João Jorge
Medtech R&D @ CSEM

11.09.2025

EE512 – Applied Biomedical Signal Processing

MODULE 01 – INTRODUCTION

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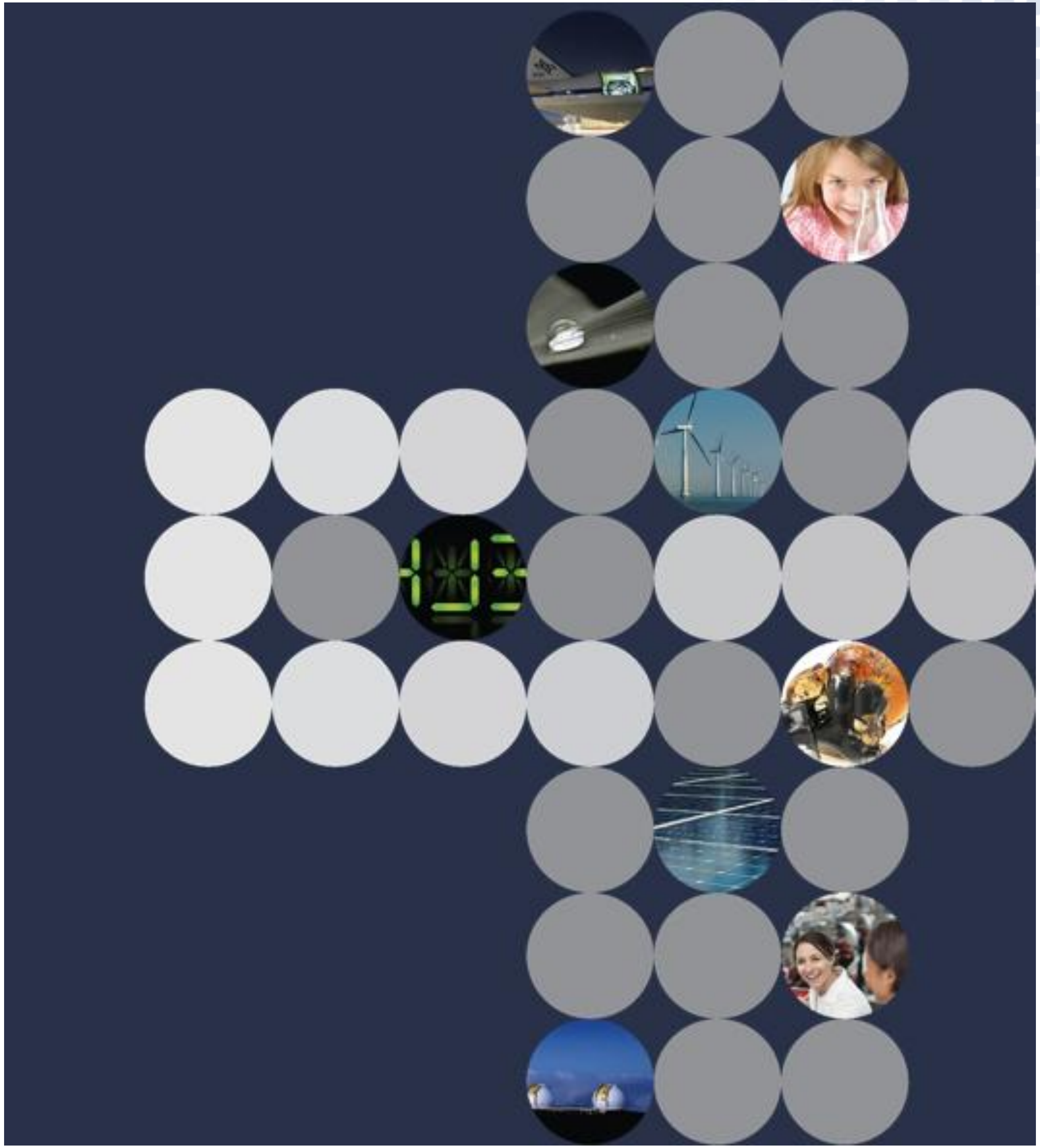
OUTLINE FOR TODAY

- **Introduction to the course**
  - Motivation & goals
  - Course format & organization
  - Course evaluation

- **Introduction to biomedical signals**
  - Sensing and signal processing
  - Electrocardiography (ECG)
  - Photoplethysmography (PPG)
  - Electroencephalography (EEG)

- “Mini-labs” and demo



MOTIVATION

- **Physiology** can be monitored with various technologies
- Extracting **objective, quantitative information** is extremely valuable
  - **Medical:** clinical diagnosis and decisions

Acquired signals per se may not be directly useful

- Parameters of interest “hidden”
- Confounds, artifacts

Vital parameters

Heart rate (HR)

Peripheral oxygen saturation (SpO2)

Respiration rate (RR)

Signal processing

- Improving signal quality
- Data selection / exclusion
- Parameter estimation:
  - Model-based
  - Data-driven (e.g. ML)

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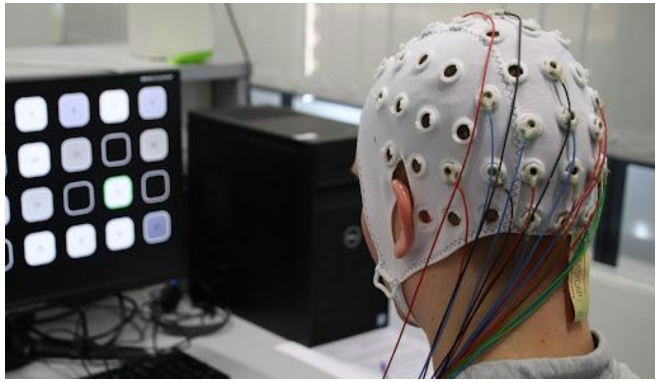
MOTIVATION

- **Physiology** can be monitored with various technologies
- Extracting **objective, quantitative information** is extremely valuable
  - **Medical:** clinical diagnosis and decisions
  - **Research:** basic physiology, pathologies, new therapies
  - **Sports:** assessing performance, improvements
  - **Wellness:** tracking general well-being, sleep quality, stress
  - **Human-machine interfaces:** decoding of movements and thoughts

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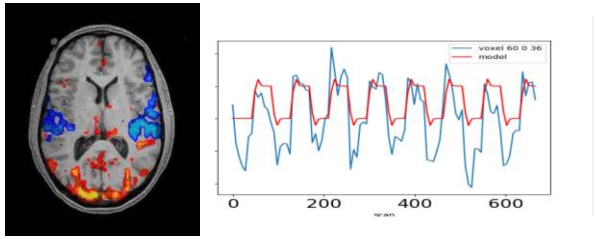
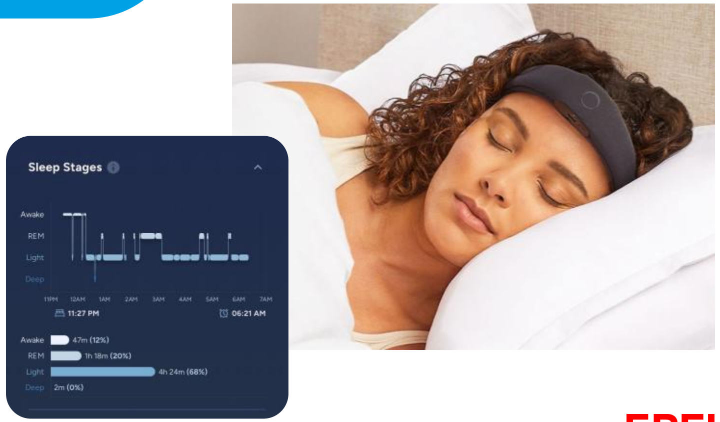
GOALS OF THIS COURSE

- Introduce **fundamental concepts** of biomedical signal processing
- Promote intuition and experience with **real biomedical signals** and **applications**

Signal processing

- Filtering, resampling
- Transforms, representations
- Combination of multiple channels
- Combination of different modalities
- Parameter estimation / pattern recognition
  - Model-based
  - Data-driven (e.g. machine learning)





Transversal to many applications, biomedical and otherwise

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ABOUT THE TEACHERS

CSEM – Swiss center for Electronics and Microtechnology

- Swiss non-profit research & technology organization (RTO)
- **Mission:** drive **applied R&D** to help the industry grow with technological innovation, via:
  - Cooperation agreements
  - Creation of start-ups
  - Licensing (technology, IP, algorithms)
- Close collaborations with Universities
  - Internships
  - Master theses
  - PhD theses

SitemMedTech HUB

550+ experts

97MCHF turnover

46 start-ups &spin-off

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ABOUT THE TEACHERS

- **Main activities at Medtech BU**
  - New technologies for vital sign monitoring
  - R&D on all device aspects: hardware, software, data flow, **signal processing**
  - Emphasis on compact / wearable devices

COURSE FORMAT

- Weekly sessions on Thursday, 15:15 to 19:00
  - 1st part theory followed by practical session
  - **Practical sessions** (“labs”):
    - Work in groups (ideally 4 to 5 people per group)
    - Analysis of biomedical signals to answer questions / exercises
      - Most sessions will be python-based (jupyter notebooks)
      - Laptop required
    - Compile answers in a report, submit via Moodle
      - Submission generally open for 1 week (confirm deadlines on Moodle)
      - **PDF format**, with file name: **StudentName1_StudentName2_(…)_StudentName4_LabXX.pdf**
      - One submission per group is acceptable (clearly identify all group members!)

Course responsible
Dr. Mathieu LEMAY
mathieu.lemay@csem.ch

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MODULE ORGANIZATION (TENTATIVE)

Dr. João JORGE

Module 01 – Introduction

- Motivation and goals
- Course format, schedule, evaluation
- Introduction to biomedical signals

Dr. Philippe RENEVEY

Module 02 – Basics I

- Sinusoids and complex exponentials
- Fourier transforms
- Normalized frequency
- Linear filter design

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18.09.2025
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02.10.2025
09.10.2025
16.10.2025
Break
30.10.2025
06.11.2025
13.11.2025
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04.12.2025
11.12.2025
18.12.2025
Exam - TBD

MODULE ORGANIZATION (TENTATIVE)

Dr. Philippe RENEVEY

Module 03 – Basics II

- Stochastic signals and filtering
- Auto- and cross-correlation
- Power spectral density
- White noise

Dr. Martin PROENÇA

Module 04 – Time-frequency

- Motivation for time-frequency analysis
- The short-term Fourier transform (STFT)
- Spectrograms in practice
- Wavelet analysis

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Exam - TBD

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MODULE ORGANIZATION (TENTATIVE)

Dr. João JORGE

Module 05 – Linear models I

- Autoregressive (AR) signal modeling
- AR model estimation
- Linear prediction
- Spectral estimation

Dr. João JORGE

Module 06 – Linear models II

- Moving average (MA) signal modeling
- ARMA signal modeling
- Linear system identification
- Adaptive modeling

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Exam - TBD

MODULE ORGANIZATION (TENTATIVE)

Dr. Adrian LUCA

Module 07 – Frequency tracking

- Concept of instantaneous frequency
- Hilbert transform
- Teager-Kaiser operator
- Adaptive filter frequency tracking

TBD

Module 08 – Midterm exam

- Mock exam for practice purposes
- Questions from Modules up to 07
- Does not count for evaluation
- Optional

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Exam - TBD

MODULE ORGANIZATION (TENTATIVE)

Dr. Guillaume BONNIER

Module 09 – Singular value decomposition

- Matrix rank
- Singular value decomposition (SVD)
- Least-squares solution using SVD
- Singular spectrum analysis

Dr. Karen ADAM

Module 10 – Principal component analysis

- Basics of principal component analysis (PCA)
- PCA and SVD
- Dimensionality reduction
- Blind source separation

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Exam - TBD

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MODULE ORGANIZATION (TENTATIVE)

Dr. Ramin SOLTANI

Module 11 – Classification and regression

- Linear / non-linear regression
- Classification / clustering
- Feature selection
- Training / testing / validation

Dr. Clémentine AGUET

Module 12 – Intro to neural networks I

- Perceptron
- Multilayer perceptron (MLP)
- Activation functions
- Gradient descent and backpropagation

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Exam - TBD

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MODULE ORGANIZATION (TENTATIVE)

Dr. Clémentine AGUET

Module 13 – Intro to neural networks II

- Convolutional neural networks (CNN)
- Recurrent neural networks (RNN)
- Regularization: dropout, batch normalization, weight decay, early stopping

TBD

Module 14 – Open Q&A

- Open questions & answers
- To consolidate theory and prepare for exam

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Exam - TBD

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COURSE FORMAT

- The **moodle** page is the central platform for the course
  - Theory slides, practical questions & code, report submission, communications
  - If you are registered but do not have access to the moodle, please contact mathieu.lemay@csem.ch

- **Pre-requisites** for the course
  - Analysis, linear algebra, fundamentals of Fourier analysis and digital filtering
  - Also welcome: physiology, (bio)physics…
  - The reality: diverse student backgrounds attending the course
  - If unsure: follow the first two modules (Basics I and II), and try the practical sessions

- **Literature suggestions** (more general)
  - *Discrete-Time Signal Processing* by Alan V. Oppenheim
  - *Digital Signal Processing* by John G. Proakis and Dimitris G. Manolakis

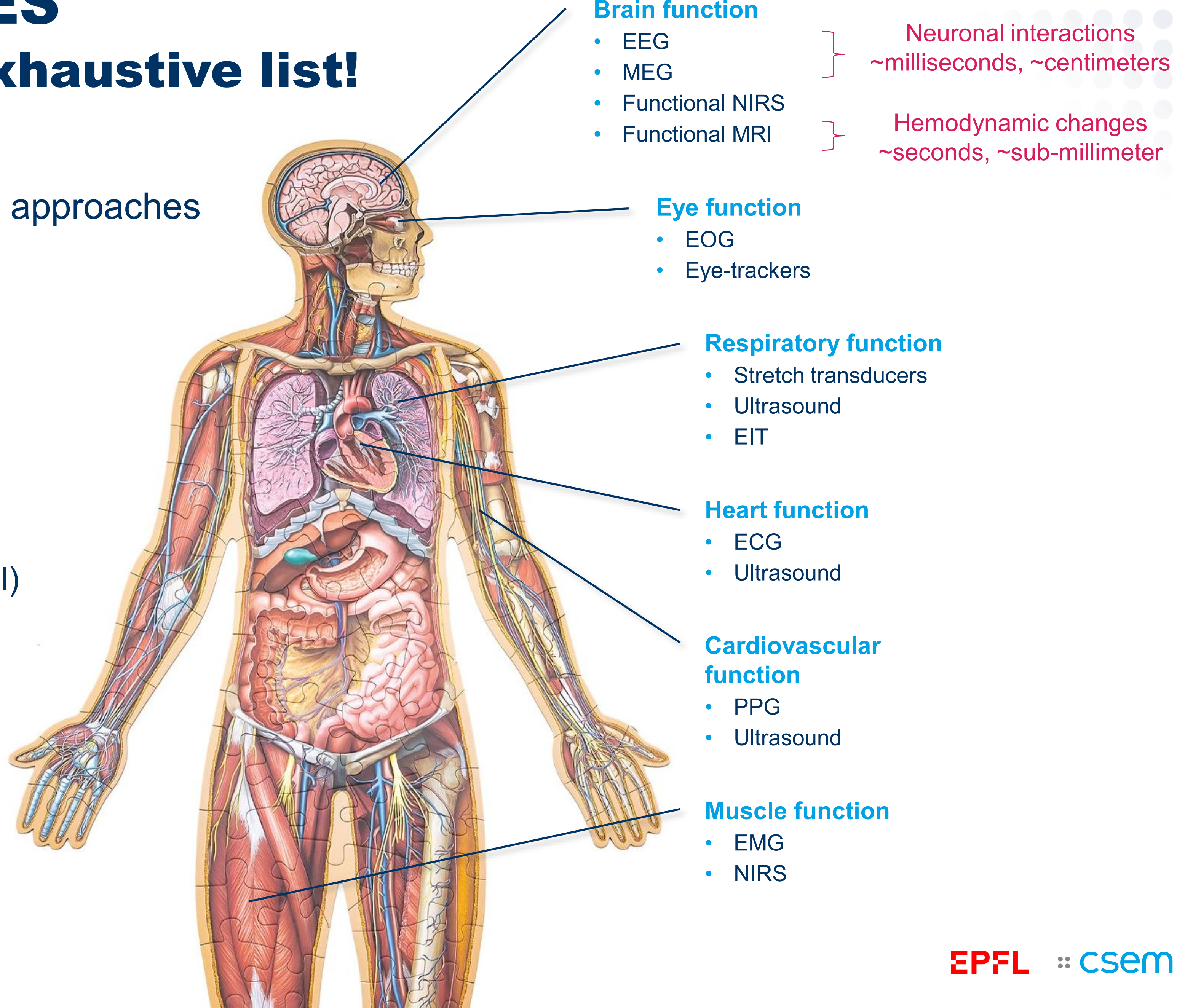
COURSE EVALUATION

- **Evaluation elements**
  - Final exam: 65% of final score
  - Lab reports: 35% of final score
    - All reports count equally

- **Note:**
  - Lecture attendance is not mandatory
  - “Mini-labs” of today do not count for evaluation
  - Final exam is “open book” : any print-outs, slides, study notes, books can be consulted
    - Electronic devices (e.g. smartphones, tablets, laptops) cannot be used
  - Midterm (mock) exam does not count for evaluation
    - It is meant to give you an idea about the real exam
  - Some “exam-like” questions will also be presented during class

SENSING MODALITIES
Some examples – non-exhaustive list!

