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# Biological approaches to electrical conduction in non-metallic materials for engineered products

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## ABSTRACT

The use of electricity is so pervasive that life without it is unimaginable today. The scope of electricity is even widening to encompass wearables and draperies in domestic and professional surroundings. The typical way of conducting electricity is through metallic wires and conduits, which often are integrated permanently into engineered products. This means that we have more and more products with mixed materials that are difficult to recycle, thereby creating a major bottleneck towards the achievement of sustainable urban and rural environments. If electricity could be conducted in another way, new design options would become possible. The bioworld offers ways for conducting electricity without metallic interconnects. Examples range from electric discharges by electric eels to electrolocation by fish to bacterial protein networks that conduct electrons. A review of electrical conduction mechanisms in the bioworld suugests the feasibility of incorporating the underlying bioworld principles in engineered products.

**Keywords:** Action potential, electricity, electronic conduction, engineered biomimicry, ionic conduction

## 1. INTRODUCTION

Modern life appears impossible without electricity. The use of electrical appliances has grown immensely with the increase in population as well as technological advancements, and it is expected to continue to grow. The International Energy Agency projects that global electricity demand for electric vehicles will increase by 2030 at least fivefold from its 2019 level.[1] Hence, the following question arises: Shall we be able to meet the growing demand for electricity in a world of finite resources? Most notably, the extensive use of metals for electrical conduction causes concern, since electrical appliances are becoming more complex and utilize an ever wider variety of metals ranging from structural metals such as steel and aluminium to rarer metals such as gold, indium, platinum, cadmium, and gallium in semiconductor devices.

In addition to this proliferation of the types of metals in engineered products, the processing of metals often consumes a lot of energy since high temperatures are required. Metal-bearing ore is also expensive to mine, resulting in high prices.

There is a large variation in the abundance of different types of metals in our planet's crust. Metals such as iron and aluminum are several orders of magnitude more abundant than other widely used metals such as copper, lead, and zinc. Even scarcer is the availability of rare-earth metals such as dysprosium, terbium, europium, neodymium, and yttrium which the US Department of Energy finds to be critical in the short term.[2] The eight geologically scarcest materials are antimony, bismuth, boron, copper, gold, molybdenum, rhenium and zinc. It is not likely that we will run out of any metal soon. What will happen is that scarcity will drive up the price of some metals rapidly. Henckens *et al.* at The University of Utrecht have analyzed sustainable (i.e., eco-responsible) extraction rates and identified several metals whose extraction needs to be reduced in order to meet the net-zero target.[3]

While attention has been focused on recycling of precious metals in electronics, it is also worthwhile considering whether there could exist more sustainable alternatives to metals. In this context, the bioworld is a

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huge resource of concepts and ideas to solve technical problems.[4] It is also a large source of inspiration for addressing sustainability problems,[5] since all organisms rely on available materials when growing and supply other organisms with materials when they die. In other words, recycling and circular economy are essential for the bioworld to be regenerative.

In the same manner as electricity has become ubiquitous in the industrialized world, electrical conduction and signal propagation are omnipresent in the bioworld. Nearly every living being uses electricity for communicating between its different parts.

The use of metals for conducting electricity introduces another challenge after the useful life of an engineered product ends. When a decommissioned product is either landfilled or incinerated, its materials are lost and can not be used in other products; furthermore, the environment is polluted sooner or later. Another end-of-life scenario involves recycling. Metals represent a challenge for recycling when they are mixed with other materials and when used in products that are uneconomical to recycle. More and more electronic devices are placed in everyday products such as household appliances, clothes, shoes, bags, etc. Many such products are disposed of by incineration and the ones that can be recycled face the challenge posed by the commingling of materials. What are needed are electricity conductors made from abundant materials that are also easy to recycle.

Our aim in this paper is to review biological mechanisms for conducting electricity and describe perspectives on how these mechanisms might be utilized in novel approaches for conducting electricity in engineered systems and products. We address the issue of whether a paradigm shift is possible in electrical conduction to include sustainability principles gleaned from the bioworld.

## 2. ACHIEVABLE CONDUCTIVITY

Electrical conduction can be categorized as either electronic or ionic. Electronic conduction is the result of the motion of electrons due to a force created by an externally applied electric field.[6] Metals conduct electricity through this flow of electrons. Semiconductors have a related conduction mechanism: the absence of an electron in a lattice can also be transported by an electric field, the absence functioning as an equivalent particle called a *hole*. Holes are positively charged, whereas electrons are negatively charged. Ionic conduction is based on the net motion of ions under the influence of an externally applied electric field. This type of electrical conduction most often occurs in a liquid medium containing ions, with molten salts and solvated liquids (such as water) as examples. A difference between these two conduction mechanisms is that some ions have a net positive charge (cations, e.g., $Na^+$) and others have a net negative charge (anions, e.g., $Cl^-$), but electrons are always negatively charged. Figure 1 illustrates the two mechanisms of electrical conduction.

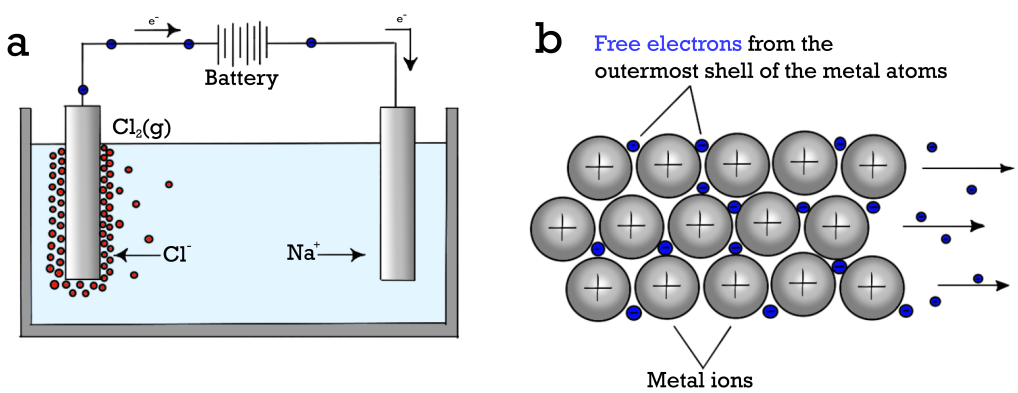


Figure 1. (a) Ionic conduction in an electrolytic cell containing NaCl solution. (b) Electronic conduction in a metal.

