EPFL

COM202 – Signal Processing

Introduction to Signal Processing

Why is signal processing super cool?

- do you like music?
  - audio editing, DAWs, synthesizers, guitar pedals…
- do you like photography or video?
  - image processing, visual effects, super-resolution
- do you like video games?
  - audio spatialization, physical models, controllers…
- do you like sports?
  - lightweight cameras, smart sensors, video analytics
- do you like electronics? astronomy? biology? finance?
  - signal processing is everywhere

What is a “signal”?

quantitative description of the evolution of a natural phenomenon

What does the word "signal" makes you think of?

" It say … us. "

Signals and signal processing

- leitmotif: signals contain *information*
- signal processing is about:
  - discovering
  - extracting
  - analyzing
  - modifying
  - transmitting

  } information

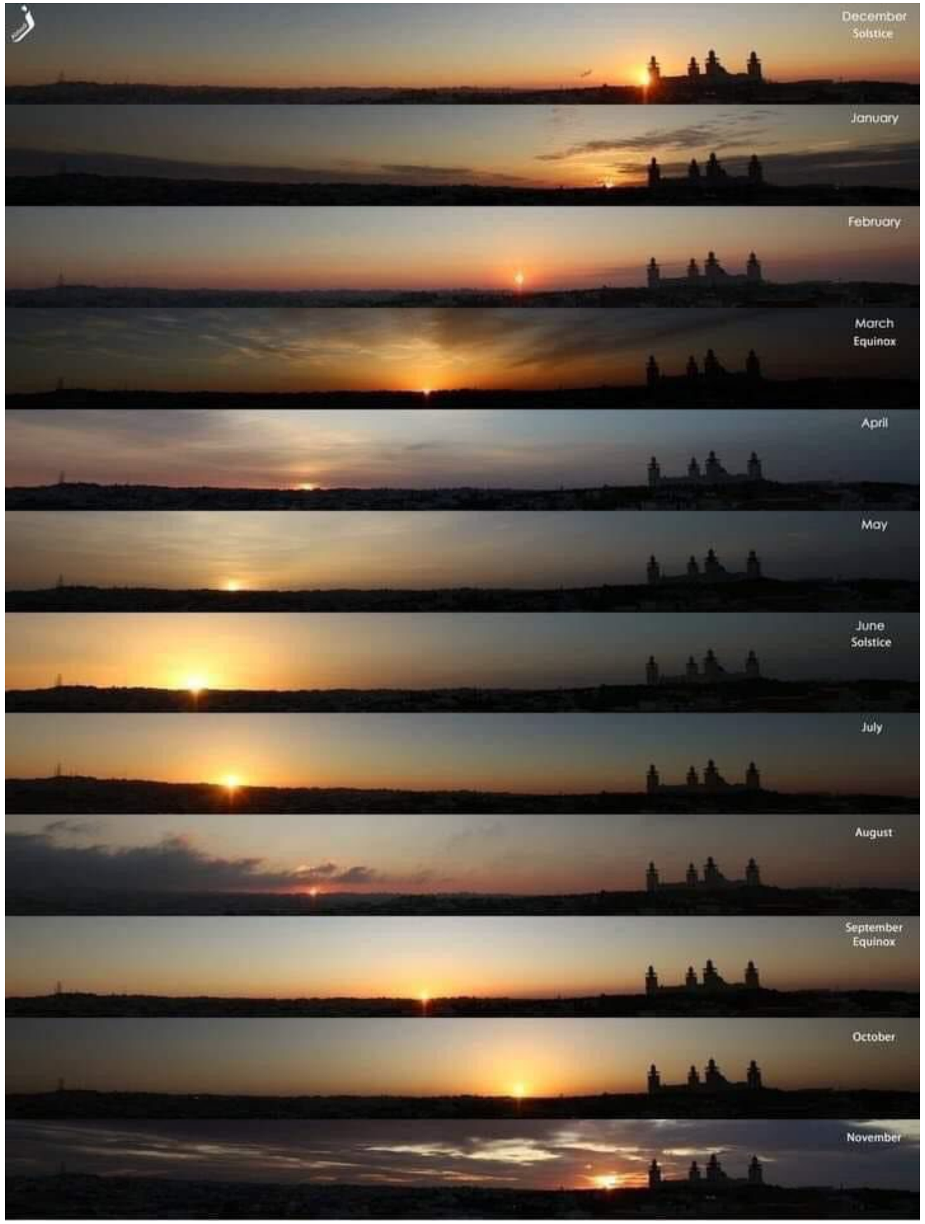
SP is the first engineering discipline to focus on the ***physical nature of information***

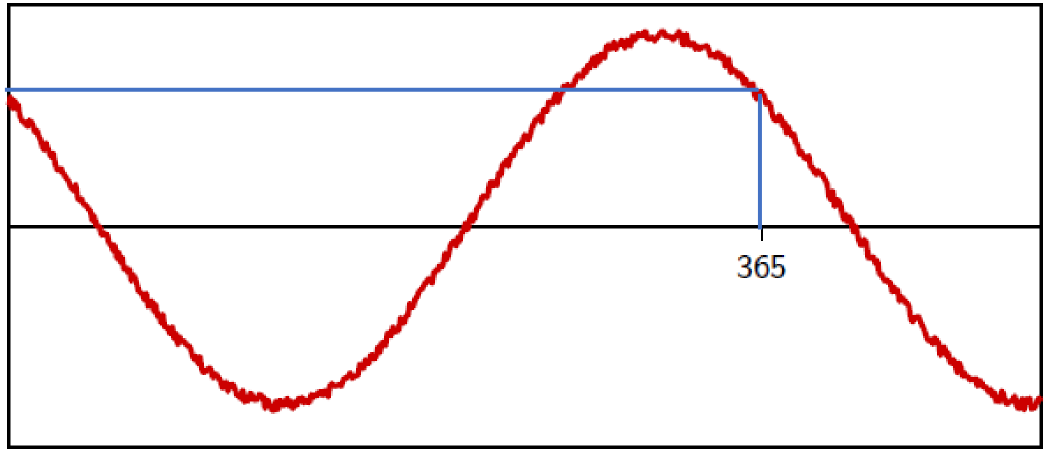
A quick history of signal processing

Let's start at the *very* beginning…

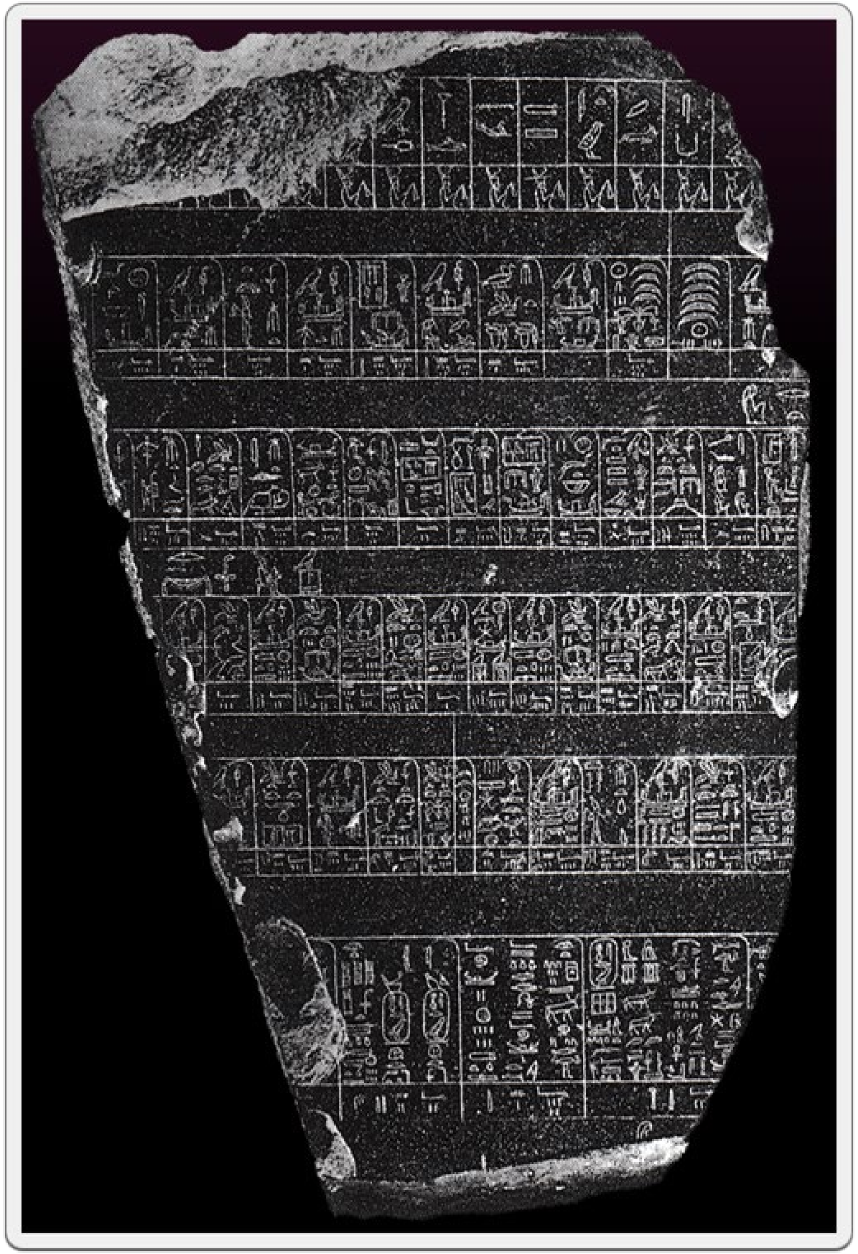
- how did prehistoric civilizations find out how many days are in a year?
- how did ancient empires manage the economy?

