



À la Recherche du Temps Perdu

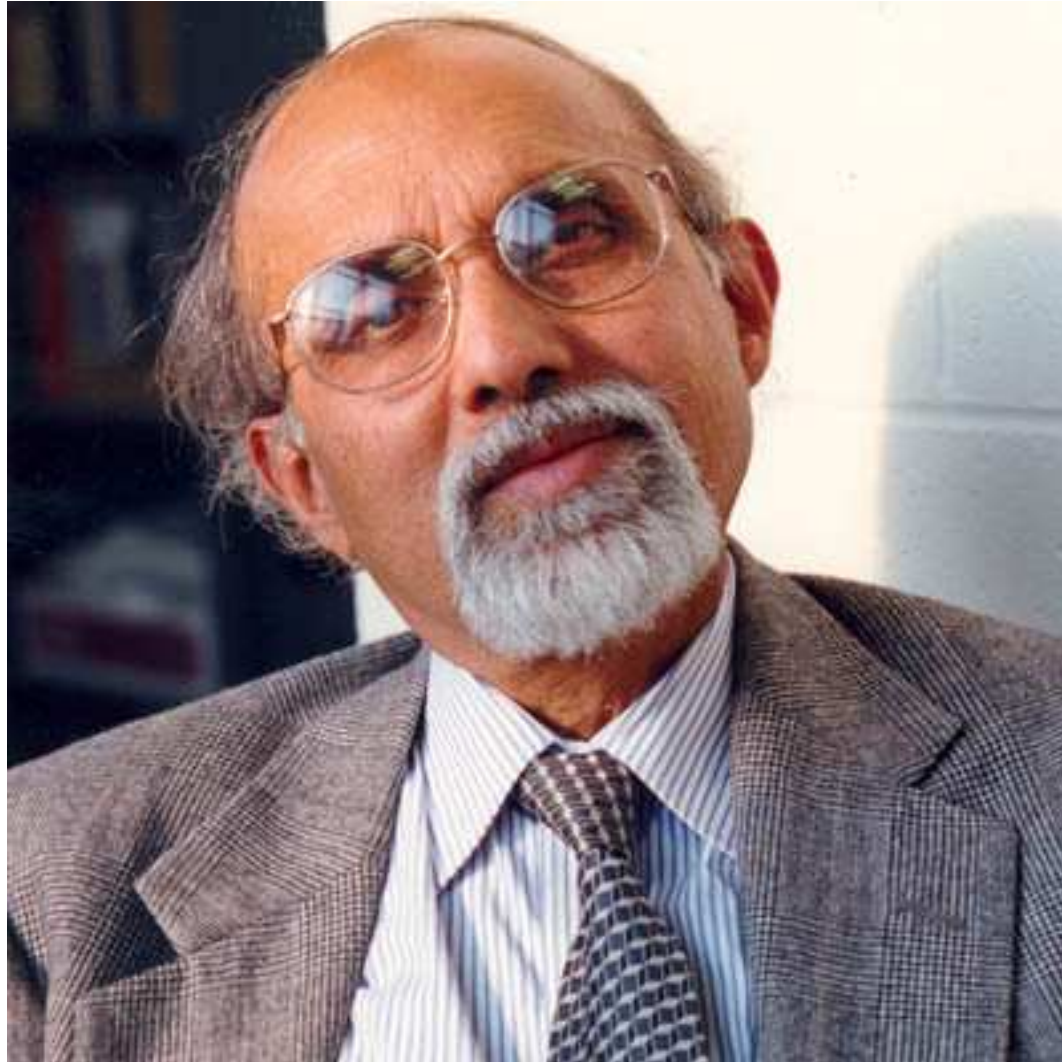
Jan C. Willems
K.U. Leuven



In Search of Time Lost

Jan C. Willems
K.U. Leuven

A tribute to Sanjoy Mitter



on the occasion of his retirement

The MIT EE Control Group — 1970



The MIT Control Group — 1970

Sanjoy Mitter

Mike Athans

Jan Willems



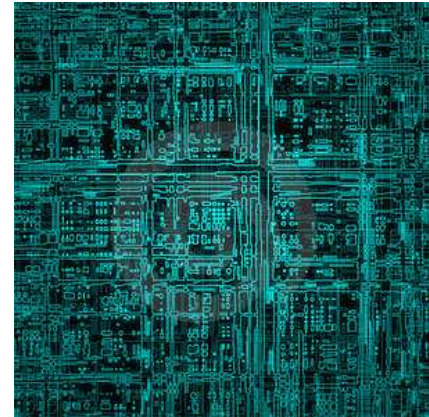
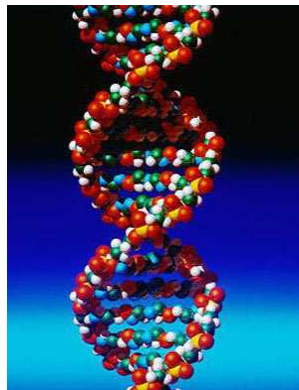
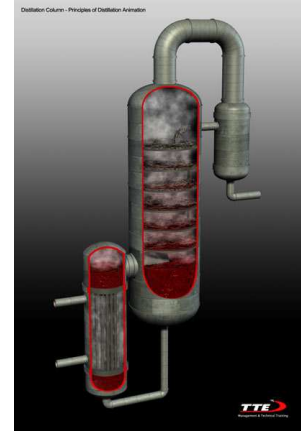
Lenny Gould

