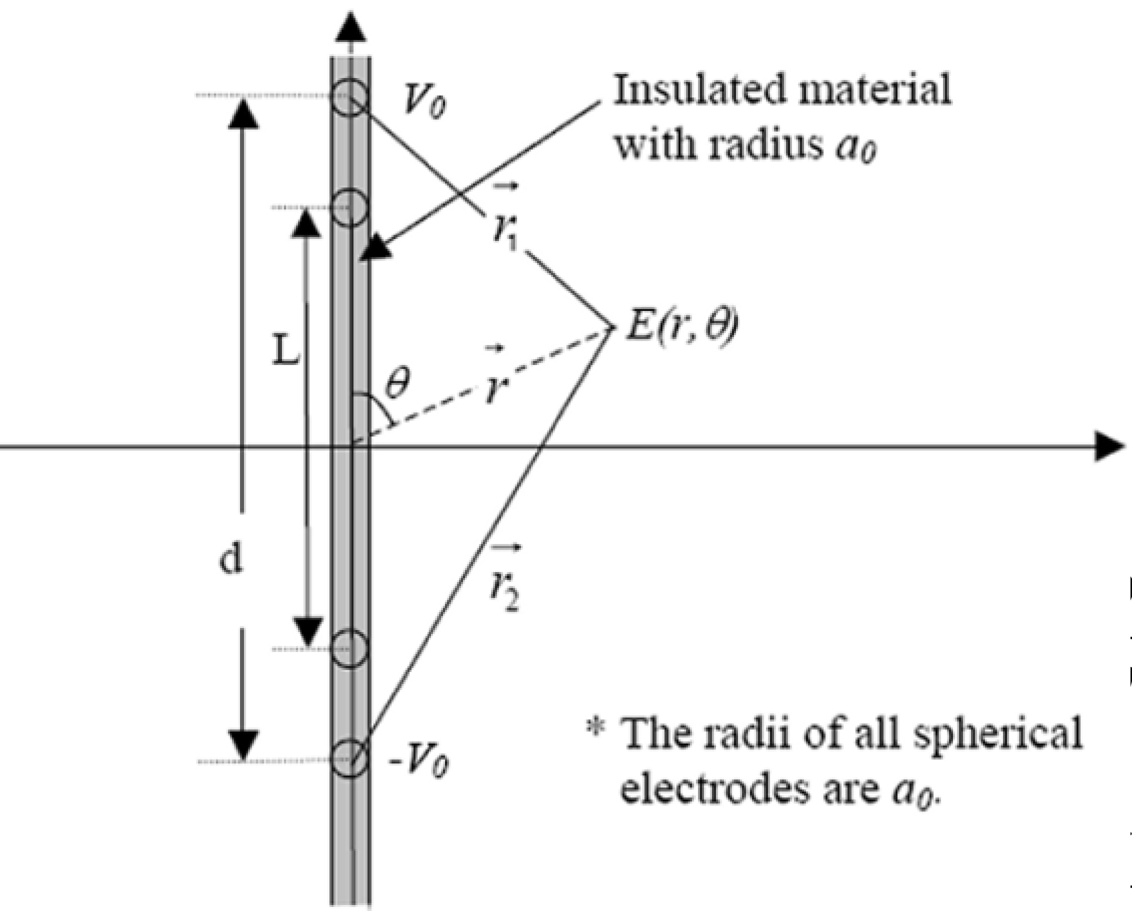
$$\Delta V(t) \approx A(t) \times L$$

$$g(t)' = \frac{1}{R(t)} = \frac{\sigma}{L^2} V(t)$$

$$\Delta V(t) \approx \frac{L^2}{\sigma}\left(\frac{1}{R_{ab}} - \frac{1}{R_{ac}}\right) = \frac{L^2}{\sigma} g_b(t) = \rho L^2 g_b(t)$$

$$V(t) = k\,\rho\,L^2\,g_b(t) + V_c$$

# Wei's model



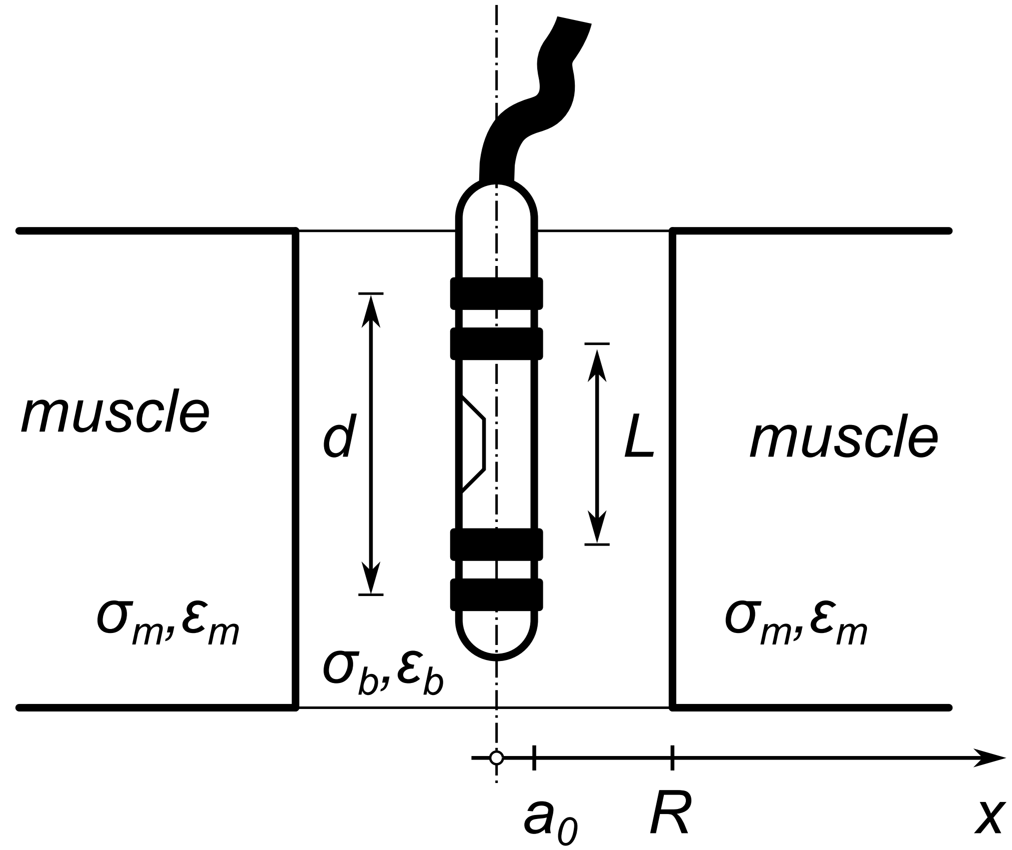

$$g_b = \frac{I}{V} = \frac{\oint_a \vec{J}\, d\vec{a}}{-\int_l \vec{E}\, d\vec{l}} = \frac{\oint_a \sigma \vec{E}\, d\vec{a}}{-\int_l \vec{E}\, d\vec{l}}$$

$$\left(r^2 \frac{\partial V}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial V}{\partial\theta}\right) + \frac{1}{r^2 \sin^2\theta}\left(\frac{\partial^2 V}{\partial\varphi^2}\right) = 0$$

$$\frac{d\,\left(d^2 - L^2\right)\,(\sigma_b + j\omega\varepsilon_b)}{4L} \times \left(\frac{1}{\sqrt{a_0^2 + d^2/4}} - \frac{1}{\sqrt{R^2 + d^2/4}}\right)$$

$$V = \frac{\beta}{(g_{\inf} - g_b)^2} - \frac{\beta}{g_{\inf}^2}$$ , where $$\beta = f(SV, g_{\inf}, g_{bmax}, g_{bmin})$$

# Dubois' model

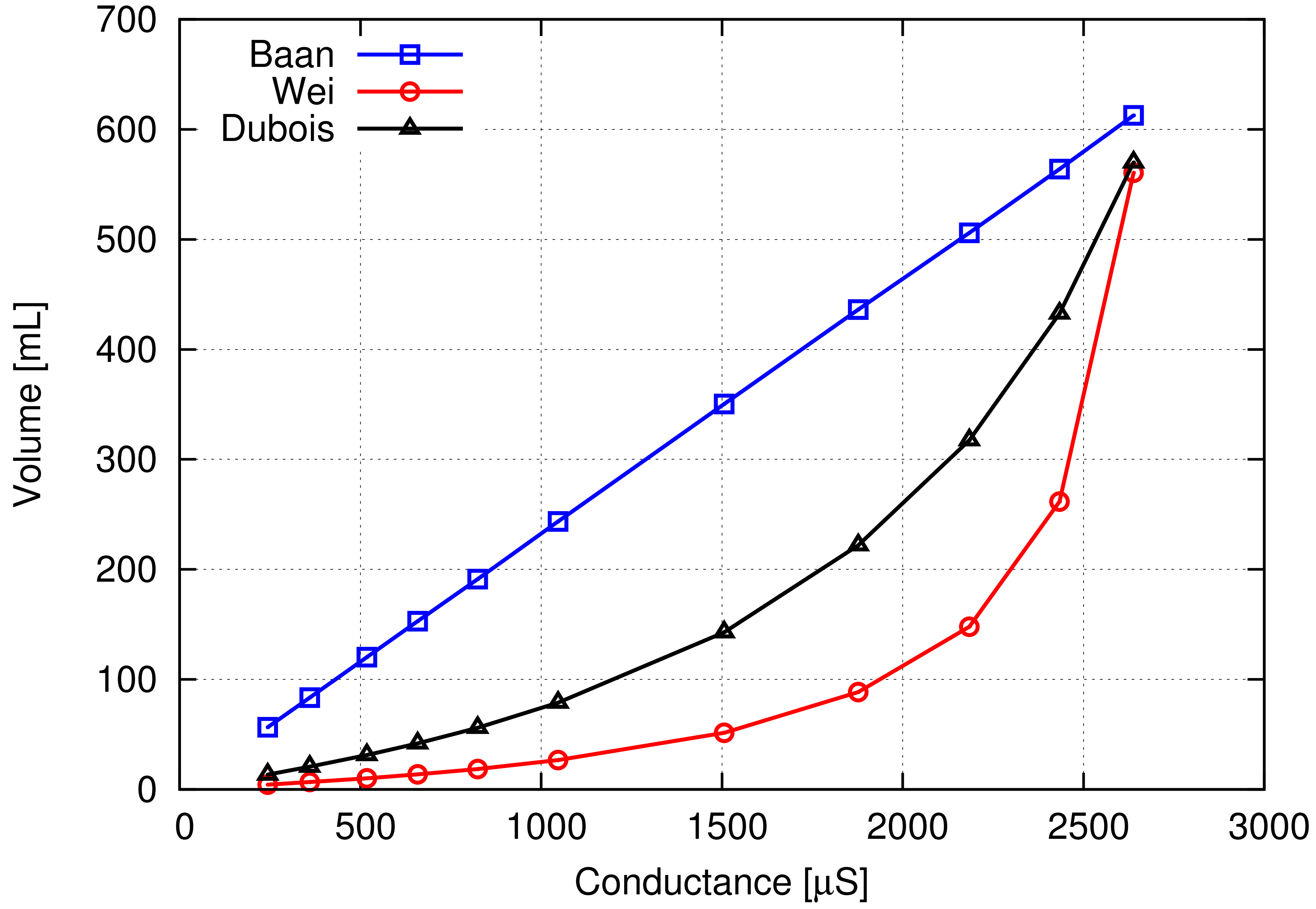



$$Y = Y_b + Y_m$$

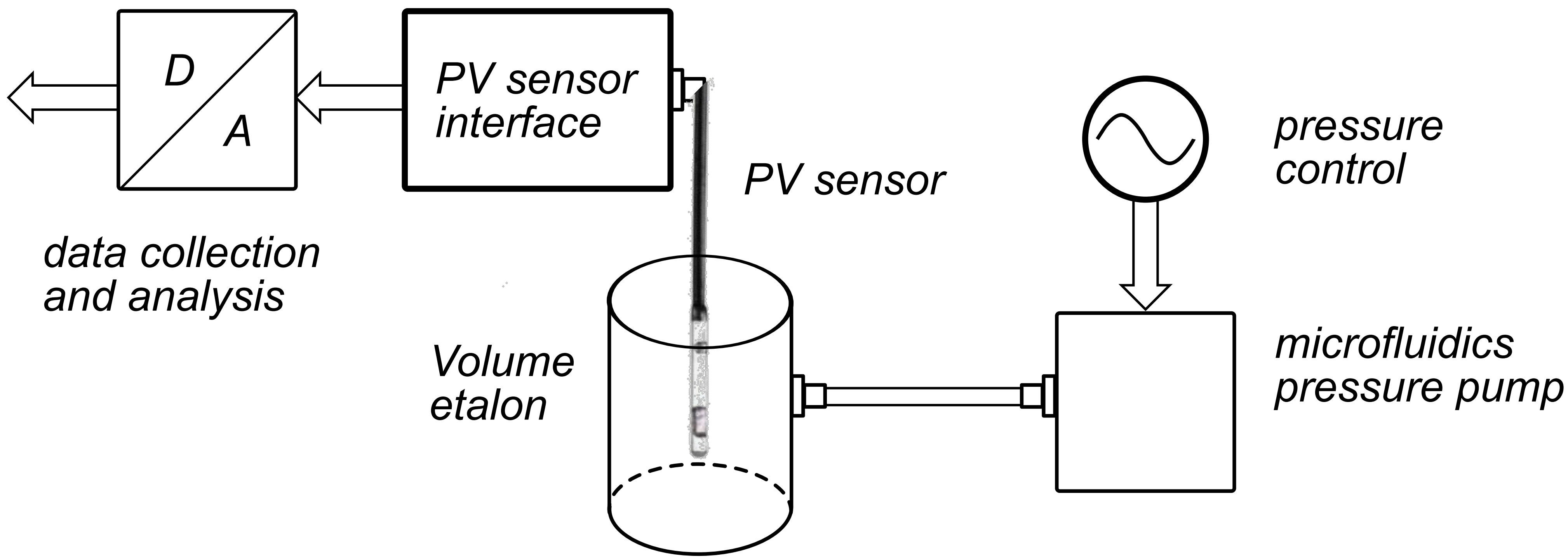
$$V = -\pi L \left[ \frac{d^2}{4} - \frac{\beta \pi^2 d^2 \left(d^2 - L^2\right) \left(\Delta\sigma + j\omega\Delta\varepsilon\right)^2}{16 L^2 \left(Y - Y_{\mathrm{inf}}\right)^2} \right]$$ , where

$$Y_{\mathrm{inf}} = \frac{\pi\, d\, \left(d^2 - L^2\right)\, \left(\sigma_b + j\omega\varepsilon_b\right)}{4L\sqrt{a_0^2 + d^2/4}}$$