Table 1. DC conductivity of common materials

| Material | Category | Type of conduction | Conductivity at 20°C (S/m) |
|---|---|---|---|
| Silver[7] | Metal | Electronic | $6.3 \times 10^7$ |
| Copper[7] | Metal | Electronic | $5.96 \times 10^7$ |
| Aluminum[7] | Metal | Electronic | $3.77 \times 10^7$ |
| Iron[7] | Metal | Electronic | $1.03 \times 10^7$ |
| Carbon nanotube (continuous)[7] | Carbon-based | Electronic | $1.03 \times 10^7$ |
| Stainless steel[7] | Metal | Electronic | $1.45 \times 10^6$ |
| Graphite (parallel to basal plane)[7] | Carbon-based | Electronic | $2 \times 10^5$ to $3 \times 10^5$ |
| Polyacetylene (doped with iodine)[8] | Plastic | Electronic | $38 \times 10^2$ |
| Polypyrrole[9] | Plastic | Electronic | $2 \times 10^2$ to $1 \times 10^2$ |
| Sea water[7] | Liquid | Ionic | 4.8 |
| Polyaniline (doped with hydrobromic acid)[10] | Plastic | Electronic | 0.46 |
| Drinking water[7] | Liquid | Ionic | $5 \times 10^{-4}$ to $5 \times 10^{-2}$ |
| Silicon[7] | Semiconductor | Electronic | $4.35 \times 10^{-4}$ |
| Air[7] | Gas | Ionic | $10^{-15}$ to $10^{-9}$ |
| PET[7] | Plastic | Electronic | $10^{-21}$ |
| Teflon[7] | Plastic | Electronic | $10^{-25}$ to $10^{-23}$ |

## 2.1 Electrical properties

The ability of a material to conduct electricity is quantified as either conductivity or its reciprocal called resistivity. Good electric conductors have very high conductivity, good insulators have very low conductivity, and semiconductors come in between the two. Table 1 lists the conductivities of a variety of materials that span the range of achievable and expected values. High conductivity is often desired as it entails minimal thermal loss of amplitude and energy as the signal travels through a material.

Values of conductivity provided in Table 1 are relevant for DC circuits, in which the polarity of the electric field remains temporally constant. In AC circuits, the polarity of the electric field changes periodically with time. Therefore, the AC conductivity of a material is a function of frequency of polarization reversal. Two other electrical properties of materials then become relevant, the dielectric permittivity and the magnetic permeability, the former related to the storage of electrical energy and the latter to that of magnetic energy.[11] At very low frequencies (50-60 Hz), such as used by electricity-supply companies for domestic, industrial, and office environments, the AC conductivity of a material is almost indistinguishable from its DC conductivity.[12]

## 2.2 Existing electronic conductors

The vast majority of electrical appliances today rely on electronic conductors wherein current flows in the form of electrons. Metals are excellent electronic conductors as the valence electrons in metallic atoms are very loosely bound to their respective nuclei. The application of even a small electric field causes every valence electron to leave the outermost shell and migrate away from its atom. Since electrons repel each other, the valence electrons freed from the outermost shells gather on the surface of the metal. Thus, electric current flows in a thin skin of the conductor. Copper is commonly used for electronic wiring as it provides a high conductivity; although not a better conductor than silver, copper is far more abundant in the earth's crust. The skin for conduction in copper is about 8.5 mm thick at 60 Hz frequency.

Electronic conduction is however not restricted to metals, since there are several other materials that possess competing conductivity and do not exhibit certain limitations of metals. The most common group of electronic conductors apart from metals are certain crystalline allotropes of carbon, including graphite, graphene, carbon fibers, and carbon nanotubes. A limitation of carbon materials is that, although they possess desirable electrical and mechanical characteristics, they can be fabricated only as objects of small dimensions; hence, they are often dispersed in a polymer to form a composite material which can be processed to form large objects. Thus, carbon nanotubes can be spun into yarns with good conducting properties.[13] Saleemi *et al.* describe the possibility

to further improve the conductivity of carbon-nanotube yarn by a method of crosslinking by esterification, a bioinspired idea arising from the cross-linked hierarchical tubular cell structure of the sarcoplasmic reticulum.[14] This modification was found to increase the conductivity of the CNT yarn by 348% from 557 S/cm to 1950 S/cm. The promising conductivity and flexibility of this material are attractive for applications such as wearable electronics.

Although polymers in general are insulating materials, there is a certain subset of polymers that exhibit the ability to conduct electrons, through the contiguous $sp^2$-hybridized carbon centers in the polymer's backbone. In such polymers, either an electron is removed from the valence band by oxidation or an electron is added to the valence band by reduction. Well-known examples of conducting polymers include polyacetylene (PA), polyaniline (PANI), and polypyrrole (PPy). The conductivities of these materials are presented in Table 1. These polymers are however rarely used in commercial applications due several limiting factors including subpar conductivity, poor processability, poor thermal stability, poor mechanical stability, and poor biocompatibility.

### 2.3 Existing ionic conductors

Ionic conduction is also used in certain electrical applications where the conductivity need not be high. Most ionic conducting materials have inherently lower conductivity than electronic conductors and thus thermally dissipate more energy to reduce the signal amplitude at the output port. Ionic conduction has the added disadvantages of high resistance and capacitance arising from the double-layer effect at the interface of an ionic conductor and an electronic conductor.[15] Furthermore, that interface is also susceptible to corrosion, if the ionic conductor contains some water.

Ionic conduction is preferred in applications in which the ionic conductor adds a desirable functionality in addition to electrical conduction. Batteries are well-known examples, the charge being stored as a dense concentration of ions in a medium. This ionic medium comprises a high concentration of a reactant in a small volume of water, although certain types of batteries such as the lithium-ion batteries are water-free. The absence of water eliminates corrosion, which enhances the longevity of the battery.

In non-invasive electroencephalography biopotential techniques, conductive gels are often used to facilitate measurement of the signal. The conductive gel has a surplus of $Cl^-$ ions and maximizes the surface area of contact between the electrode and skin.[16]

### 2.4 Limitations of ionic conduction

Although ionic conduction may be attractive due to the advantages of ionic conductors being soft, flexible, biocompatible, and metal-free, ionic conductors do have certain limitations. A major limitation is that the conductivity of even an excellent ionic conductor is poor compared to that of metals such as copper and even steel. As can be gleaned from Table 1, copper is ten million times more conducting than sea water. The conductivity of an ionic conductor depends on temperature as well as on the concentration and type of ions,[17] among other factors.

