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EEG- A Brief Introduction

Lecture Notes for BSP, Chapter 4

Master Program Data Engineering

4 Introduction

Human brain, as the most complex living structure in the universe, has been subject of many researches from various points of view. In particular, from the perspective of systems biology, brain functionality has been explored at different levels ranging from low-level chemical and molecular properties in individual neurons to high-level abstract aspects such as perception, cognition, memory and learning. Since 1875, when Caton observed the low amplitude electrical activities from the exposed brains of rabbits and monkeys, electroencephalography has been one of the most important non-invasive techniques for better understanding the human brain.

In 1924, Hans Berger, a German neurologist, conducted an experimental research aim at recording the brain's electrical activity on a strip of paper without opening the skull. He announced that: 1) weak electrical field generated in the brain can be non-invasively recorded by placing surface electrodes on the human scalp. 2) According to the functional status of the brain, such as attention, sleep, relaxation, lack of oxygen and in certain neural disease, the observed electrical activity change. 3) Depends on the site of recording on the scalp, the time varying observed oscillations (known as "brain waves") differ in shape and temporal pattern. Indeed, the present applications of electroencephalography was established by Berger's astonishing experiments. The word electroencephalogram (EEG) was also introduced by him to describe the brain electric potentials in humans. Later on, interpretation of the EEG for diagnostic purposes evolved into a discipline where functional status of the brain is evaluated based on the frequency, amplitude, morphology, and spatial distribution of the observed brain waves. This interpretation has been significantly facilitated by the advances in computer technology and modern digital signal processing methods.

In comparison to the recent advances in brain imaging techniques such as positron emission tomography (PET), single photon emission computed tomography (SPECT), magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI) which provide a good spatial resolution for studying the brain, the EEG offers a better time resolution and cheaper recording equipment; hence, it remains a powerful tool for real-time monitoring and in diagnosis of many neural and mental abnormalities.

In this chapter, the nerves system and electrical source of brain activity are firstly introduced. Then a list of common EEG patterns and brain waves are presented. Subsequently, the standard technique used for EEG recording and the EEG applications in clinical routine are briefly explained.

The main references for this chapter are:

[1] Bear, Mark F., Barry W. Connors, and Michael A. Paradiso, eds. Neuroscience. Vol. 2. Lippincott Williams & Wilkins, 2007.

[2] Sörnmo, Leif, and Pablo Laguna. Bioelectrical signal processing in cardiac and neurological applications. Vol. 8. Academic Press, 2005.

[3] Teplan, Michal. "Fundamentals of EEG measurement." Measurement science review 2.2 (2002): 1-11.

4.1 The Nervous System

The nervous system is a complex biological computing device formed by a network of gray matter regions interconnected by white matter tracts. The nervous system receives the information from different parts of the body, processes it and sends appropriate messages to various organs. It consistently detects both internal and external changes and manages to control all sorts of vital functions rapidly and accurately. The nervous system as a whole is commonly divided into the central nervous system (CNS) and the peripheral nervous system (PNS). The brain (forebrain, midbrain and hindbrain) and spinal cord form the CNS and PNS consists of nerves and small concentrations of gray matter known as *ganglia*. The two systems are closely integrated such that sensory input from the PNS is processed by the CNS, and responses are sent by the PNS to the organs of the body.

Based on the functionality, the *autonomic nervous system*, made of neurons connecting the CNS with internal organs, is divided into two parts, namely, the *sympathetic* and *parasympathetic* systems. While the sympathetic nervous system mobilizes energy and resources during times of physical exercise, stress, fear and arousal, the parasympathetic nervous system preserves energy and resources during relaxed states, including sleep.

4.1.1 Neurons

As stated in Chapter 2, information is carried throughout the nervous system by the individual processing units of its circuitry, i.e., neurons. The neuron is a specialized cell in the brain, designed to transmit information to other nerve cells and muscle fibers. In fact, due to remarkable structural and functional properties of interconnected neurons, the brain is in some way involved in everything we do (e.g., thinking, dreaming, playing sports, or even sleeping) and controls our overall stability. Each neuron consists of a soma (also known as cell body), dendrites, and an axon. The cell body consists of intracellular fluids and contains the cell nucleus. The axon extends from the soma and often gives rise to smaller branches before ending at nerve terminals. Dendrites extend from soma and receive messages from other neurons. Through a junction, called synapse, the information is introduced into the neuron from other neurons. Synapses are mostly located on the dendrites or on the soma. Changes in chemical and electrical properties of extracellular fluids in synaptic cleft can increase or decrease the voltage across the membrane. When neurons receive or send messages, electrical impulses are transmitted along their axons. Nerve impulses involve the ionic exchange between the intracellular and extracellular fluids through opening and closing of ion channels. Ion channels are selectively permeable molecular tunnels that pass through the cell membrane and allow ions to enter or leave the cell. The ionic exchanges creates an electrical current that produces small voltage changes across the cell membrane. The difference in ionic concentrations between the inside and outside of the cell's membrane determines the ability of the neuron to generate a so called *action potential*. The fired action potential regenerates itself and propagates along the axon. When it reaches the end of an axon, it triggers the release of particular chemical substances known as *neurotransmitters*. Released at nerve terminals, neurotransmitters diffuse across the synaptic cleft and bind to the specified receptors located on the membrane of the target (post-synaptic) neuron. Similar to an on-off electrical switch, the receptors active or de-active the target cell by altering its membrane potential which eventually causes an action potential initiation, neurotransmitter release inhibition, a muscle contraction or the stimulation of an enzyme activity. Figure. 4-1 depicts a small clamp of the nervous system at the level of cells and synapses.

