


Signal & Data Analysis in Neuroscience
2018
Part 1: Introduction

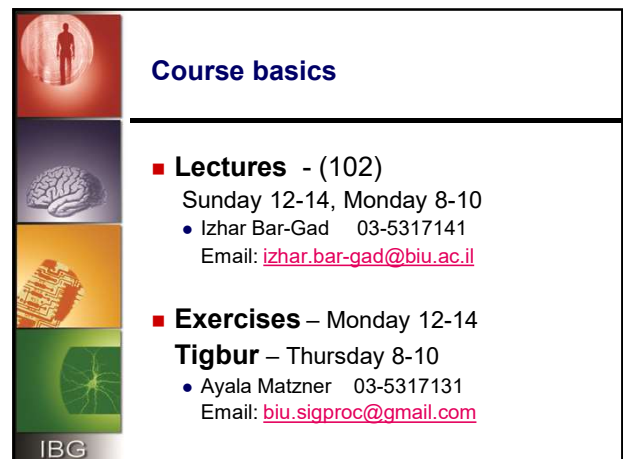
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Overview

- Course logistics
- Signals & data in neuroscience
- Signal & data analysis
- Digital signals

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Course basics

- **Lectures** - (102)
Sunday 12-14, Monday 8-10
 - Izhar Bar-Gad 03-5317141
Email: izhar.bar-gad@biu.ac.il
- **Exercises** – Monday 12-14
Tigbur – Thursday 8-10
 - Ayala Matzner 03-5317131
Email: biu.sigproc@gmail.com

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Course Web Site

<https://www.ibglab.org/sda-2017>

- Contains: contact info, presentations, recitations, exercises, syllabus & additional links.

Also accessible through <http://www.ibglab.org/>





- The presentations will (hopefully) be available on the web site at least one day before the lectures.
- The course is (hopefully) video-taped and accessible on the brain center server.

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Course target & non-target


- Target:** Provide some of the *knowledge* and *tools* required for analyzing different neuroscience related signals & data.
- Result:** The course covers a very wide range of topics stemming from statistics, mathematics, engineering & computer science.
- Non-target:** Replace the wide range of general courses available elsewhere which are covered briefly and specifically in this course.

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Disclaimer

- Many of the topics presented during the course will be (over-?) simplified for our special case and thus, in some cases may not be exact.
- Some topics will even go through different definitions as we progress through the course.
- This means that in the future you might find out that some of the things you learnt are not exactly "the ultimate truth".



Course requirements


- Prerequisites
 - MATLAB programming
 - Probability theory, statistics (verify using 1st tirgul)
 - Basic calculus, algebra
 - Basic neurophysiology
- Notes
 - This course is **not** open to external/independent "listeners". Every student must do the exercises & make a presentation.
 - This course will require around six hours weekly for **exercises** and in many cases a couple of more hours for handling **reading materials**.



Syllabus


1. Signals & Data in Neuroscience
2. Stochastic processes
3. Point processes and the Poisson model
4. Single process assessment
5. Multiple processes assessment
6. Neural encoding
7. Bayesian decisions
8. Neural decoding
9. Information theory
10. Frequency domain
11. Filters
12. Spectral analysis
13. Wavelets
14. PCA / ICA
15. Clustering
16. Optimization

The order of the lessons might vary due to unforeseen reasons.




Course grades

- Home assignments – **50%**
 - 10 **individual** home assignments, each assignment counts for 5% of the final grade.
 - Assignments are either weekly or bi-weekly, in any case they must be submitted before the next (or following) Monday at **8AM**.
- Exam – two parts – different days (each 25%) – **50%**
 - Computer based - Computational questions.
 - Paper based - Analytical questions.
- The final grade in the course is dependent on **passing** each of the sections (assignments & exams).




Rules

- The small rule
 - Not coming to class is fine.
 - Being late for class is unacceptable.
- The (very) big rule
 - A low grade in an exercise is fine.
 - Cheating/Copying is unacceptable.
- Academic dishonesty will result in extremely severe consequences.







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- Signals & data in neuroscience
- Digital signals



Definitions I





- **Signal** is a a detectable physical quantity by which *information* can be transmitted.
- **Information** is the state of a system of interest.
- **Signal processing** is the processing, amplification and interpretation of signals
- **Signal analysis** is the extraction of information from a signal.

Definitions II

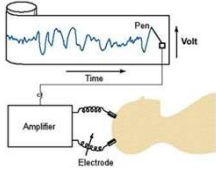
- **Data** is factual information used as a basis for reasoning, discussion, or calculation which typically includes useful and irrelevant or redundant information and must be processed to be meaningful.
- **Data analysis** is the act of transforming data with the aim of extracting useful information and facilitating conclusions.