In addition to significantly lower conductivity, the faradaic impedance stemming from the interface of an electronic conductor (metal) and an ionic conductor (electrolyte) also limits the use of ionic conductors. This impedance is caused by the capacitance of the double layer between the metal and the electrolyte as well as by the resistance of the chemical reduction or oxidation processes occurring when charge is transferred between the two mediums.[18] Ideal ionic devices must not involve metals in order to avoid faradaic impedance, but it is difficult to envision complex electric devices based completely on ionic conduction, due to the inherent limitations of ionic conductors. Therefore, the presence of several interfaces endowed with faradaic impedance as well as the low conductivity of ionic conductors are significant impediments.

Polarization (as illustrated in Figure 2) of the ionic medium may also prove an important limitation in certain applications. As the concentration of ions in a medium is finite, the movement of these ions is only able to occur with some delay after an external electric field is turned on or off. With increasing polarization of the electrolyte, the resistance will also increase drastically. In DC circuits this is detrimental because the polarization occurs quickly; however, it is possible to circumvent this limitation by using AC circuits, since the frequent re-polarization of ions means that the resistance remains nearly constant over time.

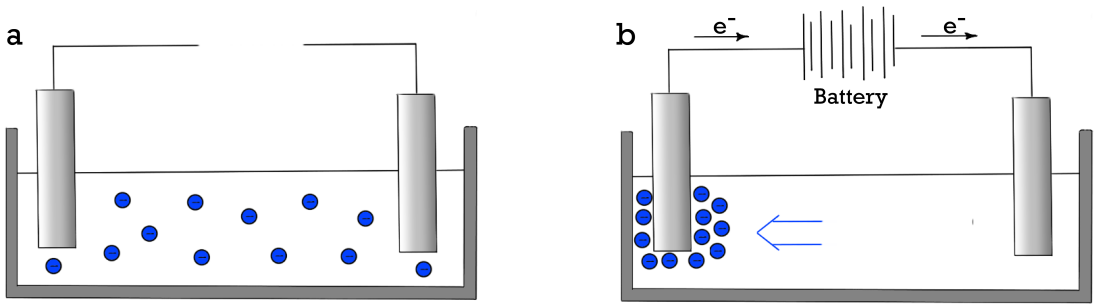


Figure 2. Polarization in a simple electrolytic circuit due to the application of a DC voltage. (a) No potential difference is present across the ionic solution, and so the ions are homogeneously distributed throughout the liquid. (b) Cations are mobilized near the cathode, and anions near the anode, when a battery is connected to the two electrodes.

## 3. ELECTRICAL SYSTEMS IN THE BIOWORLD

Electricity is conducted in the bioworld mainly through ionic conduction, because many different ions are found in abundance in extracellular and intracellular fluids. Indeed, biological neural networks transfer information through ionic transport in axons. However, electronic conduction is also found in specific organisms through means different than metals. In this section, we describe a few different electrical systems in the bioworld in order to understand how these bioelectrical systems might be inspirational for the reduction of metals in engineered systems.

### 3.1 Ionic conduction in the bioworld

Most electric signals in the bioworld propagate through ionic conduction, in large part due to neuronal networks being commonplace.

#### 3.1.1 Nerve impulse and action potentials

Neural networks in mammals consist of many cells called neurons that transfer signals to each other by means of channels called axons filled with an ionic fluid containing mainly $K^+$, $Cl^-$, and $Na^+$ ions.[20] Ionic concentration in an axon is kept stable by transferring specific ions through a lipid bilayer membrane to maintain a resting potential difference between the intracellular and the extracellular fluids. This resting potential difference has been measured to be about $-60$ mV, the outside of the axon being positively charged compared to the inside.

The lipid bilayer membrane of the axon has several different kinds of ion-transfer channels that allow passage of specific ions. These channels are divided into categories of being either *open* which allow passage of ions permanently; or *chemically gated* which are open or closed, depending on the presence of molecules of a specific type; or *voltage gated* that only allow for the passage of ions at a specific potential difference between the inside and outside of the axon. When the neuron is stimulated enough for it to send molecules to a chemically gated ion channel which then allows an influx of $Na^+$ ions due to the negative equilibrium potential of the axon, the potential difference is called the *action potential*.

If the stimulus to the neuron is intense enough to allow for the potential difference for an axon to reach the threshold potential of about –50 mV, the voltage-gated ion channels will open to cause a depolarization of the axon to approximately 50 mV before certain gates close and the re-polarization of the axon occurs. The momentary depolarization causes a wavefront of opposite polarization, whereby the newly entered $Na^+$ ions seek to move and diffuse in the negatively charged ionic fluid throughout the length of the axon.

If the initial positive charge of the action potential was the only charge introduced to the axon, the wavefront would simply diffuse over a short distance. However, throughout the length of the axon, many ion channels reside in the lipid bilayer. These channels almost continuously refresh the wavefront potential, since the voltage-gated

ion channels cause new influx of extracellular positively charged ions. The reason for the process to being nearly continuous is that the lipid bilayer membrane of the axon is wrapped in concentric layers of a structure named myelin that blocks the ion channels of the axon. Myelin is not continuous along the entire length of the axon but has regularly spaced gaps called the *nodes of Ranvier* where ion channels are clustered and which allow the depolarization wavefront to be refreshed.

This discrete conduction has two main beneficial effects: First, it allows for high signal speed due to the electrical current flowing rapidly in the cytoplasm compared to the time it takes to regulate ion channels. Second, the constant refreshing of the polarization wavefront causes the signal to maintain its strength. This is what allows the axon to communicate over a long distance with minuscule power consumption. As an example, the human brain constantly transmits signals among its ∼100 billion neurons with a power consumption of only 20 W.[21] The functional principle of the action potential is illustrated in Figure 3 as an abstracted version of the biological phenomenon.