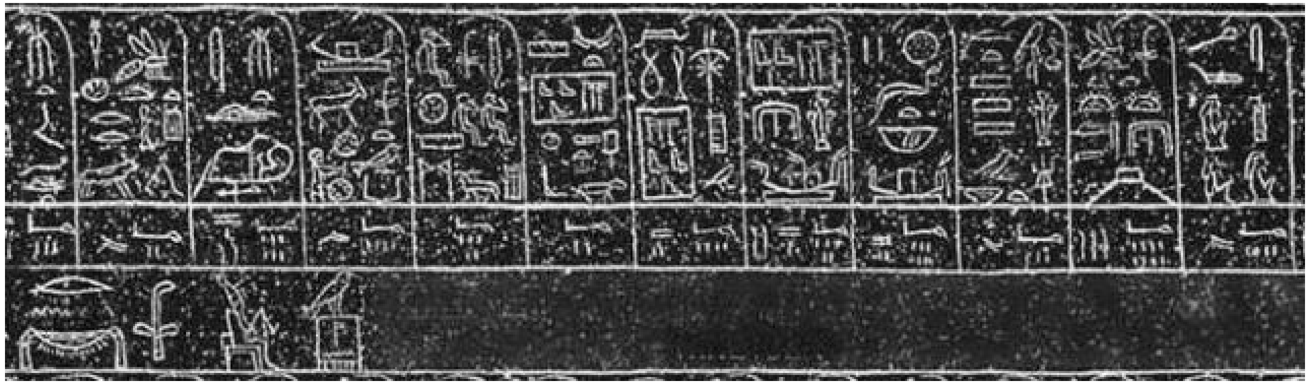
From observation to information

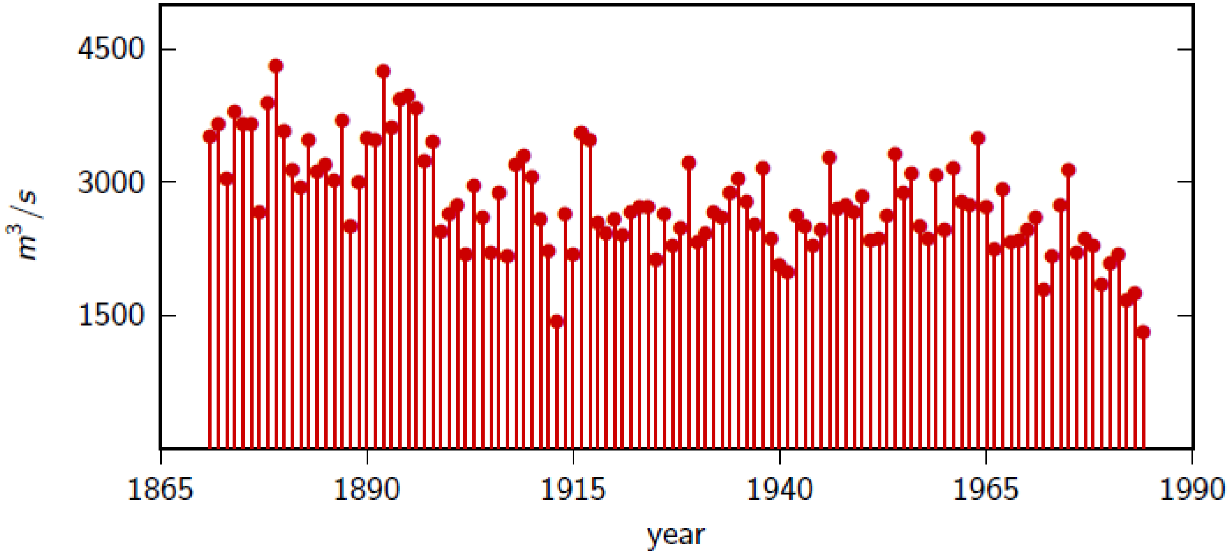




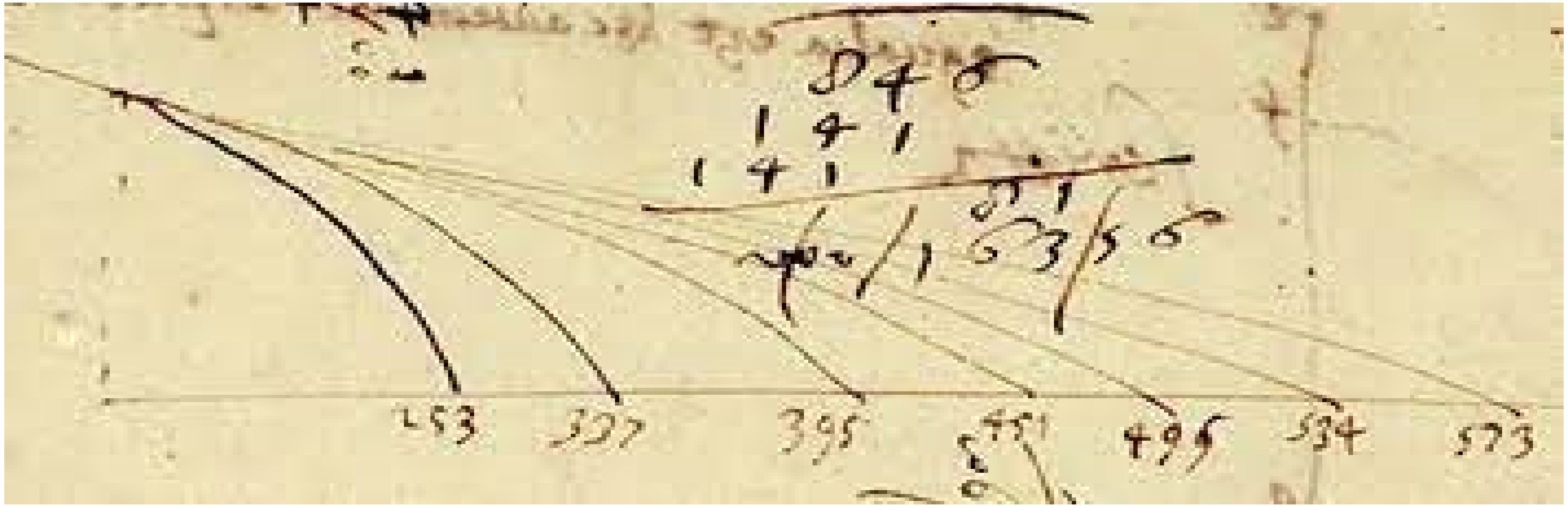
Signal processing in ancient Egypt





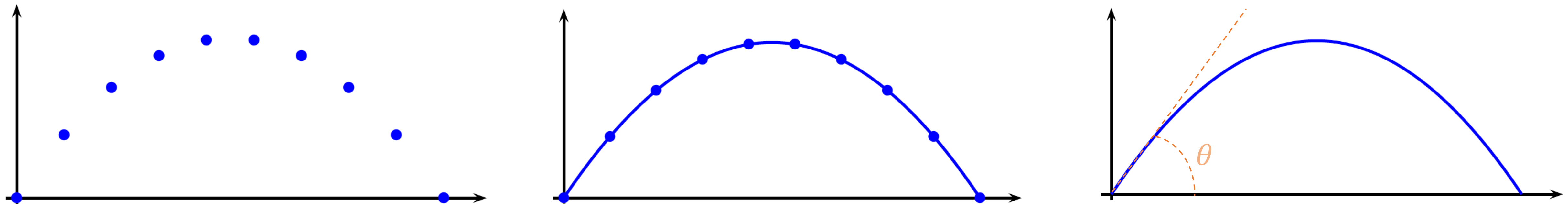


Signal processing in the Age of Reason



Galileo, 1608

From observation to *models*

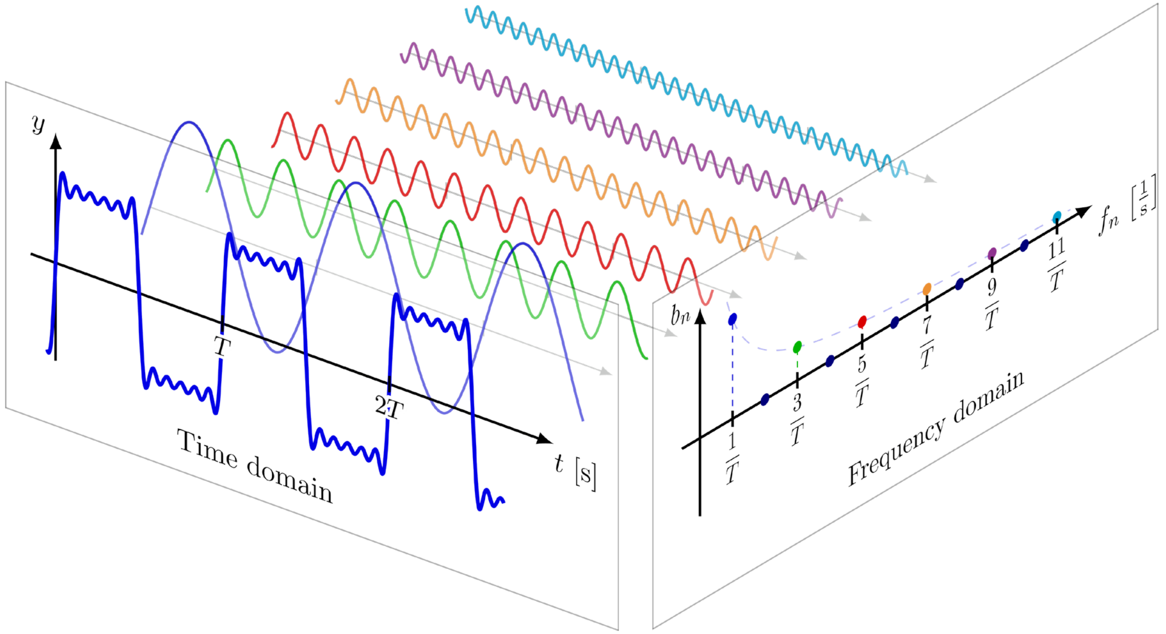


$$\boldsymbol{x}(t) = \boldsymbol{v}_0 t + \frac{1}{2}\boldsymbol{g}t^2$$

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} v\cos\theta \\ v\sin\theta \end{bmatrix} t + \begin{bmatrix} 0 \\ g/2 \end{bmatrix} t^2$$

The intellectual road to signal processing

- Leibniz and Newton formalize calculus (1680)
  - functions of a real variable
  - differentiation, integration
  - differential equations
- Lagrange, Euler, et. al. work on numerical methods (1710 – 1780)
  - partial differential equations, wave equation
  - numerical approximations
- Fourier introduces his transform (1822)



Isn’t that just “normal” science?

- so far, no one is talking about “signals”
- most of the scientific work is focused on *understanding* the natural world

- signals appear when the attention moves to *communications*
- key turning point comes with the discovery of electromagnetism
- scientists now want to *create* new physical phenomena

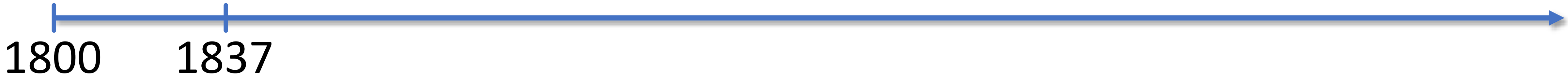
Milestones in signal processing

1800

Alessandro Volta invents the first battery

Niepce's first photograph (1827)

Milestones in signal processing



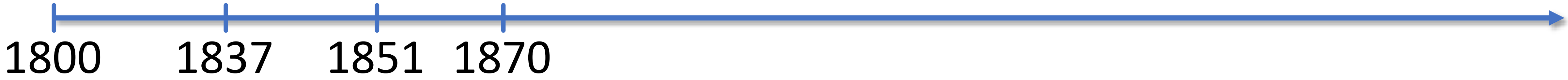
the first wired telegraph networks

Milestones in signal processing

1800 1837 1851

first transatlantic
telegraph cable

Milestones in signal processing



Alexander Bell and the first telephone

Edison's phonograph (1877)

Milestones in signal processing

1800 — 1837 — 1851 — 1870 — 1900

Guglielmo Marconi's first radio broadcast

first vacuum tube (1906)

Milestones in signal processing

1800 1837 1851 1870 1900 1930

first commercial television

Milestones in signal processing

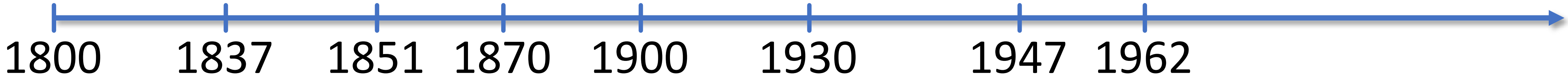
1800 1837 1851 1870 1900 1930 1940

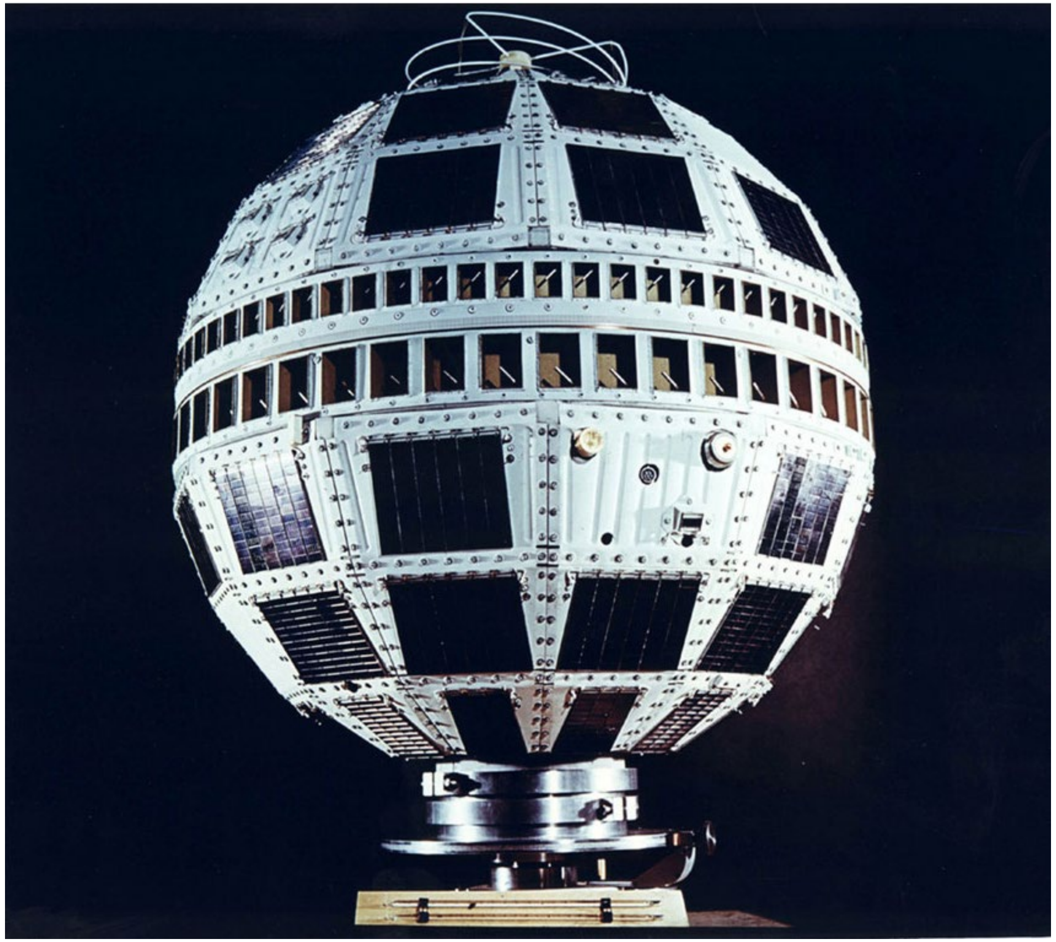
Milestones in signal processing

1800 1837 1851 1870 1900 1930 1947

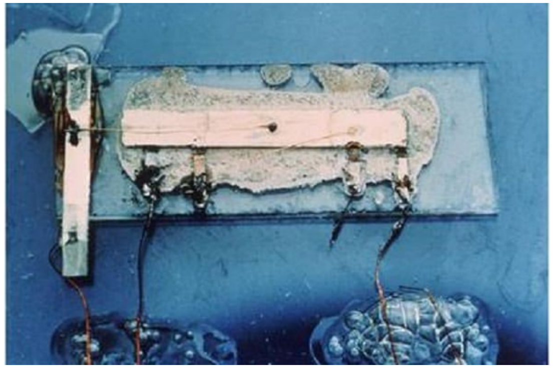
invention of the transistor

Milestones in signal processing



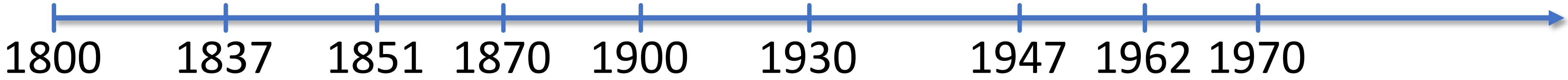


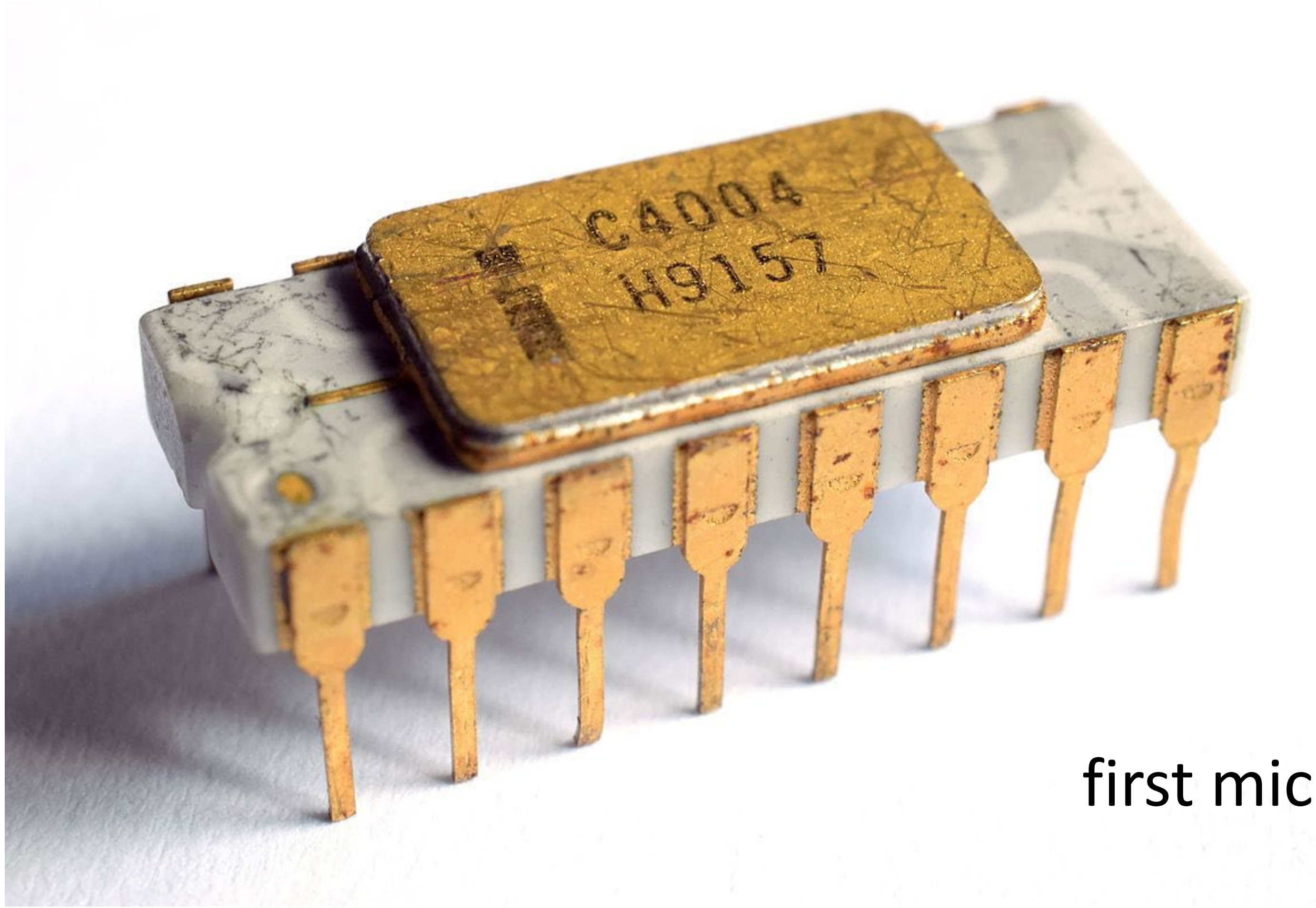
Telstar 1, the first telecommunication satellite



invention of the microchip

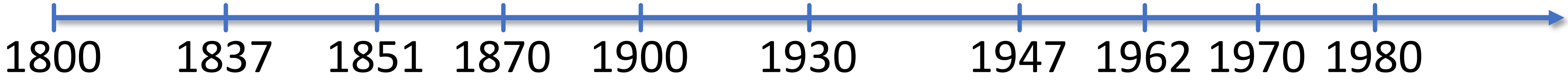
Milestones in signal processing





first microprocessor

Milestones in signal processing



the compact disk: digital audio enters the consumer market

Milestones in signal processing

1800 1837 1851 1870 1900 1930 1947 1962 1970 1980 1999

first connected smartphone

1900 to 1960: the “golden era” of classic SP

- incredible advances in technology:
  - passive and active electronic components
  - commerce and wartime boost R&D

- fundamental theoretical results
  - time-frequency analysis
  - understanding of transmission lines
  - filter design
  - systematization of control theory

classic (analog) signal processing speaks the language of calculus

No cell phones in old sci-fi movies

No cell phones in old sci-fi movies

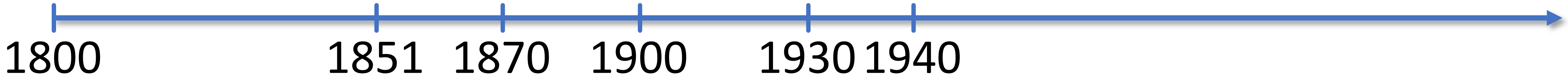
No cell phones in old sci-fi movies

No cell phones in old sci-fi movies. But why?