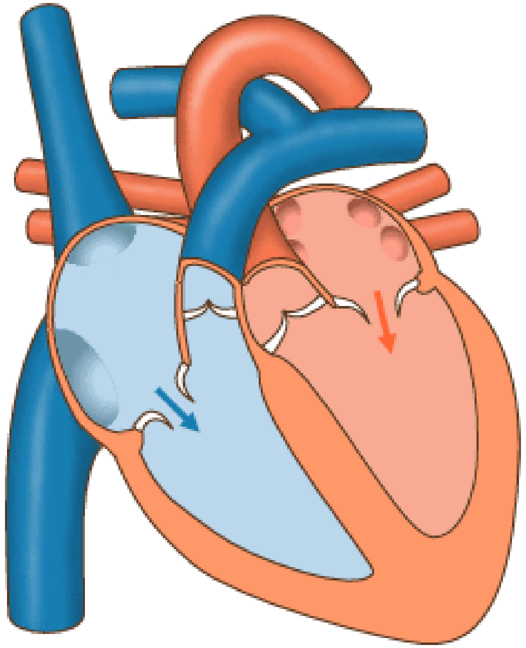
- Wide variety of sensors and sensing approaches
- Different sensitivity to:
  - Biophysical phenomena
  - Parameters of interest
  - Interferences & confounds
- And differences in:
  - Resolution (spatial, temporal, spectral)
  - Coverage
  - Invasiveness
  - Portability
- **Knowing the sensor is key to effective signal processing**

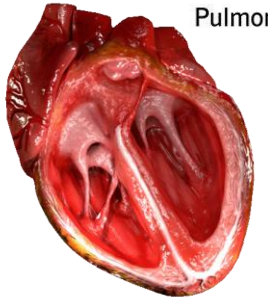


HEART FUNCTION

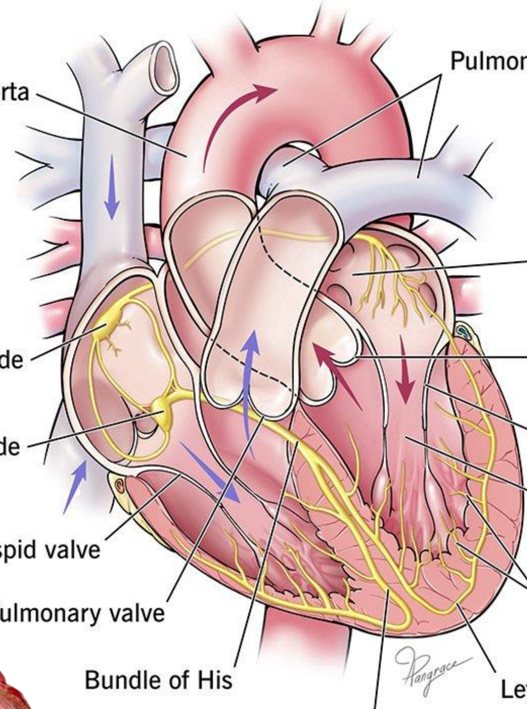
- Blood flow through the heart requires well-timed muscle contraction across different chambers
- Triggered by electrical signals from SA node, propagated through dedicated conduction system

Blood flow

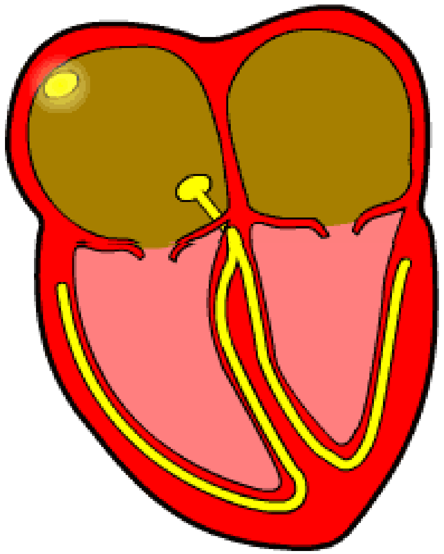




Cardiac conduction system



Atrial conduction



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HEART FUNCTION AND DYSFUNCTION

- Various problems can disrupt the electrical conduction, with important health consequences
- Identifying the type of disruption is key to proper diagnosis and management

Sinus (normal) rhythm

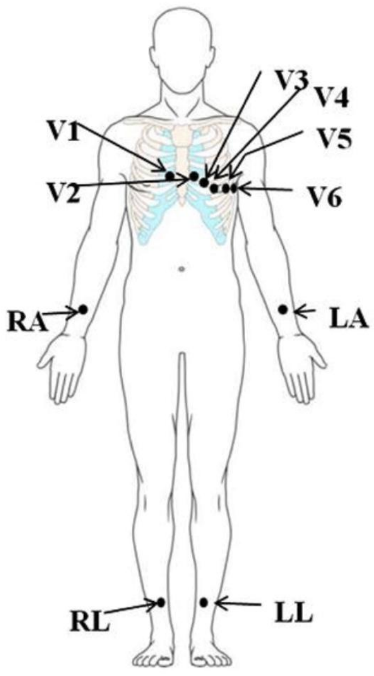
Example arrhythmia : atrial fibrillation

- Rapid & irregular atrial depolarization
- Leads to irregular activation of the ventricles
- Prevalence of 3–7% in elderly population
- Symptoms: syncope, chest pain, fatigue, palpitations, heart failure and stroke
- Management: medication, lifestyle, surgical intervention

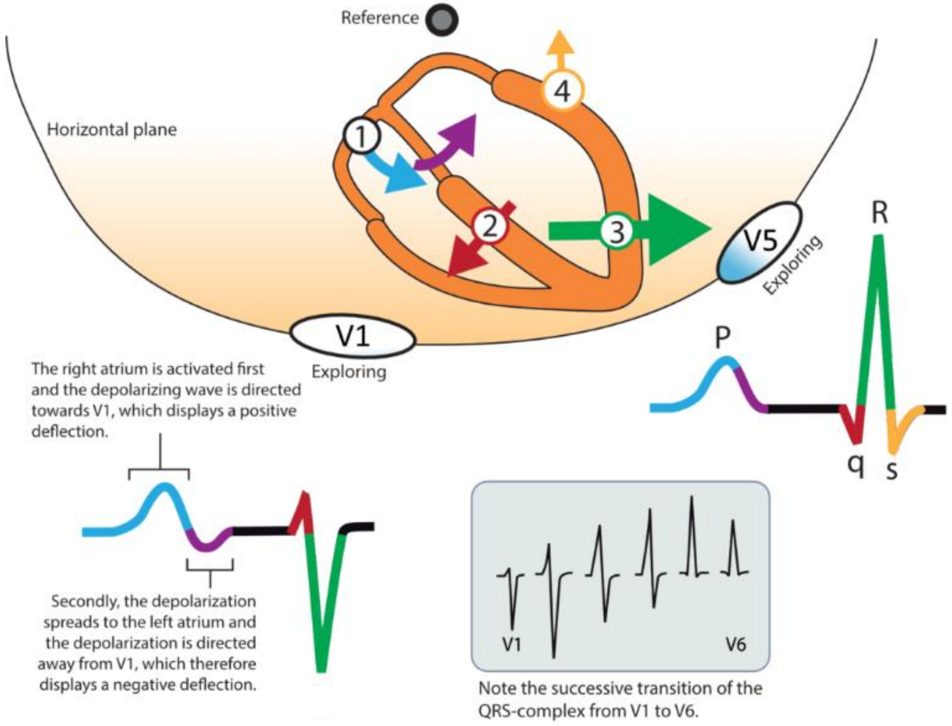
ELECTROCARDIOGRAPHY

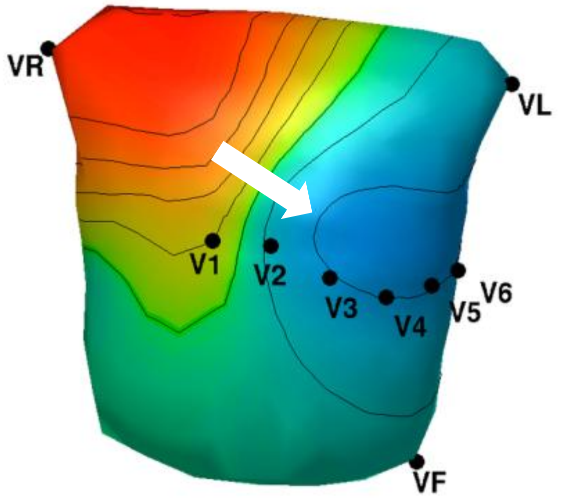
- **ECG** measures differences in electric field potential generated by the electrical activity of the heart – depolarization and repolarization of the muscle in every contraction cycle

Electrode positions in standard 12-lead ECG



Different periods of the cycle seen by different electrodes



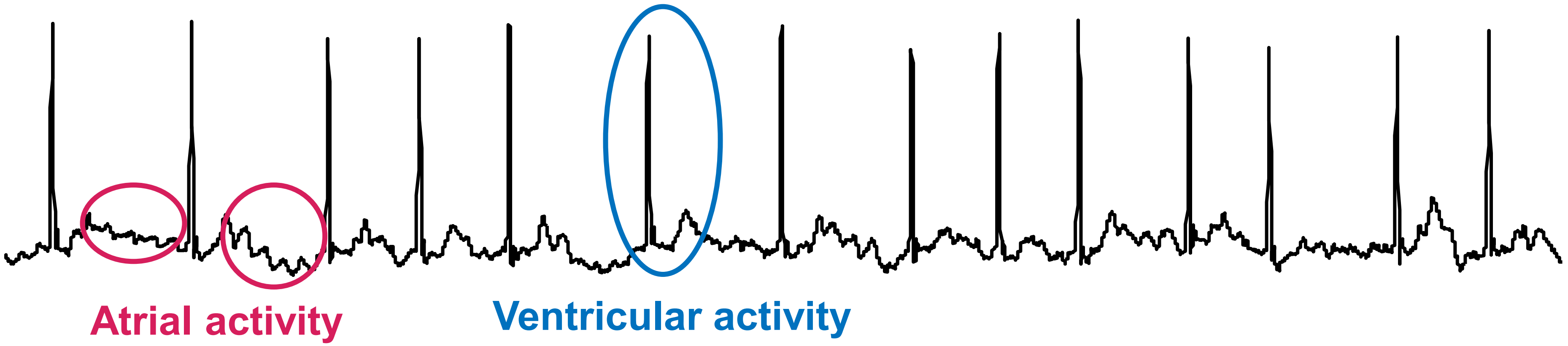


The dominant current propagation at a given moment in the heart can be seen approximately as an **equivalent current dipole**, with a characteristic electric field measurable at the surface

ELECTROCARDIOGRAPHY

- Deviations to the standard ECG wave morphology are informative of pathologies
  - Which segments of the heart's electrical conduction system are affected, and how?
  - Heart beat regularity is also informative
- ECG is the most commonly used tool for clinical evaluation of **arrythmias**

Atrial fibrillation



ELECTROCARDIOGRAPHY

Ventricular bigeminy: arrhythmia in which there is a single ectopic beat (e.g. premature ventricular contraction, PVC), following each regular heartbeat

Ventricular trigeminy: same as bigeminy with a pattern of three beats

ELECTROCARDIOGRAPHY

Atrial flutter: arrhythmia in which the heart's upper chambers (atria) beat too quickly

Second-degree AV block: conduction block between the atria and ventricles

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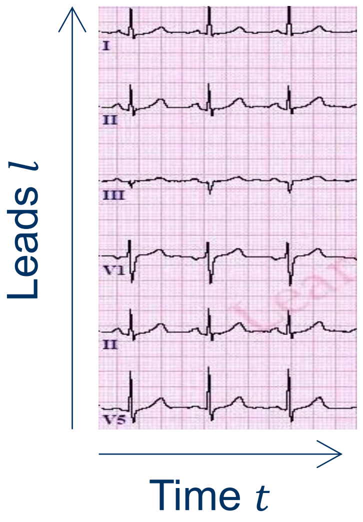
ELECTROCARDIOGRAPHY

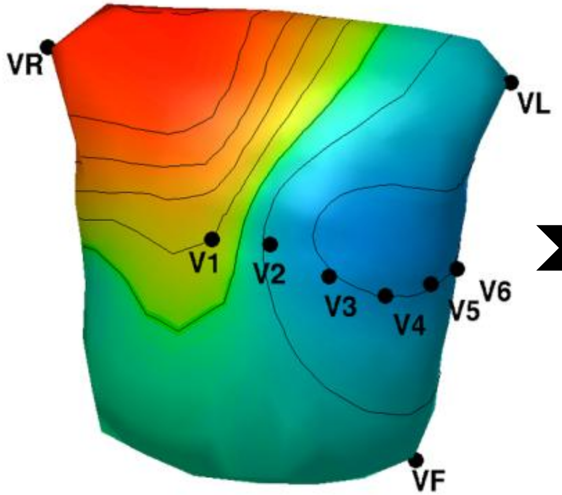
- Combining **multiple channels** (sensors) helps augmenting available information
- Can be represented as a **vectorcardiogram** (**VCG** on x,y,z components) :

$$\vec{V}(t) = T\Phi_{ECG}(l,t)$$ T is a pre-defined linear operator

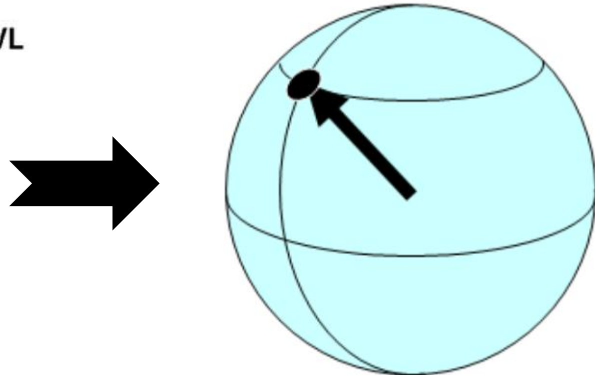
Multi-channel (12-lead) ECG
$\Phi_{ECG}(l,t)$



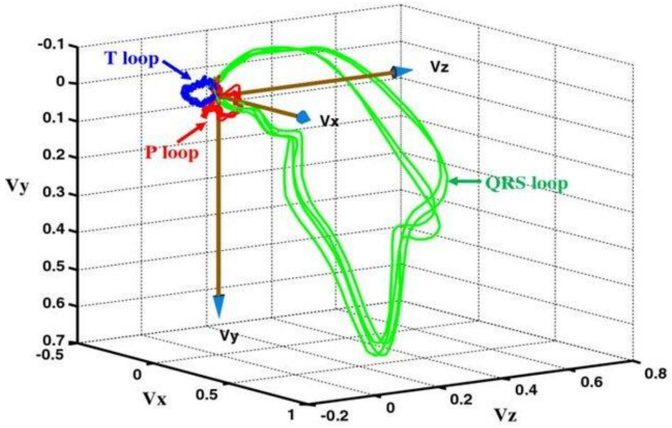
Body surface potential
at each time t



VCG (dipole)
at each time t
$\vec{V}(t)$



VCG distribution
each time t is a point in the loop trajectory



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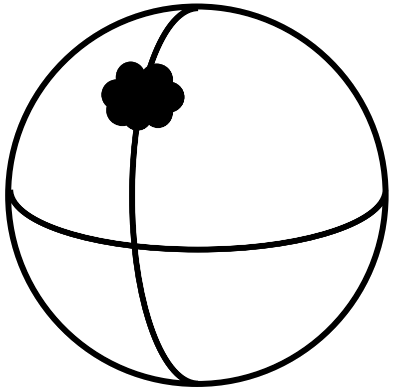
ELECTROCARDIOGRAPHY

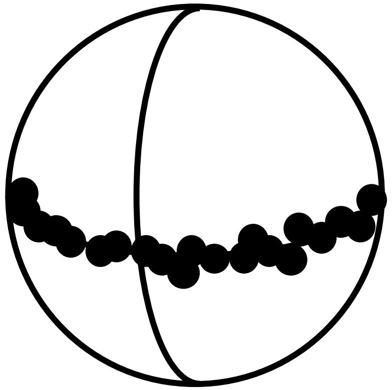
- The VCG distribution can be further simplified, e.g. via **eigenvector decomposition**
- Three eigenvalues λ_1, λ_2 and λ_3 are computed and normalized ($\lambda_1 + \lambda_2 + \lambda_3 = 1$)
- The three eigenvalues offer a summary description of the distribution
- Some example scenarios (idealized):

Peak distribution



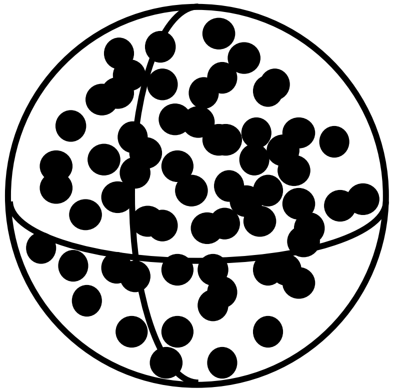
$\lambda_1 \sim 1$
$\lambda_2 \sim \lambda_3 \sim 0$

Distribution along a great circle



$\lambda_1 \sim \lambda_2 \sim 1/2$
$\lambda_3 \sim 0$

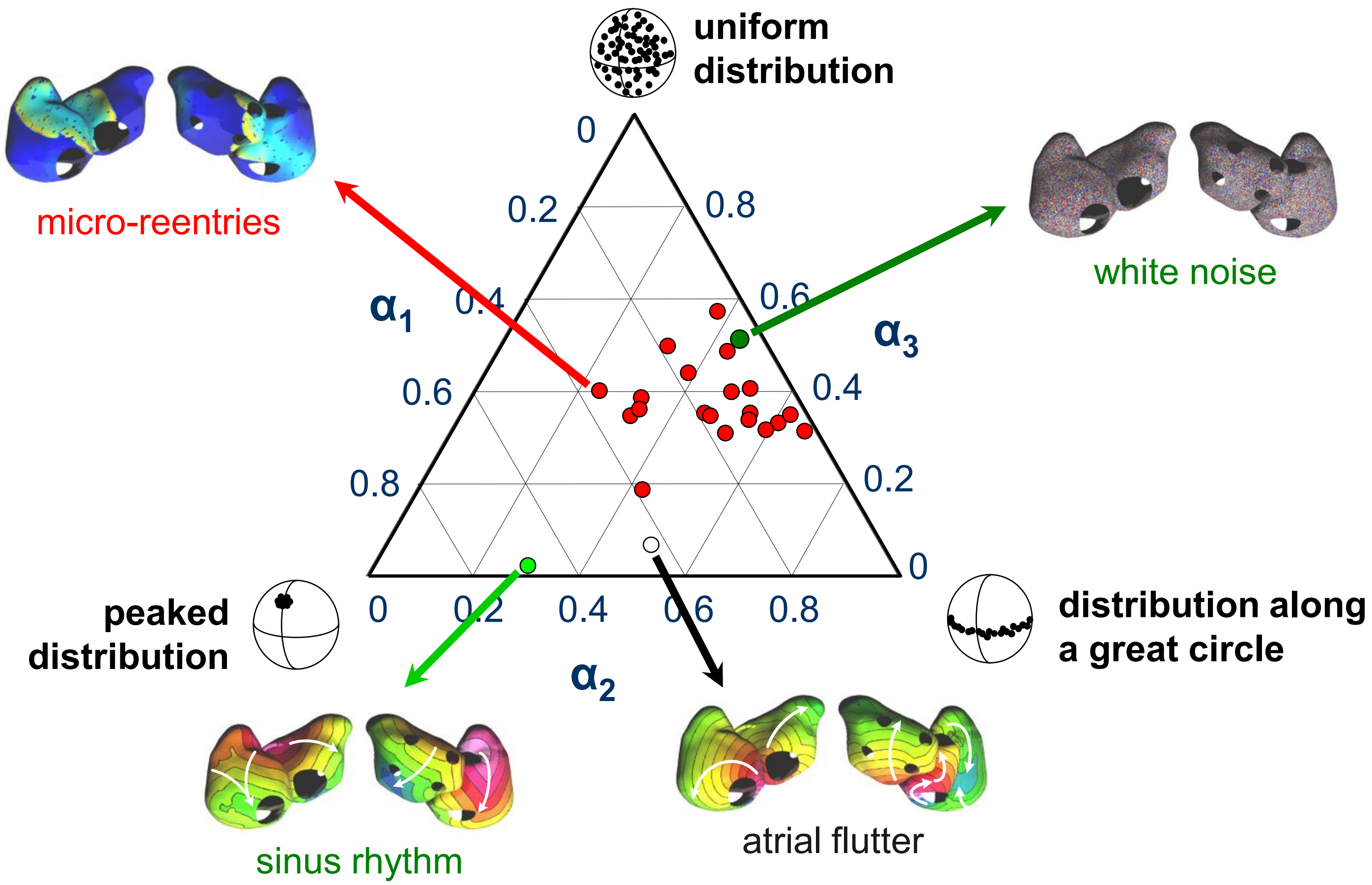
Uniform distribution



$\lambda_1 \sim \lambda_2 \sim \lambda_3 \sim 1/3$

ELECTROCARDIOGRAPHY

- The three-eigenvalue representation shows meaningful patterns
- This can be used for **automatic** pattern analysis (e.g. clustering), classification (e.g. arrhythmias)