# Models comparison



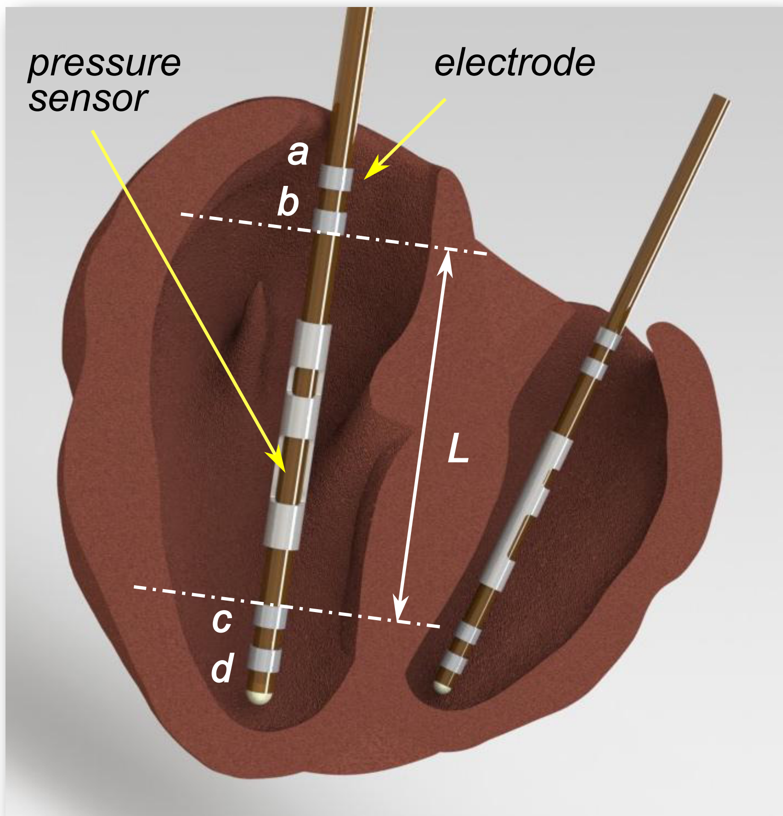
# Sensor calibration

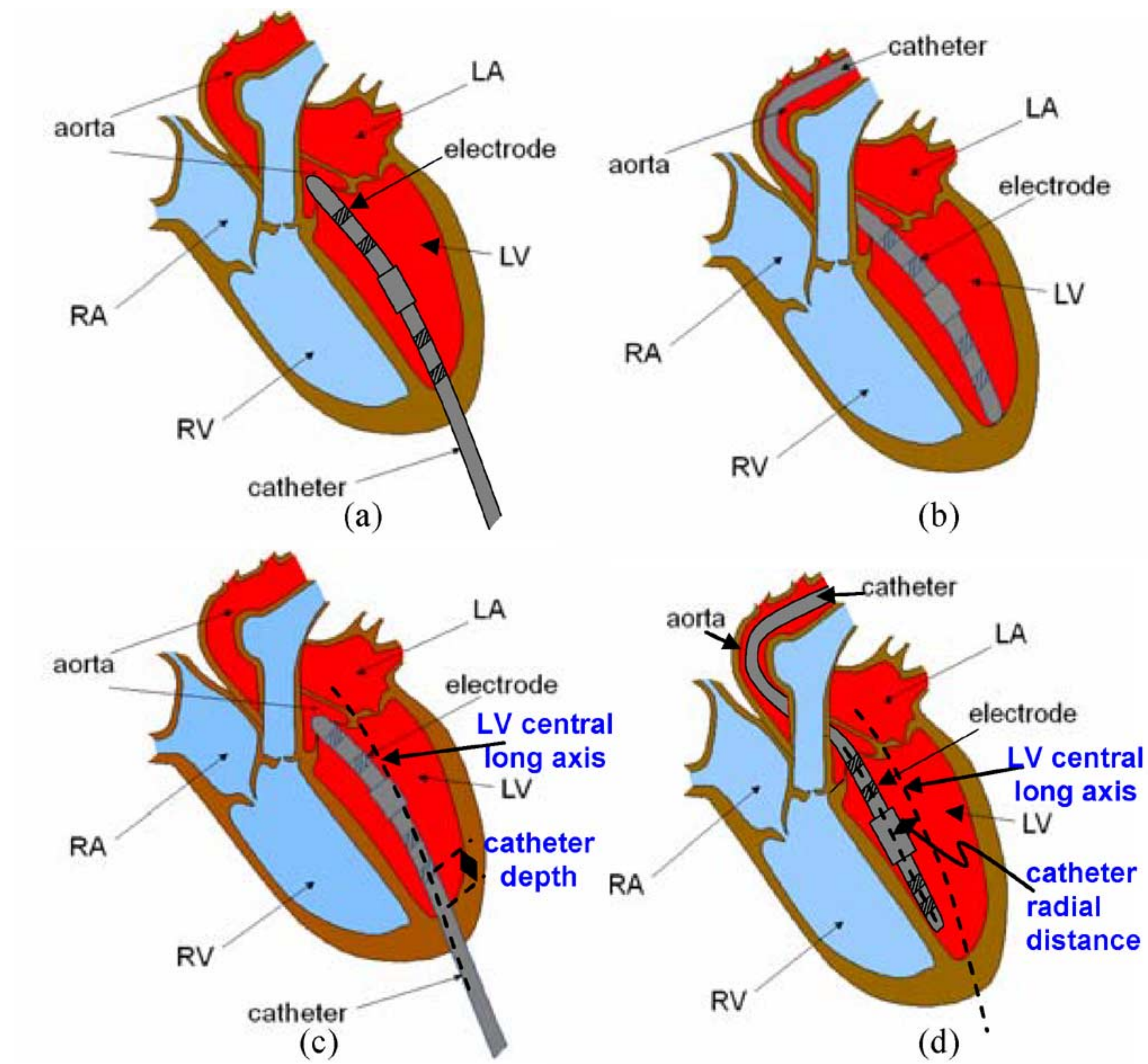



## Main challenge:

- PV measurement is <u>relative</u>

# Sensor insertion



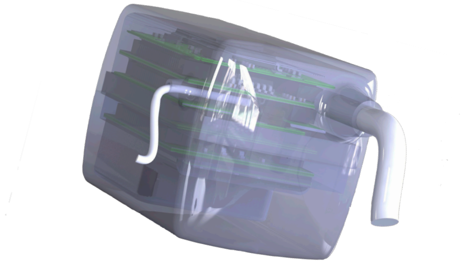




C.L. Wei, 2009

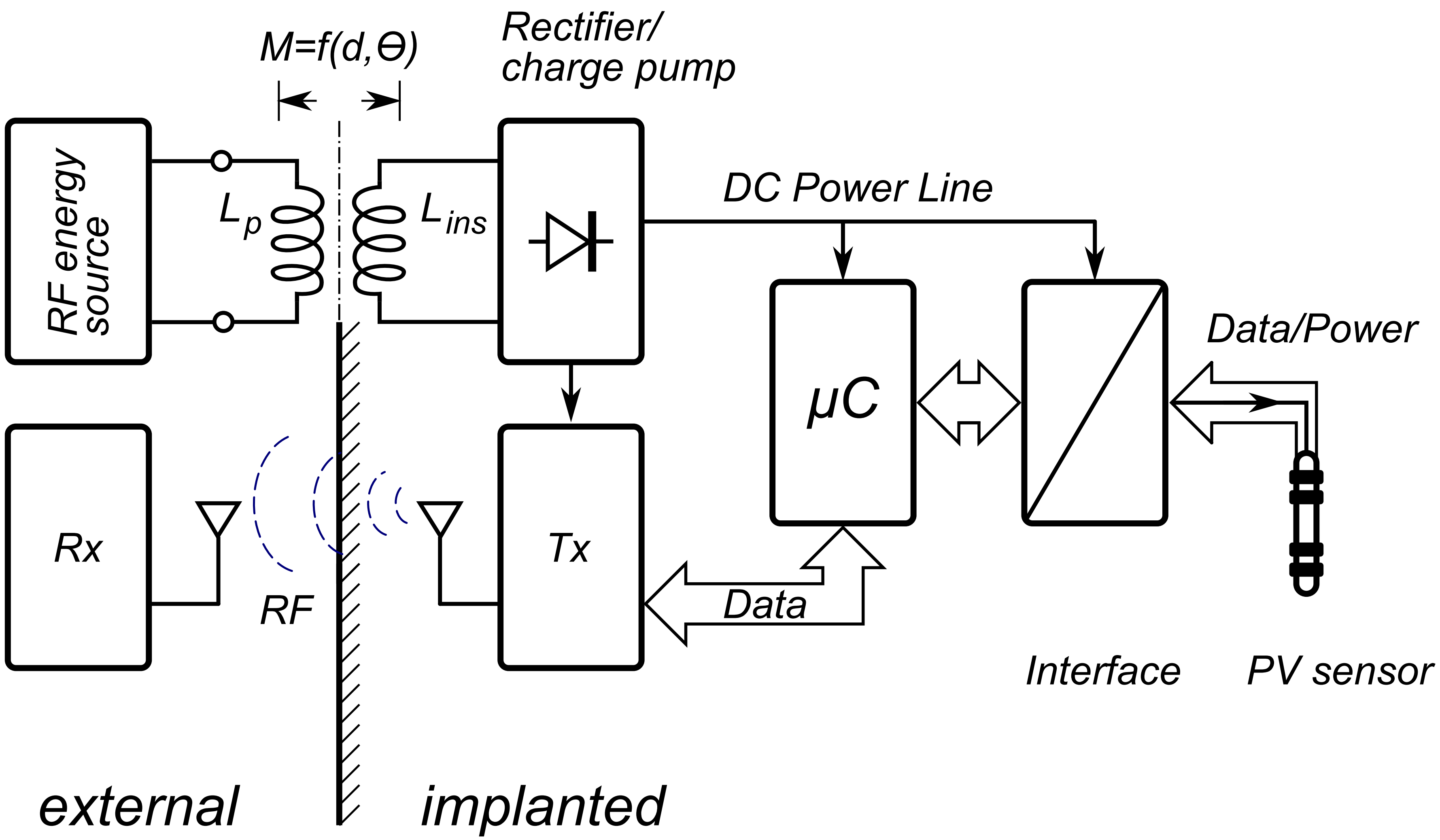
## Main challenge:

- Catheter insertion and mechanical bending

# System Architecture



# System architecture




## Main challenges:

- System's size
- Power source
- Transmission losses

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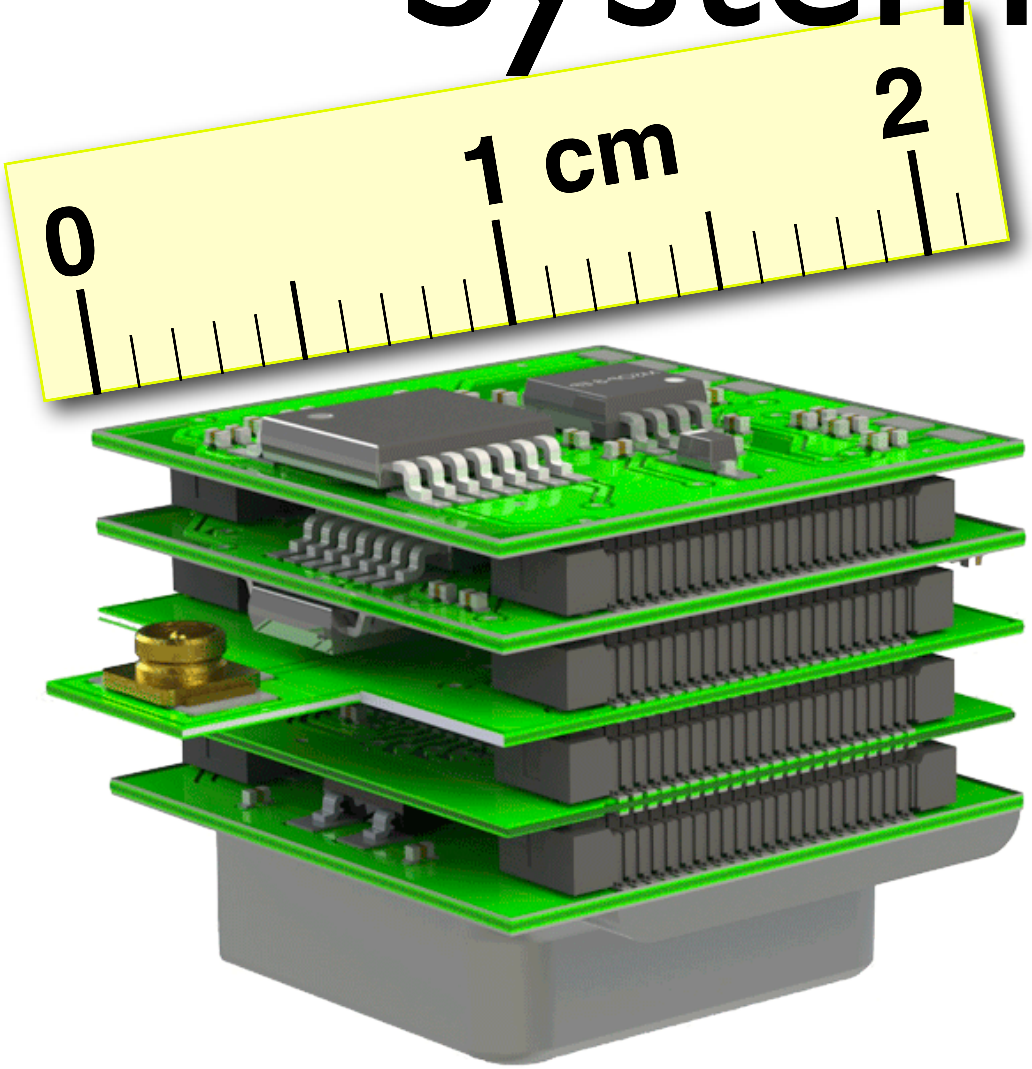
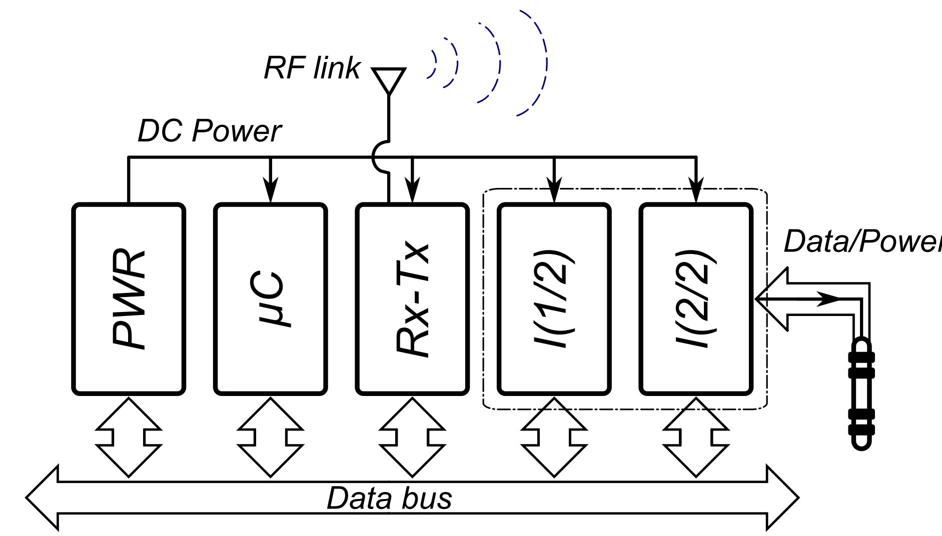
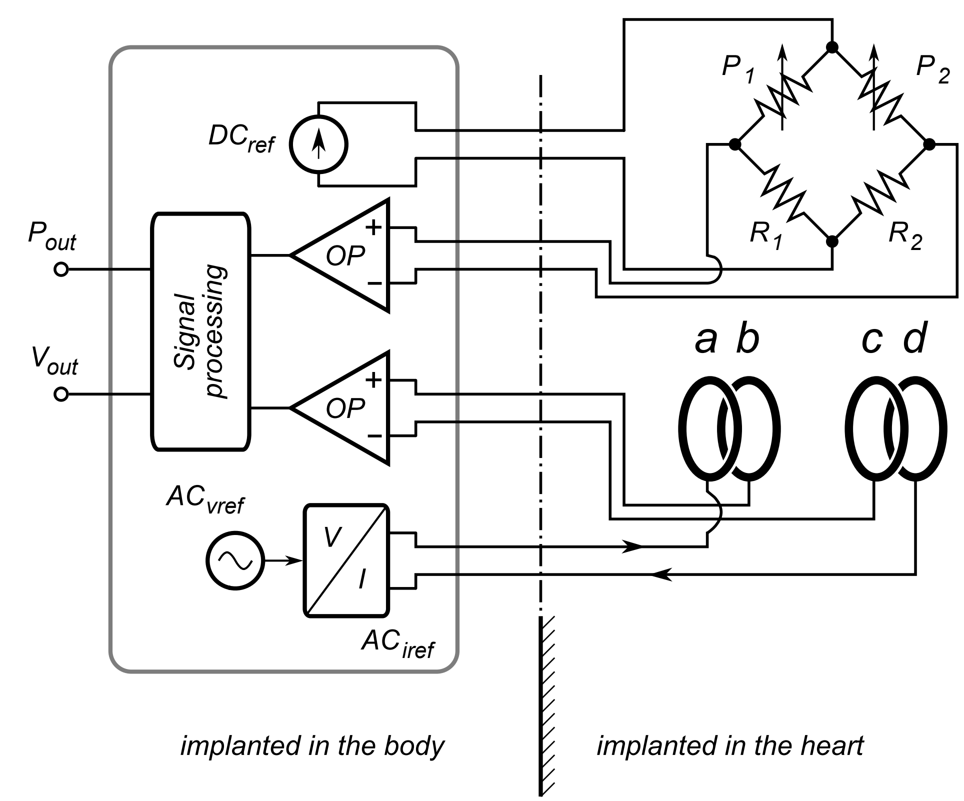
# System architecture



