EMR'13
Lille
Sept. 2013

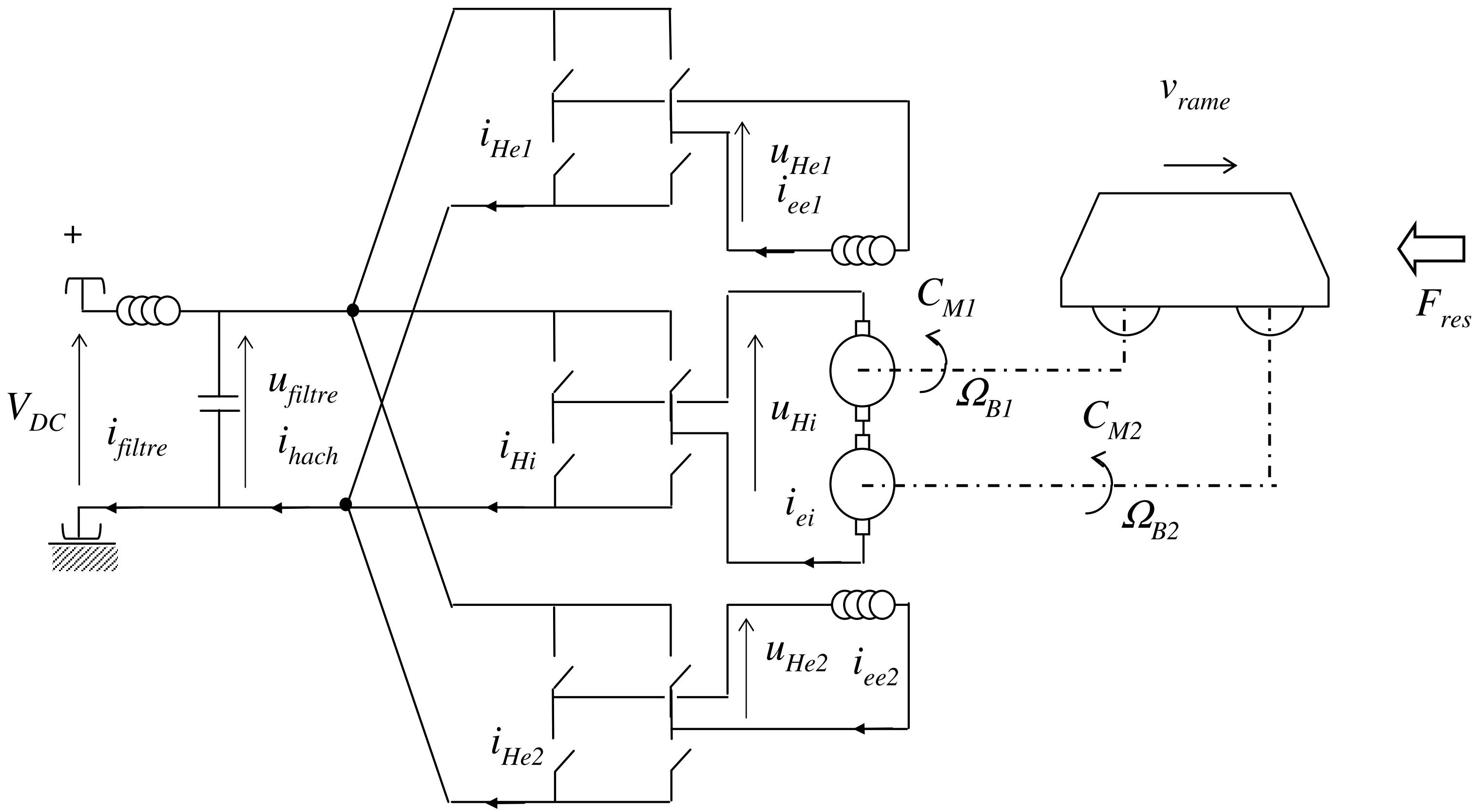
Summer School EMR'13
"Energetic Macroscopic Representation"

« System, Energy and Causality »

Prof. Alain BOUSCAYROL, (L2EP, University Lille1, France)
Prof. C.C. CHAN (University of Hong-Kong, China)
Dr. Philippe BARRADE (EPF Lausanne, Switzerland)

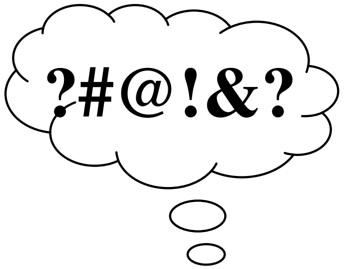
Improvement of a railway traction system

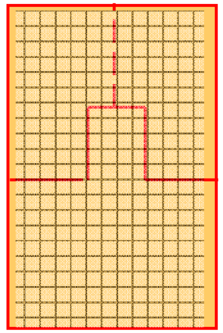
- Complex system
- Multiphysical system
- Sizing? Performances? Control?



Simulation for ever!

Launching Matlab/Simulink is more and more a "Pavlov reflex"





system simulation

↓

behavior study

But:

- Why simulation?
- Which constraints and objectives?
- Which level of accuracy?
- How to be sure of the results?

Six Principles of Integrated System Design

- **Debate, define, revise and pursue the purpose/objective**
  Reflexion before action (…)
- **Think "Holistic" (Systemic)**
  The whole is more than the sum of the parts –
  and each part is more than a fraction of the whole
- **Be creative (multi-level vision)**
  See the wood before the trees
- **Follow a disciplined procedure**
  Divide and conquer, combine and rule
- **Take account of the people**
  To err is human ; Ergonomics; Ethics & Trust
- **Manage the project and the relationships**
  All for one, one for all

Prof. CC. Chan

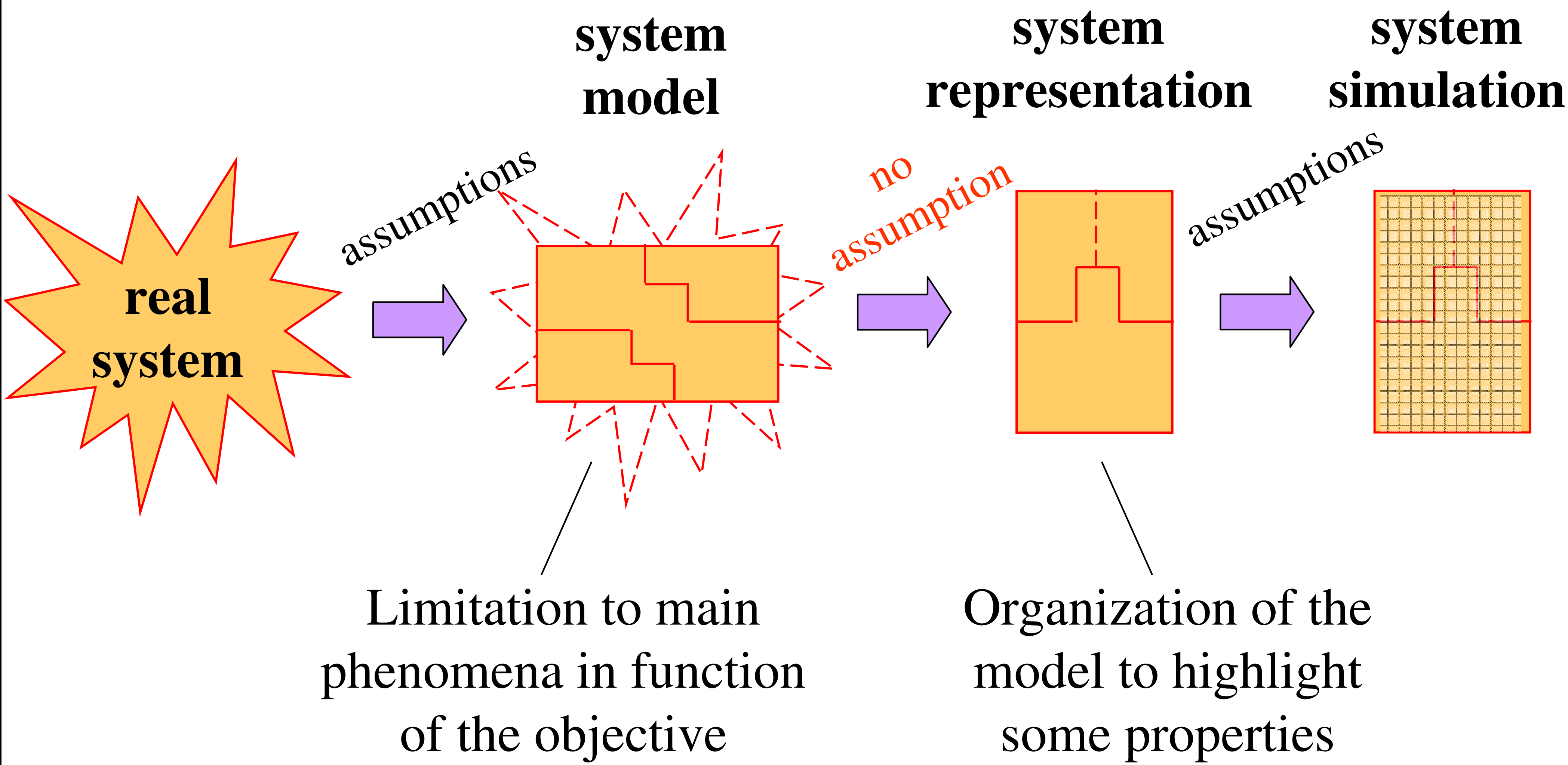
1. **Model, Representation and simulation**
   - Different models
   - Different representations
   - Different simulation approaches