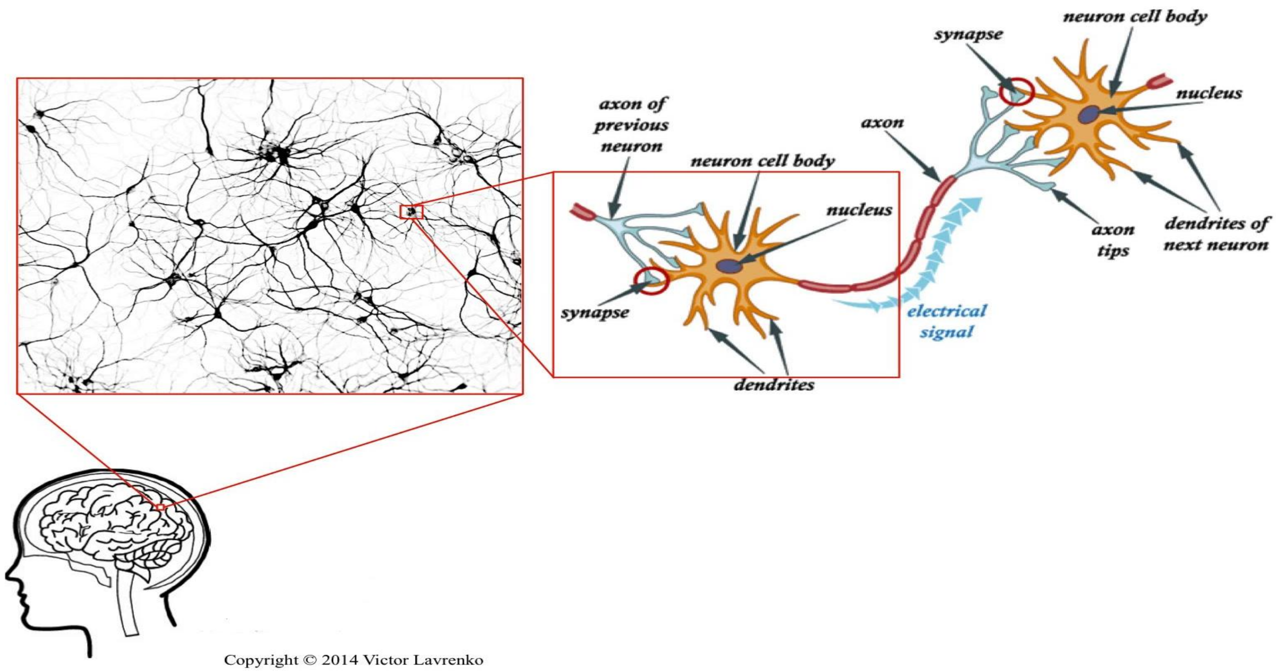

Figure 4-1: The brain and the neurons [https://www.youtube.com/watch?v=W8_ktKKyW5A].

4.1.2 The Brain

From the system level perspective, the brain is organized into different parts with specific properties and roles that are wired together in a specific way to make the brain a multi-task complex system (see Figure 4-2). The largest part of human brain is called *cerebrum* and is known to be associated with higher order functions, including thinking, planning, decision making, perceiving, understanding language, in general, to control our voluntary behaviors. The cerebrum is divided into two hemispheres, namely, the right hemisphere and the left hemisphere. The outermost layer of the cerebrum is covered by a sheet of tissue called the *cerebral cortex*. Due to its gray color, the cerebral cortex is mostly referred to as gray matter in biological text books. More than two-thirds of cerebral cortex is folded into grooves which causes the human brain to have wrinkled appearance. Because of these grooves, the brain's surface area is effectively increased such that many more neurons can be included. In order to understand the function of the cerebral cortex, it is often divided into various zones (see Figure 4-2):

- **Frontal lobe:** is responsible for motor movements and control, higher cognitive skills, such as thinking, planning, and decision making, organizing; and for many aspects of personality and emotions.

- **Parietal lobe:** is responsible for sensory processes, attention, and language. Damage to the left side of the parietal lobe can result in difficulty in understanding spoken and/or written language. If the left side is injured, the ability to navigate spaces (even familiar ones) may be impaired.
- **Occipital lobe:** is responsible for visual information processing, including recognition of shapes and colors.
- **Temporal lobe:** is responsible for auditory information processing and sensory information fusion/ integration. It is believed that the temporal lobe plays a role in short-term memory and in the learned emotional responses, respectively, through its hippocampal formation and its amygdala.