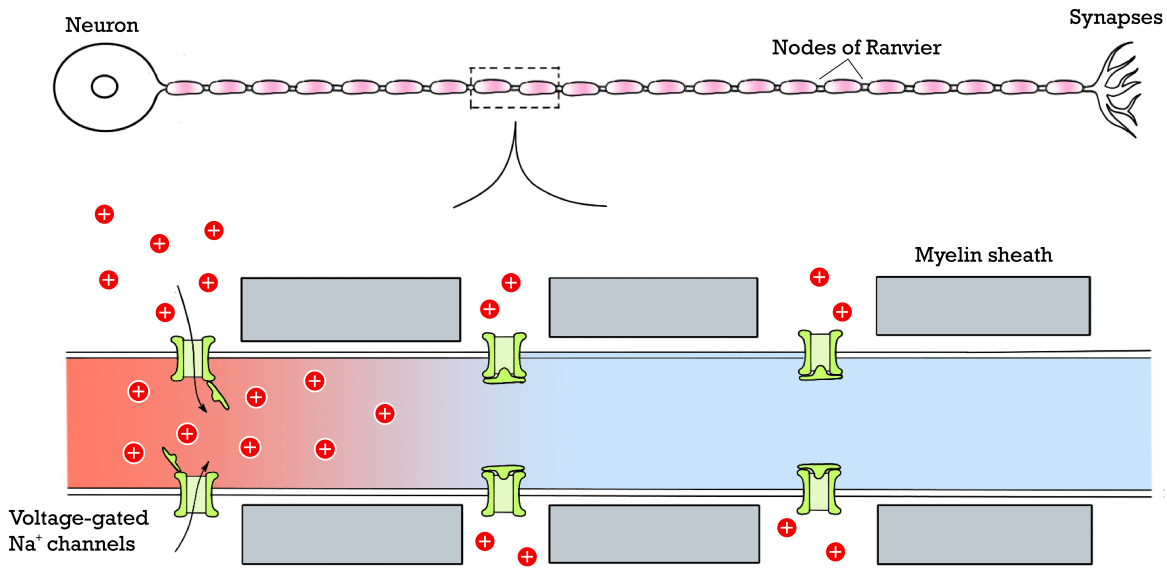


Figure 3. Visualization of a signal being sent from a neuron through an axon to a terminal which synapses to other cells. The action potential is triggered by opening chemically gated ion channels at the neuron which causes polarization. An influx of $Na^+$ ions occurs at every node of Ranvier to refresh the action potential. Based on the description from Hillis *et al.*[20]

### 3.1.2 Piscine electroreceptors

In many species of marine animals, specialized sensing organs are essential to monitor the surroundings. The lateral line system present in many fish allows for delicate sensing of the changes in pressure of surrounding water to detect nearby movement and other mechanosensory stimuli. Certain species of fish have also evolved specialized sensing organs which allow for measurements of the electric field surrounding them. Hence, these fish sense objects around them (e.g., to navigate through the obstructed rivers of the Amazon Basin) but, more importantly, these fish can sense the very weak electric fields of other animals in the water either to hunt prey or to avoid predators.[22]

Every fish functions as a weak battery with the ion gradients of the cells causing an electric field. Changes to this electric field can occur due to motion and respiration. Thereby, piscine species of the class *chondrichthyans*, among others, are able to sense and capture prey.[23] Sharks are well known to utilize electroreception with several

sensing organs located around the mouth. When hunting, a shark first uses its olfactory and aural mechanisms to detect prey at a long distance, then ocular and mechanical mechanisms at shorter distances, and finally its electroreceptive organs to sense that the prey is located exactly outside of the mouth before striking.[24] The nocturnal hunting behavior of sharks can also be attributed to the ability of the electroreceptors to detect prey when other senses such as vision are inhibited. Other advantages of electroreception depending on the species include: foraging, conspecific detection, predator avoidance, learning and habituation, and navigation using the geomagnetic field.[25]

The electroreceptive sensing organs have different manifestations determined by evolutionary adaption, but all of these manifestations have much in common. Among predatory species, the main electroreceptive functionality comes as the ability to orientate weak electric fields for capturing prey.

Another name for the electroreceptive sensing organ is the *ampullae of Lorenzini*, after its discoverer. The organ is a network of ampulla-shaped canals that extend from internal sensory cells to exterior dermal pores that are clearly visible (Figure 4). These pores are filled with a crystalline gel which allows for the passage of an electric current into the cells. The apical ends of the ampullae meet together in subdermal clusters of bulbous pouches whose walls have hundreds to thousands of electrosensitive hair-cell receptors and their supporting cells. The ampullae radiate from these clusters in all directions, allowing highly sensitive sensing in three-dimensional (3D) space. The number of these pores correlates with factors such as phylogenetic relatedness, morphological similarity, species distribution within and across habitats, and diet preferences.[25] The number of pores ranges from the relatively low 148 in the Port Jackson shark *Heterodontus portusjacksoni* to the much higher 3067 found in the scalloped hammerhead shark *Sphyrma lewini*.

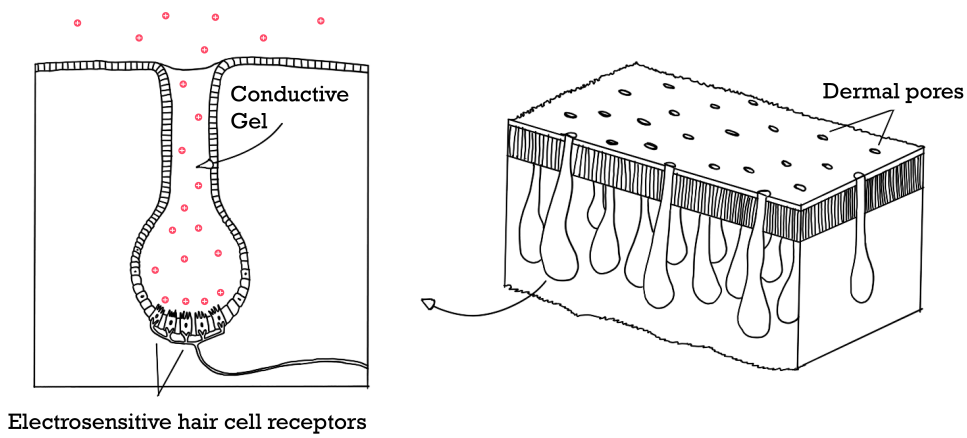


Figure 4. Bulbous pouches connected to the dermal pores in an electroreceptive organ. The pouches are covered with electrosensitive hair-cell receptors that are able to detect the electric field of another organism. Based on the description by Newton *et al.*[25]

The sensitivity of these electroreceptors is phenomenally high, with some cartilaginous fish able to detect changes in the electric field as small as 5 nV/cm. The crystalline gel filling the canals of the ampullae of Lorenzini have been discovered to be the biological substance with the highest proton conductivity. Very likely, the presence of polyglycans in the gel enhances proton conductivity compared to water. The enhanced conduction is not for all ions but specifically for $H^+$. The conductivity of the gel has been measured to be $2 \pm 1$ mS/cm,[26] which is thus only 40-200 times lower than the state-of-the-art proton conducting polymer named Nafion.[27] The gel reduces in volume about 80% on drying, thereby confirming that it is a hydrogel.