Fred Schweppe

SYSTEMS



OIL REFINERY (GVG / PD)



Features

- ▶ **Open**
- ▶ **Interconnected**
- ▶ **Modular**
- ▶ **Dynamic**

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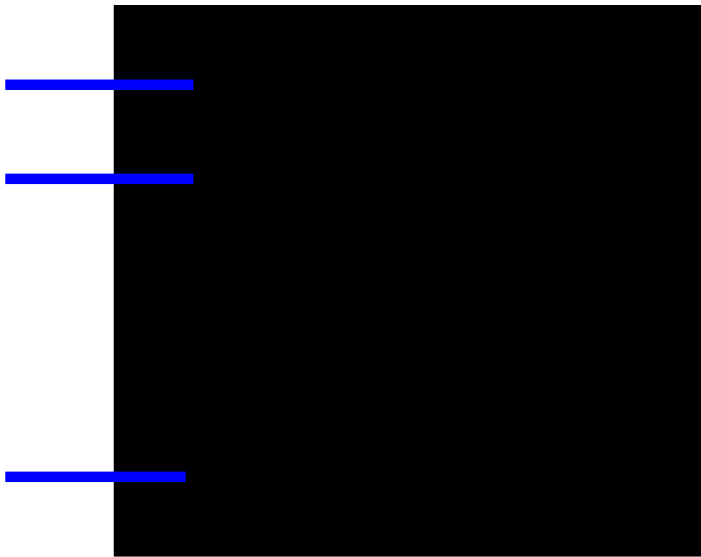
The ever-increasing computing power allows to model complex interconnected systems accurately by tearing, zooming, and linking.

~> **Simulation, model based control,
model based thinking, ...**

TEARING, ZOOMING, and LINKING

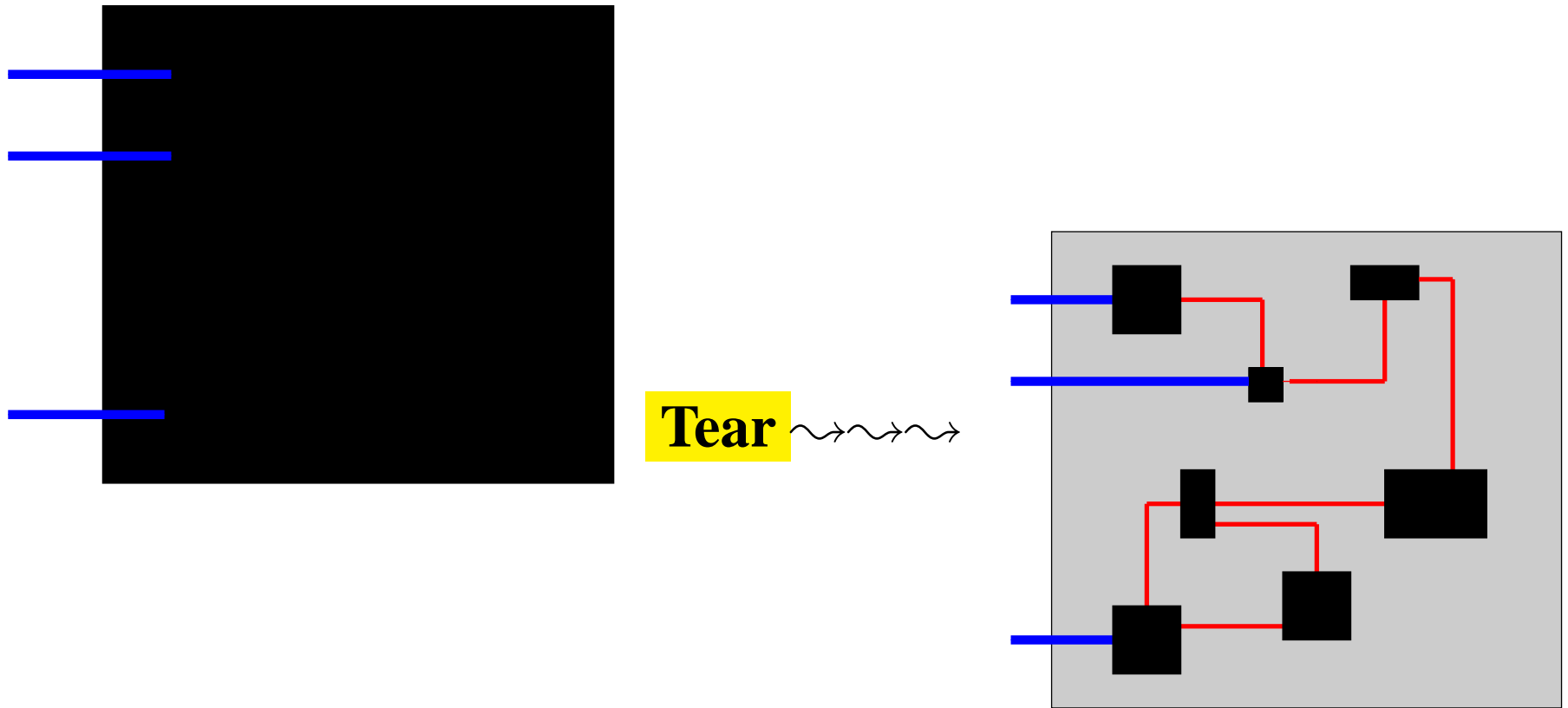
Tearing

∴ Model the behavior of selected variables !!