Axes:

$\alpha_1 = \lambda_1 - \lambda_2$

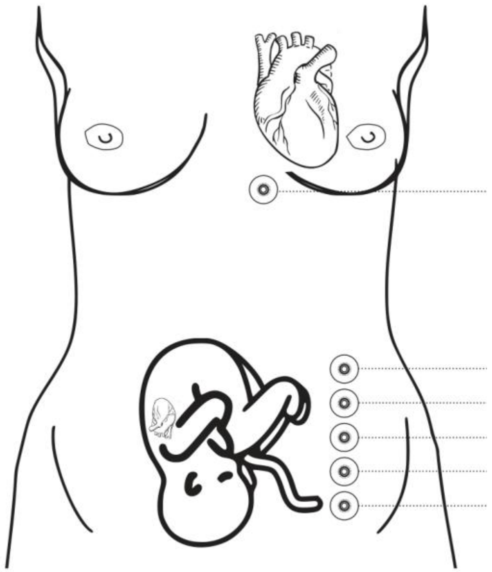
$\alpha_2 = 2\,(\lambda_2 - \lambda_3)$

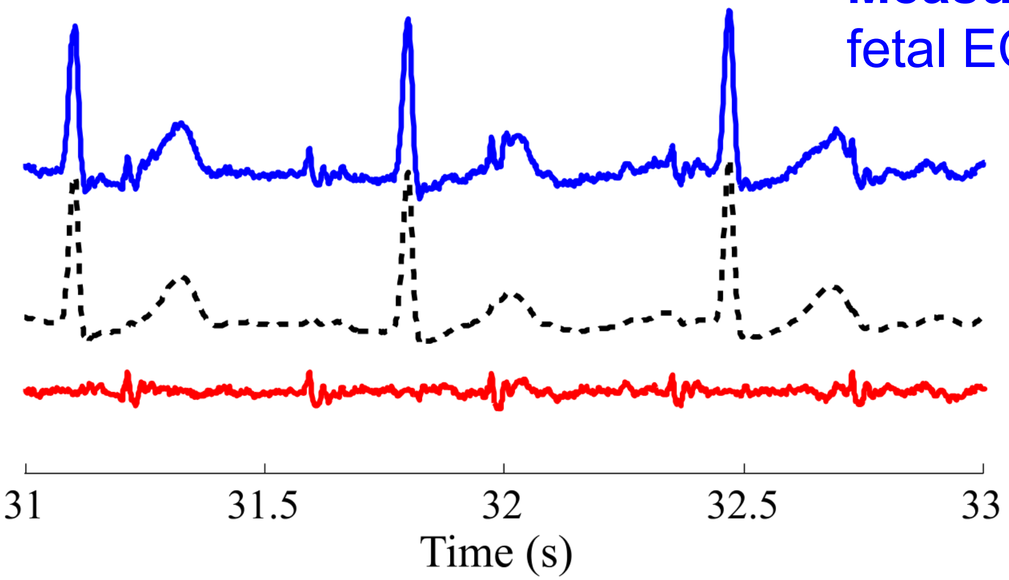
$\alpha_3 = 3\,\lambda_3$

Each point is a patient / cardiac recording

ELECTROCARDIOGRAPHY

- Another application leveraging multi-channel signals: **ECG monitoring of mother and fetus**
- Fetal ECG is typically much weaker – difficult to separate from the mother's





Measured: maternal and fetal ECG mixed together

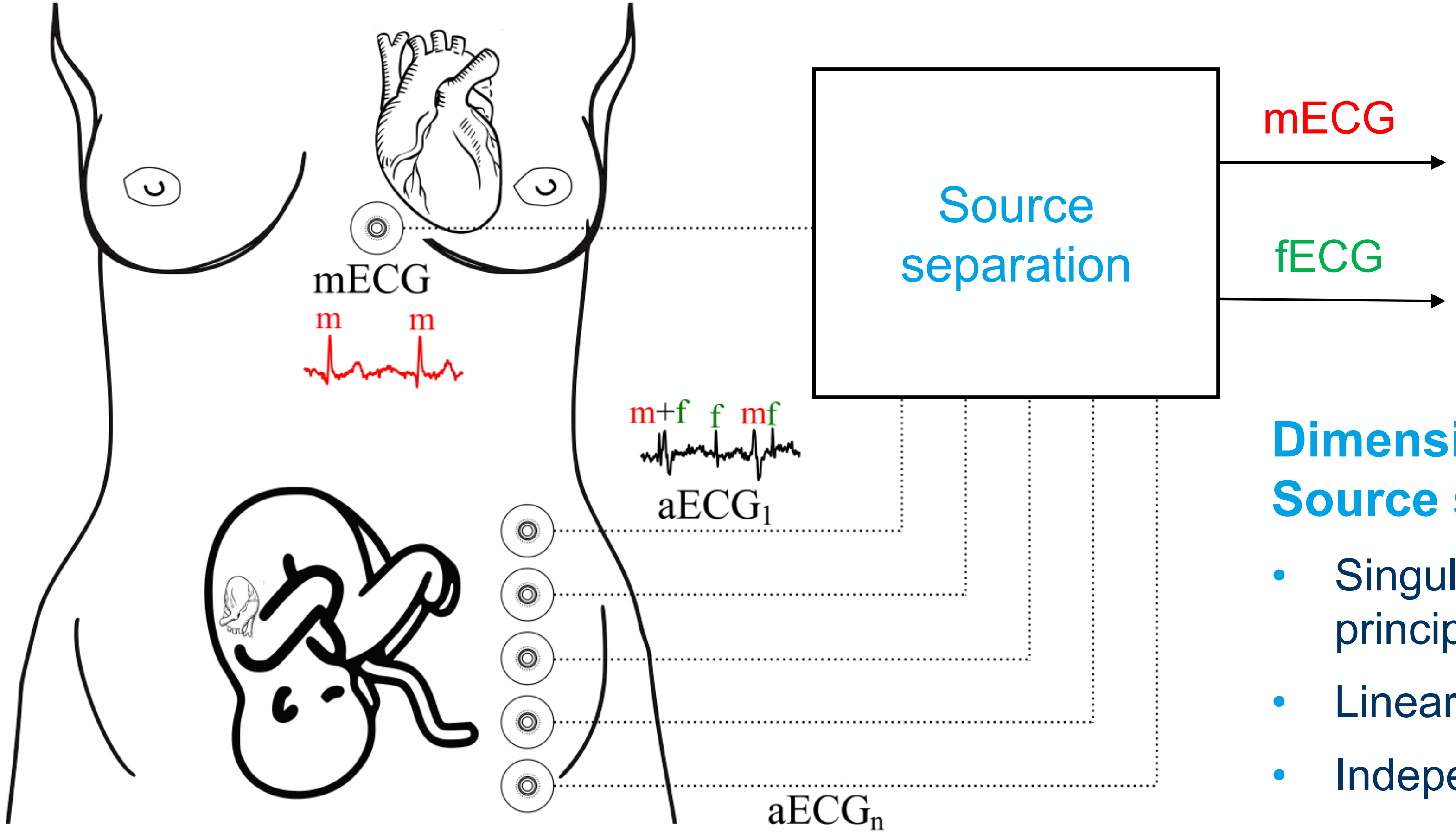
contains:

Maternal: 50 µV – **5 mV**
60 – 80 bpm

Fetal: **10 µV** – 300 µV
110 – 180 bpm

ELECTROCARDIOGRAPHY

- Different sensor positions afford different sensitivity to maternal and fetal ECG contributions
- A sensor close to the mother’s heart may be approximated as “pure” mECG

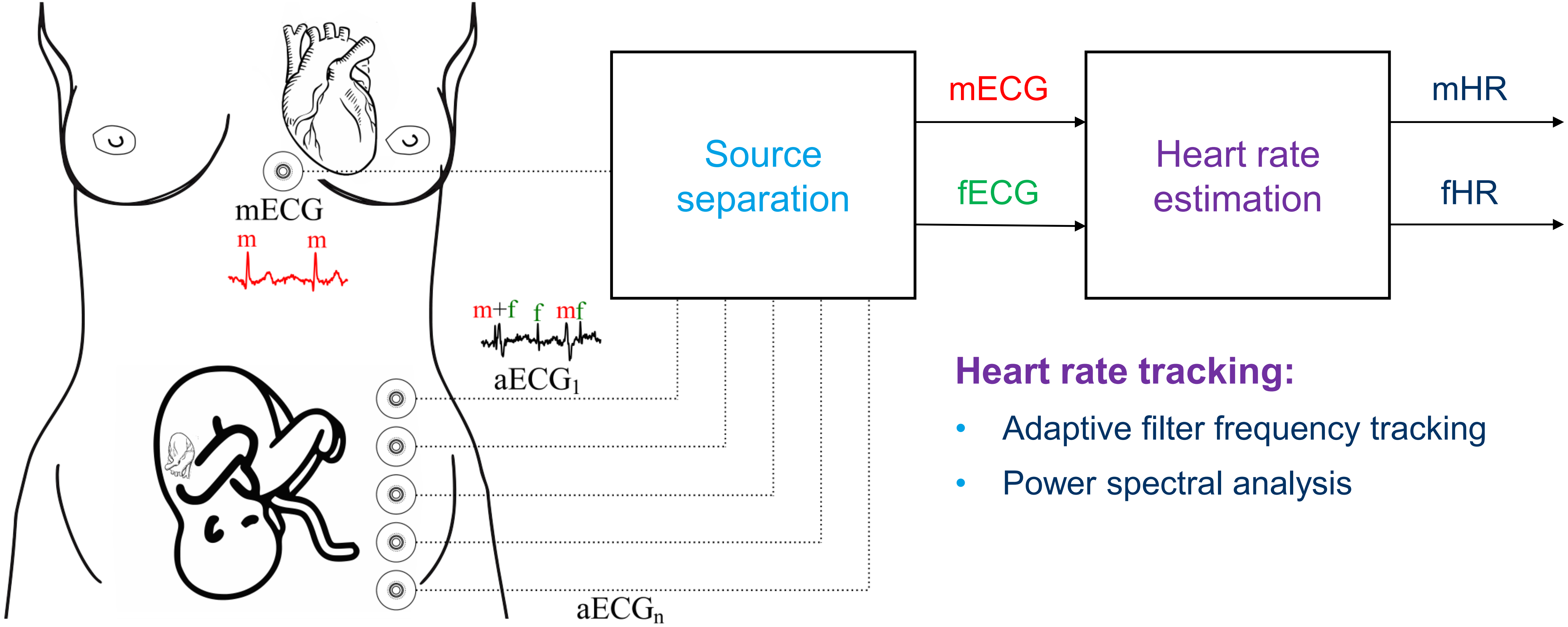


Dimensionality reduction / Source separation techniques:

- Singular value decomposition (SVD), principal component analysis (PCA)
- Linear models, adaptive filtering
- Independent component analysis (ICA)

ELECTROCARDIOGRAPHY

- Once separated, the different sources can be analyzed for parameter estimation – e.g. HR
- Some techniques require full recording (“offline” analysis), others work in real time (“online”)



Heart rate tracking:

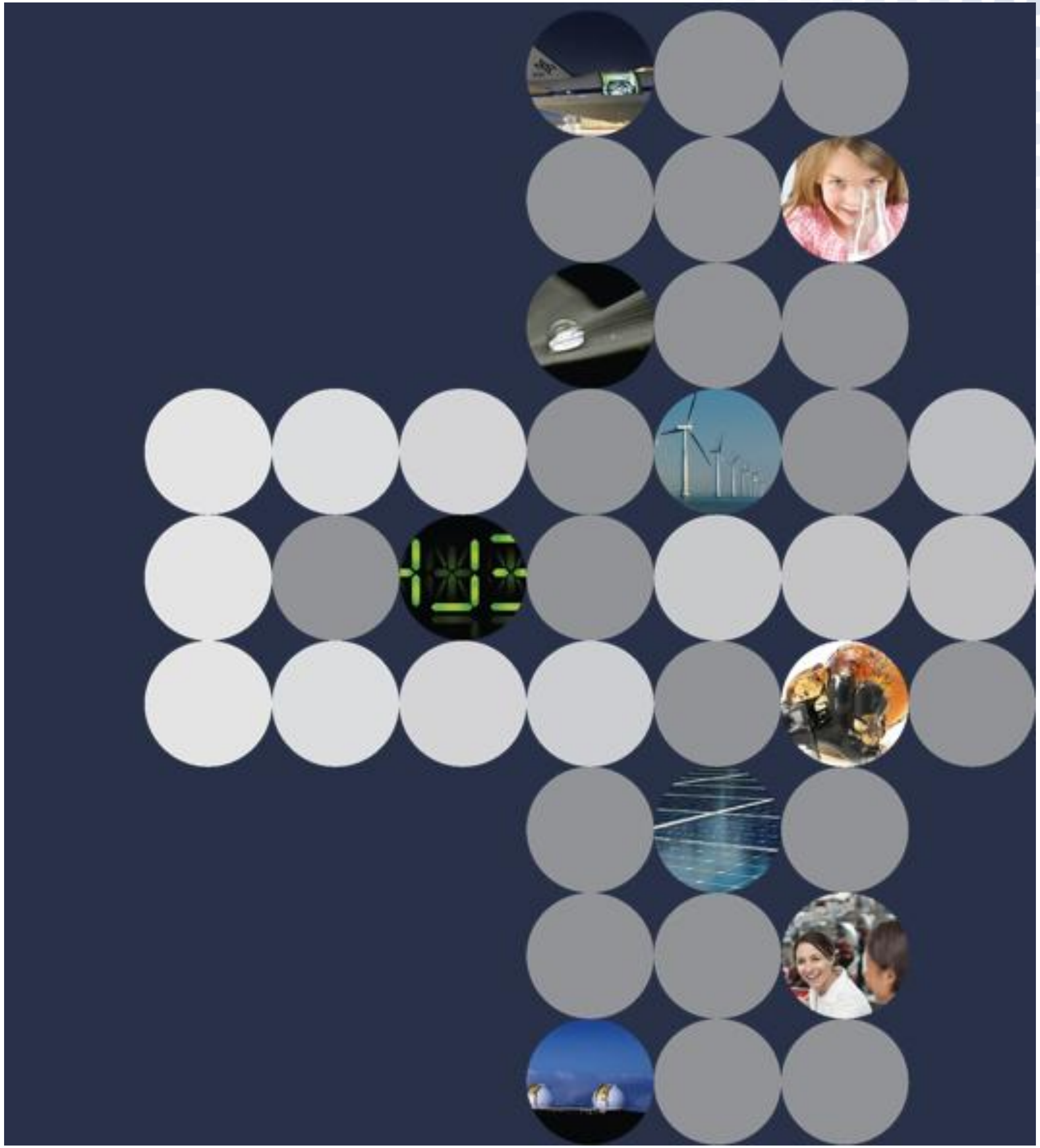
- Adaptive filter frequency tracking
- Power spectral analysis

PRACTICAL SESSION 01-I
ECG & cardiac arrhythmias

1. Download the .zip from Moodle
2. Run Jupyter notebook
   `ecg_data.ipynb`

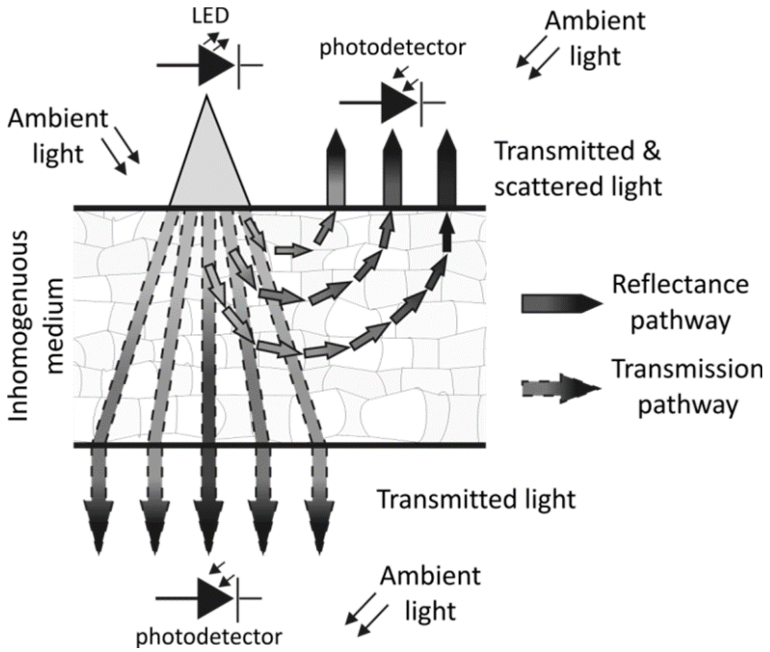
Tip for Noto:

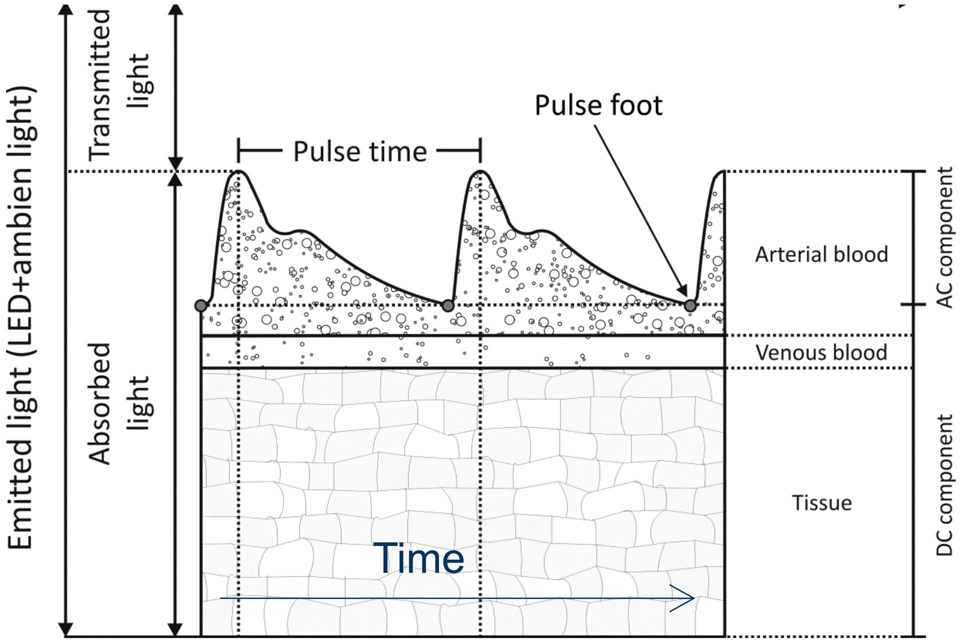
Transfer whole .zip file to noto, and then extract it there