The above mentioned structures make up the forebrain. However, there are three other key parts in forebrain: *basal ganglia* (responsible for coordinating the muscle movements and rewarding the useful behaviors), thalamus (responsible for relaying the sensory information on to the cerebral cortex) and hypothalamus (which controls the circadian rhythm, appetites, defensive and reproductive behaviors).

The midbrain plays a significant role in visual and auditory reflexes and in relaying the sensory information to the thalamus.

The hindbrain controls respiration, heart rhythms, and blood glucose levels. A major part of the hindbrain is the *cerebellum* which helps control movement and cognitive processes that require precise timing.

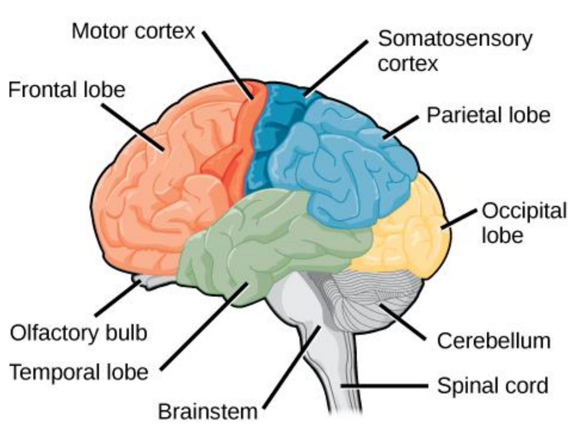

Figure 4-2: The lobes of cerebral cortex [https://courses.lumenlearning.com/boundless-biology/chapter/the-central-nervous-system/].

4.2 The Electroencephalogram, EEG Rhythms and Waveforms

The collective electrical activity of the cerebral cortex is often referred to as a brain wave or a rhythm. The reason is that the time-varying recorded signal often exhibit repetitive oscillatory patterns. As mentioned in Chapter 1, it is not possible to record the activity of a single cortical neuron in a non-invasive way and on the scalp. In fact, the electrical activity of a single neuron will be highly attenuated by thick layers of tissues (fluids, bones, and the skin) while it propagates toward the recording electrodes. However, the joint activity of many of cortical neurons produce a sufficiently strong electrical field which can be measured on the scalp.

Depends on the health condition and mental state of the subject (e.g., waking, sleeping, degree of coconsciousness), the EEG rhythms may exhibit diverse classes of patterns with different frequency ranges and amplitudes. Figure 4-3 illustrates examples of EEG patterns.

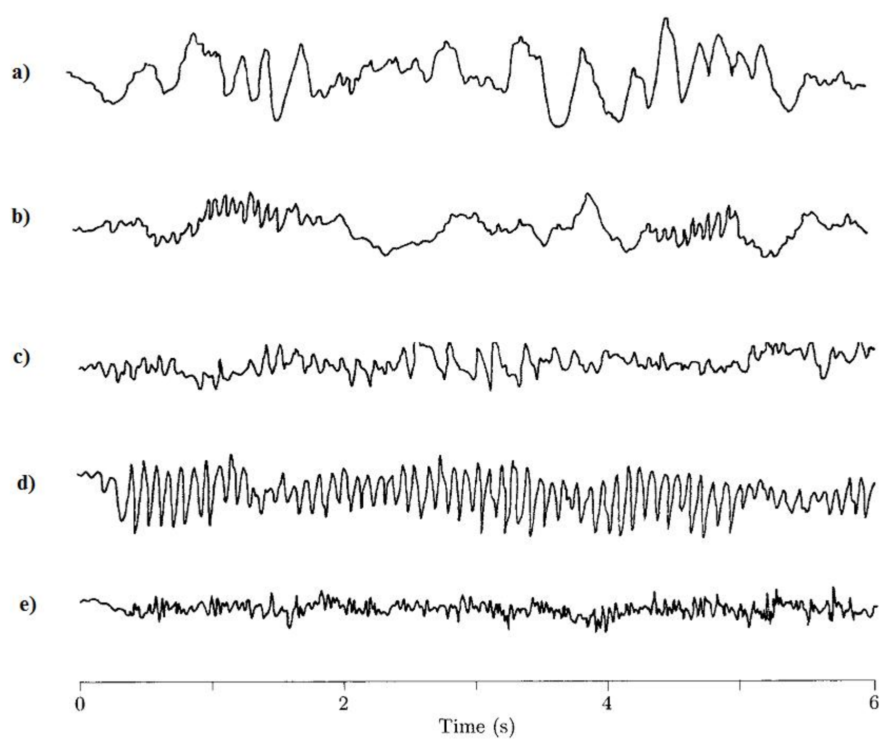

Figure 4-3: Electroencephalographic rhythms observed during various states from sleep to wakefulness: (a) deeply asleep, (b) asleep, (c) drowsy, (d) relaxed, and (e) excited [2].

