



Electrical terminology in Biofeedback

Introduction

The following is extracted in the main from the on line encyclopedia **Wikipedia**. <http://en.wikipedia.org> and is intended to give a simple overview. In some cases this is by analogy and this should not be taken as any lack of robustness to the concept.

For non English speakers the on line **Wikipedia** has an automatic translation facility.

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Voltammetry

Voltammetry is a category of electroanalytical methods used in analytical chemistry and various industrial processes. In voltammetry, information about an analyte is obtained by measuring the current as the potential is varied.

Voltammetry, and especially polarography, were advanced by Nobel Prize winner Jaroslav Heyrovsky.

>>>> See also the article *Voltammetry Retrospective.pdf*

Electromagnetism

Electromagnetism is the physics of the electromagnetic field: a field, encompassing all of space, which exerts a force on those particles that possess the property of electric charge, and is in turn affected by the presence and motion of such particles. The term **electrodynamics** is sometimes used to refer to the combination of electromagnetism with mechanics, and deals with the effects of the electromagnetic field on the dynamic behavior of electrically charged particles. Electromagnetism encompasses various real-world **electromagnetic phenomena**.

Electric and magnetic fields

It is often convenient to understand the electromagnetic field in terms of two separate fields: the electric field and the magnetic field. A non-zero electric field is produced by the presence of electrically charged particles, and gives rise to the electric force; this is the force that causes static electricity and drives the flow of electric charge (electric current) in electrical conductors. The magnetic field, on the other hand, can be produced by the motion of electric charges, or electric current, and gives rise to the magnetic force associated with magnets.

The term "electromagnetism" comes from the individual component electrical and magnetic forces involved. A changing magnetic field produces an electric field (this is the phenomenon of electromagnetic induction, which underlies the operation of electrical generators, induction motors, and transformers). Similarly, a changing electric field generates a magnetic field.

Because of this interdependence of the electric and magnetic fields, it makes sense to consider them as a single, theoretically coherent entity — the electromagnetic field. This unification, which was completed by James Clerk Maxwell, is one of the triumphs of 19th century physics. It had far-reaching consequences, one of which was the elucidation of the nature of light: as it turns out, what is thought of as "light" is actually a propagating oscillatory disturbance in the electromagnetic field, i.e., an electromagnetic wave. Different frequencies of oscillation give rise to the different forms of electromagnetic



radiation, from radio waves at the lowest frequencies, to visible light at intermediate frequencies, to gamma rays at the highest frequencies.

The theoretical implications of electromagnetism led to the development of special relativity by Albert Einstein in 1905.

The electromagnetic force

The force that the electromagnetic field exerts on electrically charged particles, called the **electromagnetic force**, is one of the four fundamental forces. The other fundamental forces are the strong nuclear force (which holds atomic nuclei together), the weak nuclear force (which causes certain forms of radioactive decay), and the gravitational force. All other forces are ultimately derived from these fundamental forces.

As it turns out, the electromagnetic force is the one responsible for practically all the phenomena one encounters in daily life, with the exception of gravity. Roughly speaking, all the forces involved in interactions between atoms can be traced to the electromagnetic force acting on the electrically charged protons and electrons inside the atoms. This includes the forces we experience in "pushing" or "pulling" ordinary material objects, which come from the intermolecular forces between the individual molecules in our bodies and those in the objects. It also includes all forms of chemical phenomena, which arise from interactions between electron orbitals.

Origins of electromagnetic theory

The scientist William Gilbert proposed, in his *De Magnete* (1600), that electricity and magnetism, while both capable of causing attraction and repulsion of objects, were distinct effects. Mariners had noticed that lightning strikes had the ability to disturb a compass needle, but the link between lightning and electricity was not confirmed until Benjamin Franklin's proposed experiments in 1752. One of the first to discover and publish a link between man-made electric current and magnetism was Romagnosi, who in 1802 noticed that connecting a wire across a Voltaic pile deflected a nearby compass needle. However, the effect did not become widely known until 1820, when Ørsted performed a similar experiment. Ørsted's work influenced Ampère to produce a theory of electromagnetism that set the subject on a mathematical foundation.

