Getting into a dialogue with the brain: Hardware, Software, Firmware, and Wetware

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Getting into a dialogue with the brain:

Why?
Basic research

Causally investigate information processing and brain dynamics…

\[ \frac{\partial}{\partial t} (\rho \, u) + \nabla \cdot (\rho \, u \otimes u) = -\nabla p + \nabla \cdot \tau + \rho \, g \]
Applications in medicine and industry: Neurotechnology

The brain

sensory information
vision, hearing, feeling

the world

touch sensors camera, microphone

neuronal states
desired interactions

computer robot arm

Brain–machine interfaces: past, present and future, Lebedev & Nicolelis 2006
Getting into a dialogue with the brain:

How?

https://de.wikipedia.org/wiki/Zuse_Z3

https://en.wikipedia.org/wiki/Neuron
IC to IC or device to device communication

Information is exchanged via complex **patterns of voltage changes / current pulses**
Neuron to neuron communication

Information is exchanged via **action potentials or spikes**
(generated by the non-linear dynamics of voltage-gated ion channels)


Interfacing neurons and electronic circuits

**Electrocorticography (ECoG)**

- **EEG**
- **Multielectrode-arrays (e.g. „Utah-Array“)**
- **Multielectrode depth probes**

[brainvision.com](http://brainvision.com)
[g-tec.at](http://g-tec.at)
[neuropixels.org](http://neuropixels.org)
[blackrockneurotech.com](http://blackrockneurotech.com)
Challenges…

…trying to talk with the brain is like trying to start a Windows app with a starter cable!
Difficulties in bi-directional communication with the brain:

→ **Scale** (…neural circuits are incredibly dense)
→ **Language** (…we do not really know how to speak „Brainish“)
→ **Connections** (…difficult to target relevant units and circuits)
→ **Reliability and durability** (…brain circuits are embedded in salty soup)
→ **Accessibility** (…invasive methods work best, but require surgery and reliable protection of the brain from electric currents and/or infections)
The situation is not hopeless…

Success stories
Helping paralyzed and handicapped persons


https://www.kurzweilai.net/how-to-control-a-robotic-arm-with-your-mind-no-implanted-electrodes-required
Helping the deaf

Cochlea implants

送到大脑的信息

https://de.wikipedia.org/wiki/Cochlea-Implantat
Deep brain stimulation

Helpful against:
- Parkinson’s disease
- Tremor
- Dystonia
- Epilepsy

Under study:
- intractable OCD
- Addiction
- Tourette syndrome
- Depression
- Alzheimer’s disease
- Pain therapy

https://www.pnas.org/doi/10.1073/pnas.1900442116
https://www.medtronic.com/de-de/fachkreise/therapien-prozeduren/neurologie-schmerztherapie/tiefe-hirnstimulation.html
Helping the blind…?

Retina prosthesis


Sending information to the brain

...yes, but...
Developing visual cortex prostheses
Visual processing in a nutshell

Visual information reaches the cortex in billions of little pieces...
...and the brain has to dynamically select and to integrate these snippets!
MTL objects, complex shapes, faces and persons

STP, MST, VIP

AIT, CIT, PIT

V2/V4

V1

...a network of recurrently coupled areas integrates information piece by piece into a coherent, global percept.

objects, complex shapes, faces and persons

simple shapes, curve segments or corners

oriented gratings, points, lines, or edges
Visual cortex prostheses for the blind

- **Wetware**
  - Lateral geniculate nucleus (LGN)

- **Hardware**
  - Camera
  - Neural implant, stimulation electrodes

- **Software**
  - Mobile computer, smartphone (translator)

- **Firmware**
  - Percept

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*Bernstein Award in Computational Neuroscience Udo Ernst*
Challenges:
How do we interface visual cortex?
How do we stimulate visual cortex?

Miss Bonnett: Image from the MRC Neurological Prostheses Unit collection (London UK) from: Lewis und Rosenfeld, *Brain Research* 2016
How do we stimulate visual cortex?

How do we stimulate (or record from…) visual cortex?

**tests in rats and mice:**

**test in monkeys:**

Challenges:
How do we talk to visual cortex?
Focusing on the essentials...

Using convolutional neural networks to segment scenes into objects and selecting behaviourally relevant parts...

https://pytorch.org/hub/ultralytics_yolov5/

Translation…
Μιλάτε „πίξελ“?
…the goal:
This is what happens if you stimulate visual cortex: phosphene percepts
This is what you will perceive…

Stimulating the brain to restore vision
Beauchamp & Yoshor 2020
How to improve the dialogue with the brain?

Increase density of electrodes…?

16 Utah arrays in a monkey!

How to improve the dialogue with the brain?

Our idea: talk to a different visual area!

- objects, complex shapes, faces and persons
- simple shapes, curve segments or corners
- oriented gratings, points, lines, or edges
Spelling with shapes and curve segments

stimulate area V4!

the "dictionary" of area V4:

Passpathy et al., Nature Neuroscience 2002
How to improve the dialogue with the brain?

Listen to what it is currently doing, and bide the right moment!

...push the neurons over threshold when they are about to fire!

unpublished data, mouse cortex, Jancke lab Bochum University
This is how it could work one day…

Demonstrator setup by Jimin Roh.
This is how it could work one day…
1. Complete mapping

2. Listen and stimulate

Human psychophysics
(Prof. Dr. Michael Herzog,
Lausanne, Switzerland)

Monkey electrophysiology
(Prof. Dr. Chris Pack,
Montreal, Canada)

Human functional imaging
(Prof. Dr. Bogdan Draganski,
Lausanne, Switzerland)

Optical imaging in mice
(PD Dirk Jancke,
Bochum, Germany)
Challenges
Simultaneous stimulation and recording

ITEM - Theoretical Electrical Engineering and Microelectronics, Cognitive Neurophysiology,
IMSAS - Microsensors, -actuators und -systems, Theoretical Neurophysics

Rotermund, Ernst, Pawelzik, Hardware X (2019)

Osipov, Strokov, Kreiter, Schander, Tessmann, Lang, Paul,
Wireless implants

Implications for a Wireless, External Device System to Study Electrocorticography

*Sensors 2017, 17*(4), 761;

https://doi.org/10.3390/s17040761
The Muskian approach…
Neuralink

https://neuralink.com/approach/
From currents to light pulses: optogenetics


Image by Lisa Berg, Synthetic Biology lab (Prof. Dr. O. Masseck, Bremen)
Observing individual neurons: Two-photon calcium imaging

GECI: genetically encoded calcium indicators (e.g. GCaMP) make neural activity visible...

State-of-the art mobile setup:
Zong et al., 2022, Cell 185, 1240–1256
Our big prosthetic family!

- David Rotermund
- Klaus Pawelzik
- Alberto Garcia-Ortiz
- Andreas Schander
- Walter Lang
- Chris Pack
- Dirk Jancke
- Bogdan Draganski
- Michael Herzog