# C Y B E R N E T I C S

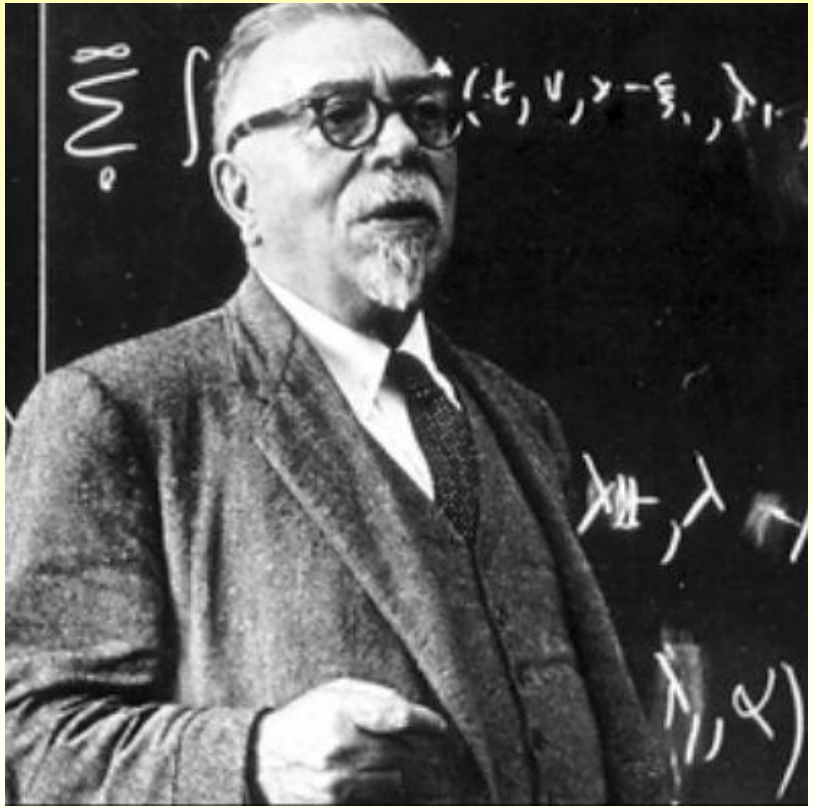
Karel Talavera

# CYBERNETICS

**“The science of communication and control in man and machines”**

***N. Wiener (1894 – 1964)***

**“The science of <u>information processing</u> and control in man and machines”**



## Object of Cybernetics:
## Acquisition, communication, processing and use of information

### Quantification and essence of information

- Data-acquisition (Wiener)
- Communication (Shannon)
- Computation (Turing) and computability (Kolmogorov)

### Use of information

- Control theory (Wiener)
- Application to:
  - machines
  - organisms
  - soft sciences
  - epistemology (meaning of knowledge, Solomonoff)
- Self-organization

# Relation to other sciences

## Metadisciplinary

## Basis

- based on logic
- not based on laws of material sciences

## Frame to order and understand

- all possible machines
- all possibilities of a machine

# Course Content

## Theory and applications

1.- Information theory: information in communication

2.- Control theory: information in regulation and control

3.- Algorithmic information theory: information in computation

# Information in communication:

## Shannon information theory

# Shannon information Theory

Aim:

to provide a mathematical approach to the acquisition and communication of information:

to quantify the minimum average amount of information needed to acquire, transmit or store messages, from a source that generates messages with a certain probability distribution.

# Some questions answered by cybernetics

## Information theory

### Information representation, content and data compression

What is "information" exactly, and can information content be measured?

How many points do you need to accurately reproduce measurements, music, pictures etc. (data representation and compression)?

### Information transmission reliability, speed and noise

How fast can messages be communicated?

Why is it possible to very accurately communicate in the presence of heavy noise?

How many characters in a text can be unreadable before we are unable to get the message?

Why can addition of noise sometimes improve information transmission?

### Information, regularity, variation and aesthetics

What is the relation between information, regularity, variation, complexity and aesthetics?

Can information theory describe the style of Bach's music?

Does Bach's music contain more information than e.g. John Cage or minimalistic music?

### Information coding, transmission, storage in living organisms

# Content

I. INTRODUCTION

II. ENTROPY AND INFORMATION

$$H = -\sum_{i=1}^{n} p_i \log p_i$$

$$I(A;B) = H(B) - H(B|A)$$

III. INFORMATION CONTENT AND SOURCE CODING

$$k = H / \log m$$

IV. INFORMATION TRANSMISSION

$$C = L \max I(Y;X) = L \max \{H(X) - H(X|Y)\}$$

V. INFORMATION IN CONTINUOUS SIGNALS

$$C = W \log (1 + P/N)$$

# Use of information in control and self-organization:

## Control theory

# Some questions answered by cybernetics

## Control theory

### Control feed-forward, feedback and behavior

Why can feedback make systems faster?

### Control and stability

Why can systems become unstable?

### Information, control and behavior

How does information control and regulate processes and behavior
in cells, organs, organisms, communities and societies?

### Information, control and disease

How can our movements be so accurate, even in the presence of external disturbance?
Why do we feel cold when we get a fever?
What has manic depression to do with control theory?
What has learning to do with feedback?