An accurate theory of electromagnetism, known as classical electromagnetism, was developed by various physicists over the course of the 19th century, culminating in the work of James Clerk Maxwell, who unified the preceding developments into a single theory and discovered the electromagnetic nature of light. In classical electromagnetism, the electromagnetic field obeys a set of equations known as Maxwell's equations, and the electromagnetic force is given by the Lorentz force law.

One of the peculiarities of classical electromagnetism is that it is difficult to reconcile with classical mechanics, but it is compatible with special relativity. According to Maxwell's equations, the speed of light is a universal constant, dependent only on the



electrical permittivity and magnetic permeability of the vacuum. This violates Galilean invariance, a long-standing cornerstone of classical mechanics. One way to reconcile the two theories is to assume the existence of a luminiferous aether through which the light propagates. However, subsequent experimental efforts failed to detect the presence of the aether. In 1905, Albert Einstein solved the problem with the introduction of special relativity, which replaces classical kinematics with a new theory of kinematics that is compatible with classical electromagnetism.

In addition, Relativity theory shows that in moving frames of reference a magnetic field transforms to a field with a nonzero electric component and vice versa; thus firmly showing that they are two sides of the same coin, and thus the term **Electromagnetism**.

Failures of classical electromagnetism

In another paper published in that same year, Einstein undermined the very foundations of classical electromagnetism. His theory of the photoelectric effect (for which he won the Nobel prize for physics) posited that light could exist in discrete particle-like quantities, which later came to be known as photons. Einstein's theory of the photoelectric effect extended the insights that appeared in the solution of the ultraviolet catastrophe presented by Max Planck in 1900. In his work, Planck showed that hot objects emit electromagnetic radiation in discrete packets, which leads to a finite total energy emitted as black body radiation. Both of these results were in direct contradiction with the classical view of light as a continuous wave. Planck's and Einstein's theories were progenitors of quantum mechanics, which, when formulated in 1925, necessitated the invention of a quantum theory of electromagnetism. This theory, completed in the 1940s, is known as quantum electrodynamics (or "QED"), and is one of the most accurate theories known to physics.

Frequency



Sine waves of various frequencies; the lower waves have higher frequencies than those above.

Frequency is the measurement of the number of times that a repeated event occurs per unit of time. It is also defined as the rate of change of phase of a sinusoidal waveform.

Examples

- The frequency of the standard pitch A above middle C is usually defined as 440 Hz, that is, 440 cycles per second (Listen ([help](#)·[info](#))) and known as concert pitch, to which an orchestra tunes.



- A baby can hear tones with oscillations up to approximately 20,000 Hz, but these frequencies become more difficult to hear as people age.
- In Europe, the frequency of the alternating current in mains is 50 Hz (close to the tone G), however, in North America, the frequency of the alternating current is 60 Hz (close to the tone B flat — that is, a minor third above the European frequency). The frequency of the ‘hum’ in an audio recording can show where the recording was made — in Europe or in America.

Digital Signal

A **digital system** is one that uses discrete numbers, especially binary numbers, or non-numeric symbols such as letters or icons, for input, processing, transmission, storage, or display, rather than a continuous spectrum of values (an analog system).

The distinction of "digital" versus "analog" can refer to method of input, data storage and transfer, the internal working of an instrument, and the kind of display. The word comes from the same source as the word digit and digitus: the Latin word for finger (counting on the fingers) as these are used for discrete counting.

The word *digital* is most commonly used in computing and electronics, especially where real-world information is converted to binary numeric form as in digital audio and digital photography.

Analog signal

An **analog** or **analogue** signal is any variable signal continuous in both time and amplitude. It differs from a digital signal in that small fluctuations in the signal are meaningful. Analog is usually thought of in an electrical context, however mechanical, pneumatic, hydraulic, and other systems may also convey analog signals.

An analog signal uses some property of the medium to convey the signal's information. For example, an aneroid barometer uses rotary position as the signal to convey pressure information. Electrically, the property most commonly used is voltage followed closely by frequency, current, and charge.

Any information may be conveyed by an analog signal, often such a signal is a measured response to changes in physical phenomena, such as sound, light, temperature, position, or pressure, and is achieved using a transducer.