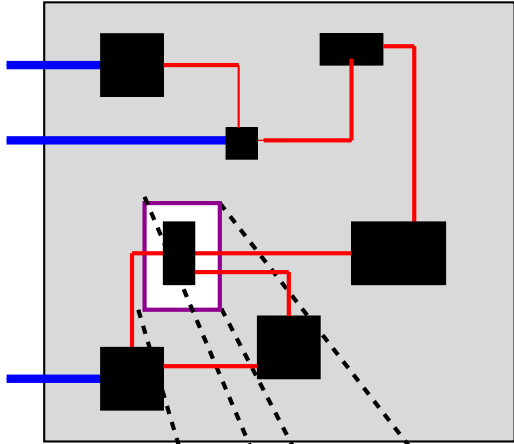


Tearing

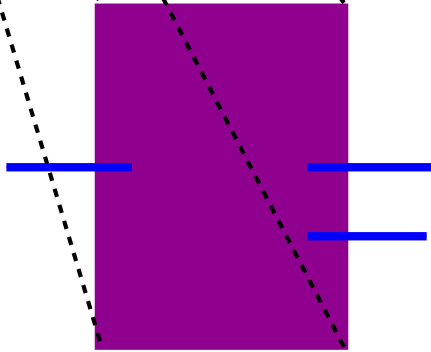
∴ Model the behavior of selected variables !!



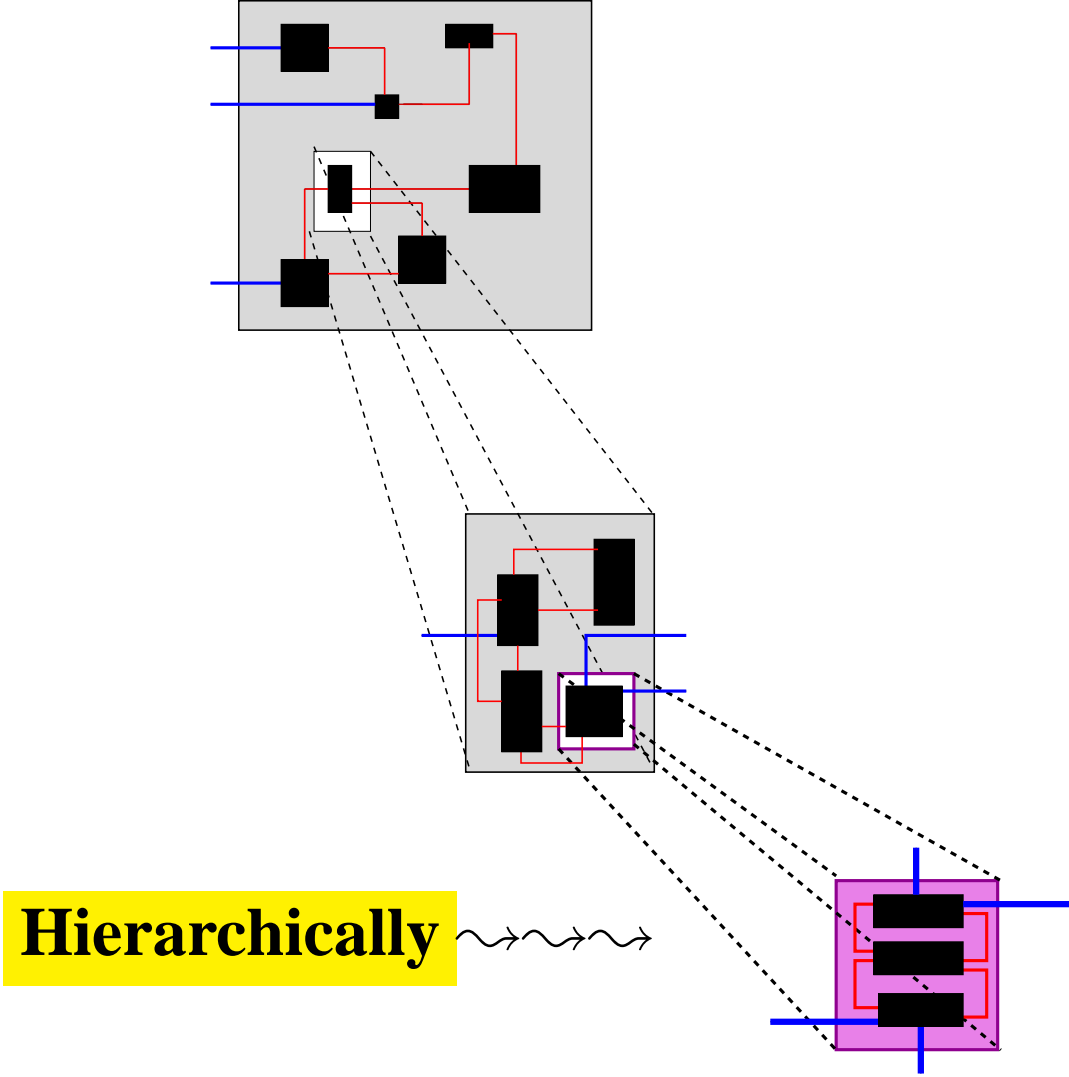
Zooming



Zoom →



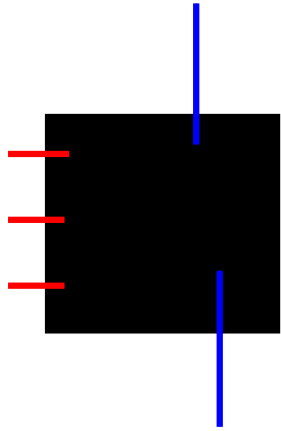
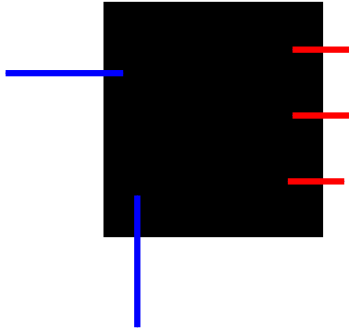
Zooming