In general, the amplitude of EEG recordings ranges from a few microvolt to hundreds millivolt. Depend on the age and mental state of the subject, the frequency content of EEG ranges from 0.5

to $30 - 40\ Hz$. However, to provide a clinically insightful characterization of the recordings, the EEG rhythms are often classified into the following five different frequency bands:

- Delta rhythm ($< 4\ Hz$). It has a relatively large amplitude and is mainly encountered during deep sleep. In normal adult, it is not usually observed in the awake. Therefore, it can be indicative of cerebral damages, brain diseases and mental disorders.
- Theta rhythm ($4 - 7\ Hz$). It is observed during drowsiness and in certain stages of sleep.
- Alpha rhythm ($8 - 13\ Hz$). It occurs mostly in normal subjects while they are relaxed and awake with closed eyes. Opening the eyes causes the amplitude of this rhythm to significantly drop. The amplitude of alpha rhythm is higher when the EEG is recorded from the occipital regions.
- Beta rhythm ($14 - 30\ Hz$). This fast low amplitude rhythm is observed during the certain stages of sleep when the cortex is highly active. The beta rhythm is stronger when it is recorded from frontal and central regions of the scalp.
- Gamma rhythm ($> 30\ Hz$). It is associated with a state of active information processing of the cortex. The gamma rhythm can be observed during finger movement when the electrodes are located over the sensorimotor area of the cortex.

In Figure 4-4, these rhythms are depicted.

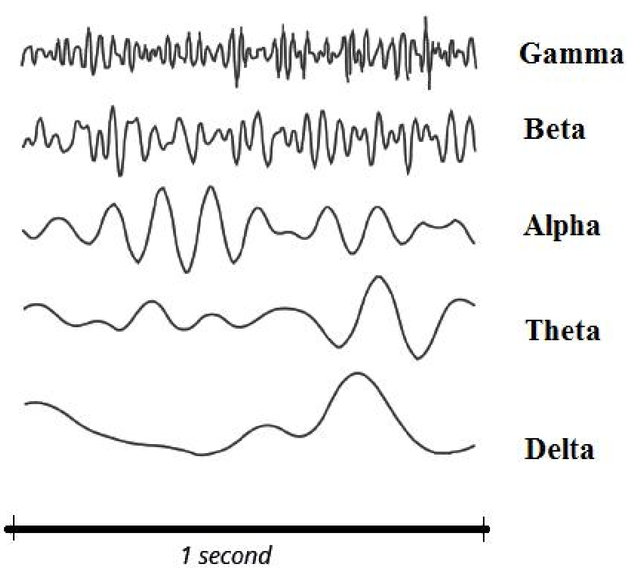

Figure 4-4: Brain wave samples with dominant frequencies in gamma, beta, alpha, theta, and delta ranges [https://imotions.com/blog/eeg/].

It is worth mentioning that each rhythm is not present at all times. For example, the gamma rhythm lasts only for a few seconds. Besides, EEG is highly sensitive to a continuum of states ranging from stress state, wakefulness to resting state, hypnosis, and sleep.

In addition to above mentioned rhythms, there are three other classes of rhythms which are indicative of different stages of sleep or occurrence of epileptic seizure or spike waves.

- **Sleep rhythms.** During the sleep, brain alternatively (several times during one night) passes through two functional states, namely, non-rapid eye movement sleep (NREM) and REM sleep. Non-REM sleep state, associated with resting of the brain and the bodily functions, is further divided into stage I, stage II, stage III, and stage IV (see Table 4-1 and Figure 4-5). During the non-REM sleep, high degree of synchrony of cortical neurons causes the EEG rhythms to have large amplitude. However, in stage III and IV, slow delta waves show higher proportions. During the sleep stages, a number of transient waveforms, such as vertex waves, sleep spindles, and K complexes, usually occur. Vertex waves constitute responses to external stimuli (e.g., sounds) and characterize the earlier sleep stages. Sleep spindles are characterized by bursts of alpha-like activity with a duration of $0.5 - 1$ s. The K complex consists of fusion of sleeps spindles and vertex waves. During the REM, the eyes, move rapidly back and forth in an erratic pattern. Therefore, when the electrodes are located close to the eyes, a tooth-saw pattern can usually be recognized in EEG. As rapid eye movement sleep corresponds to an active brain, the EEG resembles that of awake brain where the beta rhythms show higher proportions.

Table 4-1 Characteristics of the four non-REM sleep stages and the REM sleep [2].

Sleep Stage	sleep depth	waveforms
1	Drowsiness	From alpha dropouts to vertex waves
2	Light sleep	Vertex waves, spindles, K complexes
3	Deep sleep	Much slowing, K complexes, some spindles
4	Very deep sleep	Much slowing, some K complexes
REM	REM sleep	Desynchronization with faster frequencies