2. **Systems and interaction**
   - Systemic approach
   - Cartesian Approach

3. **Energy and causality**
   - Integral causality
   - Delay and risks

« 1. Model, Representation and Simulation »

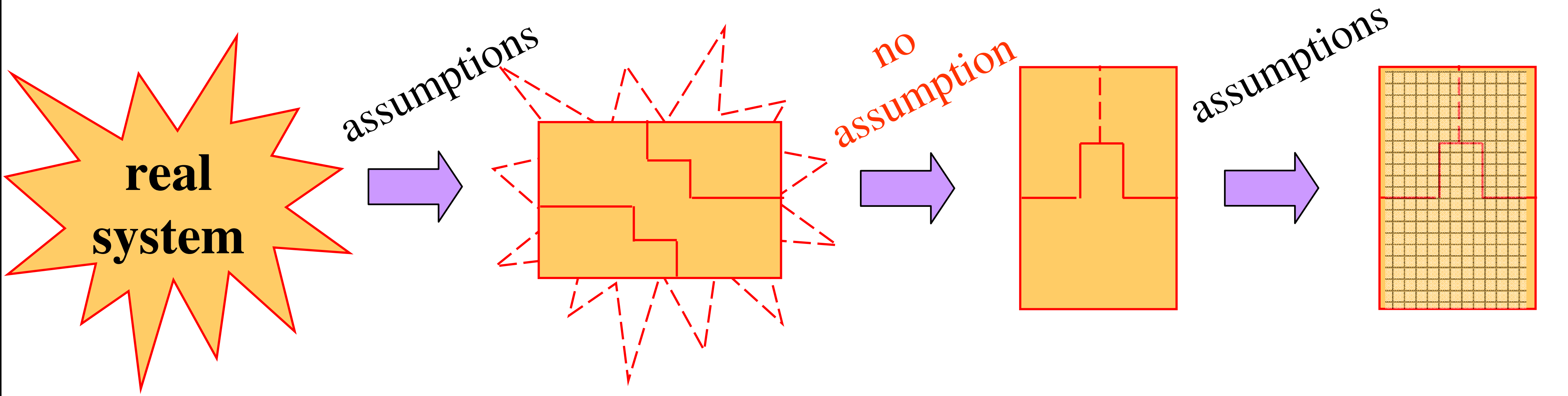
What different steps before simulation?



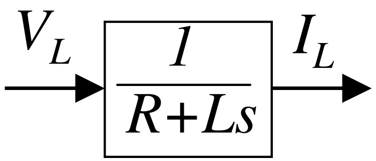
Intermediary steps are required for complex systems

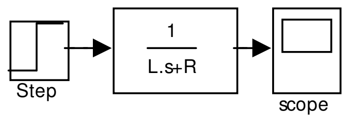
- Basic example -

system model | system representation | system simulation



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





smoothing inductor

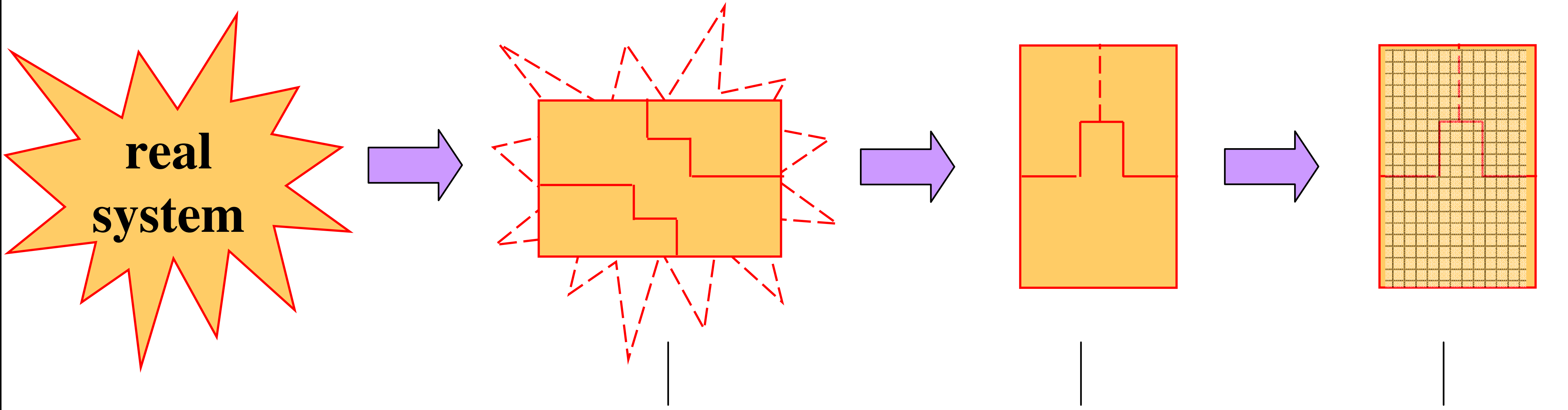
(low frequency dynamical model)

(bloc diagram +Laplace)

(Simulink © +Range Kutta)

- Different categories -

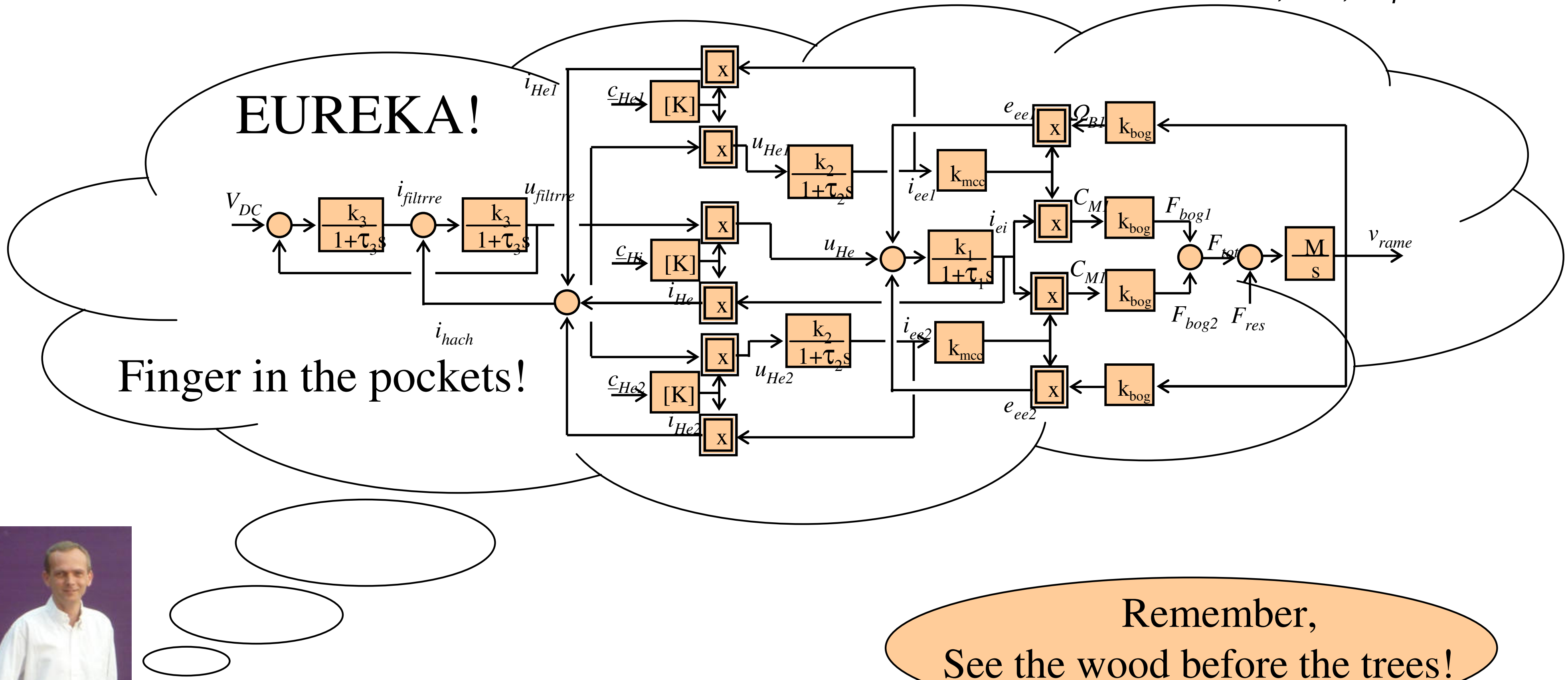
system model — system representation — system simulation



- dynamical / quasi-static / static
- structural/functional
- causal/non-causal
- backward / forward

Different possibilities at each step in function of the objective

- Limitation of classical bloc diagrams -



Remember,
See the wood before the trees!