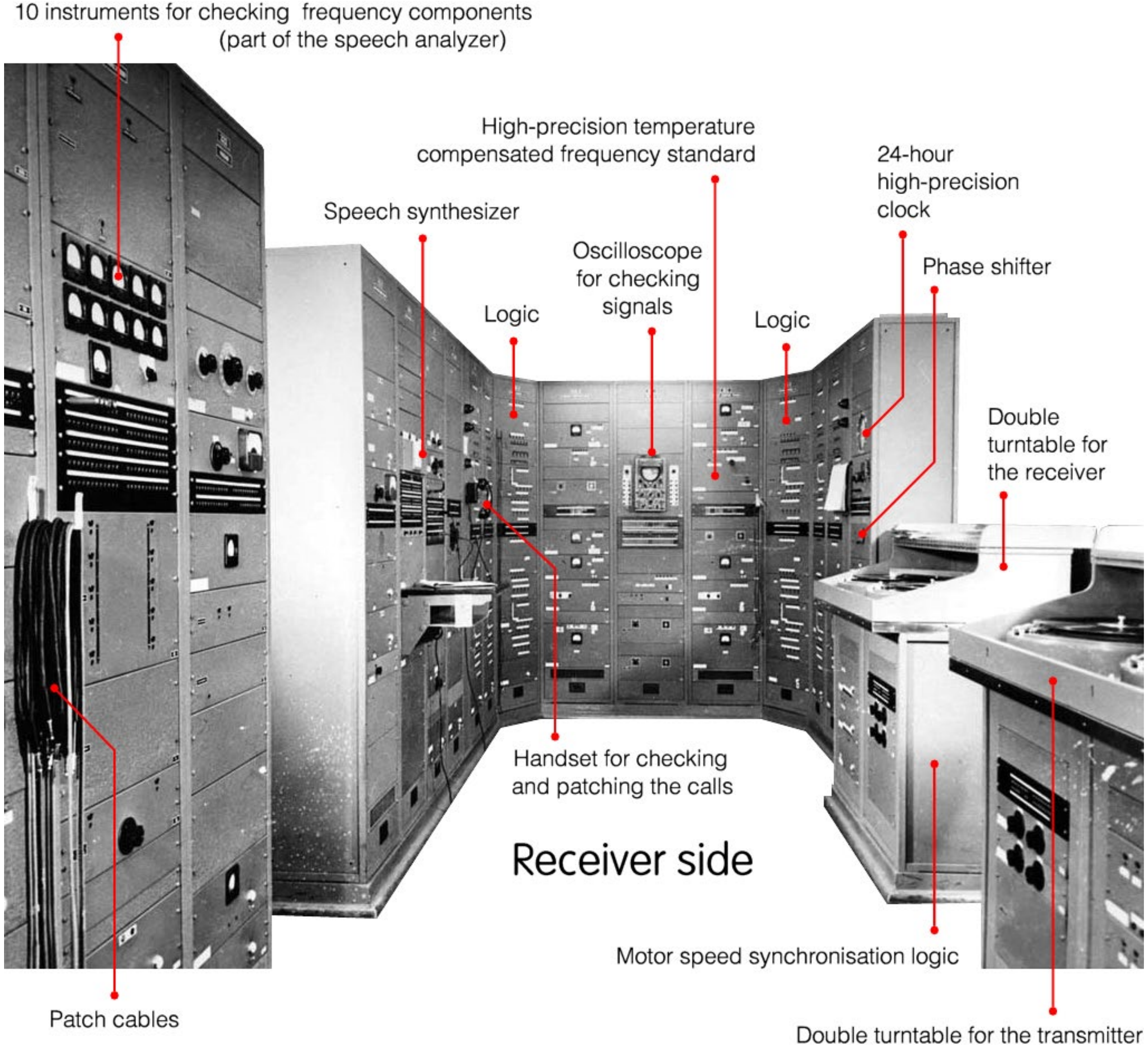
- What people failed to imagine:
  - miniaturized portable devices
  - multi-purpose devices (phone/music player/camera)
  - inexpensive data storage
  - inexpensive worldwide communications

- The missing ingredient? ***Digital*** signals.
- The digital revolution made all information “equal”:
  - same storage devices
  - same communication channels
  - same processing chips
- R&D could focus on a single unified goal: digital signal processing

When did the digital revolution begin?



The SIGSALY system (1942)



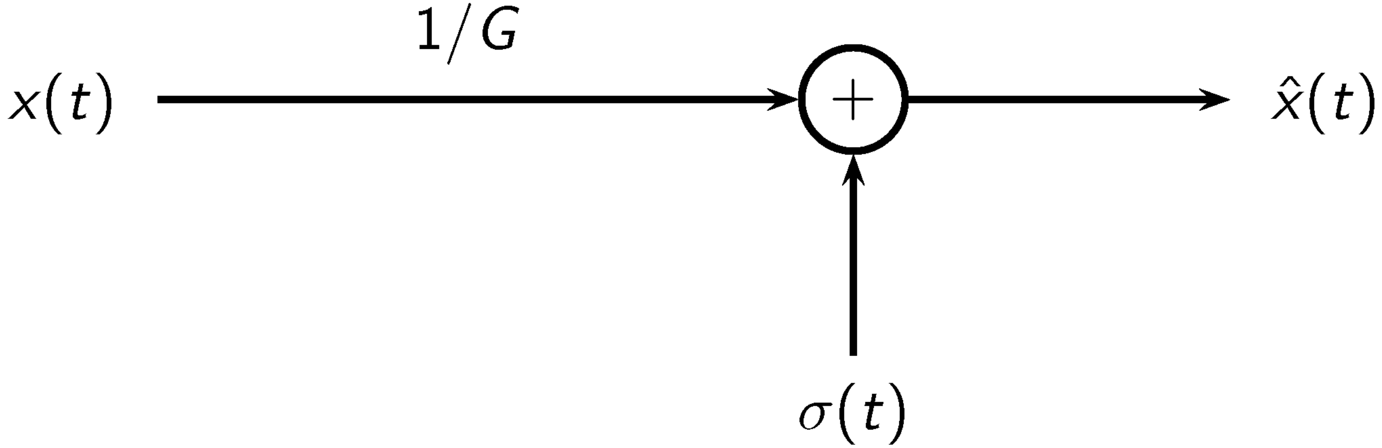
The main ingredients of SIGSALY

- secret scrambling codes recorded on phonograph records
- Pulse-Code Modulation (PCM)

- PCM was the most revolutionary idea
- still in use today
- easier to understand in a simpler scenario: reducing noise in telecommunications