For example, in an analog sound recording, the variation in pressure of a sound striking a microphone creates a corresponding variation in the voltage amplitude of a current passing through it. An increase in the volume of the sound causes the fluctuation of the current's voltage amplitude to increase while keeping the same rhythm.

Disadvantage



The primary disadvantage of analog signaling is that any system has noise, that is, random variation in it. As the signal is copied and re-copied, or transmitted over long distances, these random variations become dominant. Electrically, these losses can be diminished by shielding, good connections, and several cable types such as coaxial or twisted pair.

The effects of noise make signal loss and distortion impossible to recover, since amplifying the signal to recover attenuated parts of the signal amplifies the noise as well.

Modulation

Another method of conveying an analog signal is to use modulation. In this, some base signal (e.g., a sinusoidal carrier wave) has one of its properties modulated: amplitude modulation involves altering the amplitude of a sinusoidal voltage waveform by the source information, frequency modulation changes the frequency. Other techniques, such as changing the phase of the base signal also work.

Analog circuits do not involve quantisation of information into digital format. The concept being measured over the circuit, whether sound, light, pressure, temperature, or an exceeded limit, remains from end to end.

Clocks with hands are called analog; those that display digits are called digital. However, many analog clocks are actually digital since the hands do not move in a smooth continuous motion, but in small steps every second or half a second, or every minute.



Electrical resistance

A 75-ohm resistor, as identified by its electronic color code. A multimeter might be used to verify this value.



Electrical resistance is a measure of the degree to which an object opposes the passage of an electric current. The SI unit of electrical resistance is the ohm. Its reciprocal quantity is **electrical conductance** measured in siemens.

The quantity of resistance in an electric circuit determines the amount of current flowing in the circuit for any given voltage applied to the circuit.

$$R = \frac{V}{I}$$

where

R is the resistance of the object, usually measured in ohms, equivalent to $\text{J}\cdot\text{s}/\text{C}^2$

V is the potential difference across the object, usually measured in volts

I is the current passing through the object, usually measured in amperes

For a wide variety of materials and conditions, the electrical resistance does not depend on the amount of current flowing or the amount of applied voltage. V can either be measured directly across the object or calculated from a subtraction of voltages relative to a reference point. The former method is simpler for a single object and is likely to be more accurate. There may also be problems with the latter method if the voltage supply is AC and the two measurements from the reference point are not in phase with each other.

Causes of resistance

In metals

A metal consists of a lattice of atoms, each with a shell of electrons. This can also be known as positive ionic lattice. The outer electrons are free to dissociate from their parent atoms and travel through the lattice, creating a 'sea' of electrons, making the metal a conductor. When an electrical potential difference (a voltage) is applied across the metal, the electrons drift from one end of the conductor to the other under the influence of the electric field.

In a metal the thermal motion of ions is the primary source of scattering of electrons (due to destructive interference of free electron wave on non-correlating potentials of ions) - thus the prime cause of metal resistance. Imperfections of lattice also contribute into resistance, although their contribution in pure metals is negligible.



The larger the cross-sectional area of the conductor, the more electrons are available to carry the current, so the lower the resistance. The longer the conductor, the more scattering events occur in each electron's path through the material, so the higher the resistance. [1]

In semiconductors and insulators

Semiconductors have properties that are part-way between those of metals and of insulators. A silicon boule has a grayish metallic sheen, like a metal, but is brittle, like glass. It is possible to manipulate the resistive properties of semiconductor materials by doping those materials with atomic elements, such as arsenic or boron, which create electrons or holes which can move across the material lattice.

In ionic liquids/electrolytes

In electrolytes, electrical conduction happens not by band electrons or holes, but by full atomic species (ions) traveling, each carrying an electrical charge. The resistivity of ionic liquids varies tremendously by the salt concentration - while distilled water is almost an insulator, salt water is a very efficient electrical conductor. In biological membranes, currents are carried by ionic salts. Small holes in the membranes, called ion channels, are selective to specific ions and determine the membrane resistance.