I. DESCRIPTION OF OPEN LOOP SYSTEMS

Transfer function $T = u_2/u_1$

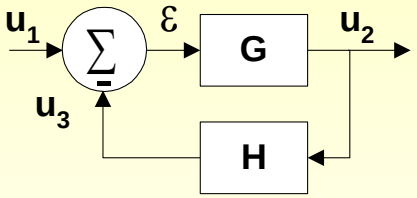
II. SYSTEM ANALYSIS

A. Time domain analysis

B. Frequency domain analysis

Bode diagram and polar diagram

III. ANALYSIS OF CLOSED SYSTEMS




$T = G/(1+GH)$

IV. STABILITY OF CLOSED SYSTEMS

Nyquist stability criterion

V. PRACTICAL METHODS

VI. DYNAMICS OF COMPLEX SYSTEMS

# Some questions answered by cybernetics

## Self-organizing systems

### Order and chaos, determinism and predictability

Why can order be spontaneously generated?

What is chaos? Why is "deterministic" not equivalent to "predictable"?

### Information, coding and fractals

How long is the coast of Great Britain (fractals)?

How can our DNA contain enough information to specify our complete body structure?

Does DNA of adapted species encode environmental information?

### Information networks and life

How can complex networks of interacting processes give rise to life?

### Self-organisation, evolution, game theory and cooperativity

Why is trying to be better than your opponent not always the best long term strategy?

How can cooperativity spontaneously develop in purely egocentric community (evolution)?

# Information in Computation:

Algorithmic Information Theory
(Algorithmic complexity theory
Kolmogorov complexity theory
Resource-bounded complexity)

# Applications

# Examples of applications

## Applications of Information Theory

- Neural information processing
  - Capacity of receptors and neurons
  - Stochastic resonance in receptors
  - Information processing and memory and learning
  - Long Term Potentiation
  - Detection of direction of origin of sounds
- Genetic information processing
  - Coding; Capacity; Transmission; Error correction.
- Immunological information processing
  - Recognition; Clonal selection; Diversity.
- Computer science: Biomolecular information processing machines
  - The DNA computer
- Simple examples of information technology: coding
  - Compression and storage voice, music, images and data; Telecommunication

# Examples of applications

Applications of Control Theory

Photoreceptors

Cerebral ischemia reflex

Pupil reflex

Muscle spindle and reflex control of posture and movement

Hunger and thirst

Temperature regulation

Mechanisms of homeostasis

# Examples of applications

Applications of self organizing systems

Natural selection in evolution

The emergence of cooperativity

# Toledo site

## Cybernetics H02H5

- Announcements
- Course Information
- Course Documents
  - Course texts
  - Extra
    - Simulations
    - Publications
- Communication

  Discussion Groups
- External Links

  Websites and interesting papers

# Algorithmic Information Theory: Complexity theory

## Complexity theory forms basis of artificial intelligence

Limits of computability

Foundation for theories of model selection

Foundation for theories of prediction

## Complexity theory is formal philosophy of knowledge

Is induction possible or can we only falsify hypotheses (Popper)?

Can we eventually know the "truth"?

Why do we have to choose the simplest hypothesis (Occam)?

What does it mean "understanding some process"?

Is the "whole" the sum of its "parts" ("holism versus "reductionism")?

## Complexity theory is thermodynamics information processing

What is the relation between information and the second law of thermodynamics?

Information entropy = thermodynamic entropy

Reversible computation: What is the theoretical minimum amount of energy dissipated in computations?

INTRODUCTION: COMPUTABILITY.

TURING MACHINES.

COMPLEXITY THEORY AND COMPUTABILITY.

- Introduction: roots of complexity theory
- Description complexity
- Computational complexity
- “Resource-bounded” complexity

INDUCTIVE REASONING.

- What is induction?
- Bayesian theory of inference
- Complexity and induction
- Applications
- Some complexity-related measures

# Examples of applications

## Applications of Algorithmic Information Theory

- Physics
  - Thermodynamic entropy and information and complexity
- Computer science
  - Energy cost of computation
  - Reversible computation
- Biology
  - Information coding in communication by living organisms
- Philosophy: knowledge theory
  - Complexity and induction

# Algorithmic Complexity Theory

Aims to quantify information content of individual 'objects'
and to construct universal description and learning methods.

Essence: defines algorithmic complexity
(as (semi-)measure of information content individual objects)
as the shortest program that can reproduce the data
independent of language.

Based on discovery of existence of 'universal language'

Discovered independently via totally different approaches by
- Ray Solomonoff
  via investigation in epistemology of induction and artificial intelligence
- Andrei Kolmogorov
  via investigation of foundations of probability theory and randomness
- Greg Chaitin
  via investigation in computer science on complexity of algorithms

# Algorithmic Information Theory: Complexity theory

## Description, paradoxes, description length and complexity

What is a "description" exactly?

What is the length of the shortest possible description of a sequence or an object?

Why can some descriptions lead to paradoxes?

## Cause and chance, probability theory and statistics

What is a "cause", and what is "probability"?

What is the relation between information complexity and statistics?

## Computability, Turing machines and Complexity

What are the theoretical limits of what can be computed?

## Induction: model selection and prediction

How to choose the 'optimal' model for a set of data?

How to optimize prediction based on the 'optimal' model?

Since 'optimal' models are only 'semi-computable', how to find the best approximation?

## Machine learning and complexity