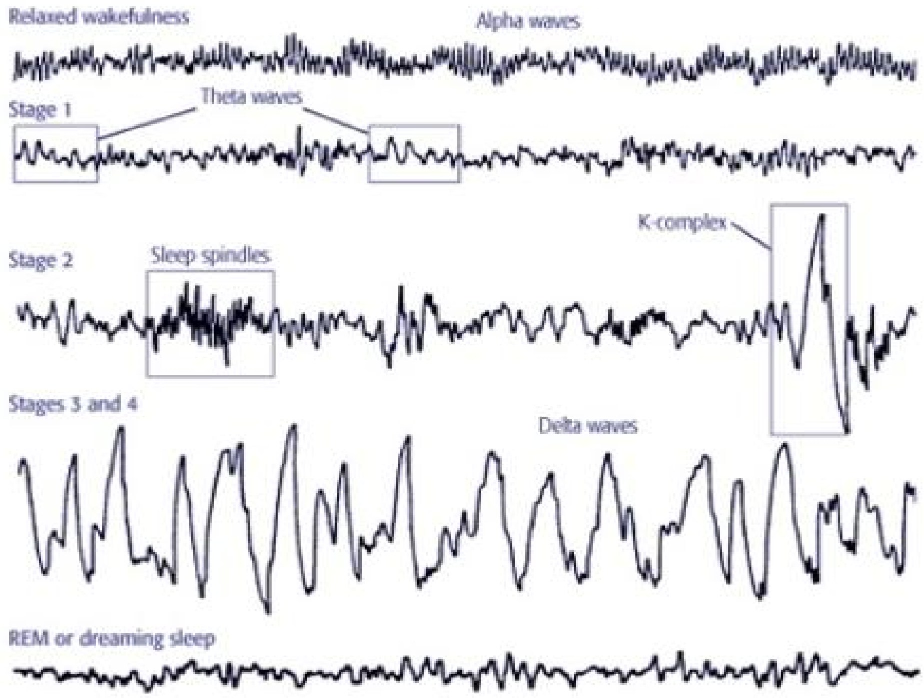

Figure 4-5: EEG during wakefulness and different stages of sleep
[https://www.slideshare.net/anshukg/sleep-53787522].

- **Spikes and sharp waves (SSWs).** Due to their irregular, unpredictable temporal patterns (also known as paroxysmal activity), these transient waveforms are distinct from the EEG background activities. SSWs mostly appear in the EEG recorded from subject suffering from epileptic seizures. They occur between the so called Ictal events which, in fact, are epileptic seizures. A spike is typically differentiated from a sharp wave by its duration: a spike often lasts $20 - 70\ ms$, while a sharp wave has the duration in range $70 - 200\ ms$. Spikes may occur as isolated events (single spikes) or in various types of runs such as spike-wave complexes (consists of a spike followed by a slow wave, and polyspikes complexes (consist of multiple spikes superimposed on a slow wave).

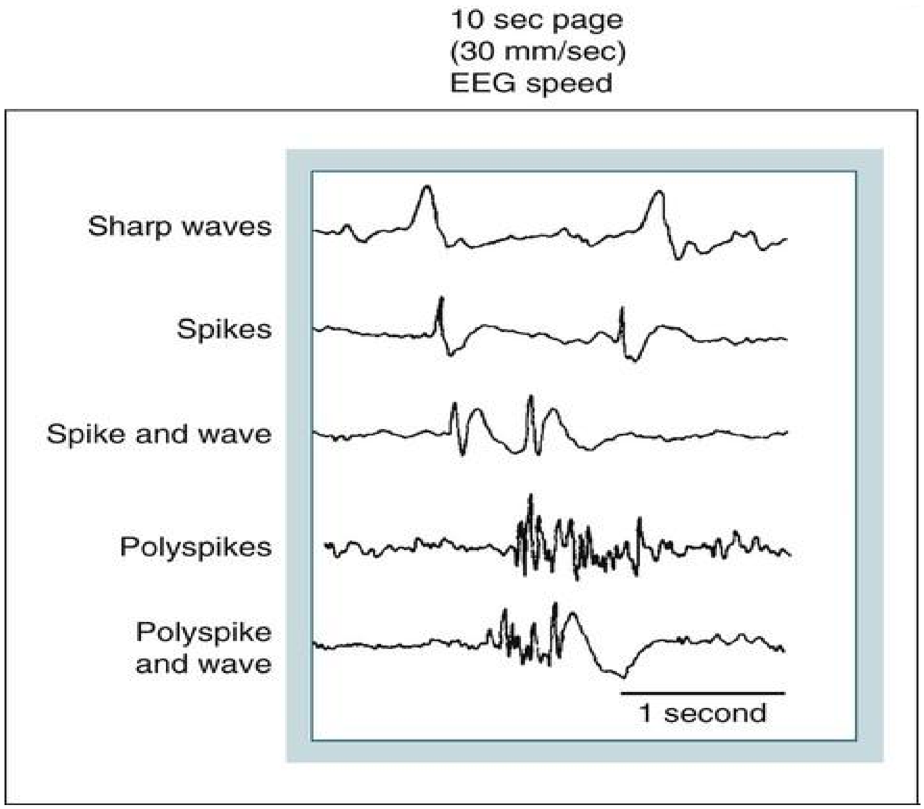

Figure 4-6: Sharp waves, spikes, spike and wave, polyspikes, and polyspike and wave [https://neupsykey.com/clinical-electroencephalography-and-nocturnal-epilepsy/].