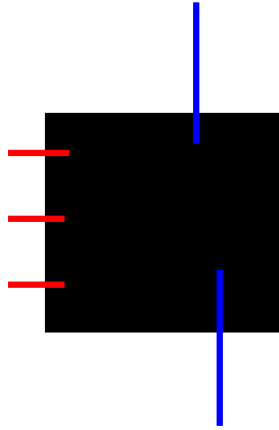
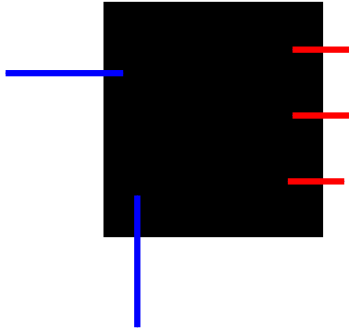
Hierarchically →

Proceed until subsystems (‘modularity’) are obtained whose model is known, from first principles, or stored in a database.

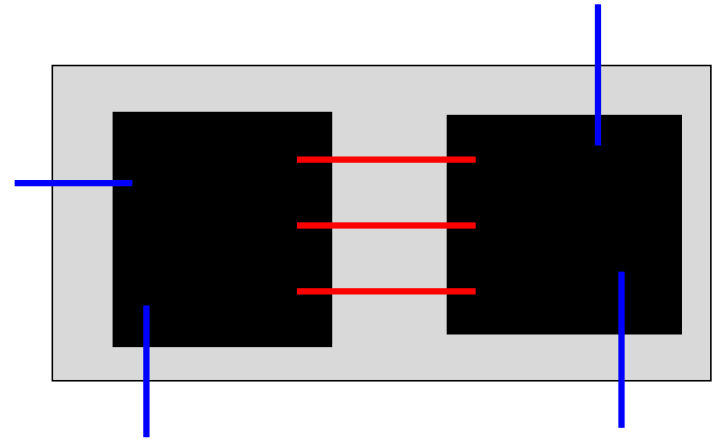
Linking



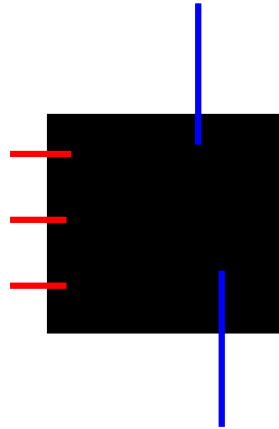
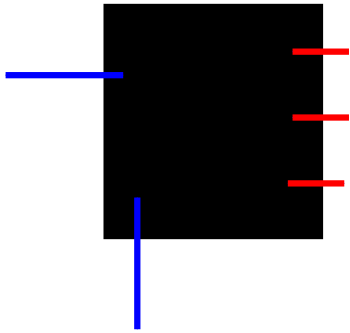
Linking



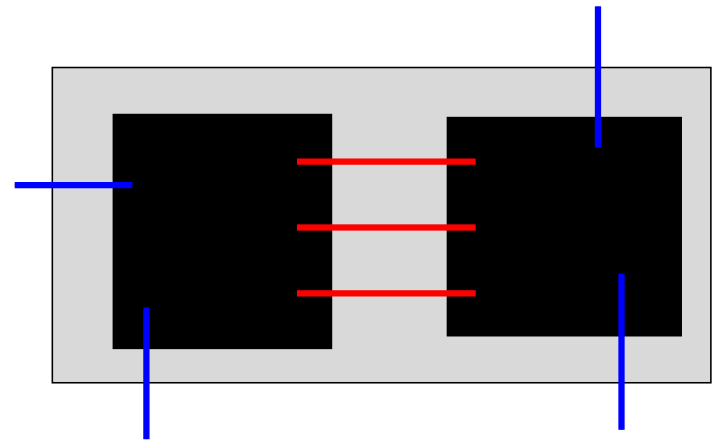
Link ~~~~~>



Linking



Link ~~~~~>



Tearing, zooming, and linking

~> **computer assisted modeling**

& 'Paths Ahead'

OPEN and CONNECTED

Accurate modeling requires

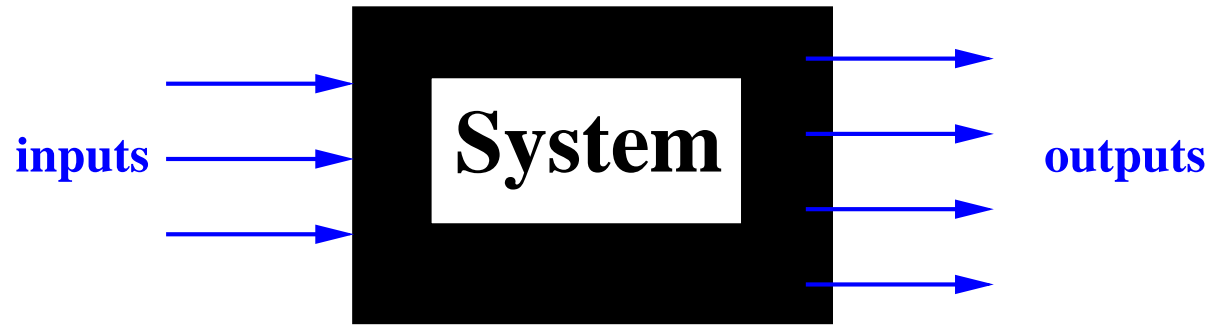
- 1. The right concepts for describing open (physical) systems**
- 2. The right concepts for describing (physical) interconnections**

