Tallinn University of Technology, May 2025

TAL TECH

Estonian Doctoral School

“Energy & Systems”

....

Prof. Alain BOUSCAYROL, Prof. Betty LEMAIRE-SEMAIL

L2EP
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Université de Lille

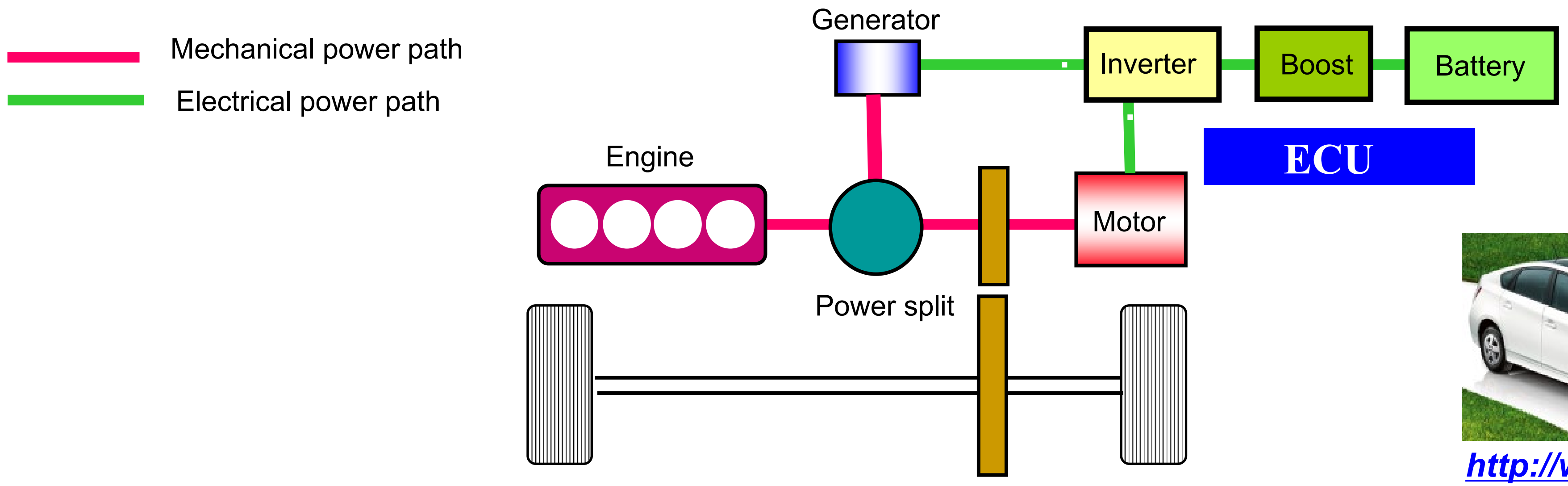
Arts et Métiers Sciences et Technologies

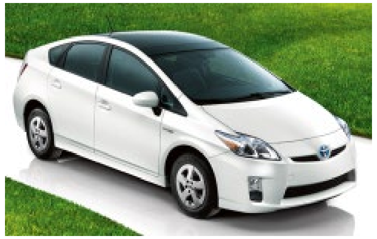
centralelille

JUNIA Grande école d'ingénieurs

Complex multi-physical systems

- More complex systems
  - Hybrid systems … several technologies and operations to combine
  - Example: THS from Toyota (hybrid electric vehicle)





http://www.toyota.com/

How to manage the various power flows?

How to optimise energy consumption?

multi-layer control ?

Complex multi-physical systems

- More efficient systems with same performances
  - New systems for reduction of energy consumption…

    …for higher performances
  - Example: VAL subway (Siemens)

1984 – VAL 206
First automatic subway

position accuracy

2000 – VAL 208
new PM machines

loss reduction

201x – NeoVAL
new supply system

more energy recovery

How to ensure high dynamical and efficiency?

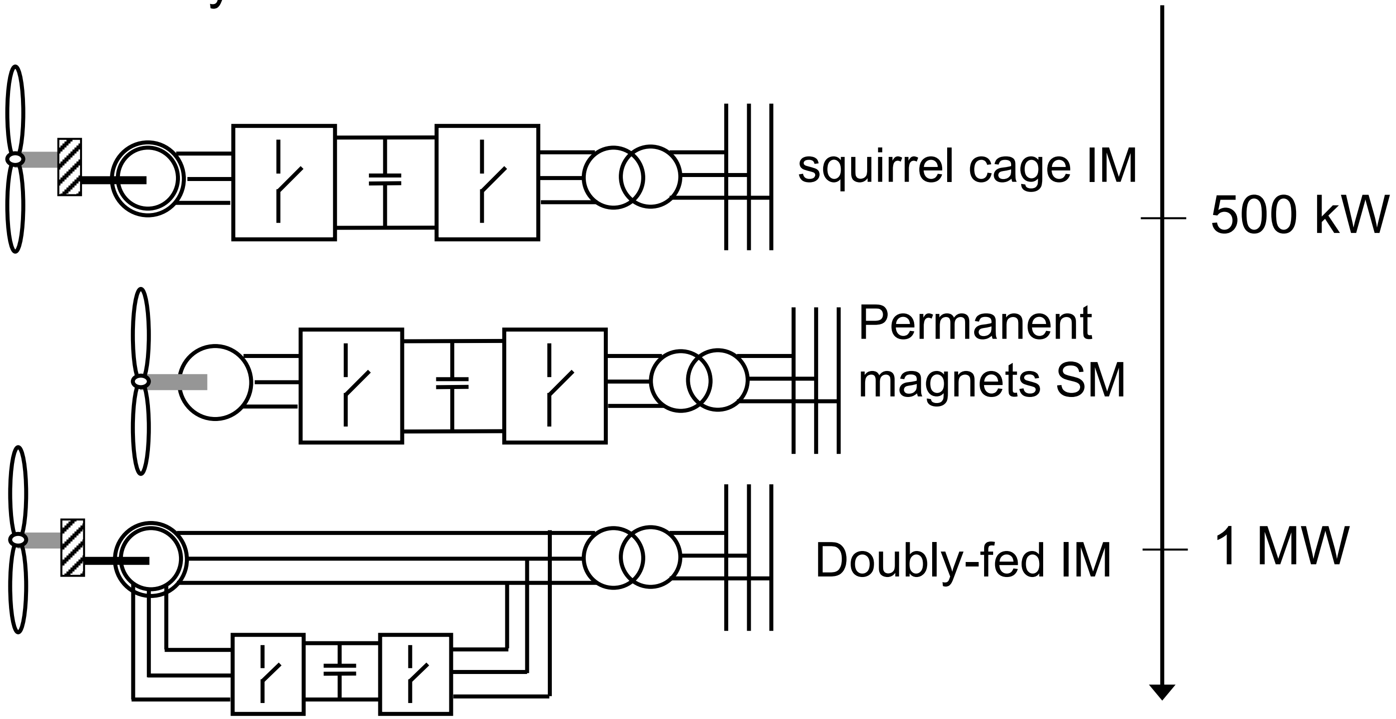
(double objective : dynamics and energy)

multi-objective control ?

Complex multi-physical systems

- More renewable energy conversion systems
    - Different systems for different applications and ranges
    - Example: wind energy conversion systems

© 1998 Danish Wind Turbine Manufacturers Association



How to design systems?

How to compare systems?

How to control the different systems?

flexible control?

Complex multi-physical systems

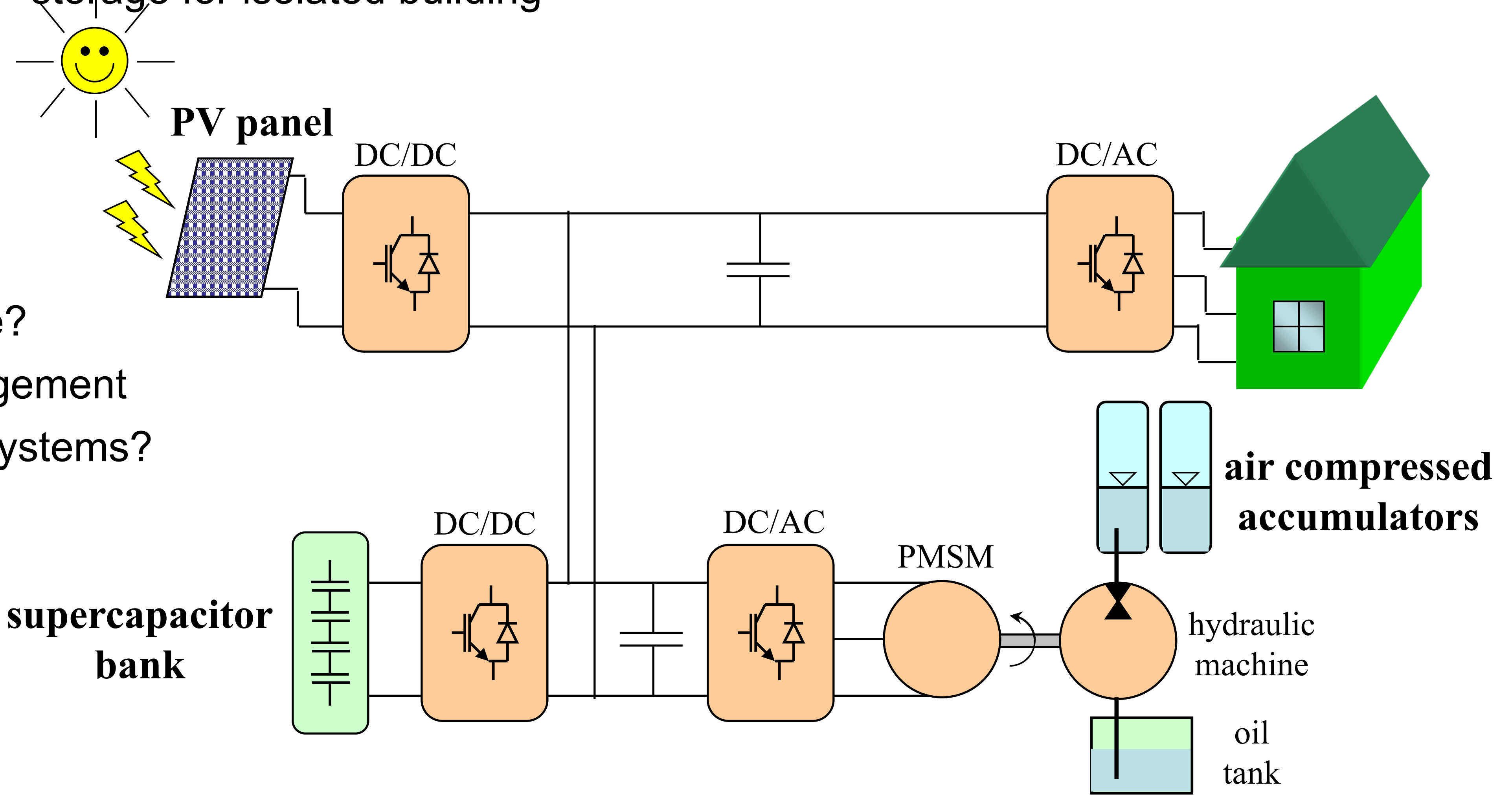
- More flexible supply systems
  - Balanced between generation and load
  - Example of PV + storage for isolated building

[Bossmann & al. 2007]

(Switzerland)

How to design storage?

Optimal energy management between subsystems?

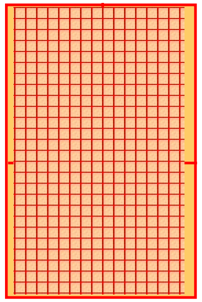


Typical process

Simulation for ever!

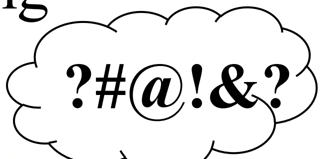
Launching Simulation Software is more and more a “Pavlov reflex”

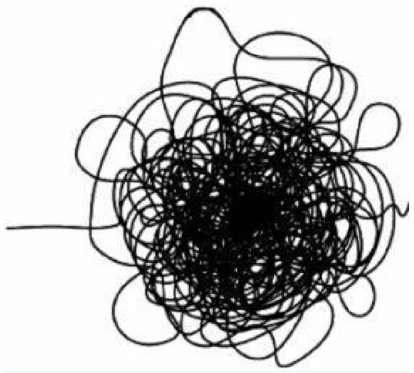
Fast development
with
“copy & paste”



system simulation

Nightmare
for finding
errors





results

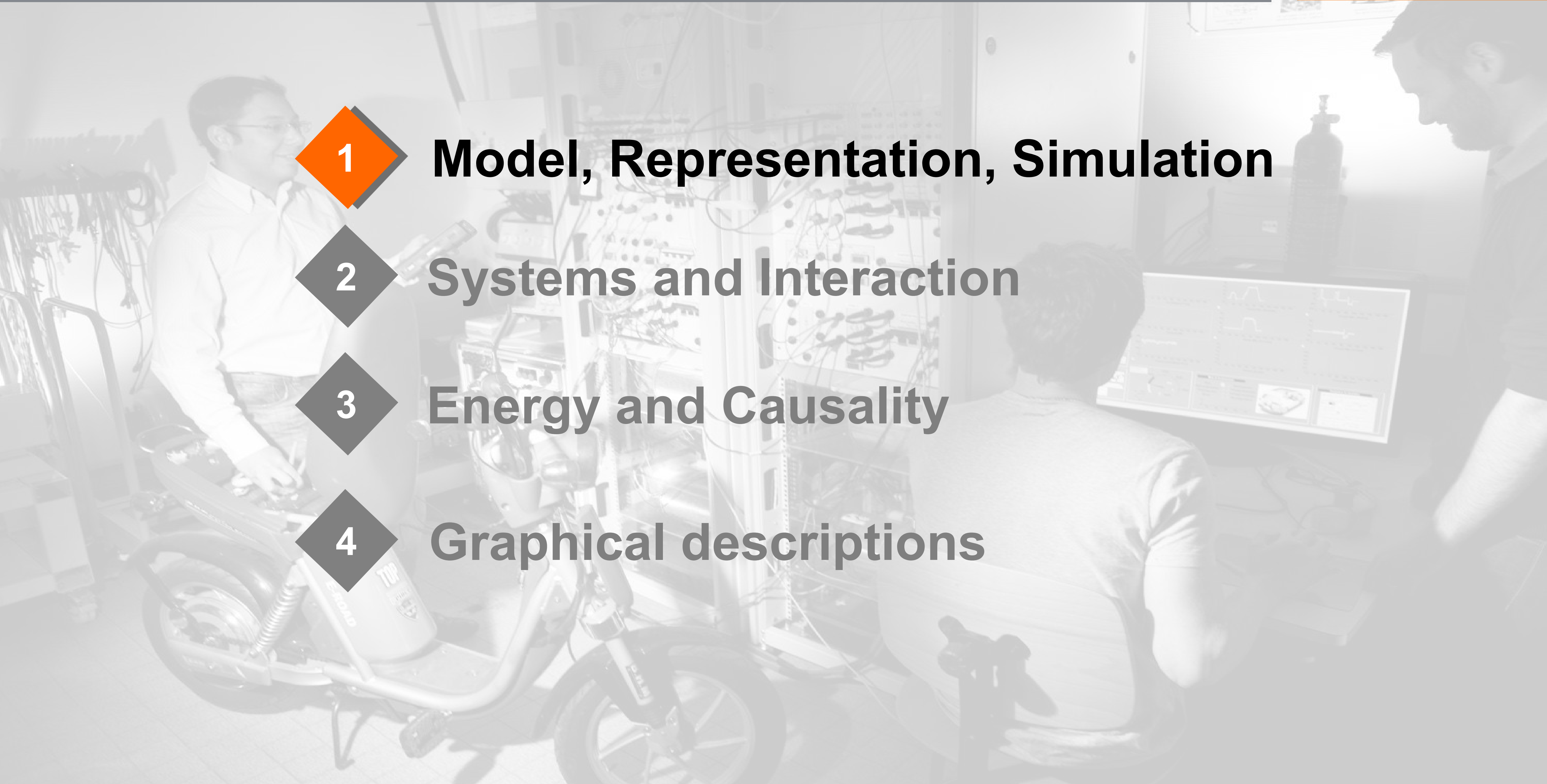
confidence?
accuracy?