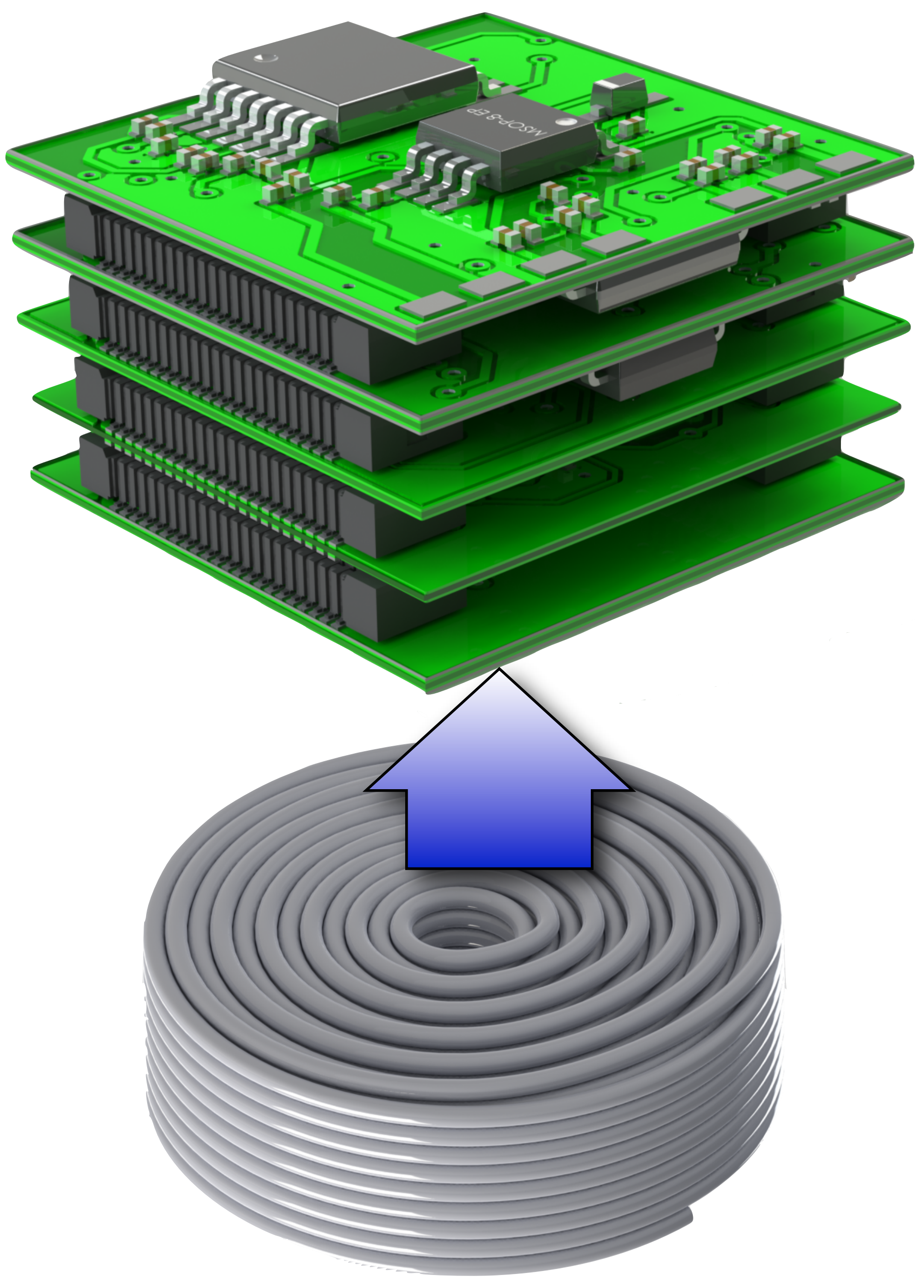




Main challenges:

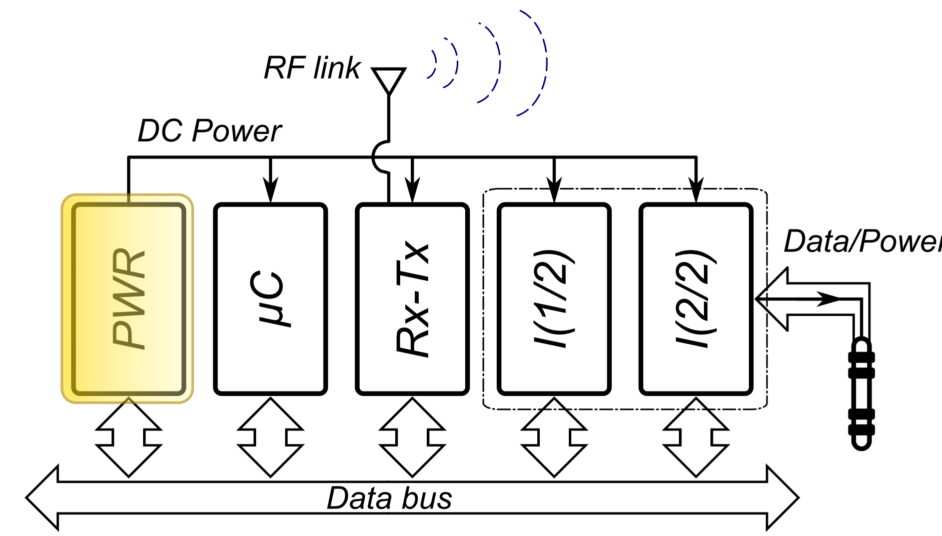
- 3D design
- size

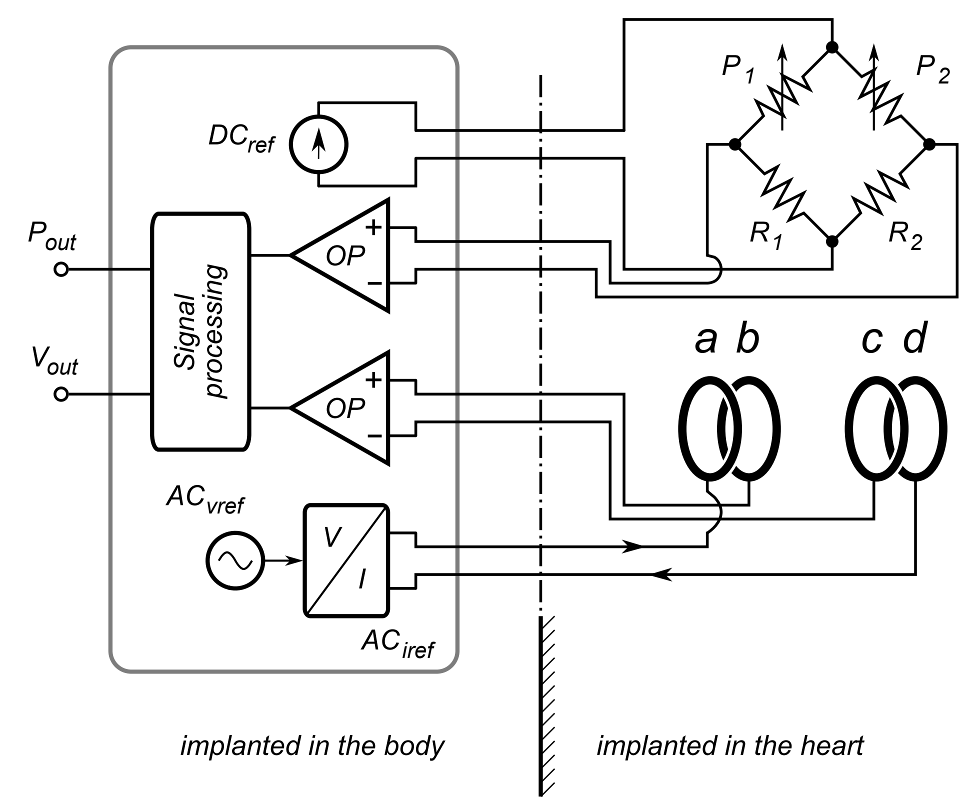
# System architecture



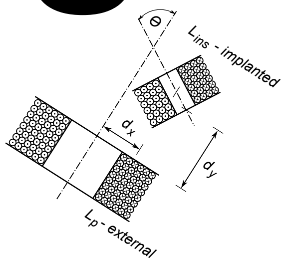
← PWR

← inductive RF link



# Energy Harvesting

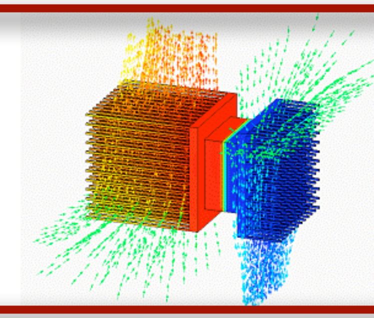


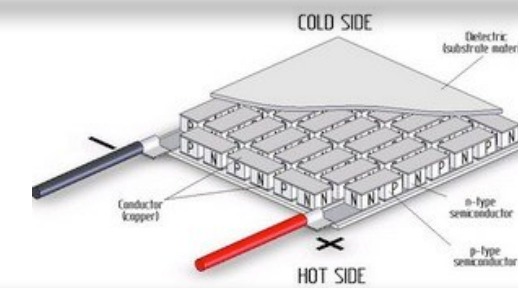
# Energy harvesting sources

| Energy source | Performance | Note |
|---|---|---|
| Ambient RF | $< 1\mu W/cm^2$ | A few mW with a short distance inductive coupled systems [20]. |
| Ambient light | $100mW/cm^2$ (direct sunlight)<br>$100\mu W/cm^2$ (office light) | Assuming common polycrystalline solar cells at 16%-17% efficiency, while standard monocrystalline cells approach 20%. |
| Thermoelectric | $60\mu W/cm^2$ | at $\Delta T = 5°C$; typical thermoelectric generators $\leq$ 1% efficient for $\Delta T < 40°C$. |
| Vibrational | $4\mu W/cm^3$ (human)<br>$800\mu W/cm^3$ (machine) | Predictions for 1 $cm^3$ generators. |
| Ambient airflow | $1mW/cm^2$ | Demonstrated in microelectromechanical turbine at 30 liters/min. |
| Push buttons | $50\mu J/N$ | MIT Media Lab Device. |
| Hand generator | $30W/kg$ | Nissho Engineering's Tug Power. |
| Heel strike | $10 - 800\mu W$ | $7W$ potentially available (1cm deflection at 70kg per 1Hz walk) |