An interesting feature of these electroreceptors is that their sensitivity can be tuned to match the magnitude and the frequency of the electric field emitted by a specific organism. This is done by an adaptation of the voltage-gated ion channels of the afferent nerve cells to match the action potential threshold to the desired

sensitivity and frequency range.[25] Since piscine electroreceptive sensors are highly sensitive and map electric fields in 3D space, they can serve to inspire technoscientists to come up with or improved sensing systems.[4]

### 3.1.3 Earthworms

Earthworms use an electrically mediated mechanism to stay clean when moving in moist soil. Now, soil does not adhere to the earthworm surface as it does to many other types of surfaces. The explanation is a thin aqueous film that prevents the soil from getting in direct contact with the earthworm surface. The aqueous film is kept in place in an electric double layer (EDL) with an electric potential which is a combination of resting and action potentials.[28]

The EDL is formed by cells in the earthworm cuticle, the cell wall functioning as a dielectric barrier (Figure 5). An electric charge is built up on the inner surface of the cell wall due to ionic exchanges through the rest of the cell wall. The electric charge creates an electrostatic force on the outer surface of the cell wall so that a layer of immobile ions is formed. Called the Stern layer, its thickness is only about one ionic diameter. Outside the Stern layer there is a diffuse EDL wherein the ions can move while also being attracted to the underlying surface. The result is an electro-osmotic flow with the aqueous layer acting as a lubricant between the earthworm and the soil.

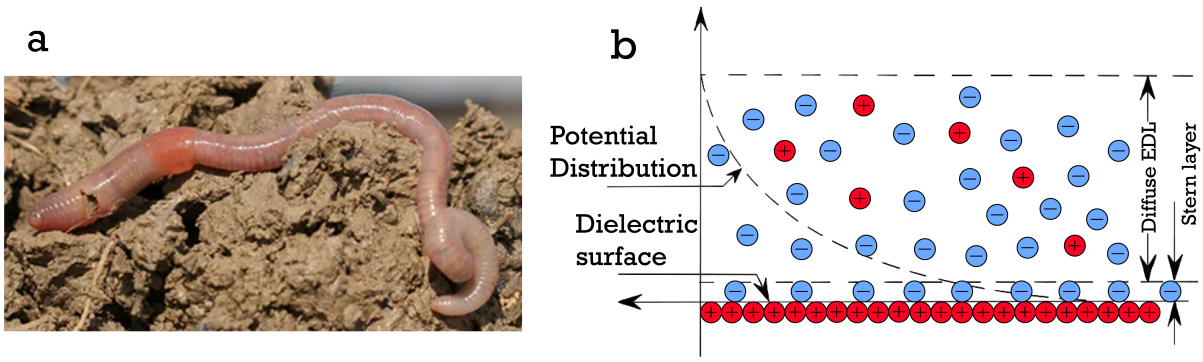


Figure 5. (a) An earthworm stays clean in dirty surroundings, thanks to an EDL. (b) Visualization of the Stern layer and the diffuse EDL, along with the electric potential. Figure based on a description by Zu *et al.*[28]

### 3.1.4 Electric eels

Although the 21 species of electric catfish and the 60 species of electric rays hunt using electricity, the best examples of ionic conduction in the bioworld are provided by the three species of electric eels: *Electrophorus electricus*, *E. varii*, and *E. voltai*.[29] In addition to active electroreception, electric eels are capable of paralyzing prey using strong electric shocks. In open-circuit conditions, *E. voltai* has been measured to deliver peak discharges of an impressive 860 V;[29] in short-circuit conditions, the output current is around 1 A.[30] However, as the electric eel is not able to maintain the intense electric fields, the shocks last about 3 ms. Even so, the electric eel's ability to control and withstand such intense shocks is an incredible feat, from which there is much to learn.[31]

The electric organ of the electric eel consists of an extensive array of cells named electrocytes. A simplified version of these electrocytes is illustrated in Figures 6 and 7 with a innervated membrane (labeled A) and a non-innervated membrane (labeled B) that separate the intracellular and the extracellular fluids from each other. Each electrocyte is able to generate a momentary voltage of about 150 mV. By combining the cells in series and parallel, the entire array can deliver intense shocks.

The electrocytes are, most of the time, in a resting state wherein the $Na^+/K^+$-ATPase ion pumps and $K^+$ ion channels maintain the ionic-concentration difference between the extracellular and the intracelullar fluids. Concentrations are approximately 170 mM $Na^+$ and 5 mM $K^+$ in the extracellular fluid, and about 10 mM $Na^+$

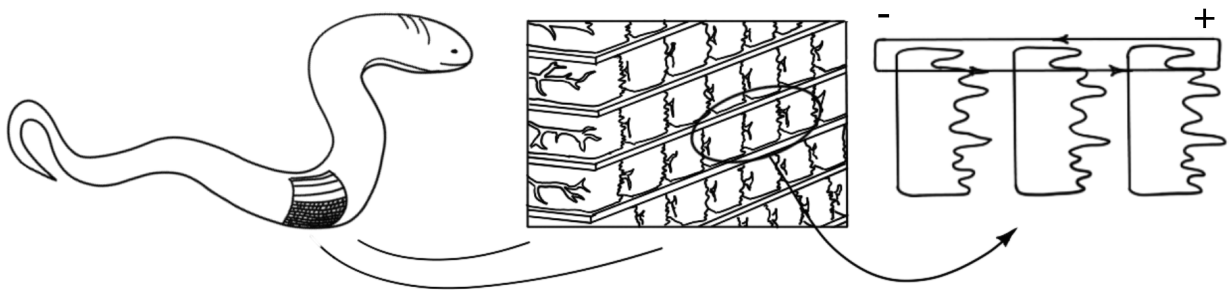


Figure 6. The electrocytes of the electric eel are stacked in an array with a combination of serial and parallel connections. The non-innervated membrane of every electrocyte has a rough wavy surface to maximize contact with the extracellular fluid. Based on the description by Schroeder *et al.*[31]