1 Model, Representation, Simulation

2 Systems and Interaction

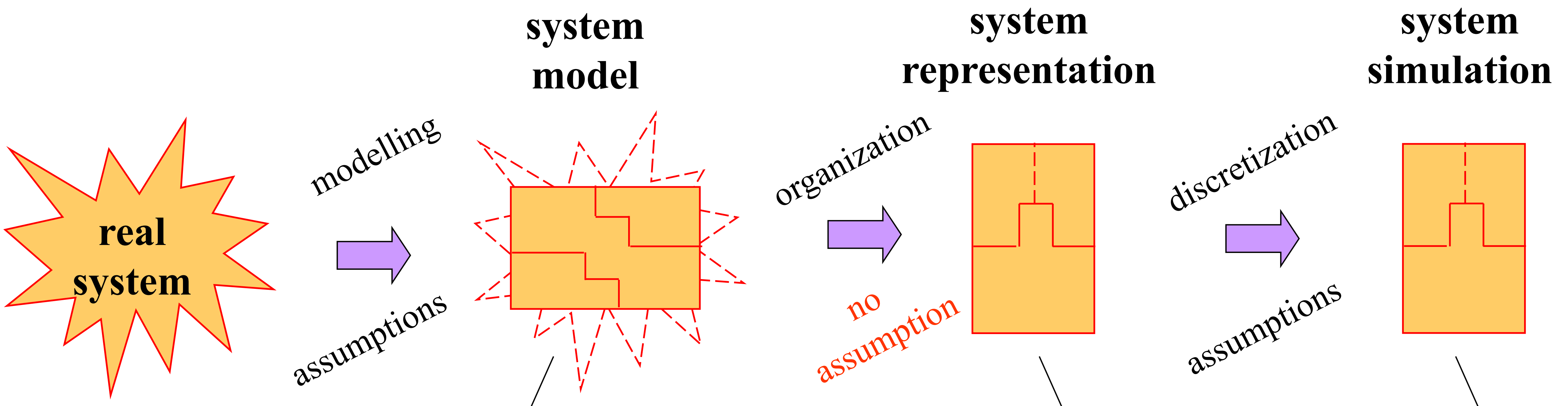
3 Energy and Causality

4 Graphical descriptions



1. **Model, Representation, Simulation**
2. Systems and Interaction
3. Energy and Causality
4. Graphical descriptions

From real system to simulation



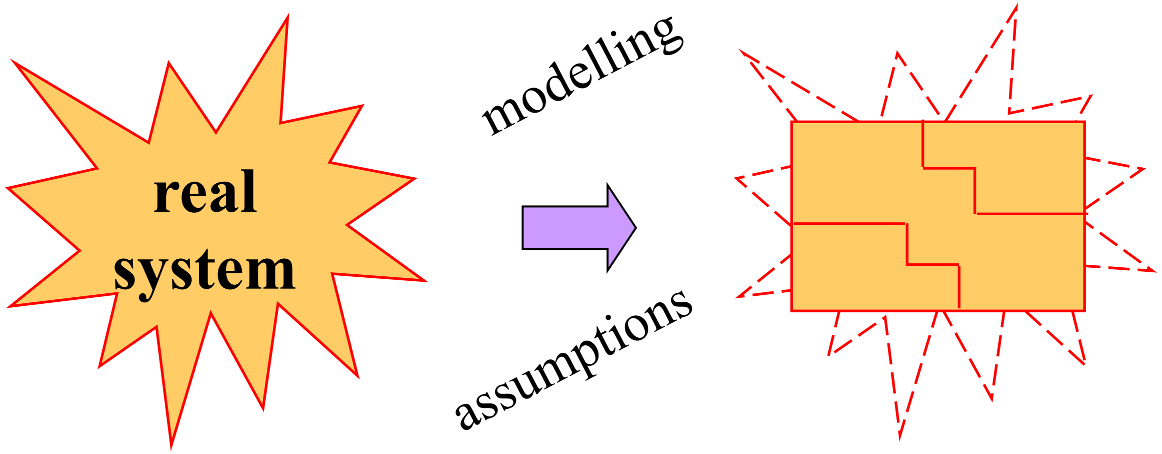
Limitation to main phenomena in function of the objective

Organization of the model to highlight some properties

Prediction of system behavior

Intermediary steps are required for complex systems

Basic example



real system

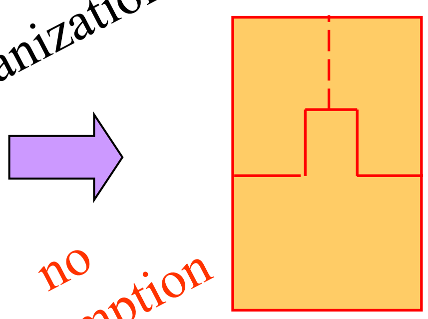
modelling

assumptions

system model

organization

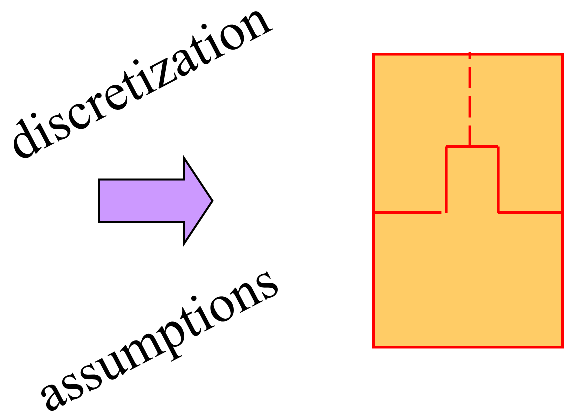
no assumption



system representation

discretization

assumptions

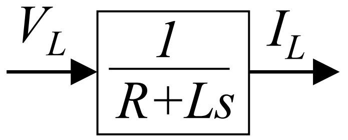


system simulation

smoothing inductor

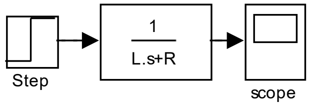
$$v_l = L\frac{d}{dt}i_L + Ri_L$$

(low frequency dynamical model)



$$V_L \rightarrow \boxed{\frac{1}{R+Ls}} \rightarrow I_L$$

(bloc diagram +Laplace)



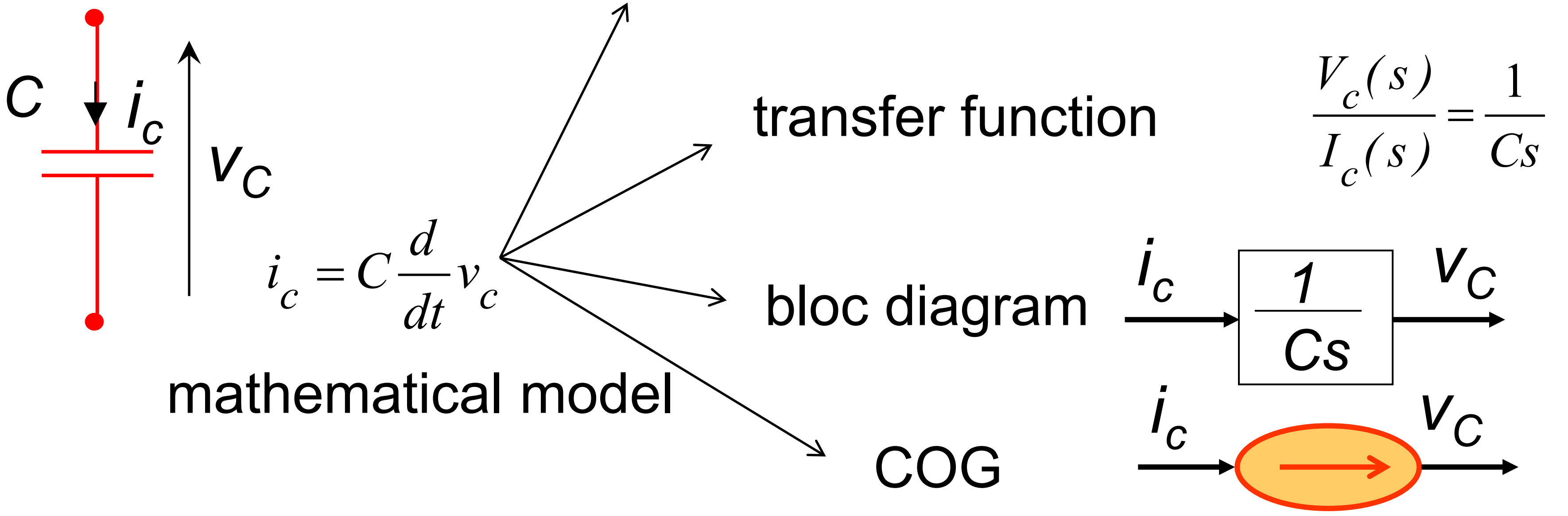
(Simulink © +Range Kutta)

Model vs. Representation

Model = description based on physical laws
(validity range function of assumptions)

Representation = organisation of a model
in order to highlight some properties

<u>Example</u>: capacitor



$$i_c = C\frac{d}{dt}v_c$$

mathematical model

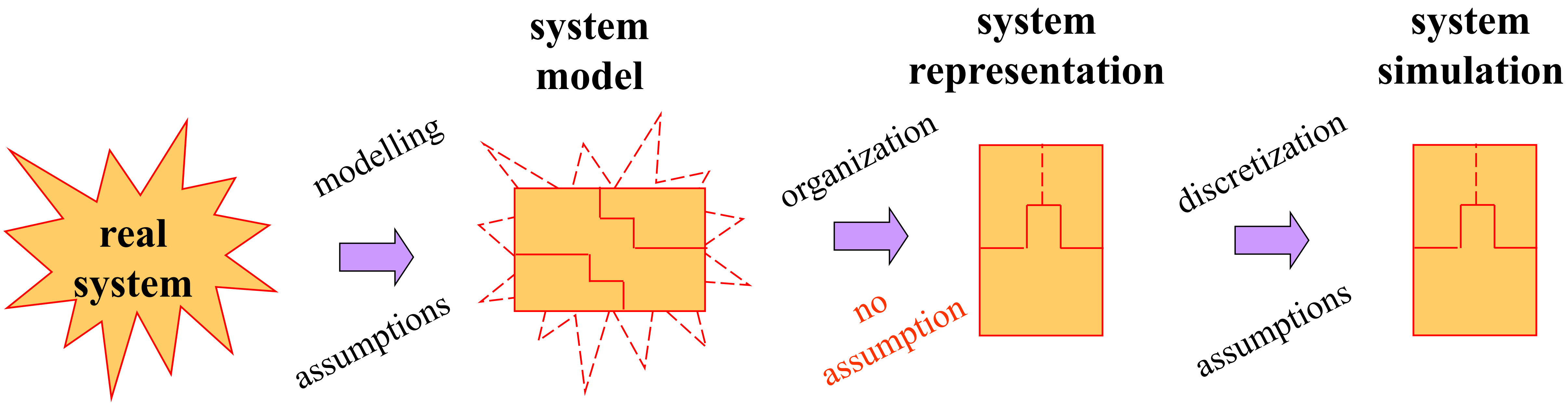
state space representation $\frac{d}{dt}v_c = \frac{1}{C}i_c$

transfer function $\frac{V_c(s)}{I_c(s)} = \frac{1}{Cs}$

bloc diagram $i_c \rightarrow \boxed{\frac{1}{Cs}} \rightarrow v_C$

COG

Different choices at every steps



system model

system representation

system simulation

real system

modelling

assumptions

organization

no assumption

discretization

assumptions

- dynamical
  / quasi-static
  / static

- structural/functional
- causal/non-causal

- backward
  / forward

Different possibilities at each step in function of the objective

Dynamical vs. static model

Which subsystem model?

Static model

- steady state operations
- no transient states
- fast computation time
- global behavior

Dynamic model

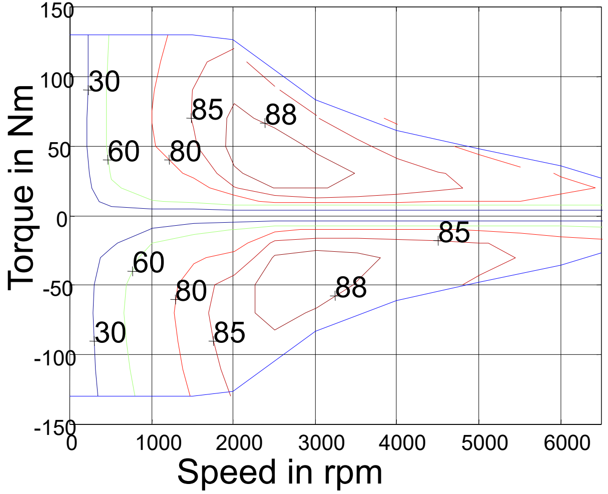
- transient state operations
- but also steady state operations
- long computation time
- detailed behavior

Quasi-static model

- static model + main time constant
- intermediary computation time
- intermediary behavior

Example of electrical machines

static efficiency map



$$i_{DC} = \frac{T_{em}\Omega + P_t(T_{em},\Omega)}{U_{DC}}$$

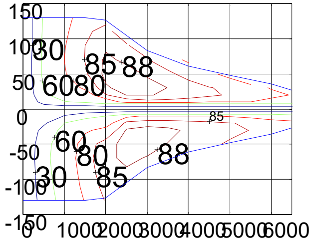
dynamic model

$$\begin{cases} V_{Sd} = R_S i_{Sd} + \cancel{\frac{d\phi_{Sd}}{dt}} - \omega_S \phi_{Sq} \\ V_{Sq} = R_S i_{Sq} + \cancel{\frac{d\phi_{Sq}}{dt}} + \omega_S \phi_{Sd} \\ 0 = R_R i_{Rd} + \cancel{\frac{d\phi_{Rd}}{dt}} - \omega_R \phi_{Rq} \\ 0 = R_R i_{Rq} + \cancel{\frac{d\phi_{Rq}}{dt}} + \omega_R \phi_{Rd} \end{cases}$$

$$T_{em} = p\frac{L_m}{L_R}\cdot(\phi_{Rd}\cdot i_{Sq} - \phi_{Rq}\cdot i_{Sd})$$

$$J\frac{d}{dt}\Omega = T_{em} - T_{load} - f\Omega$$

quasi-static model



$$+ J\frac{d}{dt}\Omega = T_{em} - T_{load} - f\Omega$$

Structural vs. functional representation

How to describe a system?