But bloc 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

« 2. System and Interaction »

How to connect multi-physical subsystems?

System = interconnected subsystems
organized for a common objective,
in interaction with its environment

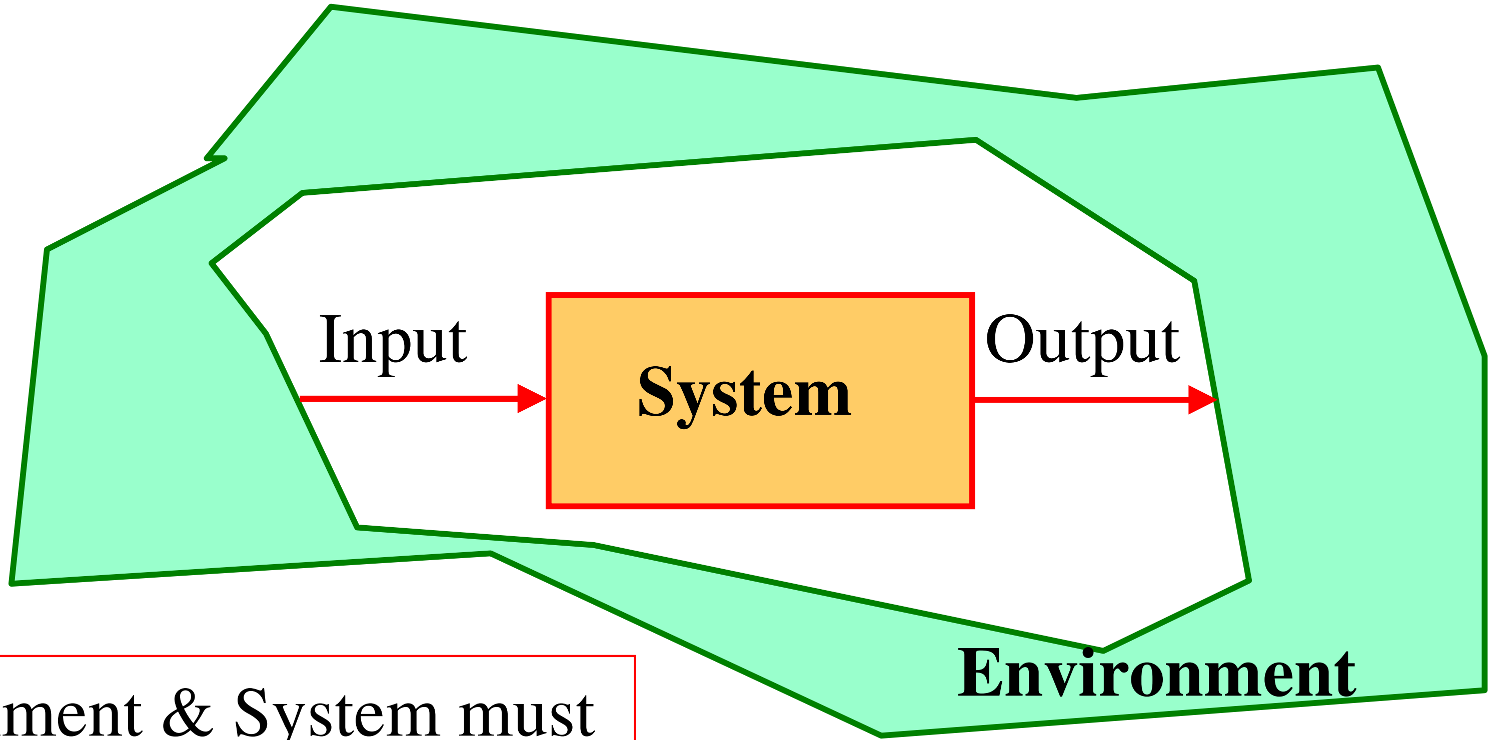
Systemic = science of study of systems and their interactions

Cartesian approach = the study of subsystems is sufficient to know the system behavior (without considering their interactions)

Interactions is the keyword

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)

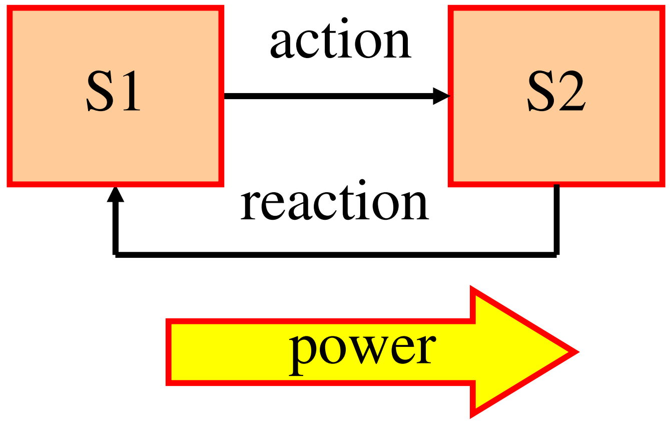


Environment & System must be defined first!

