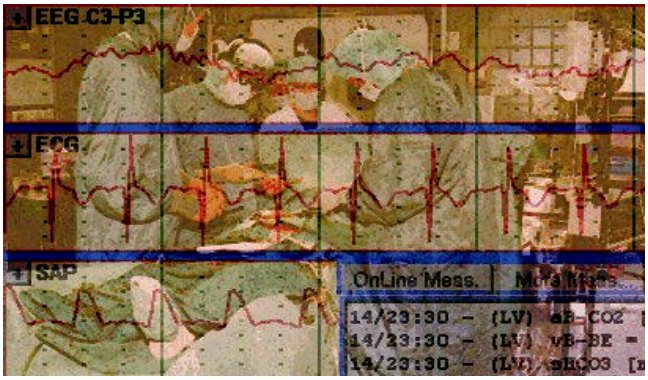
Signal Processing in Biomedical Engineering (Tfy-99.275)



Goals of the course

- To understand
  - what problems and needs are related to the acquisition and processing of signals in biomedical engineering ('biomedical signals')
  - what kind of methods are available and get an idea of how they are applied and to which kind of problems
- To get to know basic digital signal processing and analysis techniques commonly applied to biomedical signals and to know to which kind of problems each method is suited for (and for which not)

Signal

(measured) physical quantity which carries information. It usually varies as a function of an independent variable (often: time, but may also be, e.g., space, distance,..)

Biomedical signal

signal a being obtained from a biologic system / originating from a physiologic process (human or animal (-medical -> patients))

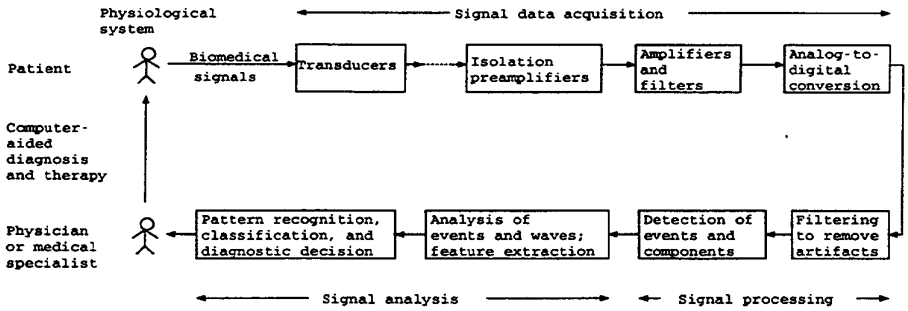
Processing of biomedical signals

all treatment of biomedical signals which occurs between their origin in a physiological process and their interpretation by their observer (e.g., clinician)

Processing of biomedical signals is application of signal processing methods on biomedical signals

→All possible processing algorithms may be used

→*Biomedical signal processing* requires *understanding the needs (*e.g. biomedical processes and clinical requirements*)* and *selecting and applying suitable methods to meet these needs*



(c) R.M. Rangayyan. A Case Study Approach to Solve Problems in Biomedical Signal Analysis. IEEE 2000.

Lectures' contents & schedule

27 hrs lectures, (9 wks * 3 hrs),
Wednesdays 14.9.2005 - 16.11.2005 (except 26.10.05), 12:00 - 15:00, room F2

	date	contents
1	14.9	Introduction to (digitised) biomedical signals; properties and basic operations.
2	21.9	Recapitulation of essential techniques; time- and frequency-domain, z-transform, filter design, discrete Fourier transform, power spectrum analysis
3	28.9	Analysis of non-stationary signals and adaptive filtering
4	5.10	(AR) modelling, event- and trend- detection
5	12.10	Wavelet analysis
6	19.10	Dealing with artefacts and noise
7	2.11	Pattern recognition, classification techniques
8	9.11	Feature extraction and selection, evaluation and assessment of methods
9	16.11	Illustration of signal processing methods used in an example field: "depth of anaesthesia" measurements

Course materials

- Lecture notes (exam questions will be based on these):
  - available at course's website: peili.hut.fi/tfy99275/
- Optional reading:
  - Rangaraj M. Rangayyan. *Biomedical Signal Analysis: A case-study approach*, IEEE Press/Wiley Inter-Science, 2002.
  - John L. Semmlow. *Biosignal and Biomedical Image Processing - MATLAB-Based Applications*, Marcel Dekker, Inc., 2004
  - Bronzino (ed.). *The Biomedical Engineering Handbook*. CRC Press/IEEE Press, 1995/2000 Chapters 54, 55, 58, 60
  - Eugen N. Bruce. *Biomedical Signal Processing and Signal Modeling*, John Wiley & Sons, 2001
  - Suresh R. Devasahayam. *Signals and Systems in Biomedical Engineering: Signal Processing and Physiological Systems Modeling*. Kluwer Academic 2000.
  - David J. DeFatta, Joseph G. Lucas, William S. Hodgkiss. *Digital Signal Processing: A System Design Approach*. John Wiley & Sons, New York 1988.

What you should do to pass the course?

- Obligatory: pass the exam
- Recommended:
  - attend the lectures
  - making exercises (and get bonus added to your exam points - points will be added before judging the outcome pass/no-pass)
  - reading materials

Exercises

- Idea: apply methods on real data to learn from experience
- class room exercises, Wednesdays 15:00-17:00 room F2 (starting 21.9) – 'pen & paper' & computer (matlab) exercises
- home exercises:
  There are 2 home exercises that you can make. They both are Matlab-based exercises that go a bit deeper into subjects we have seen during the lectures. The work mainly involves making some simple Matlab code, run it and interpret the results.

Exam

- Dates:
  - Wednesday 21.12.05 9:00-12:00
  - Wednesday 04.01.06 9:00-12:00
  - Tuesday 14.03.06 9:00-12:00
- Emphasis on understanding of the principles and merits of methods and their application – not so much on mathematical details
- Grading
  At the exam you can earn a maximum 30 points. There will be 5 questions that are each 6 points worth. But, by doing the home exercises you can earn some of those points beforehand already. For each home exercise you can get a maximum of 3 points. So, you can already have 6 points to start with if you do both exercises right.
  You can do 2, 1, or 0 home exercises. If you want, you can make the home exercises together with another student.