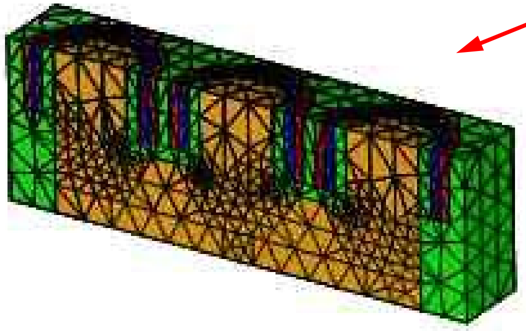
Structural description

- Physical structure in priority
- Physical links between subsystems
- Design application

Functional description

- function priority
- Virtual links between subsystems
- Analysis and control application

Example: 3-phase transformer



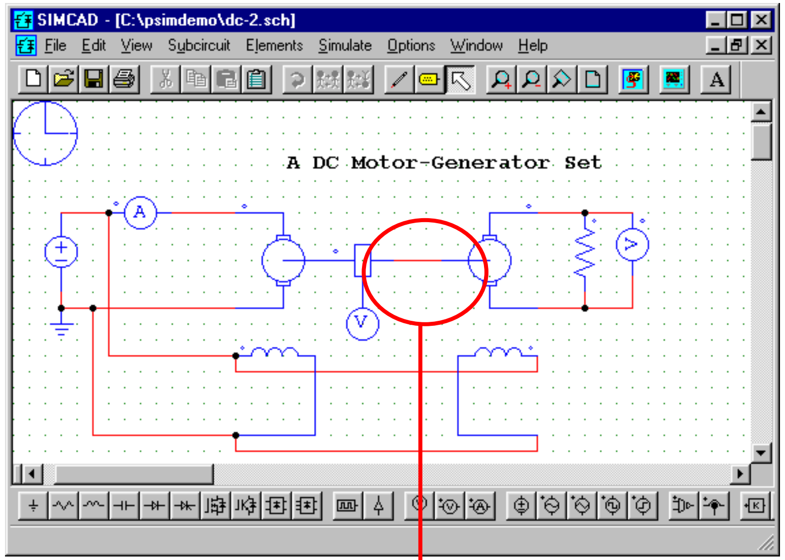
3D Finite Element Model

$$\begin{cases} \underline{v}_2 = m\,\underline{v}_1 \\ \underline{i}_1 = m\,\underline{i}_2 \end{cases}$$

Mathematic model
Assumption: ideal transformer

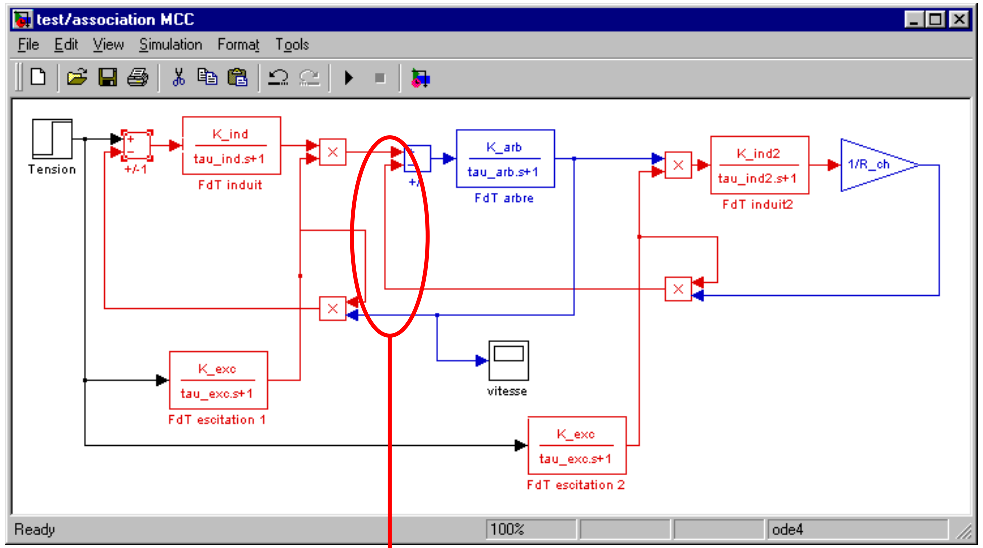
System with two DC machines

PSIM (structural)



machines connected by
a unique physical link (shaft)

Matlab-Simulink (functionnal)



machines connected by
two virtual links (torque/speed)

Causal vs. acausal description

How to connect subsystem?

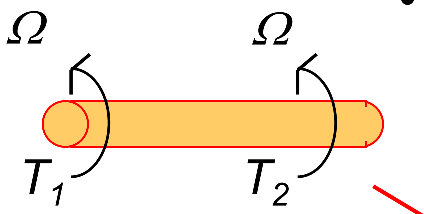
Causal description

- fixed input and output
- output = integral function of inputs
- difficult interconnection subsystems
- basic solver

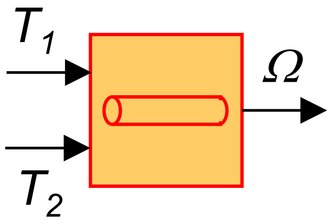
Acausal description

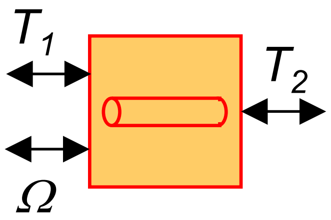
- floating inputs and outputs
- different relationships
- easy subsystem interconnection
- specific solver required
- simulation library

Example: rotating shaft



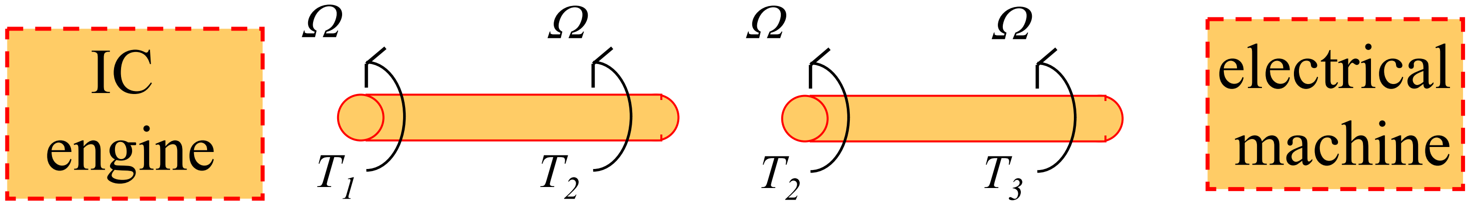
$$J\frac{d}{dt}\Omega = T_1 - T_2$$





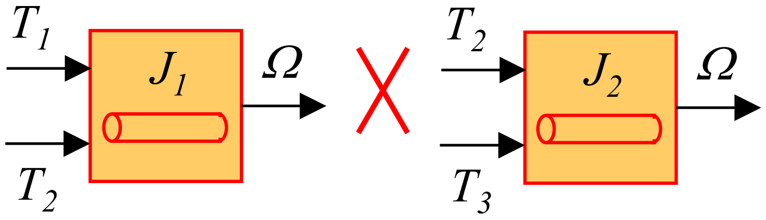
Interconnection of subsystems

Example

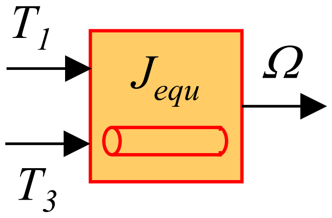


$$J_1 \frac{d}{dt}\Omega = T_1 - T_2 \qquad J_2 \frac{d}{dt}\Omega = T_2 - T_3$$

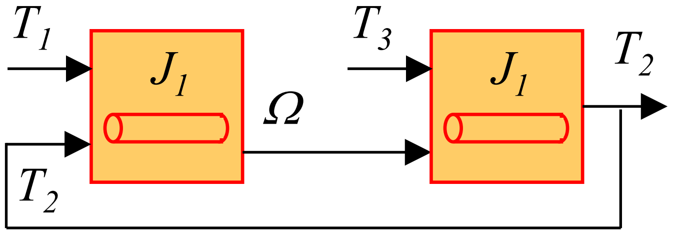
causal description



$$(J_1 + J_2)\frac{d}{dt}\Omega = T_1 - T_3$$



acausal description



↓

derivative relationship

↓

specific solver

Forward vs. backward simulation

Which method to compute the model?

Forward approach

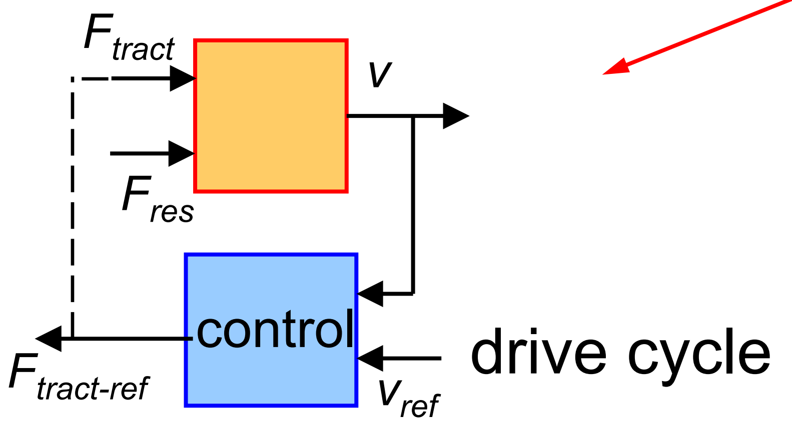
- from the cause to the effect
- respect of the energy flow
- controller required

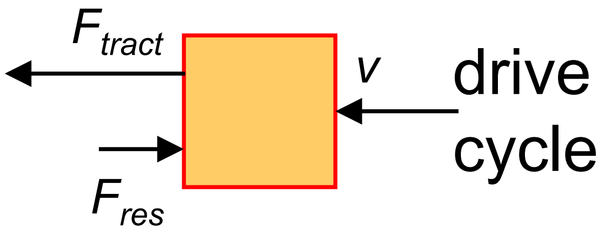
Backward approach

- from the desired effect to the required cause
- anticipate energy flow
- no controller required
- needs to know the result in advance

Example: a vehicle mass

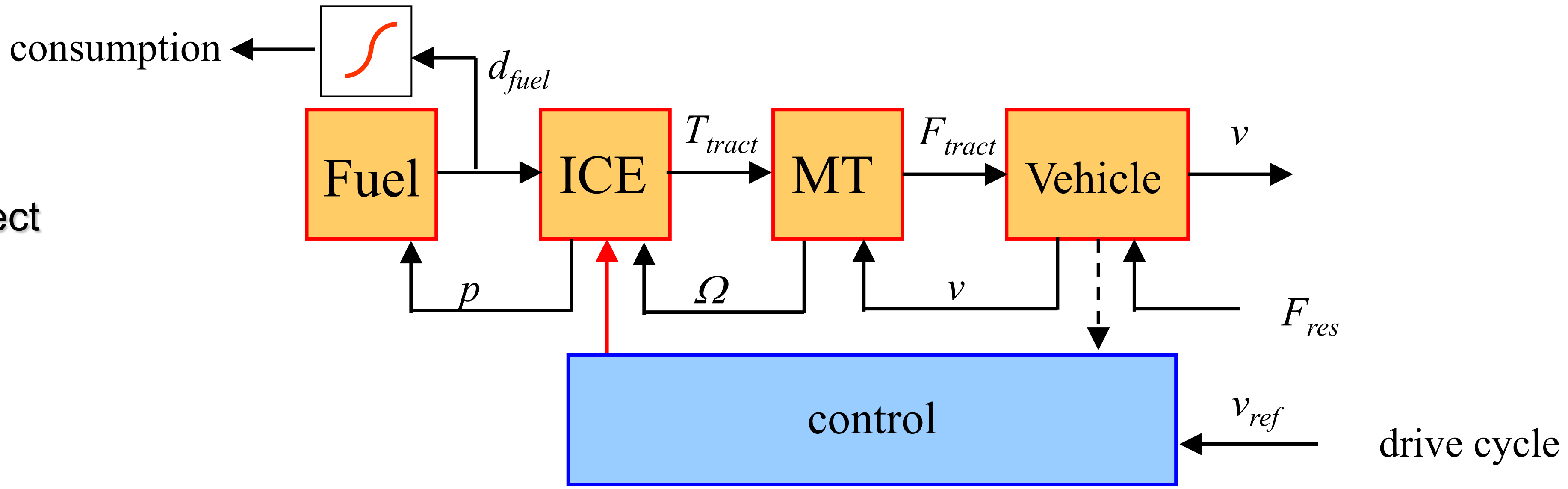
$$M\frac{d}{dt}v = F_{tract} - F_{res}$$





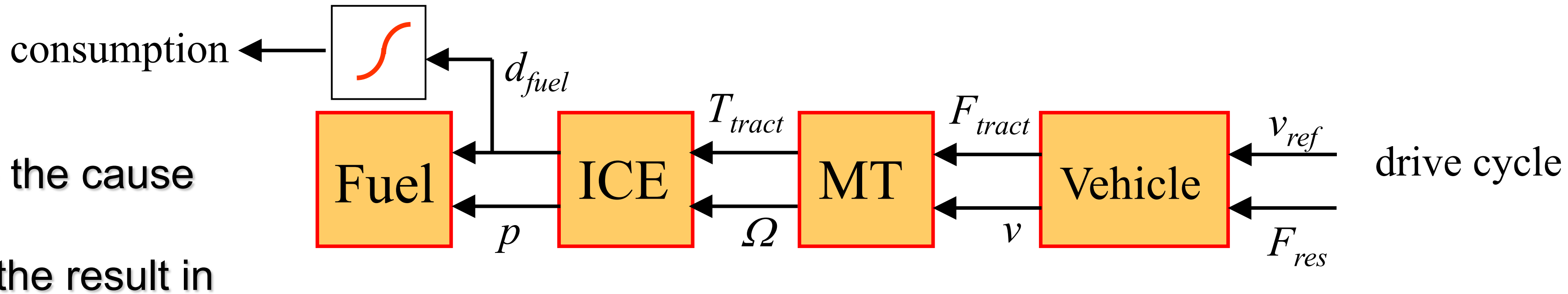
derivative relationship
(no real-time
application)