# Energy harvesting sources

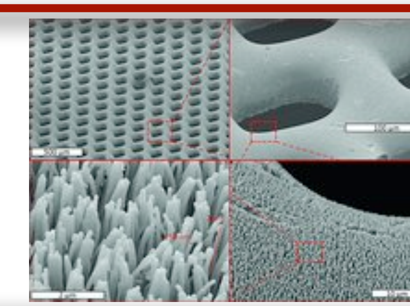
Thermoelectric - Peltier



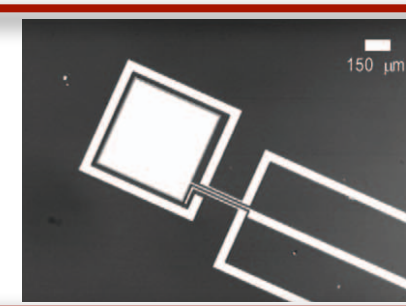


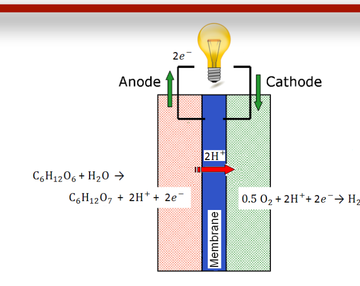

Piezo vibrational cell

Micro glass-fuel cell

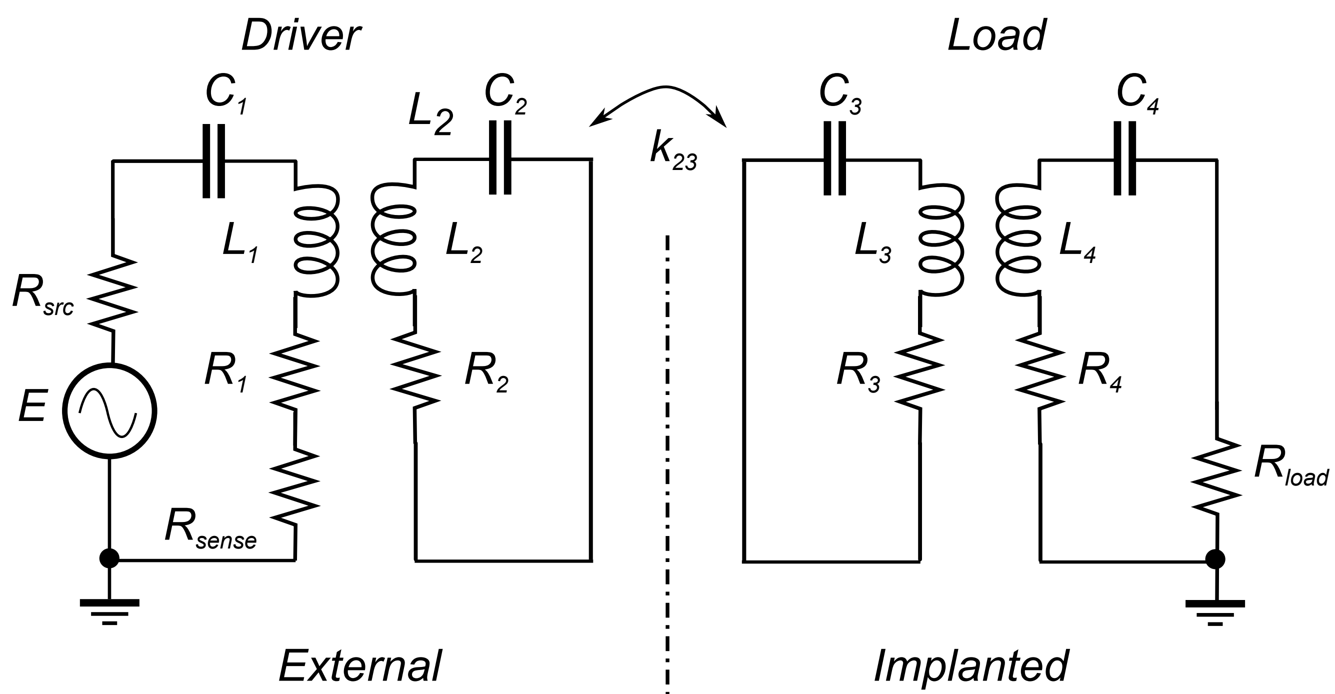


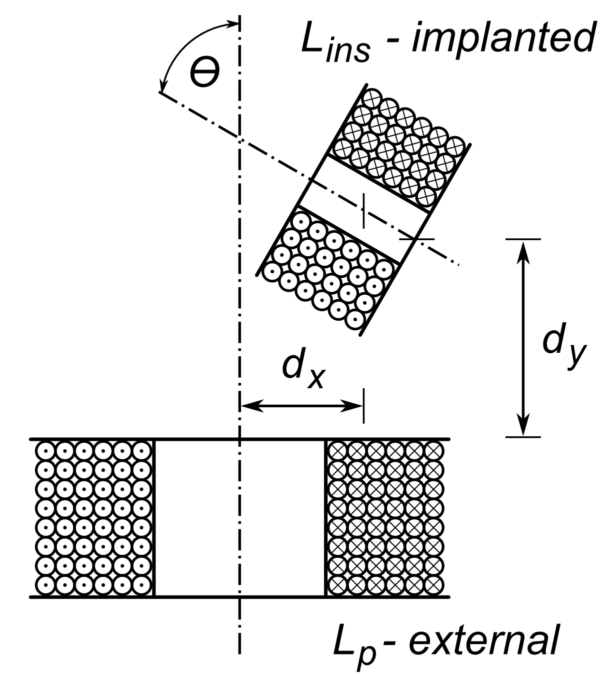
Glucose Bio-fuel cell

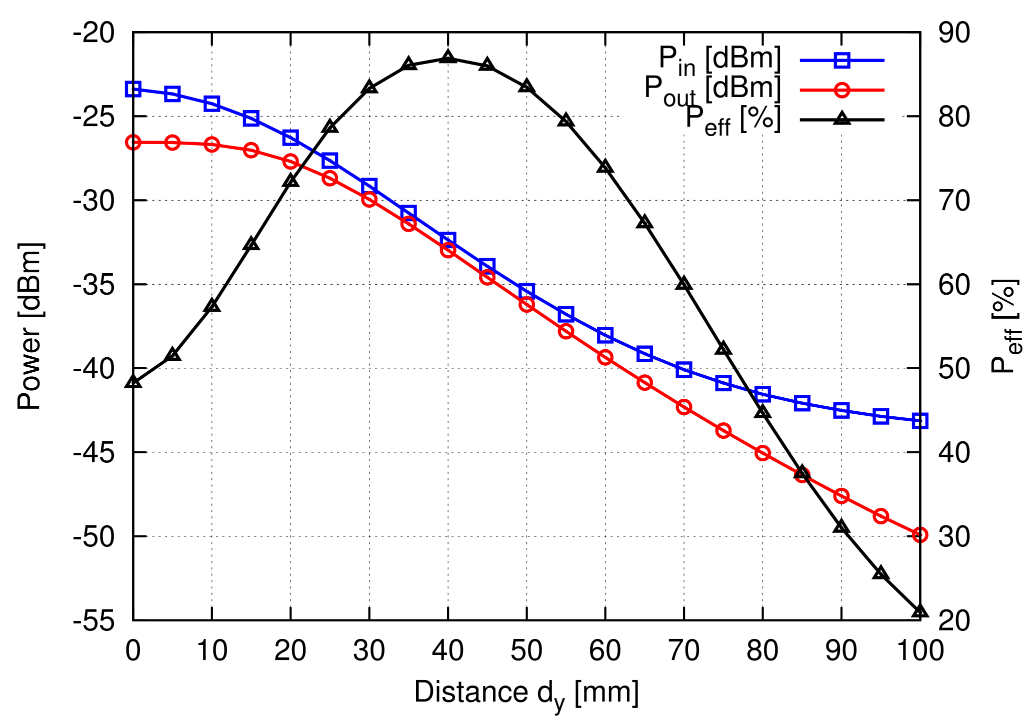


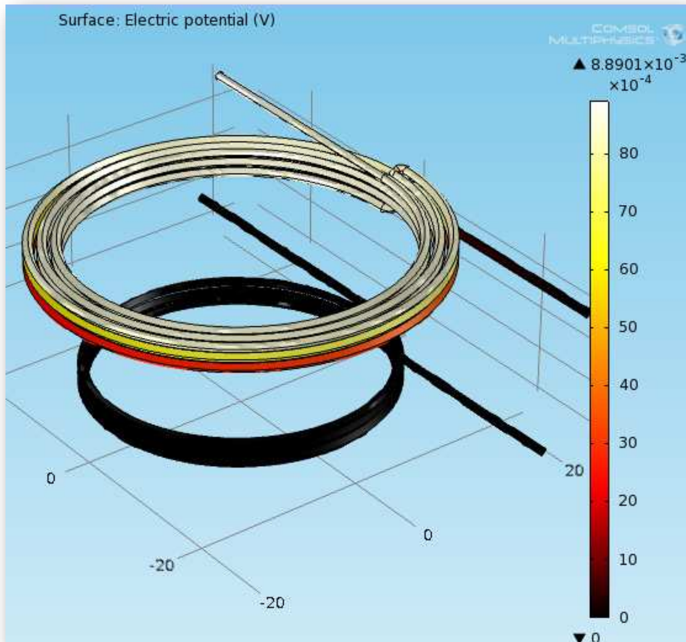
# RF energy harvesting

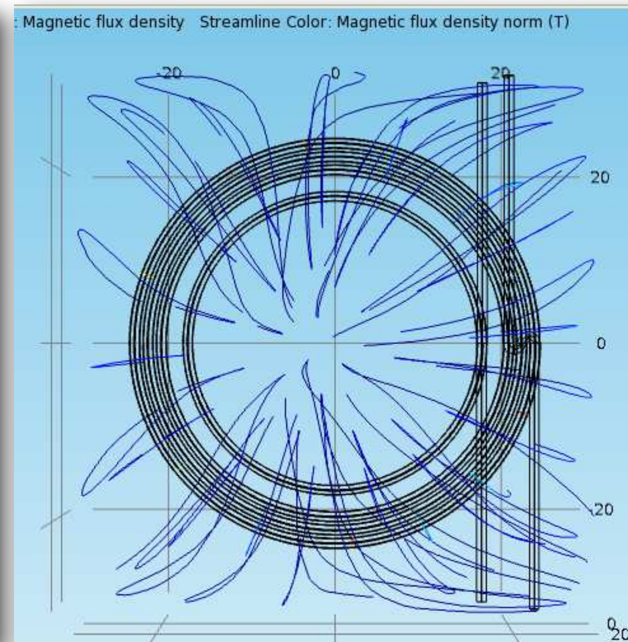


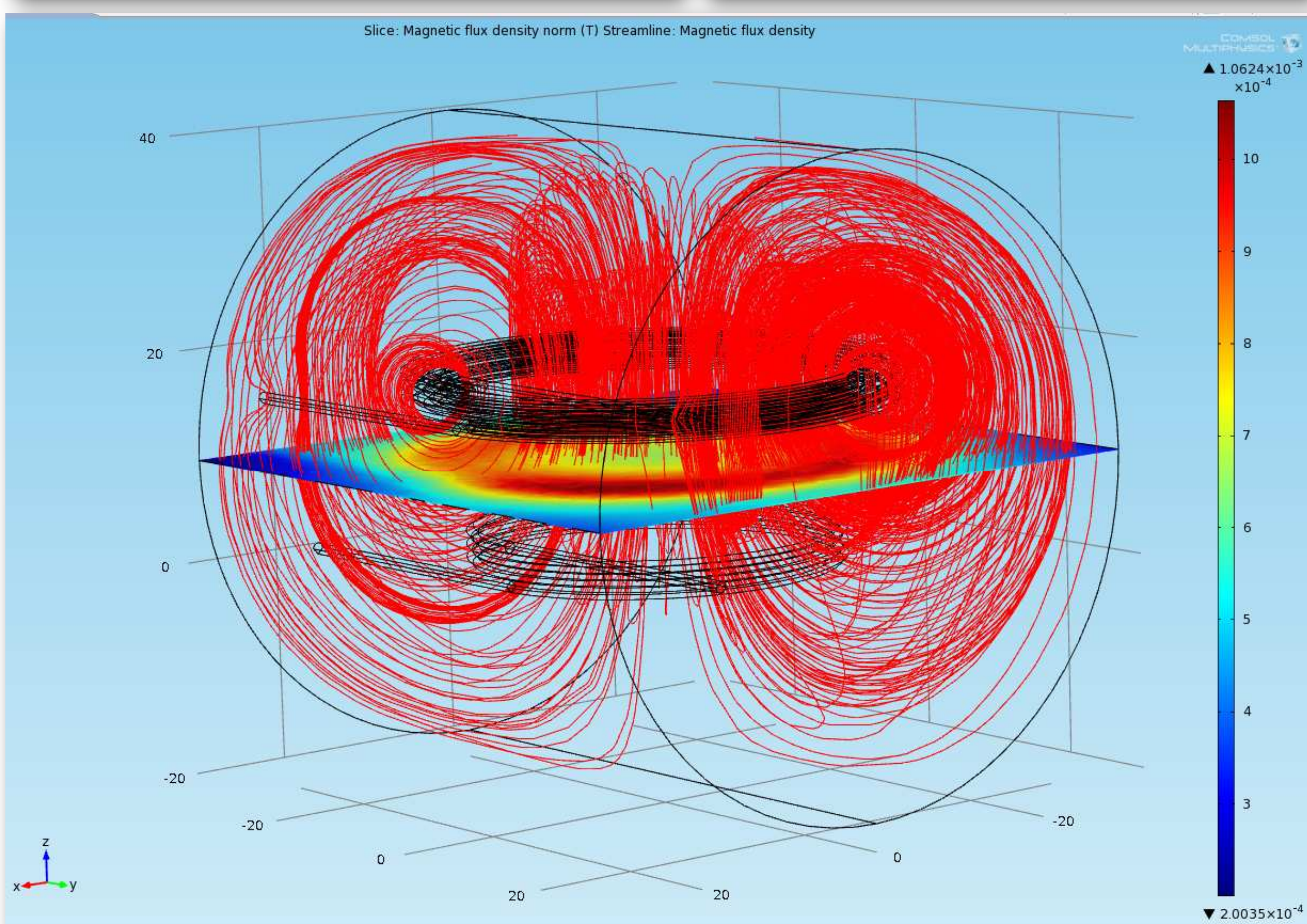



# RF energy harvesting




## Main challenges:

- Modelling
- Simulation tools
- Manufacturing and packaging

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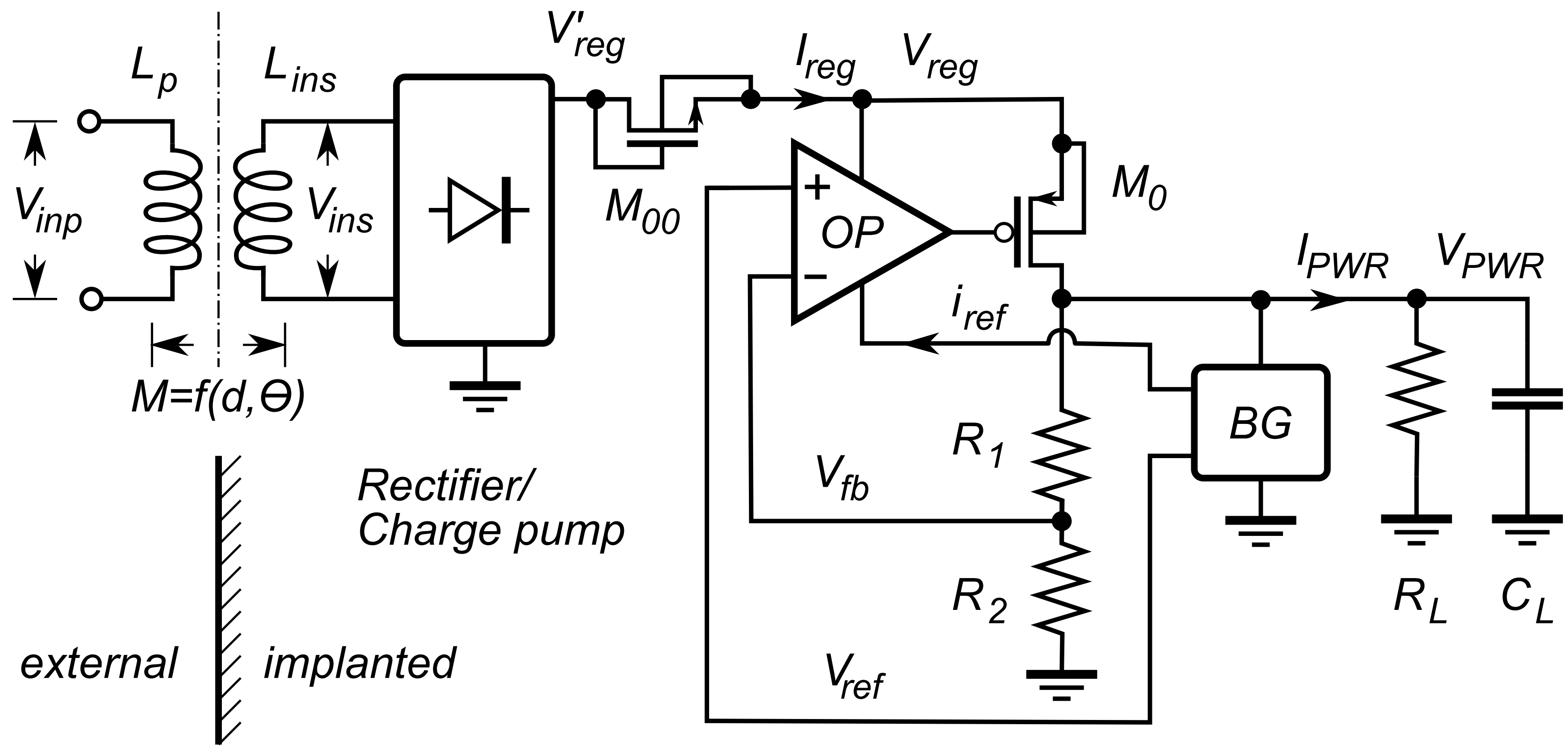
# RF energy harvesting



