Flexible and Stretchable Organic Artificial Nerves

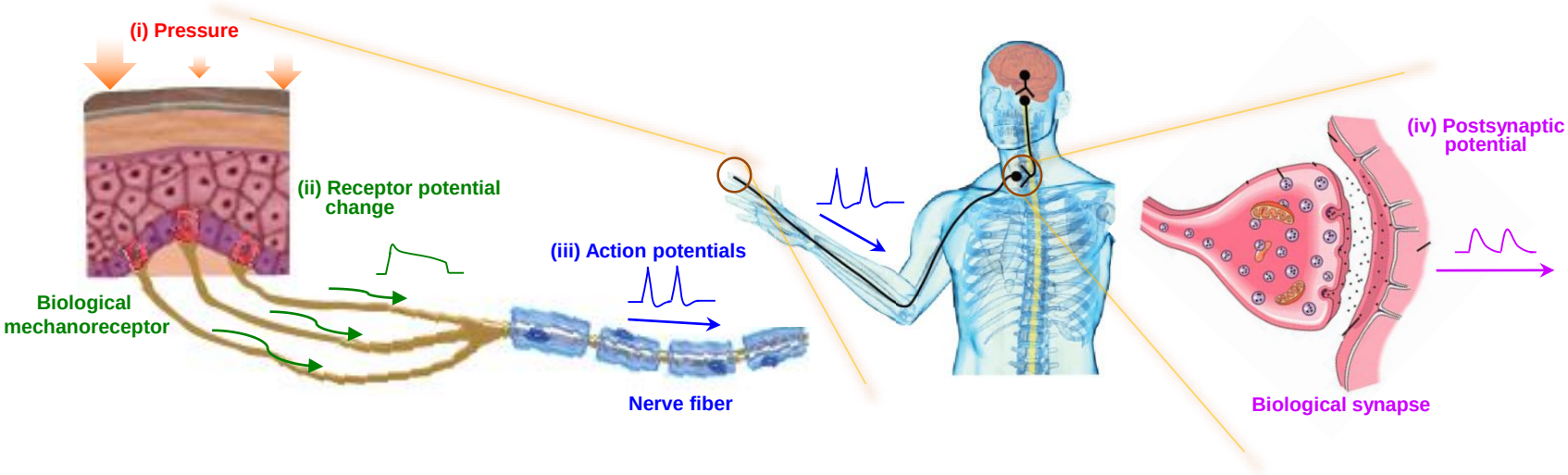
Tae-Woo Lee (李泰雨)

Dept. of Materials Science and Engineering
Seoul National University
(e-mail: twlees@snu.ac.kr)

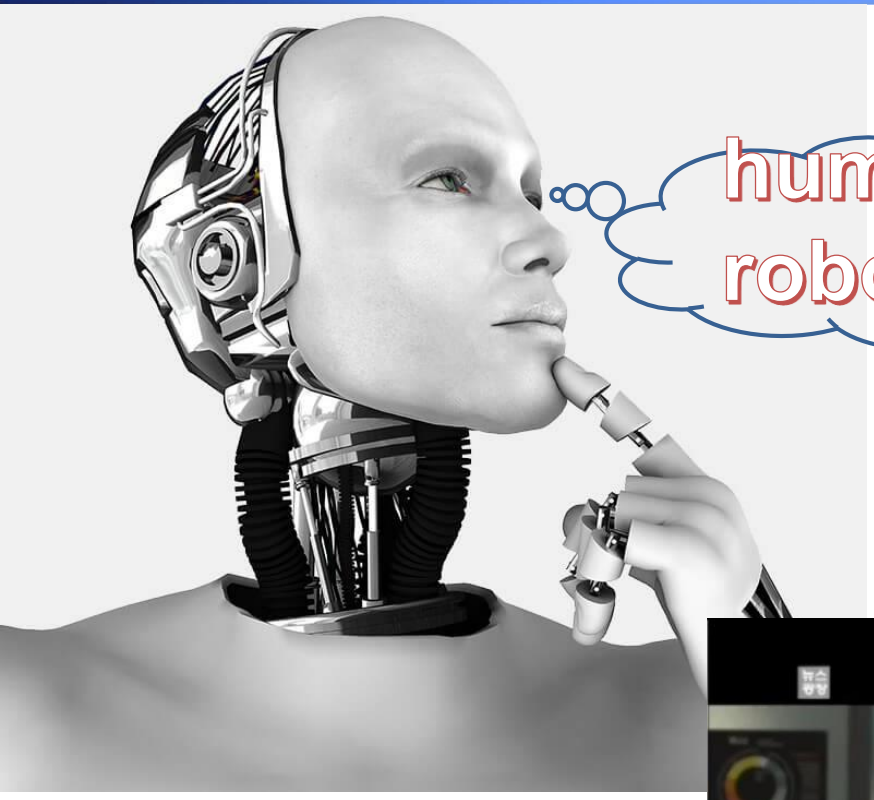
Contents

Bio-inspired systems for engineering devices

- Biological systems can inspire new generations of engineering devices.
- In our body, sensory, neural, and motor processing tasks are done extremely efficiently and robustly with extremely low energy consumption, in very little volumes
- The entire brain and body are put together with energy-efficient neurons and cells to robustly perform complex information-processing tasks.
- One can learn a lot of things from biology to develop efficient technologies, to learn to architect systems that can perform efficiently and reliably with unreliable devices, to build systems that automatically learn and adapt to a changing environment.

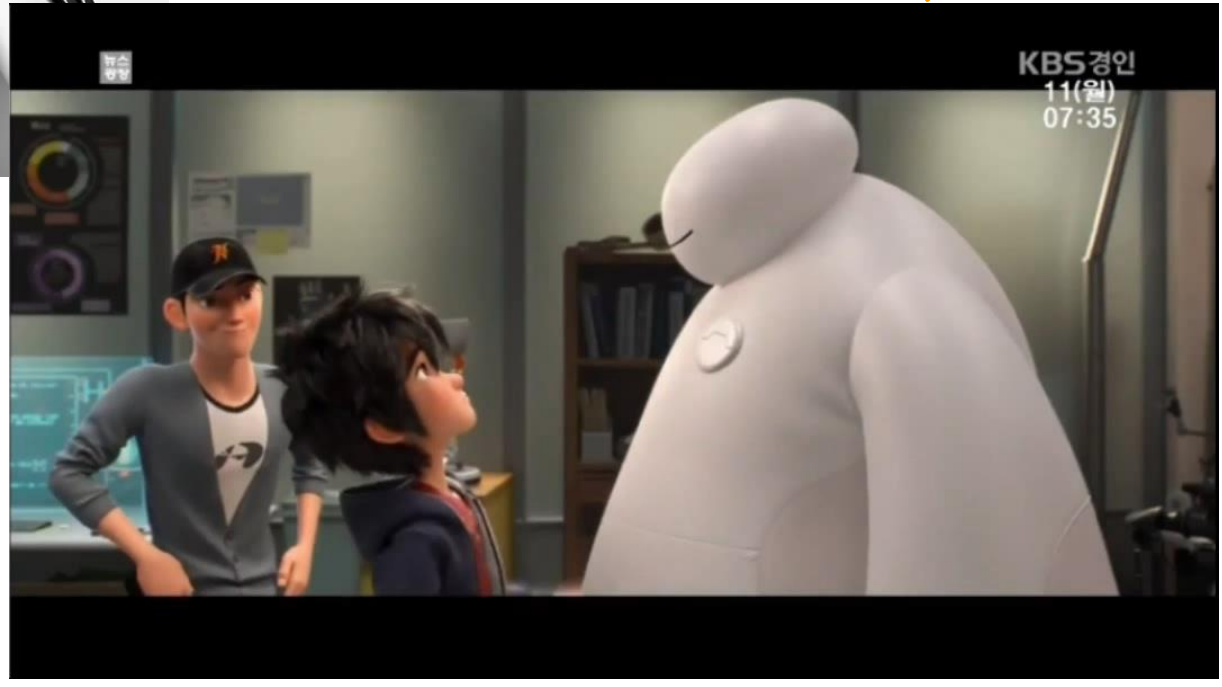


Bio-inspired electronics & soft robotics



Humanoid robots

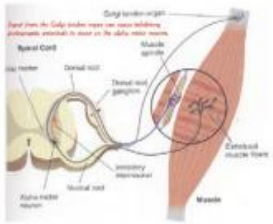
- Shape like human
- Move like human
- Sense like human
- Think like human



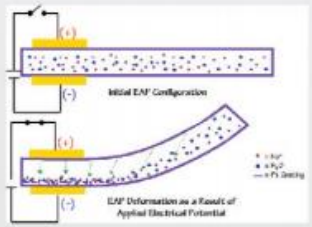
Bio-inspired soft electronics and robots

✓ **Bio-inspired electronics and robotics moves/senses/thinks like a human**

a. Muscle-tendon complex

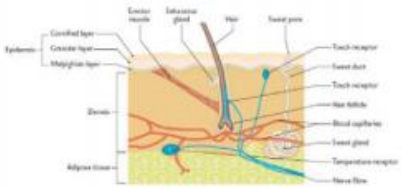


Pneumatic actuators

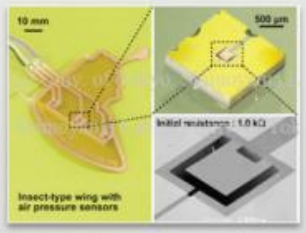


Electro-active polymer

b. Skin sensors

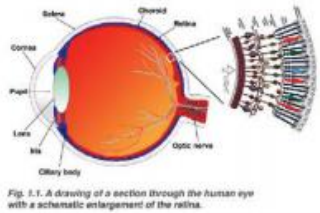


Artificial skin sensors

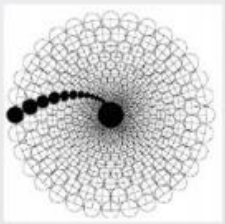


MEMS Pressure Sensor

c. Retina



Analog computing in artificial retina



Log-polar distribution of photoreceptors

d. Computing units

Graphical computing units

Distributed robot network

Artificial Muscle Motor system

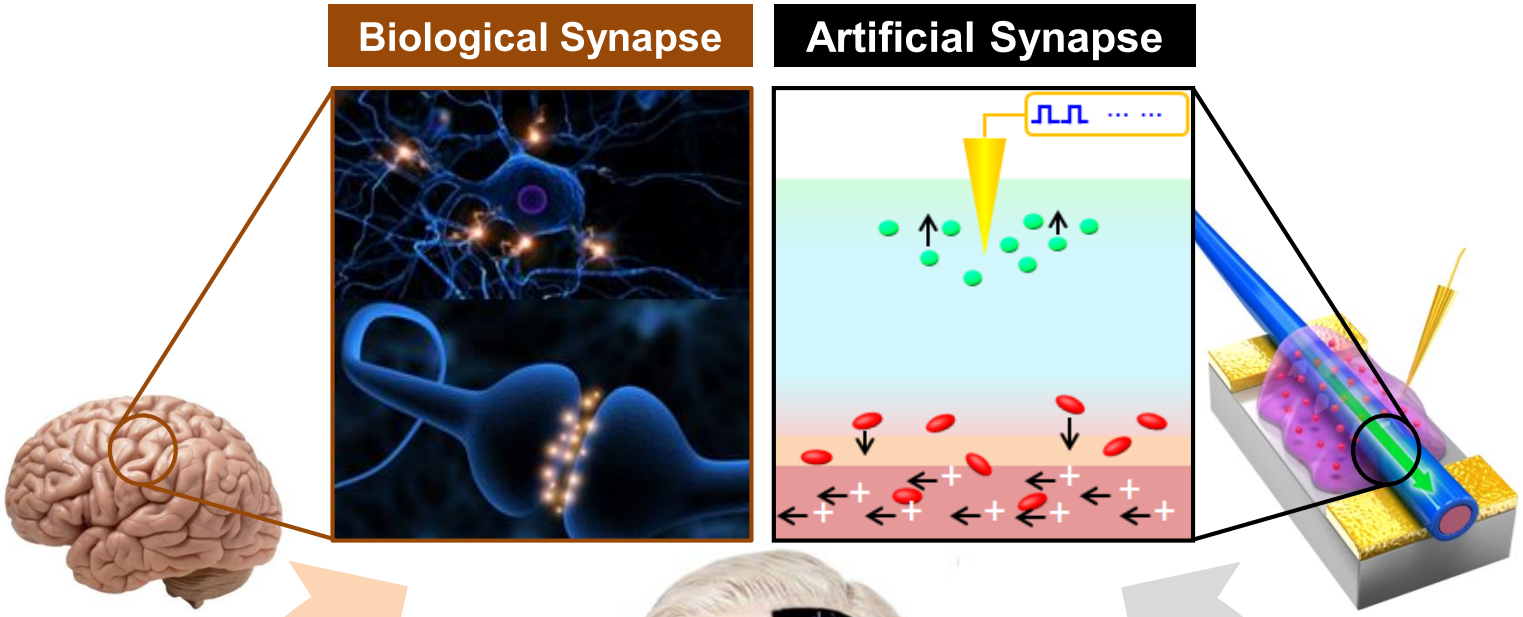
Electronic Skin & Sensors

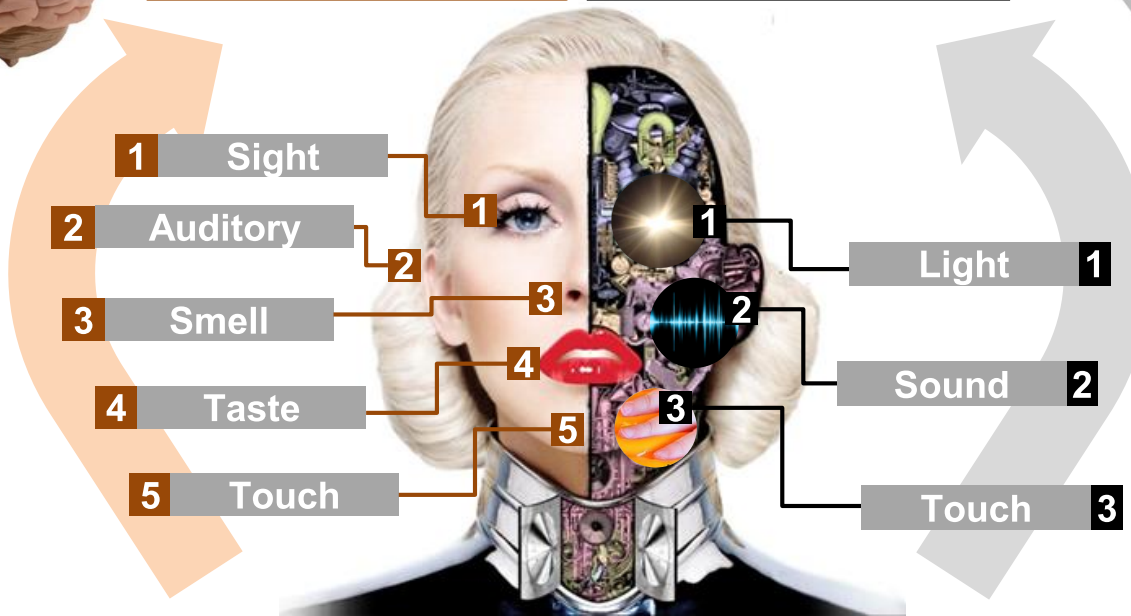
Neuromorphic Artificial Nerves

Communications of the ACM, **2012**, 55, 76-87

Our Research Direction in Flexible Electronics (Tae-Woo Lee's Group)