Example of a thermal vehicle



Forward

- from the cause to the effect (direct simulation)
- needs of control



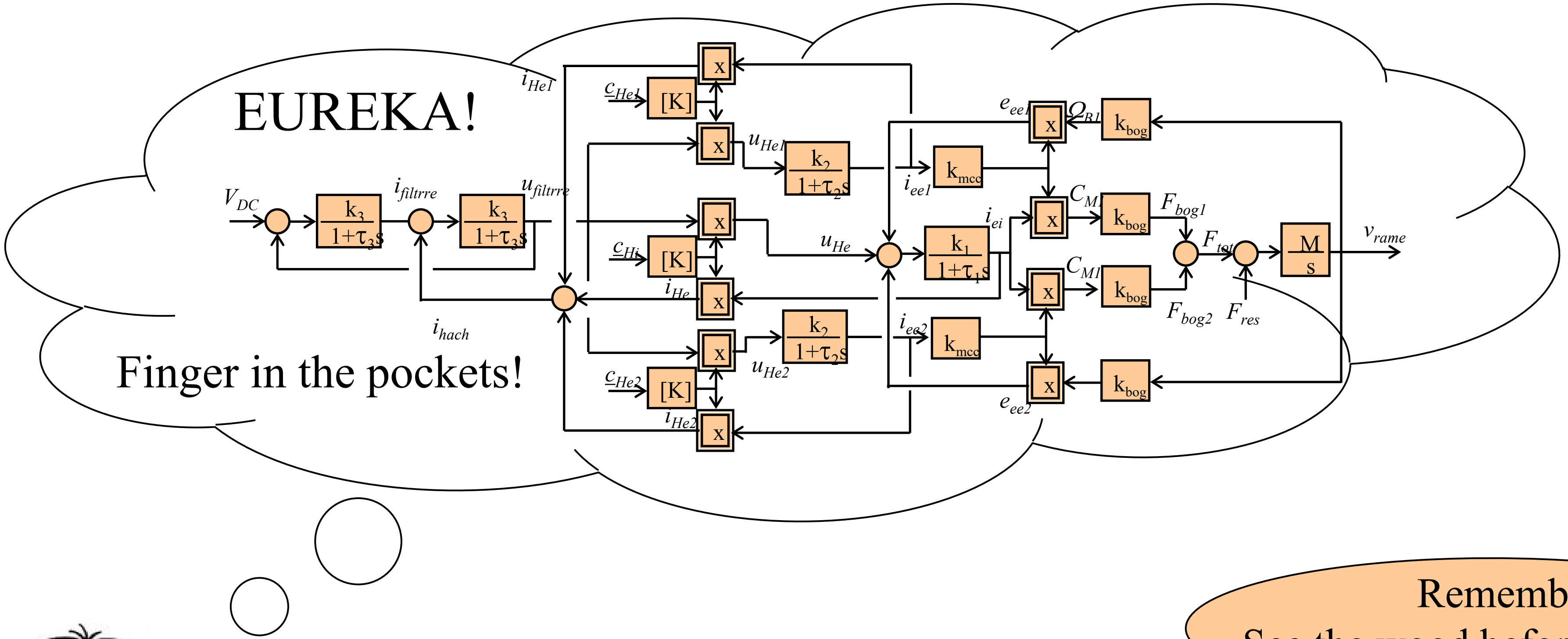
Backward

- from the effect bacsk to the cause (inverse simulation)
- needs of knowledge of the result in adavance

ICE: Internal Combustion Engine
MT: Mechanical Transmission

could be same models, but different representations (cf. I/O)

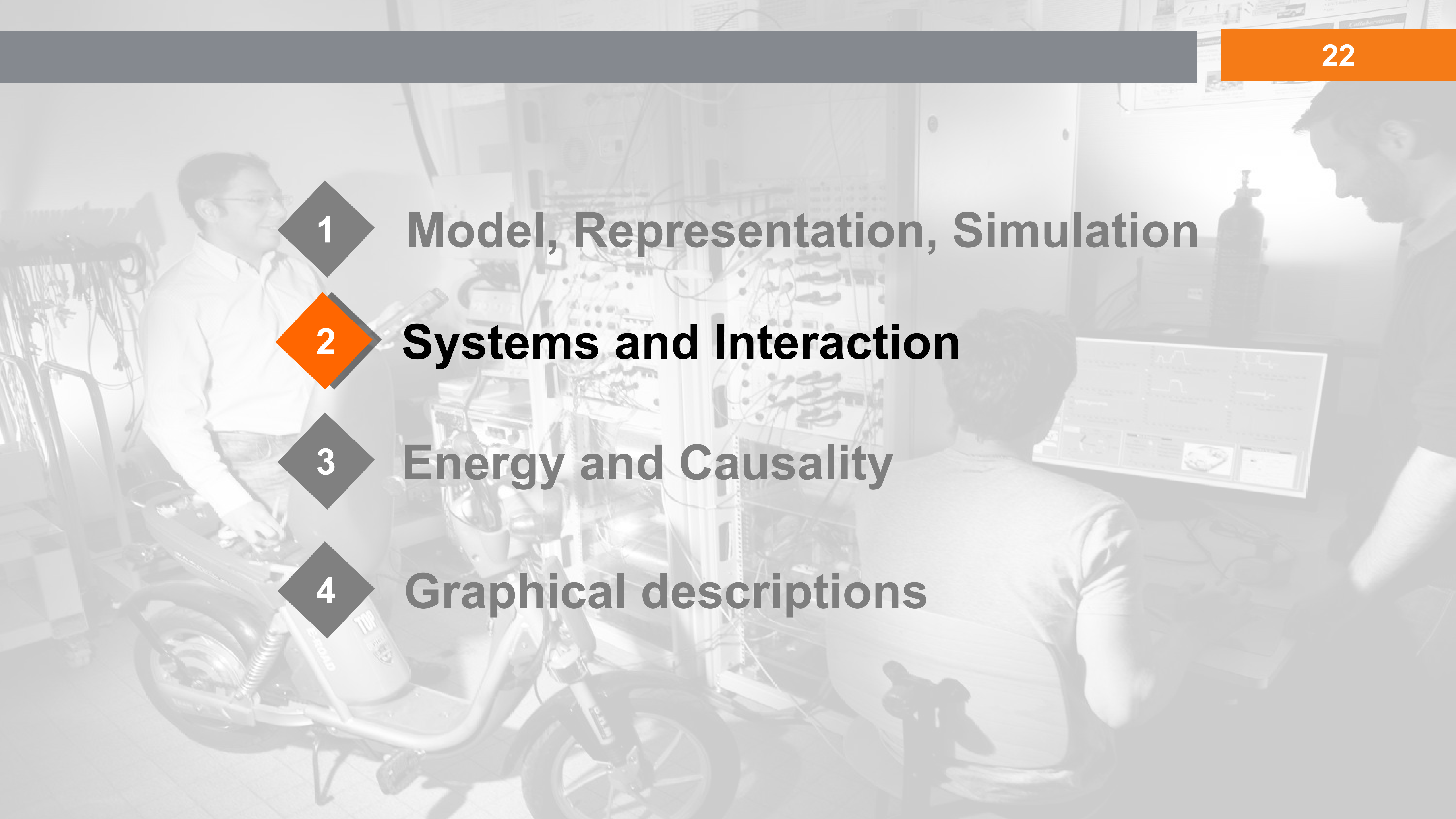
Limitation of classical bloc diagrams



But block diagrams:
- can be confusing for complex systems
- are limited to continuous and linear systems
- do not highlight energy properties
- do not highlight interaction between subsystems

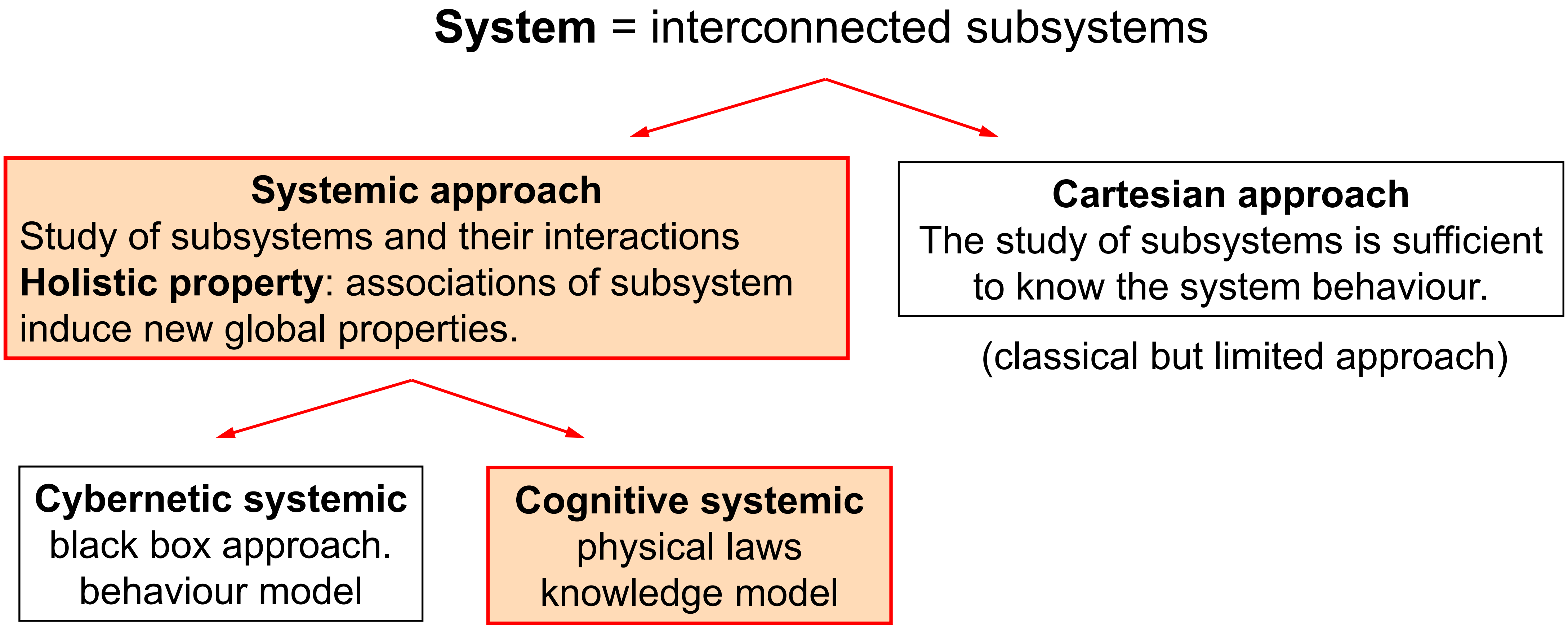
Remember,
See the wood before the trees!

Prof. C.C. Chan



1. Model, Representation, Simulation
2. **Systems and Interaction**
3. Energy and Causality
4. Graphical descriptions

Systemic Approach



System = interconnected subsystems

Systemic approach
Study of subsystems and their interactions
Holistic property: associations of subsystem induce new global properties.

Cartesian approach
The study of subsystems is sufficient to know the system behaviour.

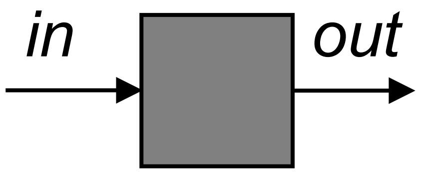
(classical but limited approach)

Cybernetic systemic
black box approach.
behaviour model

Cognitive systemic
physical laws
knowledge model

For better performances of a system
interactions and physical laws must be considered!

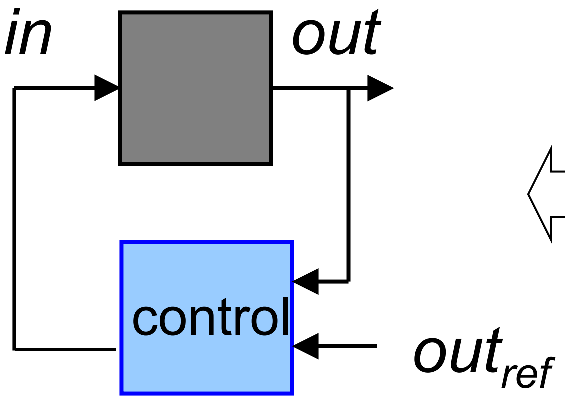
or “Black box” approach: no internal knowledge



identification test:
observation of *out(t)* from selected *in(t)*

Behavior model:
$out(t) = \mathrm{f(t)}\ in(t)$

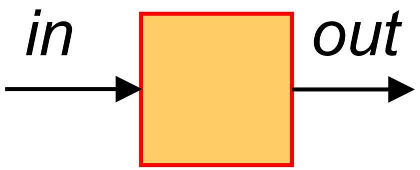
closed-loop control of *out*:
for uncertainty compensations



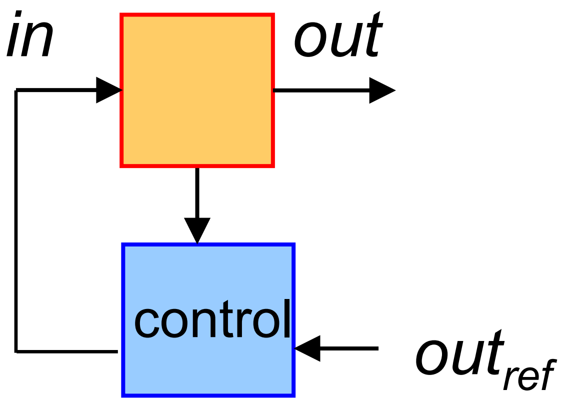
or “White box” approach: prior internal knowledge