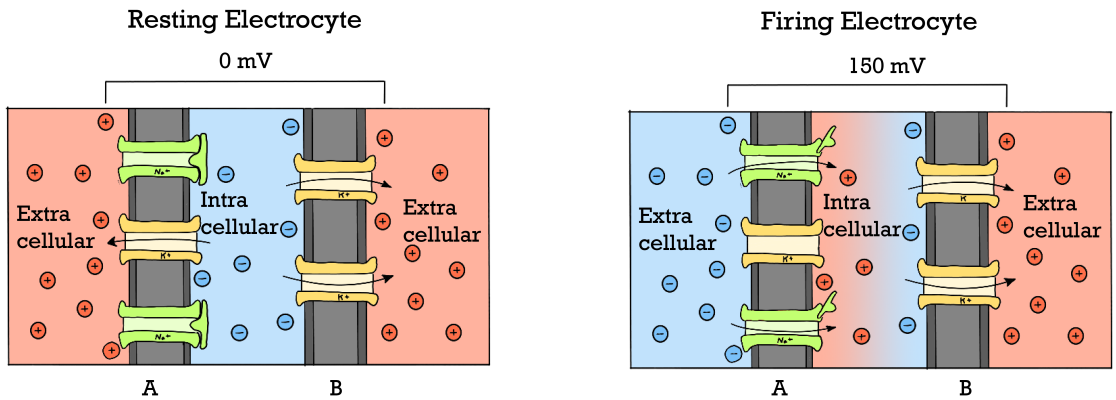


Figure 7. The two main states of the electrocyte. In the resting state the innervated $Na^+$ ion channels are closed and no potential is present between the extracellular fluids of each side of the electrocyte. In the firing state the $Na^+$ ion channels are opened, causing a potential of about 150 mV. Based on the description by Schroeder *et al.*[31]

and 170 mM $K^+$ in the intracellular fluid. The differences are significant for both $Na^+$ and $K^+$ but in opposite directions.

The sodium ions are attracted to enter the intracellular fluid but are constrained by membranes. The difference in $Na^+$ concentration causes a difference in electric charge density between the intracellular and the extracellular fluids. This difference is however balanced by the free movement of potassium ions through the innervated and non-innervated membranes, which results in a resting equilibrium state where the intracellular fluid has a much higher concentration of potassium ions than the extracellular fluid but diffusion is halted by the difference in electric potential. This is a remarkable attribute of the electrocytes, because each of these cells is able to have a high-salinity fluid on both sides of its wall due to the combination of electric-potential gradient and the ionic gradients. The high salinity of the medium is crucial for the functionality of the electrocytes, as it minimizes the resistivity of the fluid and thus maximizes the energy density.

The electric eel is able to control the charge by sending signals to the innervated end of the electrocytes in order to open the $Na^+$ channels and close the $K^+$ channels. This creates an influx of sodium ions into an electrocyte due to the concentration difference. This influx causes the extracellular fluid of membrane A to lose cations. At the same time, the difference in electric potential between the intracellular and the extracellular

fluids of membrane B causes the potassium ions to flow out of the cell. This entire process results in the potential difference of approximately 150 mV between the extracellular fluids of membranes A and B. This process occurs in each electrocyte. In order to ensure a simultaneous discharge of all electrocytes, it is necessary to slow down the signal speed of the action potentials to reach the farthest electrocytes.

#### 3.1.5 Venus flytrap

The carnivorous plant *Dionaea muscipula* (Venus flytrap) shown in Figure 8 uses ionic conduction for transmitting a signal from the sensory hairs to the activation mechanism that closes the jaw-shaped leaves.[32] The plant reacts very fast, the leaves close around the prey in about 100 ms. The mechanism works by changing the double curvature in the bistable leaves, the activation mechanism being an integral part of the leaves. The bistability of a leaf arises the orientation of the cells within it. When a leaf is open waiting for prey, it has a convex shape, i.e., it curves outwards. Once activated, the leaf flips to a concave shape and curves inwards. This is because the cells within the outer surface of the leaf are highly elongated in one direction and a change in the turgor pressure therefore causes a directional expansion.[33] The liquid pressure within the leaf cells is changed by the action potentials transported ionically through connected cells. The action potential is initiated the bending of at least two sensory hair.[34]

Figure 8. The Venus flytrap.

### 3.2 Electronic conduction in the bioworld

In the bioworld, electronic conduction typically occurs in long-chain molecules ranging from DNA to photosynthetic enzymes. According to the donor-bridge-acceptor model of electronic charge transport, electrons tunnel through the molecule and utilize thermally activated hopping to traverse longer distances.[35]

Certain anerobic sediment microbes have proven to transport electrons over distances ranging from micrometers to centimeters. In particular, the bacterium *Geobacter sulfurreducens* has been studied for its ability to conduct electrons over long distances by its Type-IV pili.[35] These pili are nanowire protein appendages that activate a method different from the redox-activated cytochrome hopping found in most microbes. Thus, it is possible to deploy peptides and proteins as electronic conductors with several attendant advantages. These advantages include their flexibility allowing self-assembly into nanostructures with highly tunable properties; safe degradation within the body after use, with controllable degradation rate; and the diversity of enzyme immobilization and cellular interfacing due to the diversity of peptides.[36] Some peptides and proteins exhibit excellent biocompatibility, in addition. These advantages makes peptides and proteins potentially useful as electrical conductors for wearables and bioelectronics.

## 4. EXAMPLES OF ENGINEERED BIOMIMICRY

In this section, we provide perspective on how the aforementioned biological phenomena have been adapted to engineering systems in certain biomimicry research.

### 4.1 Hydrogels as ionic conductors

Ionic conductors are nowadays being made as hydrogels, which are formed as 3D networks of hydrophilic polymer chains. Given the high degree of hydrophilicity, the 3D network attracts a large amount of water, so much so that the material consists of more water than the polymer. By having a hydrophilic interior as well as hydrophobic outward-facing side groups, the polymer network is able to retain the water. Thus, the hydrogel functions as a deformable solid rather than as a liquid. This is an important feature of hydrogels since it largely removes the constraint of ionic conductors being in the liquid state. Hydrogels also have several other desirable attributes such as: high toughness, biocompatibility, self-healing characteristics, optical transparency, resistance to freezing, stretchability, and strain sensitivity.[19] These are all properties that make the materials relevant for wearable conductors.

### 4.2 Bioinspired neuronal communication

The characteristics of neuronal signal conduction would be beneficial for applications requiring lossless, low-power, and long-distance communication. Beiu *et al.*[37] have suggested that, with the continuous downscaling of size in electronic circuitry, the wires connecting devices together require much more energy than the devices themselves. This is because the parasitic capacitance and the response delay do not scale favorably as the device gets smaller. An axon-inspired hexagonal communication array could theoretically be able to operate on as low as 0.01 aJ/nm by utilizing single-electron transistors as voltage-gated ion channels.