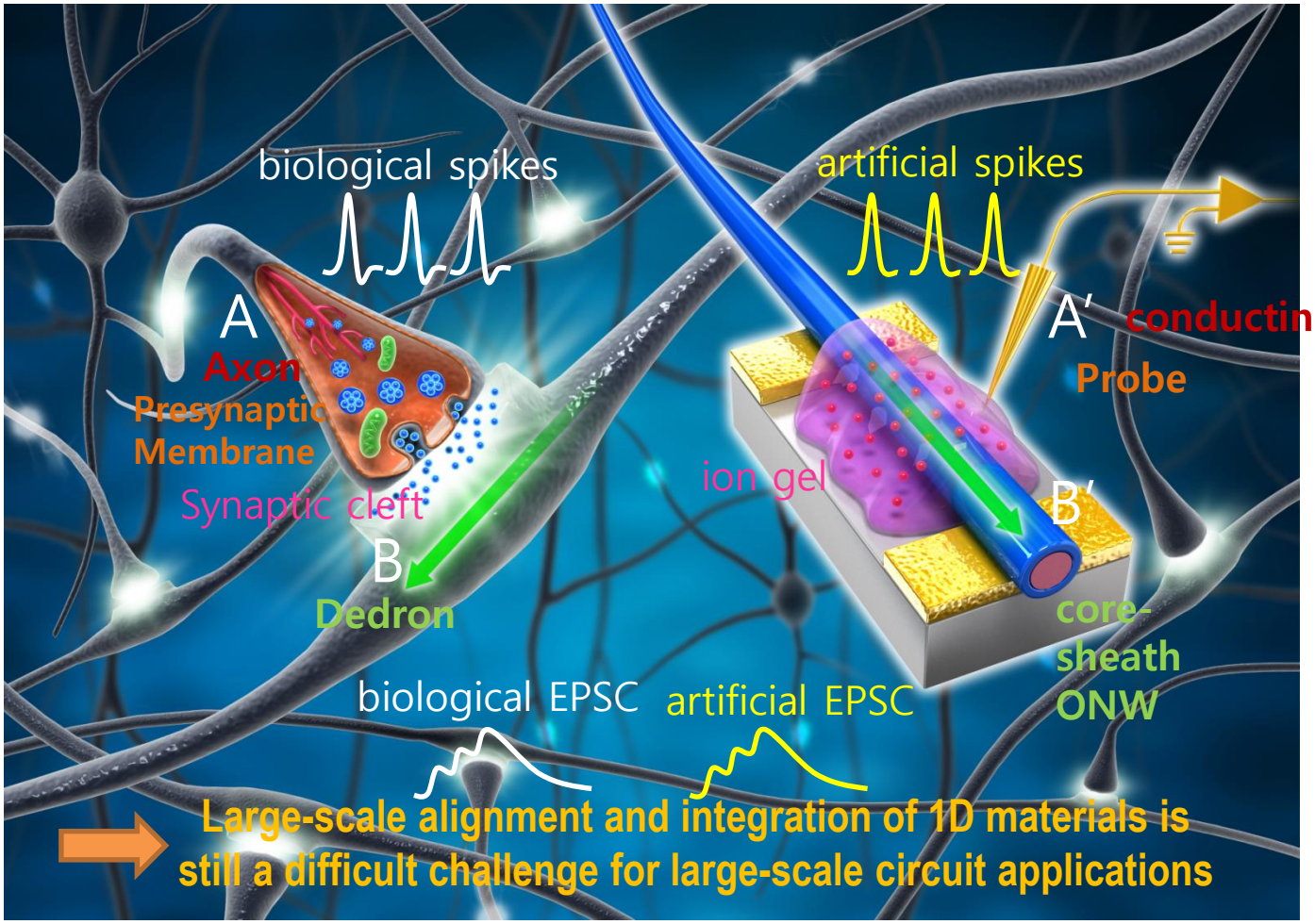
Neuro-inspired Organic Artificial Sensory Nerves





Organic Nanowire Synapses

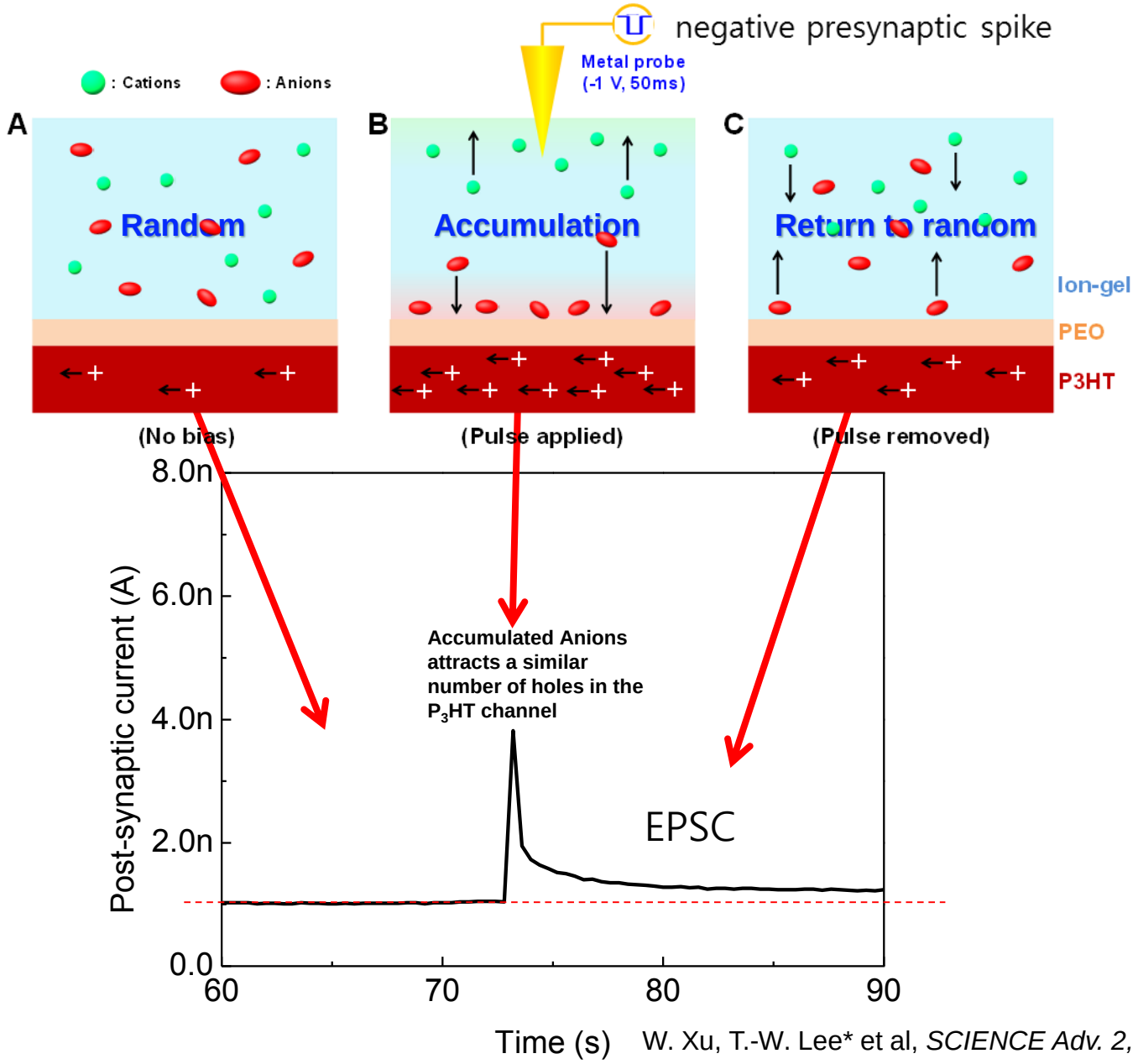
✓**ONW synaptic transistor that emulates a biological synapse not only in morphology, but also in important working principles.**



- The conductive lines and probe (A′) mimic an axon (A) that deliver presynaptic spikes from a preneuron to the presynaptic membrane.
- An ONW (B′) mimics a biological dendron (B) in which an EPSC is generated in response to presynaptic spikes and is delivered to a postneuron.

ONW Synaptic transistors (Short term potentiation)

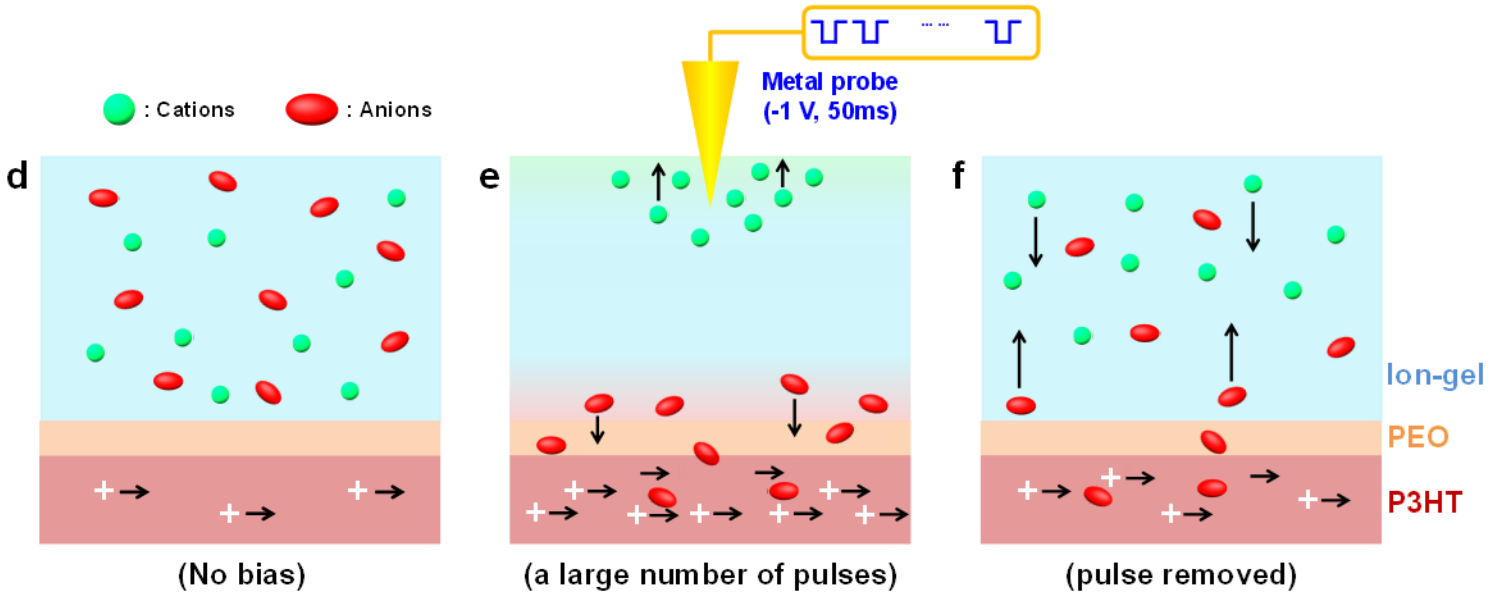
STP



W. Xu, T.-W. Lee* et al, *SCIENCE Adv. 2, e1501326 (2016)*

Schematic of the working mechanism of ONW ST for long-term plasticity

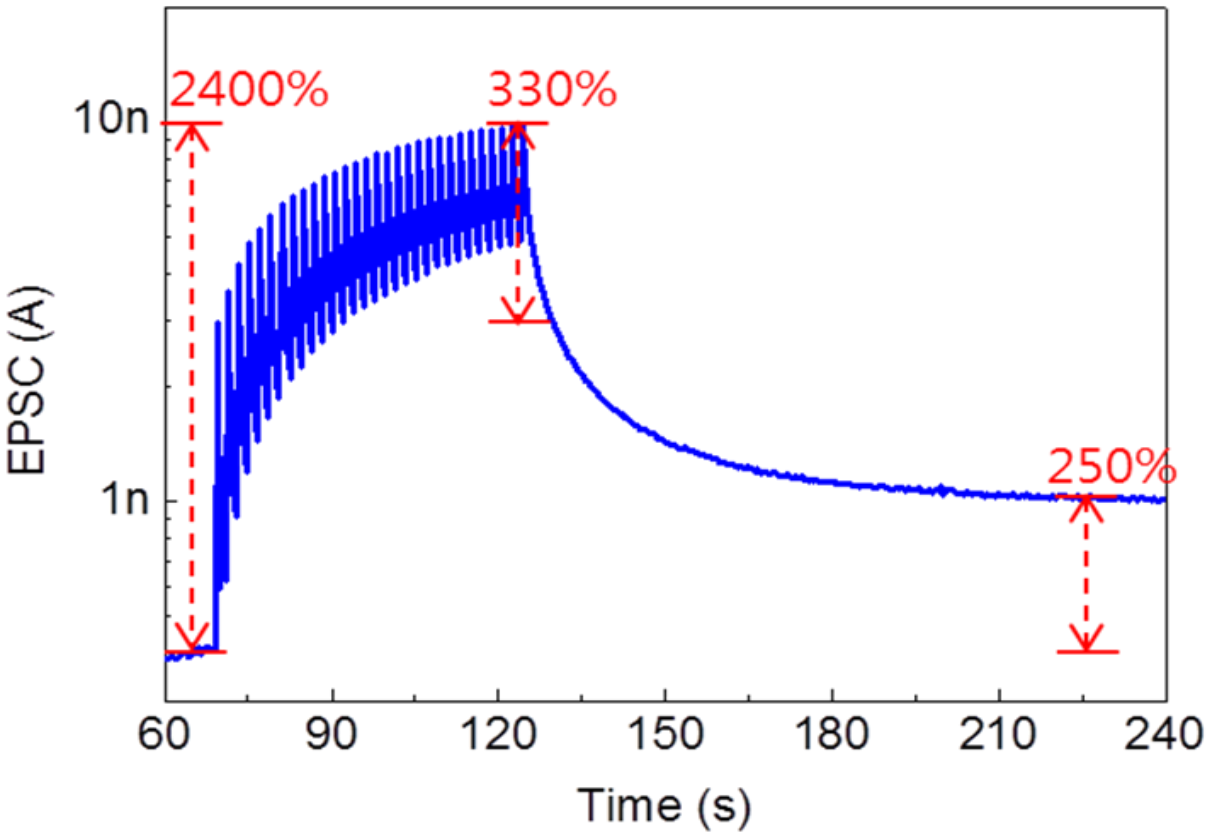
LTP



The spontaneous release of the trapped anions in the ONW is slow, inducing long-term memory.

ONW Synaptic transistors

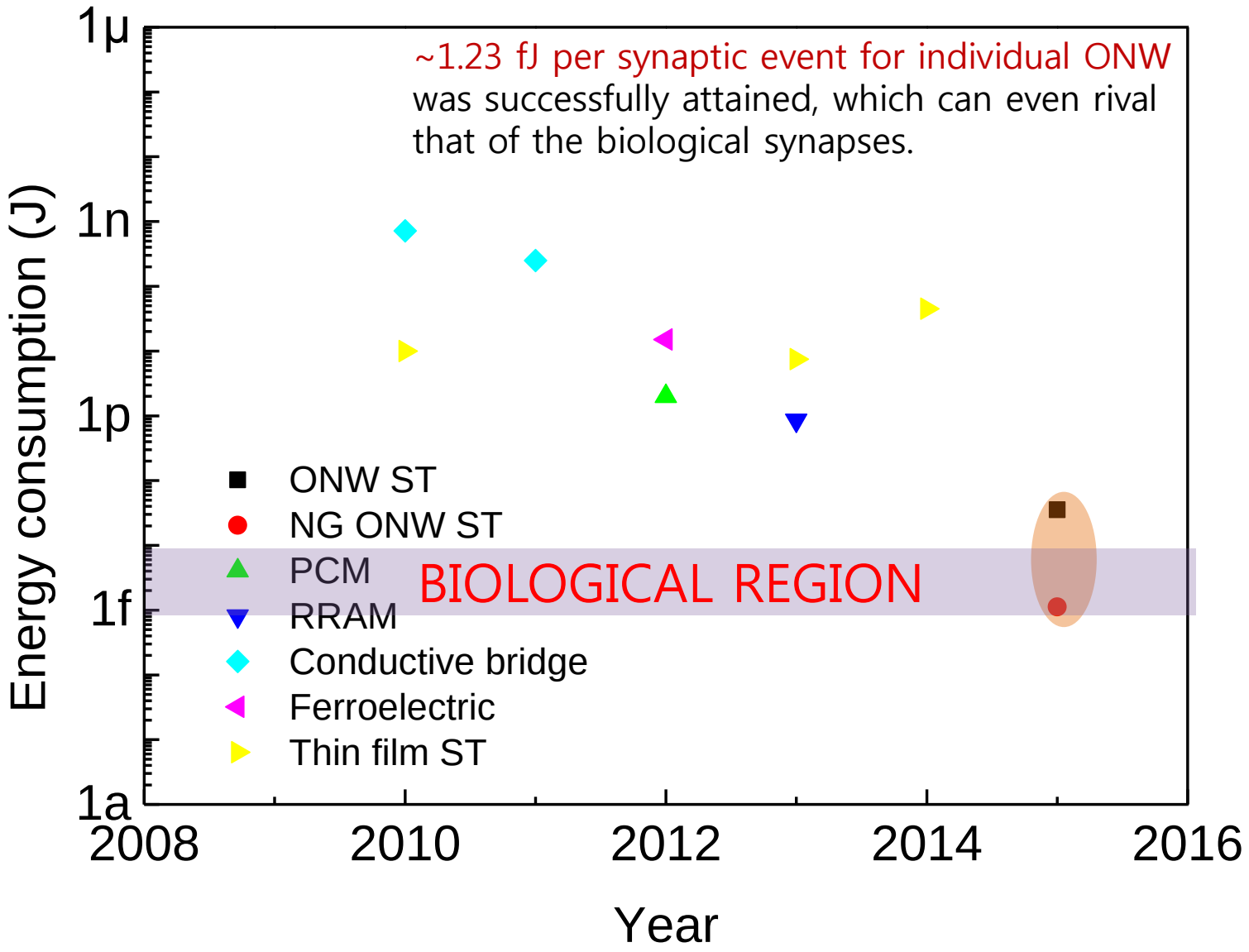
✓ Long-term plasticity



- Long-term potentiation (LTP) that usually occurs at excitatory synapses, which is a persistent increase in synaptic strength following a number of consecutive stimulations of a synapse.
- Consecutive 30 negative pulses accumulates and increased EPSC
- Long-term retention obtained