PHOTOPLETHYSMOGRAPHY (PPG)

- **PPG** works by illuminating tissues with light of certain wavelength(s) (see next slide) and then measuring:
  - Transmitted & scattered light, close to the point of emission – in **reflection PPG** (e.g. smartwatch)
  - Transmitted light passing across the tissue – in **transmission PPG** (e.g. finger clip)





- Light experiences **absorption** and **scattering** in biological tissues
- Variations in **blood volume** (e.g. from pulsatility) strongly influence the absorbed light

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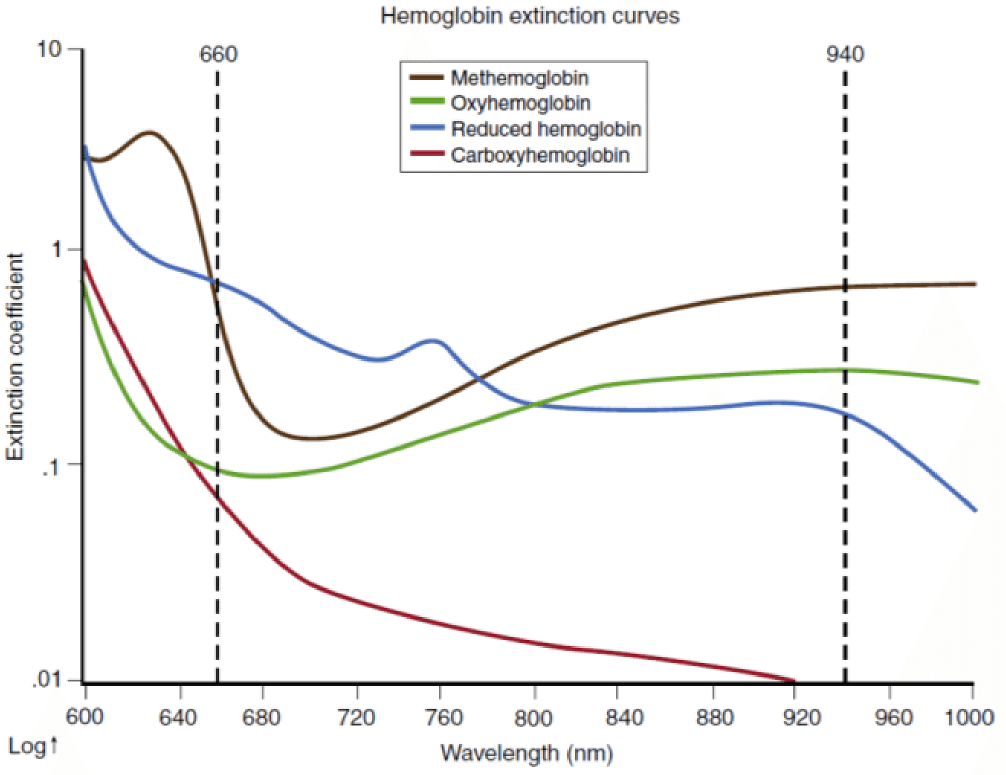
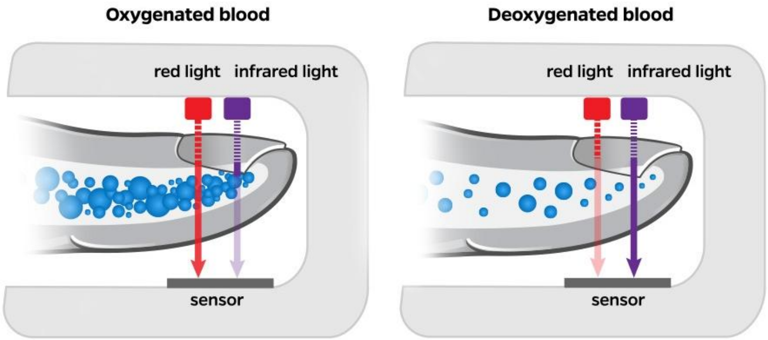
PHOTOPLETHYSMOGRAPHY (PPG)

- Different substances can have different **absorbance** for different light **wavelengths**
- **Hemoglobin** changes absorbance depending on binding (e.g. oxygenated, oxyHb vs. reduced, deoxyHb)



Tracking SpO2

- **SpO2** (peripheral oxygen saturation)
  = fraction of oxyHb relative to total Hb
- Important vital parameter (clinics)
- By measuring **multiple wavelengths**, extracting the AC part (pulsatile part linked to arterial blood), and modeling light attenuation (Beer-Lambert law), we can track the proportion of oxyHb to deoxyHb



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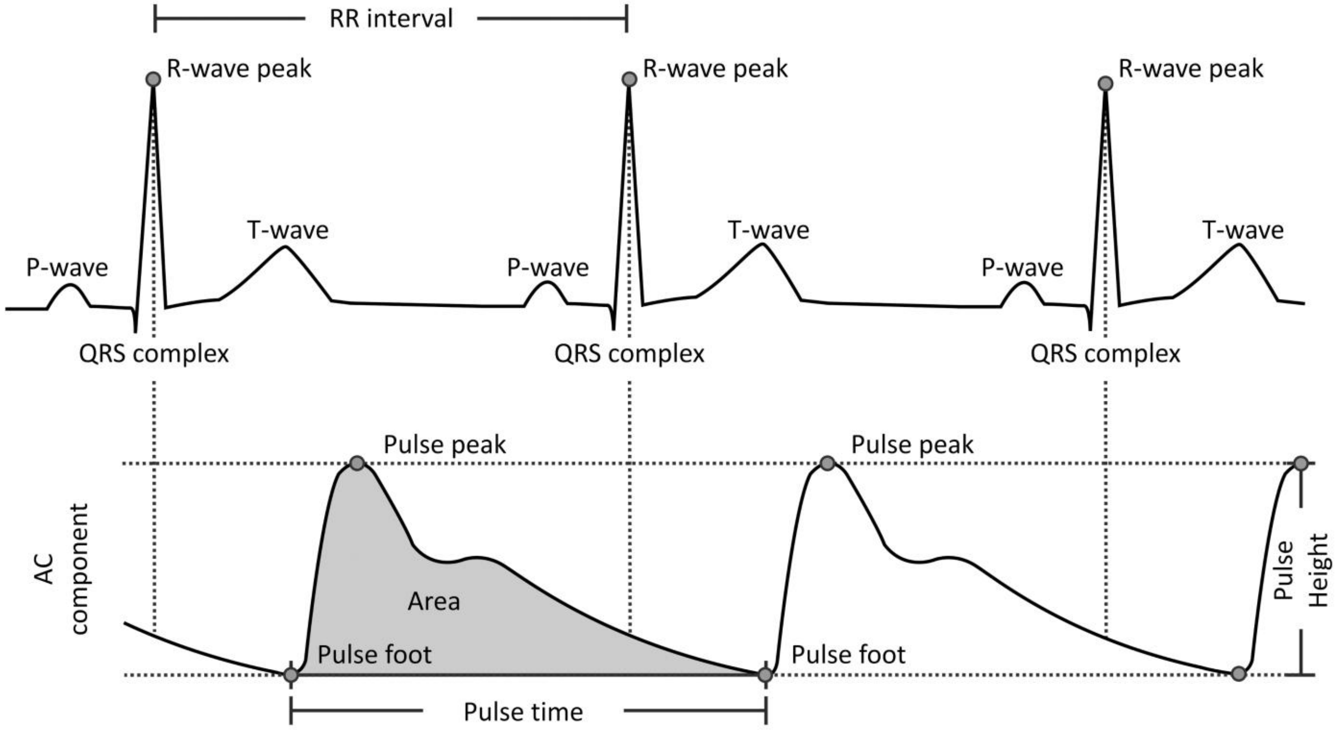
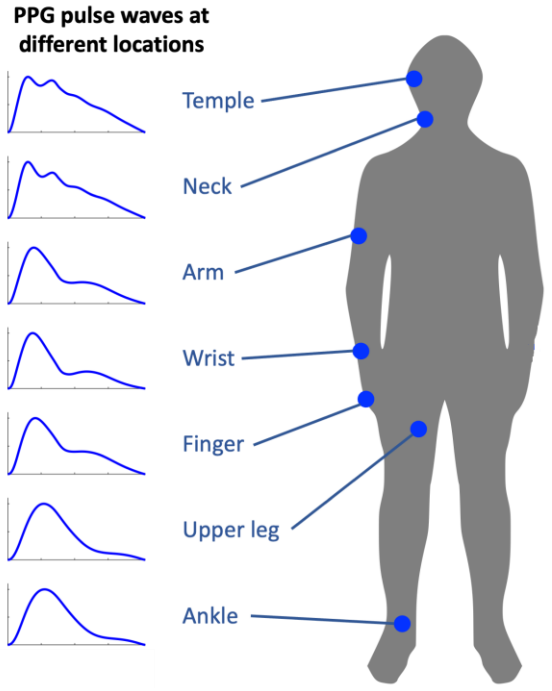
PHOTOPLETHYSMOGRAPHY (PPG)

- Naturally, ECG and PPG share information. Nonetheless:
  - **ECG** probes the electrical depolarization cycle of the heart
  - **PPG** measures blood volume pulsatility at a given location of the vasculature





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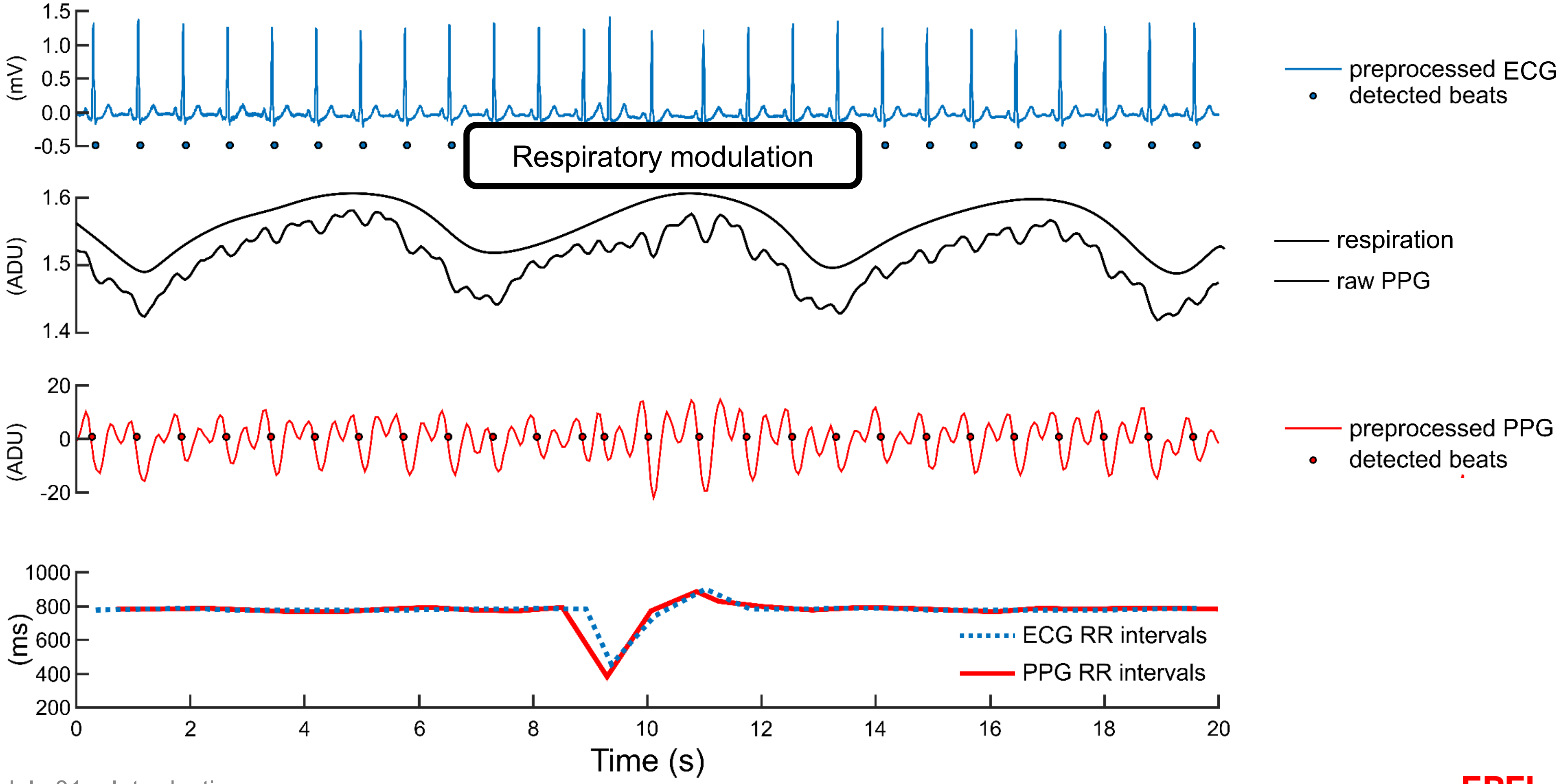
PHOTOPLETHYSMOGRAPHY (PPG)

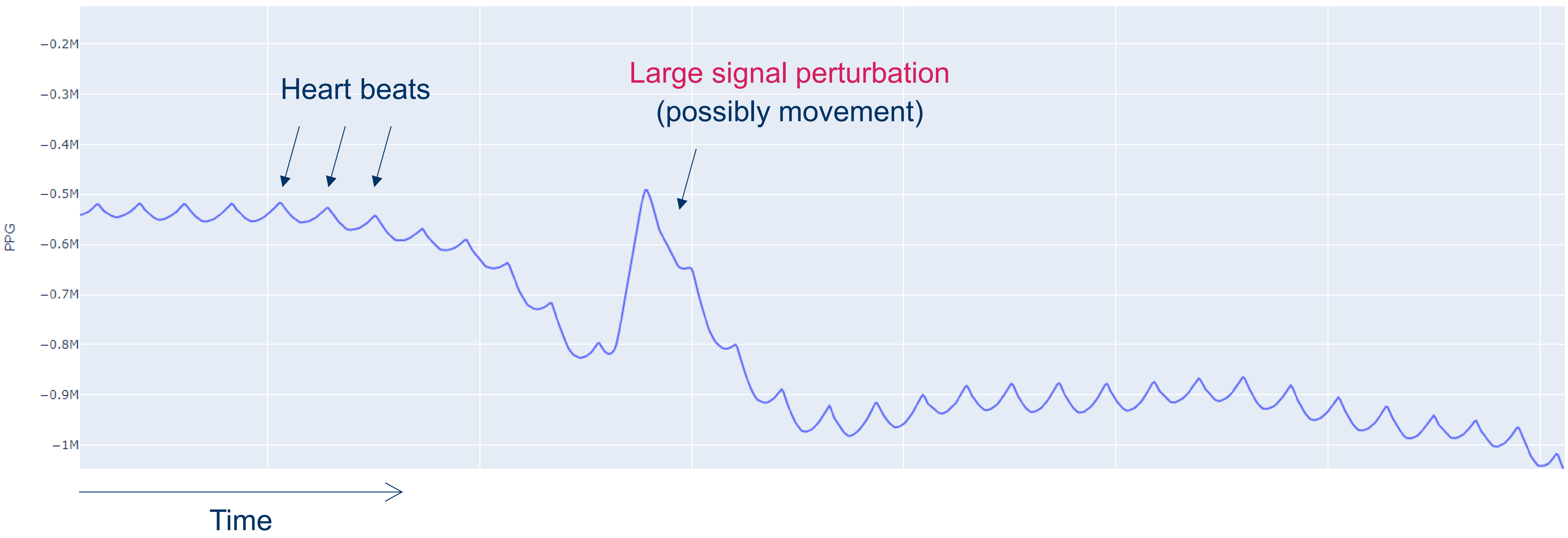
- **Respiration** affects PPG baseline and amplitude, and also the heart rate (a mechanism named respiratory sinus arrhythmia – not a pathology!)



PHOTOPLETHYSMOGRAPHY (PPG)

- **Motion** can visibly disrupt PPG signal (and many other biomedical signals)
- Sporadic motion can be addressed by excluding affected periods

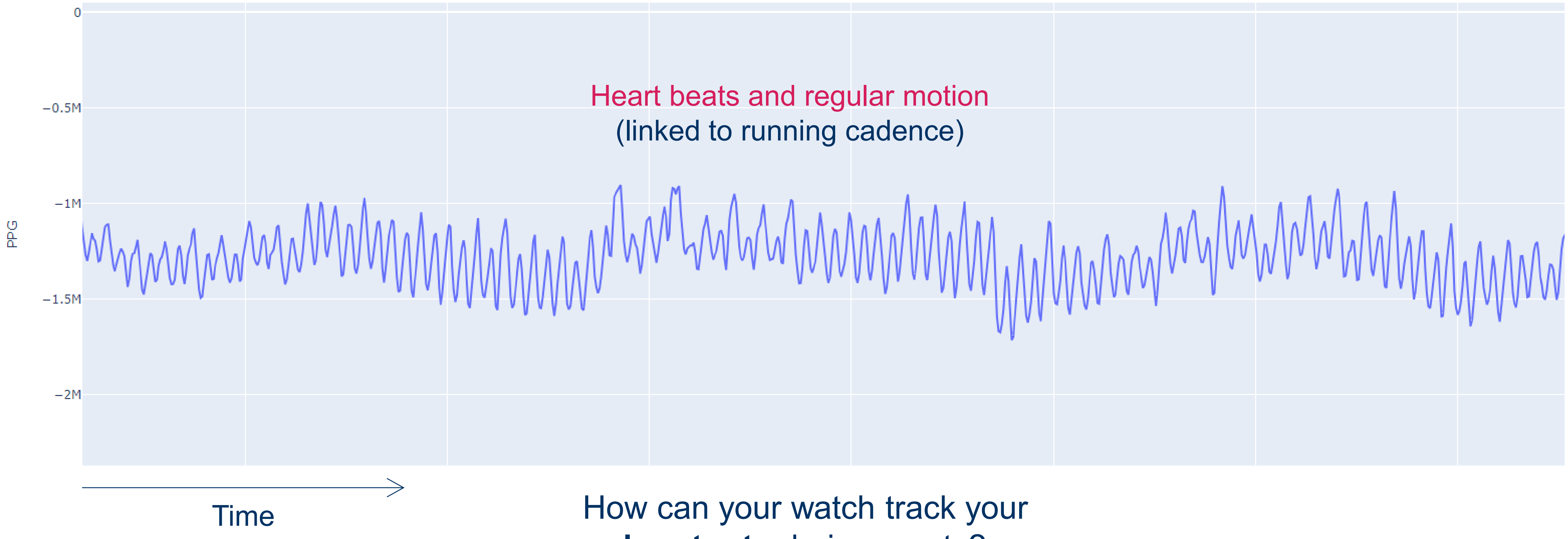
Raw PPG at rest



PHOTOPLETHYSMOGRAPHY (PPG)

- **Motion** can visibly disrupt PPG signal (and many other biomedical signals)
- Repeating motion is more challenging