Biomedical signal interpretation

- On the basis of
  - signal characteristics
    - *technical point of view*
  - signal source
    - *from where the signal originates*
  - biomedical application
    - *cardiology, neurophysiology, monitoring, diagnosis,...*

Biomedical Signals 1

- ***Bioelectric signals***: generated by nerves cells and muscle cells. Single cell measurements (microelectrodes measure action potential) and 'gross' measurements (surface electrodes measure action of many cells in the vicinity)
- ***Biomagnetic signals***: brain, heart, lungs produce extremely weak magnetic fields, this contains additional information to that obtained from bioelectric signals. Can be measured using SQUIDs.

Biomedical Signals 2

- ***Bioimpedance signals***: tissue impedance reveals info about tissue composition, blood volume and distribution and more. Usually two electrodes to inject current and two to measure voltage drop
- ***Bioacoustic signals***: many phenomena create acoustic noise. For example, flow of blood through the heart, its valves, or vessels and flow of air through upper and lower airways and lungs, but also digestive tract, joints and contraction of muscles. Record using microphones.

Biomedical Signals 3

- ***Biomechanical signals***: motion and displacement signals, pressure, tension and flow signals. A variety of measurements (not always simple, often invasive measurements are needed).
- ***Biochemical signals***: chemical measurements from living tissue or samples analysed in a laboratory. For example, ion concentrations or partial pressures (pO2 or pCO2) in blood. (low frequency signals, often actually DC signals)
- ***Biooptical signals***: blood oxygenation by measuring transmitted and backscattered light from a tissue, estimation of heart output by dye dilution. Fiberoptic technology

Some Signal Types

- **random** signals (also the term stochastic is used instead of random)
- **transients** are signals of finite duration (for example evoked potentials)
- **periodic signals** have a basic wave shape repeating itself an infinite number of times on the time axis
- white noise noise with a uniform frequency spectrum

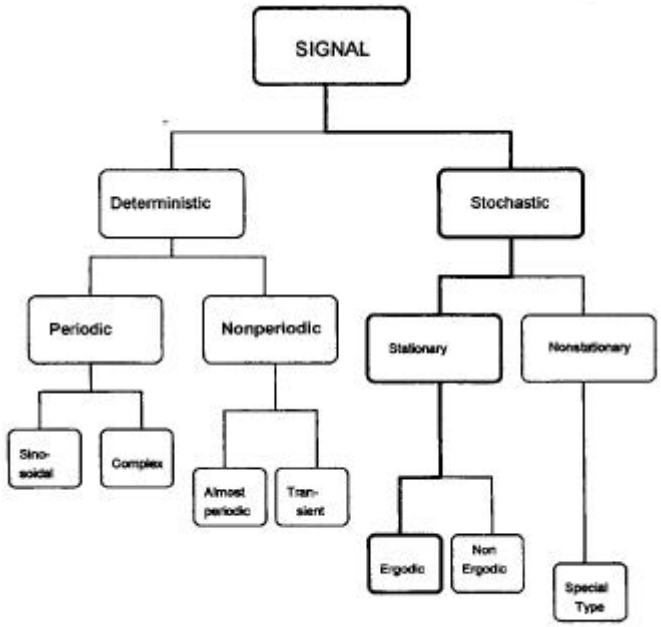
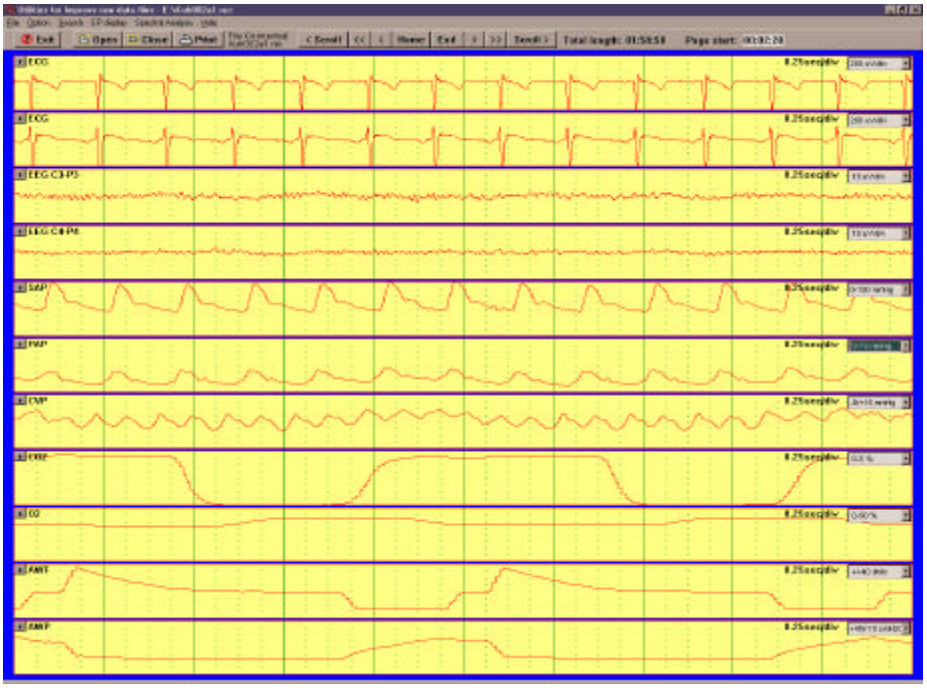
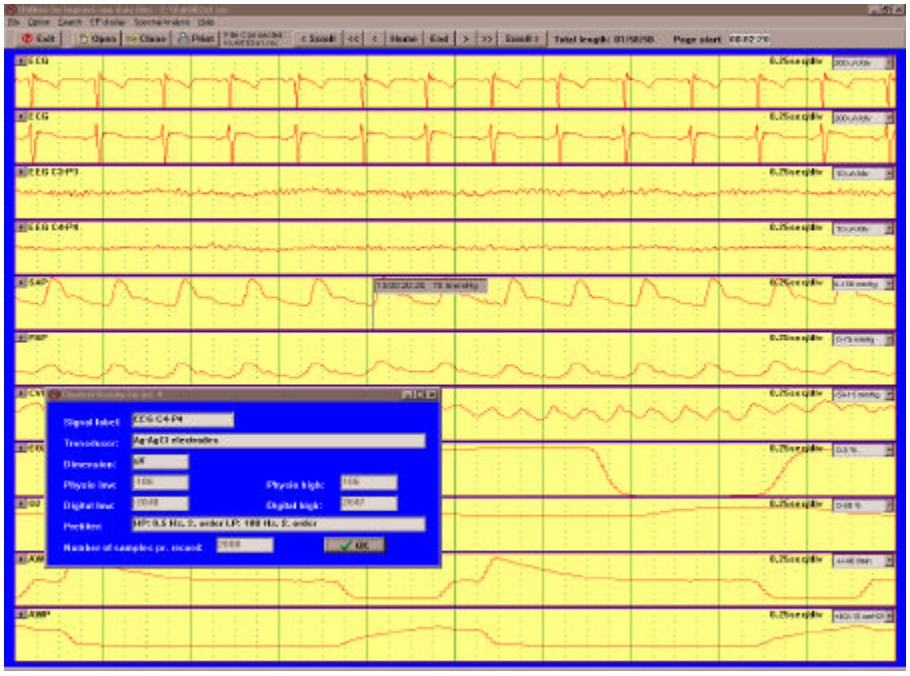
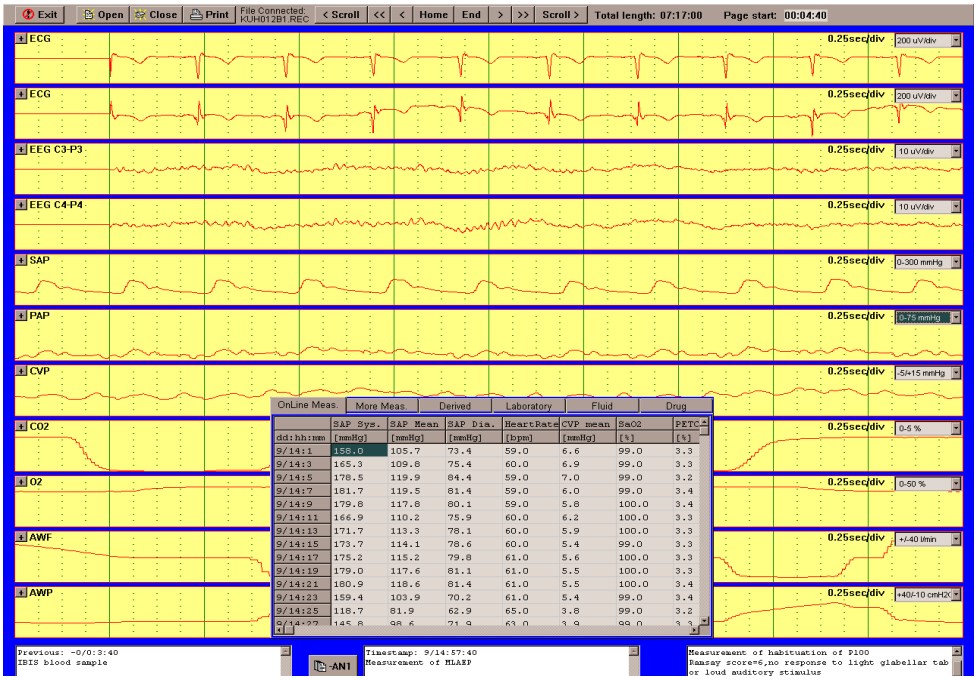