W. Xu, T.-W. Lee* et al, *SCIENCE Advances, 2, e1501326 (2016)*

Energy consumption per synaptic event of current available synaptic devices

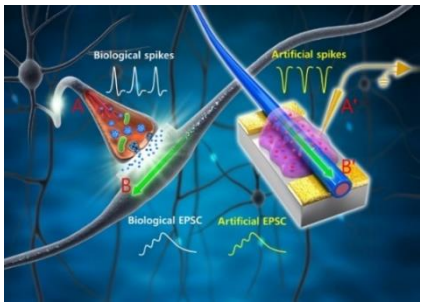


W. Xu, T.-W. Lee* et al, *SCIENCE Advances, 2, e1501326 (2016)*

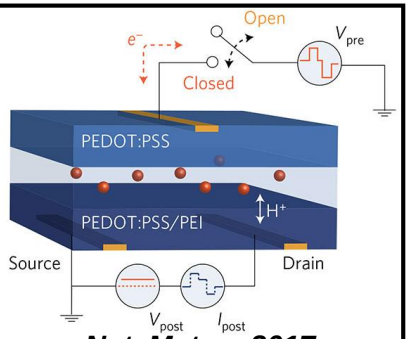
Contents

Artificial Central Nervous System – Brain-inspired Computing

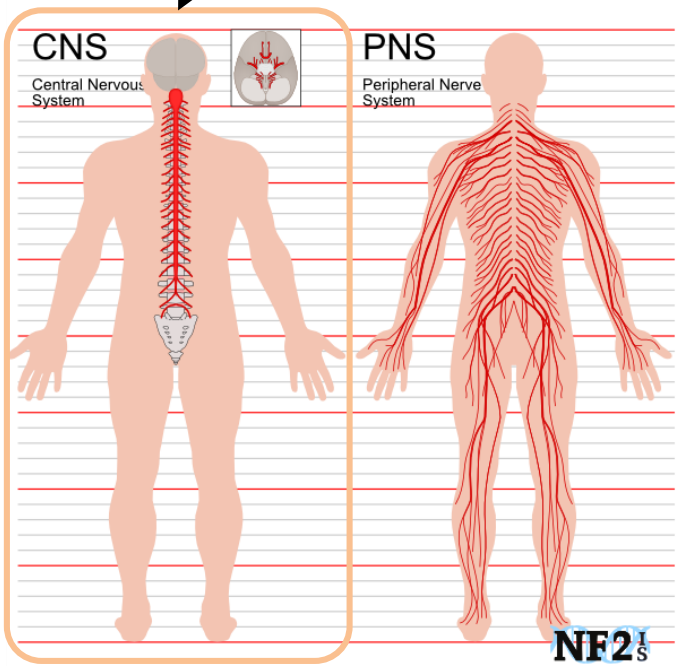
✓ *Brain-inspired Organic Artificial Synapse*



T.-W. Lee et al., Sci. Adv., 2016



Nat. Mater., 2017

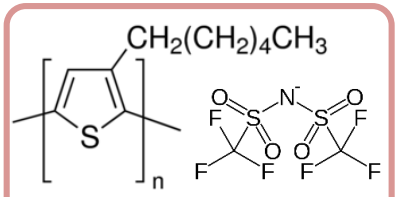


✓ *Materials for CNS*

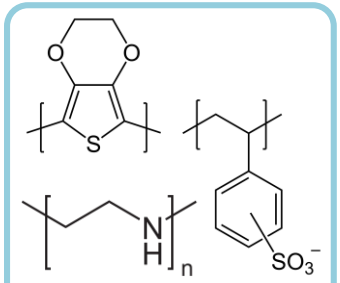
- *Long-term potentiation*
- *Non-volatile memory property*

✓ **Redox active polymer**

✓ **Electrochemical ion doping mechanism**



P3HT + [EMIM][TFSI]

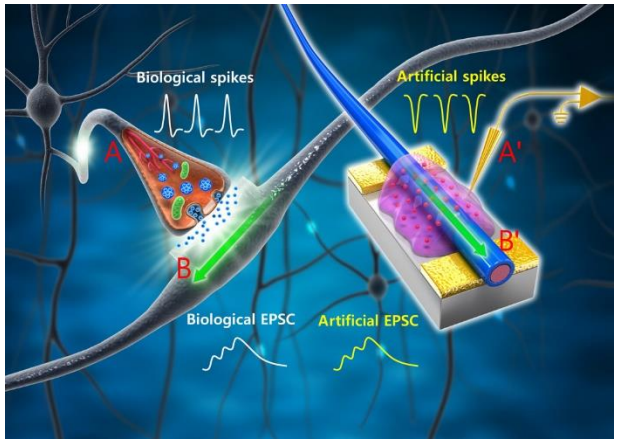


PEDOT:PSS + PEI

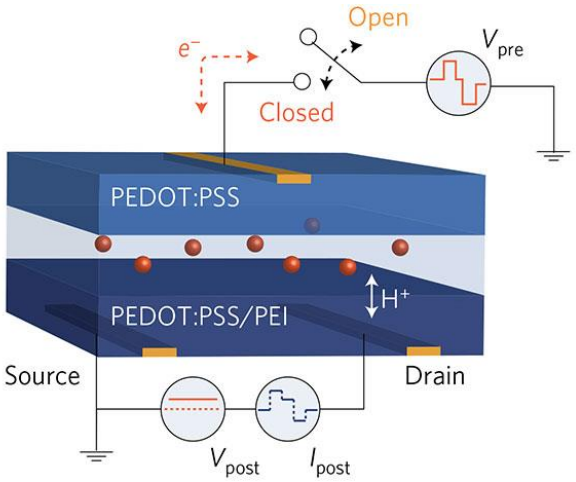
T.-W. Lee et al., Sci. Adv., 2016

Nat. Mater., 2017

ONW Synaptic Transistor to mimic Peripheral nervous System



Lee et al, Sci. Adv. **2016**, *2*, e1501326

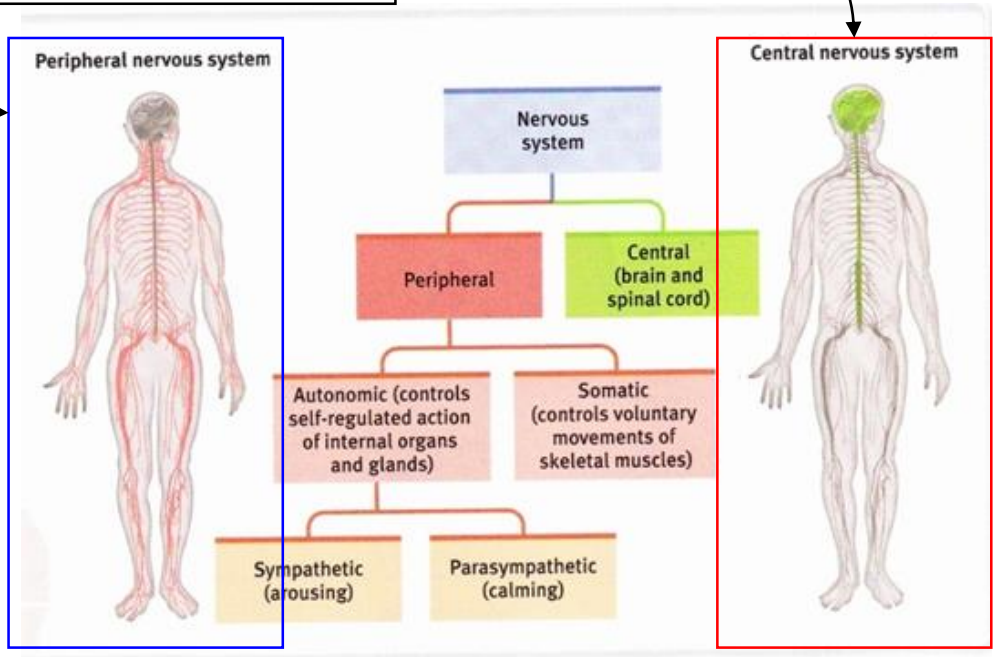


Salleo et al, Nat. Mater. **2017**, *16*, 414

Neuromorphic computing & memory

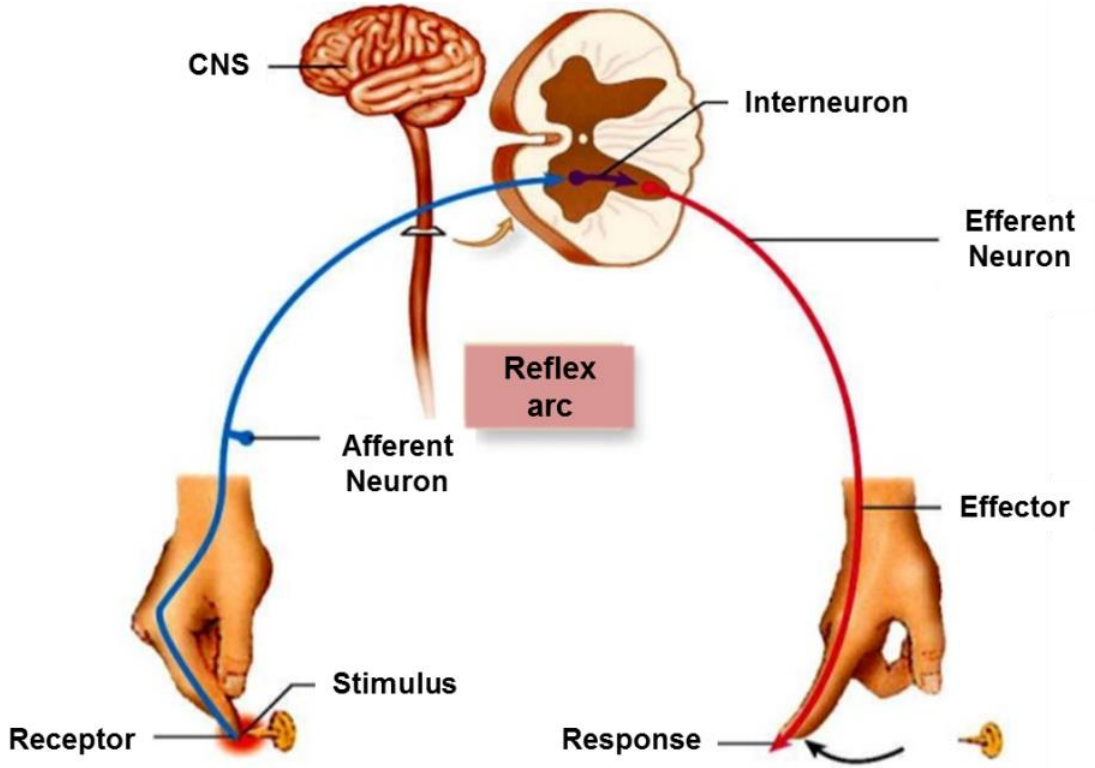
Peripheral nervous system:

1. Autonomic nerve system
2. **Somatic nerve system**:
   - Sensory neuron
   - Motor neuron



Artificial nerves

❖ **Artificial afferent and efferent nerves**



- ✓ **Afferent nerve : axons of sensory neurons carrying sensory information from body**
- ✓ **Efferent nerve : axons of motor neuron**
- ✓ **Applications of artificial nerves: robotics and prosthetics with the combination of sensors and motors**

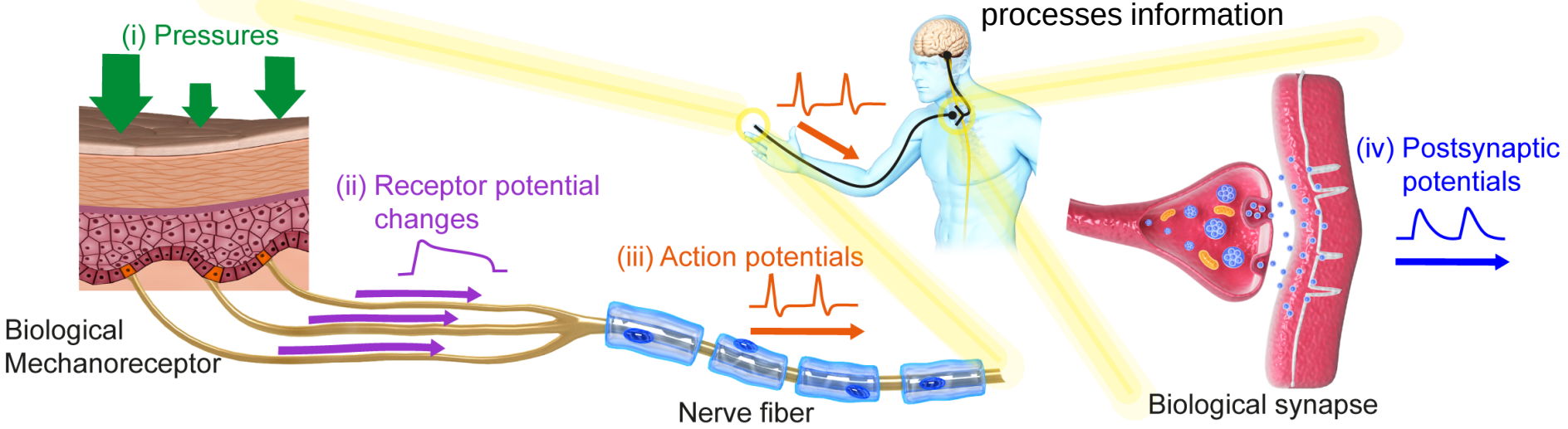
Artificial Mechano-Sensory Nerves

https://www.youtube.com/watch?v=IrYTD1xZVSs

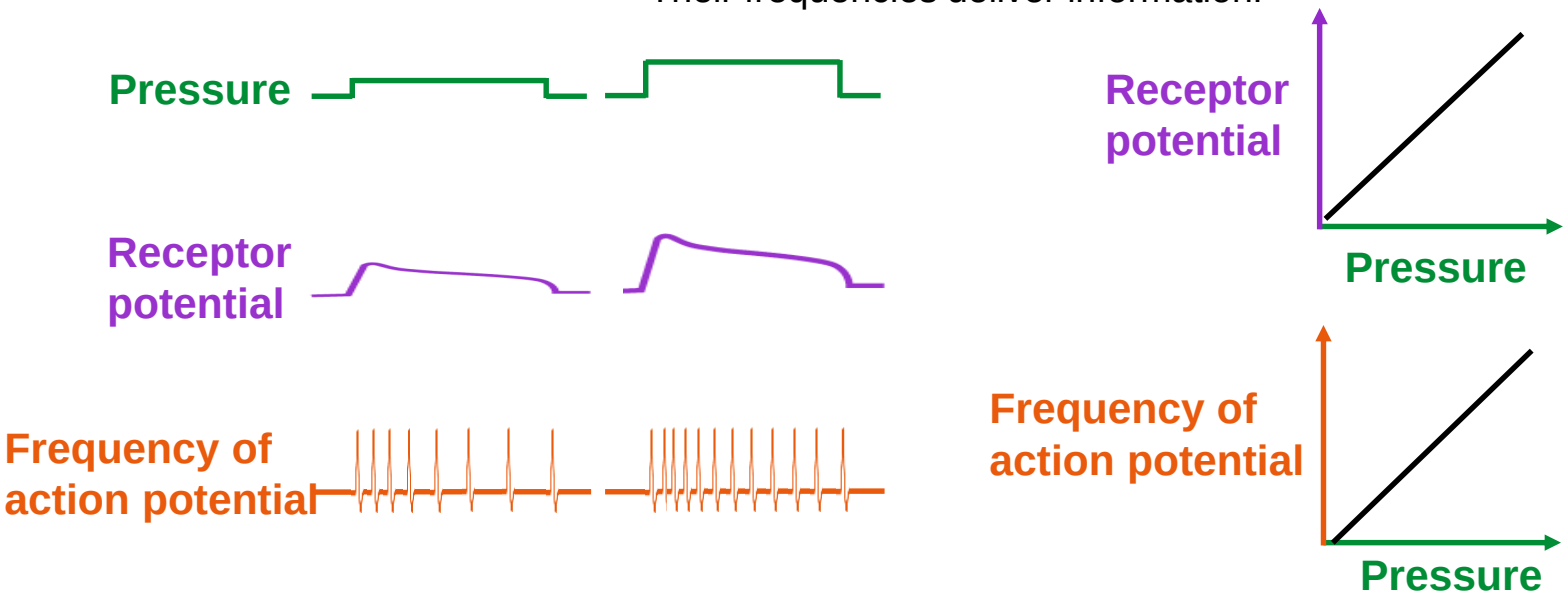
Y. Kim[+], A. Chortos[+], W. Xu[+]*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