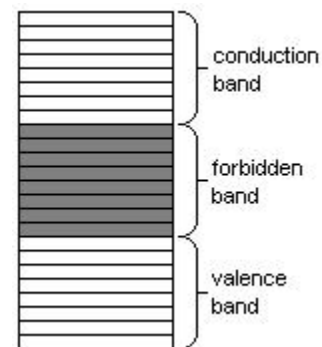
Resistance of various materials

Material	Resistivity, ρ ohm-meter
<u>Metals</u>	10^{-8}
<u>Semiconductors</u>	variable
<u>Electrolytes</u>	variable
<u>Insulators</u>	10^{16}

Band theory

Electron energy levels in an insulator.

Quantum mechanics states that the energy of an electron in an atom cannot be any arbitrary value. Rather, there are fixed energy levels which the electrons can occupy, and values in between these levels are impossible. The energy levels are grouped into two bands: the **valence band** and the **conduction band** (the latter is generally above the former). Electrons in the conduction band may move freely throughout the substance in the presence of an electrical field.



In insulators and semiconductors, the atoms in the substance influence each other such that between the valence band and the conduction band, there exists a forbidden band of



energy levels that the electrons simply cannot occupy. In order for a current to flow, a relatively large amount of energy must be furnished to an electron for it to leap across this forbidden gap and into the conduction band. Thus, large voltages yield relatively small currents.

Voltage

Voltage is the difference of electrical potential between two points of an electrical network, expressed in volts ^{VI}. It is a measure of the capacity of an electric field to cause an electric current in an electrical conductor.

Hydraulic analogy

If one imagines water circulating in a network of pipes, driven by pumps in the absence of gravity, as an analogy of an electrical circuit, then the potential difference corresponds to the fluid pressure difference between two points. If there is a pressure difference between two points, then water flowing from the first point to the second will be able to do work, such as driving a turbine.

This *hydraulic analogy* is a useful method of teaching a range of electrical concepts. In a hydraulic system, the work done to move water is equal to the pressure multiplied by the volume of water moved. Similarly, in an electrical circuit, the work done to move electrons or other charge-carriers is equal to 'electrical pressure' (an old term for voltage) multiplied by the quantity of electrical charge moved. Voltage is a convenient way of quantifying the ability to do work. In relation to electric current, the larger the gradient (voltage or hydraulic) the greater the current (assuming resistance is constant).

Electric current

Electric current is by definition the flow of electric charge. The SI unit of electric current is the ampere (A), which is equal to a flow of one coulomb of charge per second.

Current in a metal wire

In solid conductive metal, with no external forces applied, there exists a random motion of free electrons created by the thermal energy that the electrons gain from the surrounding medium. When an atom loses a free electron, it acquires a net positive charge. The free electron can move amongst these positive ions, while the position ions can only oscillate about their mean fixed positions. The free electron is therefore the charge carrier in a typical solid conductor. Given an imaginary plane through which the wire passes, the number of electrons moving from one side to the other in any period of time is exactly equal to the number passing in the opposite direction.

When a wire is connected across the two terminals of a DC voltage source such as a battery, the source places an electric field across the conductor. The moment contact is made, the free electrons of the conductor will drift toward the positive terminal under the



influence of this field. For every ampere of current, 1 coulomb of electric charge (which consists of about 6.242×10^{18} electrons) drifts every second at the same velocity through the imaginary plane through which the conductor passes.

Conventional current

Conventional current was defined early in the history of electrical science as a flow of positive charge. In solid metals, like wires, the positive charges are immobile, and only the negatively charged electrons flow in the direction opposite conventional current, but this is not the case in most non-metallic conductors. In other materials, charged particles flow in both directions at the same time. Electric currents in electrolytes are flows of electrically charged atoms (ions), which exist in both positive and negative varieties. For example, an electrochemical cell may be constructed with salt water (a solution of sodium chloride) on one side of a membrane and pure water on the other. The membrane lets the positive sodium ions pass, but not the negative chlorine ions, so a net current results. Electric currents in plasma are flows of electrons as well as positive and negative ions. In ice and in certain solid electrolytes, flowing protons constitute the electric current. To simplify this situation, the original definition of conventional current still stands.

There are also instances where the electrons are the charge that is moving, but where it makes more sense to think of the current as the movement of positive "holes" (the spots that should have an electron to make the conductor neutral). This is the case in a p-type semiconductor.