Accurate modeling requires

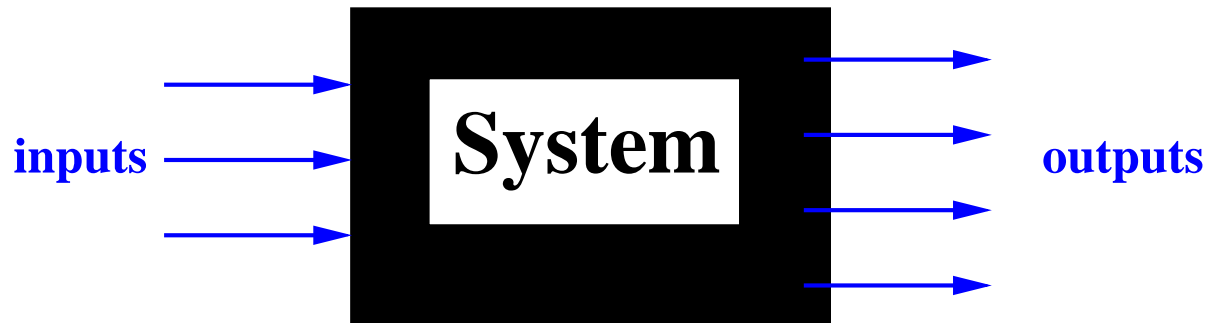
- 1. The right concepts for describing open (physical) systems**
- 2. The right concepts for describing (physical) interconnections**

Did we, system theorists, get the physics right?

Input/output systems



Input/output systems

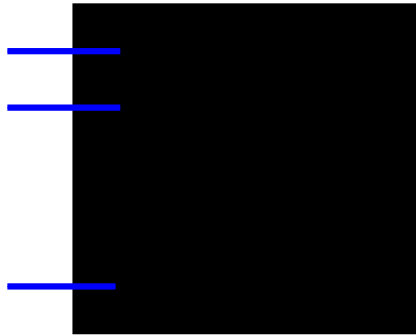


Input/output thinking is **inappropriate** for modeling physical systems.

A physical system is not a signal processor.

This observation \rightsquigarrow the **behavioral approach** in which an open system is simply viewed as a relation, as a set of constraints...

The basic idea



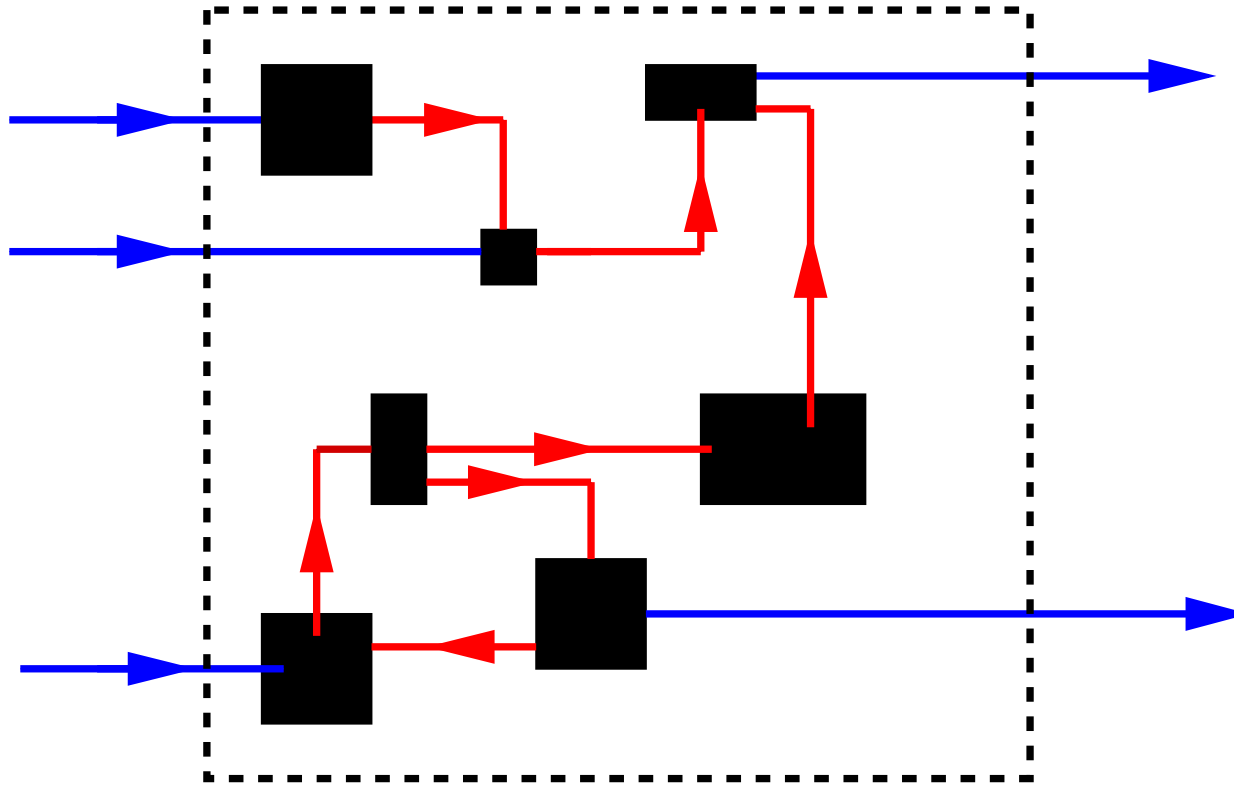
A system interacts with its environment through terminals.
On each terminal, there are **(many)** variables, e.g.