Biological mechanosensory nerve

- Network of neurons and synapses in brain processes information



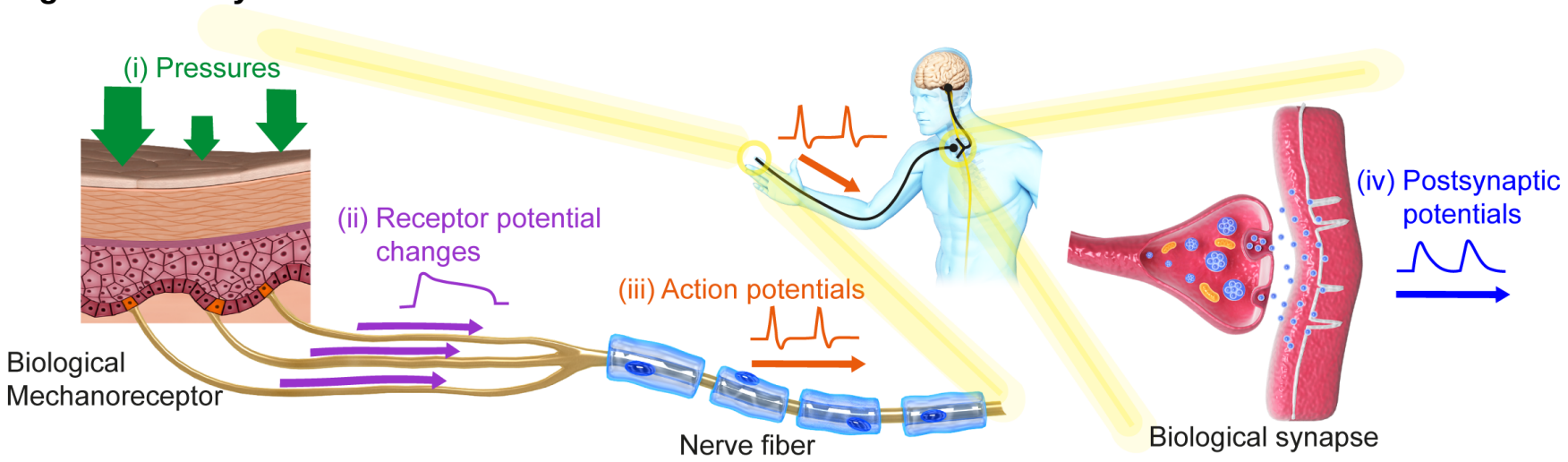
- Their frequencies deliver information.



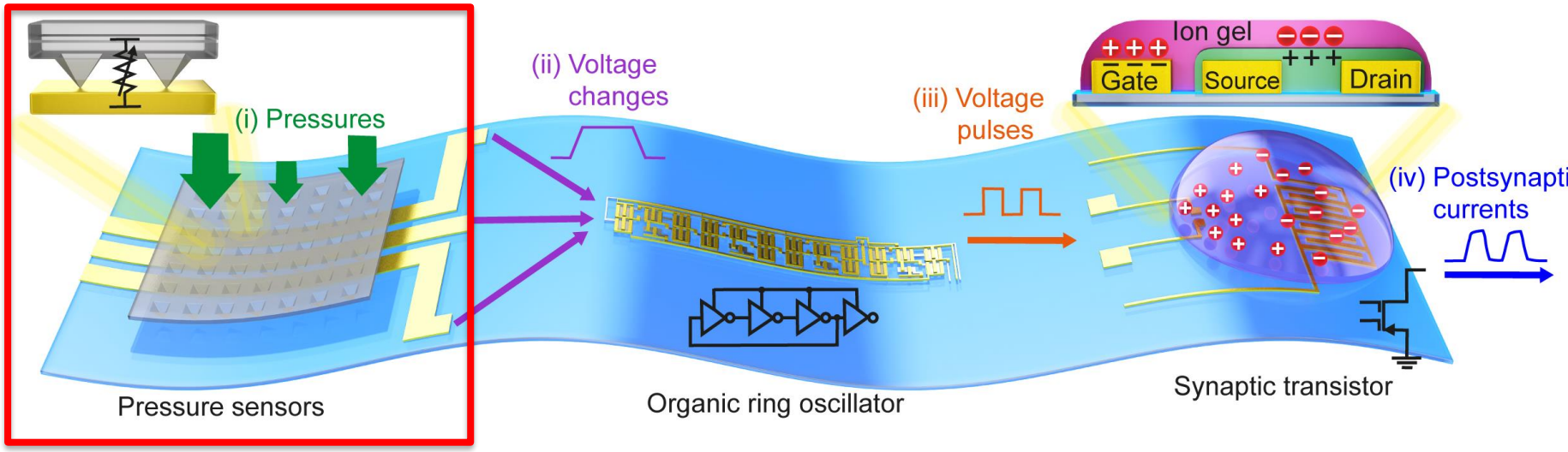
→ Biological mechanosensory system processes pressure information

Artificial mechanosensory nerve

Biological sensory nerves

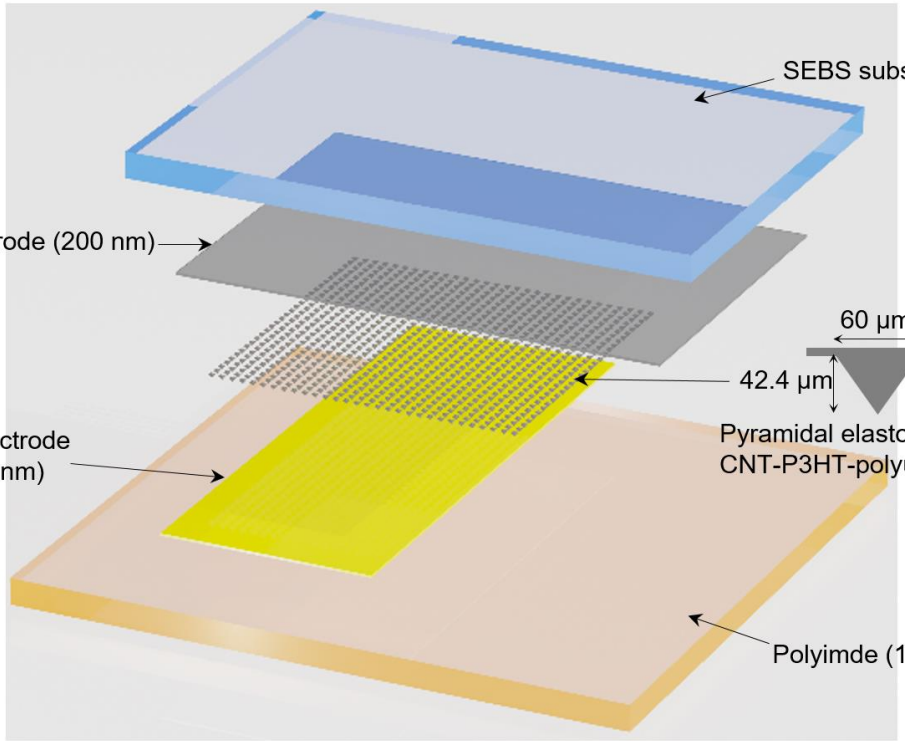


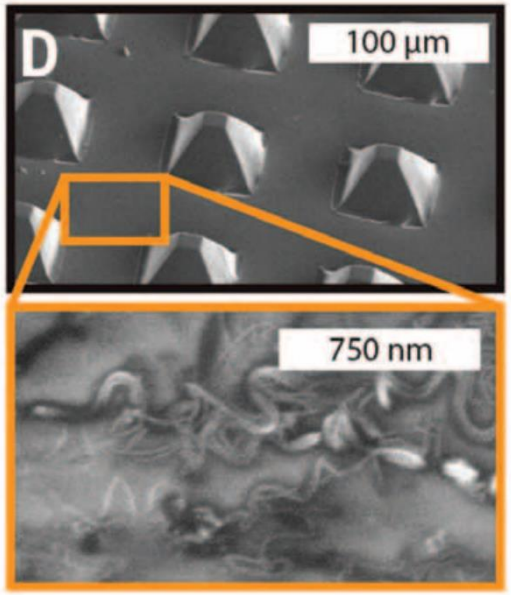
Artificial sensory nerves



Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

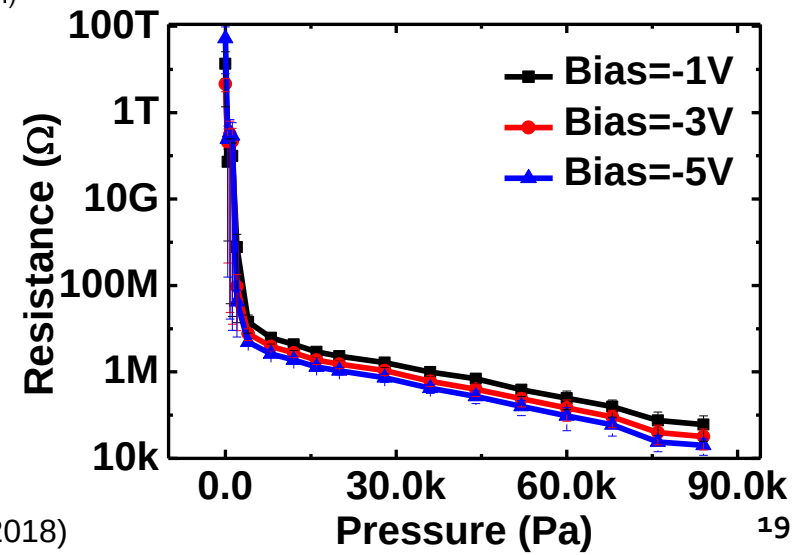
Resistive pressure sensor mimicking mechanoreceptor





Biological SA-I mechanoreceptor:
pressure input intensity = 1-100 kPa

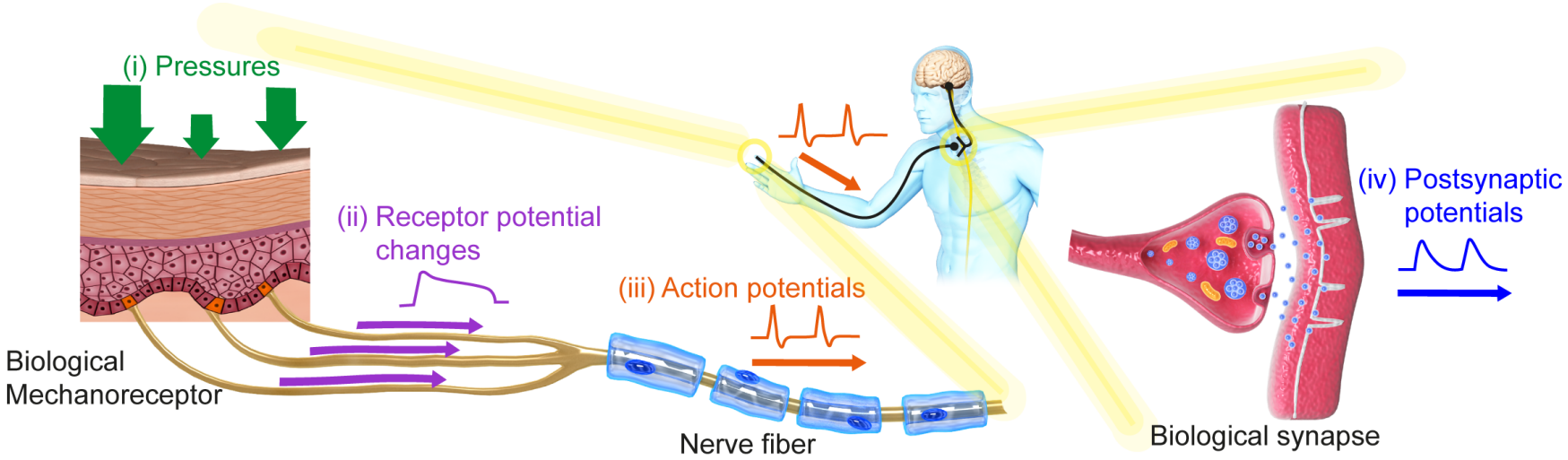
Applied pressure decreases the resistance of pressure → sensors mainly by reducing contact resistances.



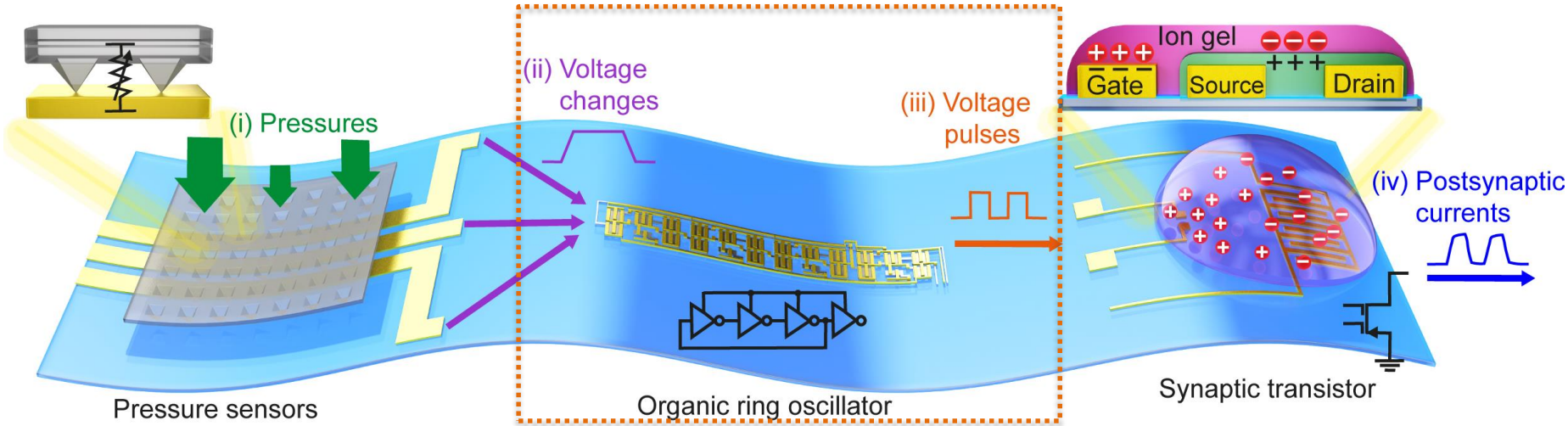
Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