- Interaction principle -

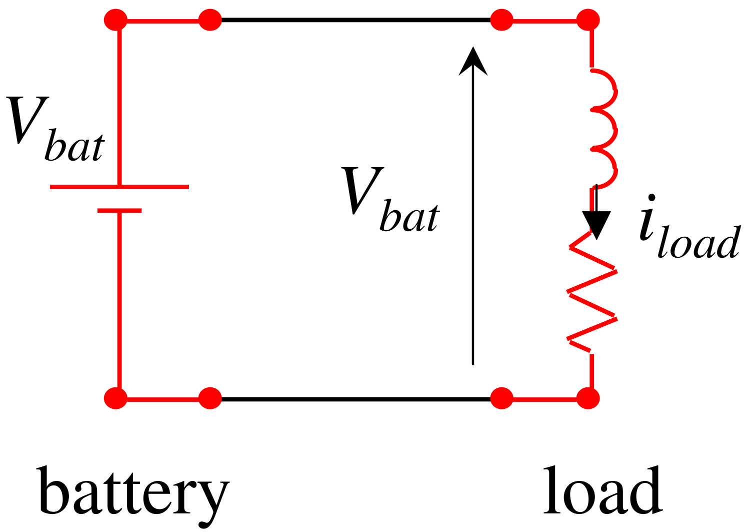
Interaction principle

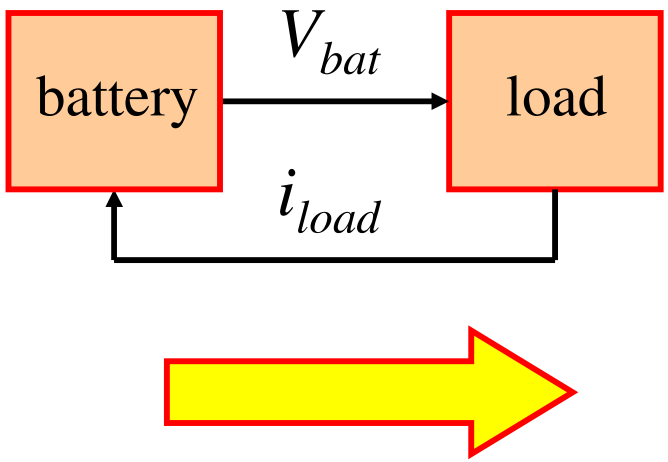
Each action induces a reaction



Power exchanged by S1 and S2 = action x réaction

Example



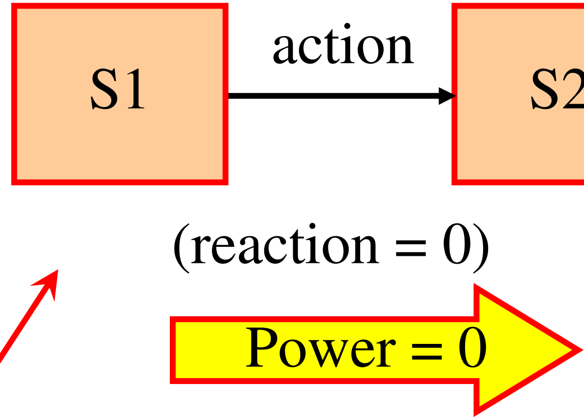


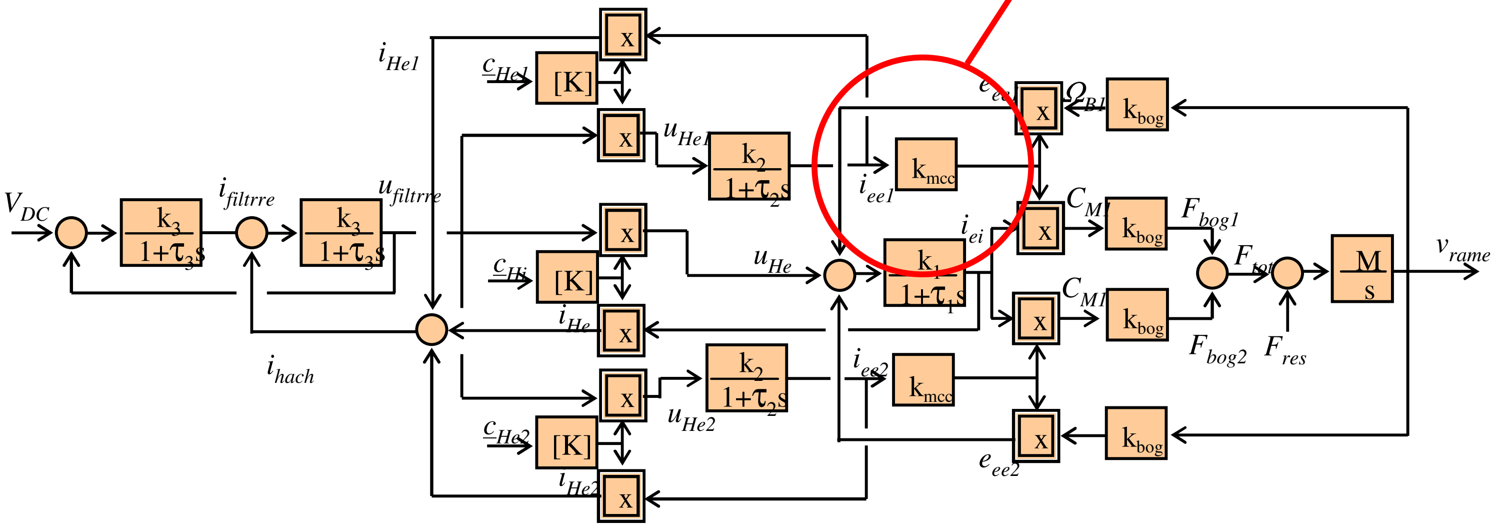
$$P = V_{bat}\, i_{load}$$

If the interaction principle is
not respected for 1 subsystem

⇩

Error in the energy analysis
for the whole system





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.

Cybernetic systemic

black box approach.

behaviour model

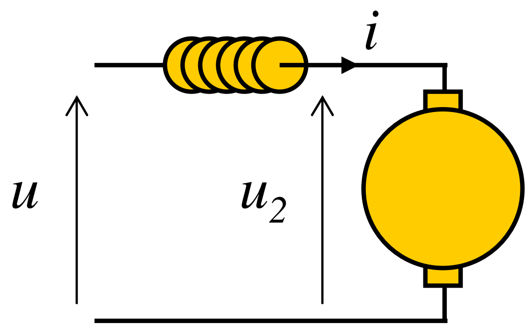
Cognitive systemic

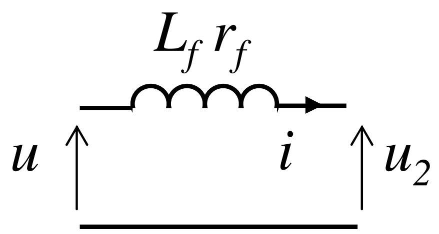
physical laws

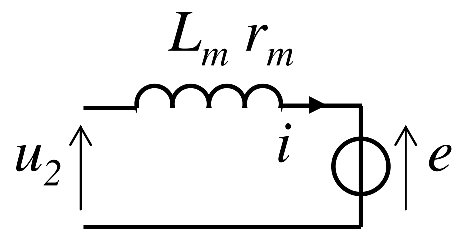
knowledge model

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

DC machine and smoothing inductor

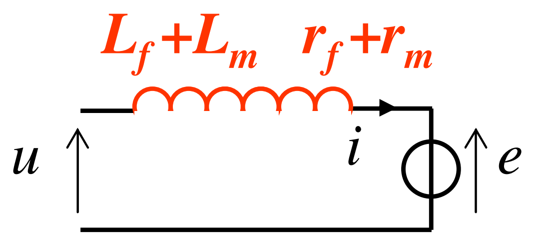






$$L_f \frac{di}{dt} = u - u_2 - r_f i$$

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



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

Association of both subsystems ⇨ must be studied globally

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

- Systemic and Cartesian approaches -

System 1 vs. System 2

Team made of partners → Systemic approach

Group made of individualists → Cartesian approach

Spain 2 – 0 France

(EMR'12, Madrid)

« 3. Energy and Causality »

How to manage energy in the best way?

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

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

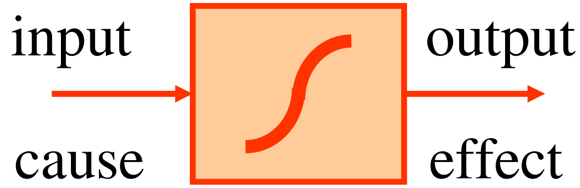
but

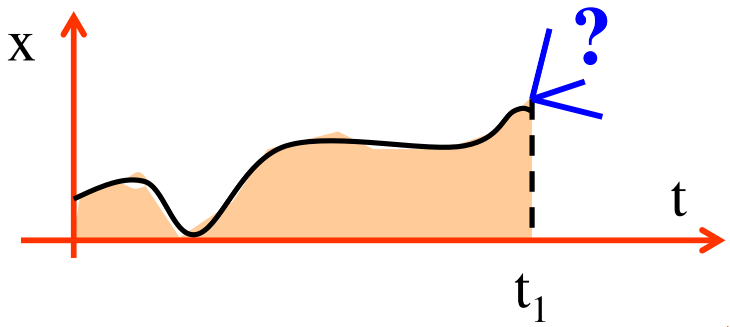
Energy dissipation: losses, reduction of efficiency

Energy accumulation: delay in energy transfer

Energy accumulation in subsystems is key transformation for safety and efficiency

Principle of causality
physical causality is integral





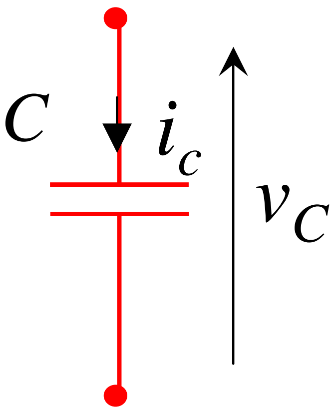
$\int x dt$ ⇨ area ⇩ knowledge of past evolution