Physical laws of
system components

Knowledge model:
$out(t) = f(t)\, in(t)$



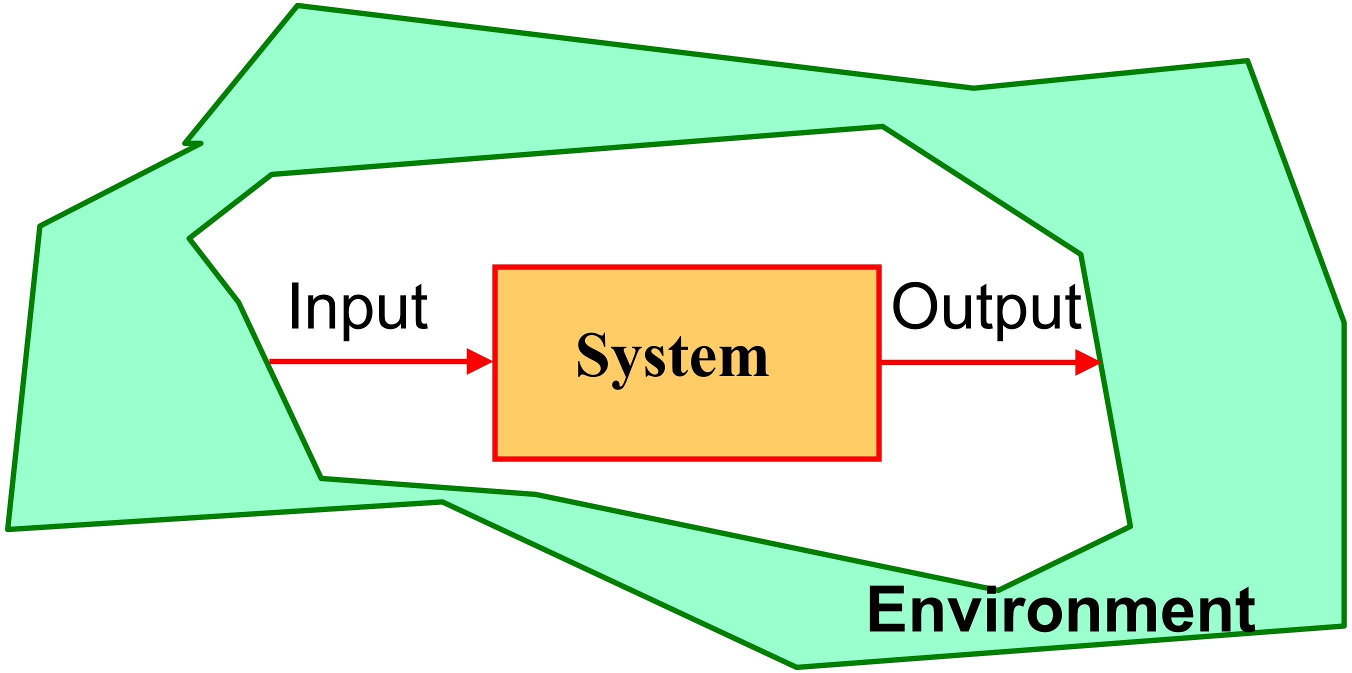
control = inversion of model:
(closed loop = an inversion way)



System & environment

Input: variable produced by the environment, imposed to the system for evolution (independent of the system)

Output: consequence of the system evolution, imposed to its environment (not directly dependant on the environment)

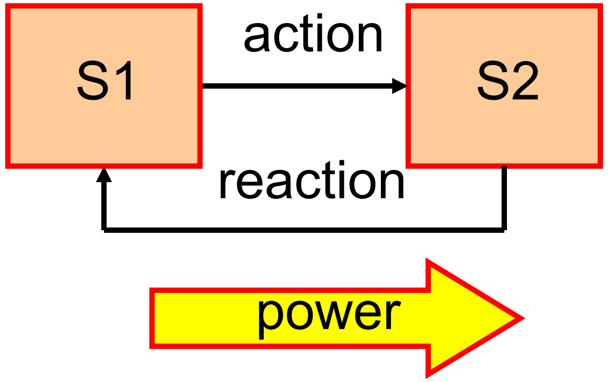


Environment & System must be defined first!

<u>Example</u>: a wind turbine

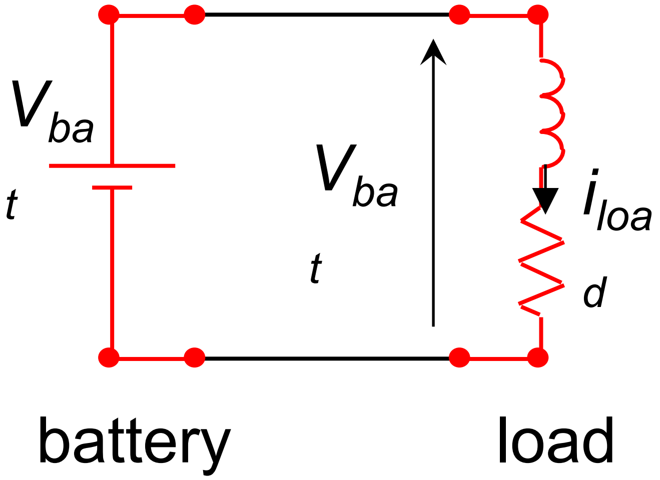
Interaction principle

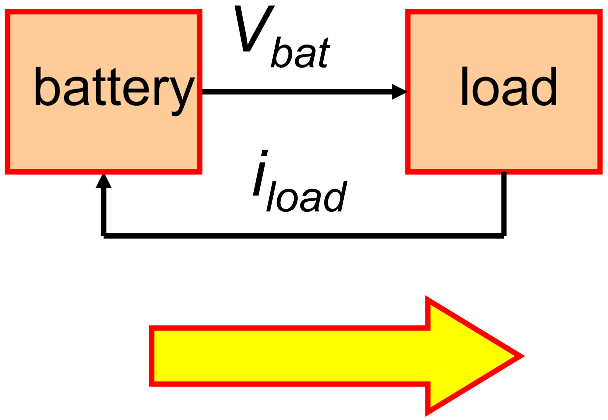
Interaction principle
Any action induces a reaction



Power exchanged by S1 and S2 = **action x reaction**

Example: battery and load





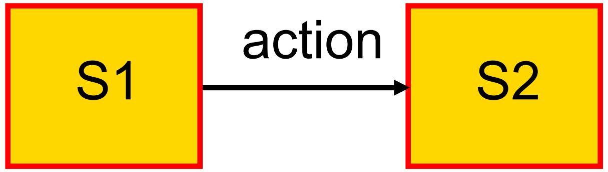
$$P(t)=V_{bat}(t)i_{load}(t)$$

Interaction mistake

If the interaction principle is not respected for 1 subsystem

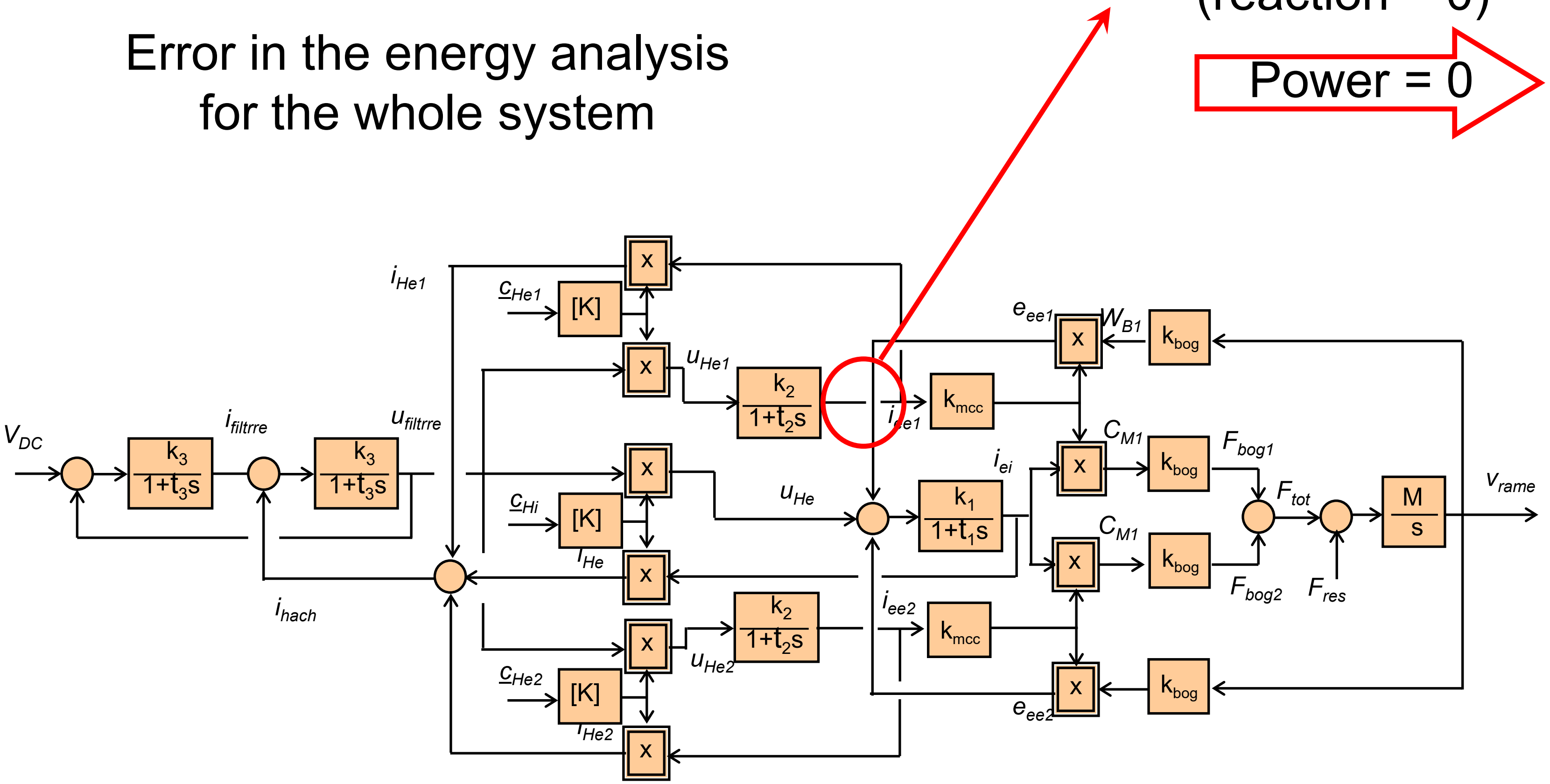
⇩

Error in the energy analysis for the whole system



(reaction = 0)

Power = 0 ⇨ false results in terms of energy !



Holistic principle

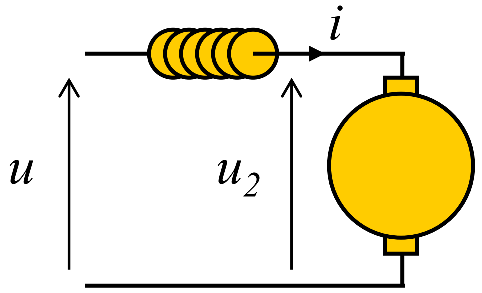
Holistic principle

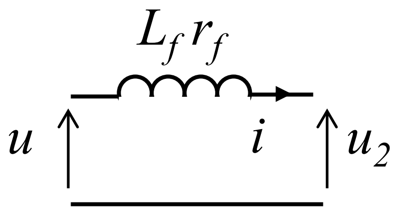
Association of subsystems can lead to:

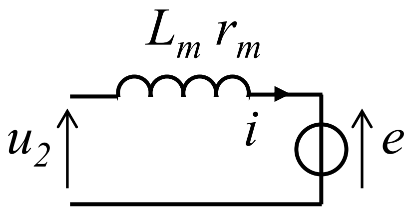
- cancelation of local properties
- emergence of new properties

S1 + S2 ≠ S1+S2

Example DC machine and smoothing inductor

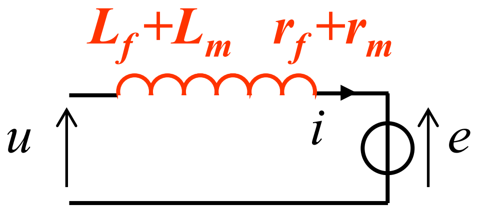






$$L_f \frac{di}{dt} = u - u_2 - r_f i$$

$$\underbrace{L_m \frac{di}{dt} = u_2 - e - r_m i}$$



$$(L_f + L_m)\frac{di}{dt} = u - e - (r_f + r_m)i$$

$$\frac{L_f + L_m}{r_f + r_m} \neq \frac{L_f}{r_f} + \frac{L_m}{r_m}$$

Association of both subsystems ⇨ must be studied globally

Questions

Systemics vs. Cartesian approach

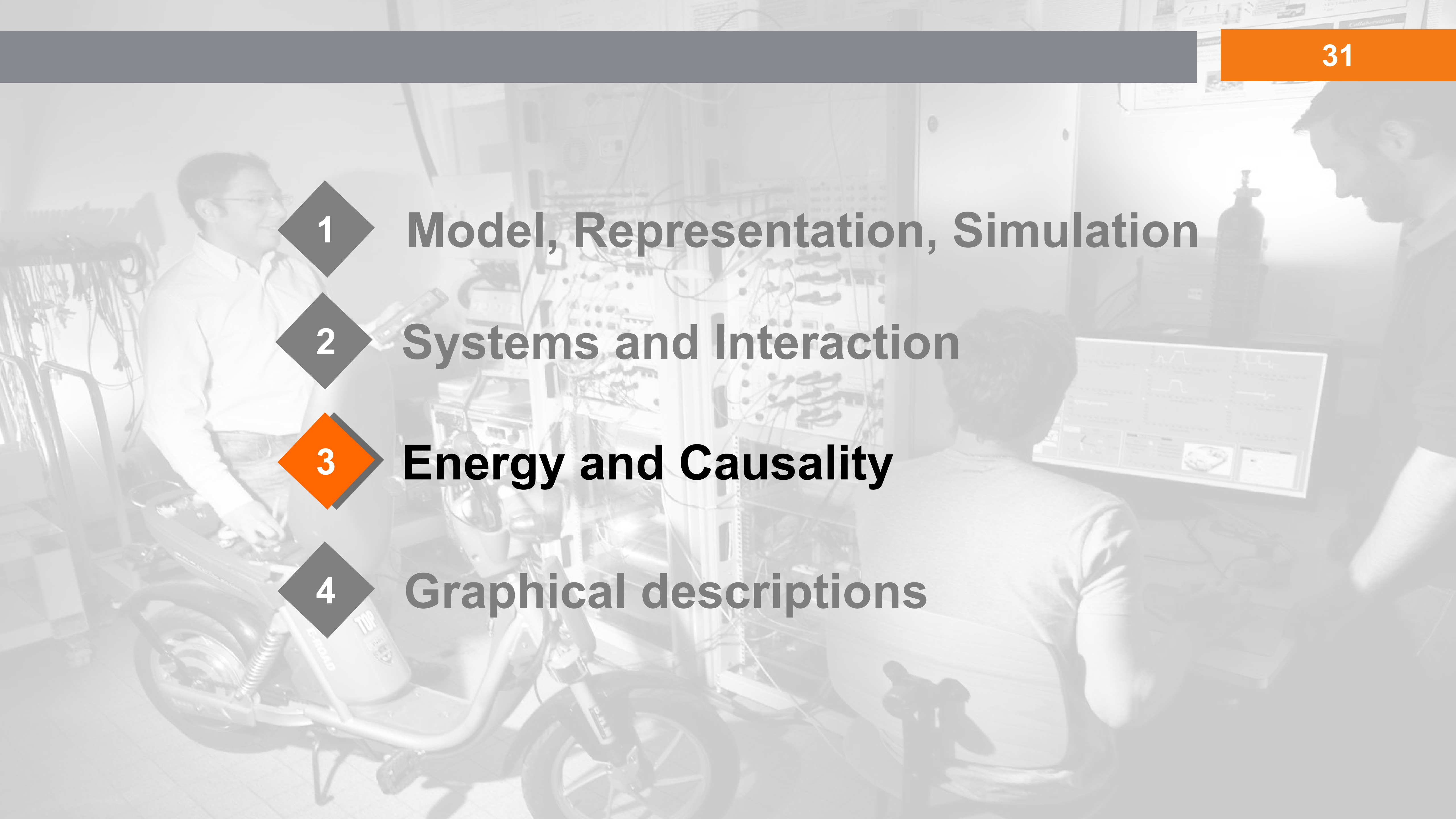
A. Systemic more global
B. Cartesian more global
C. Equivalence