Artificial mechanosensory nerves

Biological sensory nerves



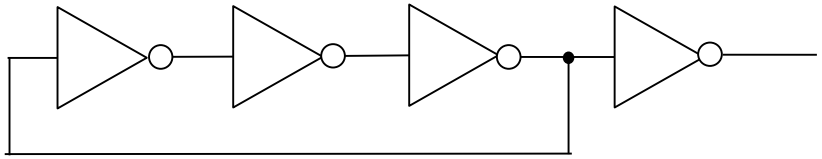
Artificial sensory nerves



Y. Kim⁺, A. Chortos⁺, W. Xu⁺*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

Ring Oscillator Output

3-stage ring oscillator

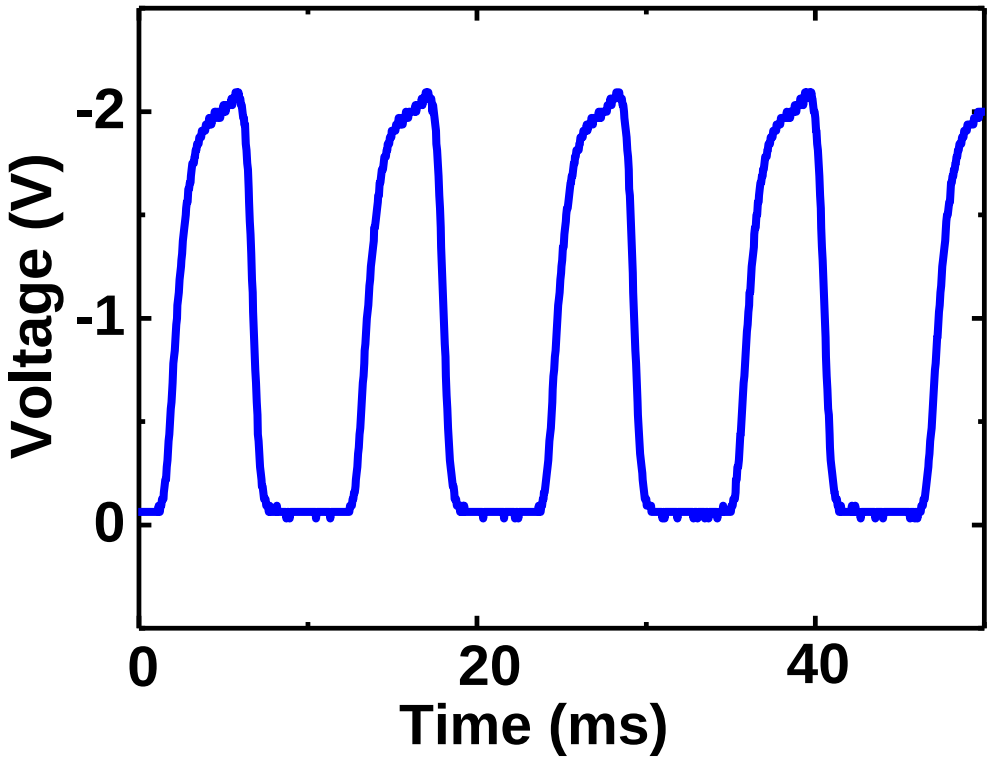


→ Voltage output

V_{DD} = -2.3 V, V_{LL} = -4.6 V, V_{HH} = 1 V

Oscillating frequency = 20-89 Hz

Biological mechanosensory nerves:
Action potential frequency range= 0.4-100 Hz



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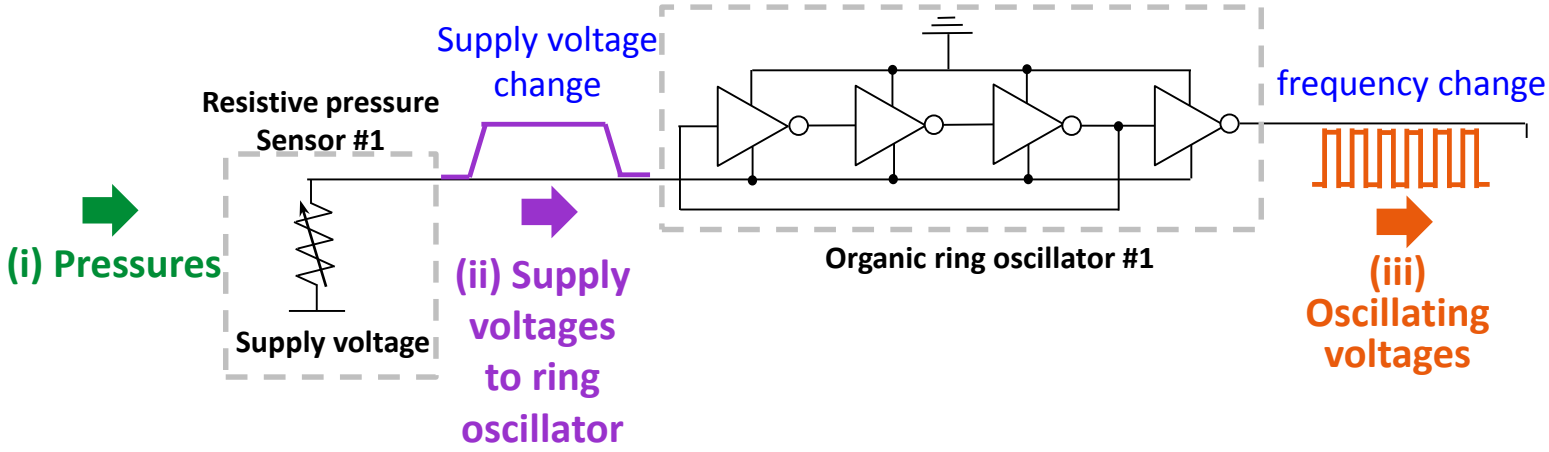
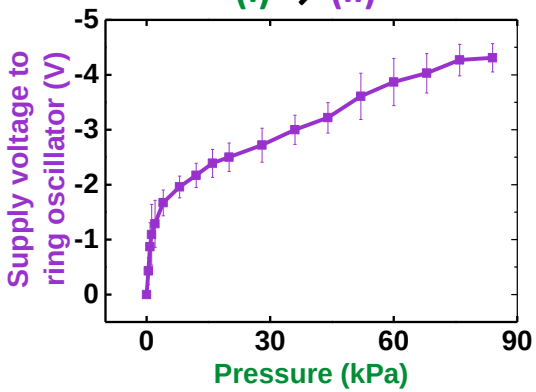
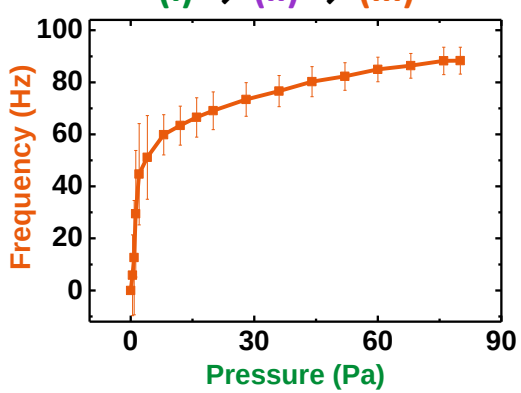
Pressure sensor + ring oscillator



(i) → (ii)

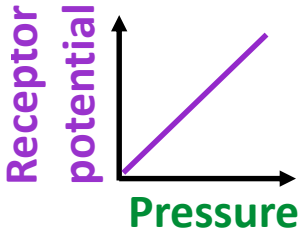


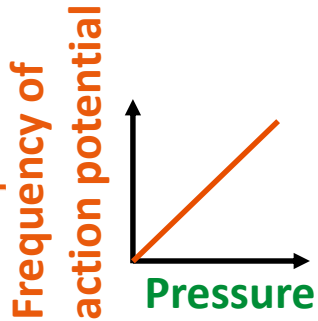
(i) → (ii) → (iii)



Pressure sensitivity= 0.4-13 Hz kPa^{-1}

Biological mechano-receptor

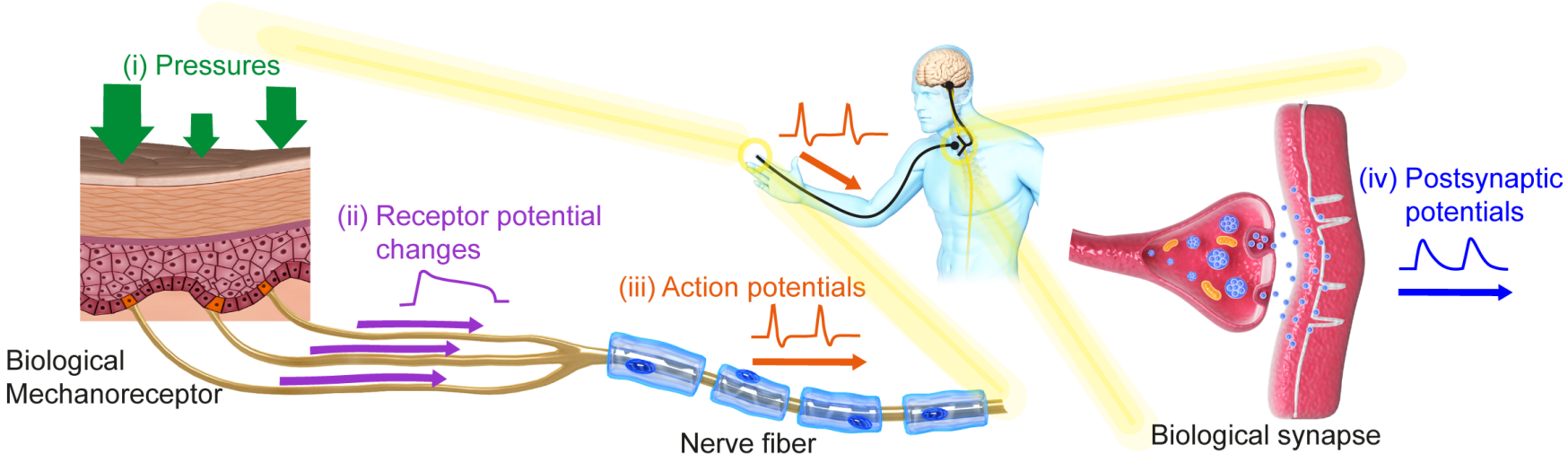




Pressure sensitivity= 2-10 Hz kPa^{-1}

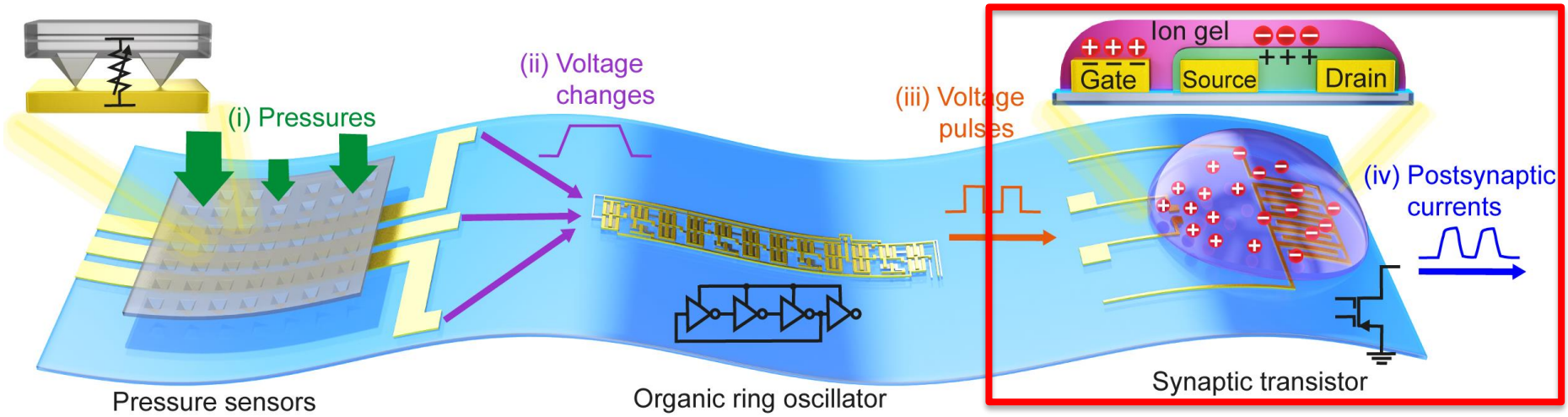
Mechanosensory nerves

Biological sensory nerves



Artificial sensory nerves

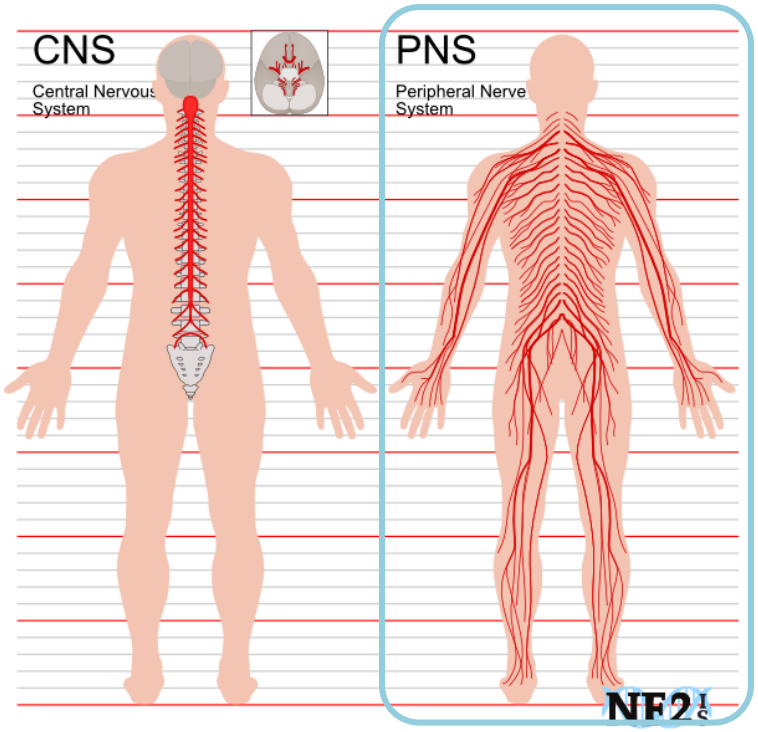
· V_{out} of ring oscillators connected to the gate of synaptic transistors



Y. Kim⁺, A. Chortos⁺, W. Xu⁺*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

Artificial Peripheral Nervous System

✓ *Neuromorphic Bioelectronics*



Emulation of Signal Transmission in Biology

→ Naturalistic Sensory and Motor Response

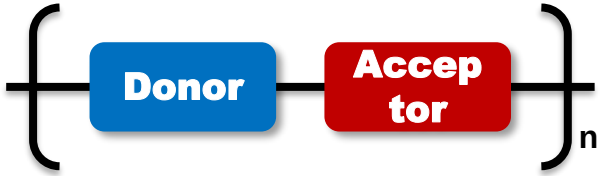
✓ *Materials design for PNS*

Short-term potentiation
Volatile & Fast decay

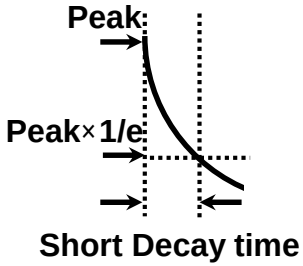
- ✓ Low ion doping efficiency
- ✓ Electric double layer