OK in real-time

~~knowledge of future evolution ⇧ slope ⇦ $\frac{dx}{dt}$~~

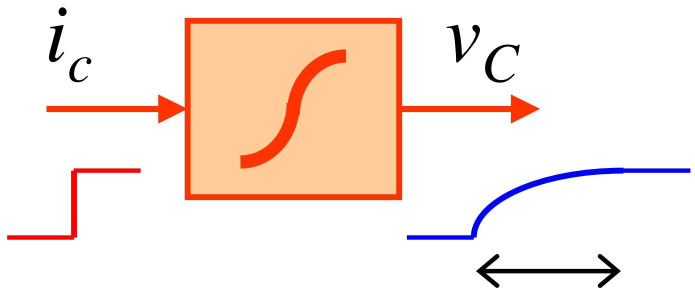
impossible in real-time

Example

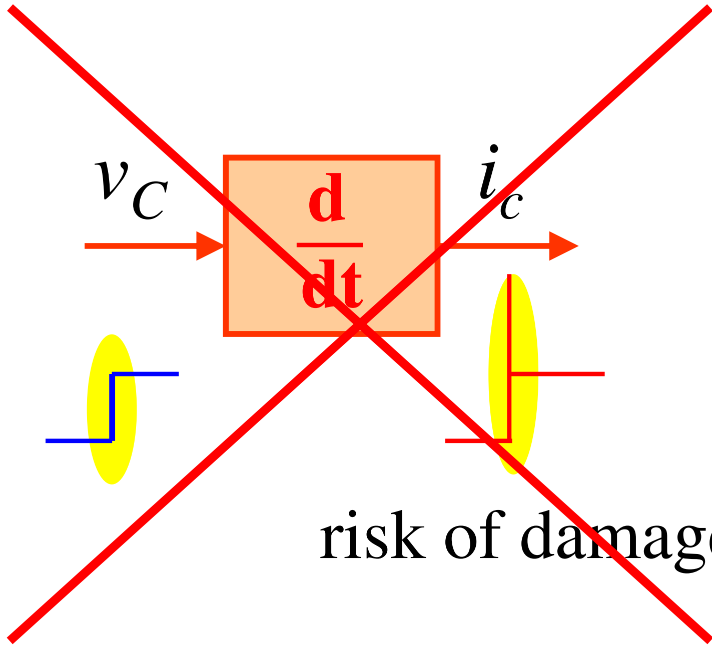


$$i_c = C \frac{d}{dt} v_c$$

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



delay
no energy disruption

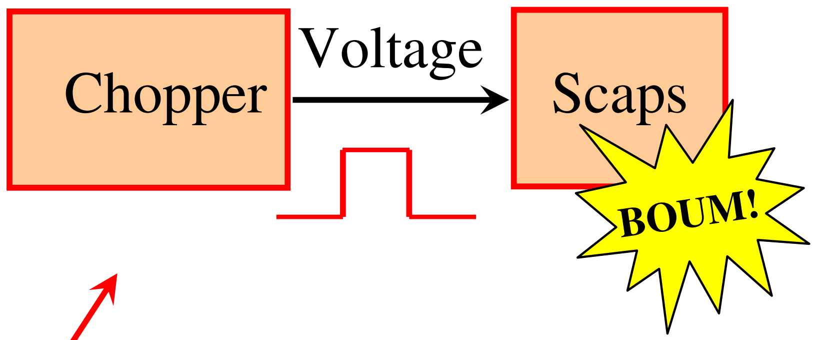


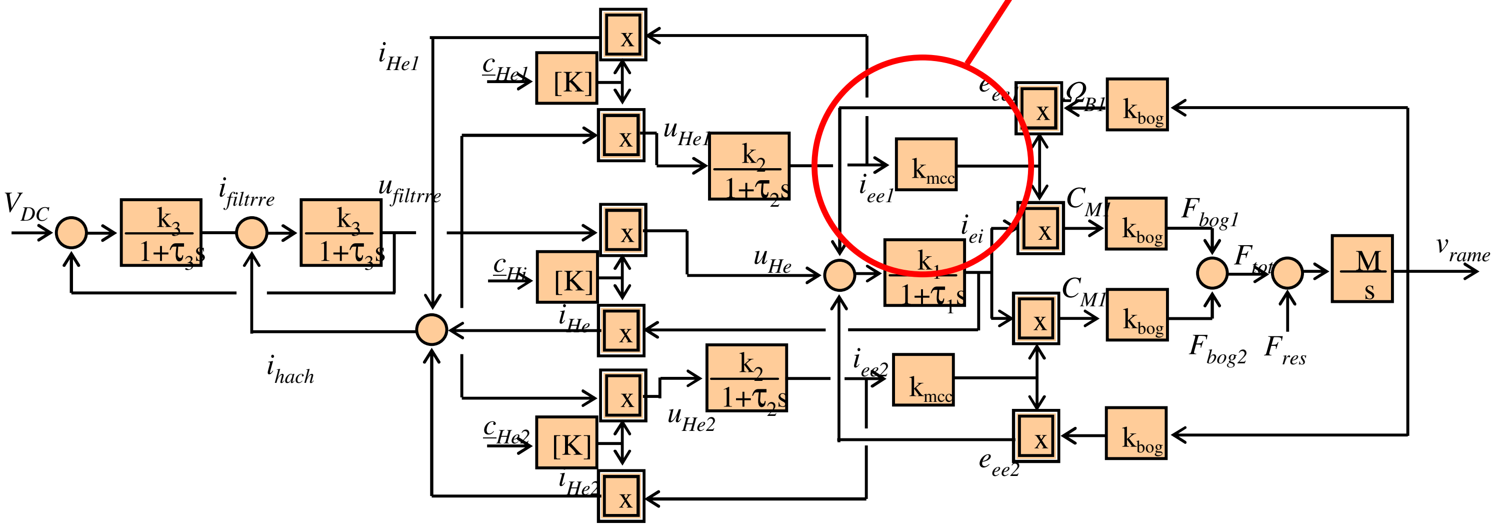
For energetic systems
physical causality is VITAL

If the causality principle is not respected for 1 subsystem

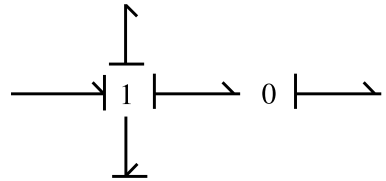
⇩

Risk of damage!
No real-time management





Energy & System

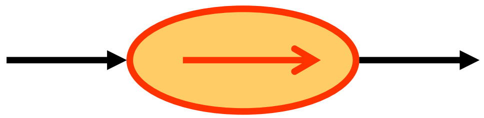


Energetic Puzzles (Laplace, France)
Bond Graph (USA, The Netherlands…)
Power Oriented Graph (Italy)
Signal Flow Diagram (Germany, Japan...)

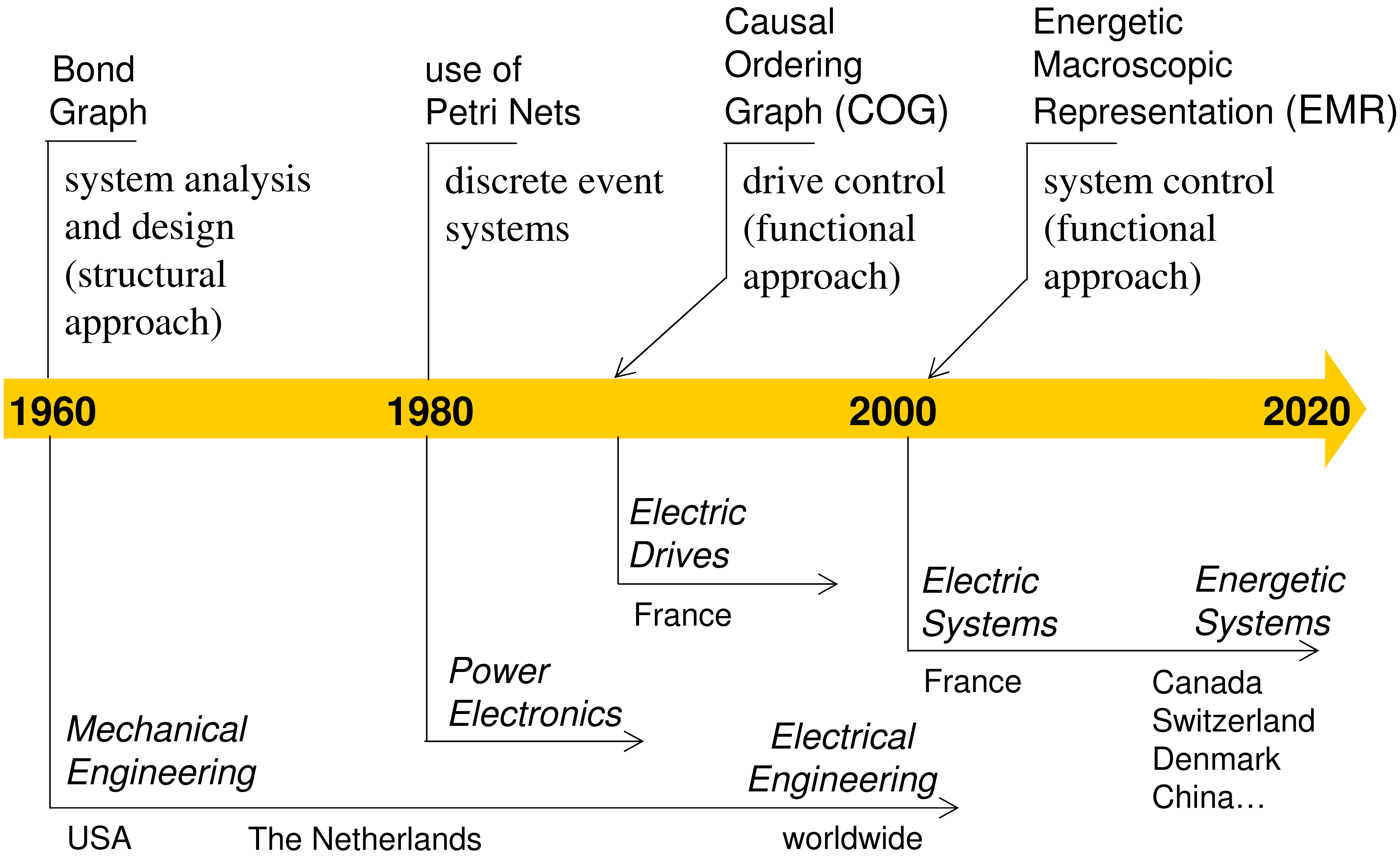
Structural description for analysis and design ⇨ mathematical model ⇩ global controls

Block diagrams
COG (L2EP-LEEI, France)
EMR (L2EP, France)

functional descriptions for simulation and control ⇨ inversion graphs ⇩ cascaded control



Remember, Dr. B,
divide and conquer!


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
Energetic
Systems
France
Canada
Switzerland
Denmark
China…
Power
Electronics
Mechanical
Engineering
Electrical
Engineering
USA
The Netherlands
worldwide

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

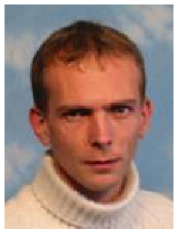
in order to respect its energy properties

graphical description = model organization

useful intermediary step

Prof. Alain BOUSCAYROL
University of Lille 1, L2EP, France
Coordinator of **MEGEVH**, French network on HEVs
General Chair of IEEE-VPPC 2010, Lille France
Co-chair of EPE'13 ECCE Europe, Lille, France

Prof. C.C. Chan
Tne University of Hong-Kong, China
Fellow, Royal Academy of Engineering, U.K.
Academician, Chinese Academy of Engineering
President, Electric Vehicle Association of Asia Pacific
Honorary Professor, University of Hong Kong



Dr. Philippe BARRADE
Ecole Polytechnique Fédérale de Lausanne, Switzerland
PhD on Electrical Engineering at Univ. Toulouse (1997)
Enginneeer at SAFT company on UPS applications (1998)
Assistant Prof. at Laboratoire d'Electronique Industrielle, EPFL since 1999
Research topics: Energy Storage Systems and Power Electronics

- References -

P. J. Barre, & al, "Inversion-based control of electromechanical systems using causal graphical descriptions", *IEEE-IECON'06,* Paris, November 2006.