FIGURE 54.1 Classification of signals according to characteristics.



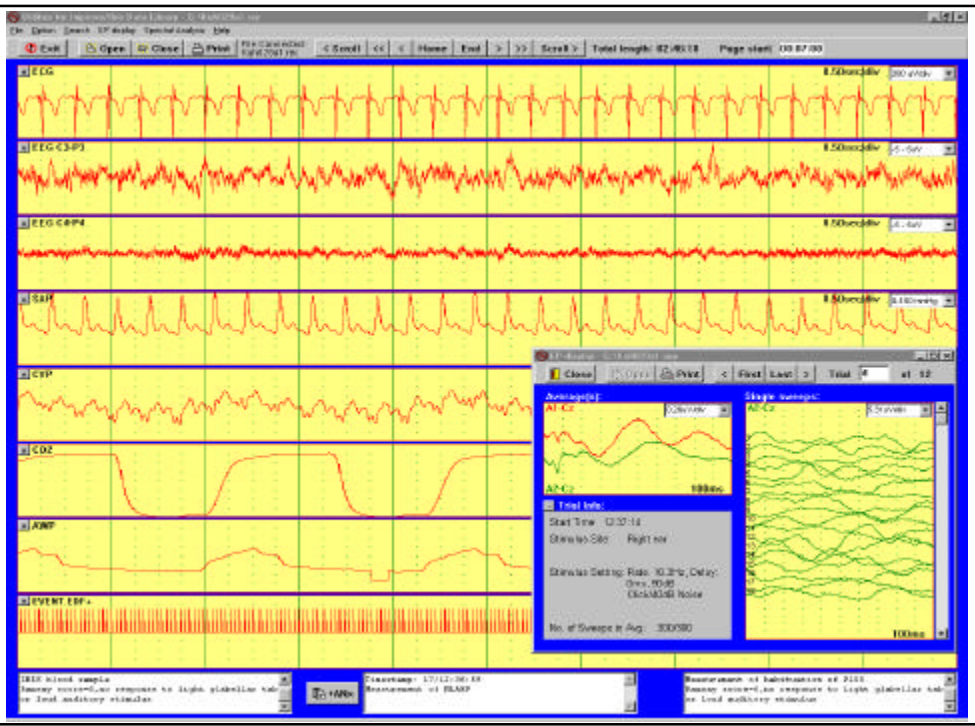




Intermittent Data

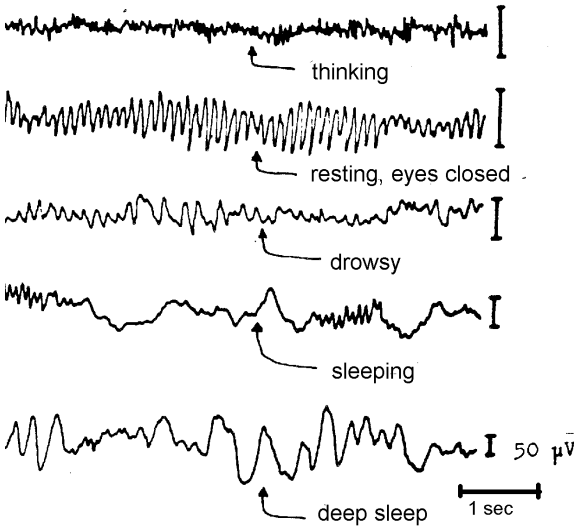
OnLine Meas. | More Meas. | Derived | Laboratory | Fluid | Drug

dd:hh:mm	Description:
9/14:14	(MV) Respiratory Rate measured [breaths/min]=12.0
9/14:14	(MV) FiO2 Measured [%]=40.0
9/14:14	(MV) VE Measured [l/min]=7.1
9/14:14	(MV) PEEP Set 1 [cmH2O]=6.0
9/14:27	(MV) PCWP [mmHg]=4.0
9/14:27	(MV) Cardiac Output [l/min]=3.7
9/14:59	(MV) Respiratory Rate measured [breaths/min]=12.0
9/14:59	(MV) FiO2 Measured [%]=40.0
9/14:59	(MV) VE Measured [l/min]=7.0
9/14:59	(MV) PEEP Set 1 [cmH2O]=6.0
9/15:13	(MV) Cardiac Output [l/min]=3.5
9/15:13	(MV) PCWP [mmHg]=3.0
9/15:21	(MV) Cardiac Output [l/min]=3.6
9/15:35	(MV) Cardiac Output [l/min]=4.3
9/15:35	(MV) PCWP [mmHg]=5.0



’random’ signal: EEG during different mental activity levels

Note: Using the term 'random' does not imply that the brain actually generates random noise. All these activities may have a function in the brain or are the consequence of another function (even though we have no idea what this is) in which the apparently random element is not random but complex and unknown. Description of the EEG in terms of random processes presupposes only a mathematical and not a physical model.



Rationales for biomedical signal processing

1. Acquisition and processing to extract *a priori* desired information

2. Interpretation of the nature of a physiological process based either on
   a) observation of a signal (explorative nature), or
   b) observation of how the process alters the characteristics of a signal (monitoring a change of a predefined characteristic)

Some objectives of applications that use biomedical signal processing

- Information gathering
  - measurement of phenomena to understand the system
- Diagnosis
  - detection of malfunction, pathology, or abnormality
- Monitoring
  - to obtain continuous or periodic information about the system
- Therapy and control
  - modify the behaviour of the system and ensure the result
- Evaluation
  - objective analysis: proof of performance, quality control, effect of treatment

Different signal processing tasks in different applications

Complexity increases

Calibration
Transformation
Time series processing
Filtering
Artefact and noise cancellation
Statistics
Feature extraction
Pattern recognition
Modelling

Example: heart rate meters

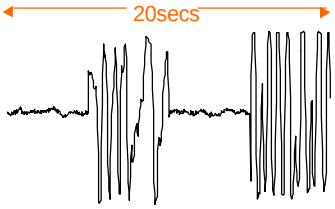
Sensor

Signal processing

Electric potential
Detection of events
Event series
Artefact processing
Instantaneous HR
HR statistics

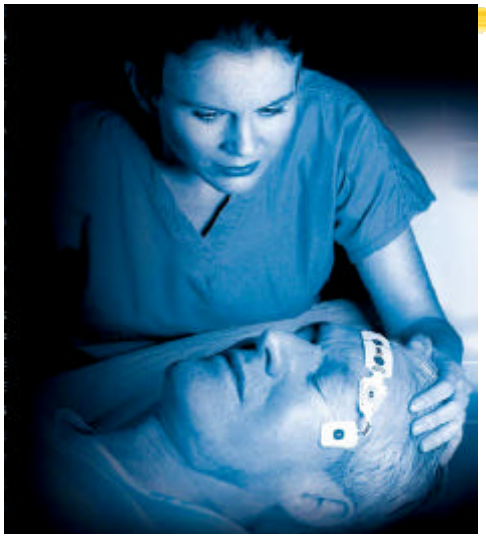
User

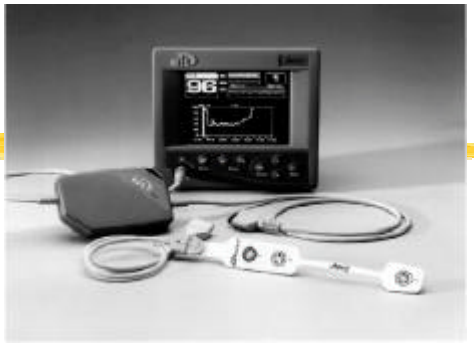
Example: IST Vivago® WristCare

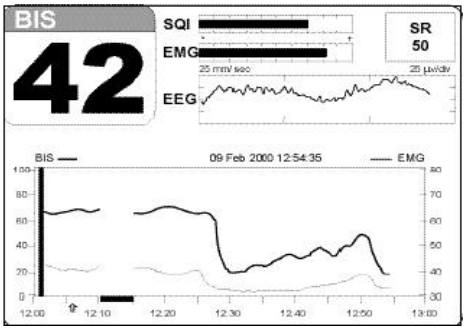


Signal processing

Aspect Bispectral Index®







Quantization of hypnotic state/sedation level: Oberver's Assessment of Alertness/Sedation Scale (OAA/S)

Hypnotic State/Sedation Level	Score
Responds readily to name spoken in normal tone	5
Lethargic response to name spoken in normal tone or says name post-op	4
Responds only after name is called loudly and/or repeatedly, or opens eyes post-op	3
Responds only after mild prodding or shaking	2
Does not respond to mild prodding or shaking	1
Does not respond to noxious stimulus	0