(Adapted from: Merriam-Webster www.m-w.com & Wikipedia www.wikipedia.com)










Data analysis example I

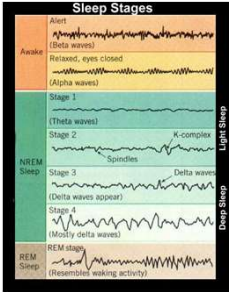
- Data: EEG (electroencephalogram)







- Data processing: Amplification, filtration, sampling & quantification.

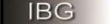
Data analysis example II







Data analysis example III


- **Information:** The state (sleep-wise) of the patient in one of the known stages.
- **Data analysis:** Based on assessing the **power, pattern** and **frequency** of the EEG and fitting to known sleep stages the **state** of the patient is found.
- This is not **ALL** the information in the data but it is the **relevant** data.







Overview

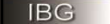
- Course logistics
- Signal & data analysis
- **Signals & data in neuroscience**
- Digital signals







Signals & data in Neuroscience

- Neuroscience is a wide field of research encompassing diverse signal and data encoding different type of information
- Sources of signals & data
 - (Neuro-) Physiology
 - (Neuro-) Anatomy
 - (Neuro-) Biochemistry
 - Psychophysics
 - Psychology
 - ...







Signals & data - examples

- Psychophysical signal of the two choice response of patients → information regarding mental state (schizophrenic vs. normal)
- Electrical signal recorded in a deep brain structure → information regarding the Parkinsonian state of the patient
- Signal of breathing and heart pulses → information regarding mother-baby interaction

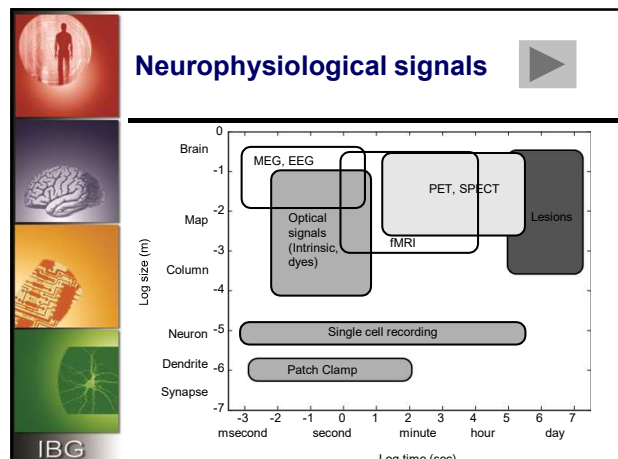
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Signals & data in Neuroscience II

- We will focus on neuronal based signals and data (mainly **neurophysiological**) relating to the **function of the brain**.
- However, the methods are fully applicable for anatomical, psychophysical, biochemical, etc. and in many cases we will show examples from other domains.

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











Overview

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- Signal & data analysis
- Signals & data in neuroscience
- Digital signals


Recommended reading:
W. Van Drongelen, Signal processing for Neuroscientists, Chapter 2







Analog signals

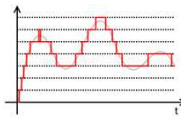
- An analog signal is any variable signal continuous in both **time** and **amplitude**.
- It differs from a digital signal in that small fluctuations in the signal are meaningful.
- The signal may constitute of any physical quantity such as electrical, mechanical, chemical, etc.
- Examples of such signals:
 1. Neuronal membrane potential
 2. CO₂ concentration in the lungs









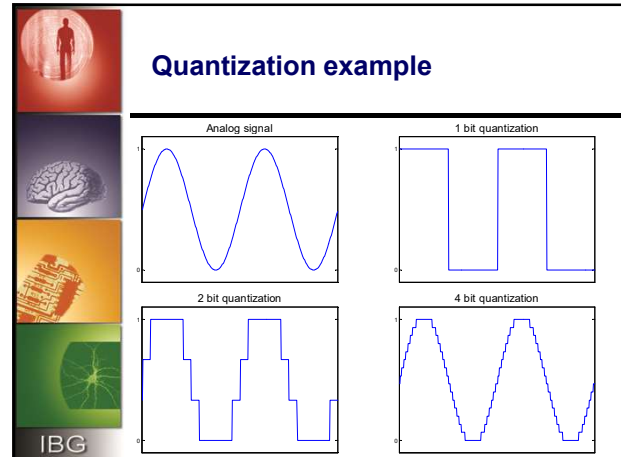
Quantization

- **Quantization** is the process of approximating a continuous range of values (or a very large set of possible discrete values) by a relatively-small set of discrete symbols or integer values.