- **Ictal EEG.** During an epileptic seizure, the EEG is characterized by an abnormal rhythm with irregular increase in amplitude. At the beginning of the seizure, a sudden change in frequency content occurs which later evolves into a rhythm with a spiky wave pattern. Because of notable variations in ictal EEG from one seizure to another, seizure detection and prediction are quite challenging whether they are approached manually or automatically (see Figure 4-7).

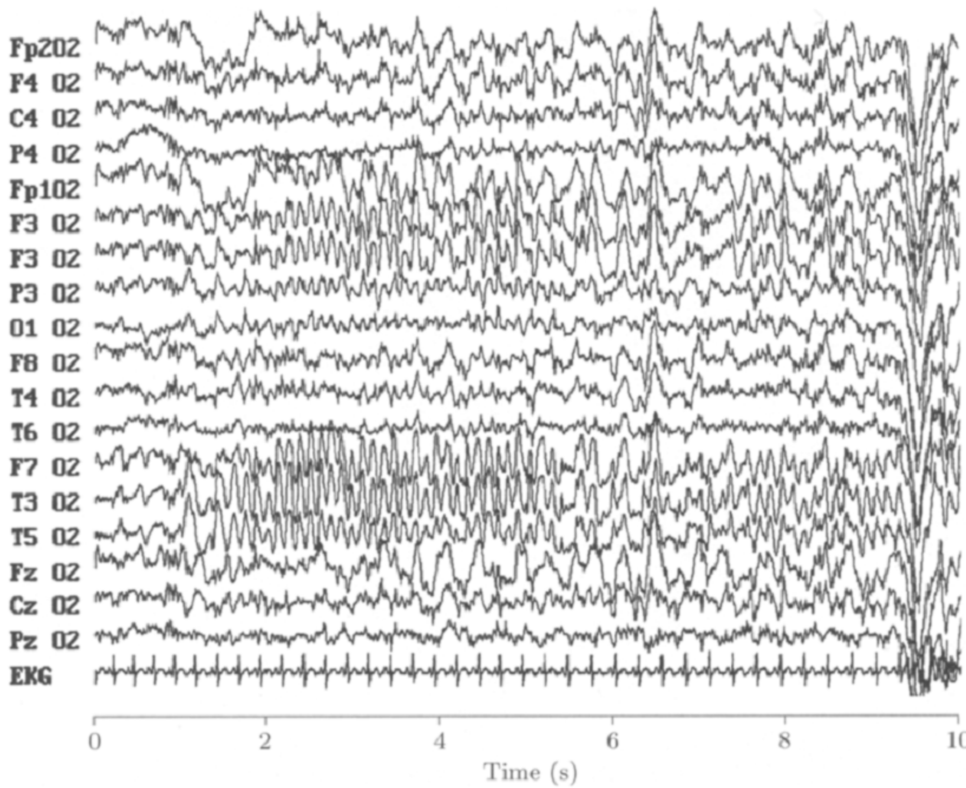

Figure 4-7: A multichannel EEG showing the onset of an epileptic seizure, occur ring after the first second. The onset is characterized by an increase in amplitude and a change in spectral content. The seizure is particularly pronounced in certain channels [2].

4.3 EEG Recording Techniques

As stated in Chapter 1, similar to other recording and measurement systems, EEG recording system typically consists of:

- surface electrodes
- amplifiers with filters
- A/D converter
- processing/storing device.

Electrodes captures the signal from the scalp, amplifiers bring the microvolt signals into the range where they can be digitalized accurately, A/D converter converts signals from analog to digital form, and processing/storing device stores, processes or displays recorded data.

Minimal configuration for mono-channel EEG measurement includes one active electrode, one (or two specially linked together) reference and one ground electrode. The ground electrode gets differential voltage by subtracting the same voltages showing at active and reference points. The multi-channel configurations can comprise up to 128 or 256 active electrodes. In $10 - 20$ system of electrode spacing, the inter-electrode distance is approximately 4.5 cm on a typical adult head. As it was mentioned above, different brain areas are related to different functions of the brain. Therefore, in this setting, each scalp electrode is located near certain brain centers (see Figure 4-8). In this system, the number '10' and '20' refer to the fact that the distance between adjacent electrodes are either 10% or 20% of the total front-back or right-left distance of the skull. Each site has a letter to identify the lobe (F: frontal, T: temporal, P: parietal, O: occipital, C stands for central region which is obviously not a lobe, and 'z' (zero) refers to an electrode placed on the mid-line) and a number to identify the hemisphere location ({2, 4, 6, 8} refer to the right and {1, 3, 5, 7} refer to left hemisphere, respectively). For instance, F7 is located on frontal lobe at left hemisphere (near the centers for rational activities), Fz (on mid-line in frontal lobe) records from intentional and motivational centers. F8 records from sources of emotional impulses. On the central part, area around C3, C4, and Cz locations are known to be related to sensory and motor functions. Locations near P3, P4, and Pz contribute to activity of perception and differentiation. Near T3 and T4 emotional processors are located, while at T5, T6 certain memory functions stand. Primary visual areas can be found bellow points O1 and O2.