Conscious

Unconscious

Table 2: Hypnotic state/sedation level scoring criteria

```
11:47:03 maanantai 06.10.2003
12:02:32 lapsi saliin
12:06:30 OOAS 5, itkee ja huutaa ja meinaa lähteä karkuun
12:08:03 anestesia alkaa....., lapsi pyörii
12:08:50 OOAS 2
12:09:31 tipan laitto, OOAS 1
12:09:56 Fentanyl 25mikrog i.v., esmeron 6,mg i.v.
12:10:50 intubaatio, OOAS0
12:11:29 putken kiinnitys
12:12:28 potilasta liikutetaan sängyllä, Bis tuli mukaan
tässä vaiheessa
12:13:39 potilasta liikutetaan
12:14:41 Pesu
12:23:26 fentanyl 15mikrog i.v.
12:23:48 Toimenpide alkaa
12:24:03 Demographic data : 4v, 13kg,
12:29:40 entropian datan saamisen kanssa ongelmia...,
väittää että artefactaa...
12:31:44 Per-dafalgan 250mg i.v.
12:42:15 Zinacef 400 mgi.v.
12:42:48 katetrin laitto
12:42:57 toimenpide loppui
12:43:04 anestesia loppui
12:45:13 extubaatio
12:45:45 ketorin 25mg i.v.
12:47:33 heräämöön
12:47:23 heräämösssä, OOAS 2, Steward1, Alderete 6,
12:51:03 OOAS3, steward1, alderete 6
….
13:47:48 OOAS5, steward 6, alderete 10
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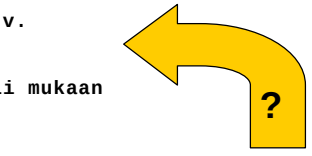
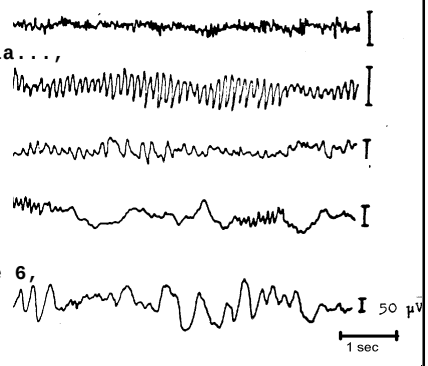
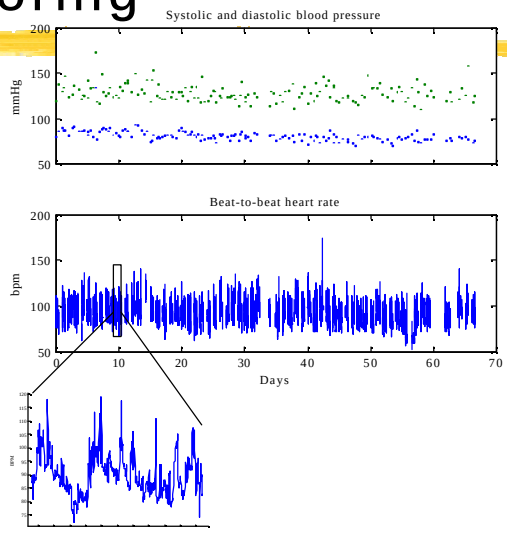


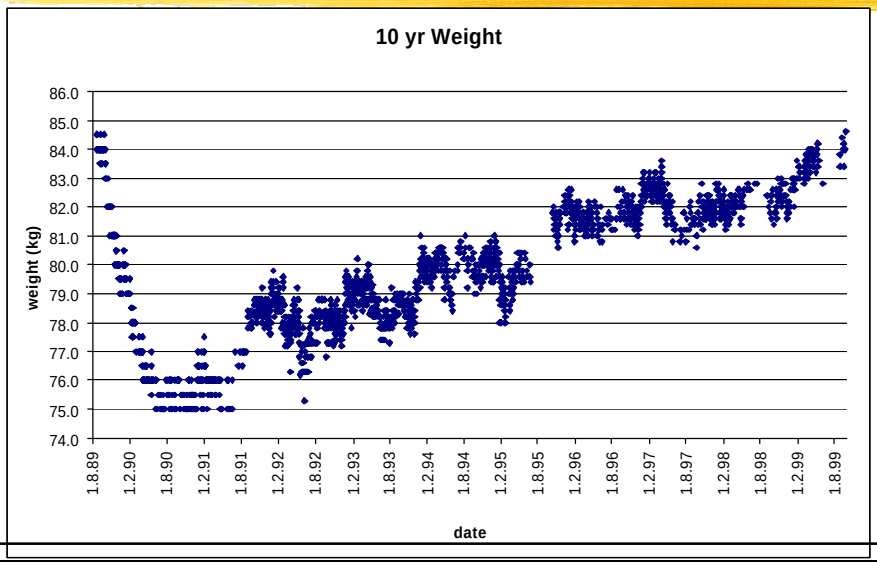


Health monitoring

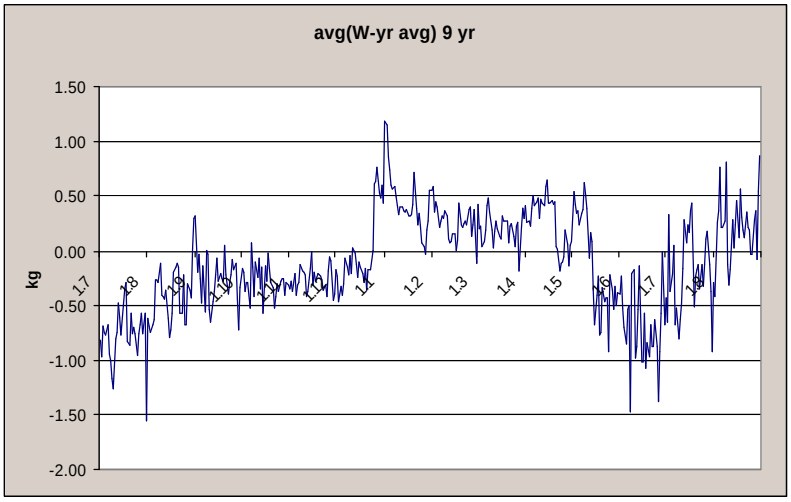


Need for processing to draw any conclusions

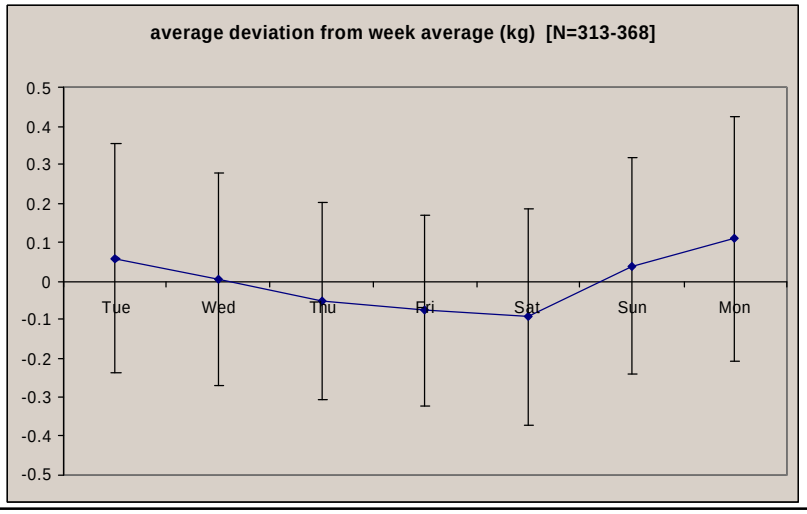
Weight recordings, 10 year view



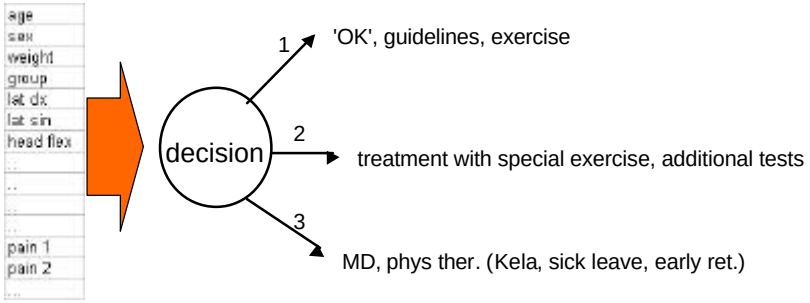
Weight recordings, average year view

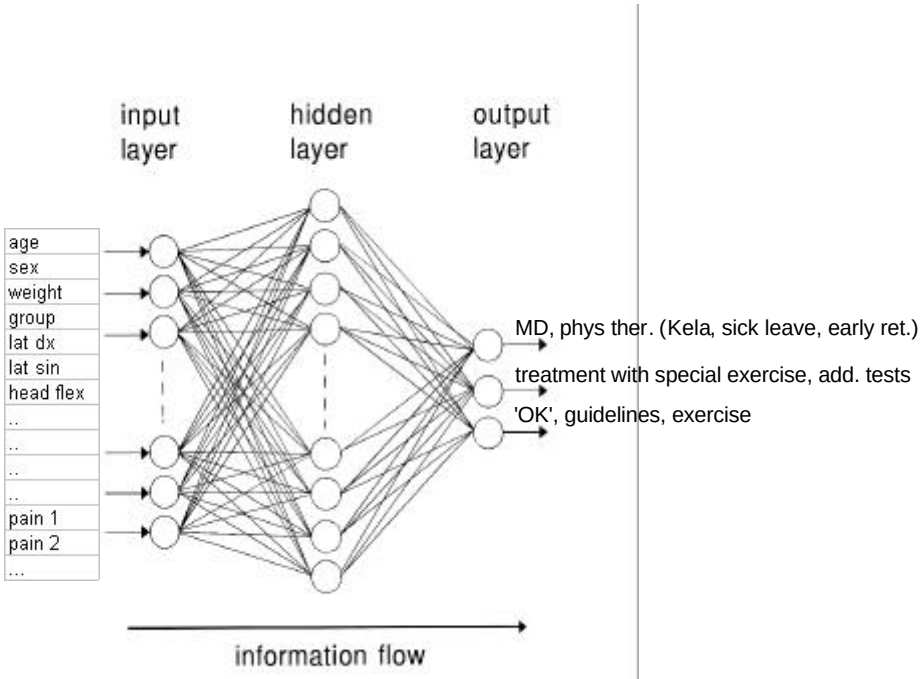


Weight recordings, average week view



Back-pain assessment





Problems in biomedical signal processing

- Accessibility
  - Patient safety, preference for noninvasiveness
  - Indirect measurements (variables of interest are not accessible)
- Variance
  - Inter-individual, intra-individual
- Inter-relationships and interactions among physiological system
  - Subsystem of interest may not be isolated
- Acquisition interference