In the past decade, much effort has been put to develop memristive devices to mimic the low power consumption and high processing speed of the massive number of neurons in the brain. Bain *et al.*[38] have cataloged the types of memristive hardware available to emulate synaptic functions for neuromorphic communication. Although the technology is highly promising, it is still limited by knowledge gaps in neurobiology, materials science, device design, neural network optimization, and software algorithms. So far, the emulation of only a few functions of neurons and synapses has been proven possible, but future breakthroughs could pave the way for a paradigm shift in information processing and communication.

### 4.3 Biomimetic electroreception

Several attempts have been made to mimic electroreception. Mintchev *et al.* developed an underwater robotic system that utilizes several electrodes to sense nearby objects.[39] The front electrodes in the system are elevated to a higher potential than the rear electrodes (which are all grounded). The electric field around the robot is altered if objects enter the vicinity, these alterations reflected in the current flowing in each electrode. The signals from the electrodes are fed to a electrolocation algorithm, making it possible for the robot to detect surrounding objects and determine their locations in 3D space. The same system can also be used to detect the location and orientation of other robot modules to enable docking, as illustrated in Figure 9.

Another example is furnished by active electrolocation for the inspection of tubular systems. Metzen *et al.* applied the principle in a catheter-based medical sensor that is able to detect diseased tissue in the wall of a blood vessel into which it has been inserted.[40] In addition, the conductivity differences among various types of tissue allow the sensor to determine which type is present and where. This diagnostic tool could prove highly useful to determine the prevalence of atherosclerotic lesions.

### 4.4 Biomimetic electricity generation

Schroeder *et al.* adapted the principle underlying electrocytes in electric eels for a hydrogel-based power source.[31] Four different hydrogels with distinct functionalities were fabricated to mimic the structure of the electrocytes. One hydrogel with high salinity functioned as the extracellular fluid, one with low salinity functioned as the intracellular fluid, a cation-selective gel would allow the passage of only sodium ions, and an anion-selective gel would allow the passage of only chlorine ions. In this biomimetic system,[4] the activation of the potential difference was not due to nerves, but rather by physical contact between the four hydrogels in the correct order. When the hydrogels were in contact, the sodium ions would move through the cation-selective gel due to the difference in ionic concentration between the low-salinity and the high-salinity gels. Analogously, the chlorine ions would move through the anion-selective gel towards the low-salinity gel. The selective movements of cations and

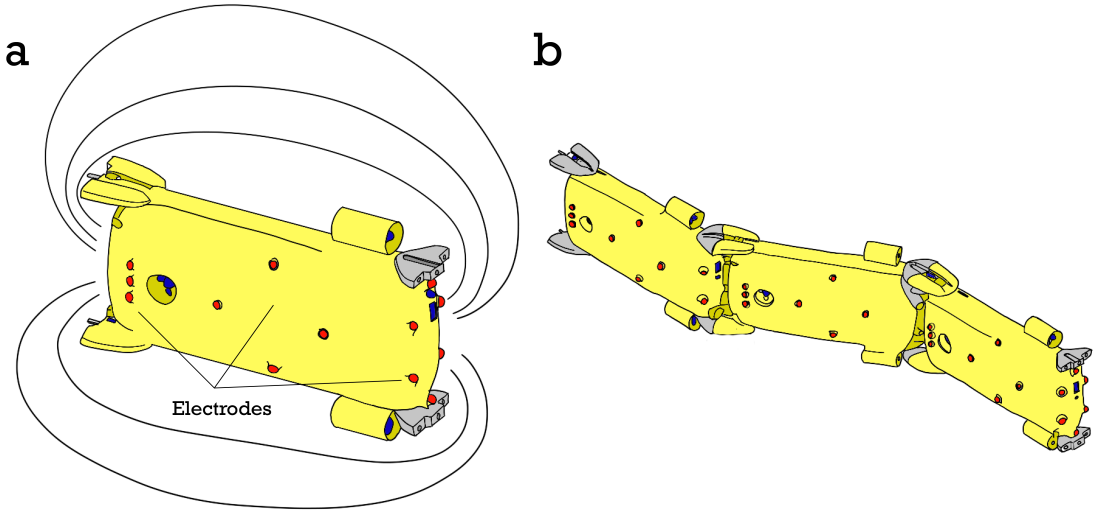


Figure 9. (a) A robot with propellers for propagation and electrodes for electroreceptive sensing scattered around the hull. The active electric field is generated between the front and rear electrodes. (b) A series of three underwater robots docked together and able to move like an eel. The electroreceptive sense of each robot is used to identify the presence and the position of the other two robots to enable docking. Adapted from Mintchev *et al.*[39]

anions due to differences in ionic concentration were able to deliver 110-V open-circuit voltage with 27 mW/m$^2$ power in every activated cell.

However, 27 mW/m$^2$ per repeat unit is too low for an engineered system to be used to power even low-power electronic devices. The Arctic electric ray *Tetronarce nobiliana* discharges more power than *E. voltai*. Although the mechanism for the electrical discharge is the same in both species, the increase in power density is the result of minimizing the conductive pathway between the membranes and maximizing the cross-sectional area of the membranes in order to significantly reduce the resistance to ionic transport. Hence, although the mimicking structure remained the same, NaCl was replaced by LiCl.[41] The maximum power density of 1.8 W/m$^2$ obtained by Guha *et al.*[41] was 67 more than with NaCl by Schroeder *et al.*,[31] and the improved system was able to power 3 LEDs in series.

The electric eel inspired the development of flexible and stretchable triboelectric nanogenerators that are able to generate electricity from touch, even through stretches and multiple twists and folds.[42] In another biomimetic project, electrocytes were stacked to develop a flexible fiber with capacitance for energy storage in textiles.[43] This was done by utilizing the inherent double-layer capacitance between a repeating sequence of aligned electron-conducting multi-walled carbon nanotubes (MWCNTs) and ion-conducting hydrogels, as illustrated in Figure 10.

### 4.5 Biomimetic grippers

Shahinpoor has used ionic polymers to make fast-acting grippers for robots mimicking the Venus flytrap.[44] The gripper is made as two lobes joined in a central spine about which the lobes can bend. Inside the lobes are sensory hairs. Both lobes and hairs are made from an ionic-polymer–metal composite (IPMC) material. When bent, the hairs produce a voltage that causes the lobes to bend via a solid-state relay. When a voltage is applied to the IPMC, hydrated calcium ions move towards the convex surface of a lobe and cause it to bend (Figure 11). The two bent lobes thus function as a gripper.