Interaction principle

A. Action = power
B. Reaction = power
C. Action x Reaction = power

Structural vs. functional

A Structural is for design
B. Functional is for control
C. There is no difference



1. Model, Representation, Simulation
2. Systems and Interaction
3. **Energy and Causality**
4. Graphical descriptions

Energy and Power

Energy [J] = amount of work that can be performed by a force, an object, a system

Power [W] = variation of energy with time $P(t) = \frac{dE(t)}{dt}$

Ideal energy conversion: energy conservation (no losses)
and instantaneous transfer (no delay)

but

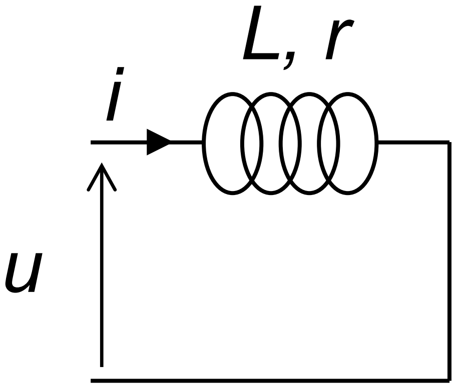
energy dissipation: losses, reduction of efficiency
energy storage: delay in energy transfer

Energy storage in subsystems
is key transformation for safety and efficiency

Energy storage

Energetic Variable = state variable = variables related to energy without instantaneous changes ⇨ delay in energy transfer

Example inductor



$$u(t) = L\frac{di(t)}{dt} + ri(t)$$

$$E(t) = \int_0^t P(t)dt = \int_o^t \left(L\frac{di(t)}{dt}i(t) + ri(t)i(t) \right) dt$$

$$E(t) = \underbrace{L\int_0^t \frac{di(t)}{dt}i(t)dt}_{\text{storage}} + \underbrace{r\int_o^t i^2(t)dt}_{\text{losses}}$$

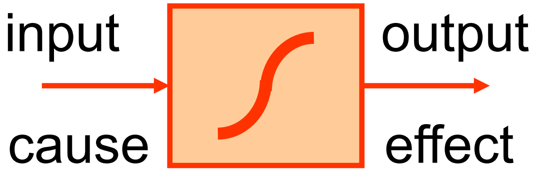
$$E_{storage}(t) = \frac{1}{2}Li^2(t)$$

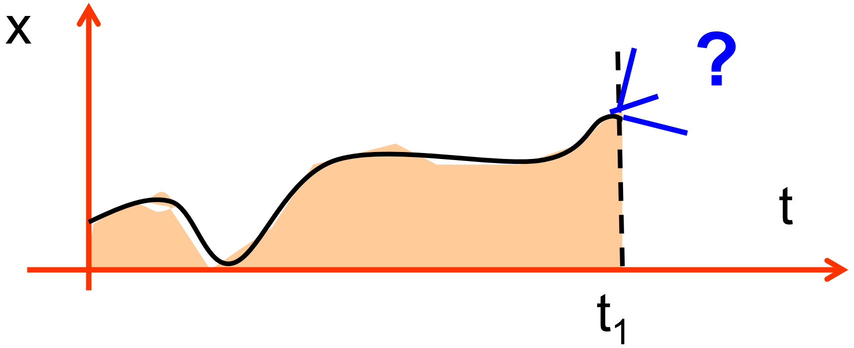
i(t) energetic variable

Causality principle

Principle of causality

the effect is consequence of the cause
i.e. output is always delayed from input
i.e. output is an integral function of input
i.e. output is an energy variable





$\int x dt$ ⇒ area

⇓

knowledge
of past evolution

OK in real-time

~~slope~~ ⇐ ~~$\frac{dx}{dt}$~~

⇓

~~knowledge~~
~~of future evolution~~

impossible in real-time

Causality principle

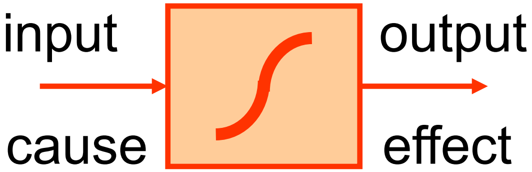
Principle of causality

the effect is consequence of the cause

i.e output is always delayed from input

i.e. output is an integral function of input

i.e. output is a energy variable



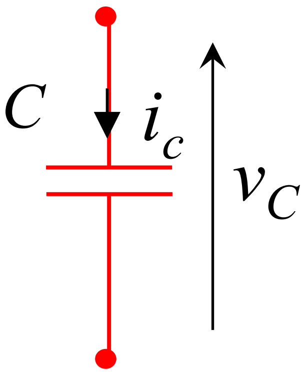
input

cause

output

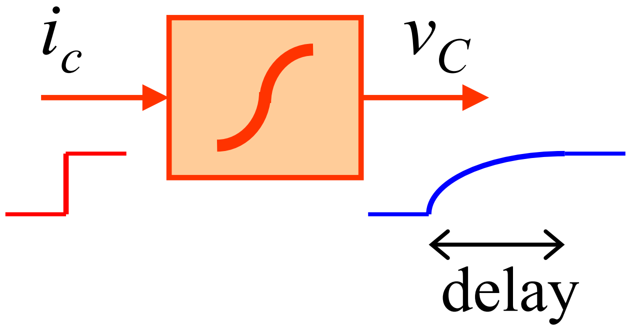
effect

Example

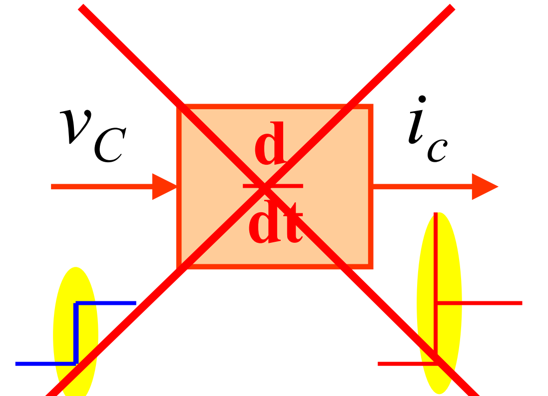


$$i_c = C\frac{d}{dt}v_c + \frac{v_c}{R}$$

$$E_c = \frac{1}{2}v_c{}^2$$



no energy disruption



risk of damage

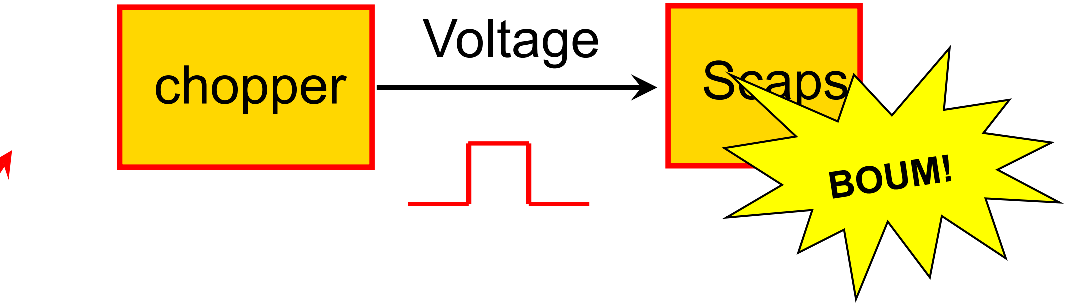
For energy conversion systems

physical causality is VITAL

Causality mistake

If the causality principle is not respected for 1 subsystem

Risk of damage!
No real-time management

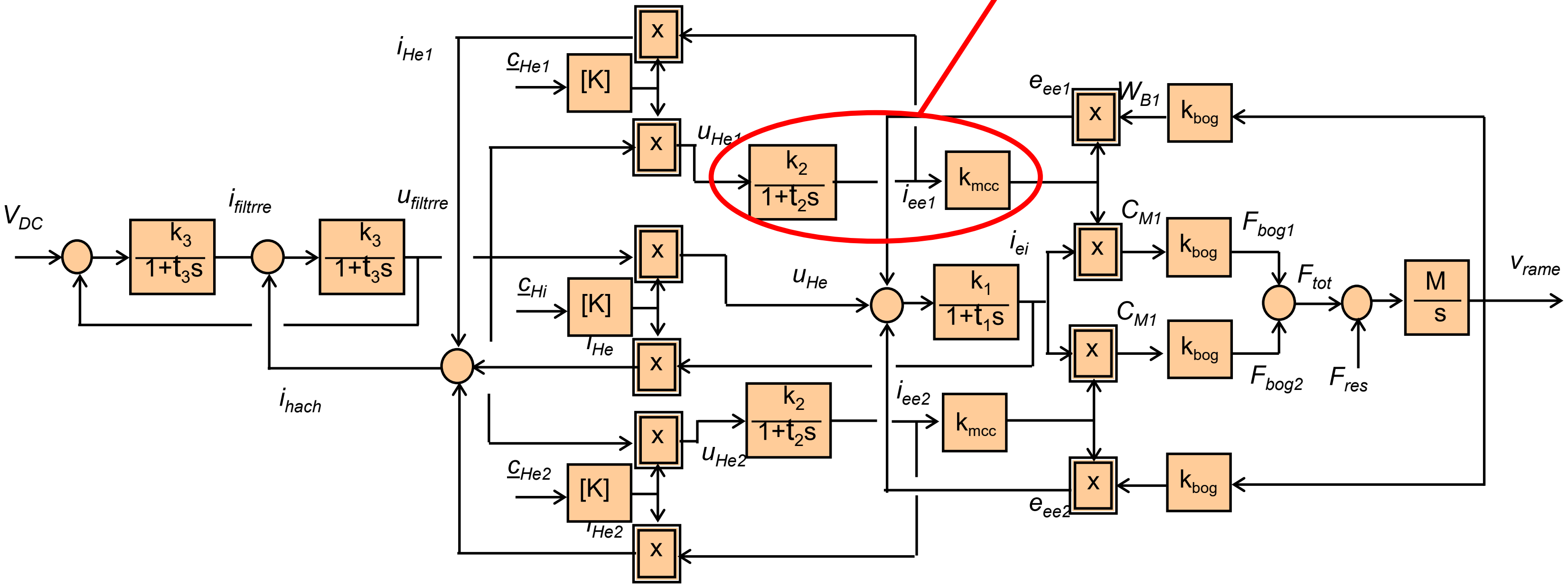


chopper

Voltage

Scaps

BOUM!



Questions

Causality principle

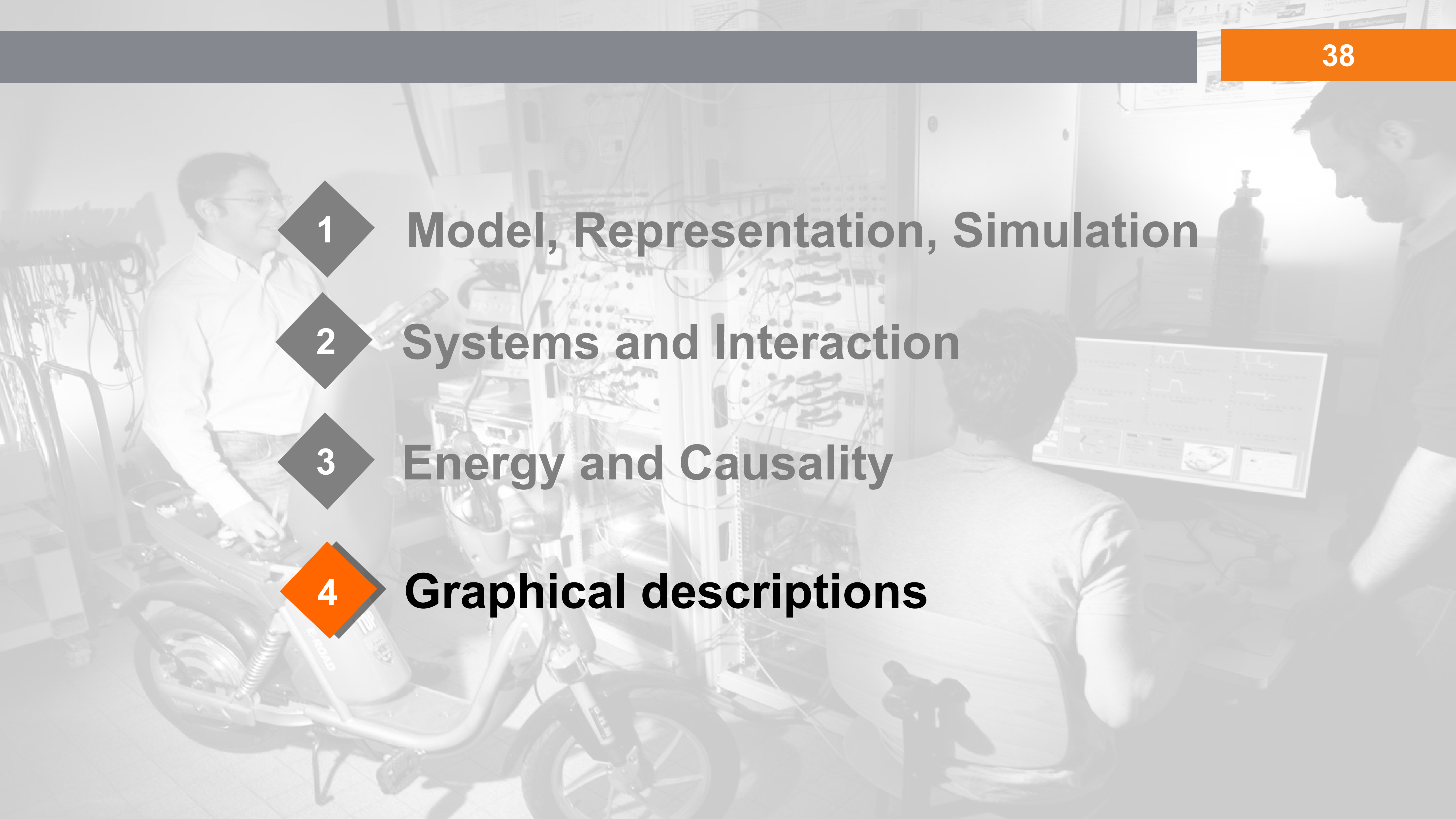
A. Output delayed from Input
B. Input delayed from Output
C. No delay between input/output