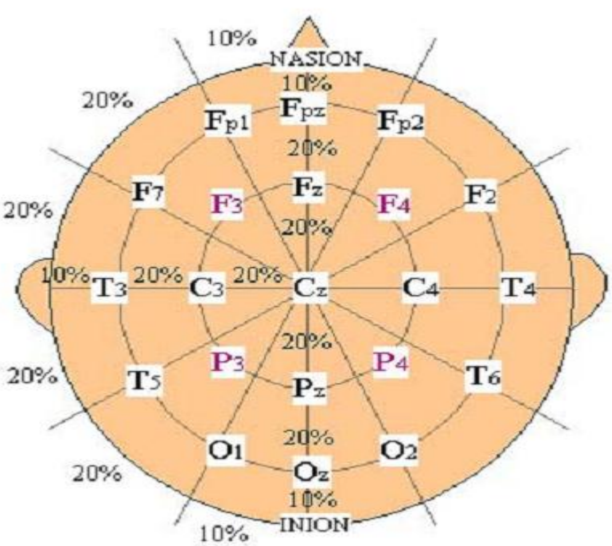

Figure 4-8: Labels for points according to 10-20 electrode placement system in EEG recording [3].

The sampling rate for EEG signal acquisition is typically higher than $200\ Hz$, when taking the frequency contents of the rhythmic activities previously given into account.

4.4 EEG Applications

The greatest advantage of EEG is its temporal resolution. Indeed, within a fraction of a second after applying the stimulation, the complex patterns of neural activity can be recorded by means of EEG recording system. Compare to the more advanced neuronal imaging techniques, such as fMRI and PET, EEG provides less spatial resolution. Thus for better allocation within the brain, EEG images are often combined with MRI scans to determine the relative strengths and positions of electrical activity in different brain regions.

The following applications of the EEG in human and animals have been so far reported:

- alertness, coma and brain death monitoring
- locating areas of damage after head injury, stroke, tumor

  In cases of restricted lesions such as tumor, hemorrhage, and thrombosis, the amplitude of EEG drastically drops and the dominant frequency decreases beyond the normal limit. Spikes and other special patterns may also appear in the EEG recordings in case of these pathological conditions.
- testing the sensory pathways (by evoked potentials) which is crucial to Multiple Sclerosis (MS) diagnosis
- cognitive engagement monitoring (by studying the alpha rhythm)

  Regarding the fact that EEG recording procedure is non-invasive, it has been widely used to study the brain organization of cognitive processes such as perception, attention, language, memory and emotion in normal adults and children. In this regard, the ERP (event related potential) technique are the most useful application of EEG recording.
- epilepsy investigation and locating the seizure origin (focus)

  A person with epilepsy suffers from seizures during which sudden, unpredictable bursts of uncontrolled electrical activity occur in a population of neurons of the cerebral cortex. Depend on the origin (focus) of the electrical activity and the way that different areas of the brain become successively recruited during a seizure, epileptic seizures are manifested in many different ways. The EEG is the principal clinical test for diagnosing epilepsy and gathering information about the type and location of seizures.

- testing the effect of drug:

  EEG patterns have been shown to be affected by a wide range of biochemical, metabolic, circulatory, hormonal, neuroelectric, and behavioral variables. Hence, by tracking changes of electric activity during such drug abuse-related phenomena as euphoria and craving, brain areas and patterns of activity that mark these phenomena can be localized.

- control anaesthesia[1] depth (“servo anaesthesia”)
- produce biofeedback situations

  “So-called mind-machines or brain-machines are devices for induction of different mind states (e.g. relaxation, top performance) by entrainment of the brain waves into desired frequency bands by repetitive visual and audio stimuli” [3]. In order to facilitate the training and make it more effective, biofeedback methods were suggested to be involved. EEG biofeedback or neurofeedback uses EEG signal as feedback input. One of the methods involved in neurofeedback training is “frequency following response”. Changes in the functioning of the brain in desired way (e.g. increase in alpha activity) generates appropriate visual, audio, or tactile response. Thus, a person can be aware of the right direction of the training.

  Some researchers believe that through the positive or negative feedback loop, it is possible to improve the mental performance of the subjects and help them to normalize their behavior and stabilize their mood. There are some findings indicating applications to certain pathological conditions such as attention deficit disorder (ADHD), major depressive disorder (MDD), epilepsy, and alcoholism.

- monitoring the human and animal brain development and aging process
- sleep and circadian rhythm disorder investigations

  Sleep disorders such as insomnia, hypersomnia, parasomnia and circadian rhythm disorder may be caused by several conditions of medical and/or psychological origin. Each of the different types of sleep disorder exhibits certain manifestations in the EEG. In order to properly investigate each disorder, it is important to quantitatively determine the time course of sleep stages changes. Figure 4-9 shows an example. Since it is not efficient to

[1] The state of temporary induced loss of sensation or awareness common in surgery and dentistry.

manually mark the sleep stages in long-run recorded data streams, it is of crucial importance to develop a system that automatically performs the sleep staging described in Table 4-1. Such system only needs to detect the different rhythms such as delta, theta, alpha, and beta and individual waves that characterize the different stages (i.e., vertex waves, sleep spindles, and the K complexes).