When a lobe is bent, the calcium ions move to one of the two surfaces and create an action potential between the two surfaces. Thus, the gripper can also function as a sensor.

The IPMC used is perfluorinated alkene polymer with short side-chains terminated by ionic groups, such as sulfonate or carboxylate, for cation exchange.[45] The polymer has large backbone chains with short side-chains

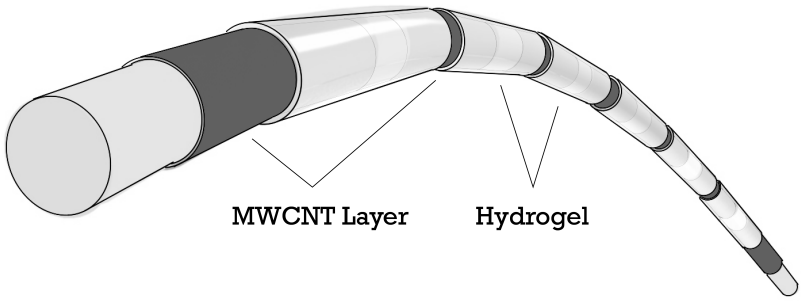


Figure 10. Fiber-shaped capacitor utilizing the faradaic impedance between an ionic hydrogel and electronic multi-walled carbon nanotubes. Adapted from Sun *et al.*[43]

that provide ionic groups which interact with water and allow the passage of appropriate ions. The polymer is infiltrated with a metal such as platinum, which forms small particles close to the surface in the polymer. Furthermore, a platinum coating serves as an electrode. Conductivity is reported to be around 0.1 S/cm.

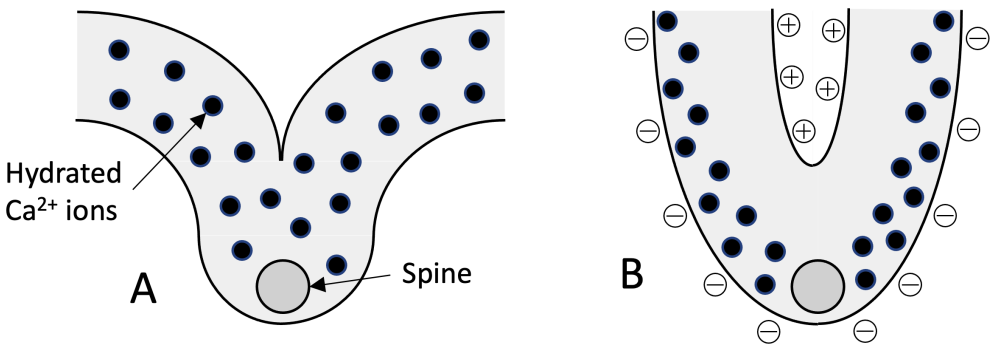


Figure 11. Snapping action of a gripper mimicking the Venus flytrap. (a) Uniform distribution of $Ca^{2+}$ ions through the thickness of a IPMC sheet in the absence of action potential. (b) Swelling and bending of the outer surface induced by through-thickness action potential. Figure based on a description by Shahinpoor.[44]

## 5. DISCUSSION AND CONCLUSION

The use of electricity is widespread in the bioworld for transmitting signals and energy as well as for causing adhesion. Electrical conduction occurs differently in engineered products than in the bioworld. From a technical viewpoint, there are advantages and disadvantages in both approaches. Metals use electronic conduction and generally have very good conductivity, which makes metals an obvious choice for electric conductors. On the other hand, mammalian brains demonstrate that a system based on ionic conduction makes very complex communication and information processing possible using very little energy. This is due to continuous self-amplification of the electric signal throughout the length of an axon. With attention being presently devoted to axon-inspired communication and memristive neuronal devices, the first steps have been taken towards the adaptation of the bioworld approach to engineered systems. This adaptation is highly necessary, not only due to the finite amount of metals available on the planet but also due to the continuous downscaling of electronics in terms of size and upscaling in terms of global prevalence.

Ionic conductors in the bioworld generally have a higher resistivity compared to electronic conductors. This is of less importance for communicating signals but is detrimental for charge transport due to the significant loss

energy to ohmic heating. It is therefor difficult to compete with metals; however, ongoing research on peptide and protein conductors with metal-like conductivity could provide novel insights.

Inspiration from the bioworld is meaningful not in terms of how to achieve very high conductivity, but rather in how systems exist that mitigate the limitations of ionic and non-metallic conductors but still provide highly functional solutions. Several electric systems exist in the bioworld for using the advantages of ionic conductance. A main advantage is the combination of the ionic concentration gradient and the electric potential gradient to jointly provide an important functionality. In the examples of action potentials and electrocytes, a combination of different ions present in the intracellular and the extracellular fluids allows for control of the influx and efflux of specific ions. Specifically, in the electrocyte example, a large concentration of potassium ions is maintained in the intracellular fluid compared to the extracellular fluid even though the potassium-ion channels are open for transport. This is due to the potassium ions being in low concentration in the intracellular fluid, thereby causing a potential gradient counteracting the ionic concentration gradient. The control of different ionic species could provide new possibilites for electrical systems and motivate to an ion-based paradigm shift.

A significant challenge when using ionic conductors is the faradaic impedance caused by an EDL between the ionic and electronic conductors. A possible solution could be to increase the surface area of the electrodes, for instance, through the use of porous electrodes.

The excellent electroreceptive sensitivity of the chondrichthyans of about 5 nV/cm is a good source of inspiration, because measurement of biopotentials is becoming increasingly used in medical and other applications.[46] The use of a conductive gel in the ampullae of Lorenzini is analogous to the use of conductive gels for EEG studies, among others. Quite likely, the structure of the biogel could be mimicked to developed a novel ionic conductive material that is highly biocompatible. A key source of inspiration from this phenomena could be gained by mimicking how the tiny dermal pores are connected to inner pouches, which increases the number density of electroreceptive hair cells to maximize surface area and improve sensitivity. In invasive EMG studies among others, it could be of interest to investigate if the conduction of the biopotential ions could be extended beyond the body to a space in which the surface area between the ionic and the electronic conductors can be maximized, thus mitigating the limitation of faradaic impedance in neurophysiology.

Modern society relies heavily on metals in electrical circuitry, but that creates problems in handling waste and for recycling/upcycling materials and products. In contrast, electrical conduction in the bioworld relies on non-metallic ionic conduction, which potentially makes recycling of materials more straightforward.

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