Causality principle

A. Out = integral of In
B. Out = derivative of In
C. Out = proportional to In

Real energy conversion systems

A. delay in energy transfer
B. losses in energy transfer
C. Power is energy transfer

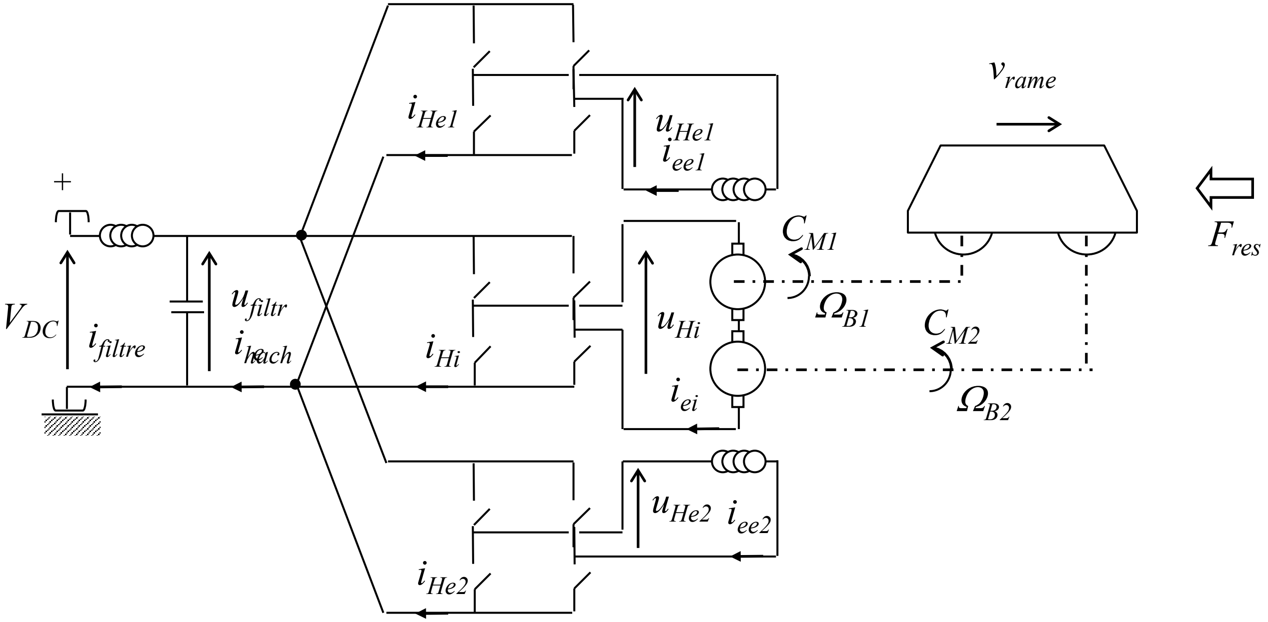


1. Model, Representation, Simulation
2. Systems and Interaction
3. Energy and Causality
4. **Graphical descriptions**

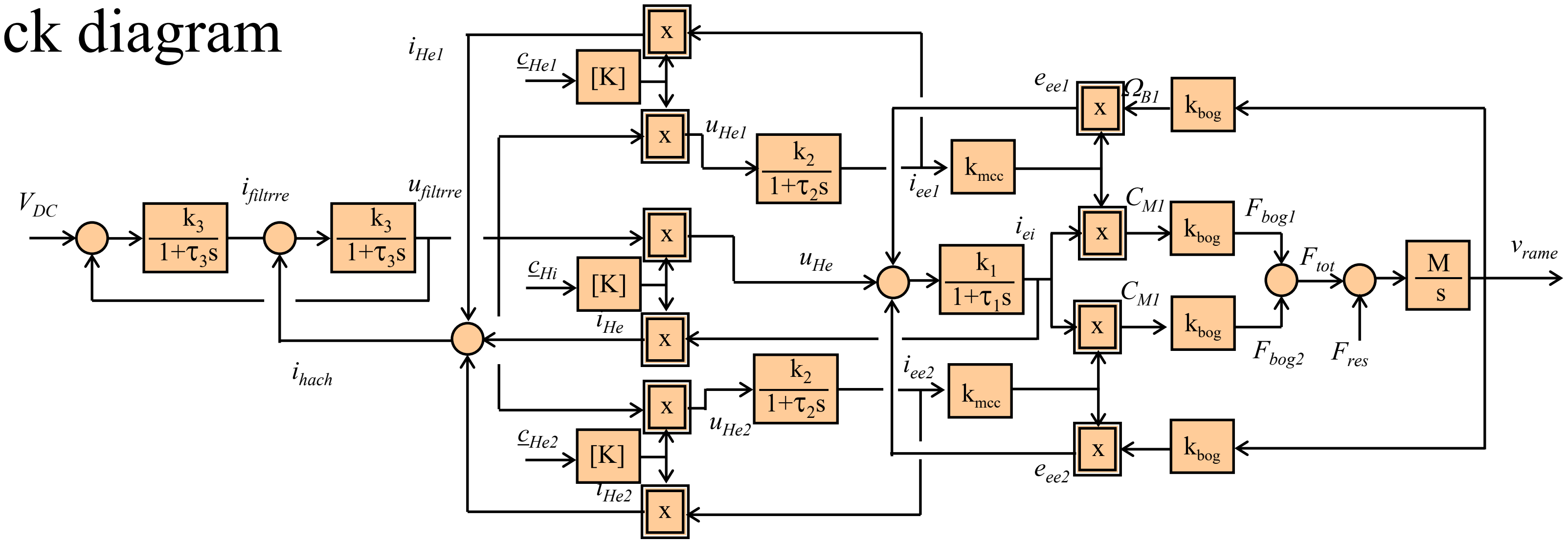
Block diagrams

Example

Subway traction system
of VAL 206
(subway of Lille)



Simplified block diagram

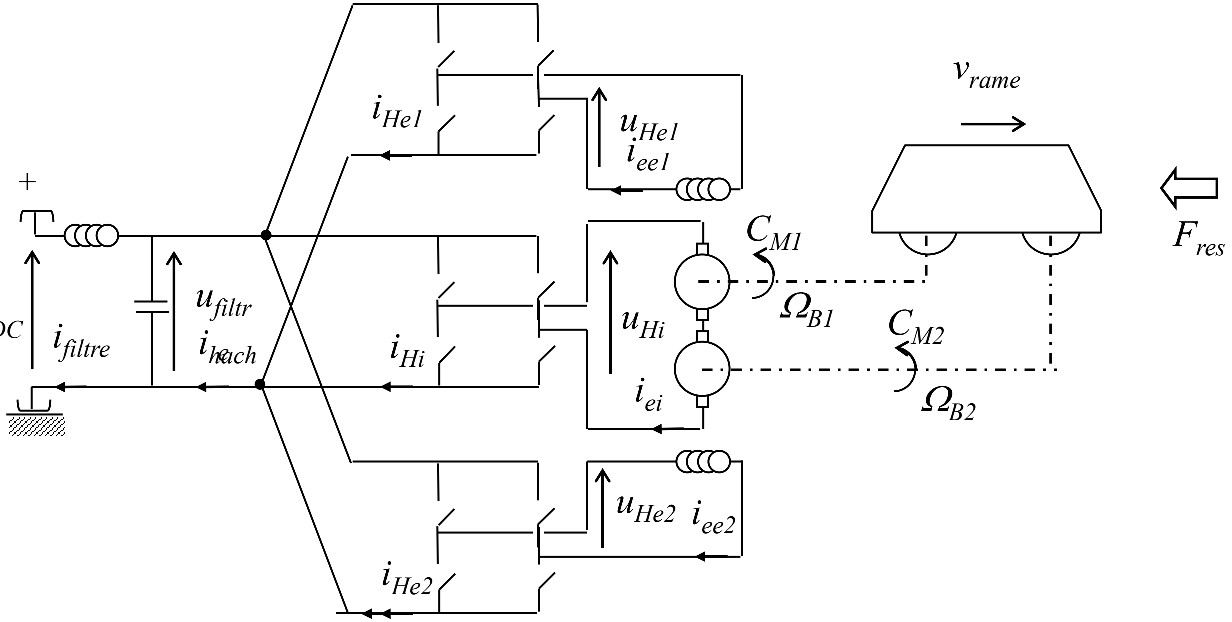


causality?
action/reaction?

Causal Ordering Graph (COG)

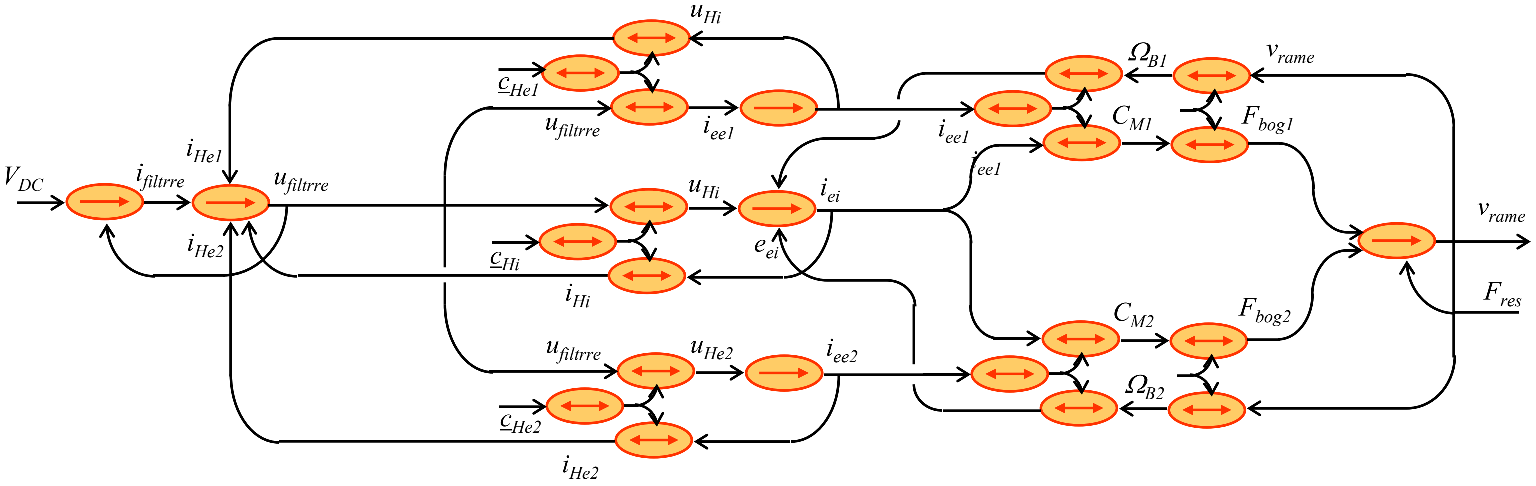
Example

Subway traction system of VAL 206



Causal Ordering Graph (COG)

[Hautier 14]

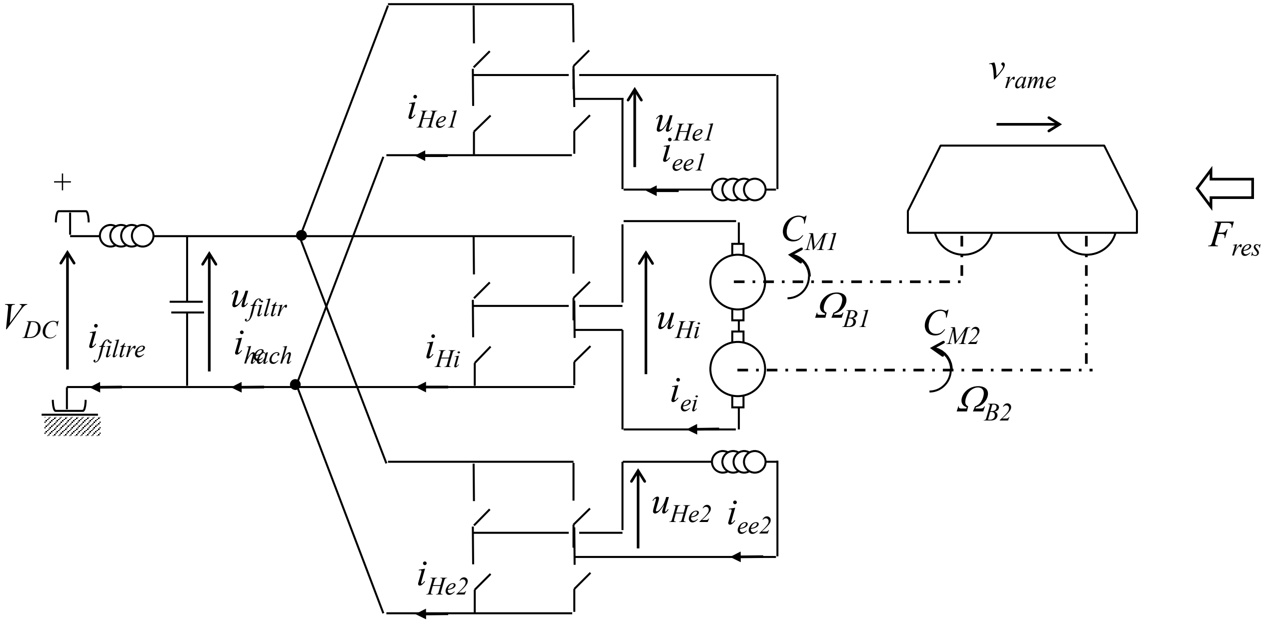


causality OK

action/reaction?

Example

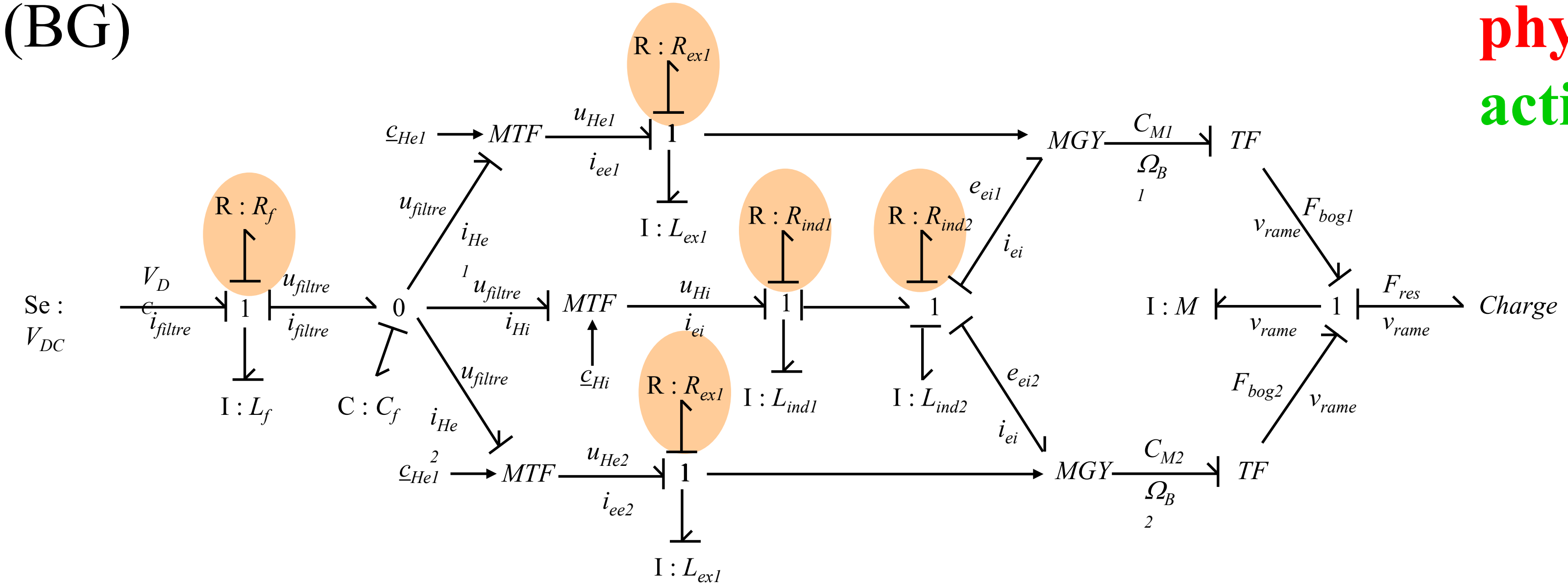
Subway traction system of VAL 206



Bond Graph (BG) [Paynter 61]

physical causality?