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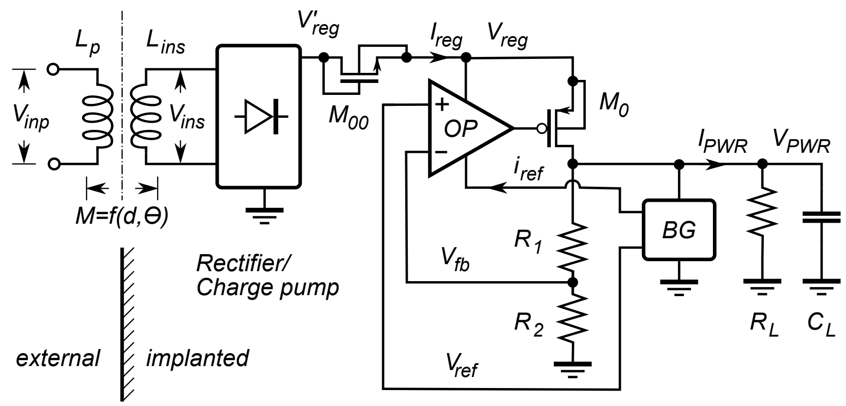
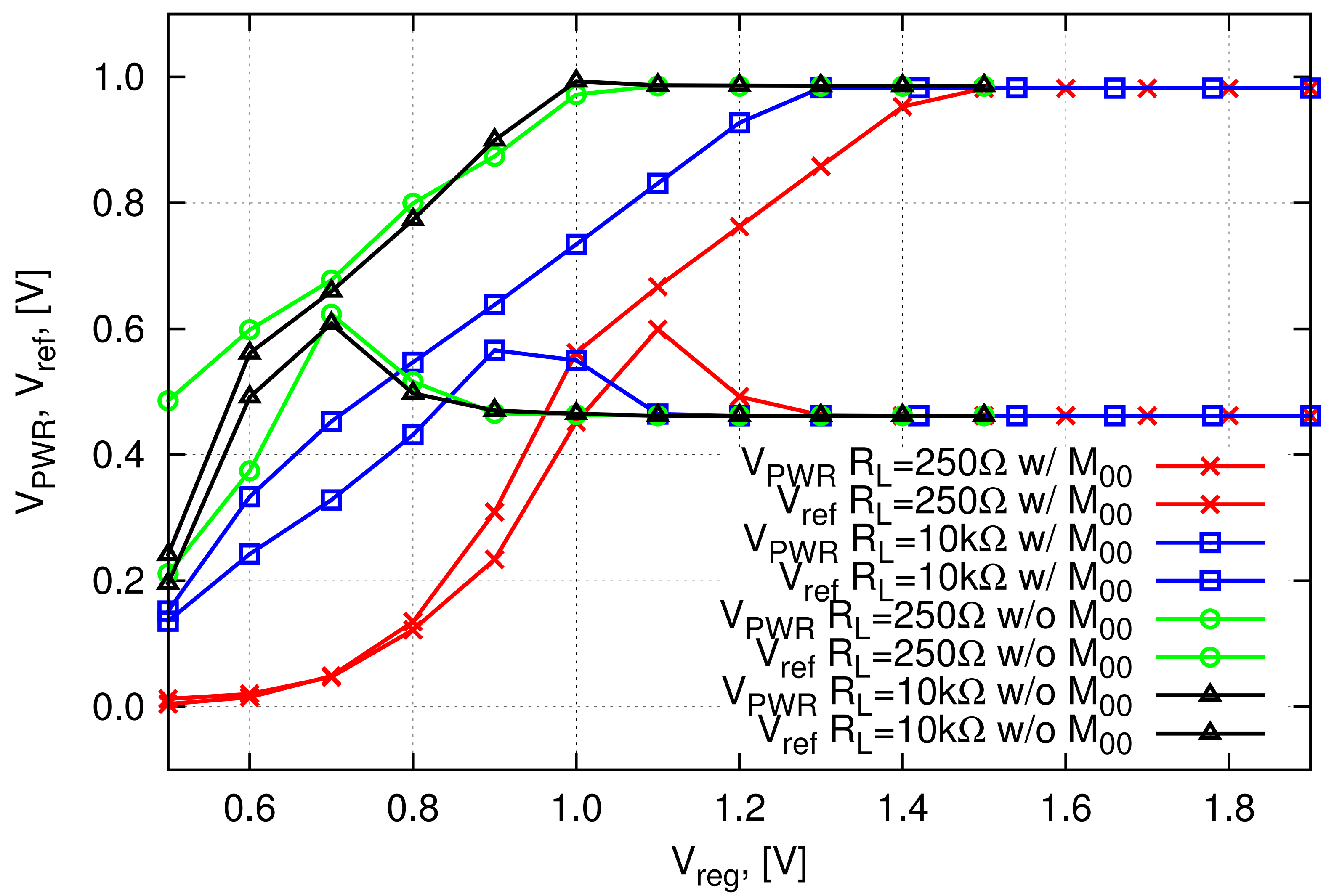
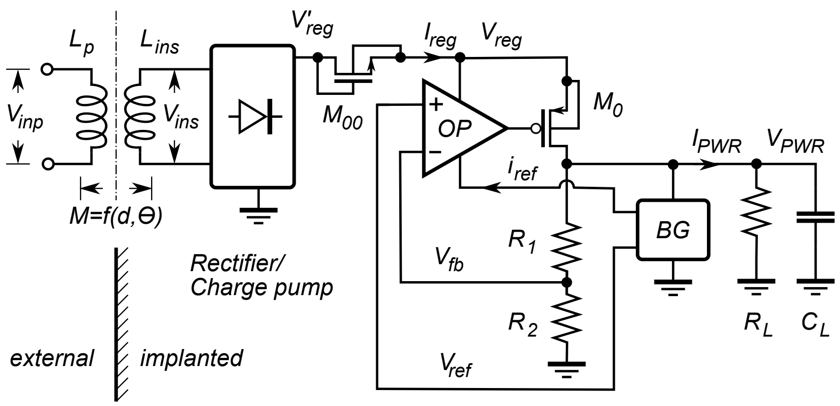