- Quantization leads to an unavoidable **error**. An analog signal is continuous, with ideally infinite accuracy, while the digital signal's accuracy is dependent on the resolution.





Quantization resolution





- The quantization process utilizes a **range** of values with specific **resolution** of the original values.
- The combination of range and resolution determines the number of bits required for the representation.

$$n_{bits} = \log_2 \left(\frac{range}{resolution} \right) \quad resolution = \frac{range}{2^{n_{bits}}}$$

Quantization resolution example

- **Example:** Recording the amplified EEG values in the range of $\pm 5V$ with $1\mu V$ resolution requires 24 bits for the representation.

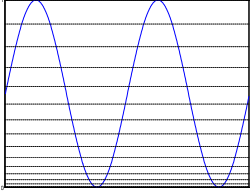
$$n = \log_2 \left(\frac{5 - (-5)}{10^{-6}} \right) = \log_2(10^7) = 23.25$$










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Quantization – variable intervals

- In the vast majority of cases the range is broken down to equal intervals.
- In some cases, variable intervals may be defined to increase precision in part of the range.







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Bad quantization

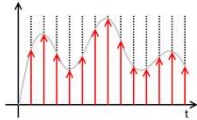
- A system is set to quantize the neuronal recording in the range of $\pm 5V$ using 12 bits. However, the spikes are not amplified but are rather in the range of $\pm 5mV$. What happens?
- A system is set to quantize the neuronal recording in the range of $\pm 5mV$ using 12 bits. However, the spikes are amplified and are thus in the range of $\pm 5V$. What happens?










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Discrete signal

A discrete signal is a signal that has been sampled from a continuous signal. Unlike a continuous signal, a discrete signal is not a continuous **function** but a **sequence**. Each value in the sequence is called a **sample**.



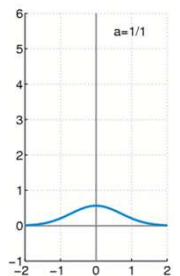
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Dirac's delta function I





- Dirac's delta function may be viewed as a limit to a family of functions, for example:

$$\delta(x) = \lim_{\sigma \rightarrow 0} \delta_{\sigma}(x)$$

$$\delta_{\sigma}(x) = \frac{1}{\sigma \cdot \sqrt{\pi}} e^{-\frac{x^2}{\sigma^2}}$$



(Oleg Alexandrov, www.wikipedia.org)

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Dirac's delta function II

- Dirac's delta function is actually not a function.





$$\delta(x) = 0 \quad x \neq 0$$

$$\int_{-\infty}^{\infty} \delta(x) dx = 1 \quad \int_{-\infty}^{\infty} f(x) \cdot \delta(x) dx = f(0)$$

Note: The value at x=0 is not defined.

$$\delta(x - \tau) = 0 \quad x \neq \tau$$

$$\int_{-\infty}^{\infty} \delta(x - \tau) dx = 1 \quad \int_{-\infty}^{\infty} f(x) \cdot \delta(x - \tau) dx = f(\tau)$$

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Kronecker's delta

- The discrete equivalent in many ways to Dirac's delta function.

$$\delta(n) = \begin{cases} 1 & n = 0 \\ 0 & n \neq 0 \end{cases} \quad \sum_{n=-\infty}^{\infty} \delta_n = 1$$

- Dirac's delta → analytic calculations.
- Kronecker's delta → numeric calculations.

$$\delta(n - k) = \begin{cases} 1 & n = k \\ 0 & n \neq k \end{cases}$$

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Sampling

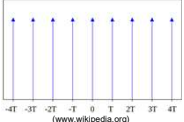
- Sampling at a single point





$$x^s(\tau) = \int_{-\infty}^{\infty} x(t) \cdot \delta(t - \tau) dt$$

- Sampling at a fixed interval T_s

$$x^s(nT_s) = \sum_{n=-\infty}^{\infty} x(nT_s) \cdot \delta(t - nT_s) = x(t) \cdot \sum_{n=-\infty}^{\infty} \delta(t - nT_s)$$

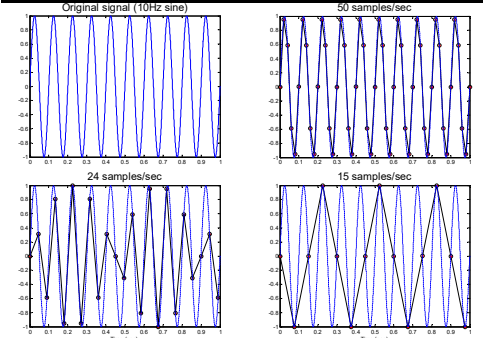
- This group of equally spaced delta functions is typically called a *Dirac comb* (δ_{T_s})







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Sampling example

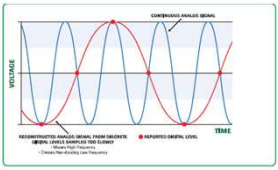











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Sampling ambiguity


- Sampling the signal may lead to ambiguities of the resulting sequence.