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, according to the SMM project of the GDR-SDSE).

A. Bouscayrol, G. Dauphin-Tanguy, R Schoenfeld, A. Pennamen, X. Guillaud, G.-H. Geitner, "Different energetic descriptions for electromechanical systems", *EPE'05,* Dresden (Germany), September 2005. (common paper of L2EP, LAGIS and University Dresden).

C.C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles", *Proceedings of the IEEE,* Vol. 95, No.4, pp. 704-718, April 2007.

C.C. Chan, A. Bouscayrol, K. Chen, "Philosophy of Engineering and Modelling of Electric Drives", International Conference on Electrical, Keynote, October 2008, Wuhan (China)

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 L2EP Lille and Honk-Kong University).

G. H. Geitner, "Power Flow Diagrams Using a Bond graph Library under Simulink", *IEEE-IECON'06,* Paris, November 2006.

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.

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

R. Zanasi, R. Morselli, "Modeling of Automotive Control Systems Using Power Oriented Graphs", *IEEE-IECON'06,* Paris, November 2006.

« Annexes »

different kinds of objectives

⇩

different kinds of modelling

Objectives:
- component design/optimization
- component control
- system analysis (efficiency…)
- energy management of the system
- ….

Which model?

Modelling:
- structural/functional models
- static/dynamic models
- causal/ acausal representations
- backward/forward simulation
- …

[Chan 2010]

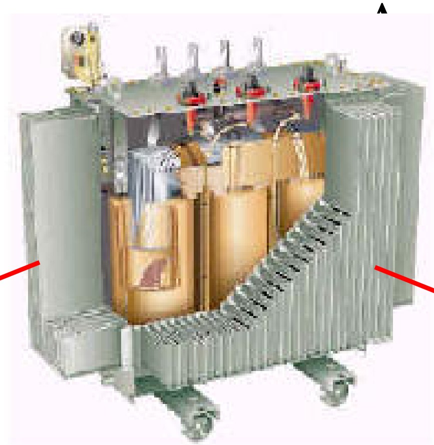
How to describe a system?

Structural description

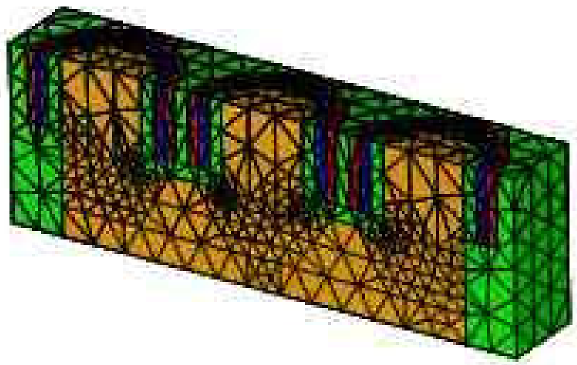
- Physical structure in priority
- Physical links between subsystems
- Design application

Functional description

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



Example



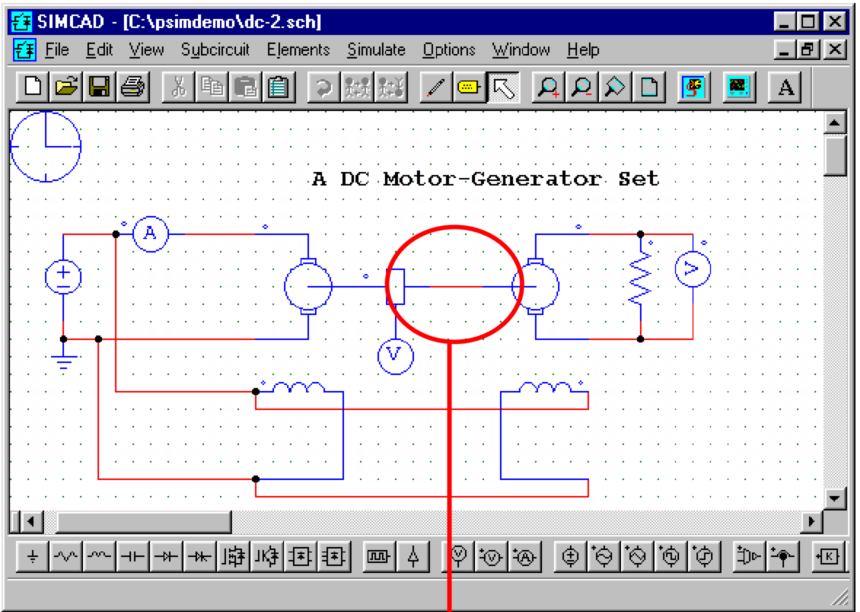
3D Finite Element Model

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

Mathematic model
Assumption:
Ideal transformer

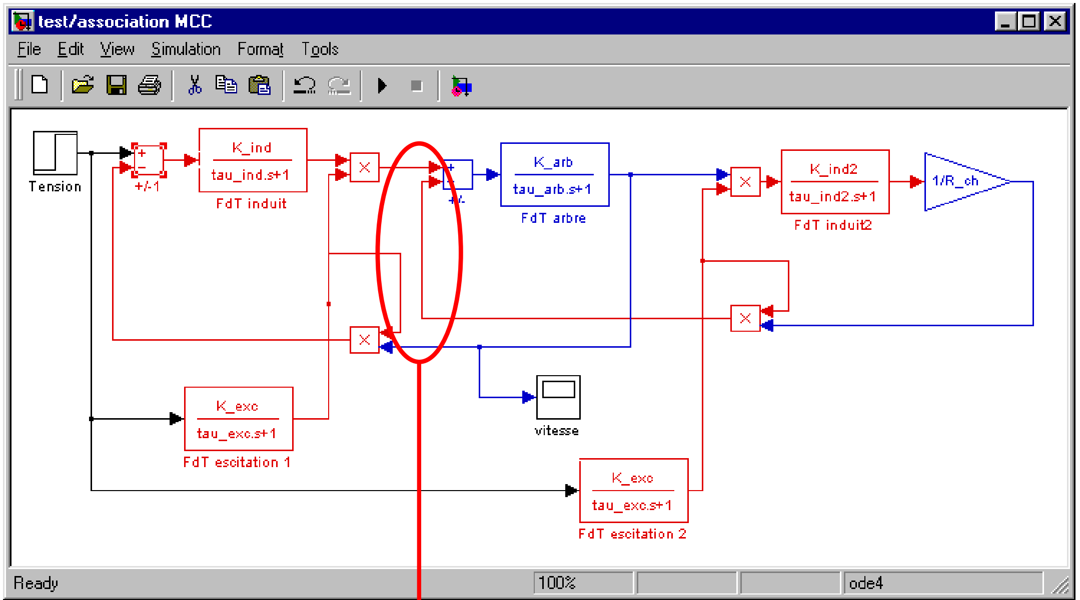
two DC machine system

PSIM (structural)



machines connected by
a unique link (shaft)

Matlab-Simulink (functionnal)



machines connected by
two links (torque/speed)

Which model subsystem?

Static model

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

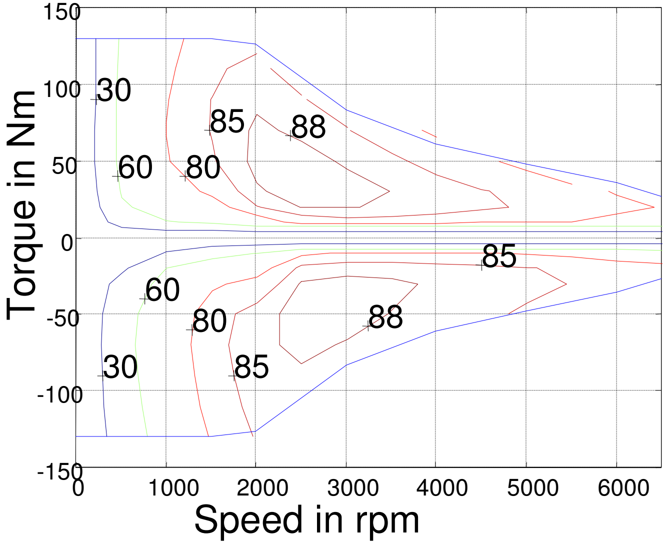
Dynamic model

- 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

static efficiency map



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

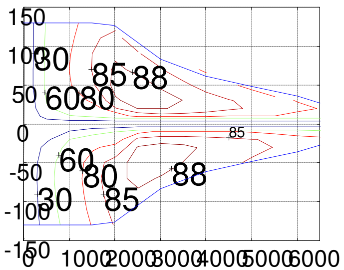
dynamic model

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

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

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

quasi-static model



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

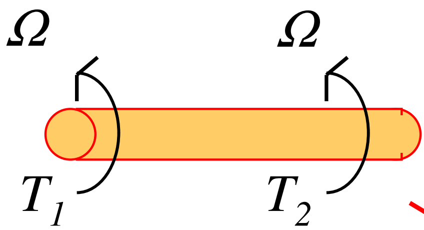
How to connect subsystem?