Raw PPG while running

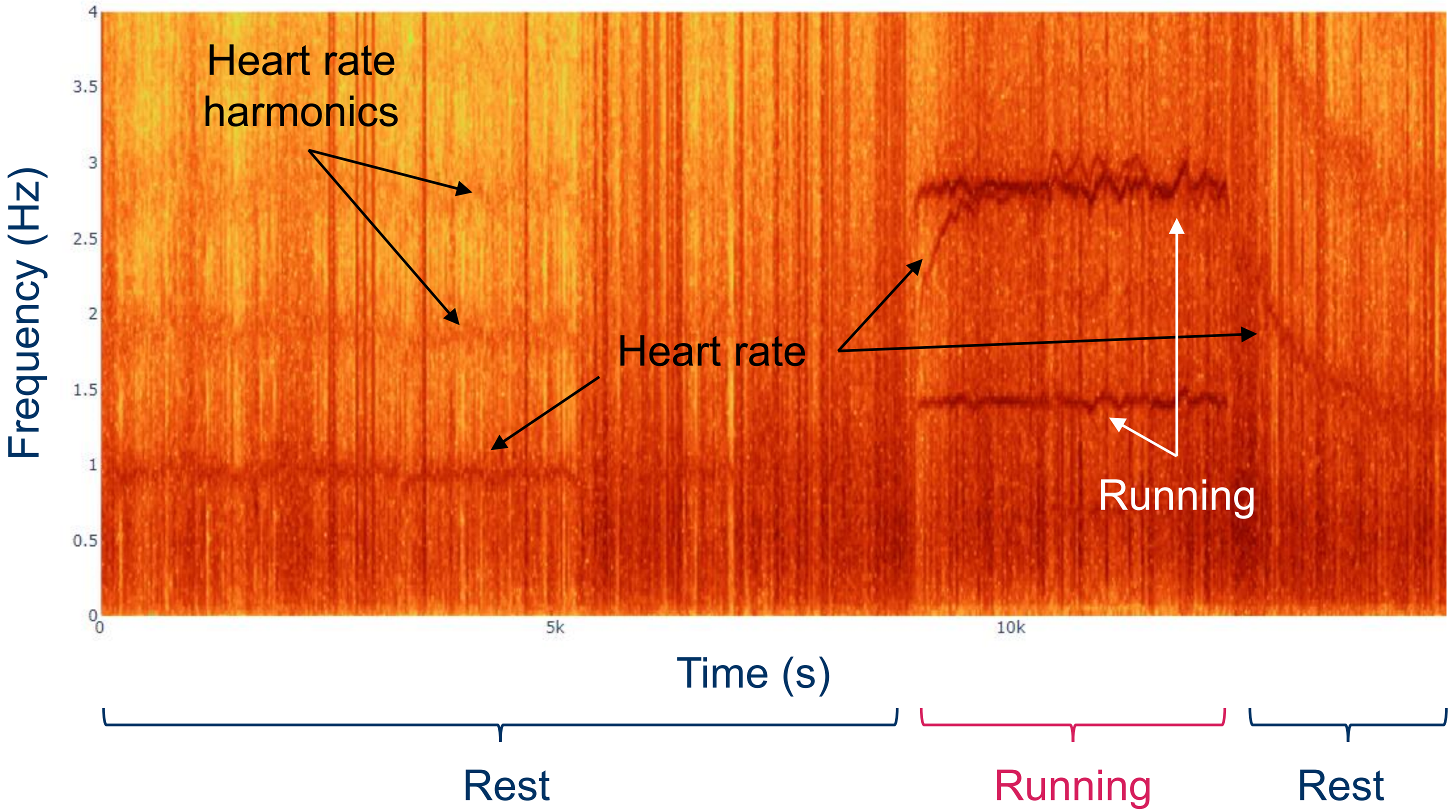


How can your watch track your **heart rate** during sports?

PHOTOPLETHYSMOGRAPHY (PPG)

- **Time-frequency representations** can be highly valuable in such a context
- Heart rate can change fast, but still less abruptly than movement

Spectrogram



(darker = stronger signal power)

PHOTOPLETHYSMOGRAPHY (PPG)

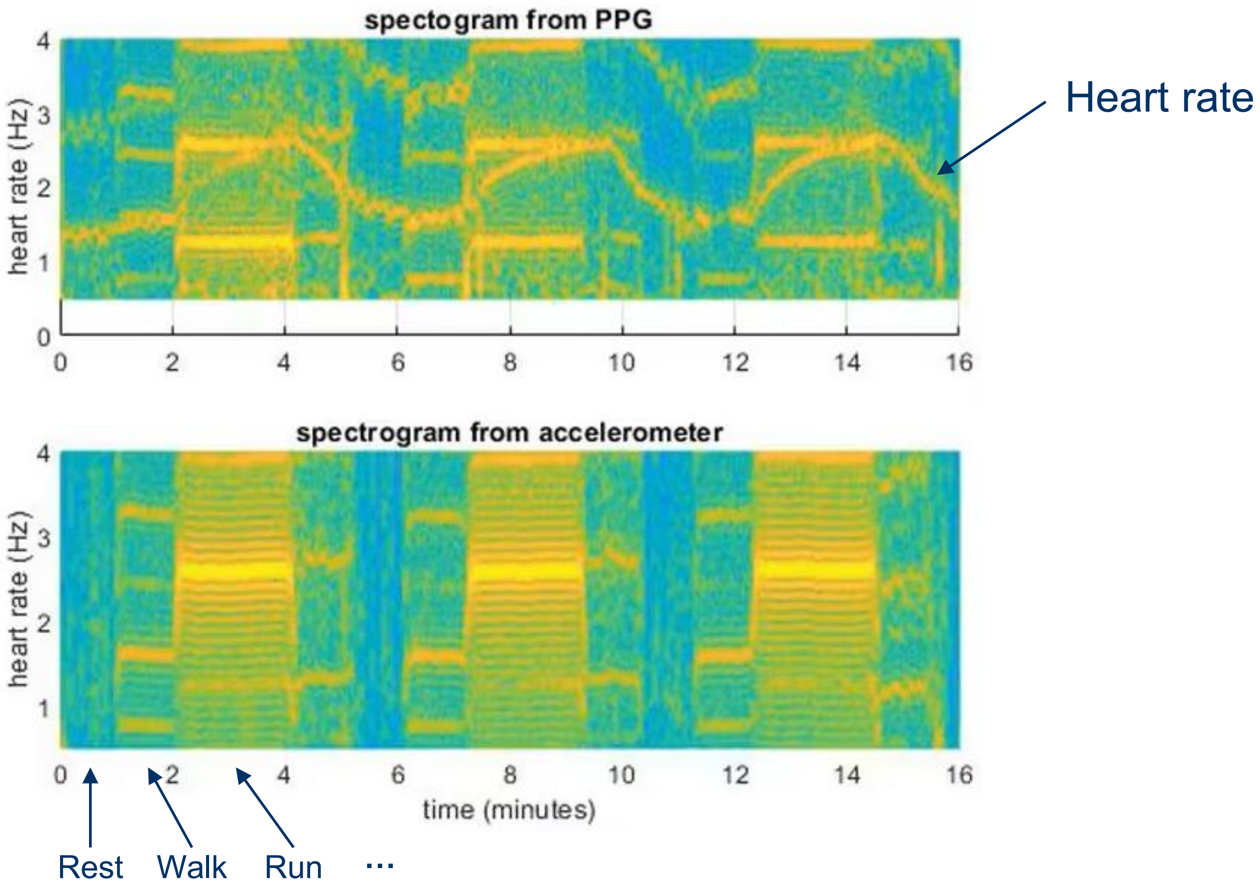
- **Time-frequency representations** can be highly valuable in such a context
- **Multimodal sensing** can also be extremely helpful

PPG

- Heart rate and motion contributions

Accelerometer

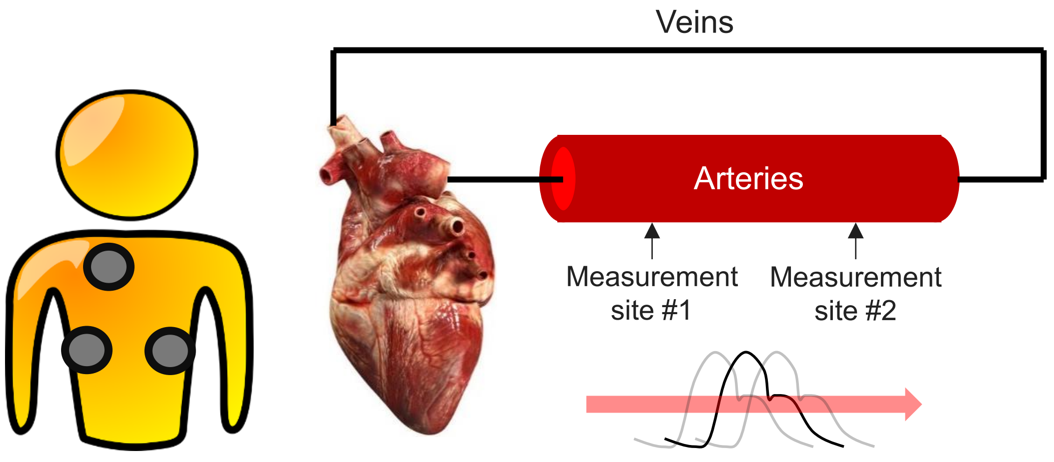
- Only motion contributions



PHOTOPLETHYSMOGRAPHY (PPG)

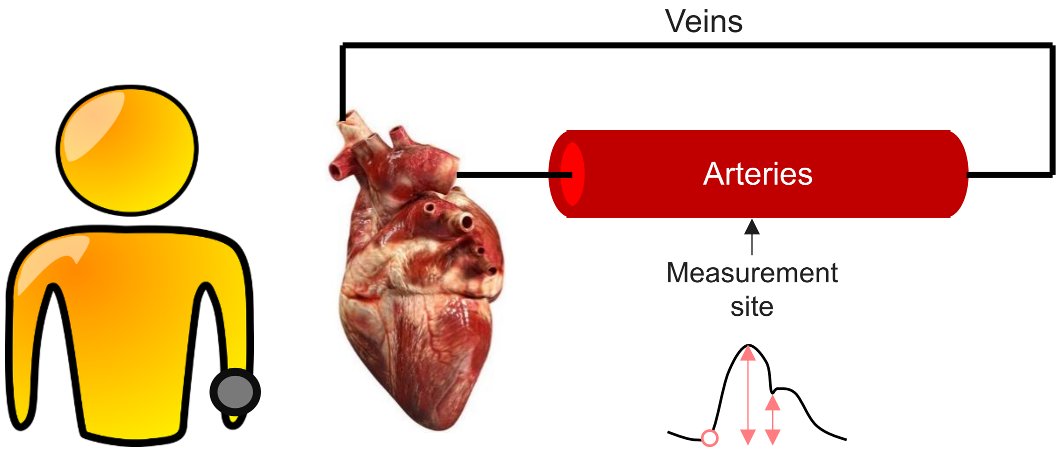
- **Blood pressure (BP)** can also be tracked based on PPG-derived information

Approaches based on
pulse wave velocity (PWV)



Measurement of the **velocity** of the pressure wave

Approaches based on
pulse wave analysis (PWA)

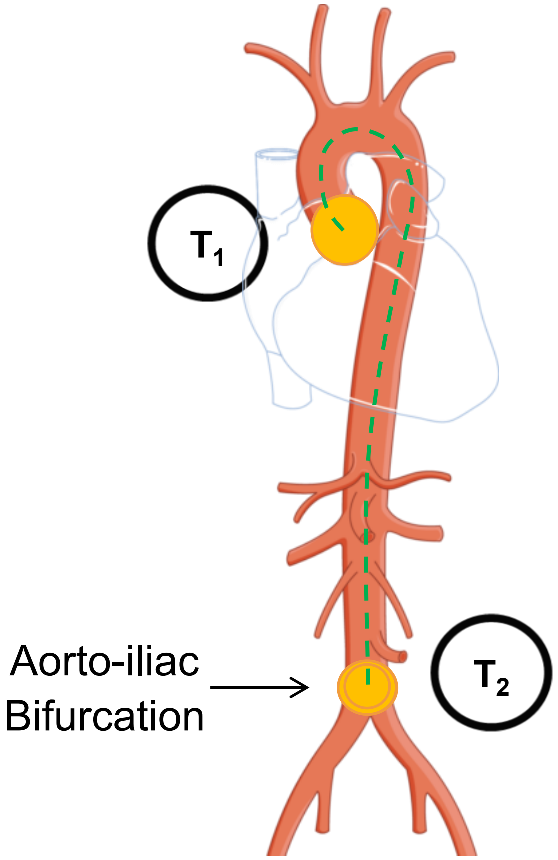


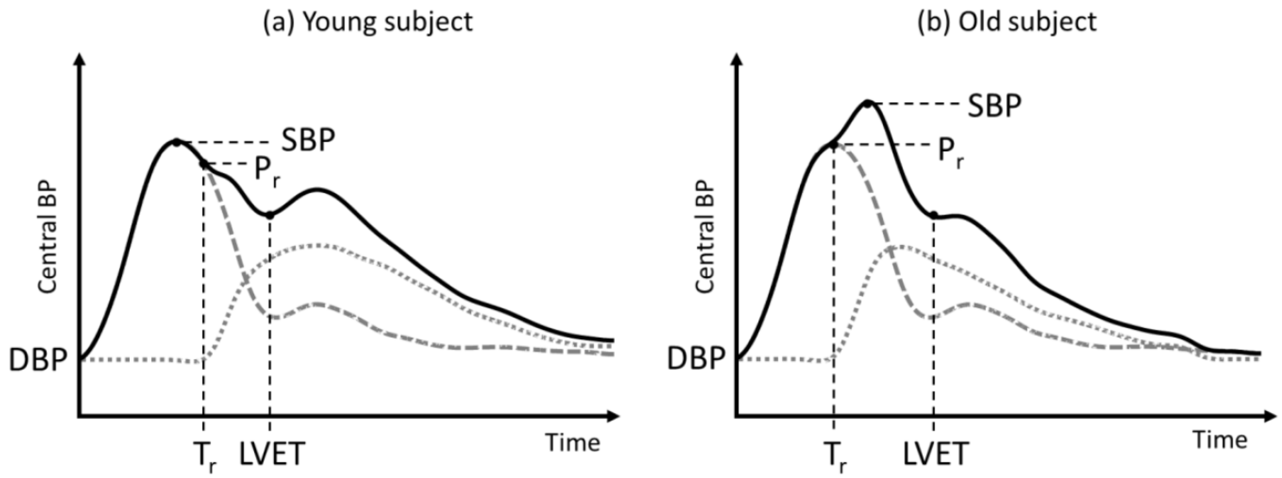
Measurement of the **morphology** of the pressure wave

➡ **oBPM®** – optical blood pressure monitoring

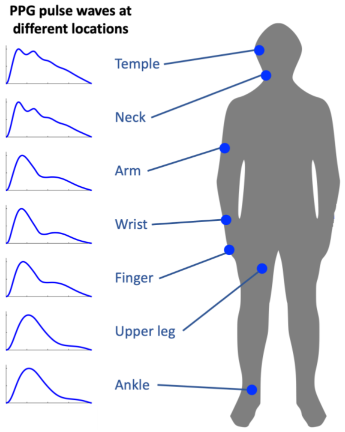
PHOTOPLETHYSMOGRAPHY (PPG)

- **Blood pressure** can also be tracked based on PPG-derived information
- **Pulse wave analysis (PWA)** can analyze **transmitted** and **reflected** arterial pulse wave components
  - These waves are affected by blood pressure and vascular system properties





T_r = Aortic time to reflection



- **PWA** and **blood pressure** estimation involve filtering, pattern recognition, regression, feature selection steps

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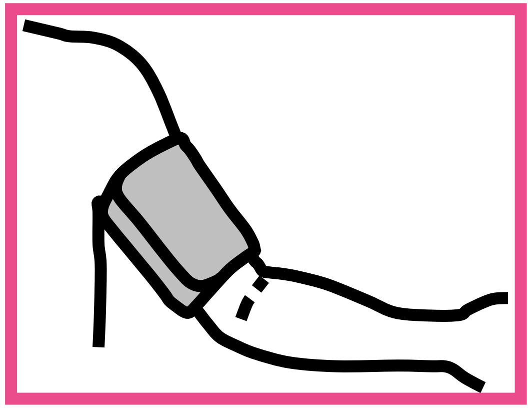
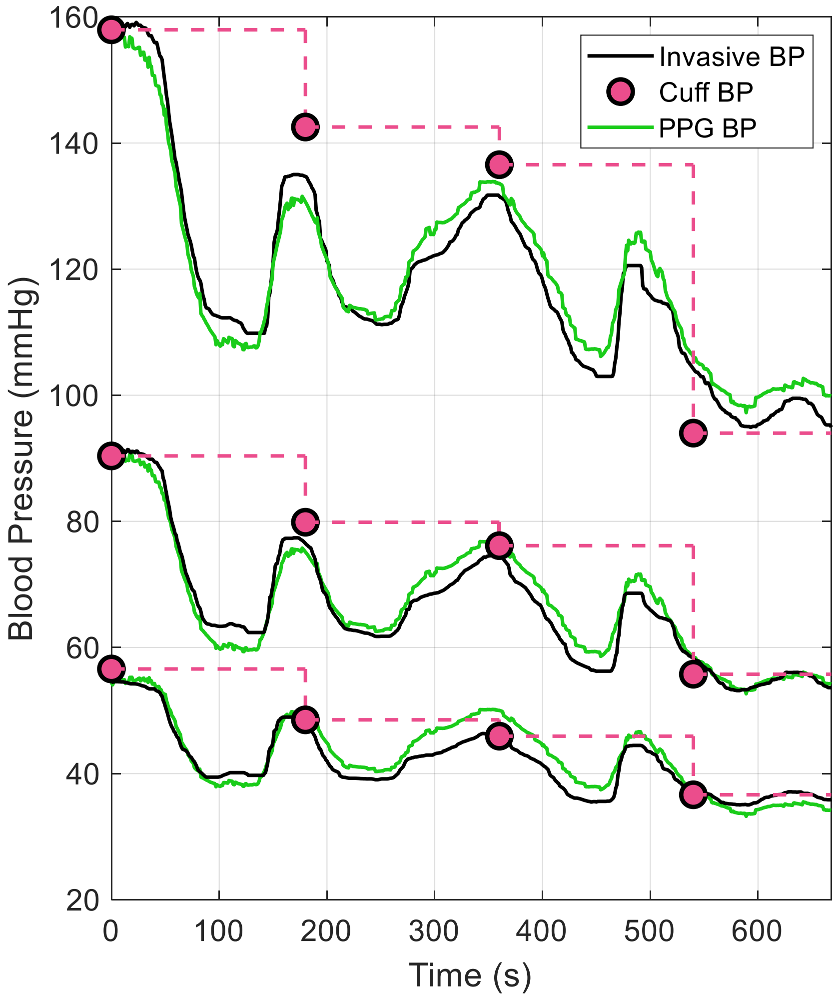
PHOTOPLETHYSMOGRAPHY (PPG)

- Unlike standard **sphygmomanometry (cuff)** devices, blood pressure (BP) tracking based on **PPG** can be performed in a continuous, non-occlusive manner