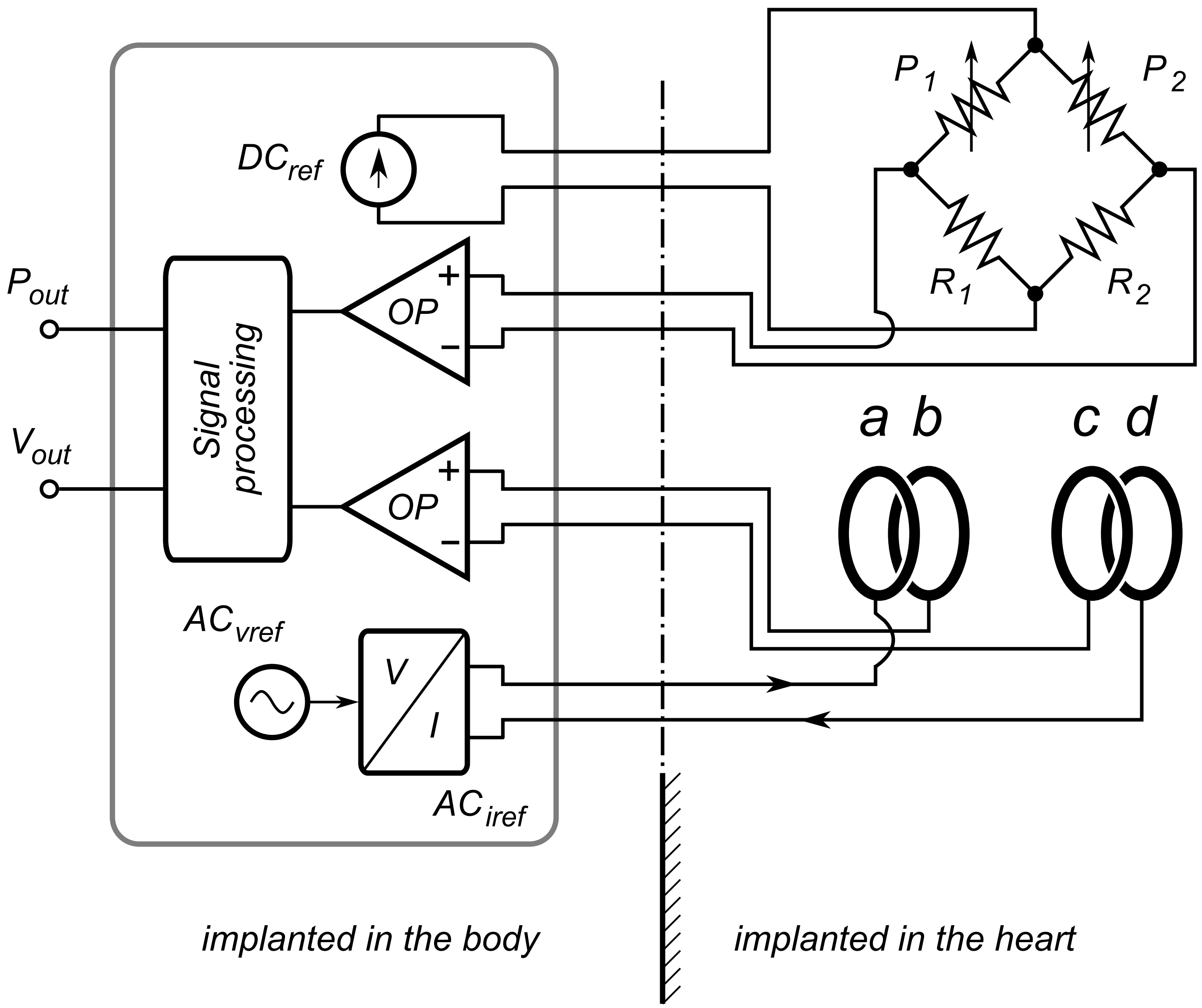
# RF energy harvesting




## Main challenges:

- Power transmission losses
- The subject's movement
- Maximum allowed power

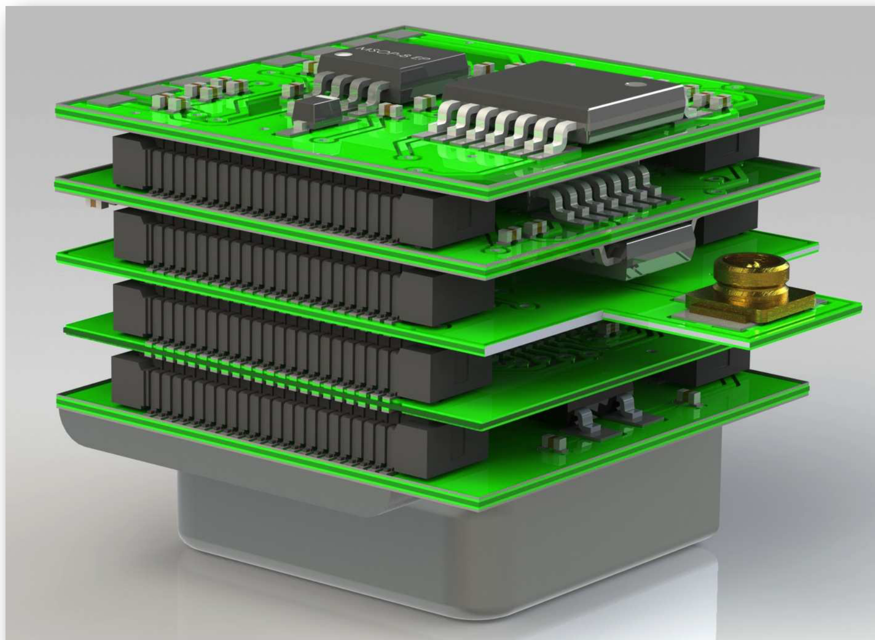
# PV sensor interface

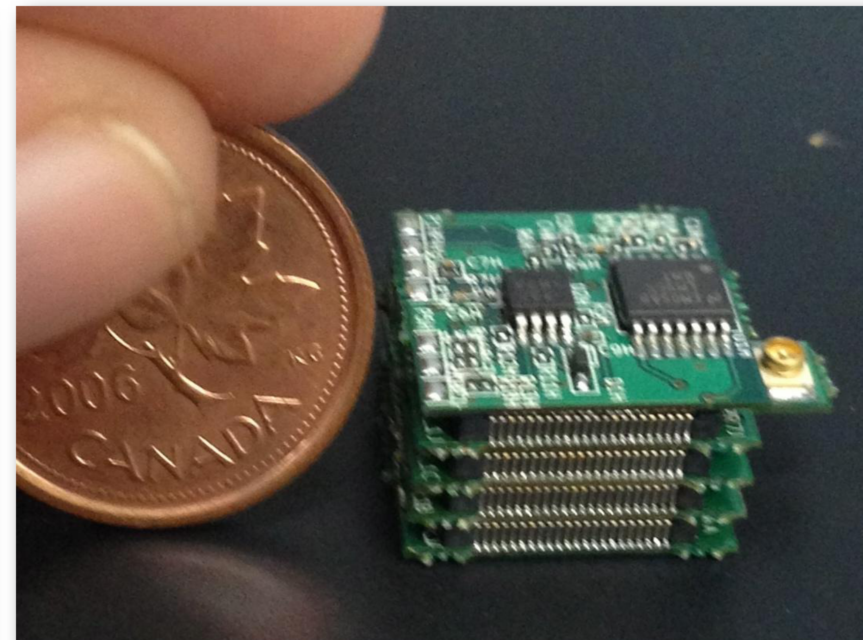


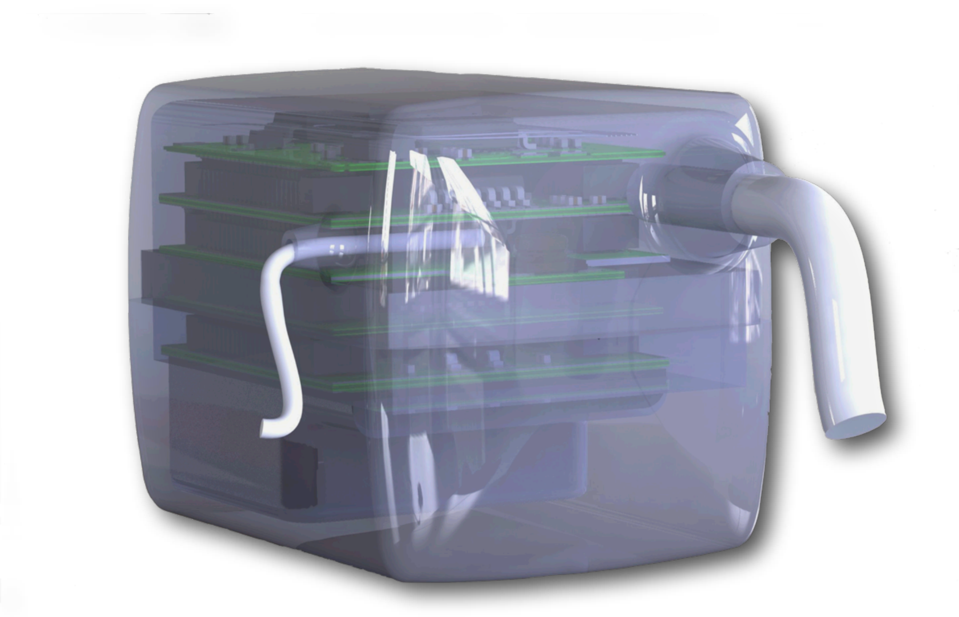

## Main challenges:

- Sensor specific
- Power consumption
- Manufacturing and packaging

# Biocompatible packaging





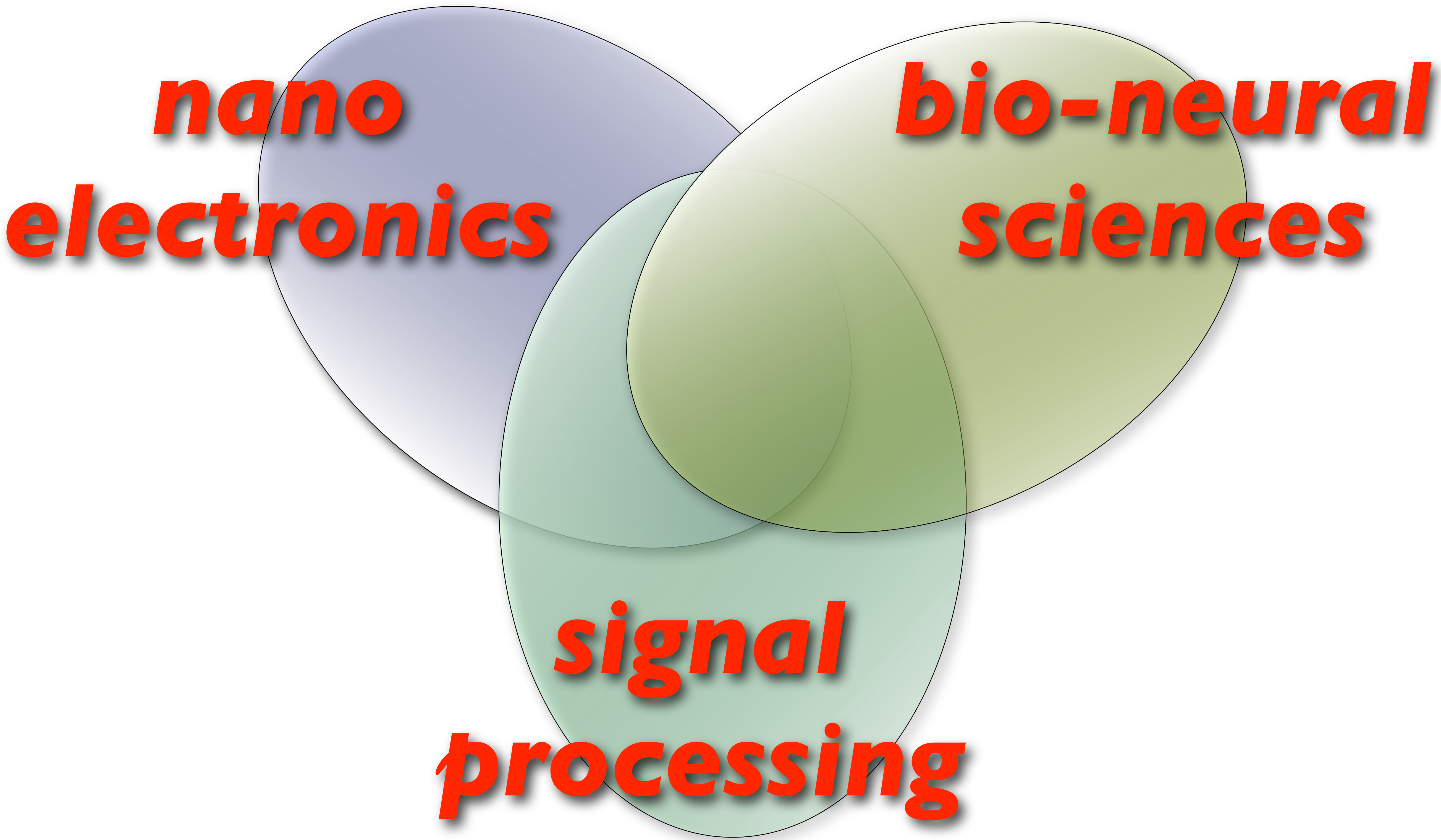



## Main challenges:

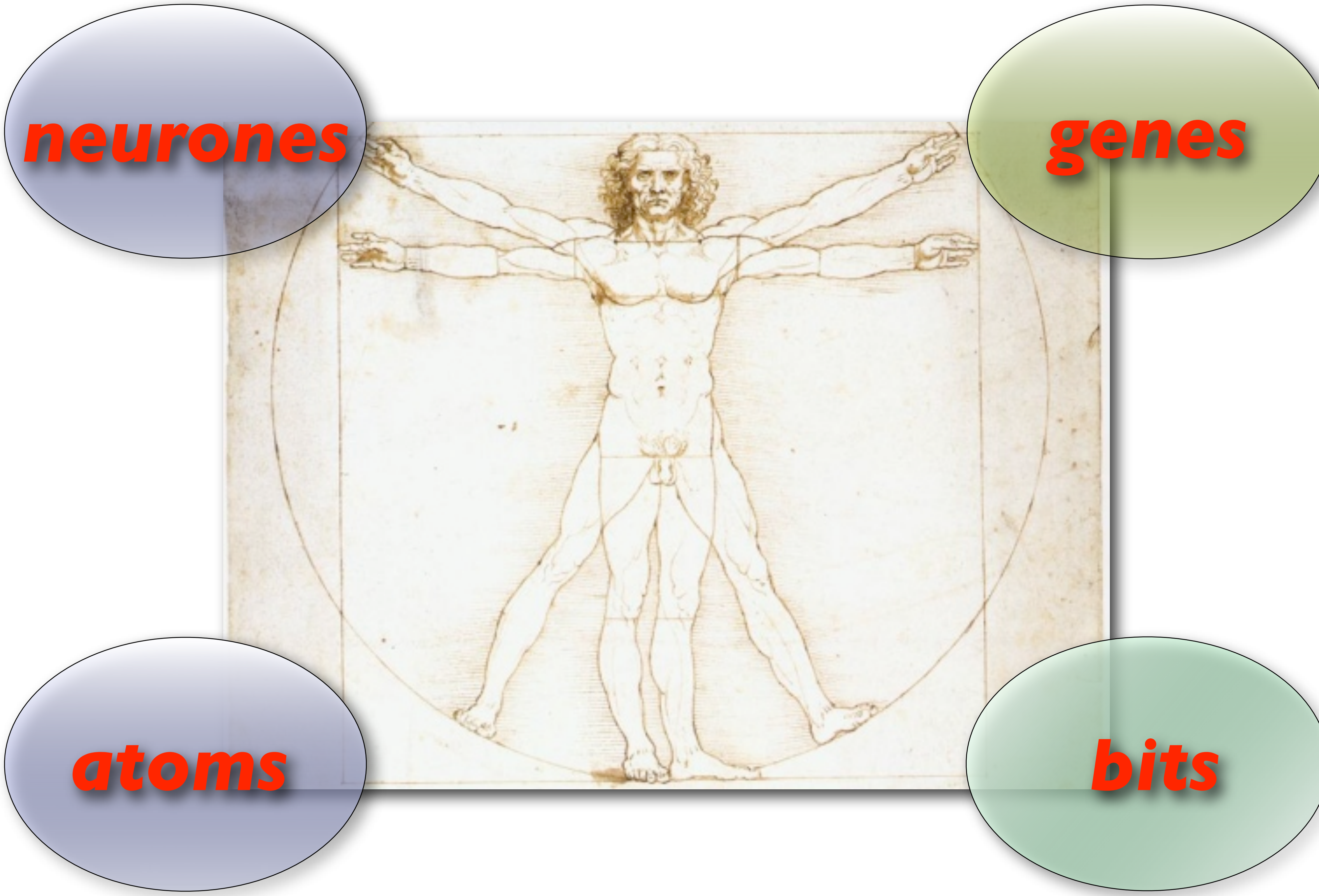
- Hostile environment
- Antenna integration
- Manufacturing
- Multidisciplinary