Causal description

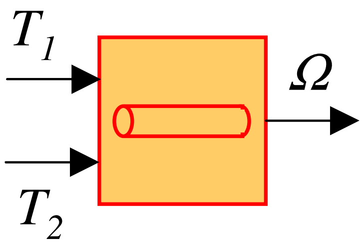
- fixed input and output
- output = integral function of inputs
- difficult interconnection subsystems
- basic solver

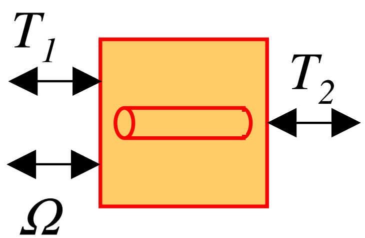
Non-causal (acausal) description

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

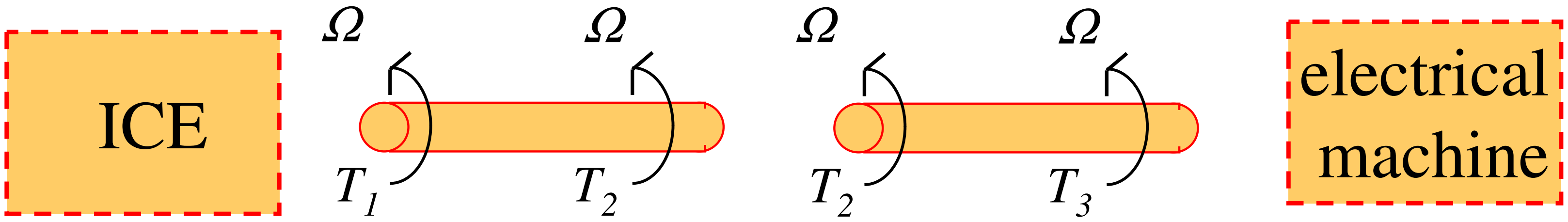


$$J \frac{d}{dt}\Omega = T_1 - T_2$$



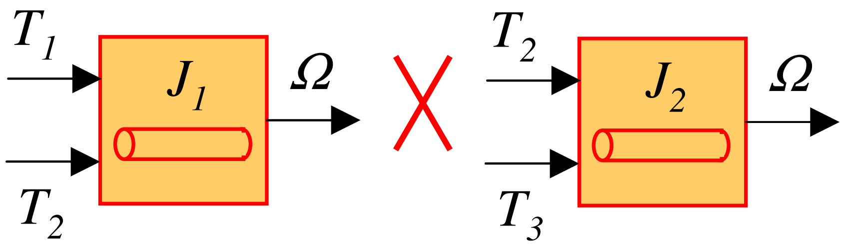


Example

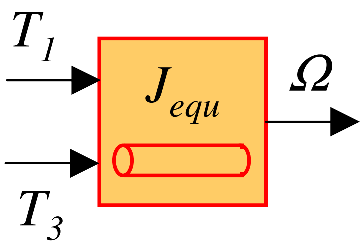


$$J_1 \frac{d}{dt}\Omega = T_1 - T_2 \qquad J_2 \frac{d}{dt}\Omega = T_2 - T_3$$

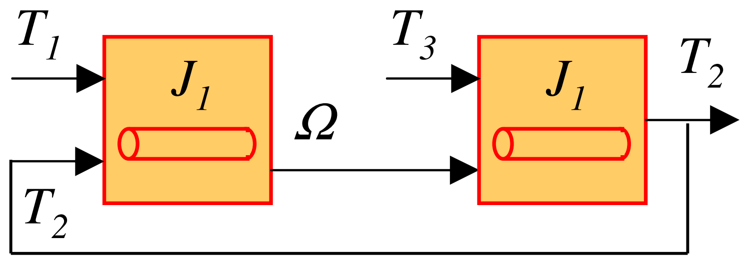
causal description



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



acausal description



derivative relationship

specific solver

Which method to compute the model?

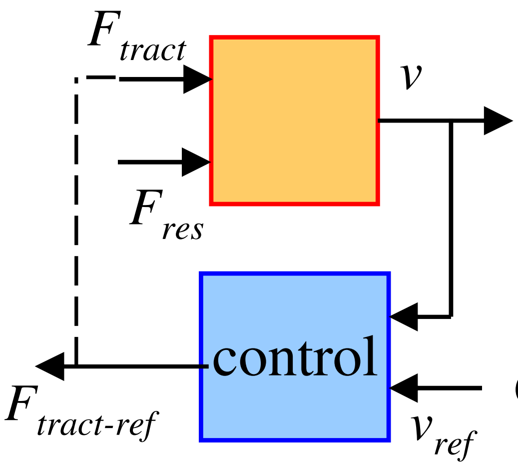
Forward approach

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

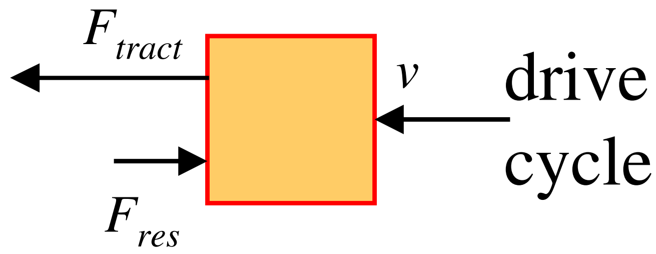
Backward

- from the desired effect to the required cause
- anticipate energy flow
- no controller required

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

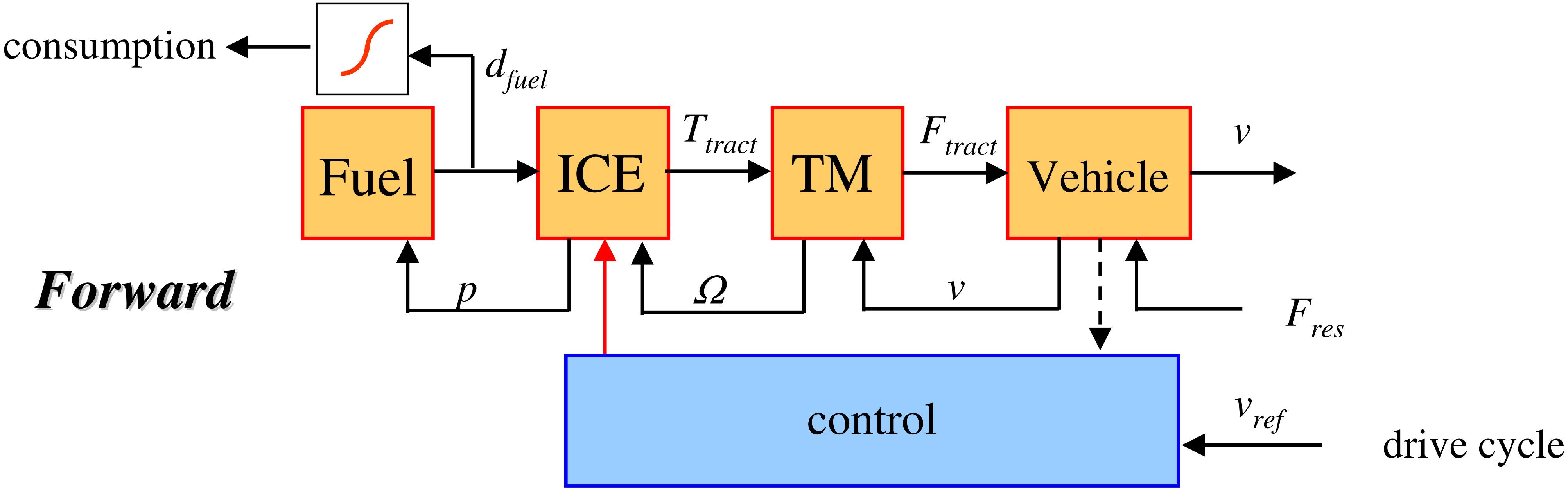


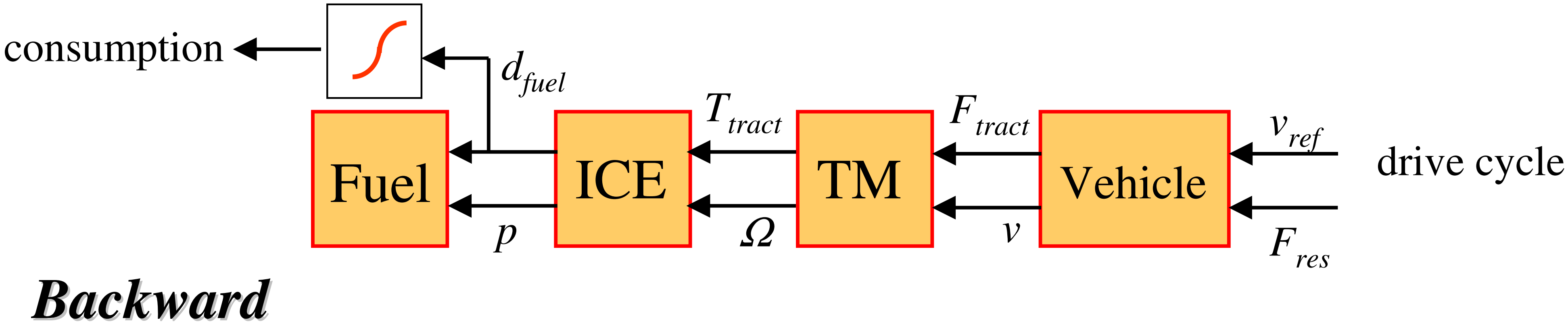
drive cycle



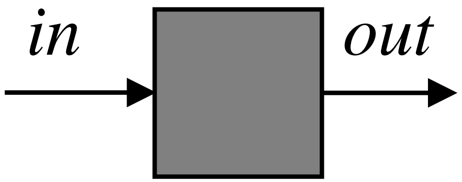
derivative relationship
(no real-time application)