Invasive BP (arterial catheter)

Cuff-based BP

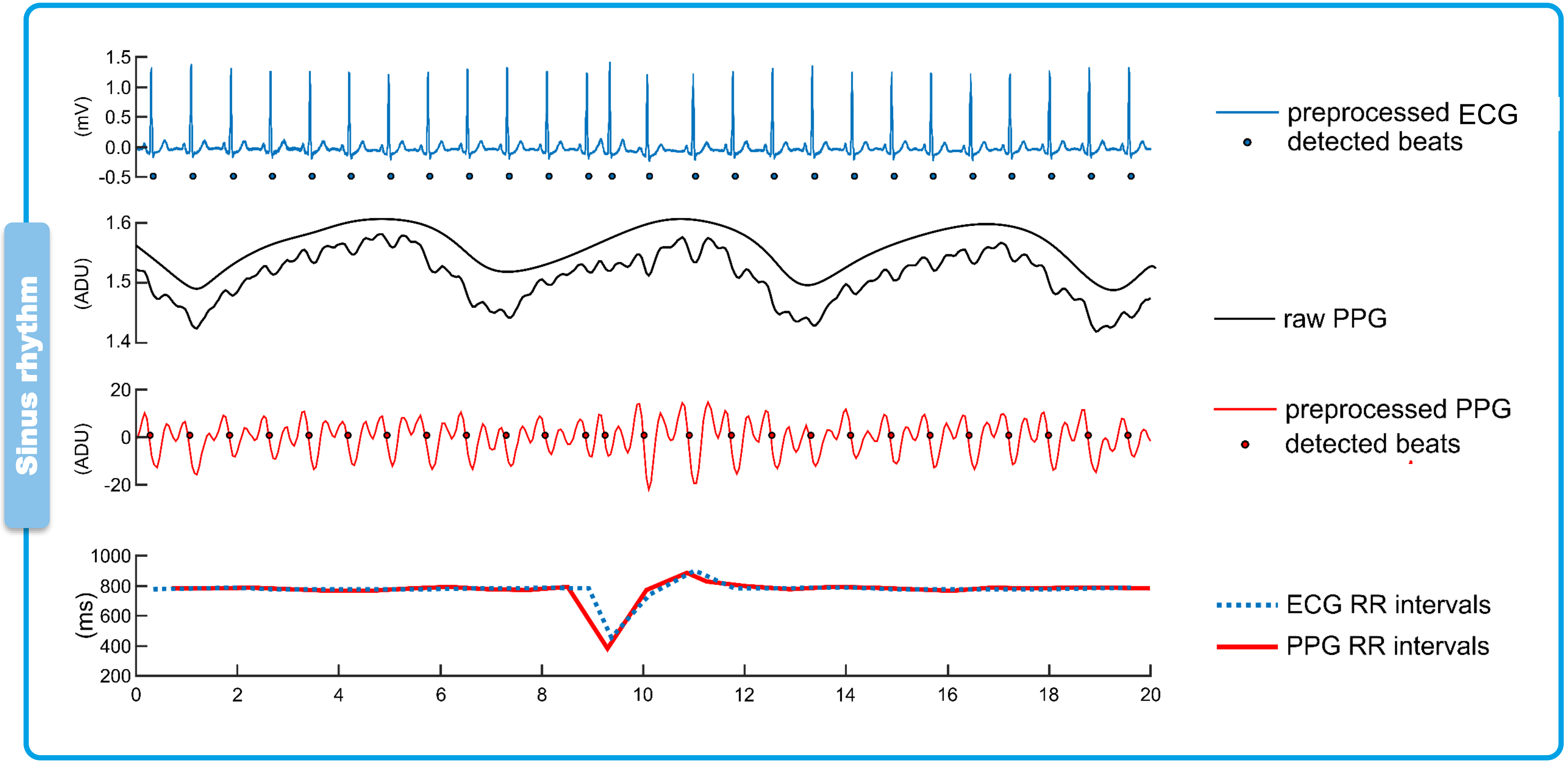




PPG-based BP

PHOTOPLETHYSMOGRAPHY (PPG)

- **Arrhythmias:** given its suitability for long-term, widely available, continuous wearable monitoring, **PPG** is highly attractive for monitoring and diagnosis of arrhythmias
- The signal is affected by arrhythmias, but differently from ECG



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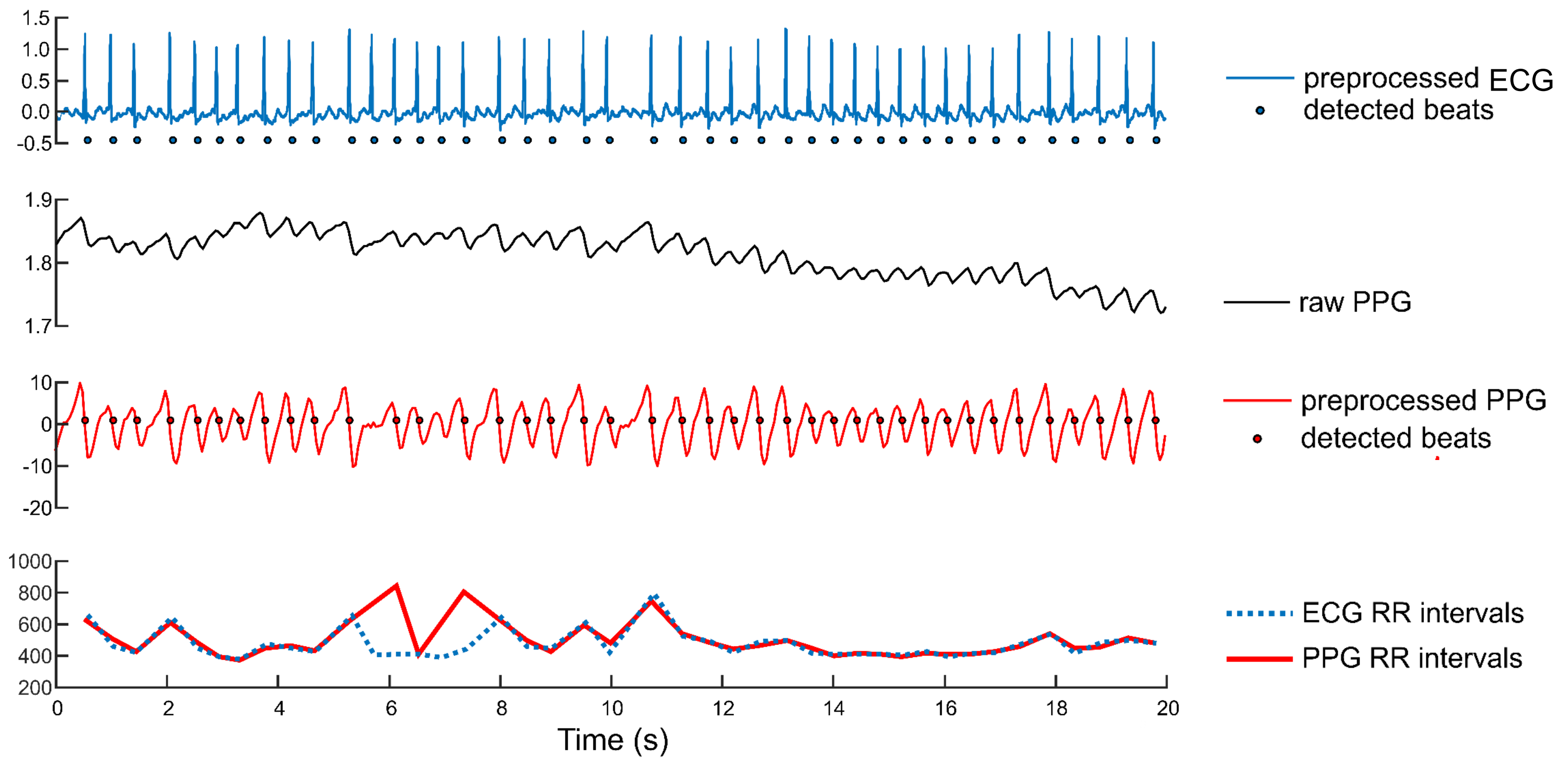
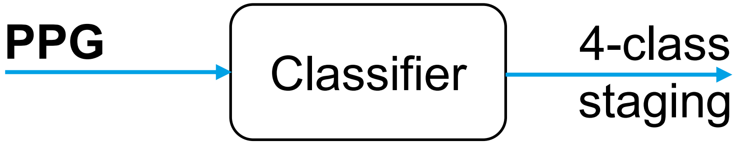
Atrial fibrillation



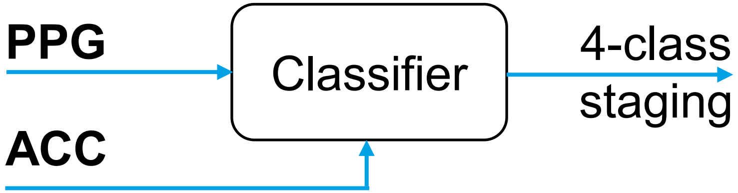
Current R&D approaches explore spectral analysis, ML with clustering, classification…

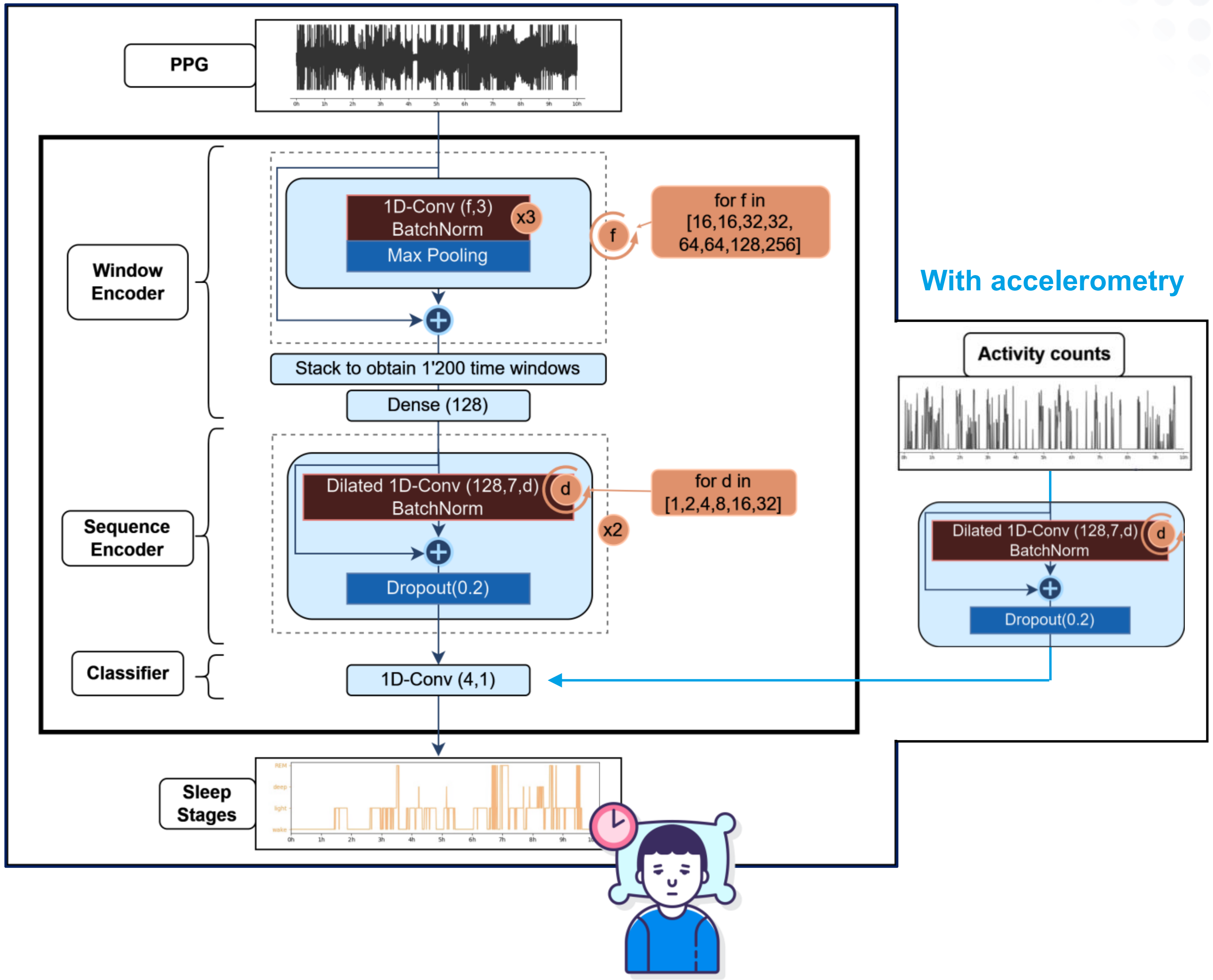
PHOTOPLETHYSMOGRAPHY (PPG)

- **Sleep** has dynamic effects on cardiovascular and respiratory function
- Recent work suggests PPG can be used for **sleep profiling / staging**
- Approaches mainly rely on **machine learning**, and particularly **deep neural networks**



- Multimodal approaches, namely with accelerometry, also promising





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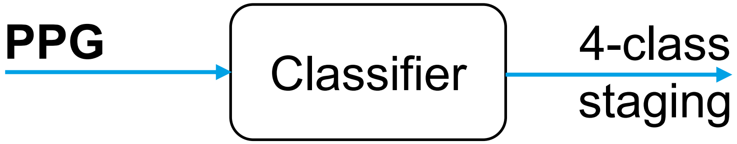

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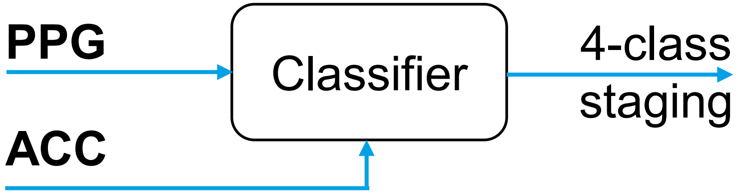
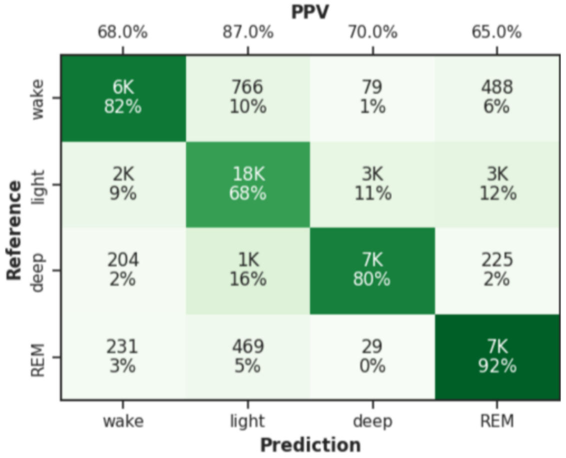
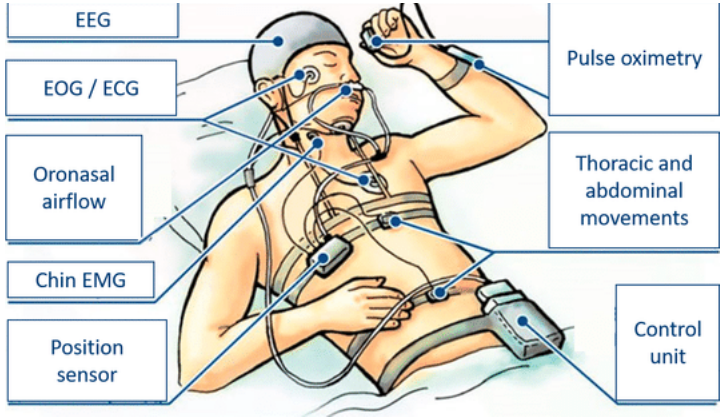


Classification performance



- Gold standard reference for supervised learning is **polysomnography (PSG)**



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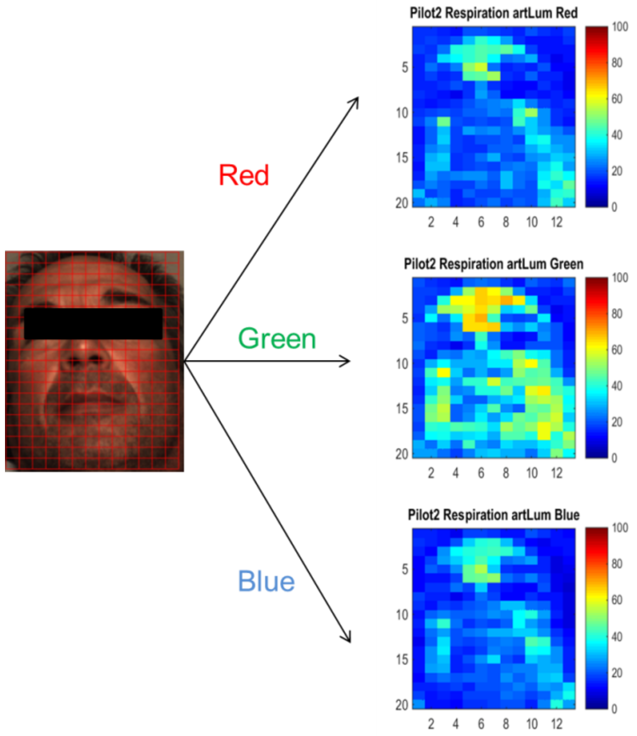
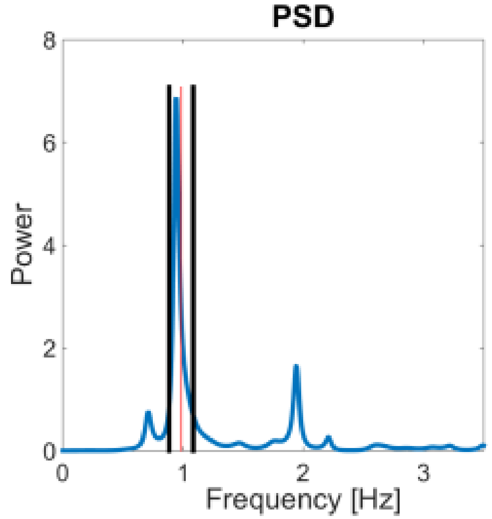
REMOTE SENSING

- **Remote / contact-free** approaches rely e.g. on camera-based signals (video) to probe vital signs
- Important challenges: sensitivity, movement of target, ambient light
- Yet, some promising results:





Dominant peak
near true heart rate

REMOTE SENSING

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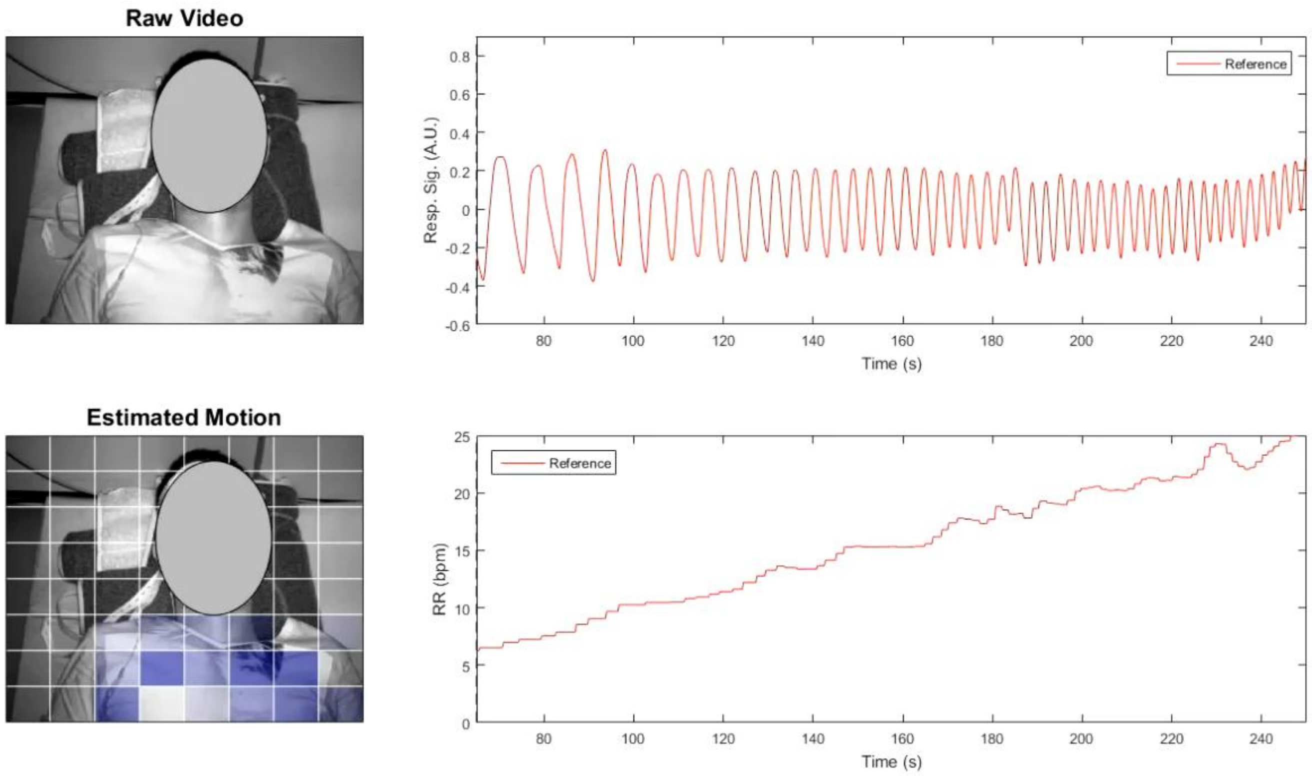
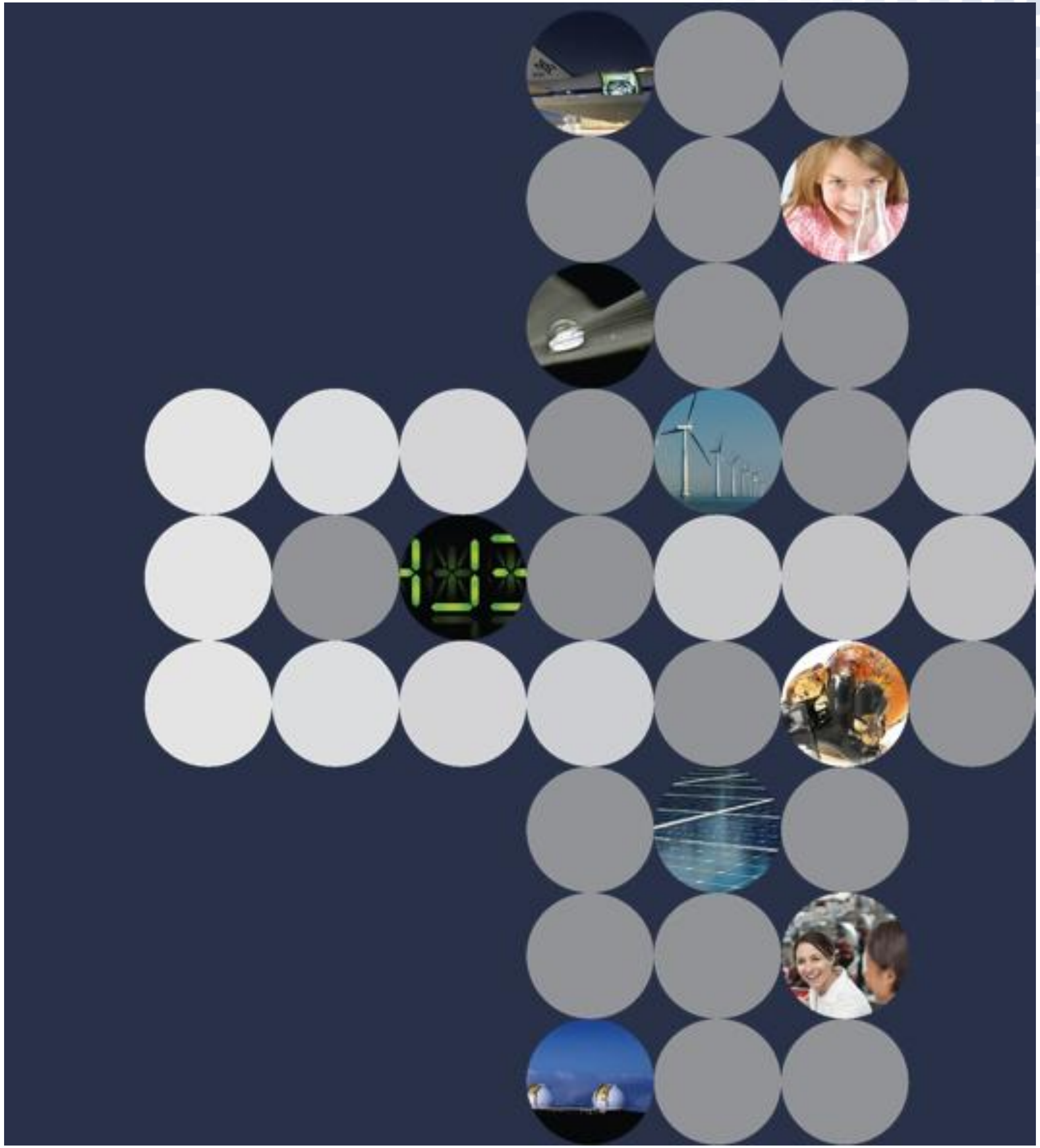


PRACTICAL SESSION 01-II
PPG & motion artifacts

1. Download the .zip from Moodle
2. Run Jupyter notebook
   `activity_data.ipynb`

Tip for Noto:

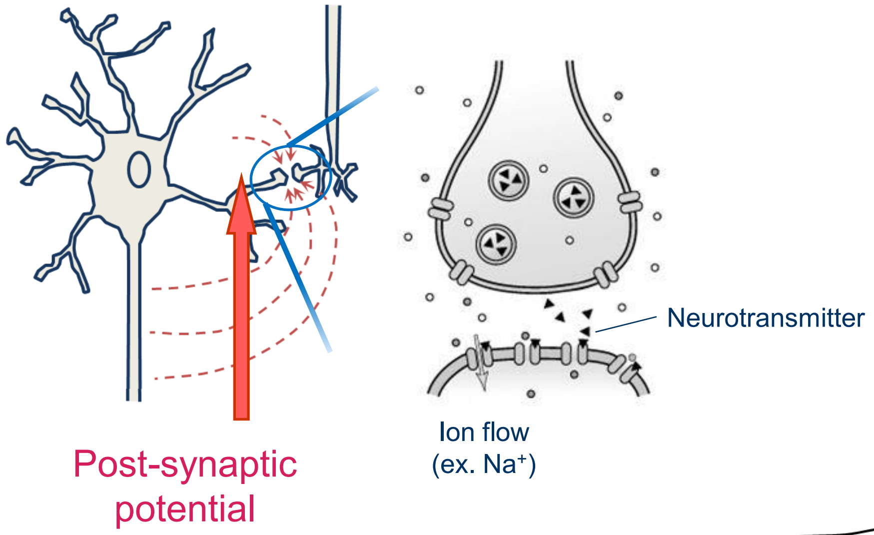
Transfer whole .zip file to noto,
and then extract it there



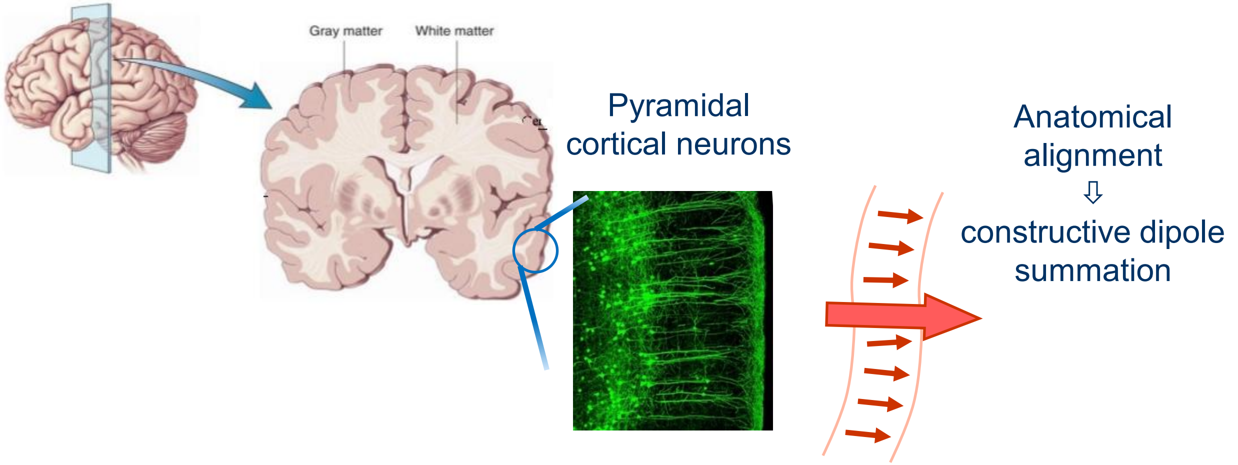
ELECTROENCEPHALOGRAPHY (EEG)

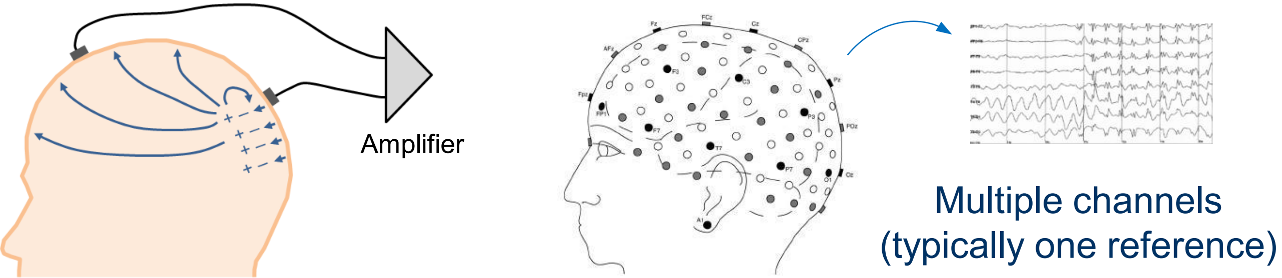
- **(Scalp) EEG** measures differences in electric field potential over the head surface generated by the **post-synaptic activity** of **large neuronal populations** (mainly cortical pyramidal neurons)

A single synapse



Large-scale synaptic activity





Electroencephalography (EEG)

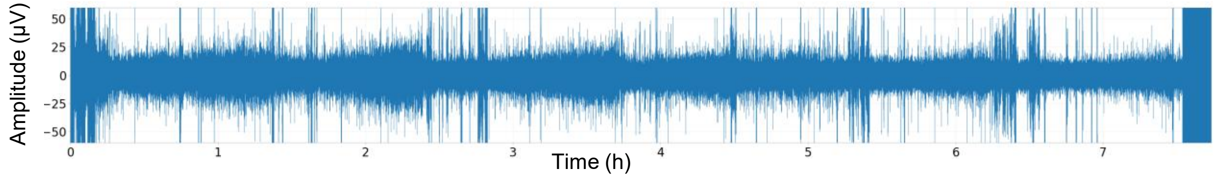
ELECTROENCEPHALOGRAPHY (EEG)

- EEG can capture meaningful **oscillations** in various **frequency bands** (alpha, beta, delta…)
- **Time-frequency representations** and **analysis** can be extremely relevant

Example: sleep profiling

Full recording: time domain

Limited usefulness



EEG @ forehead

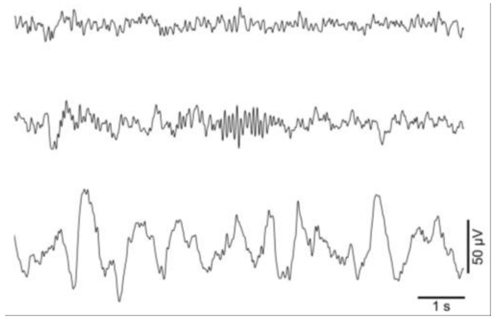
Short-term windows (sleep “microstructure”)

Very meaningful, but local

NREM N1

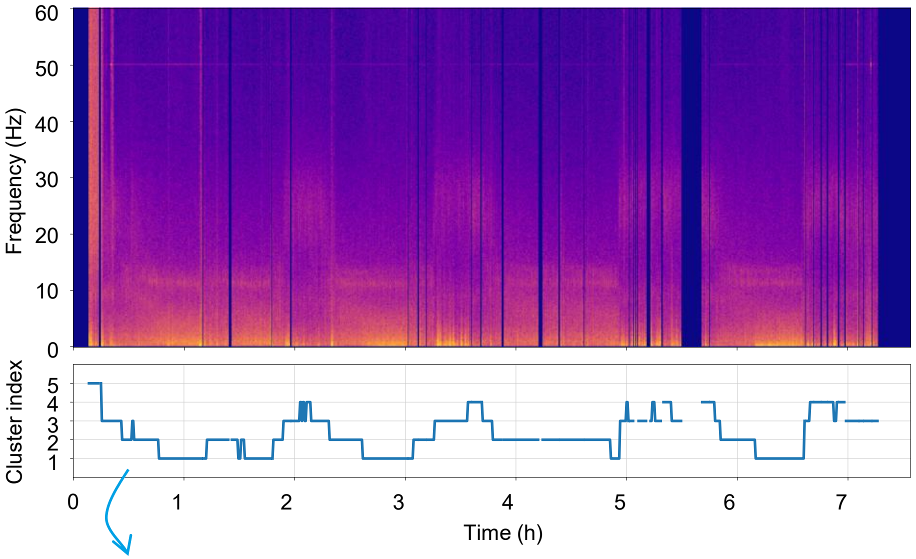
NREM N2 with sleep spindles

NREM N3 with delta activity



Full recording: time-frequency domain

Whole-night view, clear cyclic structure with frequency-specific alternations



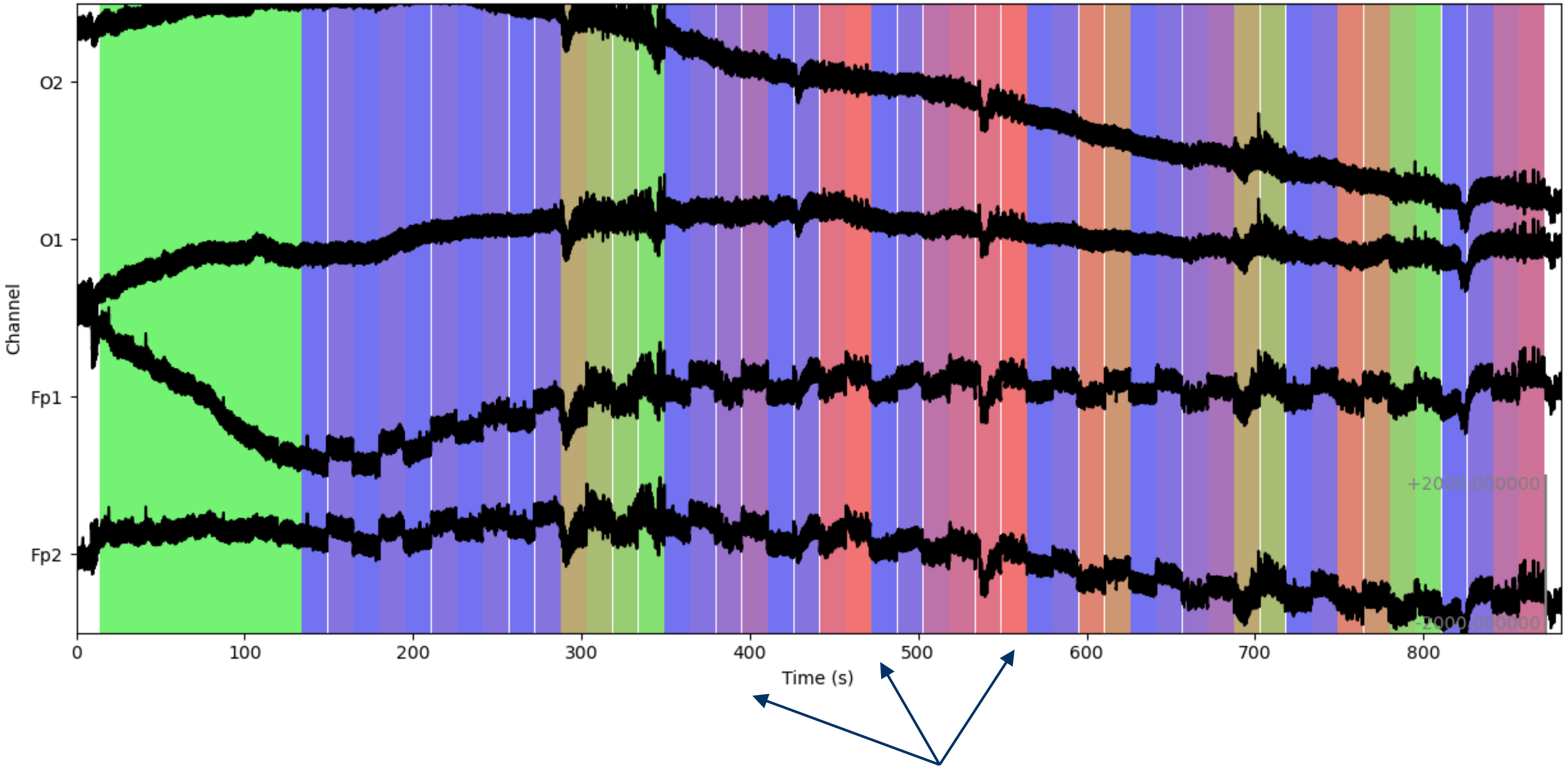
- Clustering based on spectral profile at each time *t* captures natural cyclic pattern

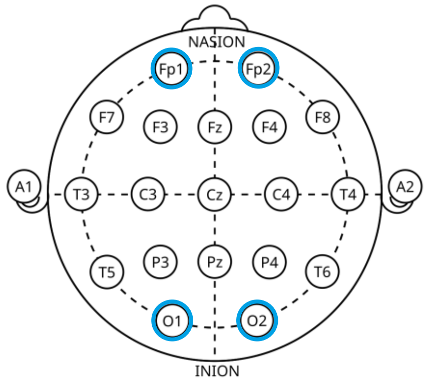
ELECTROENCEPHALOGRAPHY (EEG)