Sampling magic

WHEN A CAMERA'S FRAME RATE



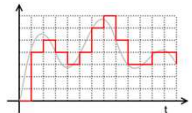
IS SYNCED TO A HELICOPTER'S ROTOR

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Digital signals

- A digital signal is a signal that is both **discrete** and **quantized**.



- Incorporation of any signal into a computer or other digital electronic equipment requires the **digitization** of that signal.

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Digitization in other domains

- Common digitization domains are amplitude and time of the signal.
- Digitization may occur across additional domain such as spatial (including multiple dimensions), spectral, etc.








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Appendix A

Neurophysiology - Methods

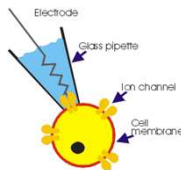
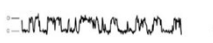












Patch clamp

- Glass pipette with a ~1 micron tip.
- Record the activity of ion channels, dendrites or whole cells.
- Records the changes in potential.

- Temporal resolution: sub ms
- Spatial resolution: sub neuron














Intracellular recording

- Single cell recording using a penetrating or patch clamped electrodes.
- Records the **subthreshold** and **suprathreshold** potential of the cell.

- Temporal resolution: sub ms
- Spatial resolution: single neuron

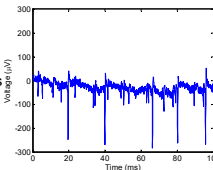














Extracellular recording – unit activity

- Record neuronal activity from an electrode outside a neuron.
- May record a single neuron, multiple single neurons, or multi-neuron activity.
- The potential reflect only the **suprathreshold** activity (spikes)
- Temporal resolution: sub ms
- Spatial resolution: single neurons










Extracellular recording – LFP

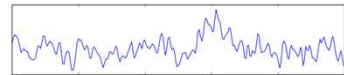
- LFP (local field potential) is recorded with electrodes outside the neurons.
- Reflects synaptic input occurring in synchrony in a population of neurons.
- Records changes in a larger volume and typically performed through larger tip electrodes.
- Temporal resolution: milliseconds
- Spatial resolution: hundreds of microns
- In its extreme case LFP is EEG...













Electroencephalography (EEG)

- Electroencephalography (EEG) is the measurement of the electric fields produced by neuronal activity.
- Electrical fields are distorted by different tissues decreasing spatial location.
- Localization is performed y comparison of the relative signal in multiple electrode.
- Temporal resolution: sub-millisecond
- Spatial resolution: >1cm

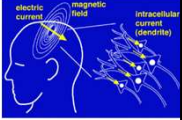













Magnetoencephalography (MEG)

- Magnetoencephalography (MEG) is the measurement of the magnetic fields produced by electrical activity in the brain
- Unlike the electrical field, the magnetic field is not distorted by different tissues and thus enable better spatial localization.
- Temporal resolution: sub-millisecond
- Spatial resolution: 1mm

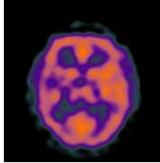
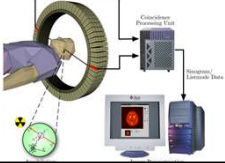


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Positron emission tomography (PET)

- A positron emitting radionuclide is injected (e.g., 2-deoxyglucose).
- Positrons interact with electrons which produce photons (gamma rays) traveling in opposite directions.
- PET scanner detects the pairs of photons.
- Temporal resolution: minutes
- Spatial resolution: 5mm

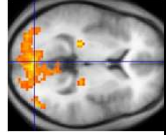



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Functional magnetic resonance imaging (fMRI)

- Hemoglobin has different magnetic properties based on its oxygenation.
- Changes in blood oxygenation are linked to neuronal activity.
- A strong magnetic field aligns the molecules and a specific electromagnetic frequency perturbs the atoms leading to emission of electromagnetic energy.
- The resulting signal – BOLD: Blood Oxygenation Level Dependent
- Temporal resolution: seconds
- Spatial resolution: 2-3 mm



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