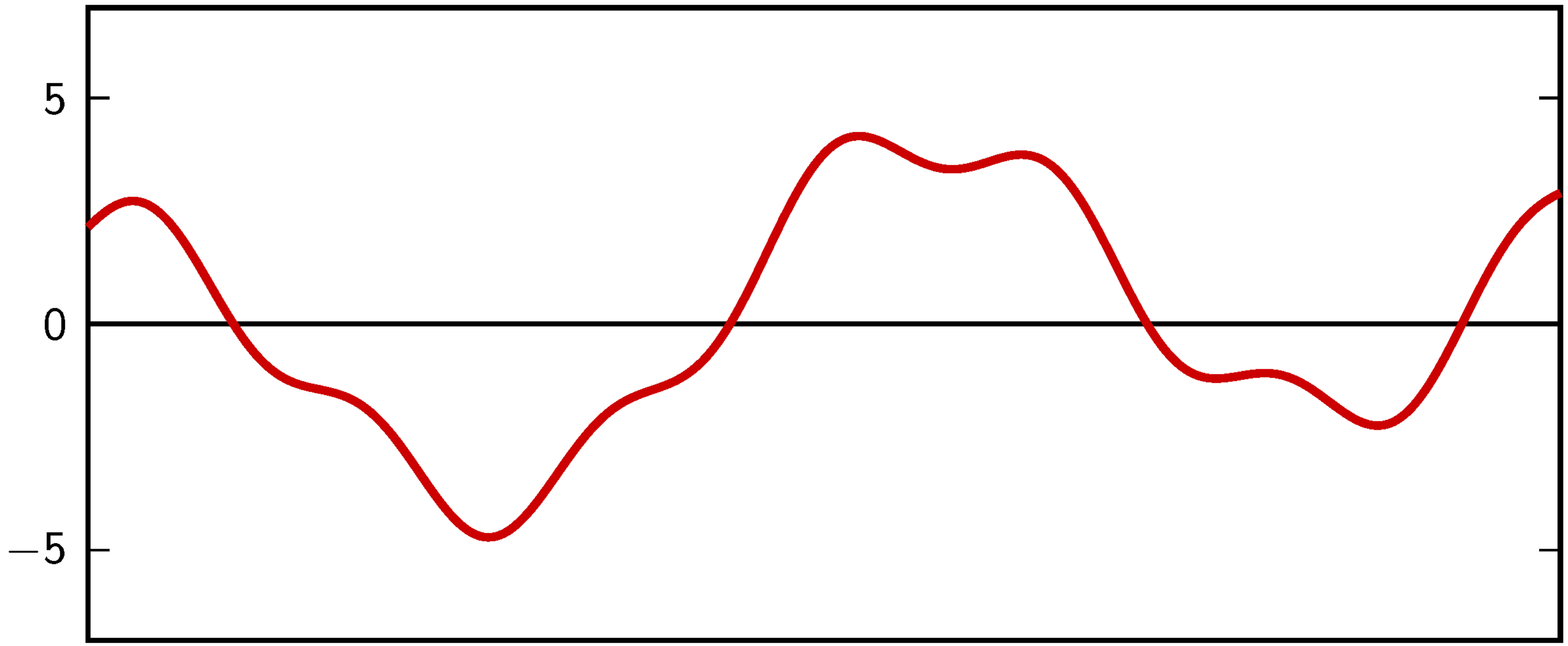
Data transmission

Transmission of analog signals



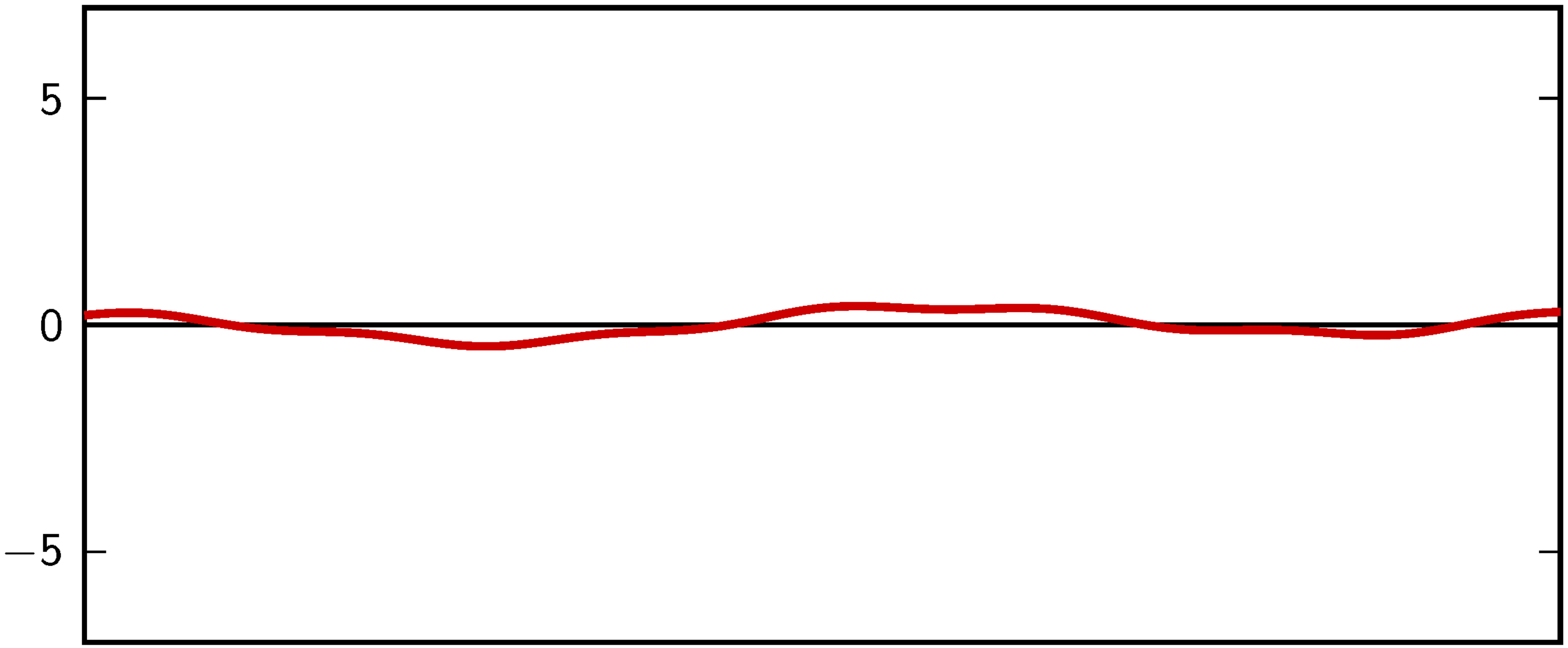
$$\hat{x}(t) = x(t)/G + \sigma(t)$$

Transmission of analog signals: attenuation and noise



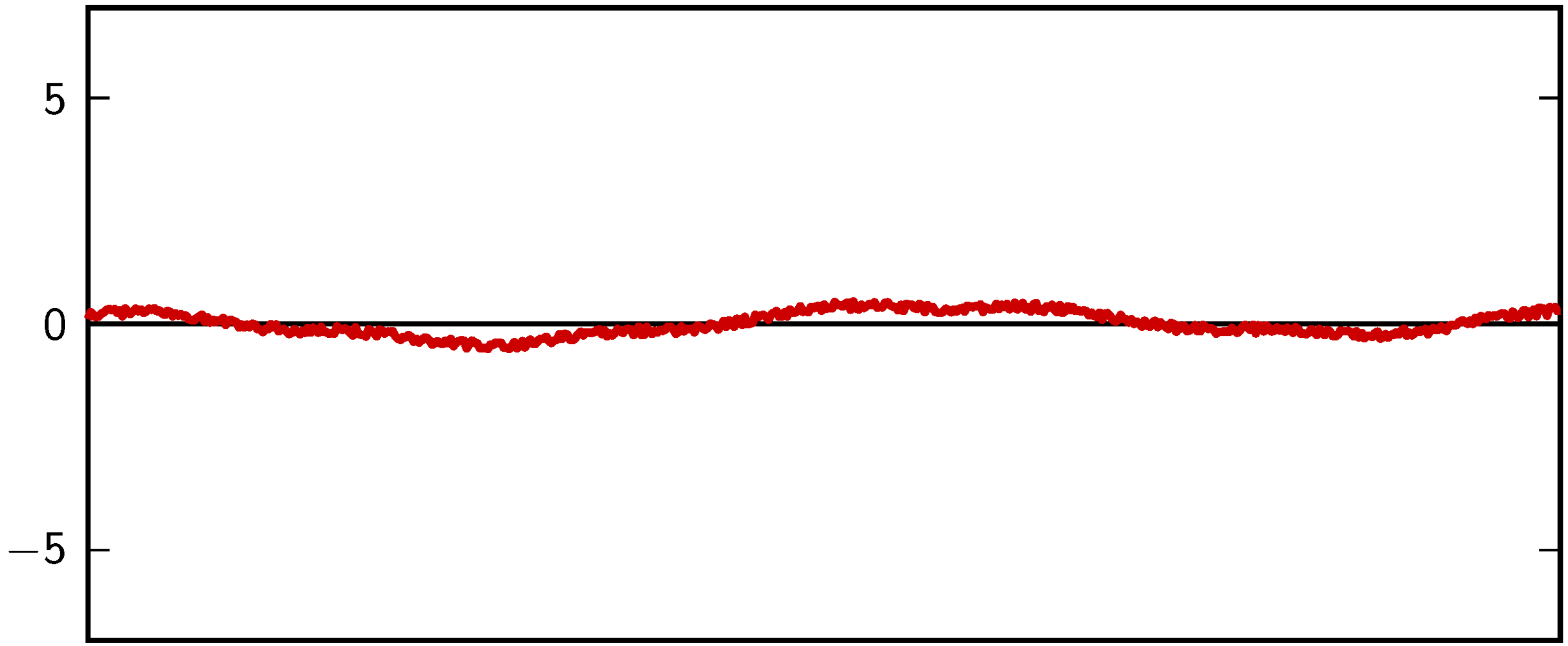
$x(t)$

Transmission of analog signals: attenuation and noise



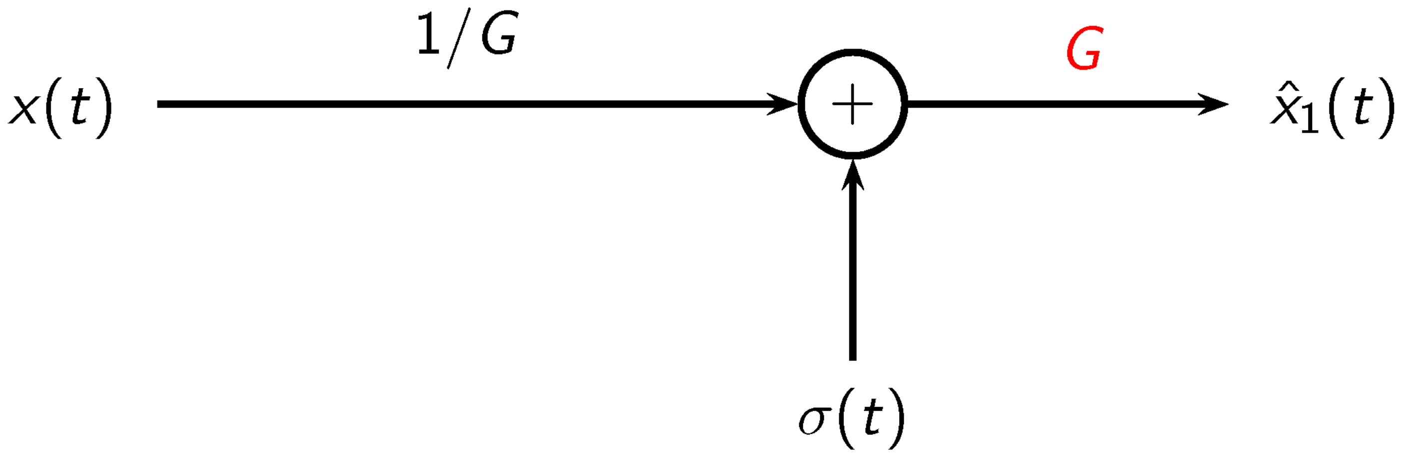
$x(t)/G$

Transmission of analog signals: attenuation and noise



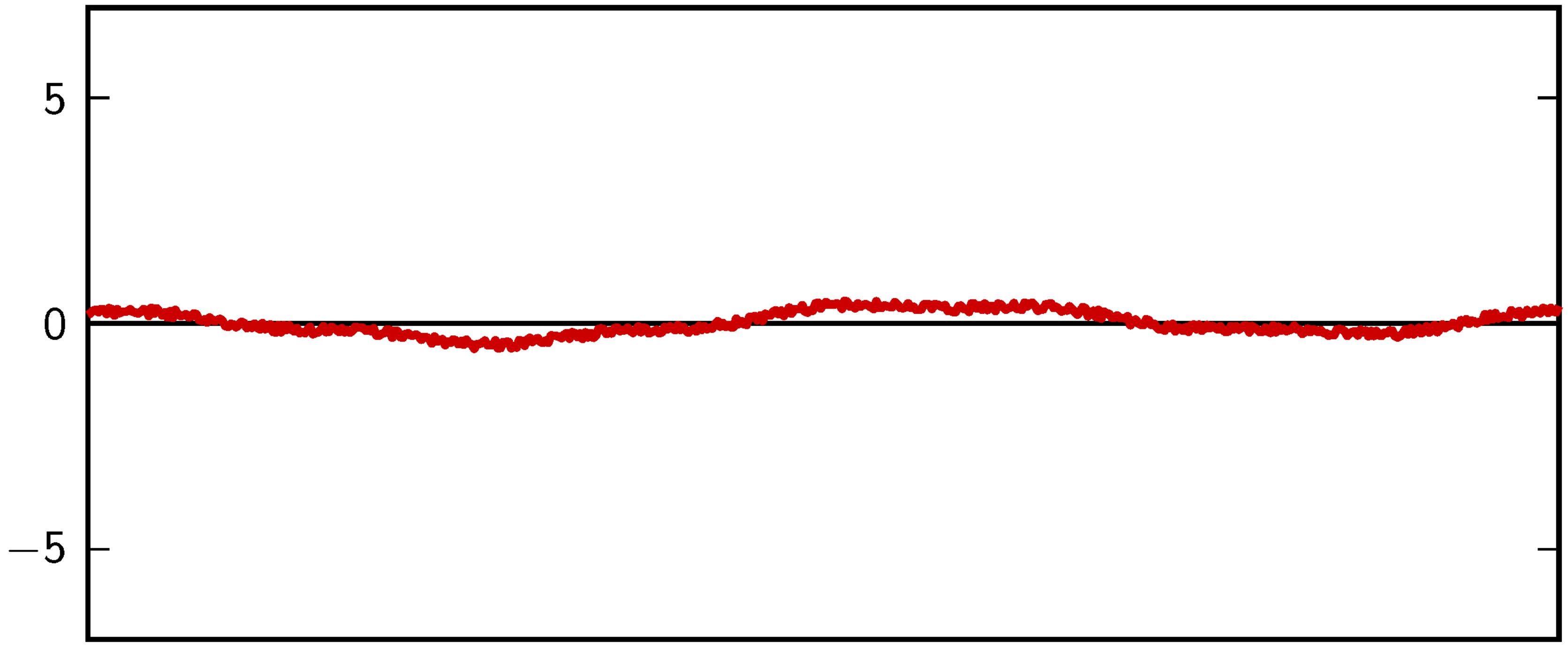
$x(t)/G + \sigma(t)$

Amplification to compensate attenuation



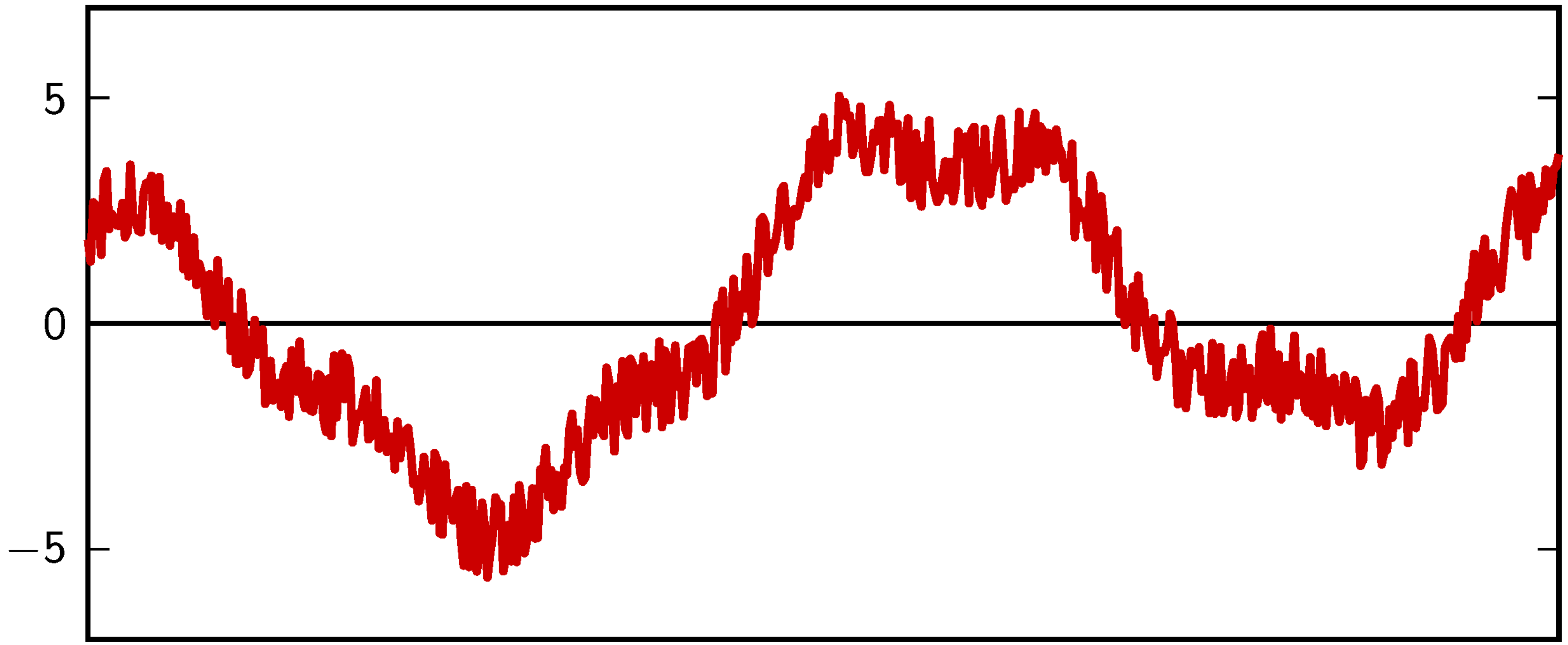
but: $\hat{x}_1(t) = x(t) + G\sigma(t)$

Side effect of amplification



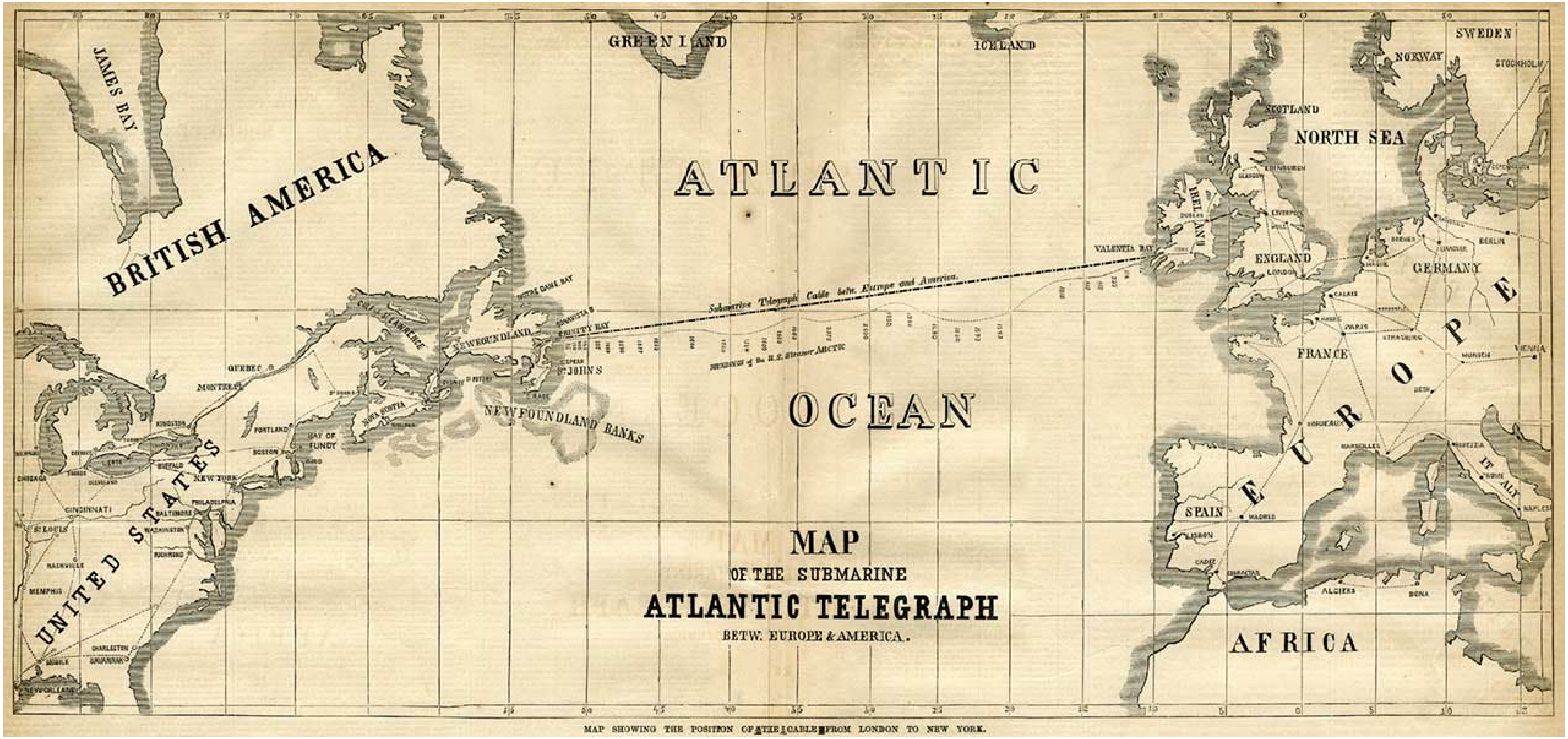
$x(t)/G + \sigma(t)$

Side effect of amplification



$$\hat{x}_1(t) = G[x(t)/G + \sigma(t)] = x(t) + G\sigma(t)$$

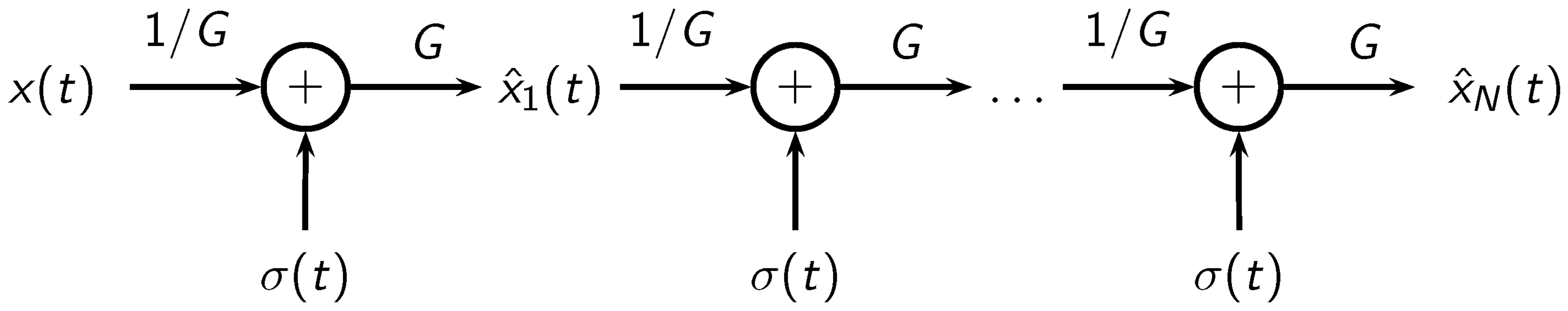