# Human Body and Technology

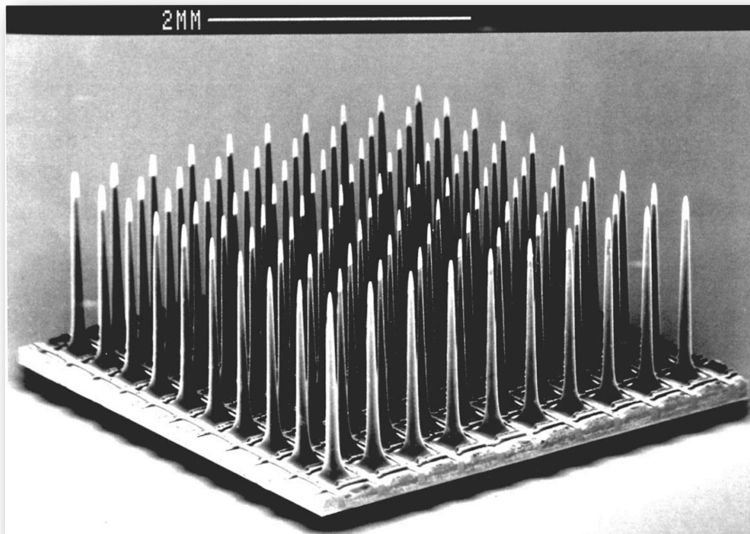
# Multidisciplinary research



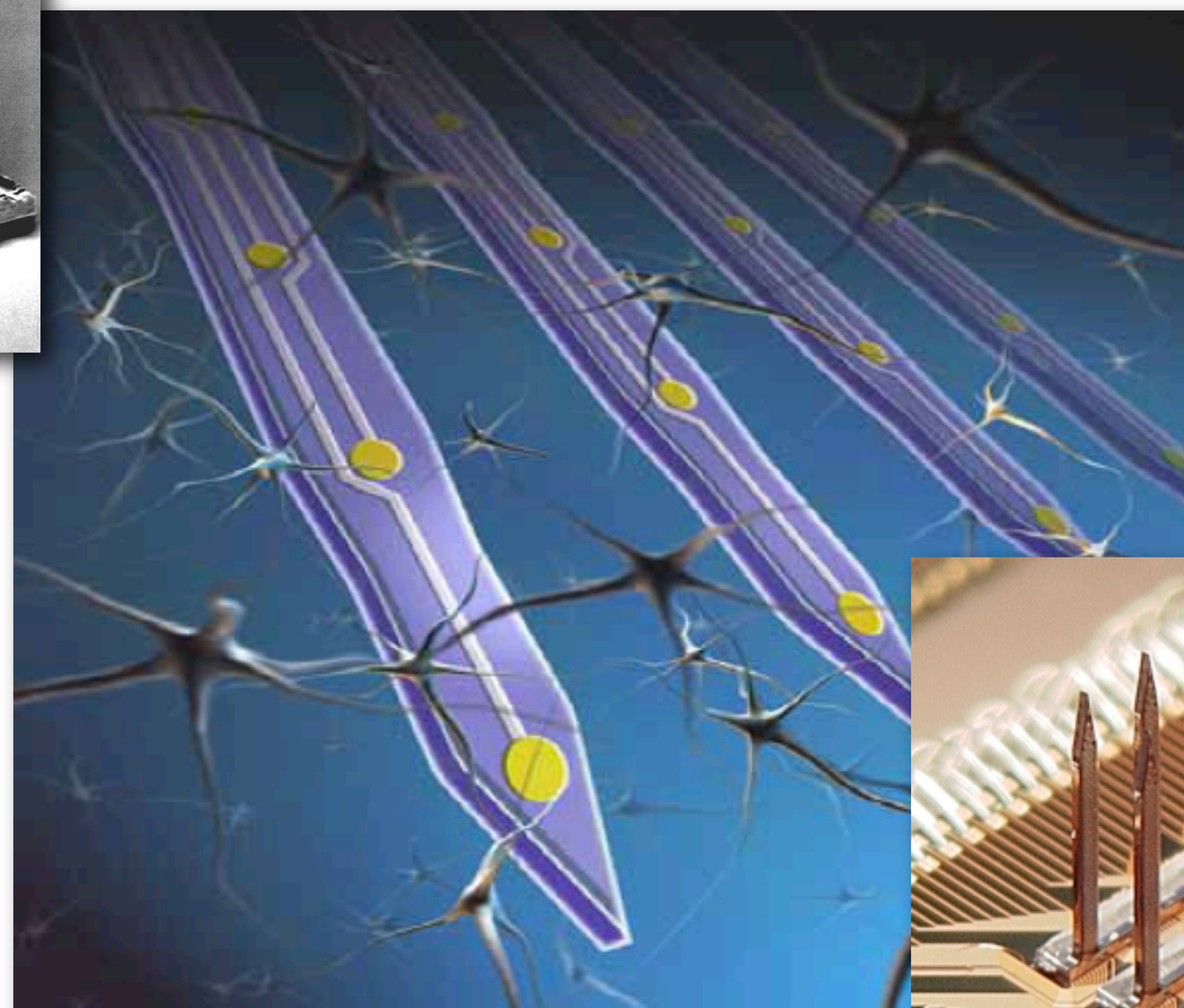
# Multidisciplinary research



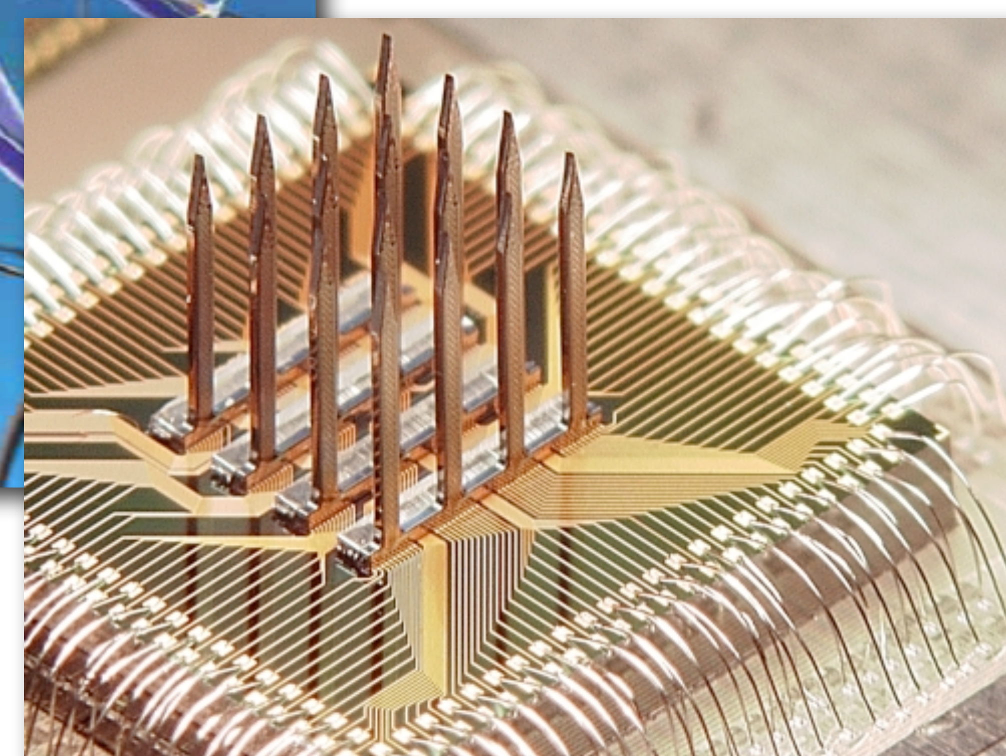
# Living to nonliving matter interface




*Utah microarray*

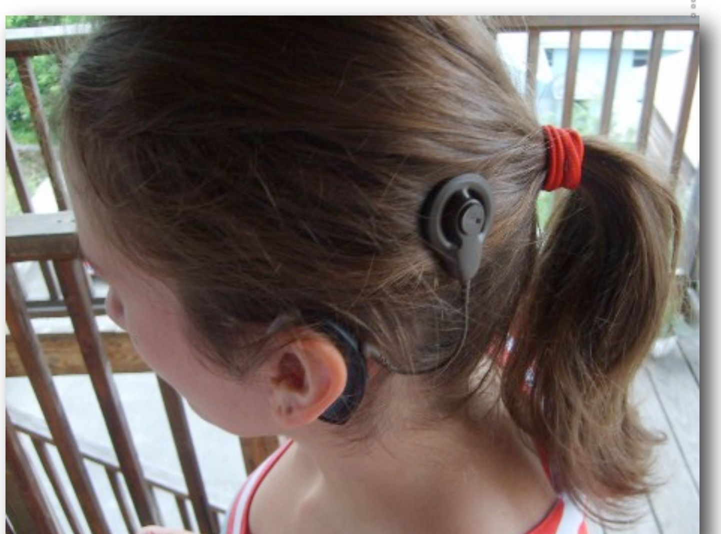


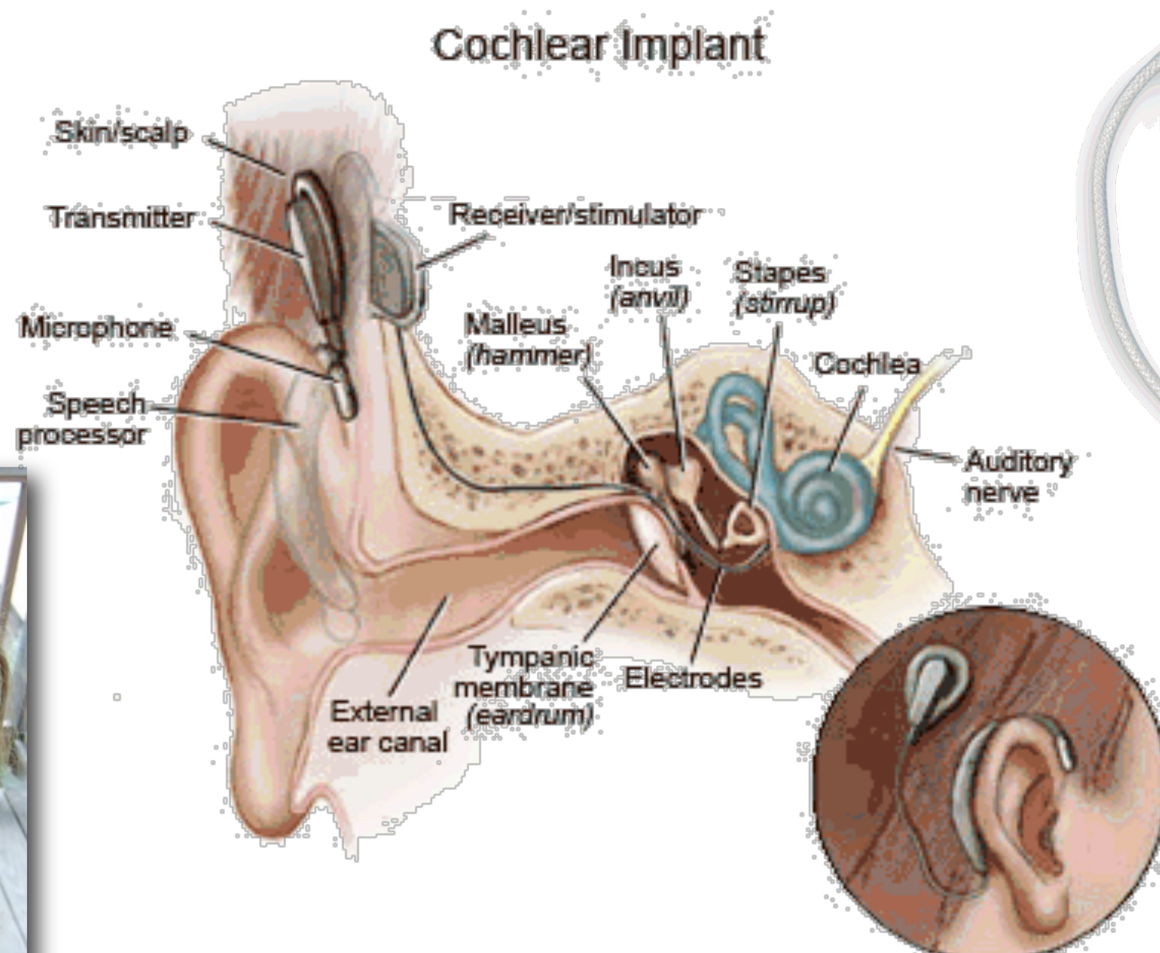
*NeuroNexus Technologies*



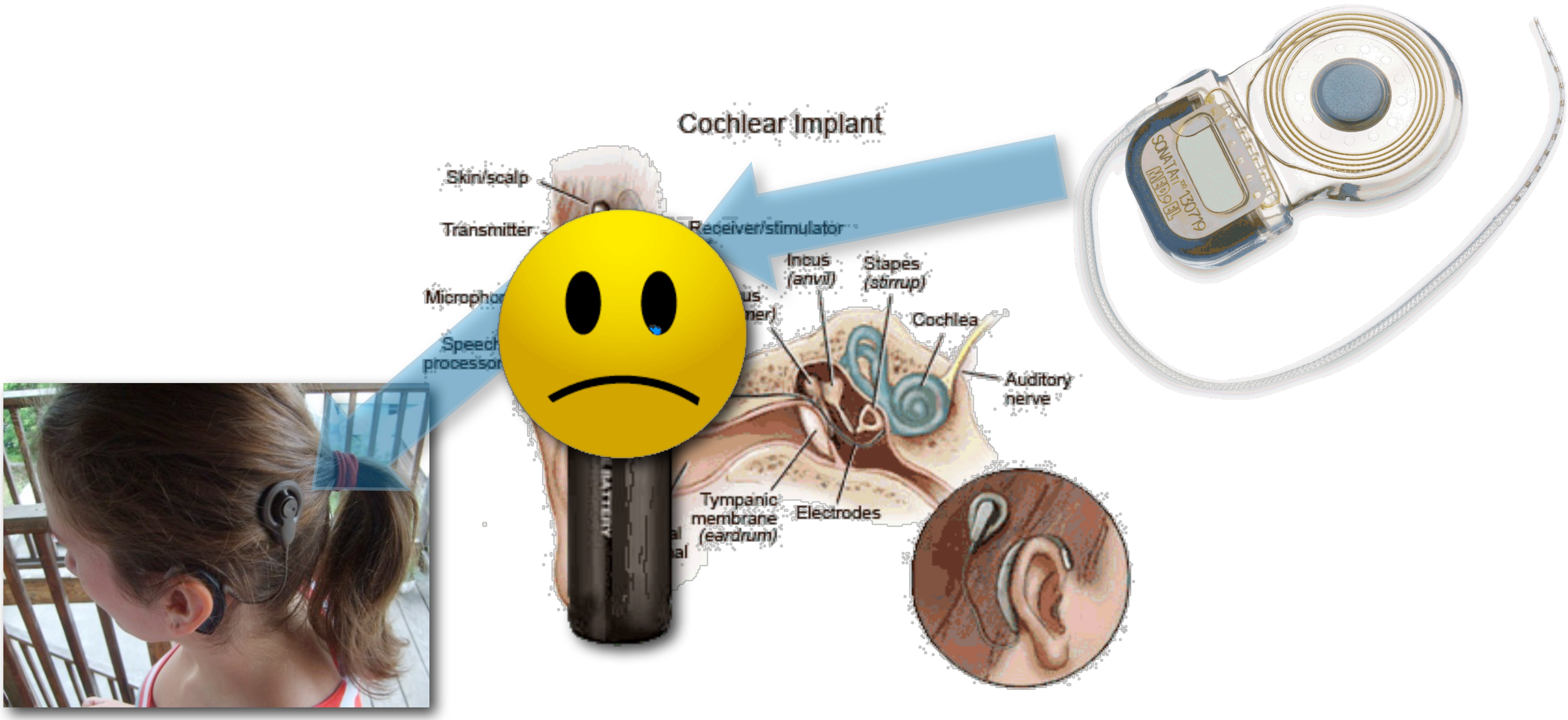
*IMEC*

# Living to nonliving matter interface

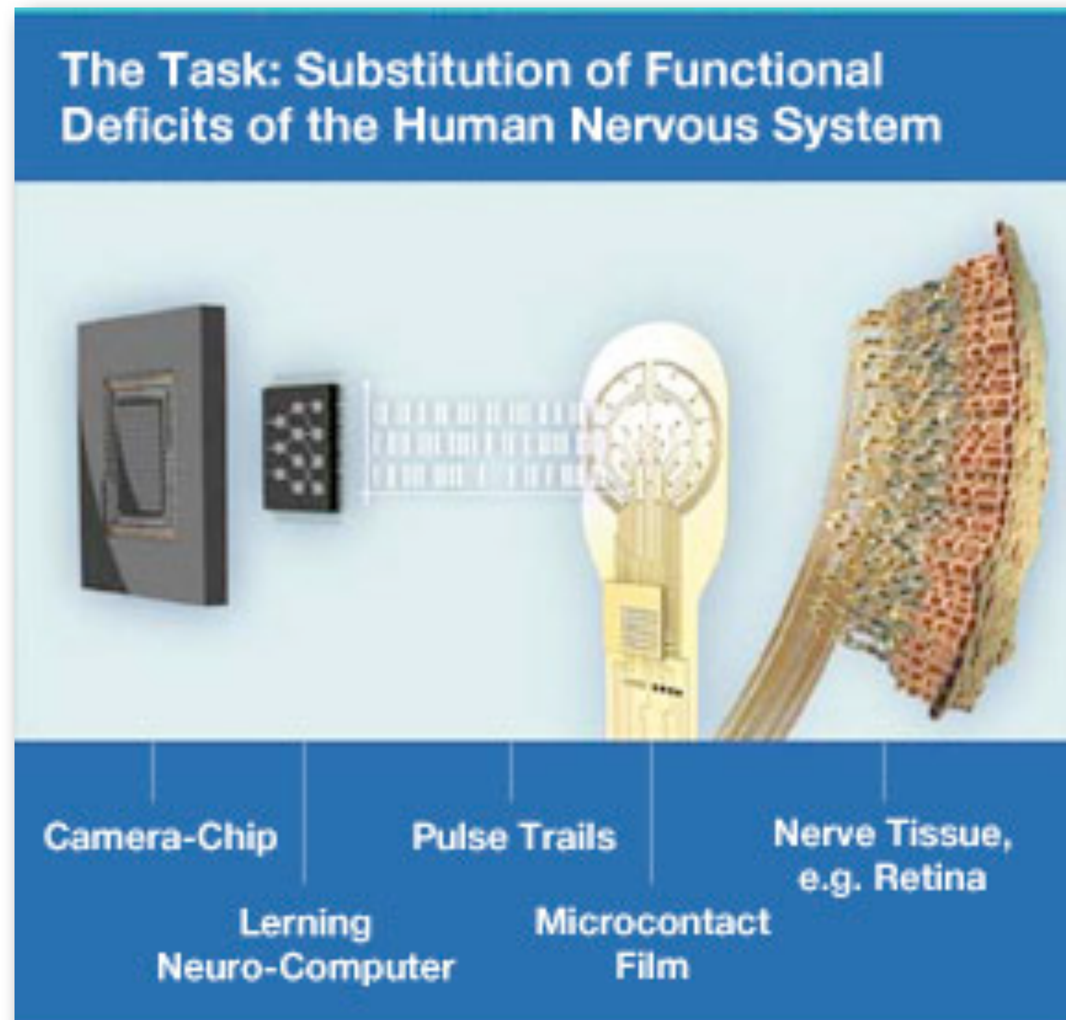





# Living to nonliving matter interface

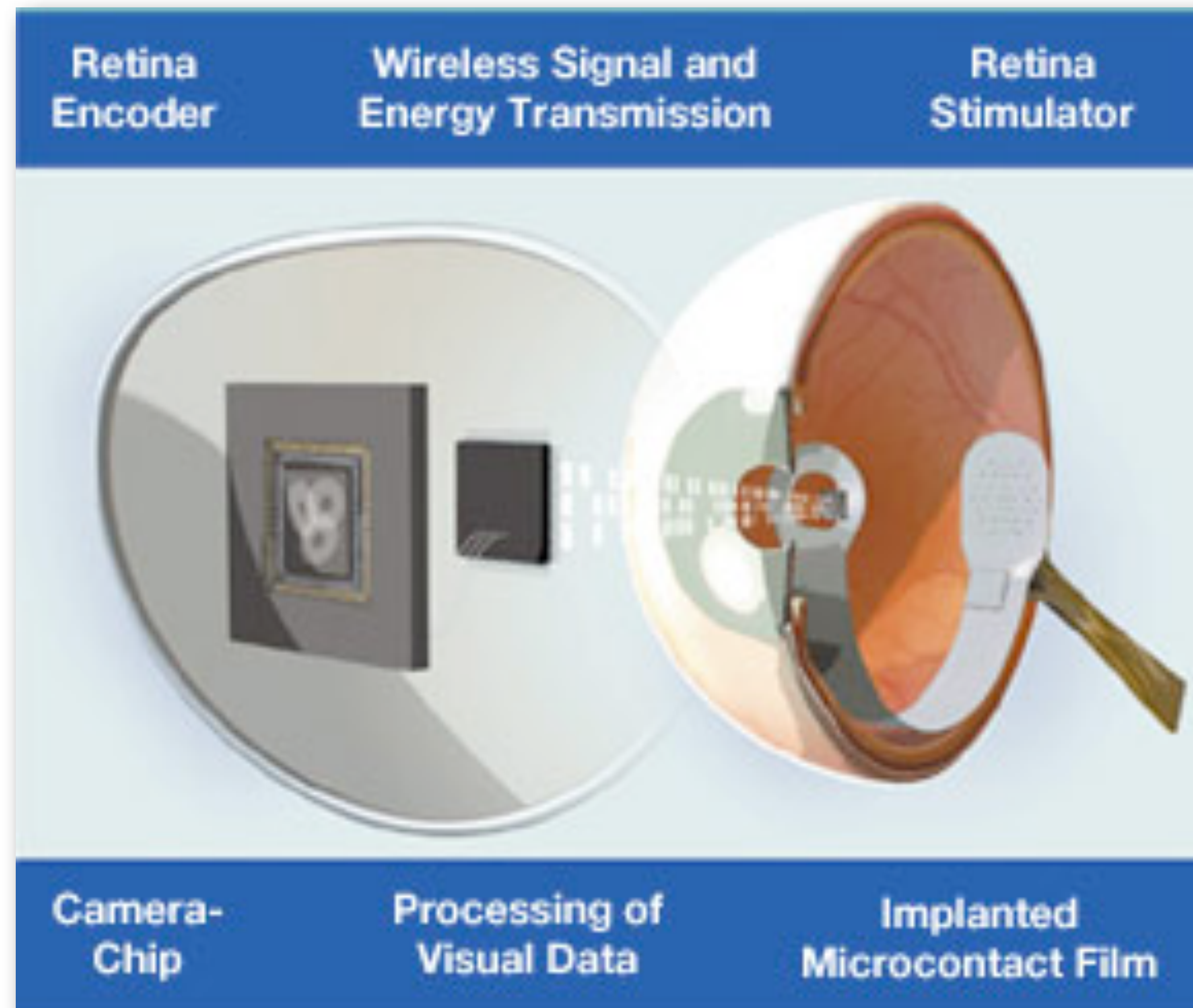


# Living to nonliving matter interface



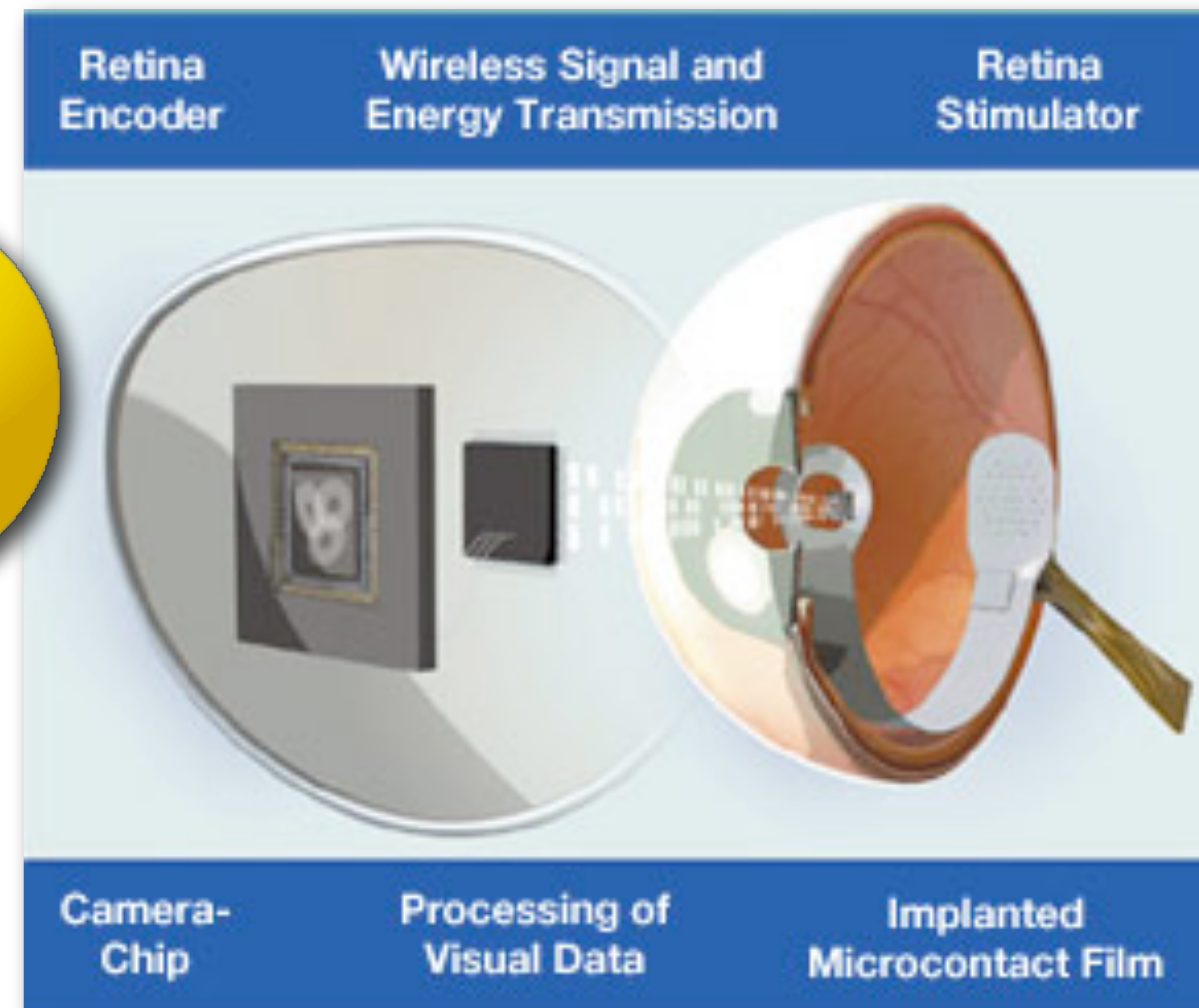

*IMI Intelligent Medical Implants*

# Living to nonliving matter interface



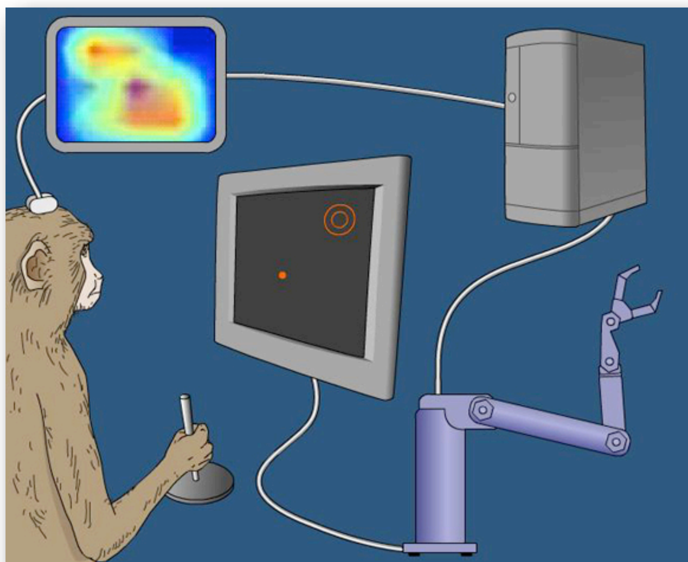

*IMI Intelligent Medical Implants*

# Living to nonliving matter interface

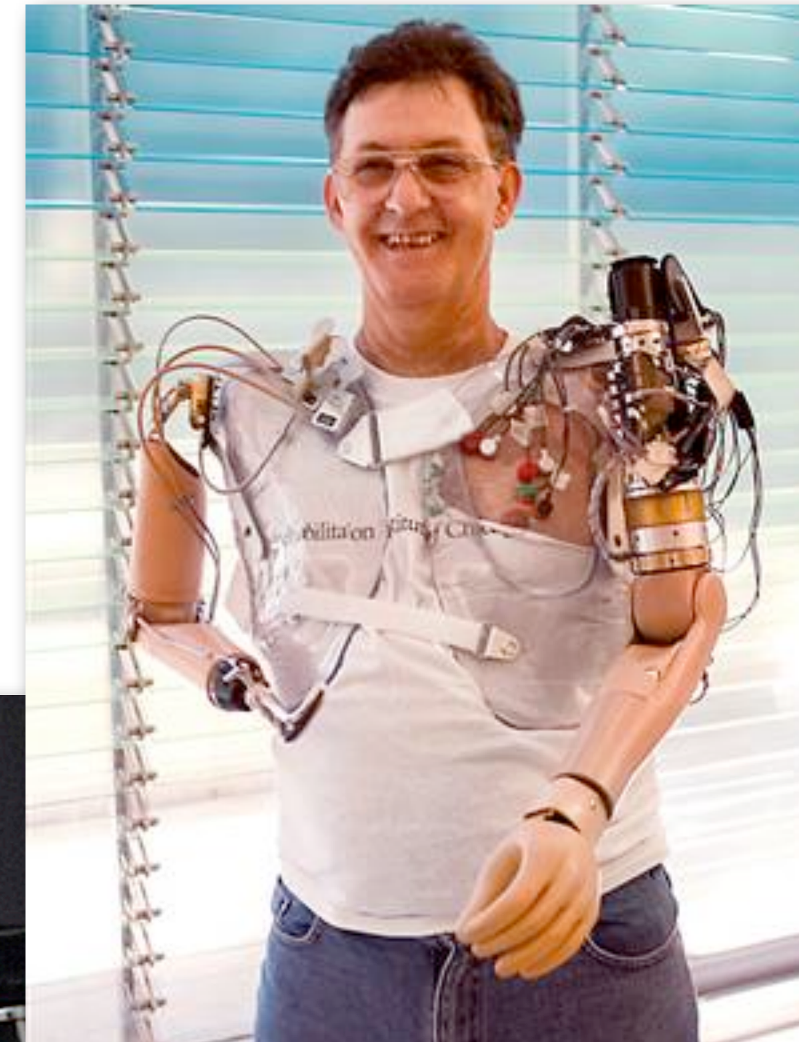



*IMI Intelligent Medical Implants*

# Living to nonliving matter interface

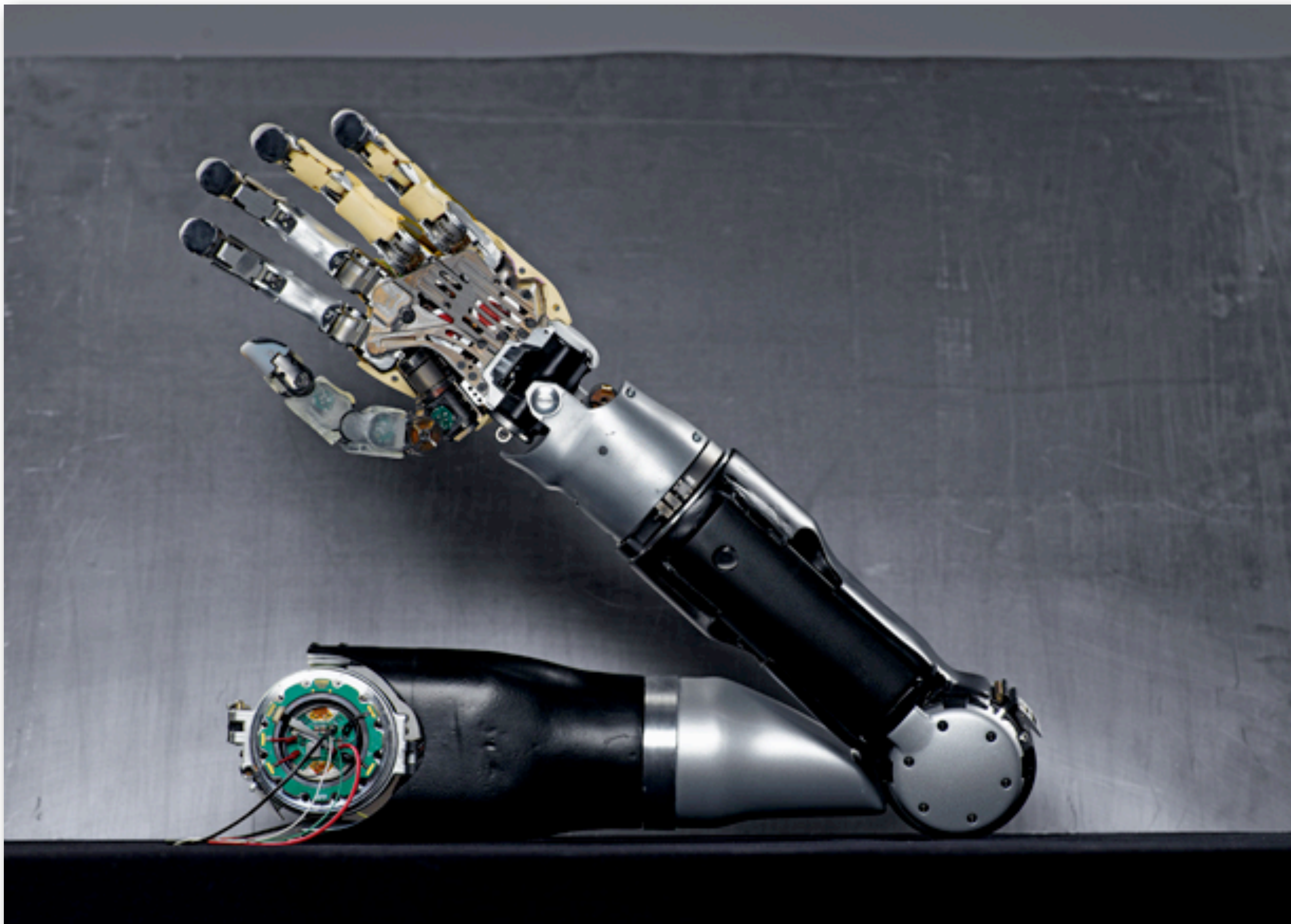


*Prof. Miguel Nicolelis, Duke University*