- ▶ voltage and current
- ▶ force and position
- ▶ pressure and mass-flow
- ▶ temperature and heat-flow

The **behavior** := all possible trajectories of these variables.

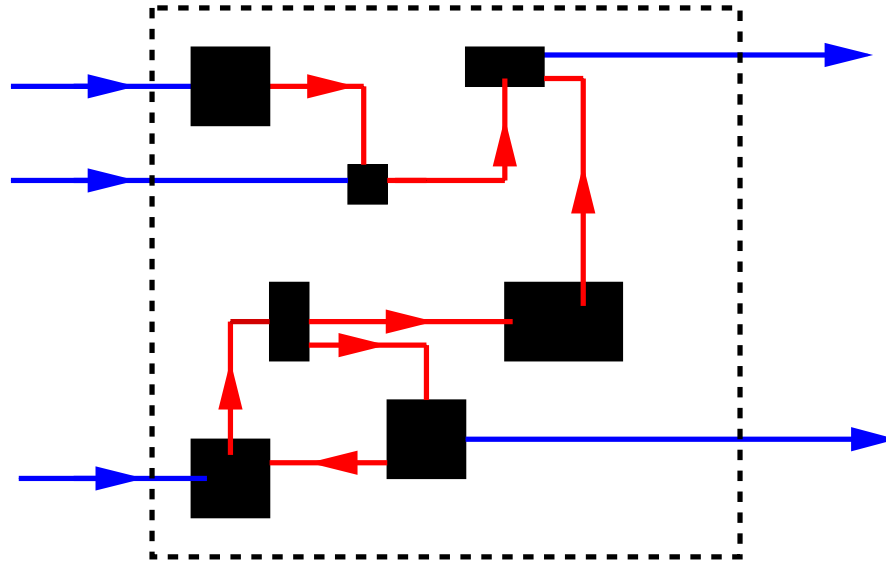
Signal flow graphs

View interconnected systems in terms of signal flow graphs:



Interconnection is viewed as output-to-input assignment.

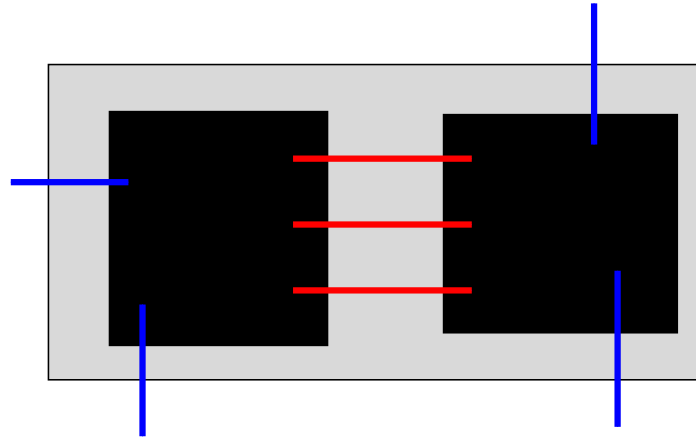
Signal flow graphs



Not appropriate for describing interconnected physical systems.

A physical system is not a signal processor.

Sharing variables



Linking means equating the variables that ‘live’ on the interconnected terminals.