Transatlantic communications



Transatlantic communications

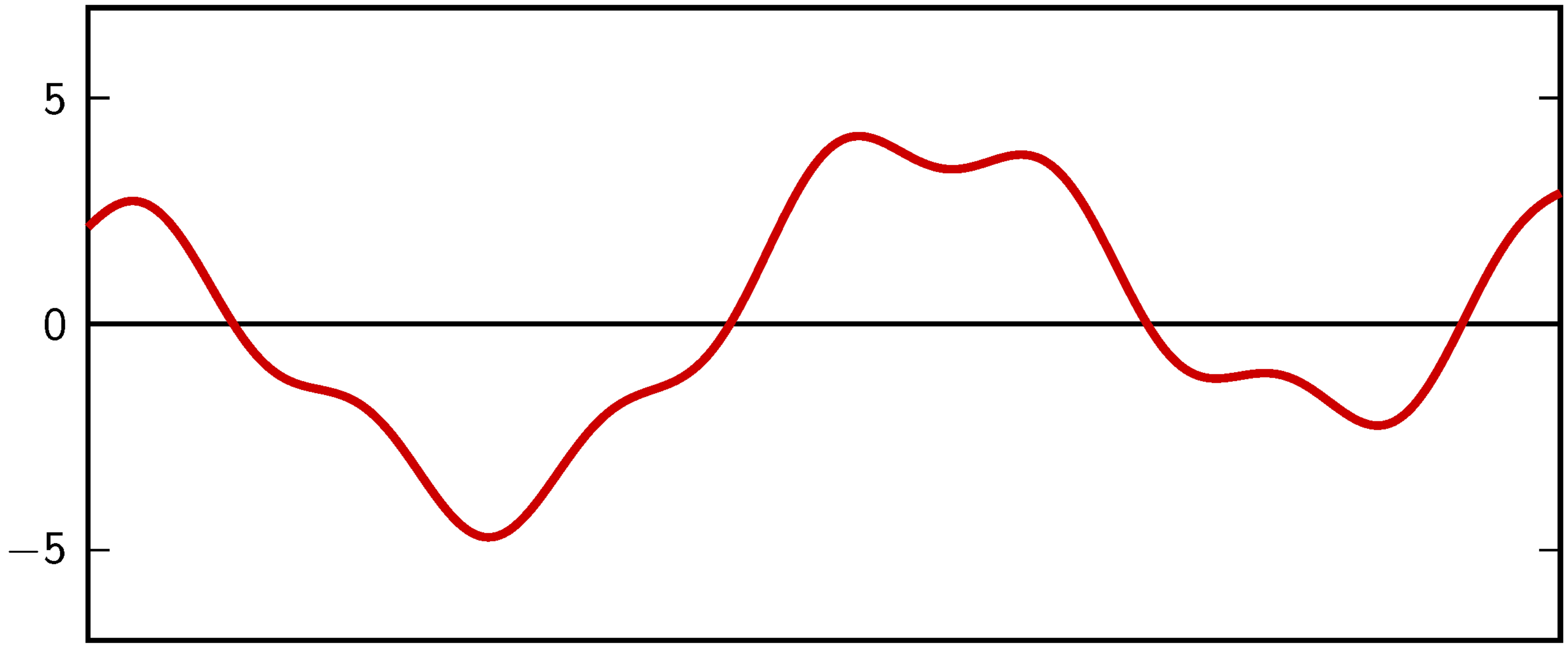
Transmitting a signal overseas

For a long, long channel we need repeaters



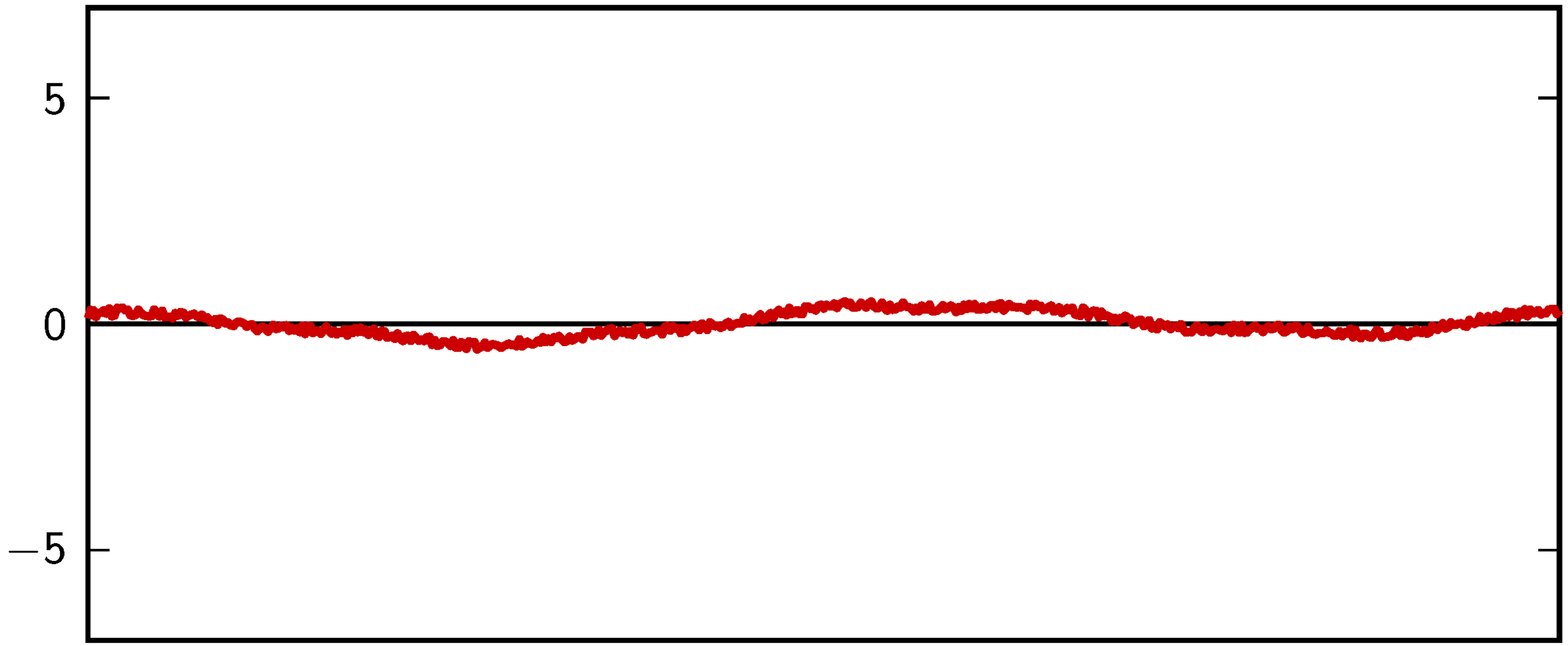
$$\hat{x}_N(t) = x(t) + NG\sigma(t)$$

Transmission of analog signals



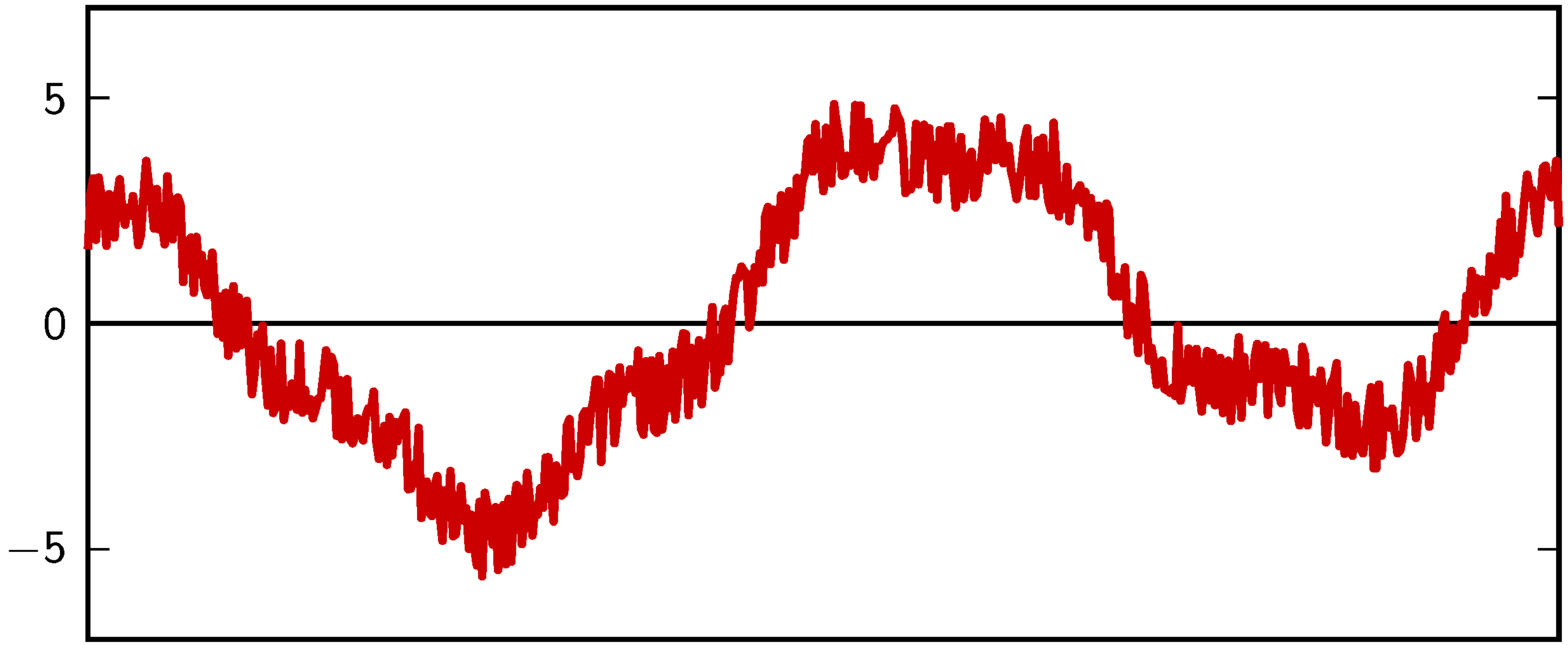
$x(t)$

Transmission of analog signals



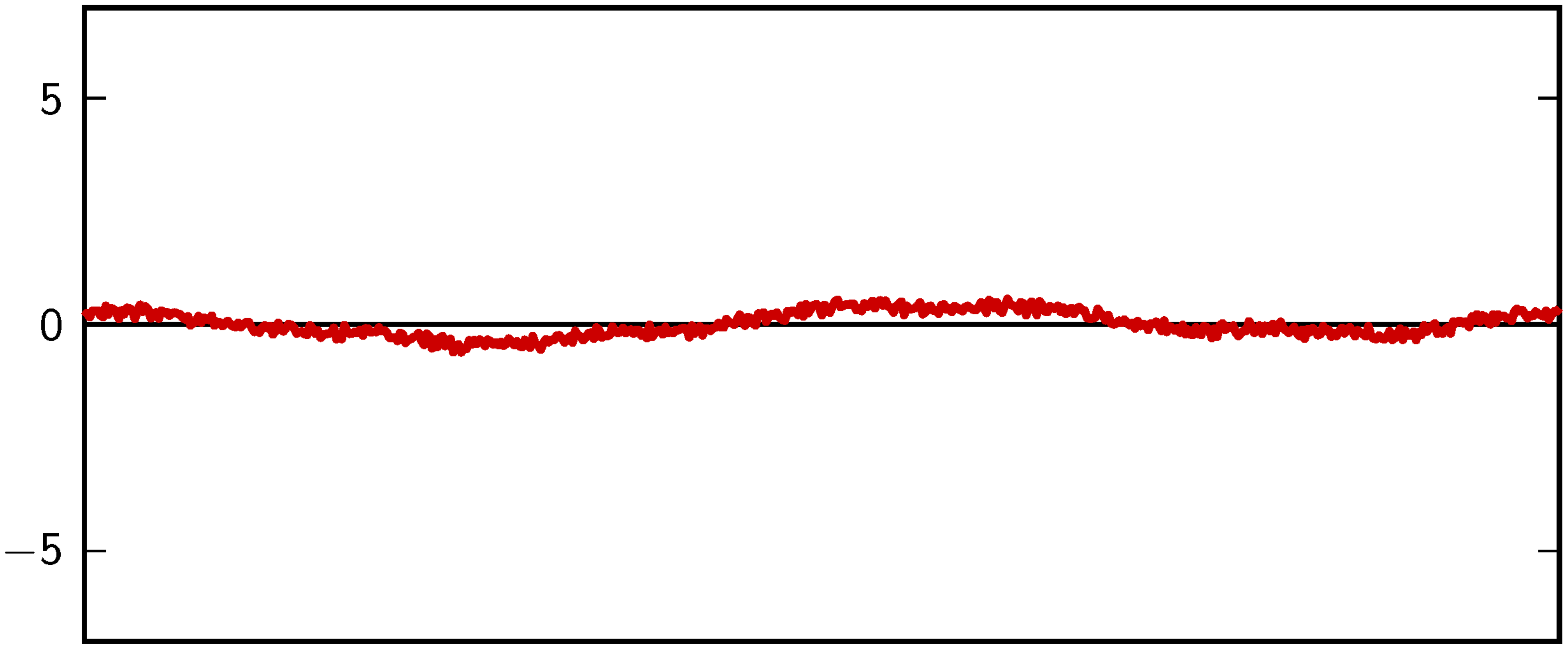
$$x(t)/G + \sigma(t)$$

Transmission of analog signals



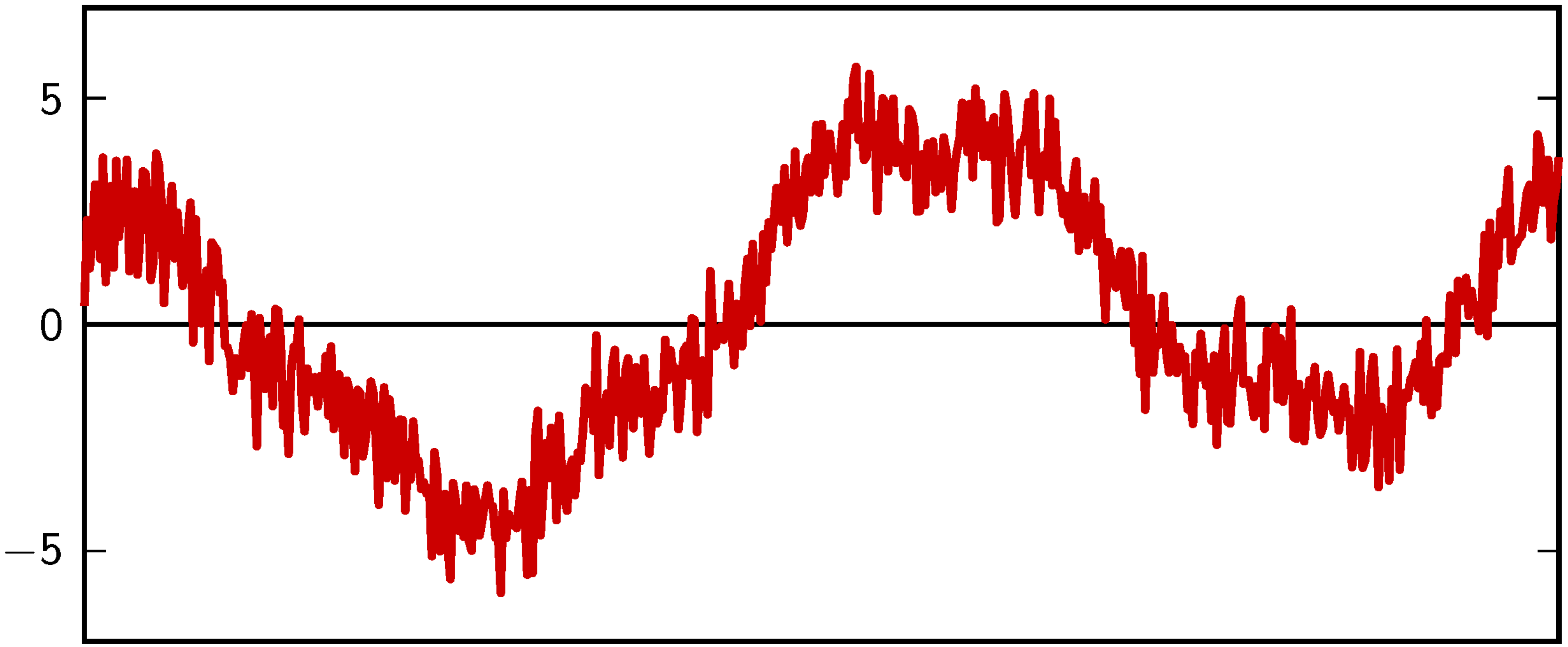
$$\hat{x}_1(t) = G[x(t)/G + \sigma(t)] = x(t) + G\sigma(t)$$

Transmission of analog signals



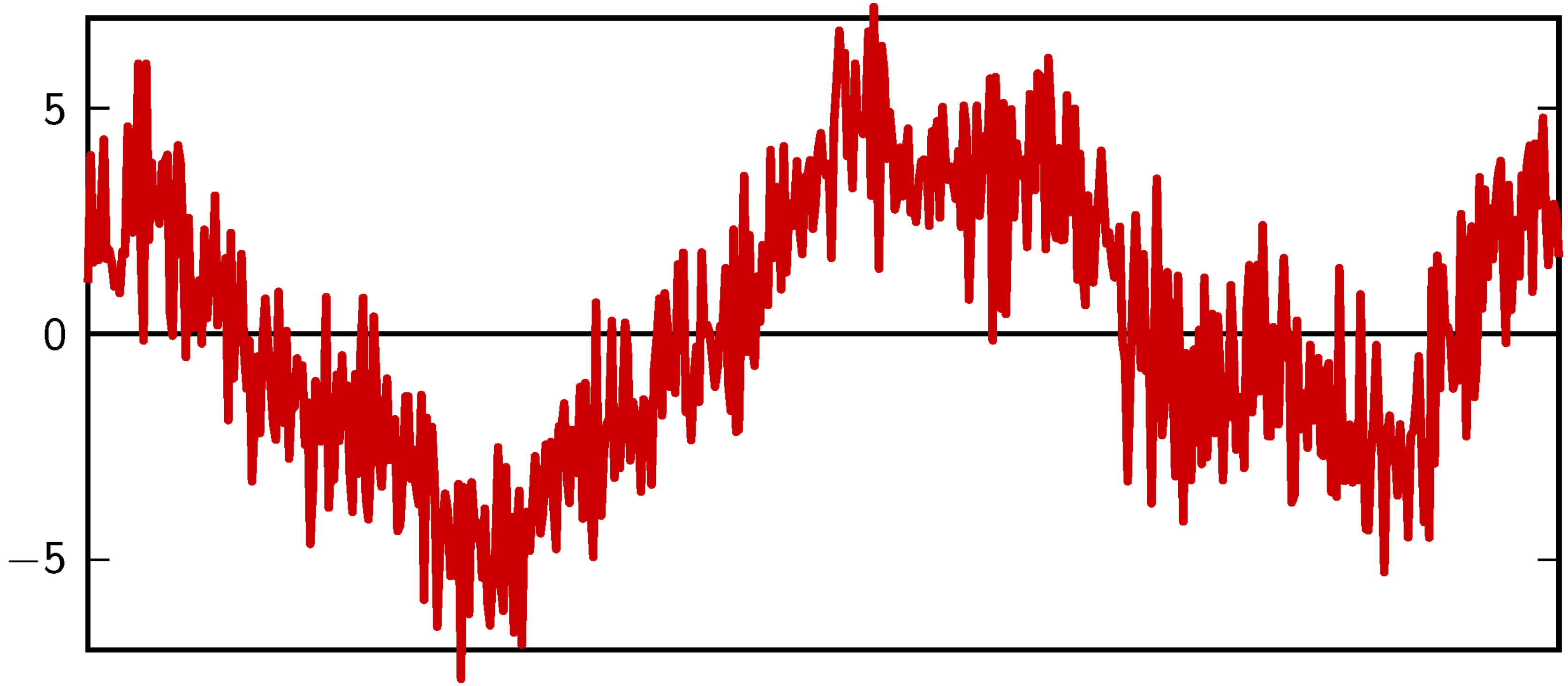
$$\hat{x}_1(t)/G + \sigma(t)$$

Transmission of analog signals



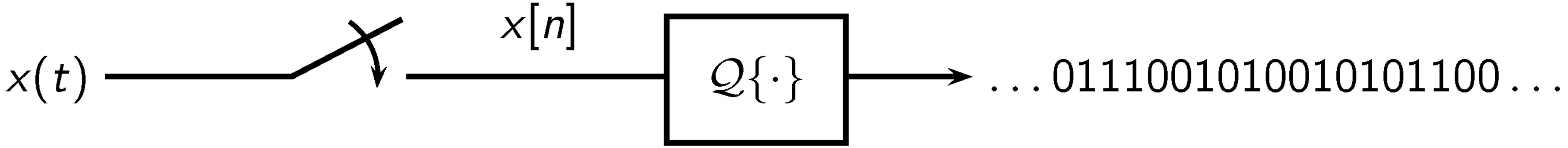
$$\hat{x}_2(t) = G[\hat{x}_1(t)/G + \sigma(t)] = x(t) + 2G\sigma(t)$$