Examples

Natural examples include lightning and the solar wind, the source of the polar aurora. The most familiar artificial form of electric current is the flow of conduction electrons in metal wires, such as the overhead power lines that deliver electrical energy across long distances and the smaller wires within electrical and electronic equipment. In electronics, other forms of electric current include the flow of electrons through resistors or through the vacuum in a vacuum tube, the flow of ions inside a battery, and the flow of holes within a semiconductor.

Electromagnetism

Every electric current produces a magnetic field. The magnetic field can be visualized as a pattern of circular field lines surrounding the wire.

Electric current can be directly measured with a galvanometer, but this method involves breaking the circuit, which is sometimes inconvenient. Current can also be measured without breaking the circuit by detecting the magnetic field it creates. Devices used for this include Hall effect sensors, current clamps, current transformers, and Rogowski coils.



Ohm's law

Ohm's law predicts the current in an (ideal) resistor (or other ohmic device) to be applied voltage divided by electrical resistance:

$$I = \frac{V}{R}$$

where

I is the current, measured in amperes
 V is the potential difference measured in volts
 R is the resistance measured in ohms

Electrical conductance

Electrical conductance is the reciprocal of electrical resistance. It is a measure of how easily electricity flows along a certain path through an object. The SI derived unit of conductance is the siemens (symbol S, equal to $1/\Omega$; alias the "mho"). Oliver Heaviside coined the term in September 1885.

Electrical conductance should not be confused with conduction, which is the mechanism by which charge flows, or with conductivity, which is a property of a material.

Relation to other quantities

Conductance is related to susceptance and admittance by the equation:

$$Y = G + iB$$

where:

- Y is the admittance, measured in siemens
- G is the conductance, measured in siemens
- i is the imaginary unit
- B is the susceptance, measured in siemens

The magnitude of admittance is given by:

$$|Y| = \sqrt{G^2 + B^2}$$



Capacitance

Capacitance is a measure of the amount of electric charge stored (or separated) for a given electric potential. The capacitance is usually defined as the total electric charge placed on the object divided by the potential of the object:

$$C = \frac{Q}{V}$$

or, according to Gauss's law, the capacitance can be expressed as the electric flux per volt

$$C = \frac{\Phi}{V}$$

where

C is the capacitance in farads, F

Q is the charge in coulombs, C

V is the potential in volts, V

Φ is the electric flux associated with the charge Q in coulombs

Energy

The energy (measured in joules) stored in a capacitance is equal to the *work* done to charge it.

Capacitance/inductance duality

In mathematical terms, the ideal capacitance can be considered as an inverse of the ideal inductance, because the voltage-current equations of the two phenomena can be transformed into one another by exchanging the voltage and current terms.

Resistance, Reactance, and Impedance

These three forces, which are closely linked, are indeed important to the beginning electricity/electronics student. The good news is that they are relatively simple to understand, and can be dealt with using a few fairly easy and standard math formulas.

Resistance is a force that tends to resist the flow of electrical current. Resistance is usually created deliberately by a resistor, a device used to create resistance in a circuit. Resistance is pretty straightforward: The more resistive a resistor is (i.e. the more ohms it's rated for), the more it restricts the flow of electricity through it. Perhaps the best news of all is that if you're working with DC (Direct Current), resistance is the only thing you



need to concern yourself with; the slightly more complicated concepts of reactance and impedance only exist in the world of AC (alternating current).

Reactance, unlike resistance, is usually undesirable in a circuit. Whereas resistance is created by a resistor to achieve some effect, reactance is an unfortunate by-product of certain electrical components. There are two basic types of reactance: **Capacitive reactance** and **inductive reactance**. Appropriately enough, capacitive reactance is created by capacitors, while inductive reactance is created by inductors. Using either of these device types in an AC circuit will introduce some reactance. Like resistance, reactance is expressed in ohms, and it behaves in much the same way as resistance, in the sense that it tends to restrict the flow of current through a circuit.

The formula for calculating inductive reactance is as follows:

$$X_L = 2 * \pi * f * L$$

X_L is the inductive reactance. X is the general electrical symbol for "reactance", and L is the symbol for "inductance" or "inductor", so put them together and you get the reactance of an inductor.

π is, as you probably guessed, the famous ratio of a circle's circumference to its diameter, to wit: 3.14, etc.

f is the frequency of the AC flowing through the circuit.