$$V_N = V_{N'} \quad \text{and} \quad I_N + I_{N'} = 0$$

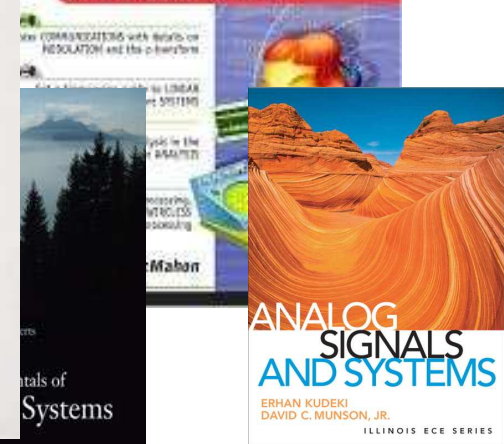
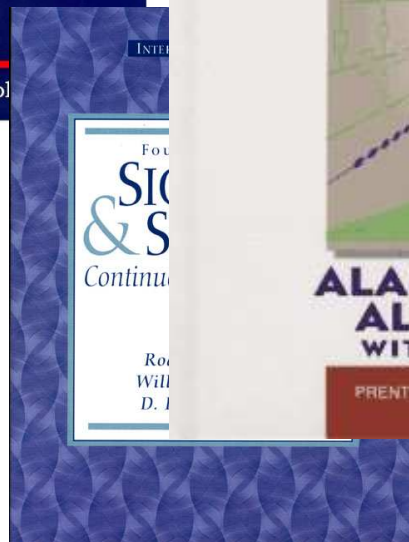
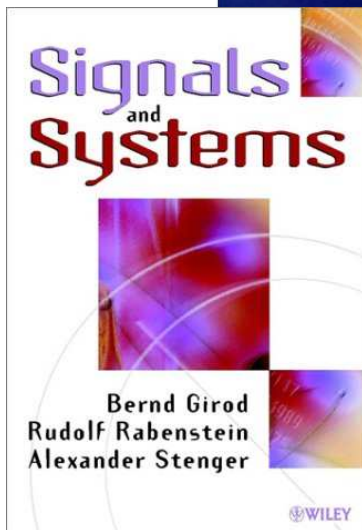
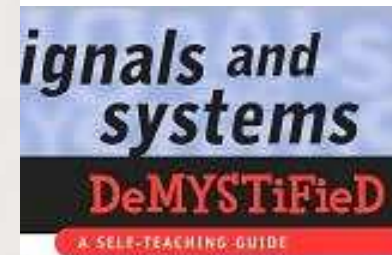
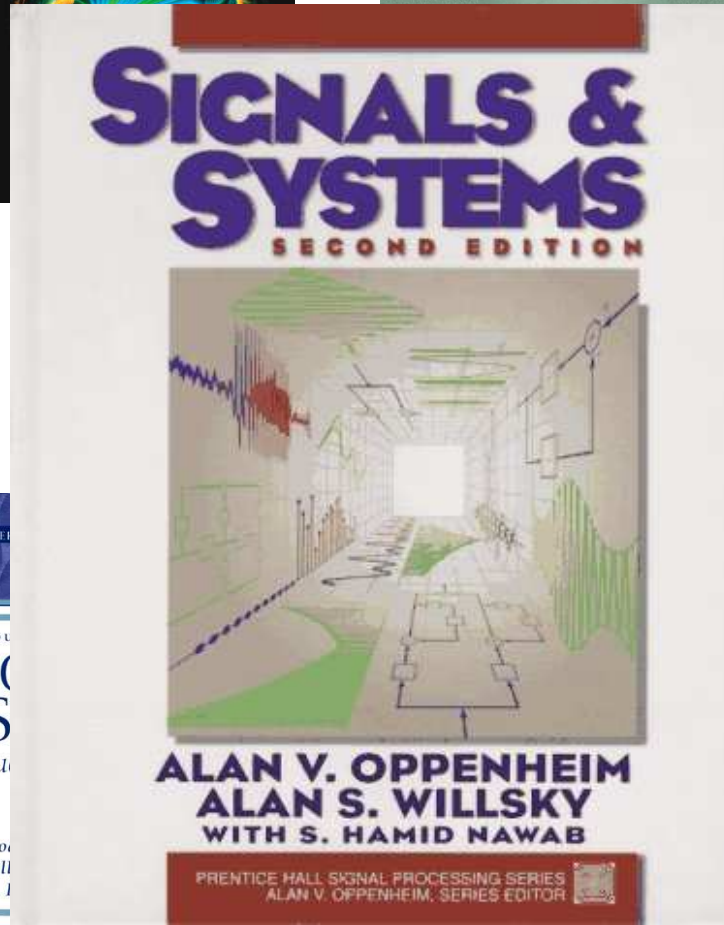
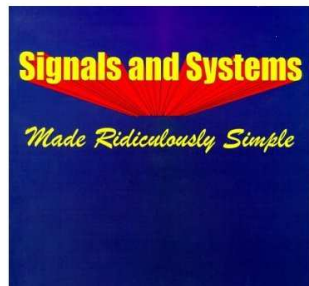
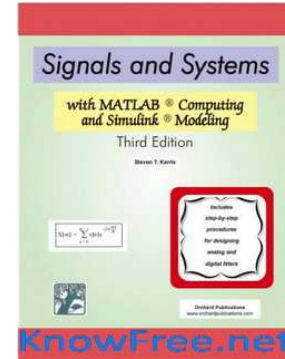
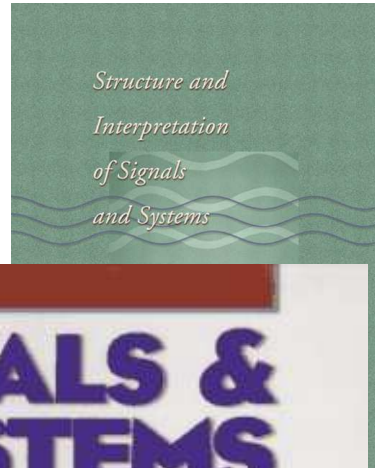
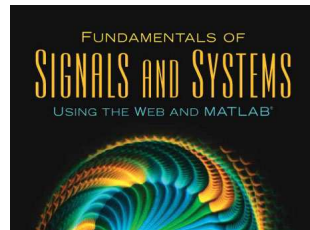
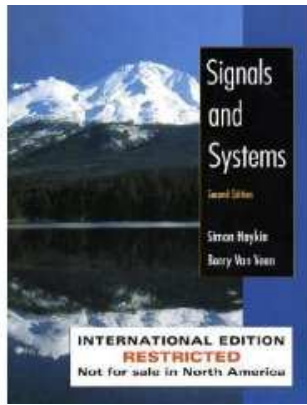
$$q_N = q_{N'} \quad \text{and} \quad F_N + F_{N'} = 0$$