Transmission of analog signals

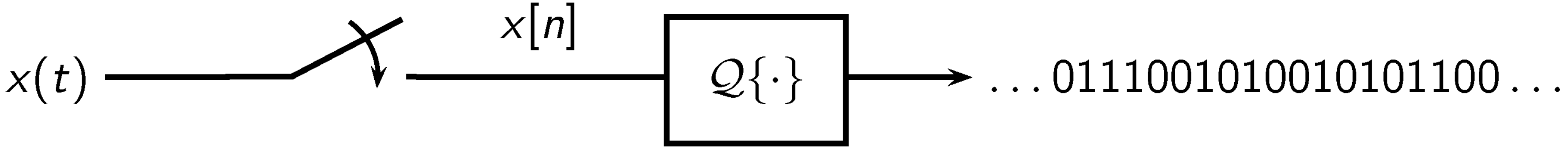


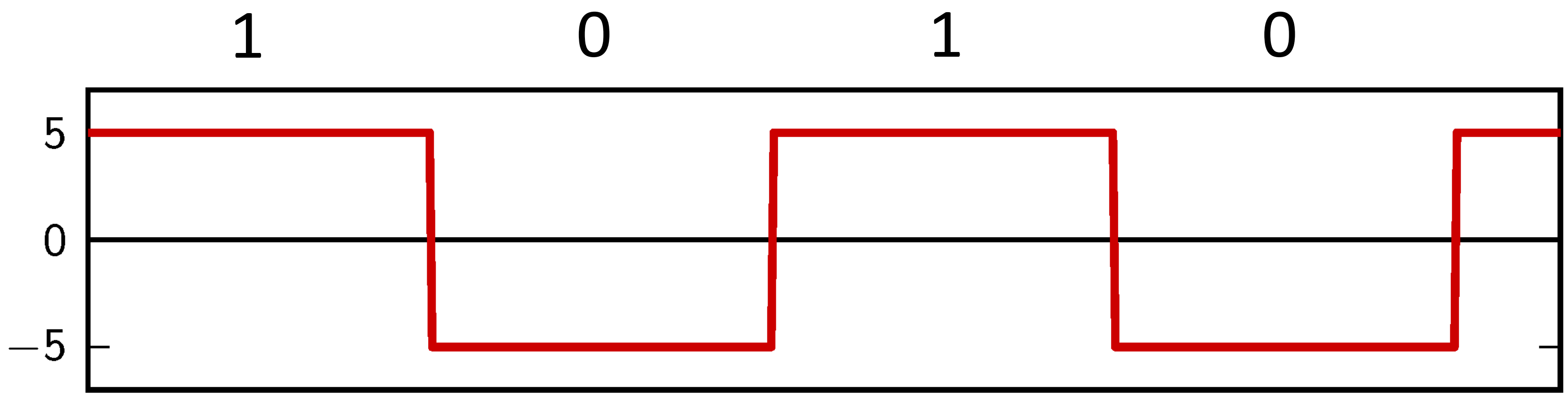
$$\hat{x}_N(t) = x(t) + NG\sigma(t)$$

Pulse Code Modulation (PCM)

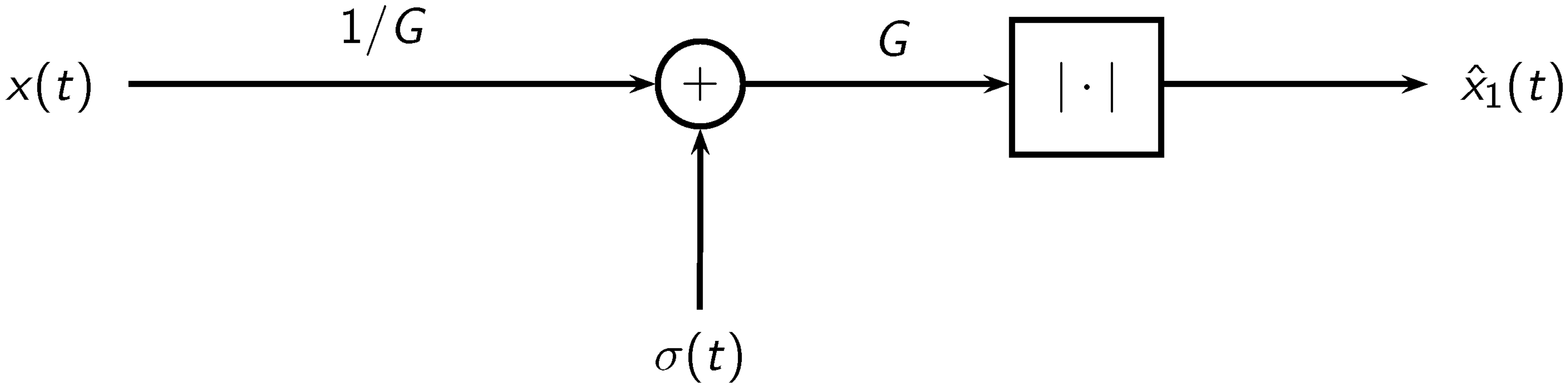


Pulse Code Modulation (PCM)