My Approaches

- ***Low ion doping efficiency***
  → Donor-Acceptor polymer

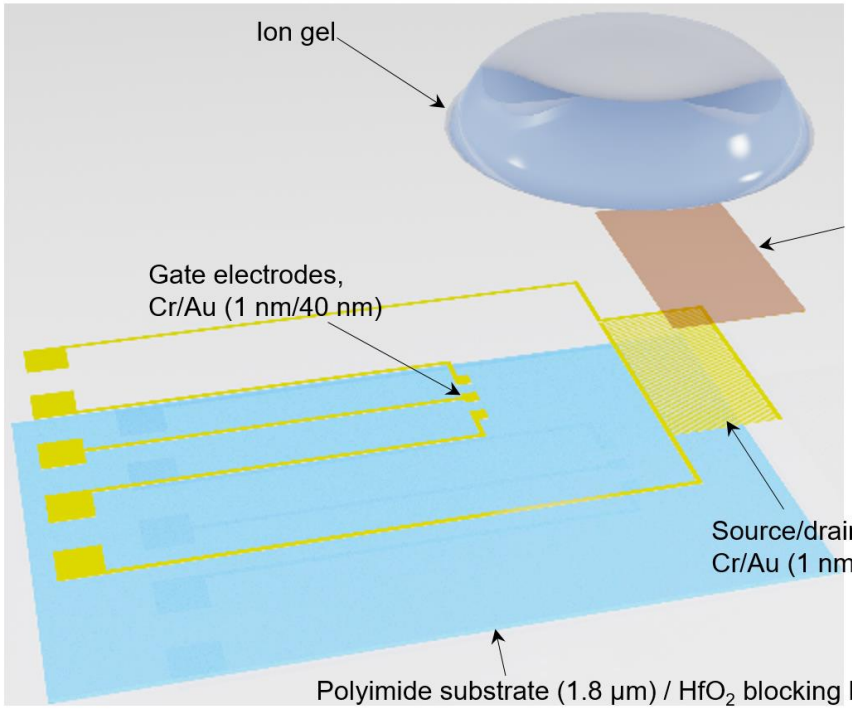


- ***Fast decay – Electrical double layer***

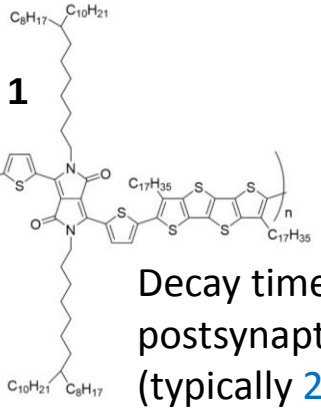


- ***Stretchable – Nanowire Transistors***

Ion-gel transistors (synaptic transistors)



Polymer 1

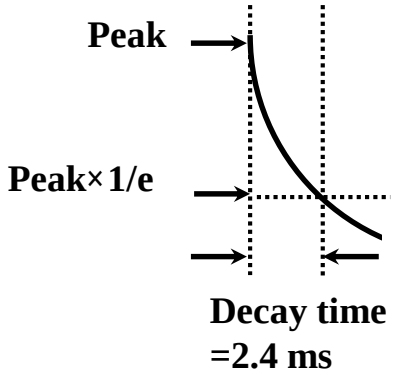


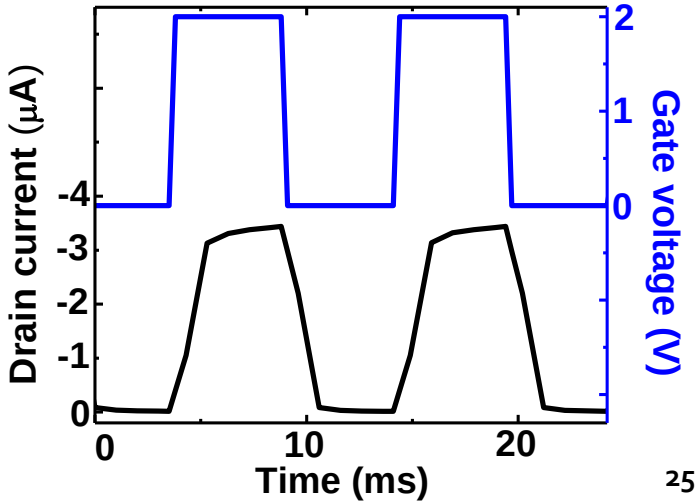
Decay times for postsynaptic currents (typically 2 to 3 ms)

Polymer semiconductors	Polymer 1	P3HT
Decay time (ms)	2.35 ± 1.02	299 ± 201 s

Decay time of postsynaptic outputs **reasonably short enough to receive pressure inputs at the desired frequency**

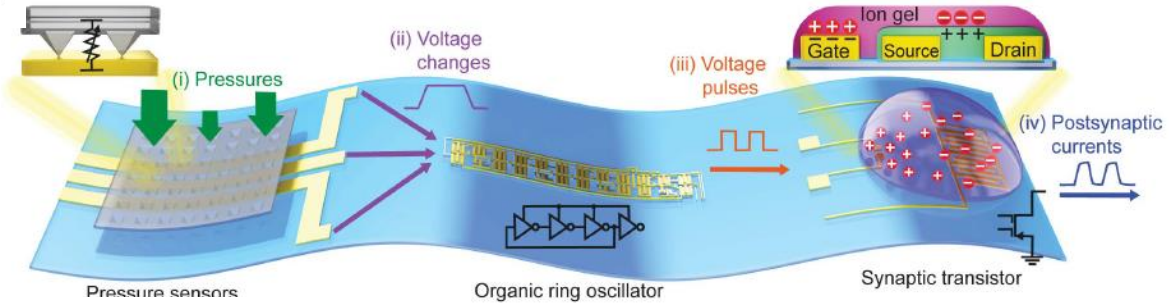
Biological Synapses in the somatosensory system: Decay time of postsynaptic currents= 1.5-5 ms

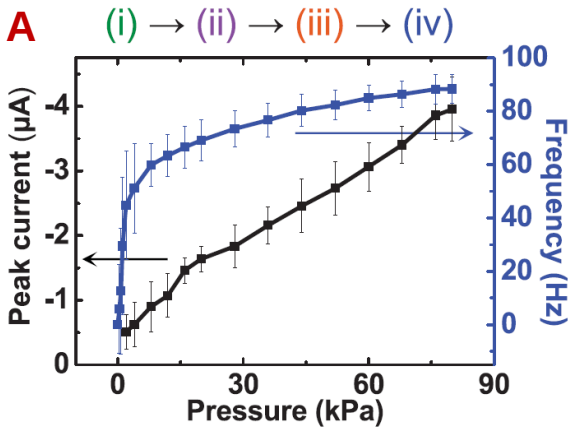


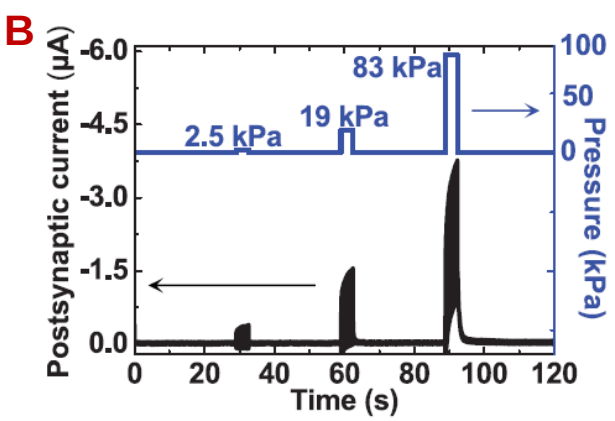


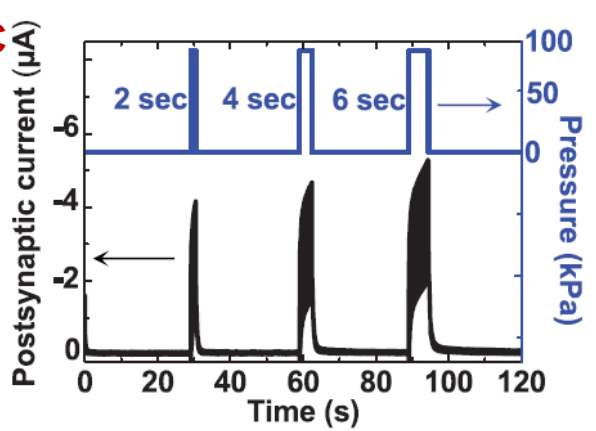
Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

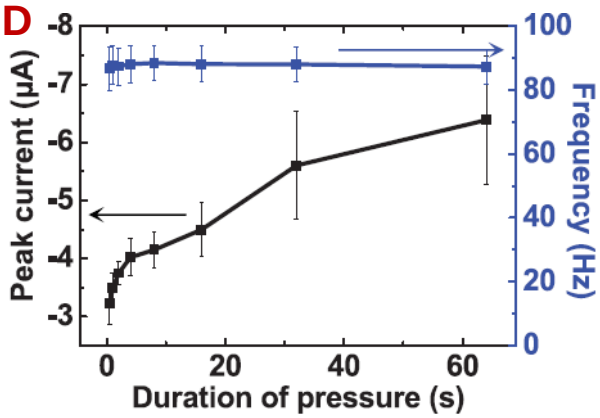
Pressure sensor + ring oscillator + synaptic transistors







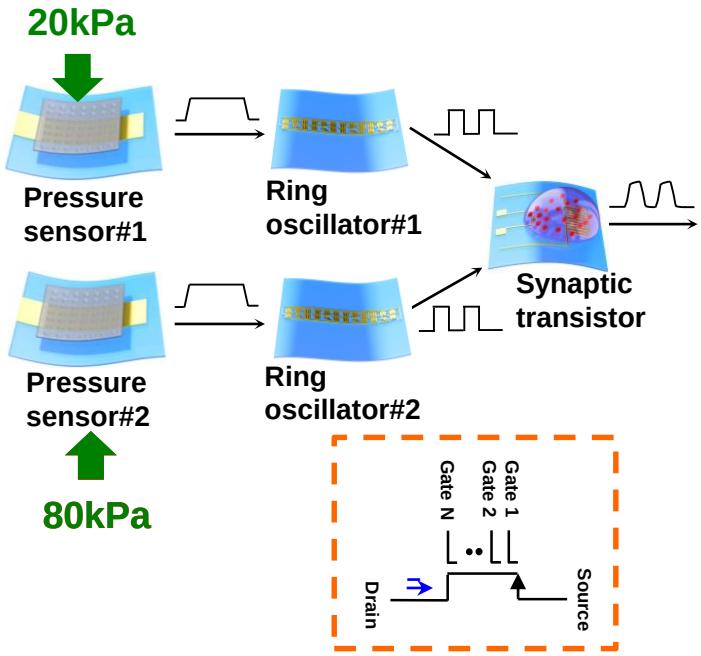


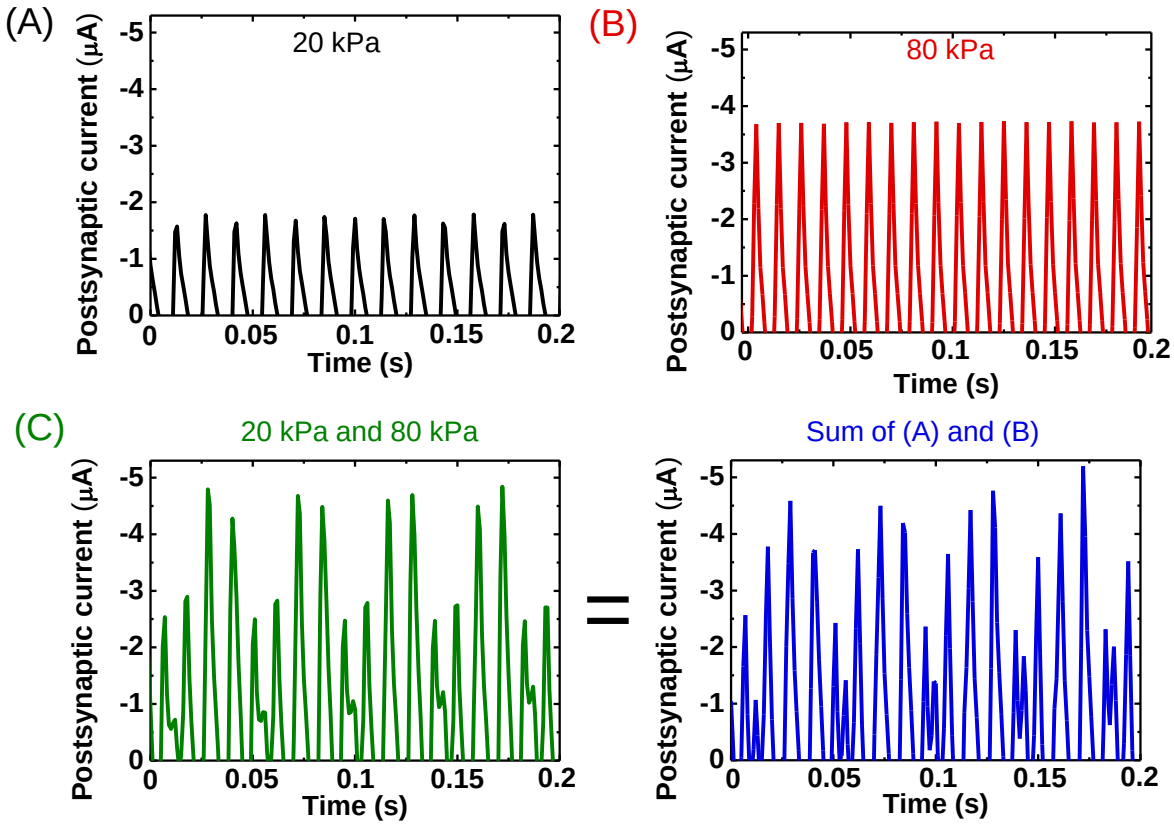


- Increase of magnitude (A, B) & duration (C, D) of pressure → increase of peak postsynaptic currents
- Frequency of postsynaptic currents independent of duration of pressure stimulus
- SA-I receptors (pressure input frequencies are <~5 Hz, pressure durations are >~200 ms)

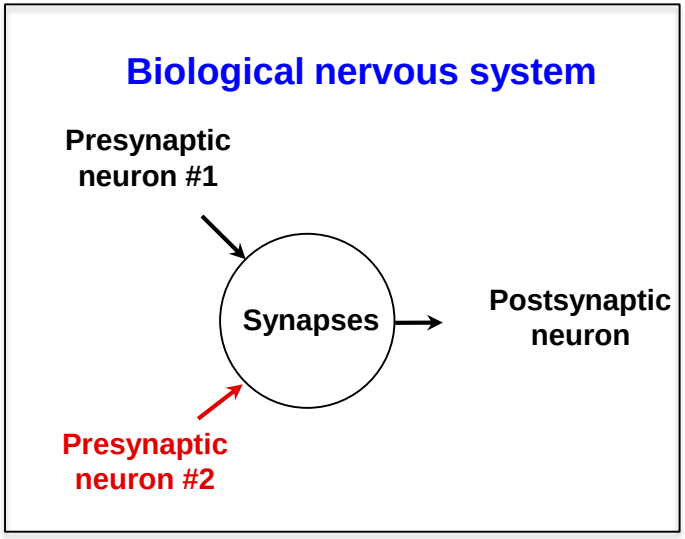
Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

Integration of pressure inputs

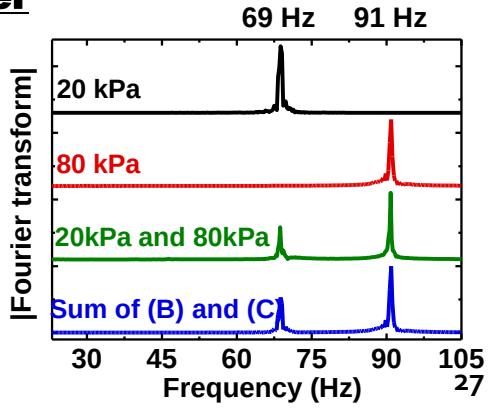




Synaptic transistor: an adder



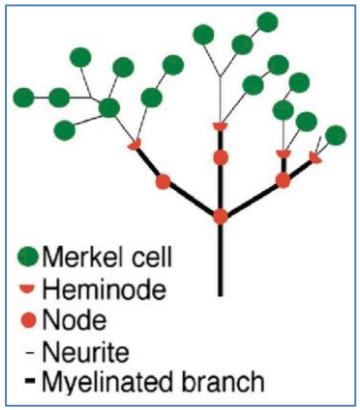
- Pressure signals from multiple pressure sensors are combined.
- Amplitude & frequency was maintained after signal integration in synaptic transistor



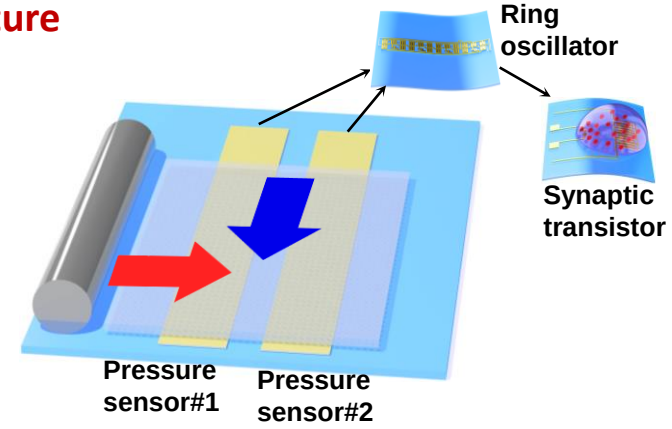
Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