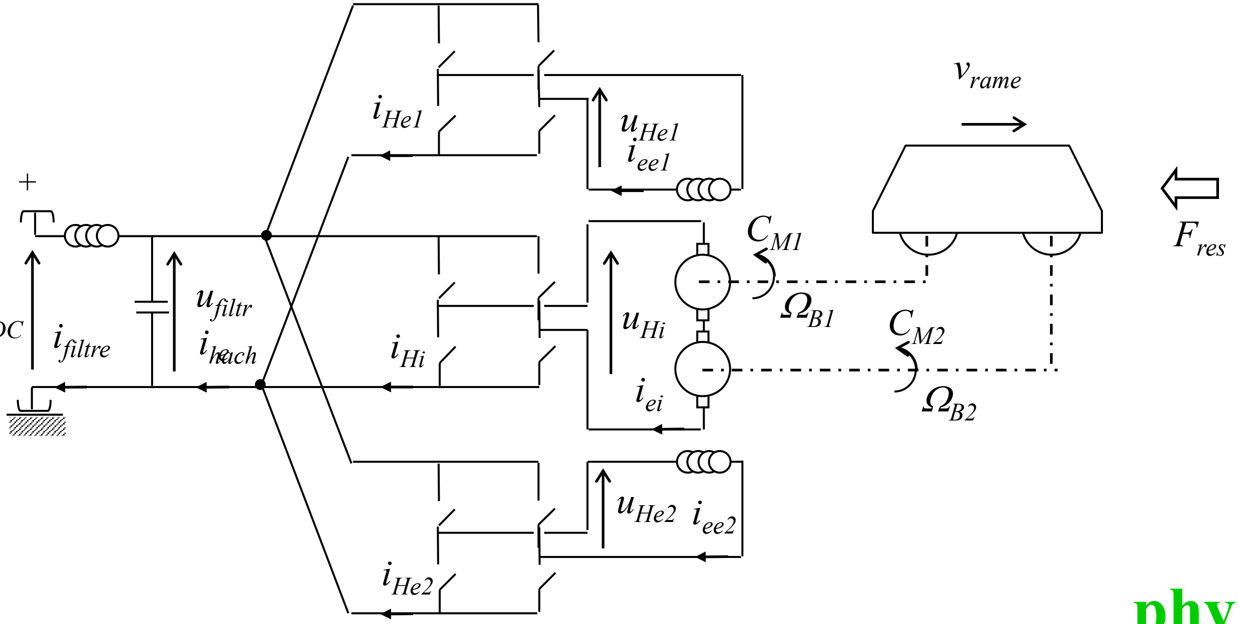
action/reaction OK



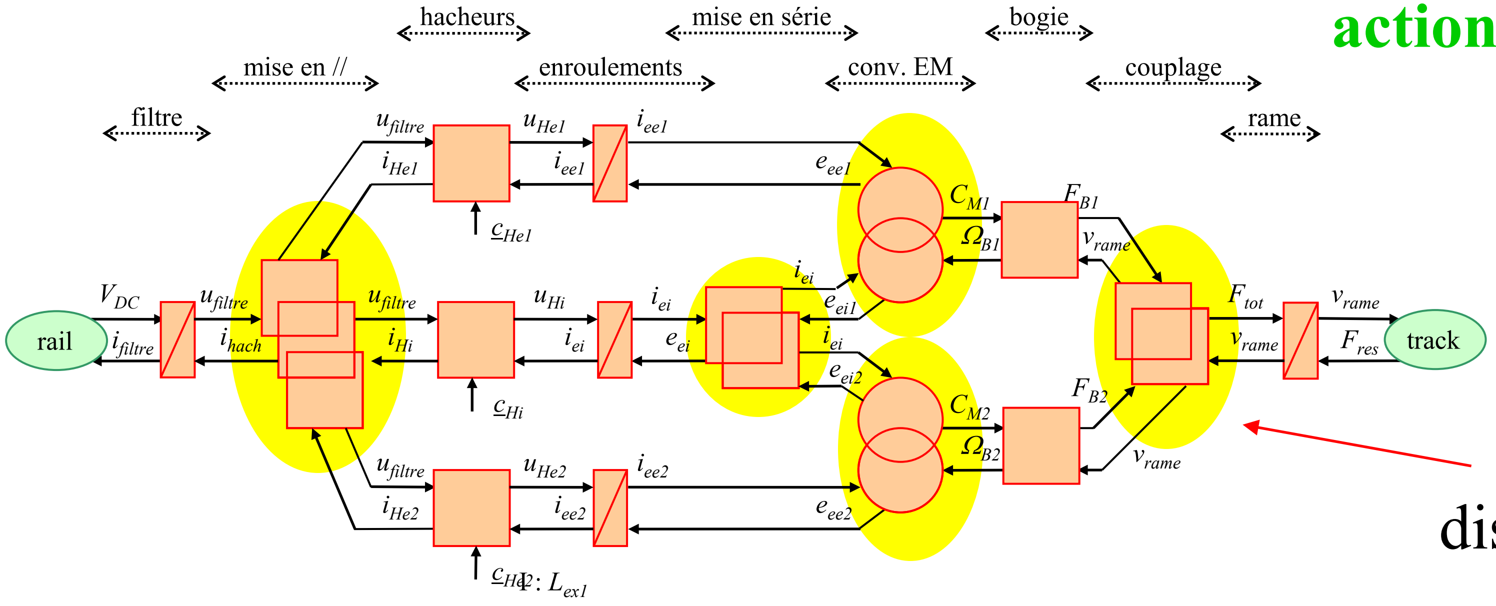
Energetic Macroscopic Representation (EMR)

Example

Subway traction system of VAL 206



Energetic Mascrocopic Representation (EMR) [Bouscayrol 12]



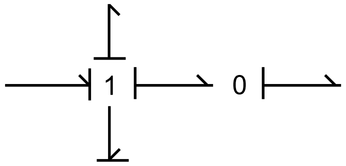
physical causality OK

action/reaction OK

energy distribution

Comparison of graphical description

Energy & System



Energetic Puzzles (Laplace, France)

Bond Graph (USA, The Netherlands…)

Power Oriented Graph (Italy)

Signal Flow Diagram (Germany, Japan...)

Structural description for analysis and design

⇨ mathematical model

⇩

global controls

Block diagrams
COG (L2EP-LEEI, France)

EMR (L2EP, France)

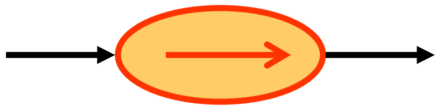
functional descriptions

for simulation and control

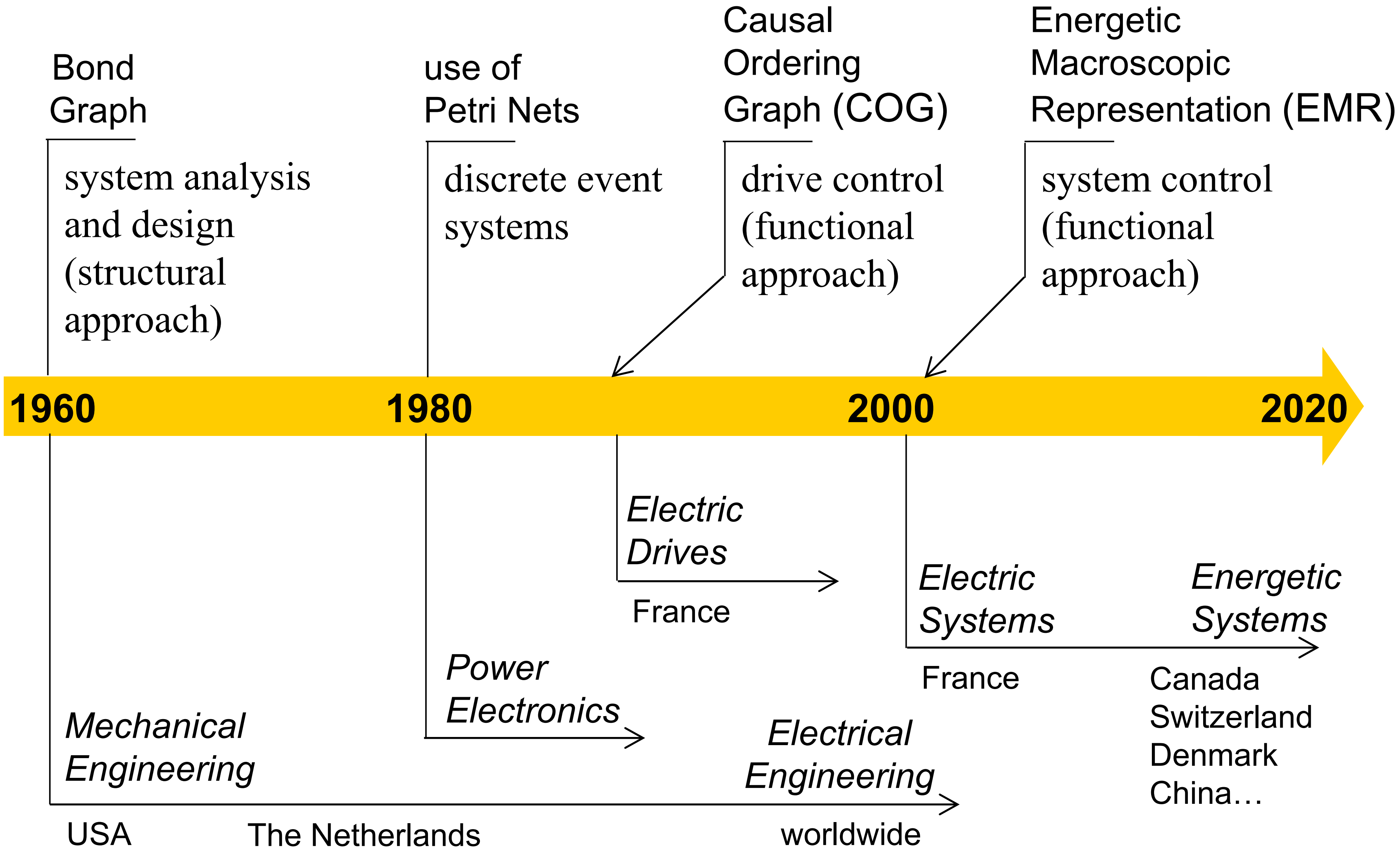
⇨ Inversion graphs

⇩

cascaded control



History of graphical description



Bond Graph

system analysis and design (structural approach)

use of Petri Nets

discrete event systems

Causal Ordering Graph (COG)

drive control (functional approach)

Energetic Macroscopic Representation (EMR)

system control (functional approach)

1960

1980

2000

2020

Electric Drives

France

Electric Systems

France

Energetic Systems

Canada
Switzerland
Denmark
China…

Power Electronics

Mechanical Engineering

Electrical Engineering

USA

The Netherlands

worldwide

Which choices?

Multi-physical system ⇨ Systemic approach

Energy management ⇨ Energetic approach
Causal representation

System control ⇨ Functional description

Real-time control ⇨ Dynamical modeling
Causal representation

Moreover a graphical description could be a valuable intermediary step for such complex systems

Conclusion

system = subsystems in interaction

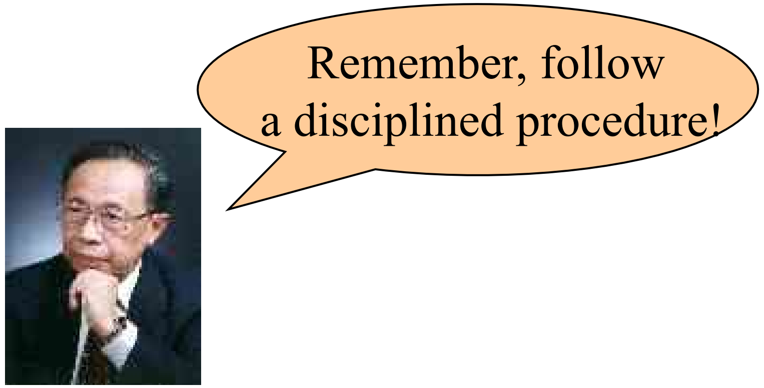
best performances require an systemic approach

energy = respect of the physical causality

energy management requires a causal approach

control = inversion of a causal model of the system

in order to respect its energy properties



Prof. C.C. Chan

graphical description = model organization

useful intermediary step

Selected references

[Astier 2012] S. Astier, A. Bouscayrol, X. Roboam, "Introduction to Systemic Design", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 1, ISTE Willey editions, October 2012, ISBN: 9781848213883

|Bouscayrol 2000] A. Bouscayrol, & al. "Multimachine Multiconverter System: application for electromechanical drives", *European Physics Journal - Applied Physics,* vol. 10, no. 2, May 2000, pp. 131-147 (common paper GREEN Nancy, L2EP Lille and LEEI Toulouse, within the SMM project of the GDR-SDSE).

[Bouscayrol 2012] A. Bouscayrol, J. P. Hautier, B. Lemaire-Semail, "Graphic Formalisms for the Control of Multi-Physical Energetic Systems", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 3, ISTE Willey editions, October 2012, ISBN: 9781848213883.

[Chan 2010] C. C. Chan, A. Bouscayrol, K. Chen, “Electric, Hybrid and Fuel Cell Vehicles: Architectures and Modeling", IEEE transactions on Vehicular Technology, vol. 59, no. 2, February 2010, pp. 589-598 (common paper of Honk-Kong University and L2EP Univ. Lille).

[Hautier 2014] J. P. Hautier, P. J. Barre, "The causal ordering graph - A tool for modelling and control law synthesis", *Studies in Informatics and Control Journal,* vol. 13, no. 4, December 2004, pp. 265-283.

[Paynter 1961] H. Paynter, "Analysis and design of engineering systems", *MIT Press,* 1961.

Thanks for your attention!

……………..

L2EP
Laboratoire d'électrotechnique et
d'électronique de puissance de Lille

Université de Lille

Arts et Métiers Sciences et Technologies

centralelille

JUNIA Grande école d'ingénieurs