L is the inductance of the inductor, in henries.

So you see, when you multiply 2 by π , by the frequency of the AC, by the inductance of the inductor, the resultant value is the inductive reactance of the circuit.

The formula for capacitive reactance is similar, but there's a twist to it:

$$X_C = \frac{1}{2 * \pi * f * C}$$

X_C is, as you might have guessed, the capacitive reactance, and C is the capacitance of the capacitor (in farads).

The two formulas for inductive reactance and capacitive reactance create interesting counterpoints. Notice that for inductive reactance, as the frequency of the AC increases, so does the reactance. Higher frequencies result in lower current. The opposite is true of capacitive reactance: The higher the frequency of AC, the less reactance a capacitor will present.

Similarly, a more inductive inductor will present more reactance, while a capacitor with more capacitance will yield less reactance.



Once you know the resistance and reactance of a circuit, the **impedance** is actually the overall opposition to current presented by the circuit. The impedance of a circuit is also expressed in ohms; Unfortunately, you cannot simply add the resistance and the reactance to get the impedance. The formula is a bit trickier than that, but for those who learned the Pythagorean Theorem, well, you'll finally have a place to use it here.

The total impedance of a circuit is **the square root of the sum of the squares of the resistance and reactance**. In other words, impedance can be represented as the hypotenuse of a right triangle. Resistance can be one of the shorter sides of the right triangle, and reactance can be the other shorter side. The longest side, the hypotenuse, is then the impedance. If you learned (and remember) the Pythagorean Theorem, you know that the square of the longest side of a right triangle is equal to the added squares of the other two sides. This formula is sometimes expressed as **a squared + b squared = c squared**, with **a** and **b** being the shorter sides of the triangle, and **c** being the longest side. Impedance, then, is:

$$Z = \text{sqrt}((R^2) + (X^2))$$

That is, impedance (which has a standard electrical symbol of Z , for some warped reason) is the square root of (resistance squared plus reactance squared).

Reactance

In the analysis of an alternating-current electrical circuit (for example a RLC series circuit), **reactance** is the imaginary part of impedance, and is caused by the presence of inductors or capacitors in the circuit. Reactance is the component of complex electric impedance of the alternating current circuit, which produces a phase shift between an electric current and voltage in the circuit. Reactance is denoted by the symbol X and is measured in ohms.

- If $X > 0$, the reactance is said to be *inductive*.
- If $X = 0$, then the circuit is purely resistive, i.e. it has no reactance.
- If $X < 0$, it is said to be *capacitive*.

The relationship between impedance, resistance, and reactance is given by the equation:

$$Z = R + jX$$

where

Z is impedance, measured in ohms
 R is resistance, measured in ohms
 X is reactance, measured in ohms
 j is the imaginary unit



Often it is enough to know the magnitude of the impedance:

$$|Z| = \sqrt{R^2 + X^2}$$

For a purely inductive or capacitive element, the magnitude of the impedance simplifies to just the reactance.

The reactance is given by

$$X = X_L - X_C$$

where X_L and X_C are the inductive and capacitive reactances, respectively.

Inductive reactance (symbol X_L) is caused by the fact that a current is accompanied by a magnetic field; therefore a varying current is accompanied by a varying magnetic field; the latter gives an electromotive force that resists the changes in current. The more the current changes, the more an inductor resists it: the reactance is proportional to the frequency (hence zero for DC). There is also a phase difference between the current and the applied voltage.

Inductive reactance has the formula

$$X_L = \omega L = 2\pi f L$$

where

X_L is the inductive reactance, measured in ohms
 ω is the angular frequency, measured in radians per second
 f is the frequency, measured in hertz
 L is the inductance, measured in henries

Capacitive reactance (symbol X_C) reflects the fact that electrons cannot pass through a capacitor, yet effectively alternating current (AC) can: the higher the frequency the better. There is also a phase difference between the alternating current flowing through a capacitor and the potential difference across the capacitor's electrodes.

Capacitive reactance has the formula

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

where



X_C is the capacitive reactance measured in ohms
 ω is the angular frequency, measured in radians per second
 f is the frequency, measured in hertz
 C is the capacitance, measured in farads