$$T_N = T_{N'} \quad \text{and} \quad Q_N + Q_{N'} = 0$$

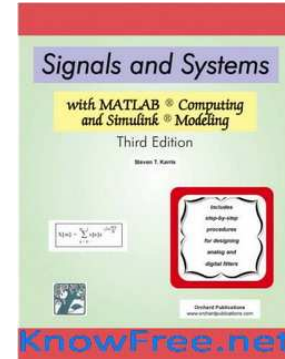
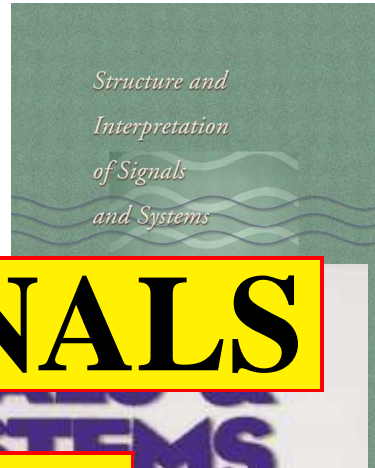
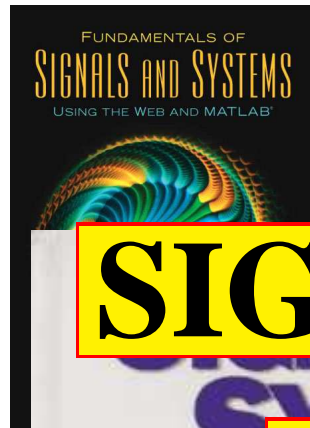
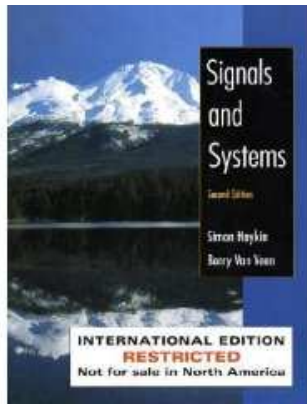
$$p_N = p_{N'} \quad \text{and} \quad f_N + f_{N'} = 0$$

Interconnection = variable sharing.

Favorite textbooks



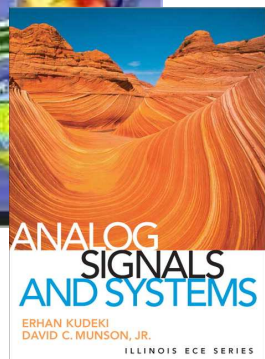
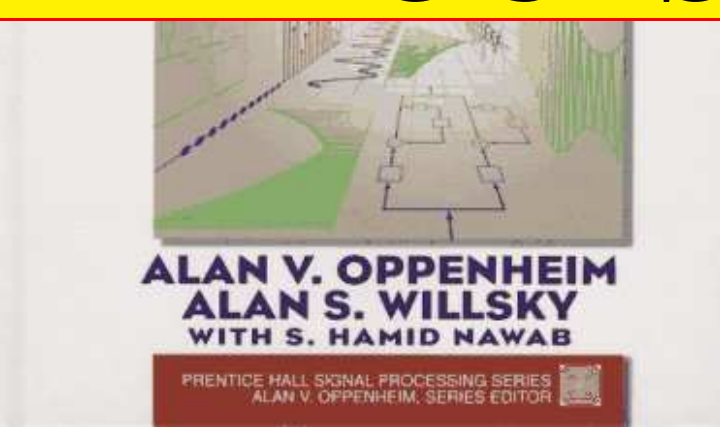
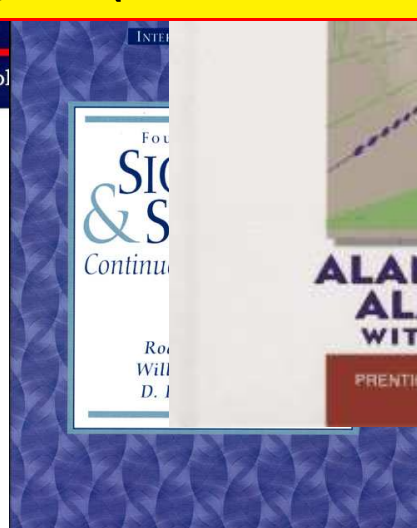
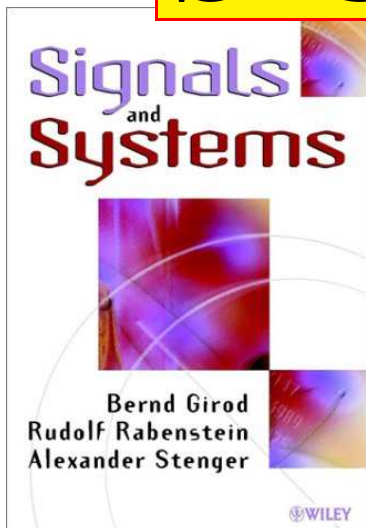
Favorite textbooks



SIGNALS

and

SIGNAL PROCESSORS



**The behavioral approach to open and interconnected systems,
Control Systems Magazine, volume 27, pages 46-99, 2007.**

Copies of the lecture frames will be available from/at

Jan.Willems@esat.kuleuven.be

<http://www.esat.kuleuven.be/~jwillems>

Thank you

Thank you

Thank you

Thank you

Thank you

Thank you

Thank you

Thank you

And, especially, ‘thank you’, Sanjoy