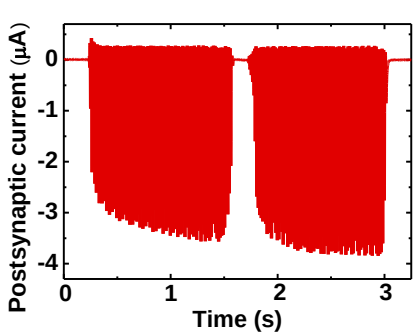
Movement recognition and braille reading

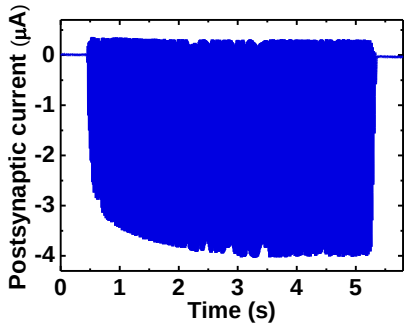
Biological mechanosensory nerves: Branched mechano-receptor structure



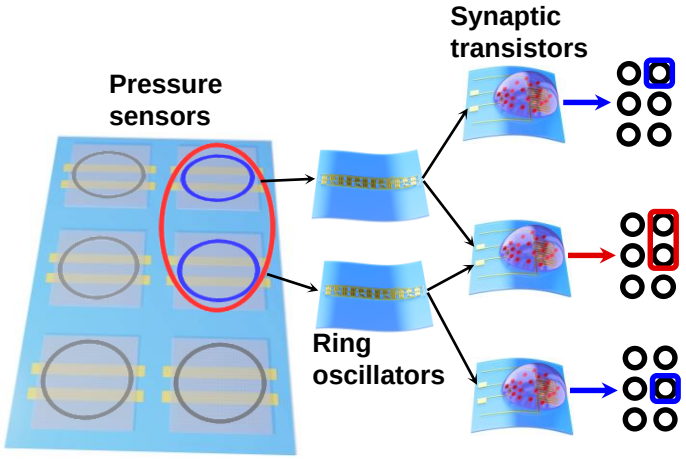
Movement recognition

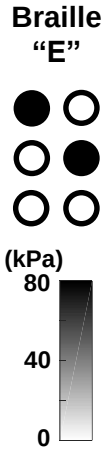


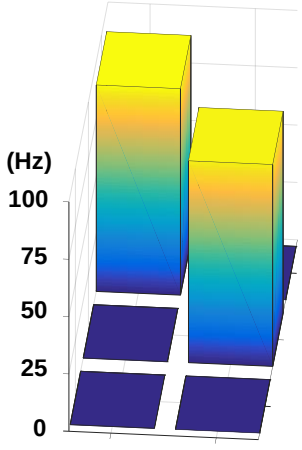




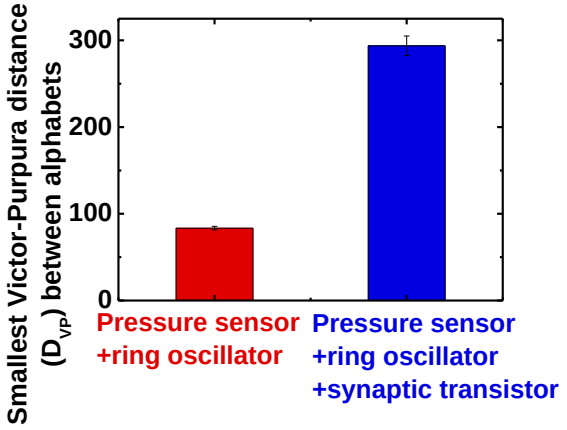
Braille reading







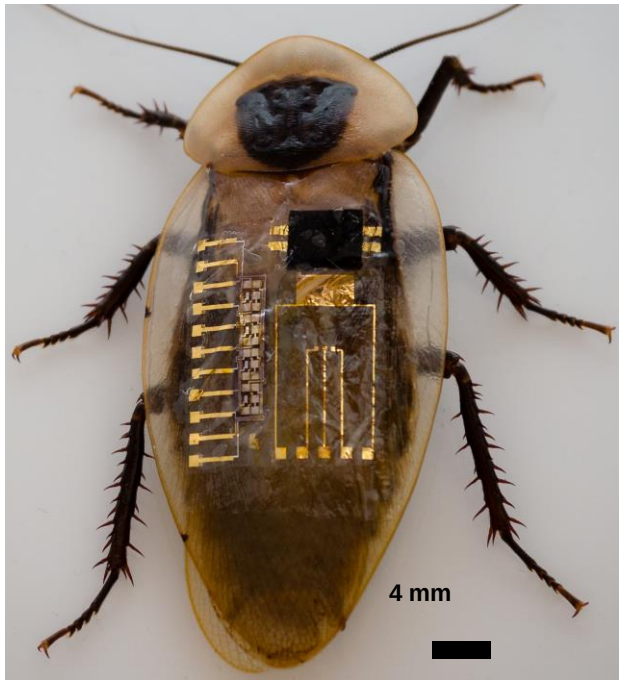
A larger D_{VP} means more dissimilarity between two spike trains.

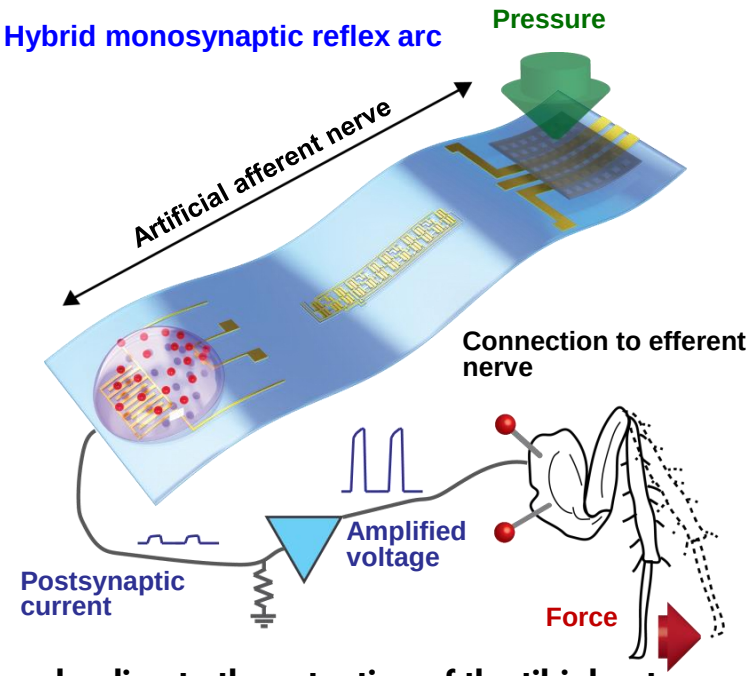


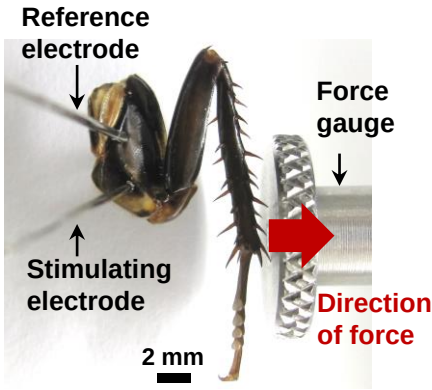
Braille letters became more distinguishable

Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

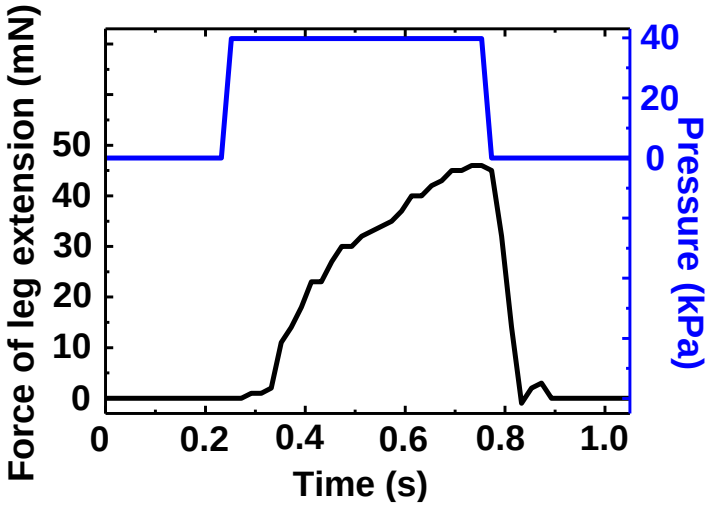
Hybrid reflex arc (artificial afferent nerve)

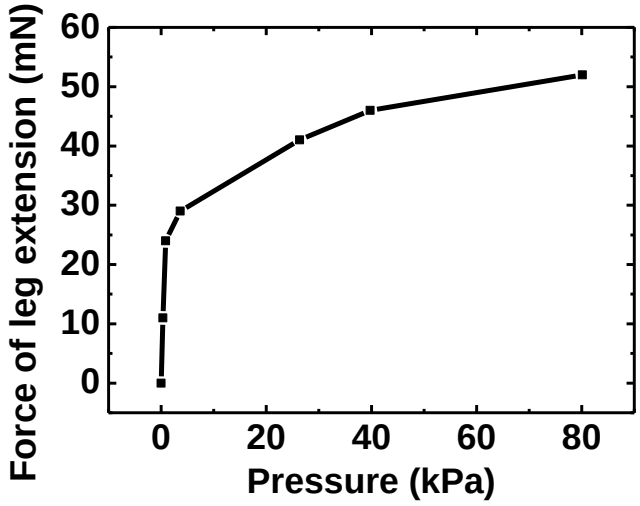




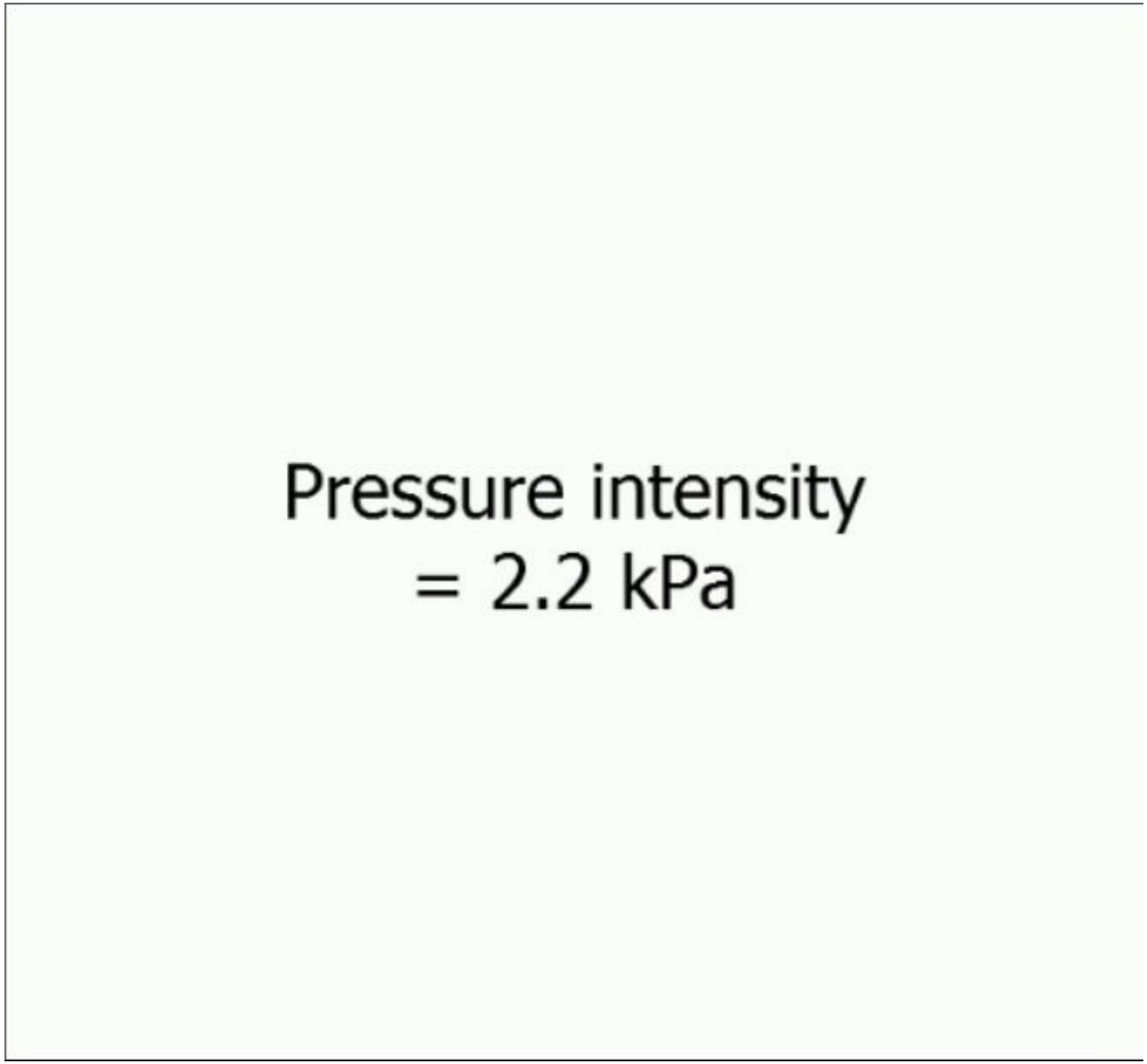


leading to the actuation of the tibial extensor muscle in the leg





Hybrid reflex arc (artificial afferent nerve)