- **EEG** offers a direct measure of neuronal activity
- However, scalp EEG signals are tiny (tens of μV), and sensitive to various perturbations

Example EEG during eyes-open/closed alternations

Before filtering



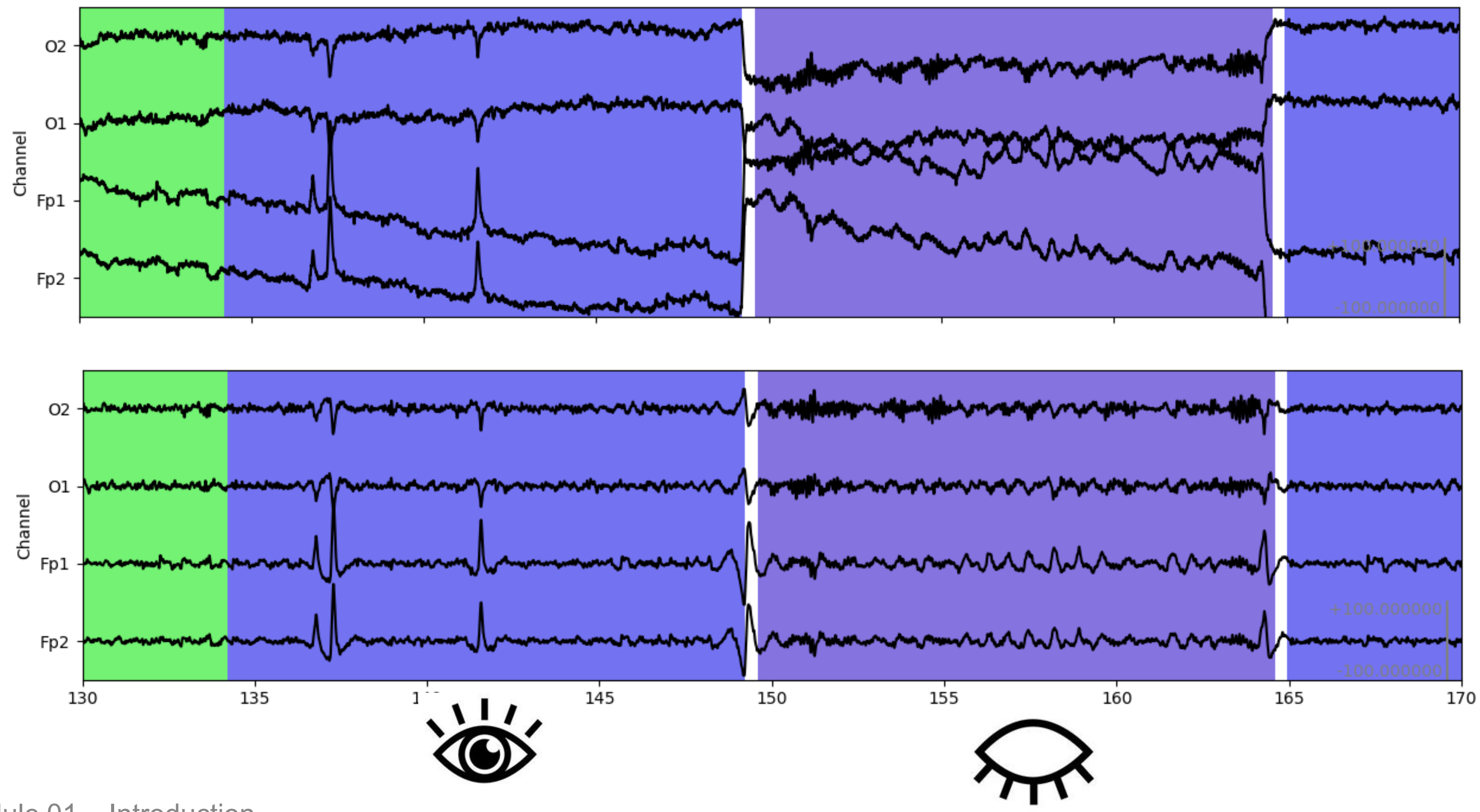


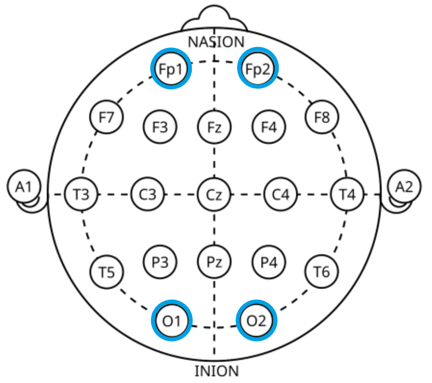
ELECTROENCEPHALOGRAPHY (EEG)

- **Filtering** reduces unwanted contributions & artifacts
- Zooming in on a task transition: eyes open to eyes closed
- Closing the eyes strongly increases EEG **alpha wave** oscillations (~10Hz) in posterior zone

Before filtering

Post filtering
(linear, 0.5 – 30 Hz)





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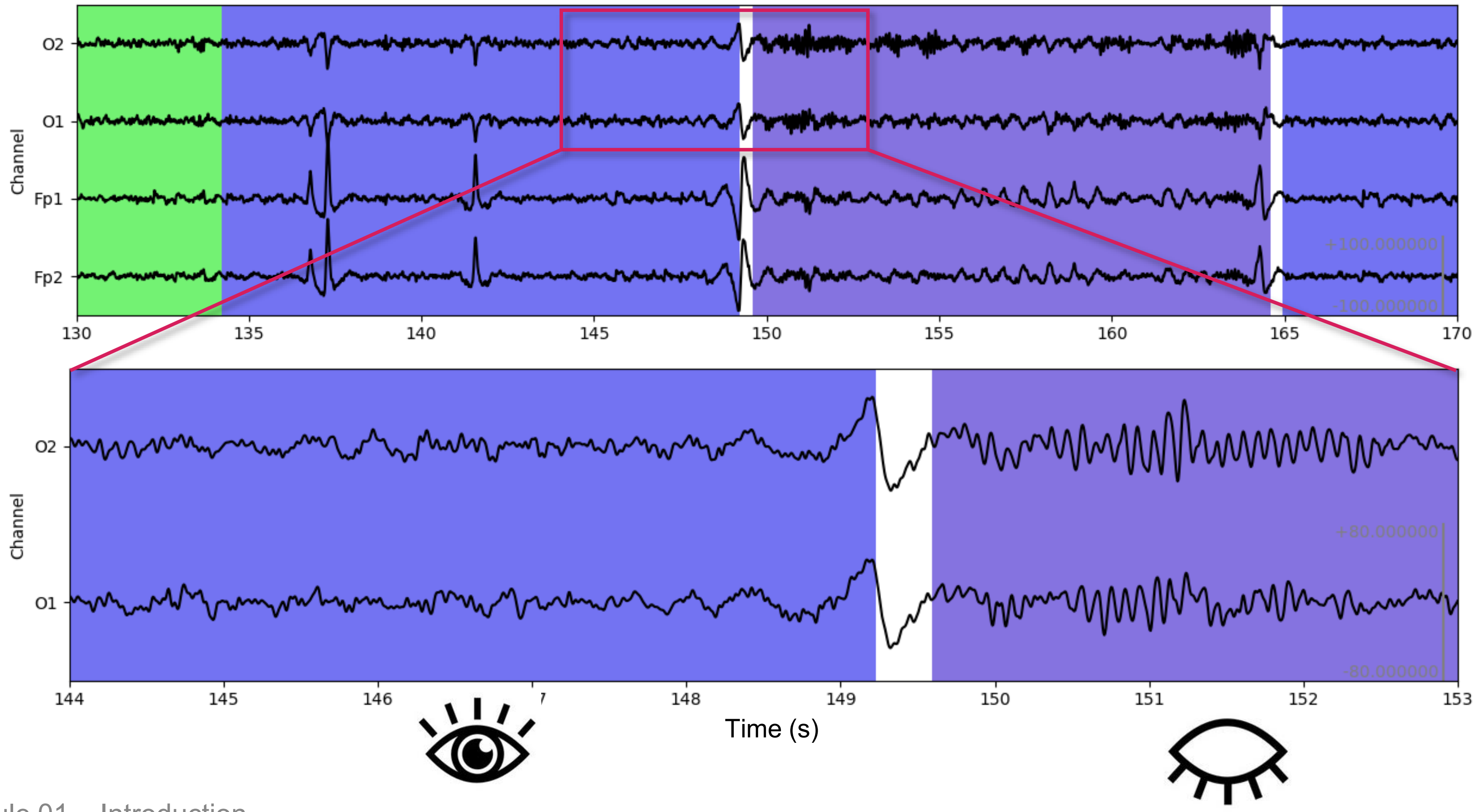
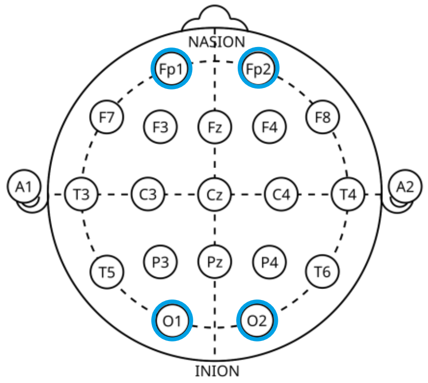
- Closing the eyes strongly increases EEG **alpha wave** oscillations (~10Hz) in posterior zone

Post filtering
(linear,
0.5 – 30 Hz)

Post filtering (zoomed)

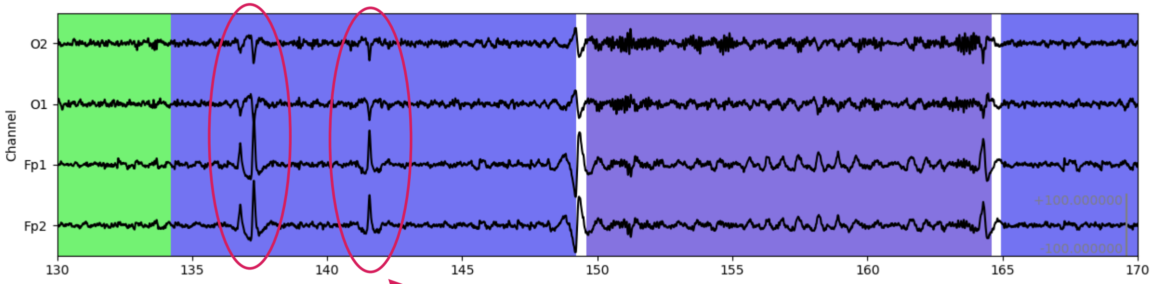


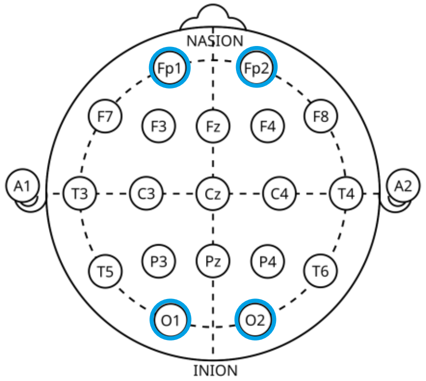


ELECTROENCEPHALOGRAPHY (EEG)

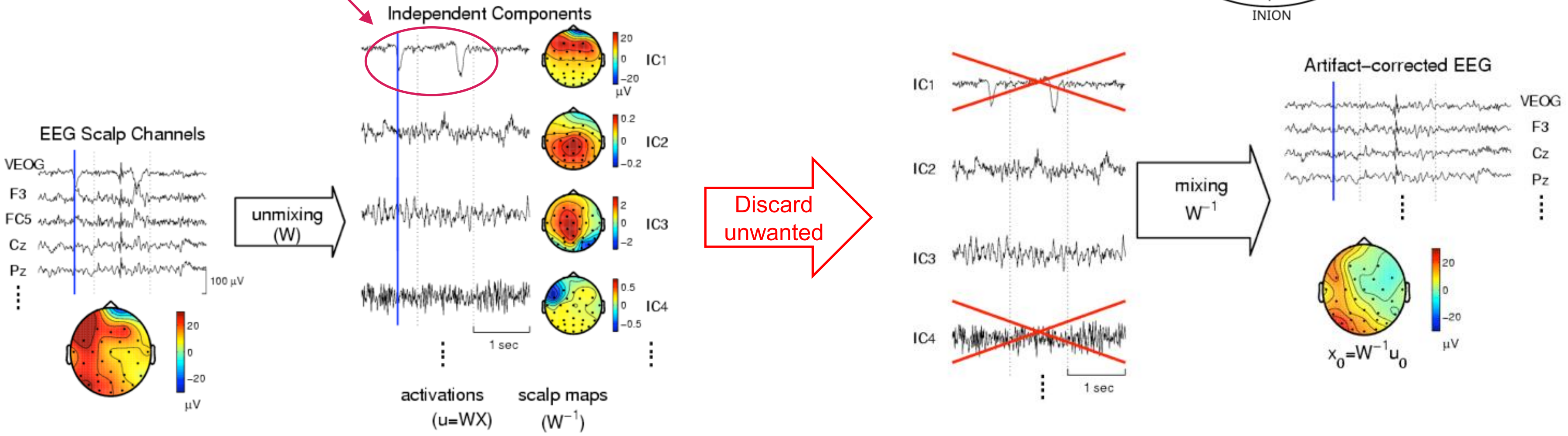
- **Filtering** reduces unwanted contributions & artifacts, but others still remain
- **Blind source separation** techniques (e.g. ICA) leverage multiple channels to identify sources

Post filtering
(0.5 – 30 Hz)





Independent component analysis



- Assumed statistically independent
- Assumed stationary (W constant)

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SOME TAKE-AWAYS FROM THIS INTRODUCTION

- There is a large variety of biomedical sensing modalities and of signal processing techniques for different aims and needs – this introduction was just a (biased) sample!

- **Knowledge of the sensor** (biophysics, substrate(s), confounds, coverage, resolution) allows optimal processing choices, and use of the information

- **Multi-channel information** can be highly valuable in, for example:
  - Functional characterization, automatic profiling (e.g. arrhythmias with VCG from ECG)
  - Separation of different signal contributions (e.g. fetal and maternal ECG, artifacts from EEG)
  - Extraction of hidden parameters (e.g. SpO2 with multi-λ PPG, PWV with multi-site PPG)

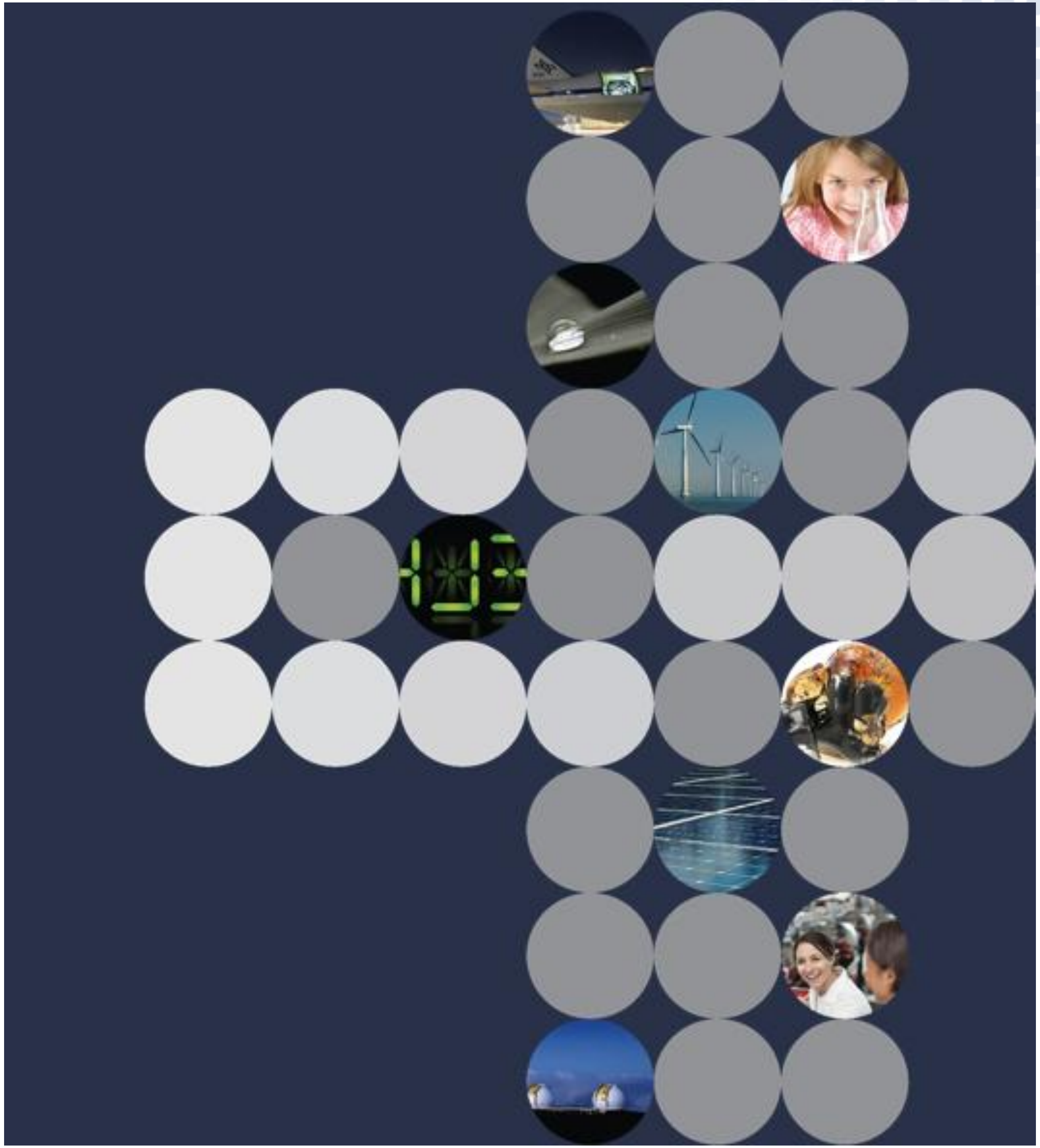
- **Multi-modal information** can be highly valuable in, for example:
  - Separation of confounds from signals of interest (e.g. PPG and accelerometry during sports)

SOME TAKE-AWAYS FROM THIS INTRODUCTION

- **Filtering** helps reducing unwanted contributions (e.g. slow signal drifts, high-frequency noise)
- Different signal **transforms and representations** can be highly useful for visualization, interpretation, extraction of parameters (e.g. time-frequency representations for heart rate tracking with PPG, sleep profiling with EEG)
- **Parameter extraction** can leverage:
  - **Model-based methods:** when known and applicable (e.g. SpO2 from multi-λ PPG)
  - **Data-driven methods:** when relationship is not fully known (e.g. sleep staging based on PPG (+ acc)), or very complex, or too computationally expensive

EE512 – Applied Biomedical Signal Processing

MODULE 01
INTRODUCTION



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