  - Instrumentation and procedures modify the system or its state

- Artefacts and interference
  - Interference from other physiological systems (e.g. muscle artifacts in EEG recordings)
  - Low-level signals (e.g. microvolts in EEG) require very sensitive amplifiers; they are easily sensitive to interference, too!
  - Limited possibilities for shielding or other protection
- Nonlinearity and obscurity of the system under study
  - basically all biological systems exhibit nonlinearities while most of the methods are based on the assumption of linearity $\rightarrow$ approximation
  - exact structures and true function of many physiological systems are often not known

Computers in biomedical signal analysis

Traditionally clinicians are doing the analysis from paper charts → time consuming & expensive

Challenge for biomedical engineer: to automate this analysis by using computers!

→ inexpensive

→ exactly repeatable

→ objective

→ fast

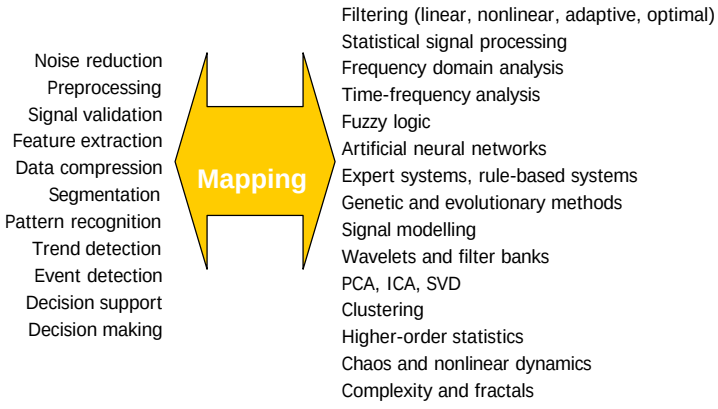
Digital Signal Processing

- digital techniques:
  - easy to implement algorithms
  - easy to adapt
  - real-time performance usually no problem
  - relatively cheap
- signals are of course also processed using analogue techniques (e.g., anti-aliasing filters), but the majority of processing is done with digital processing

Signal Processing in Biomedical Engineering

- A wide range of signal processing techniques (e.g., [adaptive] filtering, spectral analysis, time-domain analysis, freq./time analysis)
- is used for a wide range of applications (e.g., monitoring, imaging, modelling, control tasks)
- which technique to use for which application?

Signal processing methods



∴ Choose the right method for right problem

Discrete-Time Signal Analysis and Linear Systems

- Signal Analysis here is the process of defining and quantifying all signal characteristics relevant for the application at hand