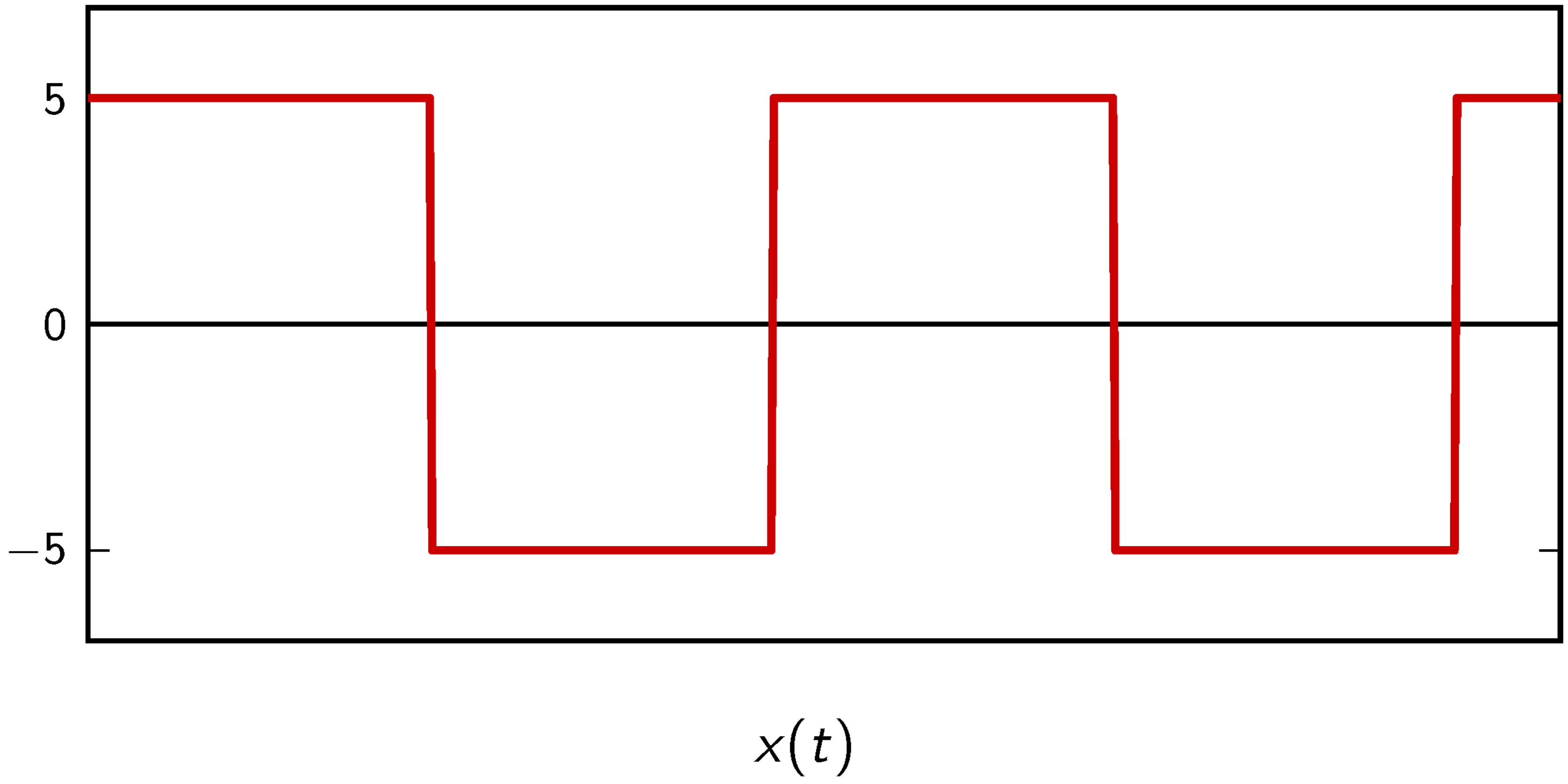


Regeneration of PCM signals

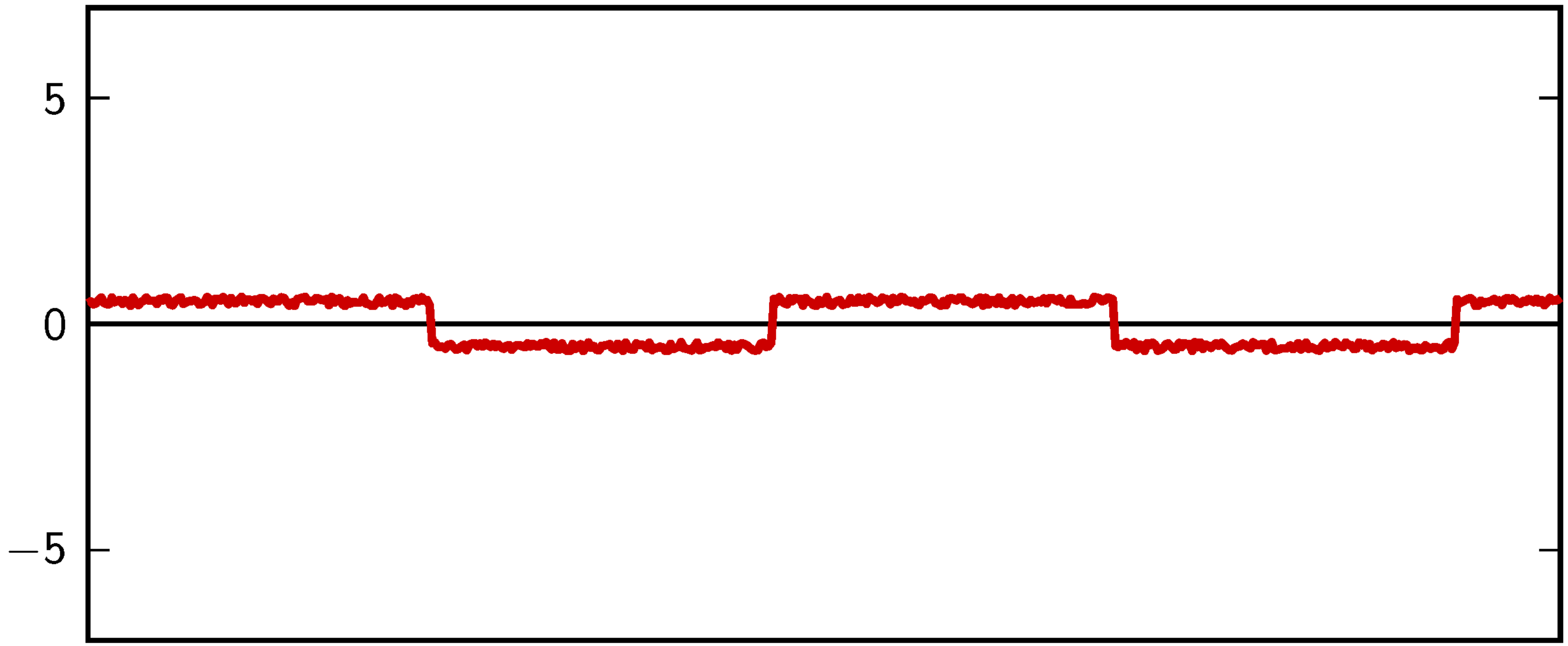


$$\hat{x}_1(t) = \text{sgn}[x(t) + G\sigma(t)]$$

Transmission of quantized signals

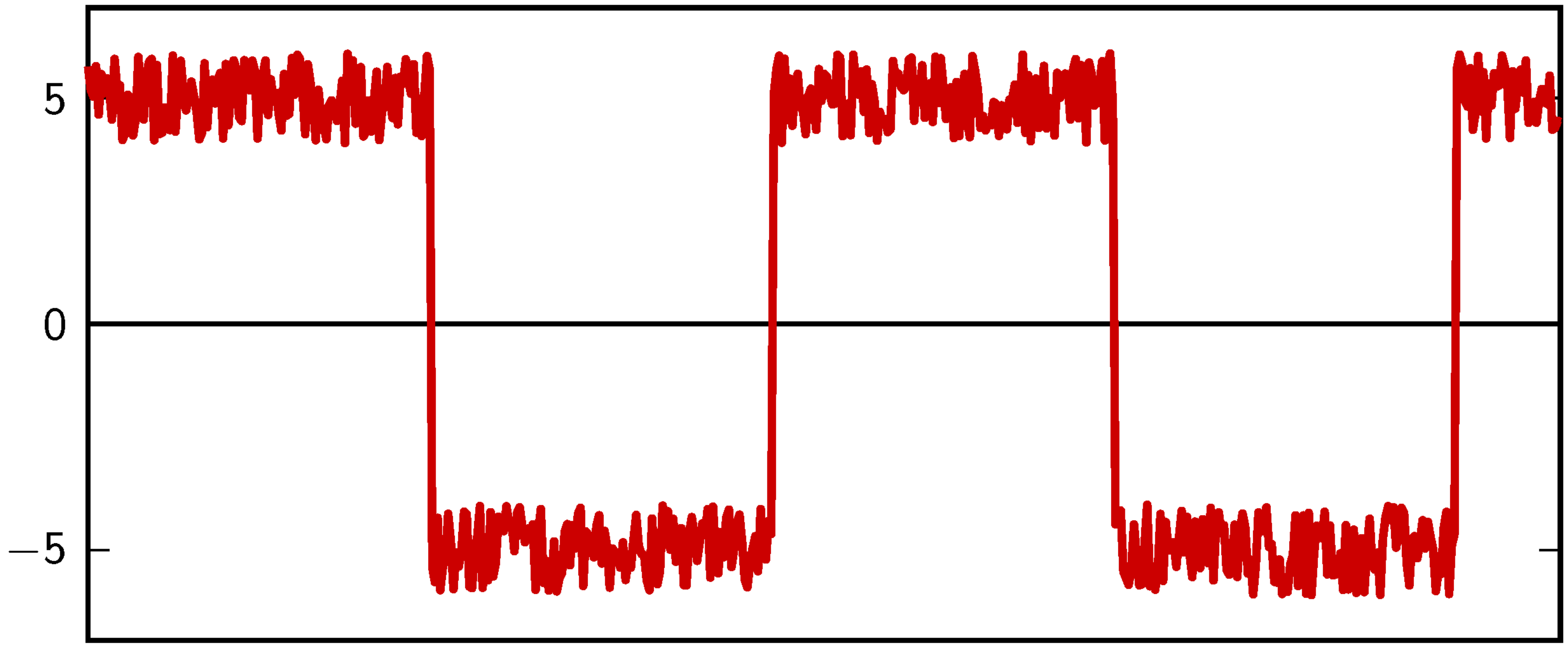


Transmission of quantized signals



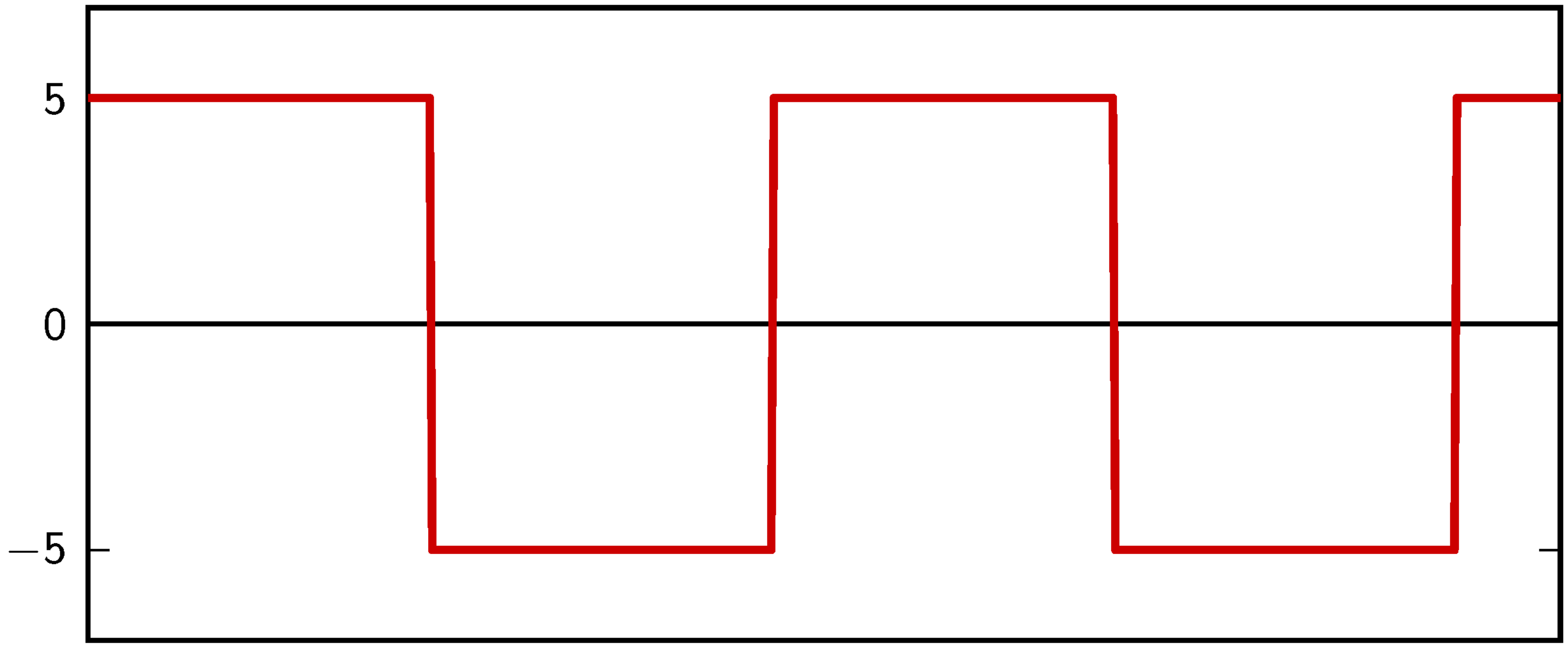
$$x(t)/G + \sigma(t)$$

Transmission of quantized signals



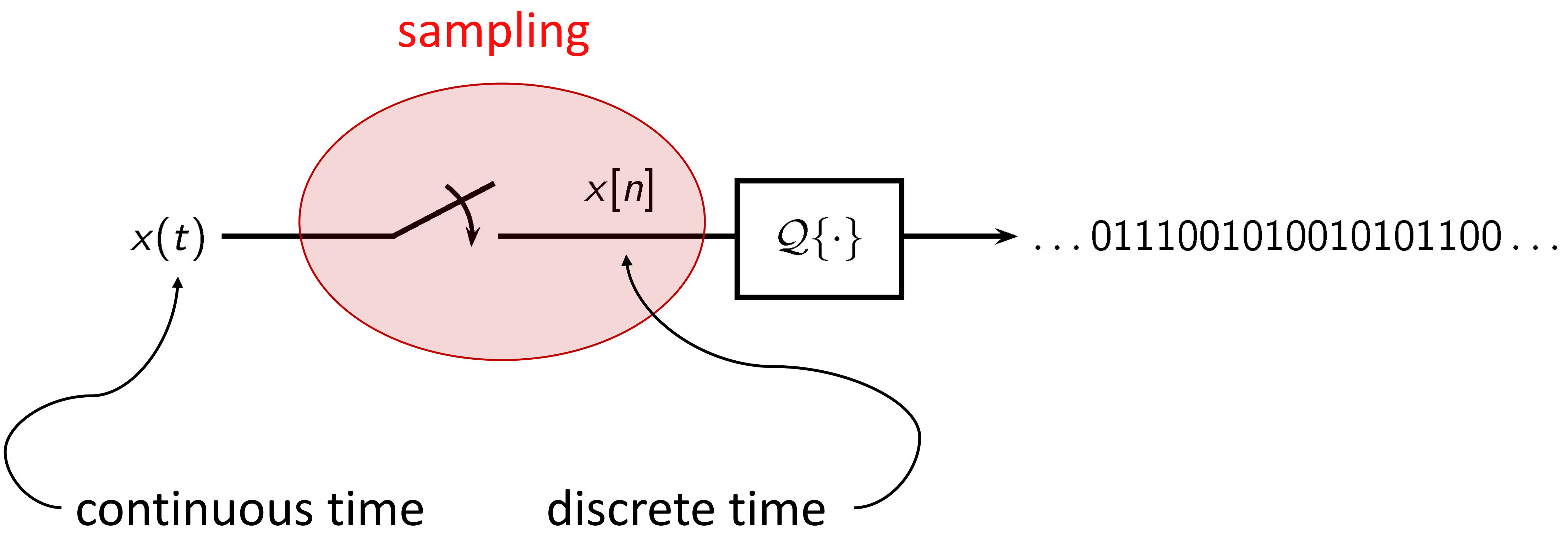
$$G[x(t)/G + \sigma(t)] = x(t) + G\sigma(t)$$

Transmission of quantized signals

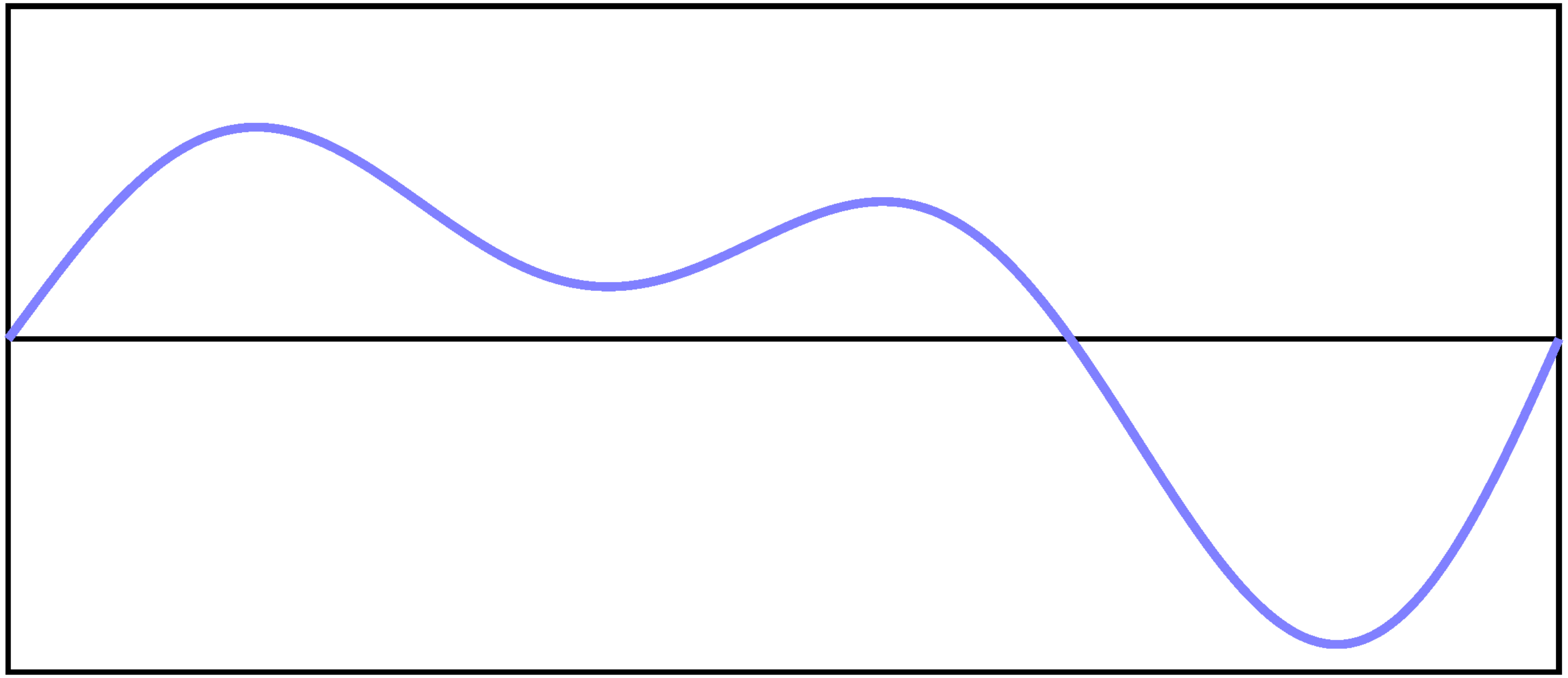


$$\hat{x}_1(t) = 5\,\mathrm{sgn}[x(t) + G\sigma(t)]$$

Pulse Code Modulation (PCM)

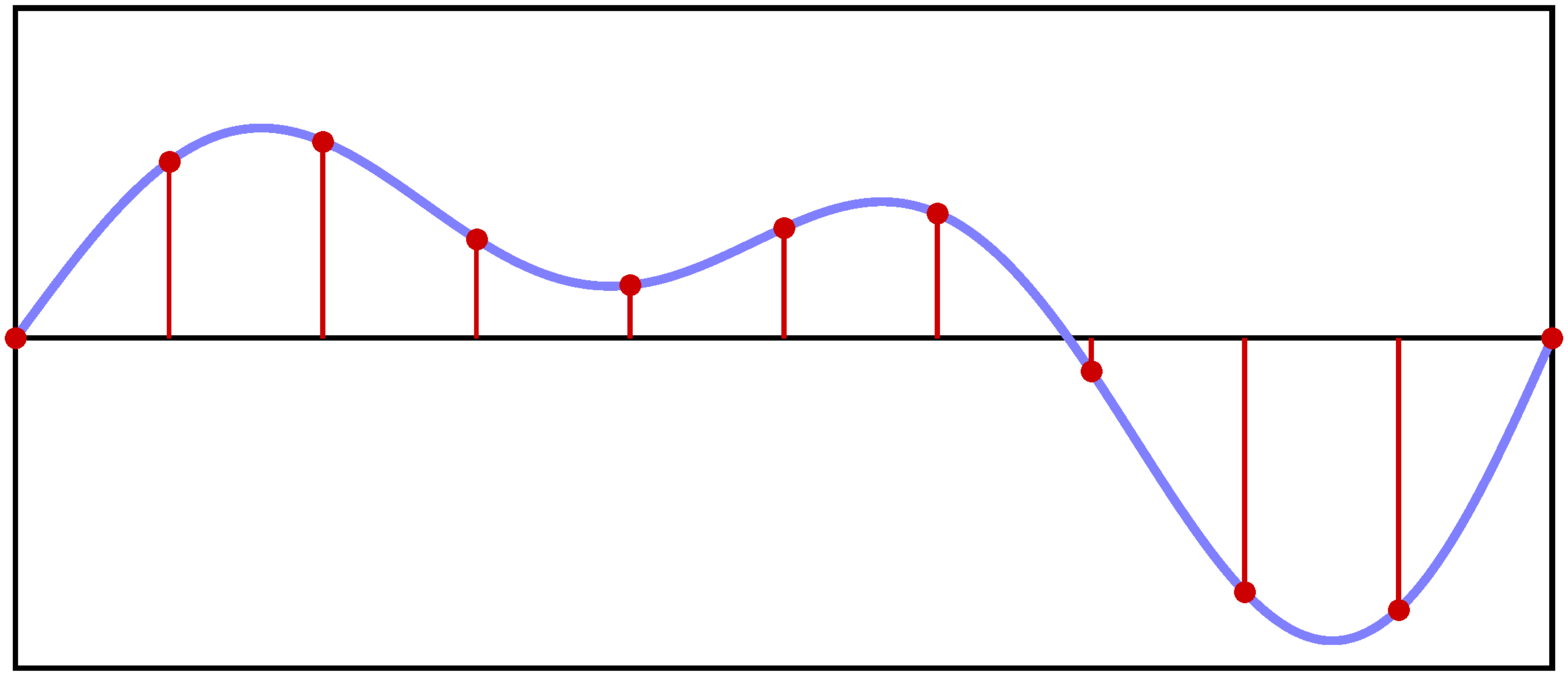


From continuous time to discrete time

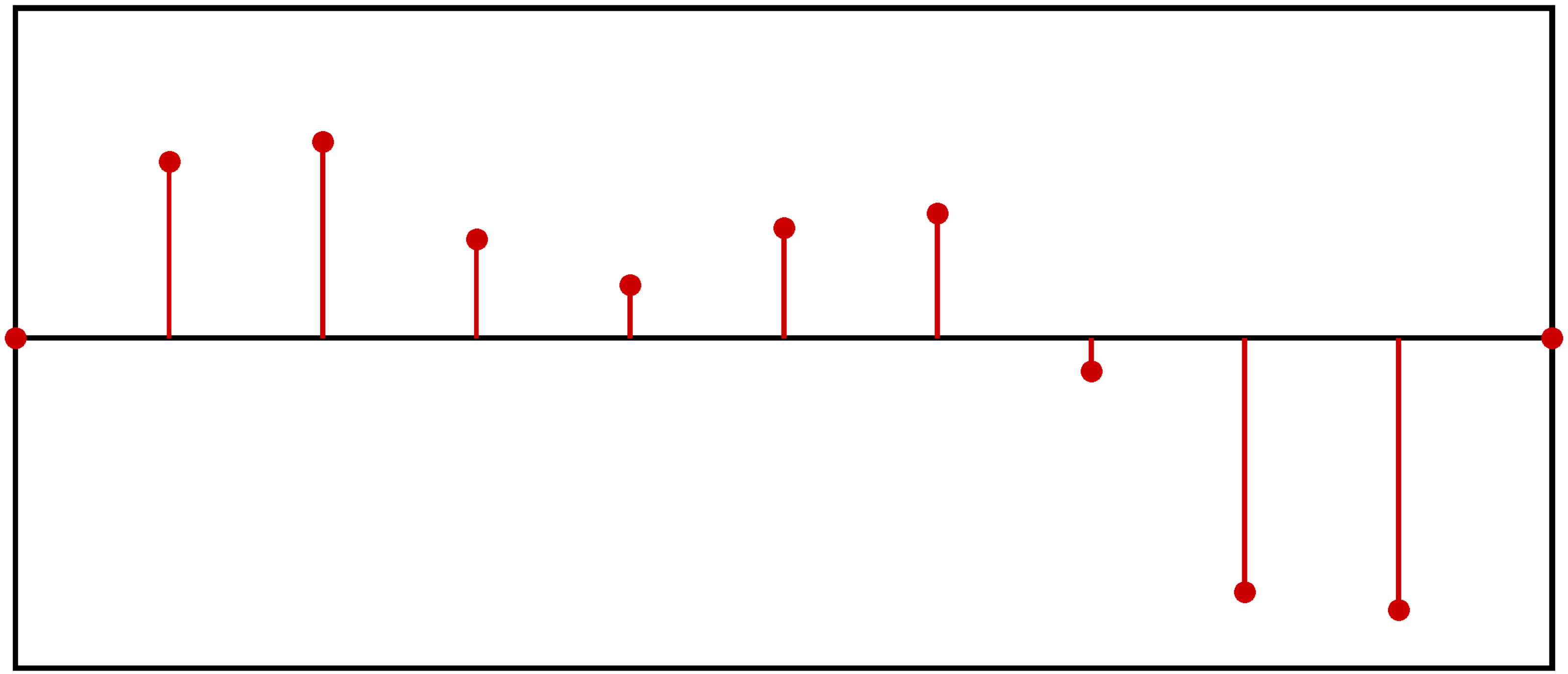


$x(t)$

From continuous time to discrete time



From continuous time to discrete time



$x[n]$

Discrete-time signals are just arrays of numbers

$$x[n] = \ldots, 1.2390, -0.7372, 0.8987, 0.1798, -1.1501, -0.2642 \ldots$$

(one could say that discrete-time signal processing is "data-driven")

The digital revolution

Digital signals allow us to fully decouple the data from its physical origin

All signals are now the same with respect to:

- storage
- processing
- transmission

The digital revolution: before

The digital revolution: after

$\{0, 1\}$

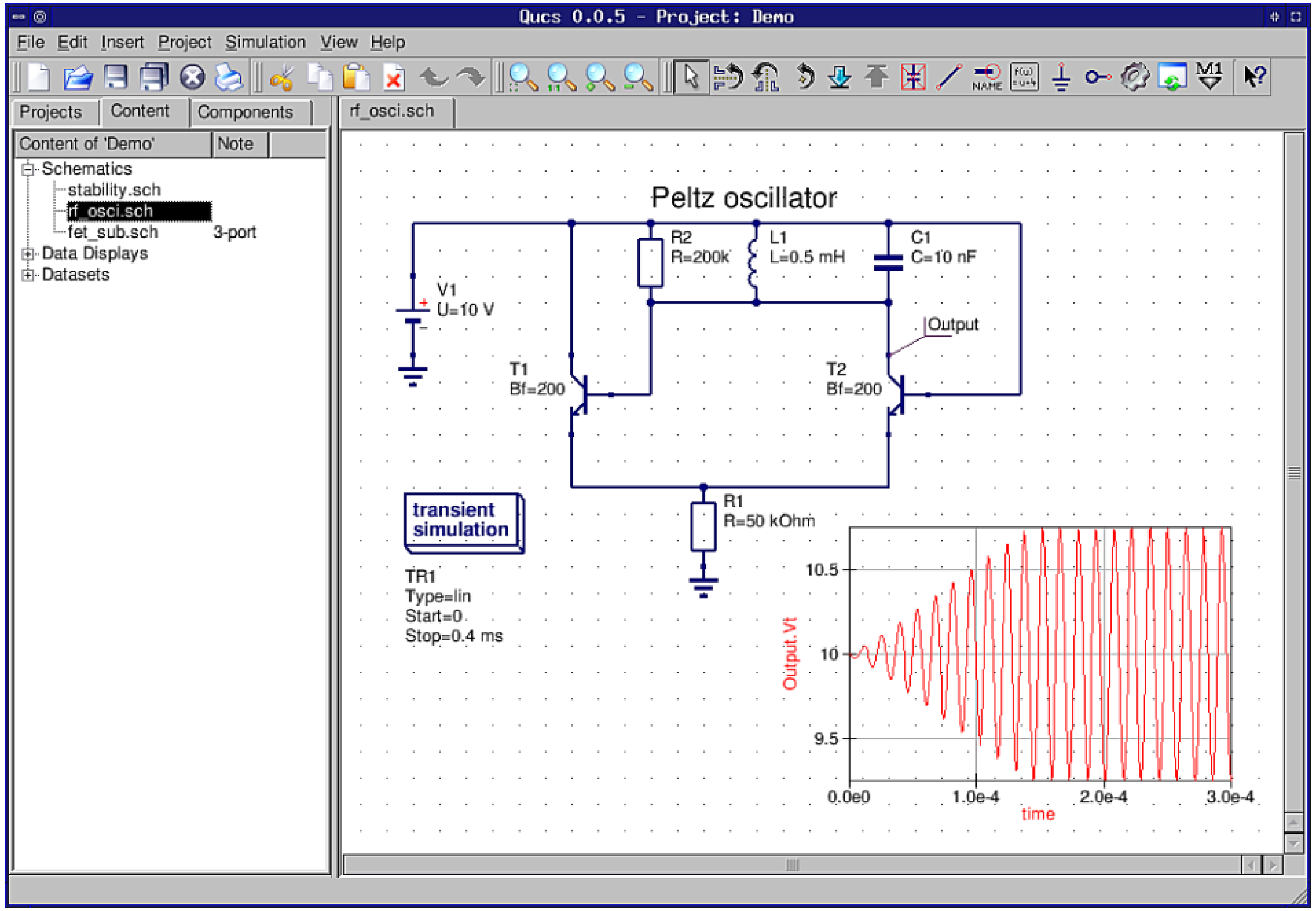
The digital revolution

Digital data resulted in:

- global focus in research
- increased device efficiency
- increased miniaturization
- lower price to consumers

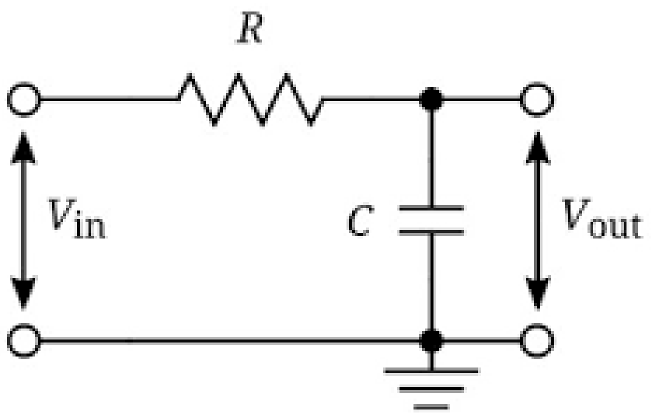
Virtualization: how signal processing became DSP

- classical signal processing focuses on electronic design
- design simulation software started to appear in the 1950s



Virtualization: how signal processing became DSP

- computers became faster and faster
- the simulated circuits became as fast as their physical realizations



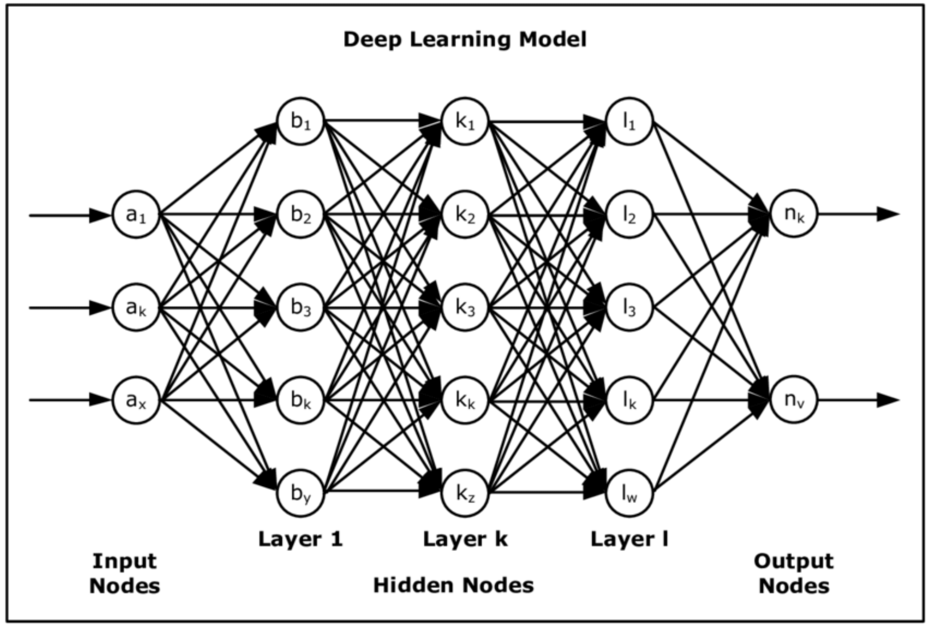

```
y[n] = (1 - t_rc) * x[n] + t_rc * y[n-1]
```

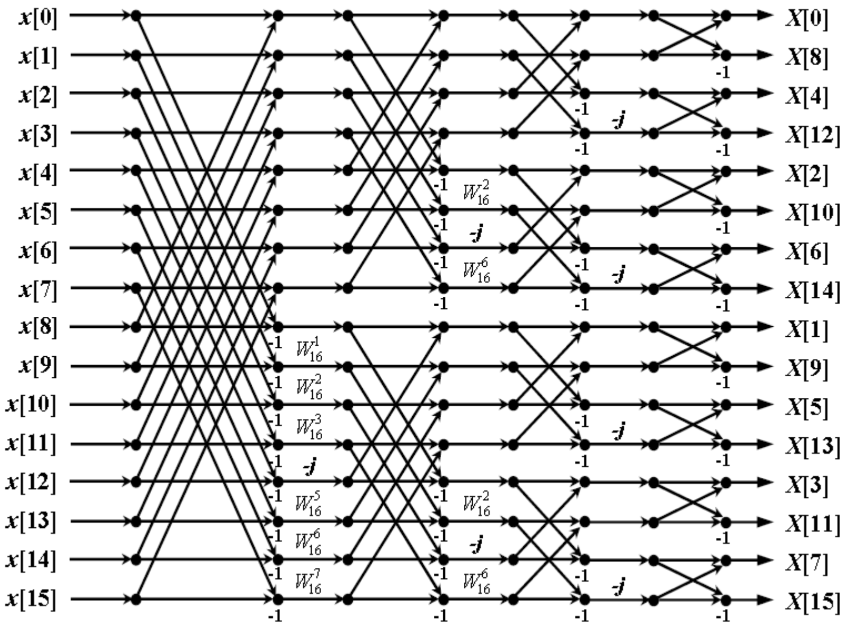
Virtualized processing: the game changers

- general-purpose hardware (e.g. your phone)
- fast algorithms for the Fourier transform (FFT)
  - error correction codes
  - MP3, JPG compression
- synergy between processing and decision logic
  - high-speed internet, media streaming services
  - gaming, VR, robotics
- adaptive signal processing
  - hands-free telephony
  - machine learning, AI

What about AI?

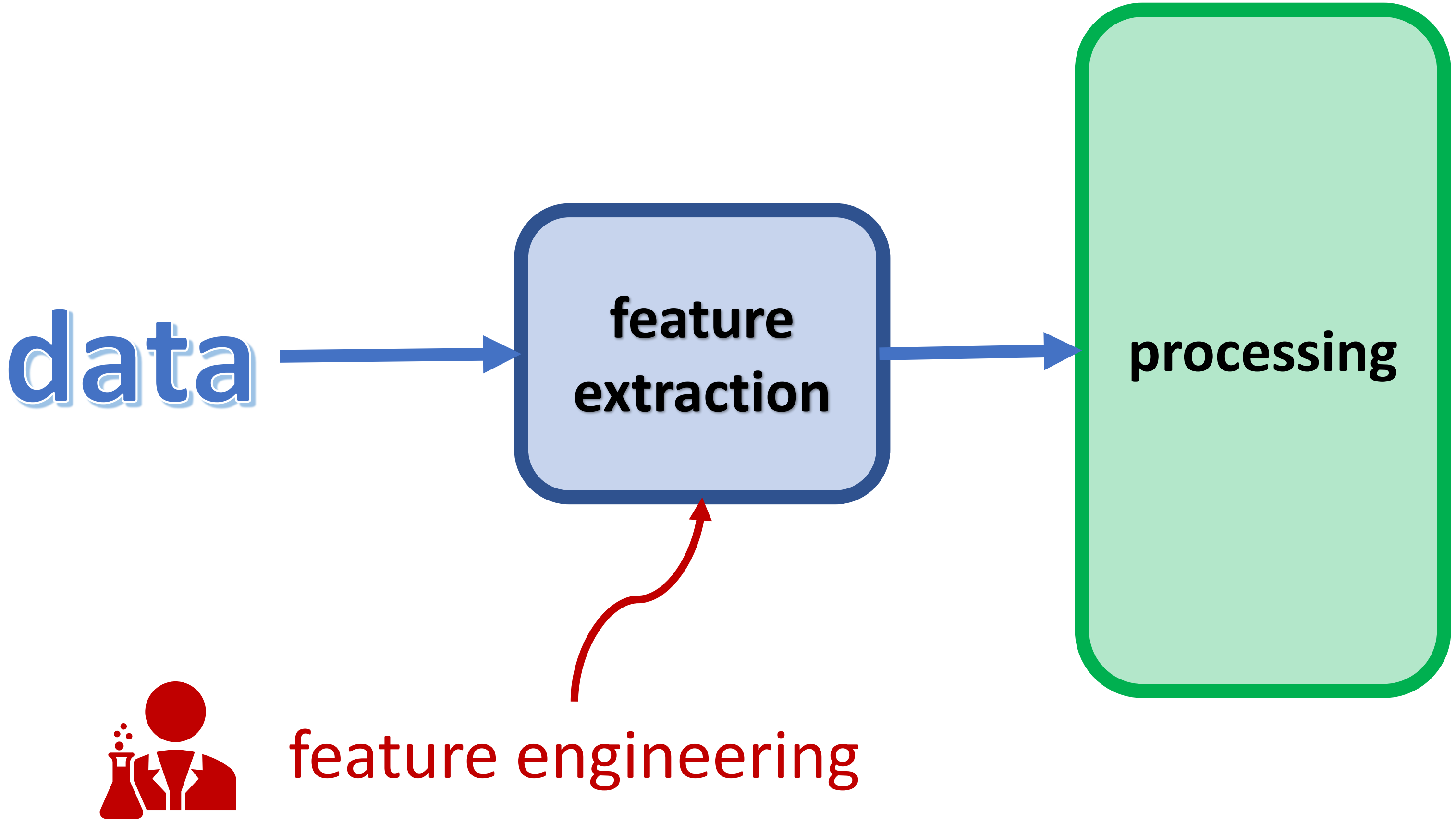
- neural networks *are* signal processing devices!
  - backpropagation was invented in 1960 by B. Widrow, the “father” of LMS
  - deep networks are large, specialized filter banks



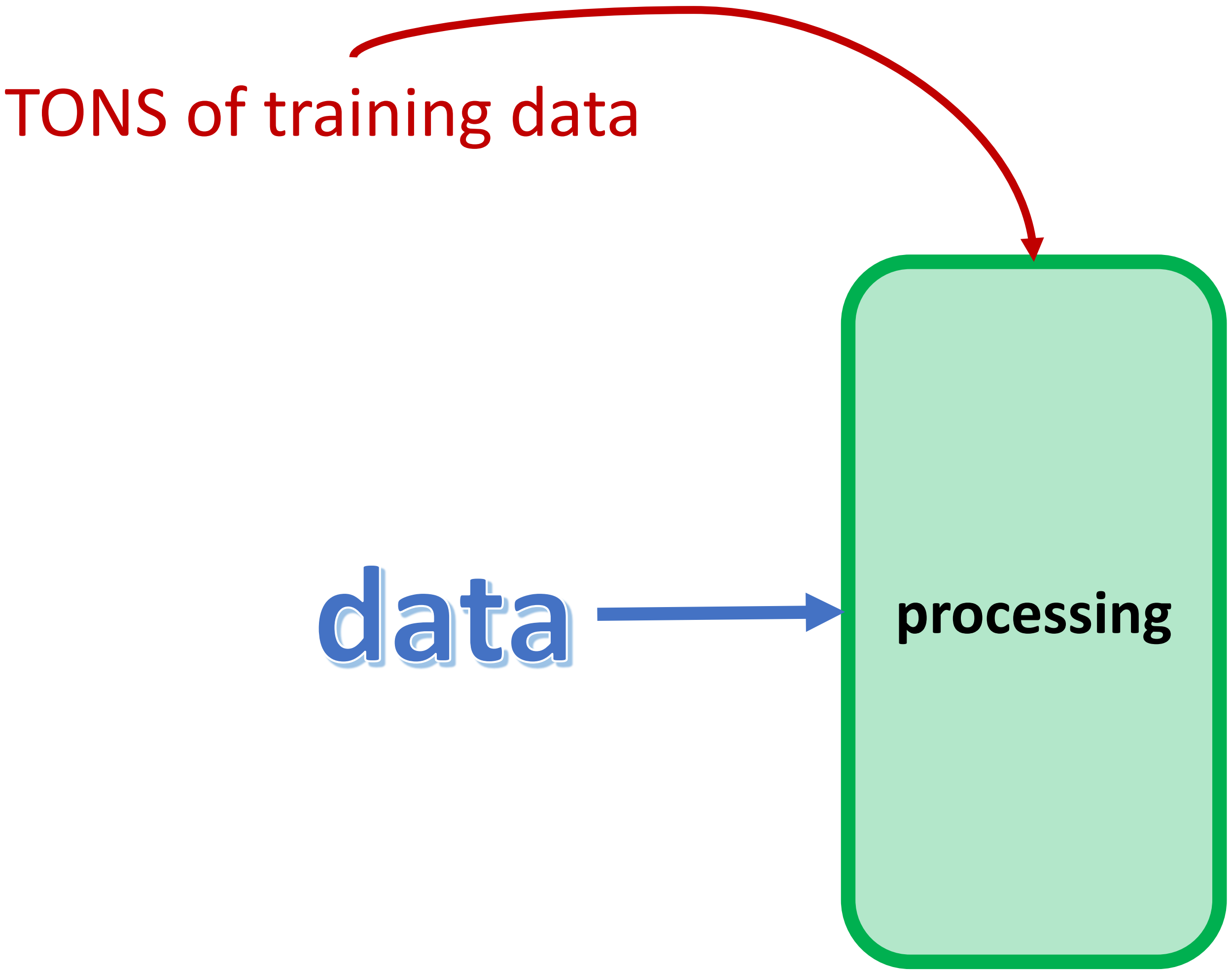


FFT “butterfly” diagram

Key difference between SP and deep learning



Key difference between SP and deep learning



wrapping up...

What you will learn in this class

- the **languages** of signal processing
  - continuous-time models and tools
  - discrete-time models and tools
  - sampling and interpolation

- how to look at signals in the **time** and in the **frequency** domain
  - duality of time and frequency (Fourier transforms)
  - choosing the right domain for the job

- how to **process** and **transform** signals
  - filters, adaptive systems
  - practical processing algorithms

My hopes for all of you, long after this class is a distant memory

you will be listening to some music and you will remember:

- that your music exists both in time and in frequency, and that you know what to look for in a spectrum
- that the tone controls on your music players are filters, and that you used to know how to design one
- that what you are listening to is simply as a sequence of integers, and that the sampling theorem is what allows you to have such an immense audio collection

good luck and try to have fun!