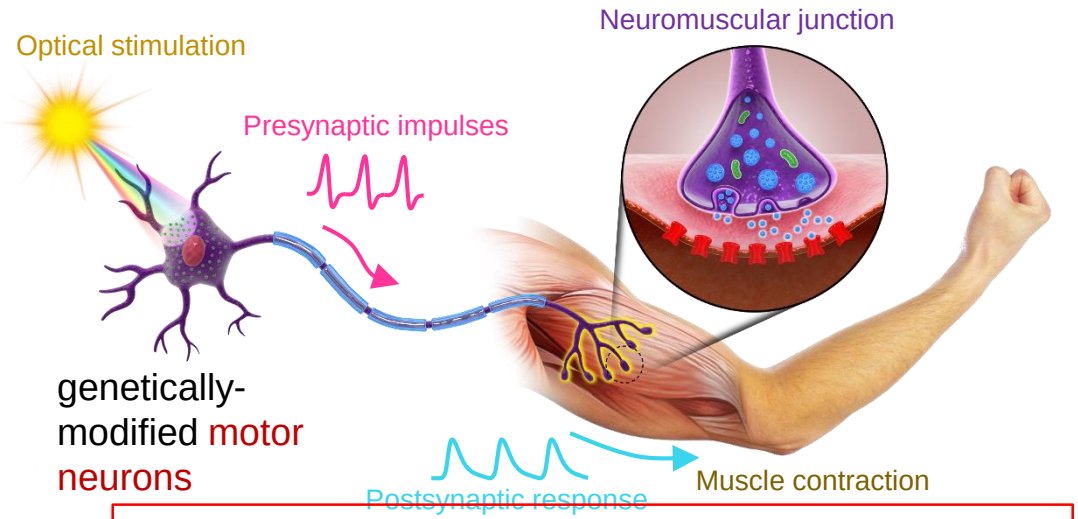


Y. Kim[+], A. Chortos[+], W. Xu[+]*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (2018)

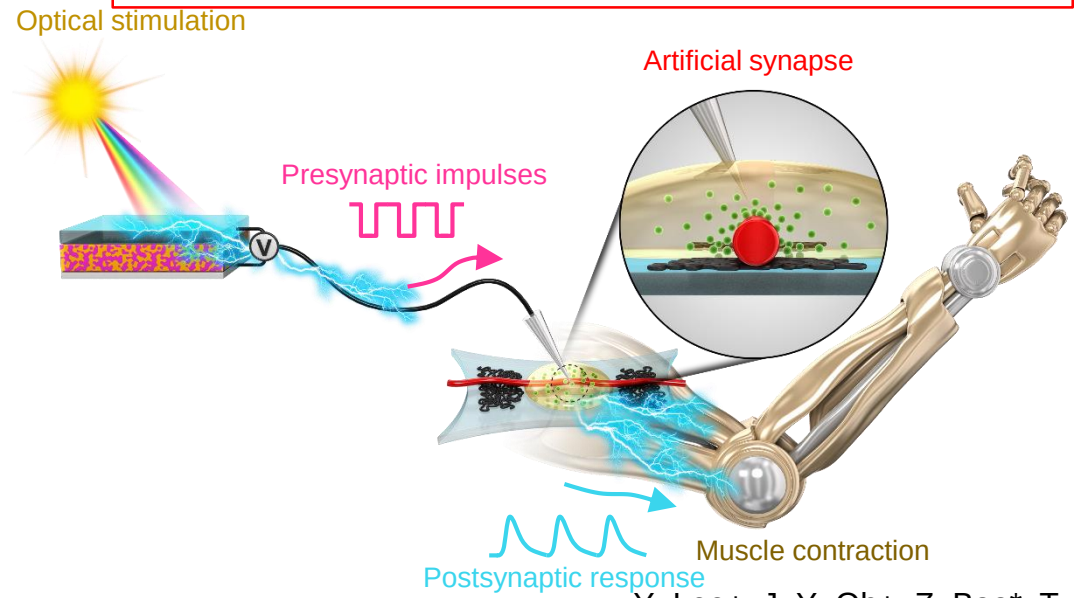
Contents

Artificial Optoelectronic Neuromuscular System

Human optogenetic sensorimotor nervous system



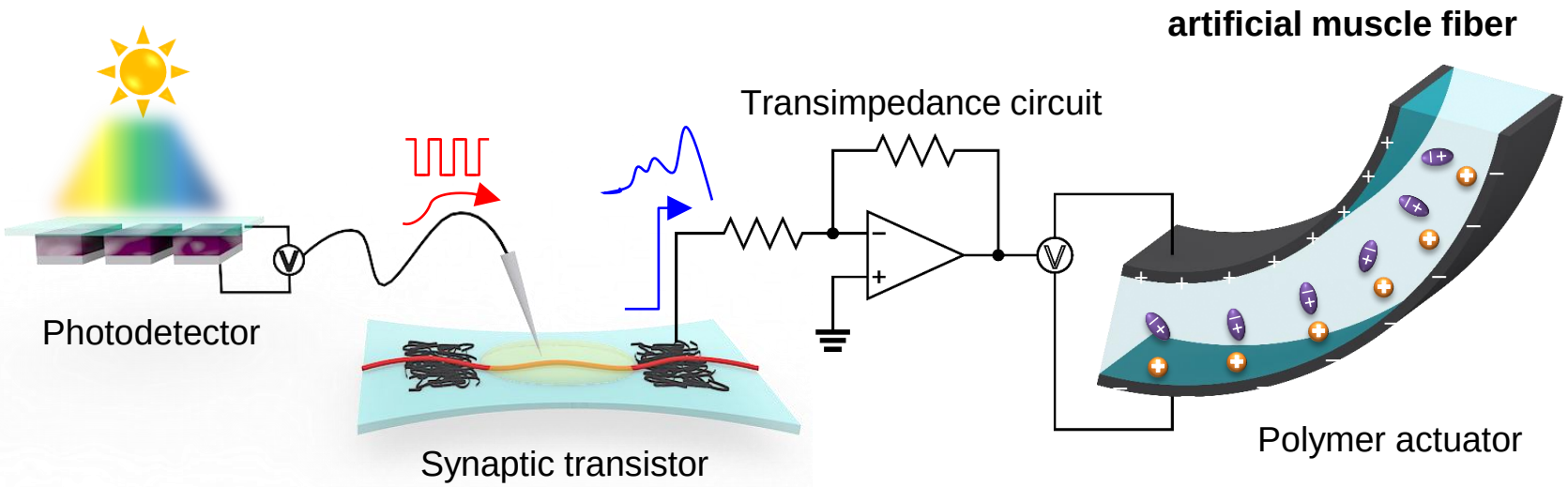
This approach is promising to restore the motor function of defective neuromuscular systems

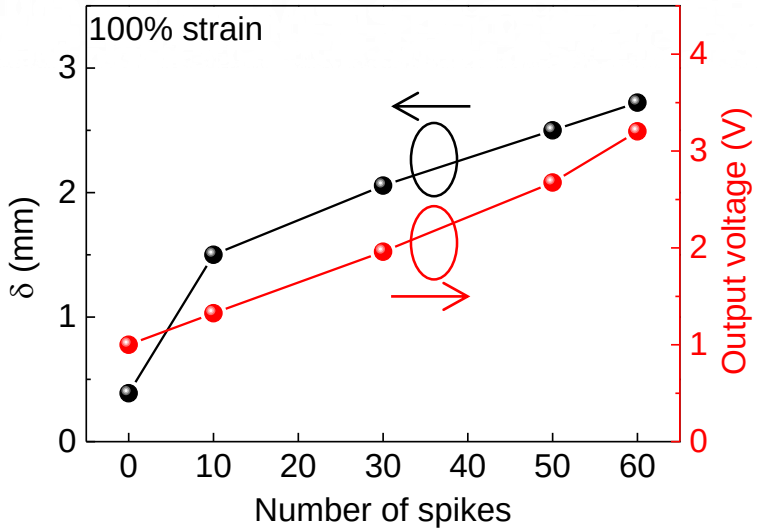


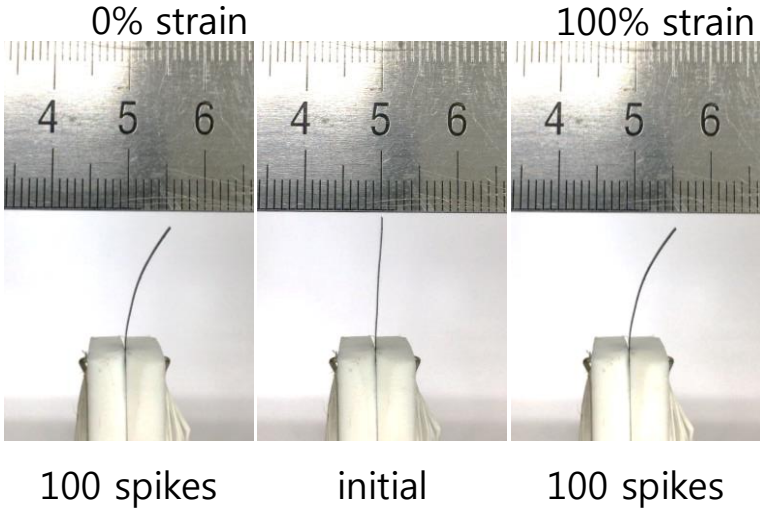
- **Stretchable artificial synapse** is necessary for artificial motor system of neuro-inspired soft robots with various motions.
- Motor Neuron
  Presynaptic membrane = Gate electrode
  Presynaptic potential = Gate voltage
- **Optogenetics**
  Photosensitive protein = Photodetector
- Neuromuscular junction
  Synaptic cleft = Ion-gel electrolyte
  Neurotransmitter = Anion
- Skeletal muscle
  Postsynaptic membrane = OSC NW
  Postsynaptic potential = Drain current
  Muscle fiber = Polymer actuator

Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, SCIENCE Adv.,* 4, eaat7387 (2018)

Optical Neuromuscular Electronic Synapse





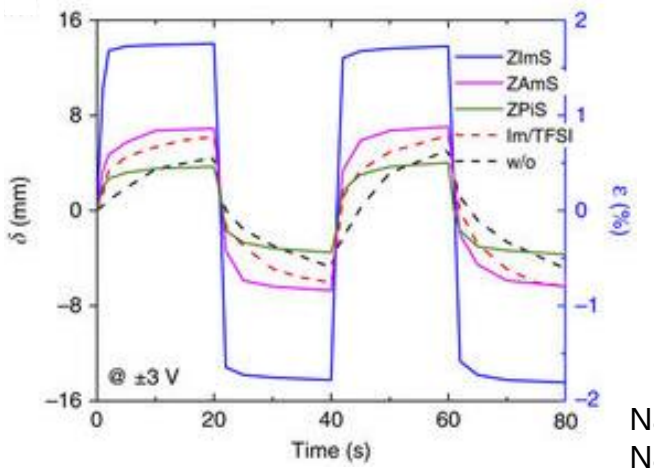


→ A novel bio-inspired somatic sensorimotor system for advanced bio-inspired electronics and neurorobotics

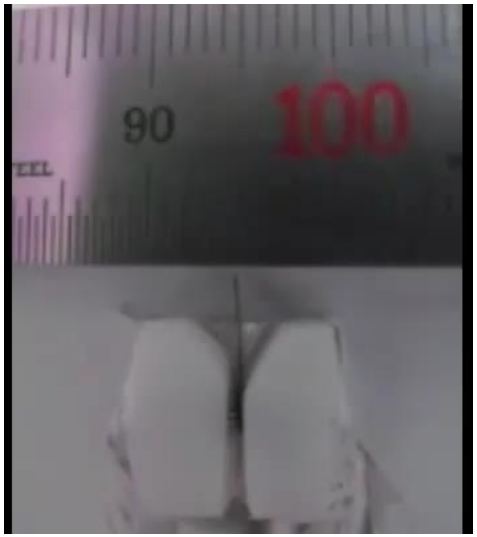
Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, SCIENCE Adv.,* 4, eaat7387 (2018)

Optical Neuromuscular Electronic Synapse

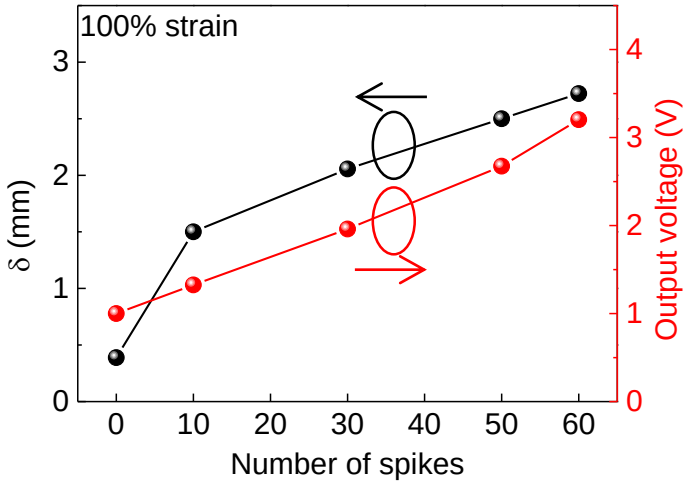
✓ **Without artificial synapse (Constant displacement with constant voltage)**



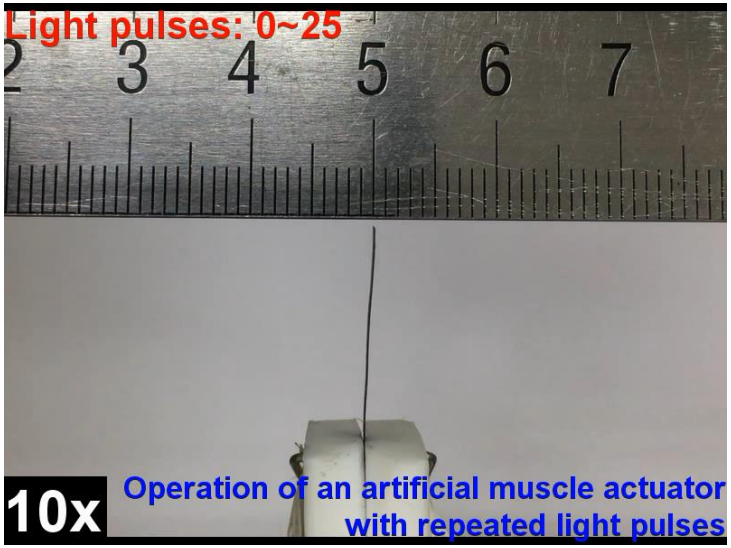
Nat., Commun., 2013,
Nat., Commun., 2016



✓ **Our synapse (Contraction of artificial muscle gradually increases as the fixed light pulses (action potentials) are applied repeatedly)**

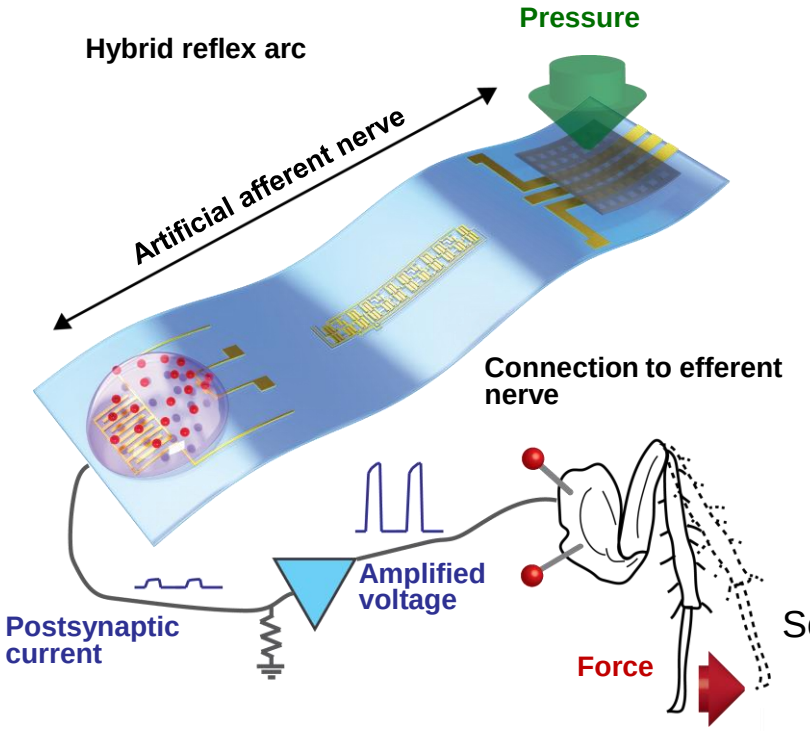


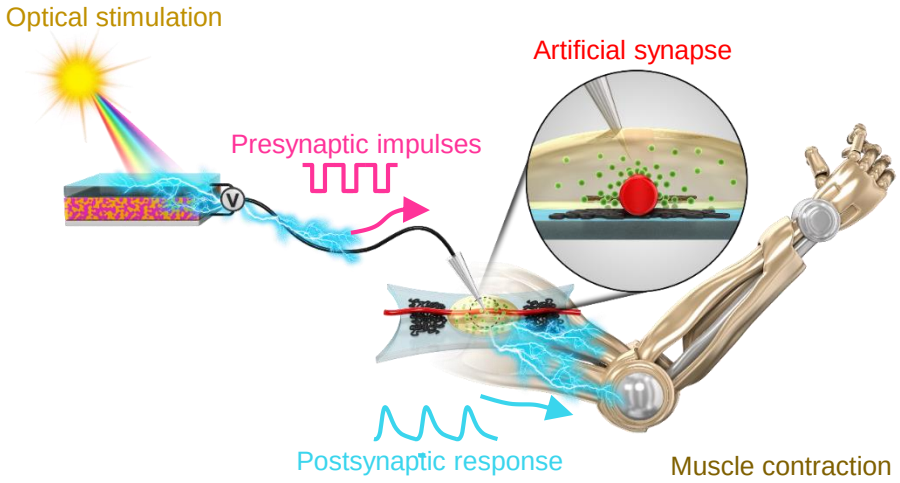
- More similar to biological muscle contraction



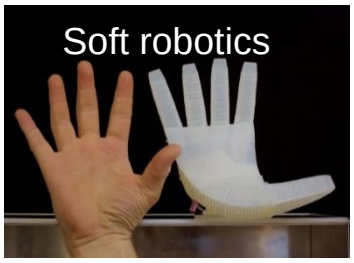
Contents

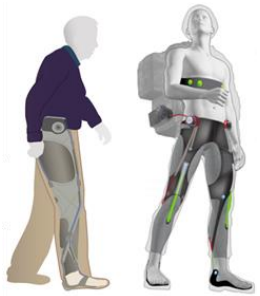
Summary





Soft exosuit prosthetics





Wearable Neuroprosthetics

- Development of a stretchable artificial synapse and a novel bio-inspired sensorimotor system.
- Suggesting a communication method of human/machine interface.
- Promising strategy to advance soft robotics, neuro-inspired robotics and neuroprothetics.

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- Mr. Yuxin Liu


POSTECH

- Prof. Hyunsang Hwang
- Prof. Moon Jeong Park