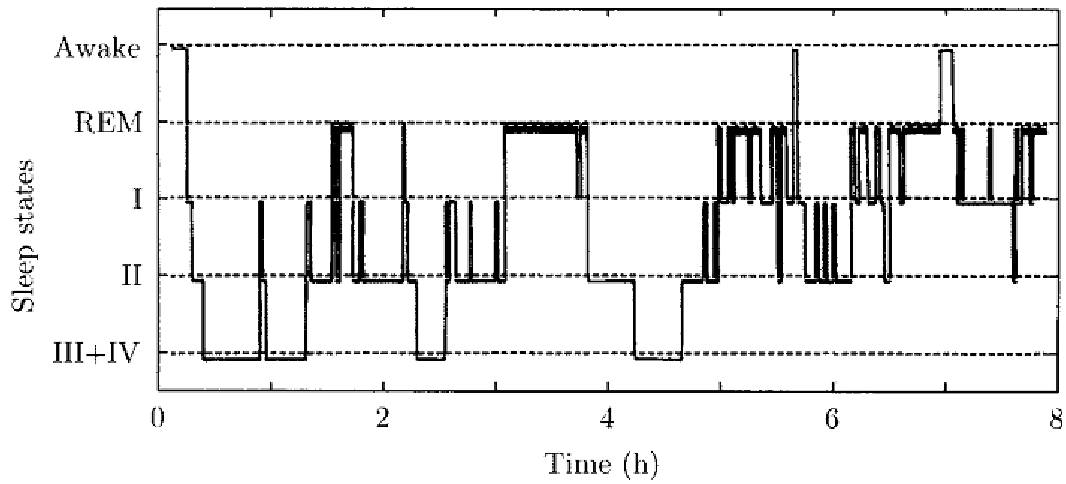

Figure 4-9: Time course of sleep stages observed during one night's sleep [2].

- mental disorders investigation
- physiological studies
- Quantitative electroencephalography (QEEG)

  Taking the advantages of technological advances, encephalography is now able to simultaneously record brain activity data from the entire head. It is therefore, a useful technique to provide a topographic map of the brain. Indeed, Quantitative EEG applies multi-channel recording technique to better determine the spatial organization of the brain and localize the regions of the brain with abnormal activity. These results are often used for topographic brain mapping represented with 2D and 3D colour maps to enhance visualization.

- brain- computer interactions (BCI)

  Brain computer interface (BCI) is a communication system that recognizes user's command only from his or her brainwaves and reacts according to them. For this purpose PC or/and subject needs to be trained. For instance, let's assume it is desired to move the arrow displayed on the screen only through subject's imaginary of the motion of his or her left or right hand. Followed by imaging process, certain characteristics of the brainwaves are raised such that it can be recognized as a command; motor mu waves (brain waves of alpha range frequency associated with physical movements or intention to move) or certain ERPs are important examples of such characteristic features. The block diagram in Figure 4-10 presents the basic components of a BCI.

BCIs must operate in real time, therefore, it is important that the signal processing does not introduce unacceptable time delays.

The most common technique for extracting characteristic features from an EEG signal is to analyze *spectral power* in different frequency bands which will be discussed in Chapter 5.

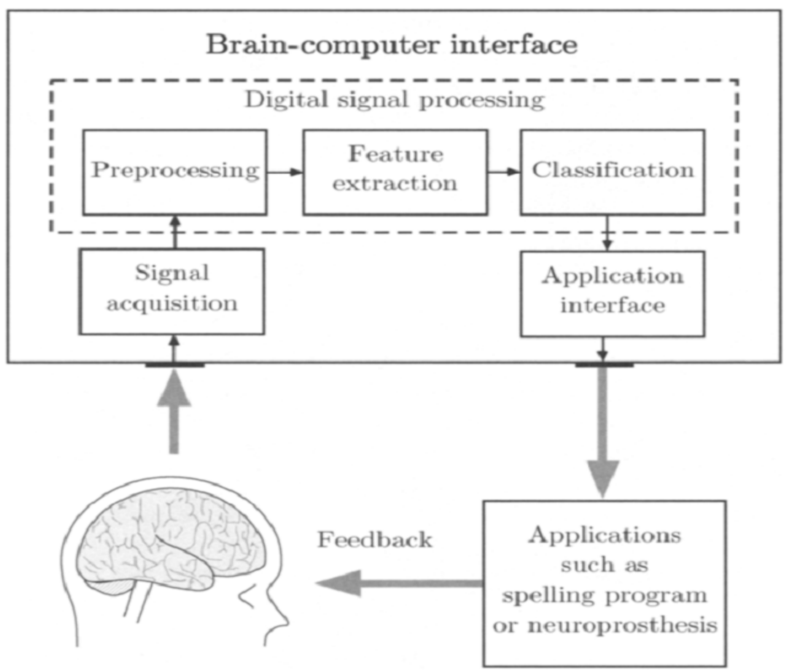

Figure 4-10: Block diagram of a typical BCI system [2].