*Mr. Jessie Sullivan, Prof. Todd Kuiken, Northwestern Medical School, Chicago*

# Living to nonliving matter interface



# Living to nonliving matter interface

Photograph by Mark Thiessen

# Living to nonliving matter interface

Photograph by Mark Thiessen

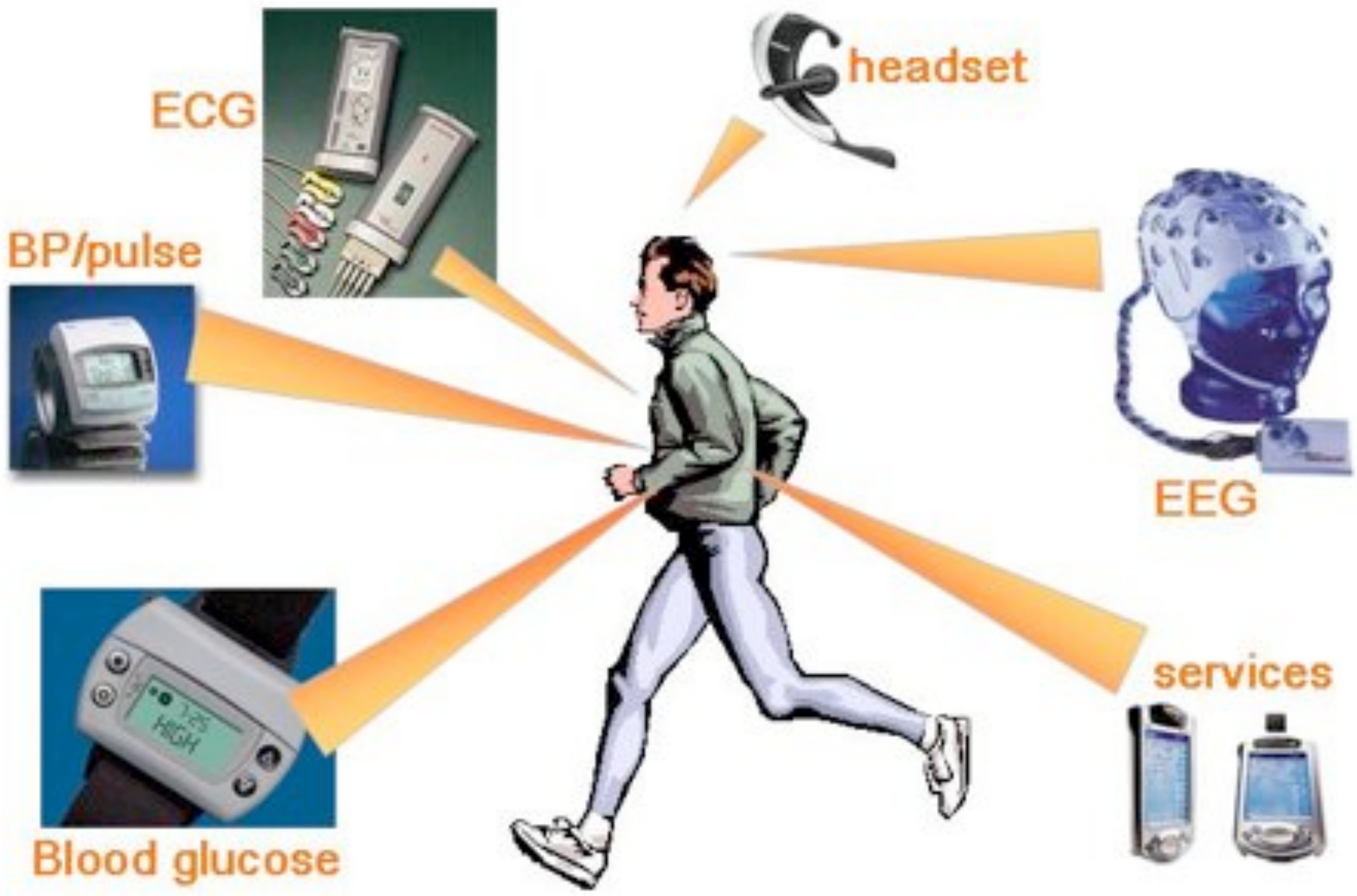
# Living to nonliving matter interface

Photograph by Mark Thiessen

# Living to nonliving matter interface

Photograph by Mark Thiessen

# eHealth



# eHealth

# eHealth


Multi-Disciplinary Team
Surgery
Primary Care
Diagnostic Labs
Specialist
Chemo/Radiation
Pharmacy
Imaging
Emergency
Home Care

# Our future anatomy?

- direct brain to sound, video, radio, and gps interface
- the inner ear language translator
- bi-directional brain to brain and machine interface
- artificial limbs, titanium skeleton, ...

# Closing comments

## Intensive research, created opportunities:

- ultra-low volume size RFIC
- processing algorithms
- 3D IC packaging
- power scavenging
- bio-battery
- heat management
- complexity
- self-repair
- ...

# Implantable Systems Laboratory

Kyle, Gail, Kyle, Kaidi, Shawon, Sneha, Sorin, and myself
(Lijun and Abdul not present)

# Our sponsors