- note: quantifying all signal characteristics is extremely difficult for most medical applications (people tend to differ, measurement circumstances tend to change), usually one strives to estimate parameters instead.

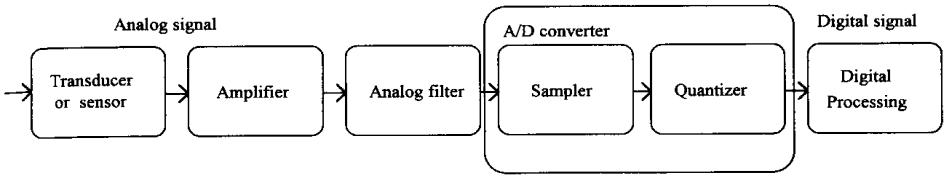


FIGURE 55.1 General block diagram of the acquisition procedure of a digital signal.

Quantization

$$x'(nT) = Q\{x(nT)\}$$

- quantized signal x' of original signal x. T is sampling interval.
  - quantization error

$$e(nT) = x'(nT) - x(nT)$$

Quantization

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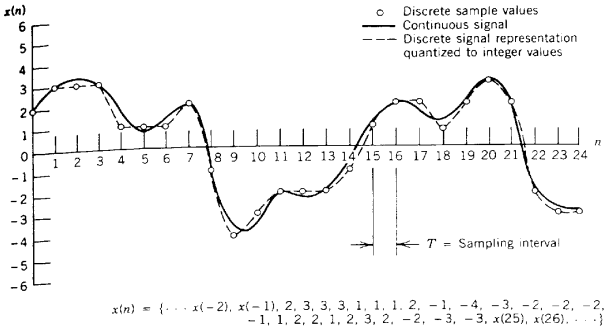


quantization error

$$e(nT) = x'(nT) - x(nT)$$

unit impulse

$$d(nT) = \begin{cases} 1 & n = 0 \\ 0 & n \neq 0 \end{cases}$$

any arbitrary sequence can be formed by shifted unit-impulse sequences

$$x(nT) = \sum_{k=-\infty}^{\infty} x(kT)d(nT - kT)$$

unit step

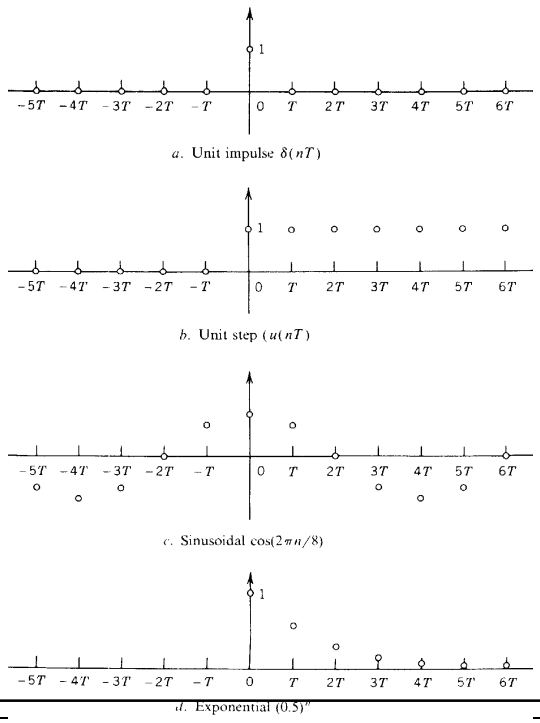
$$u(nT) = \begin{cases} 1 & n \geq 0 \\ 0 & n < 0 \end{cases}$$

sinusoidal sequence

$$x(nT) = \sin(2p \cdot f \cdot nT + f) = \sin(w \cdot nT + f)$$

complex exponential sequence

$$x(nT) = e^{j \cdot 2p \cdot f \cdot nT} = \cos(2p \cdot f \cdot nT) + j \cdot \sin(2p \cdot f \cdot nT)$$



shift operation

$$y(n) = z^{-m}x(n) = x(n-m)$$

transpose operation

$$y(n) = x(-n)$$

scalar multiplication

$$y(n) = a \cdot x(n)$$

vector multiplication (modulation)

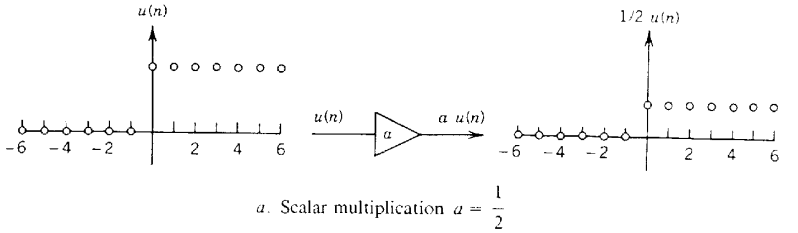
$$y(n) = u(n) \cdot x(n)$$

scalar addition

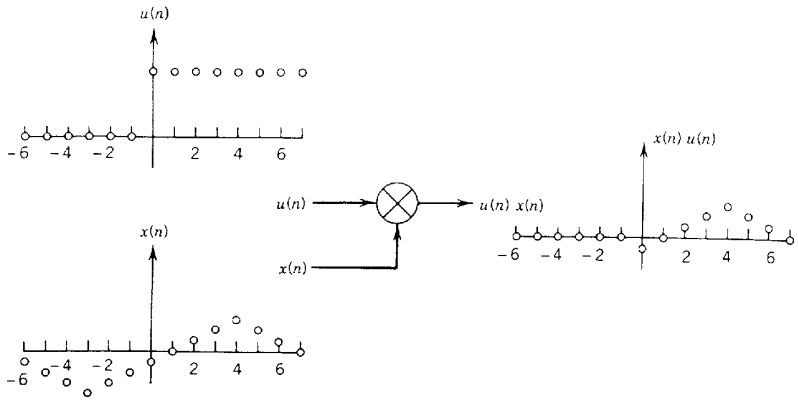
$$y(n) = a + x(n)$$

vector addition

$$y(n) = u(n) + x(n)$$



a. Scalar multiplication $a = \frac{1}{2}$



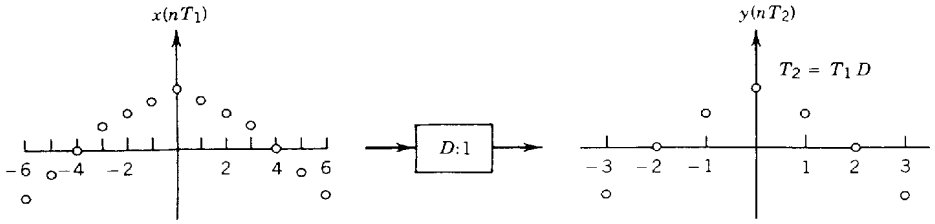
Sampling rate decrease (decimation):

$$y(mT_2) = x(mDT_1) \quad T_2 = DT_1 \quad F_2 = \frac{F_1}{D}$$

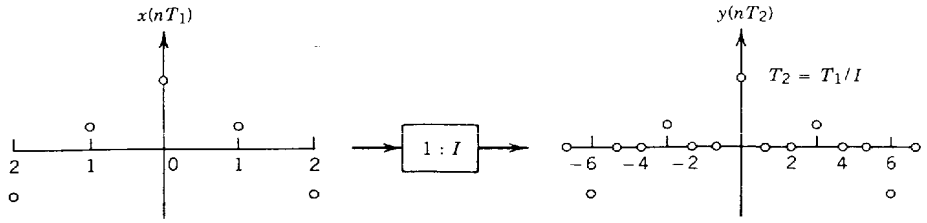
Sampling rate increase (interpolation):

$$y(mT_2) = \begin{cases} x\left(\frac{mT_1}{I}\right) & \text{for } m = \{\ldots,-2I, I, 0, I, 2I, \ldots\} \\ 0 & \text{elsewhere} \end{cases}$$

$$\text{with } T_2 = \frac{T_1}{I} \quad F_2 = IF_1$$



a. Sampling rate decrease (decimation) $D = 2$.



b. Sampling rate increase (interpolation) $I = 3$.

Linear time invariant (LTI) systems

$x(n)$: system input

$y(n) = R[x(n)]$: system output

Linearity

$$y(n) = R[a_1 x_1(n) + a_2 x_2(n)]$$

$$y(n) = a_1 R[x_1(n)] + a_2 R[x_2(n)]$$

$$R[a_1 x_1(n) + a_2 x_2(n)] = a_1 R[x_1(n)] + a_2 R[x_2(n)]$$

Time invariance $R[x(n-m)] = z^{-m} R[x(n)]$ for all m

LTI system is completely characterized by its unit-impulse response

$$h(n) = R[\delta(n)]$$

input signal (sequence)

$$x(n) = \sum_{k=-\infty}^{\infty} x(k)\delta(n-k)$$

output of a linear system with $x(n)$ as input

$$\begin{aligned} y(n) &= R[x(n)] \\ &= R\left[\sum_{k=-\infty}^{\infty} x(k)\delta(n-k)\right] \\ &= \sum_{k=-\infty}^{\infty} x(k) R[\delta(n-k)] \text{ (linearity)} \\ &= \sum_{k=-\infty}^{\infty} x(k) h(n-k) \\ (k' &= n-k) \\ &= \sum_{k'=-\infty}^{\infty} h(k') x(n-k') \end{aligned}$$

Magnitude of signals: Lp norm (p is a positive integer)

$$L_p = \|x(n)\|_p = \left(\sum_{n=-\infty}^{\infty} |x(n)|^p \right)^{\frac{1}{p}}$$

- $||x(n)||>0$ for $x(n) \neq 0$ for all n and $||x(n)||=0$ if and only if $x(n) = 0$ for all n
- $||ax(n)||=|a|*||x(n)||$ for any scalar a
- $||x(n)+y(n)|| \leq ||x(n)||+||y(n)||$ (triangle inequality)

commonly used norms

- L_1-norm: the sum of magnitudes of each sample (useful for determination of stability of linear systems)
- L_2-norm (Euclidian norm)
- L_∞-norm = max gives peak magnitude of signal

Causality (realizable in real-time):

$$y(m) = f(x(n \leq m), y(n < m));$$
$$h(n) = 0 \quad \text{for } n < 0$$

Stability: bounded input provides bounded output:

$$|y(n)| = \left| \sum_{k=-\infty}^{\infty} h(k)x(n-k) \right|$$

$$\leq \sum_{k=-\infty}^{\infty} |h(k)||x(n-k)|.$$

$$\text{let } B = \|x(n-k)\|_\infty \text{ then}$$

$$|y(n)| \leq B \sum_{k=-\infty}^{\infty} |h(k)|$$

Stability if

$$\sum_{k=-\infty}^{\infty} |h(k)| < \infty$$

$$\|h(k)\|_{l_1} < \infty$$