- Example of fuel consumption of a vehicle -





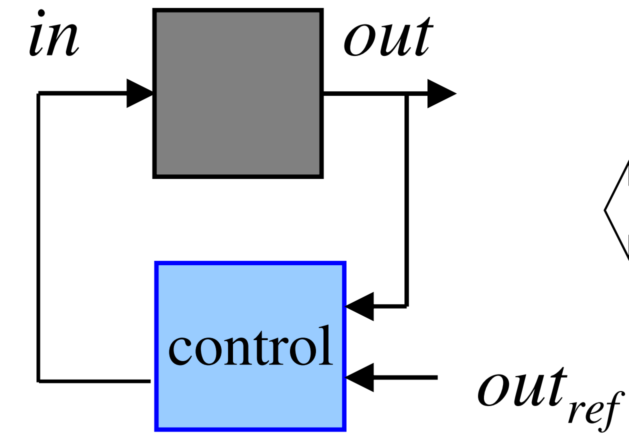
could be same models, but different representations (cf. I/O) or "Black box" approach: no internal knowledge



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

Behavior model:
out(t) = f(t) *in(t)*

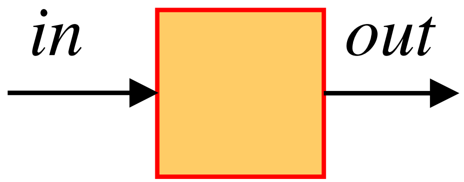
closed-loop control of *out*:
for uncertainty compensations



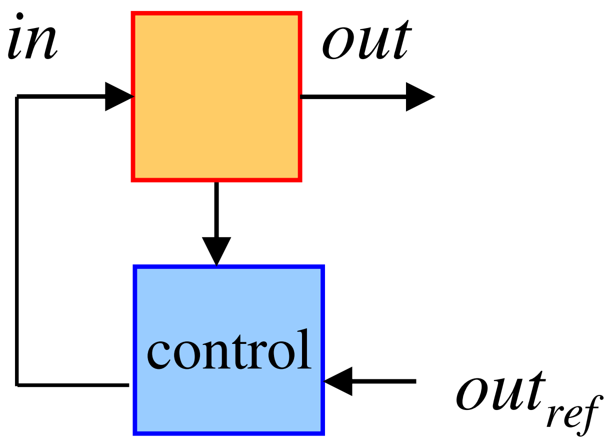
or "White box" approach: prior internal knowledge

Physical laws of system components

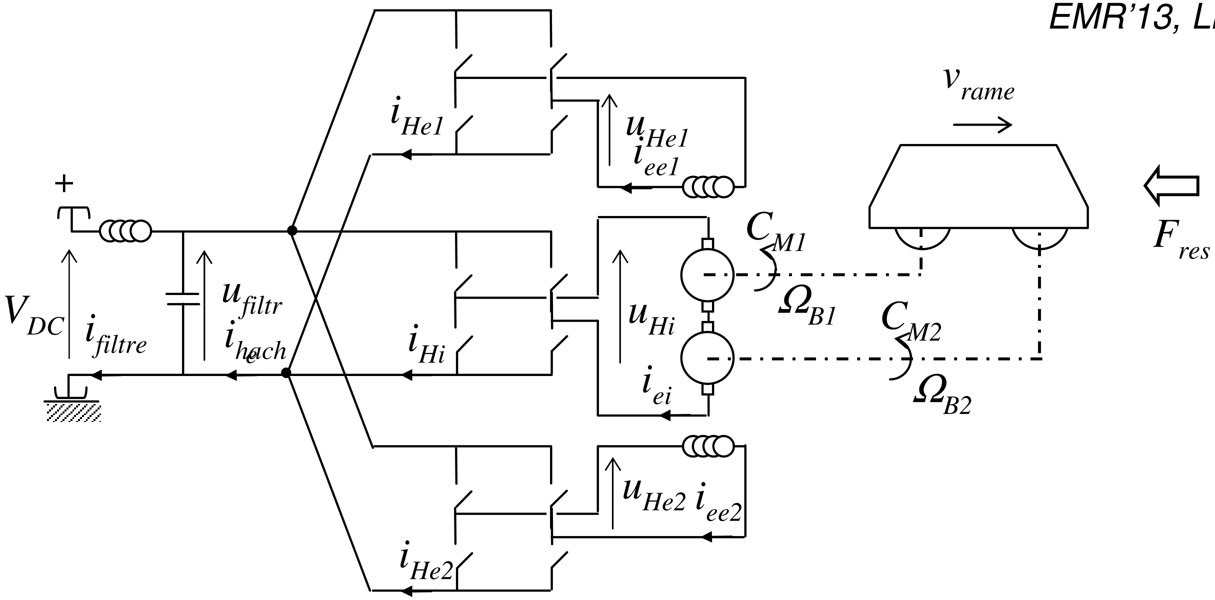
Knowledge model:
$out(t) = \mathrm{f(t)}\ in(t)$



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

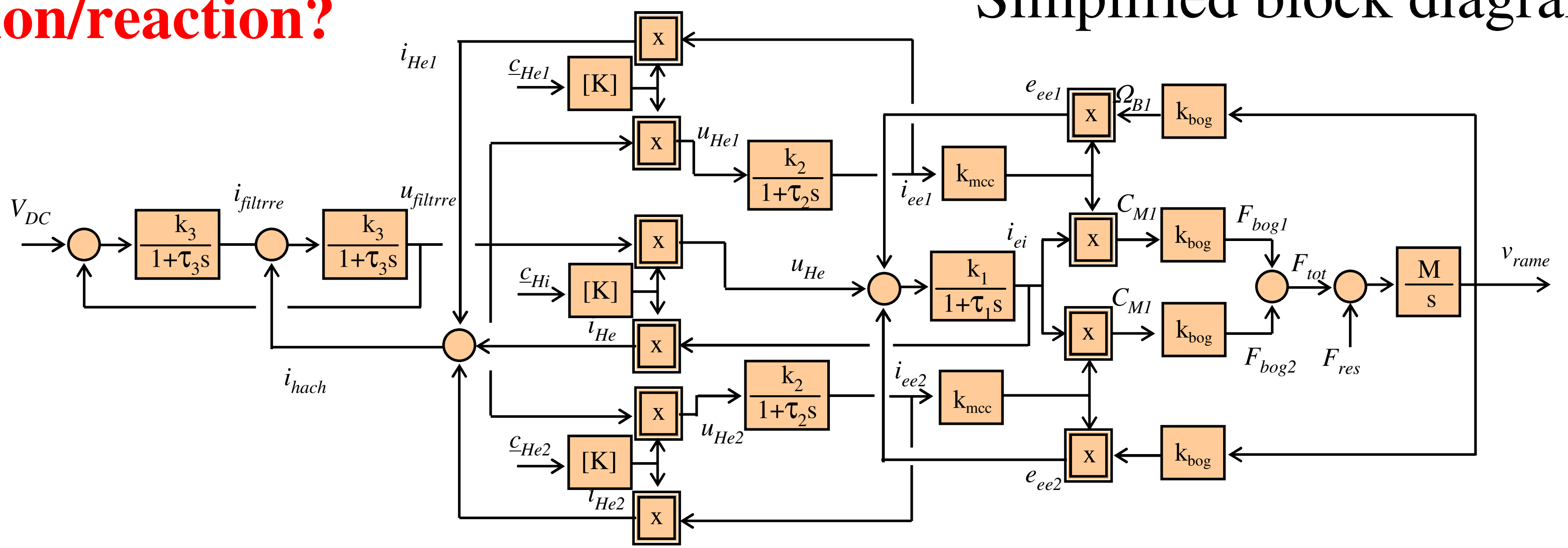


- Example of a railway traction system -

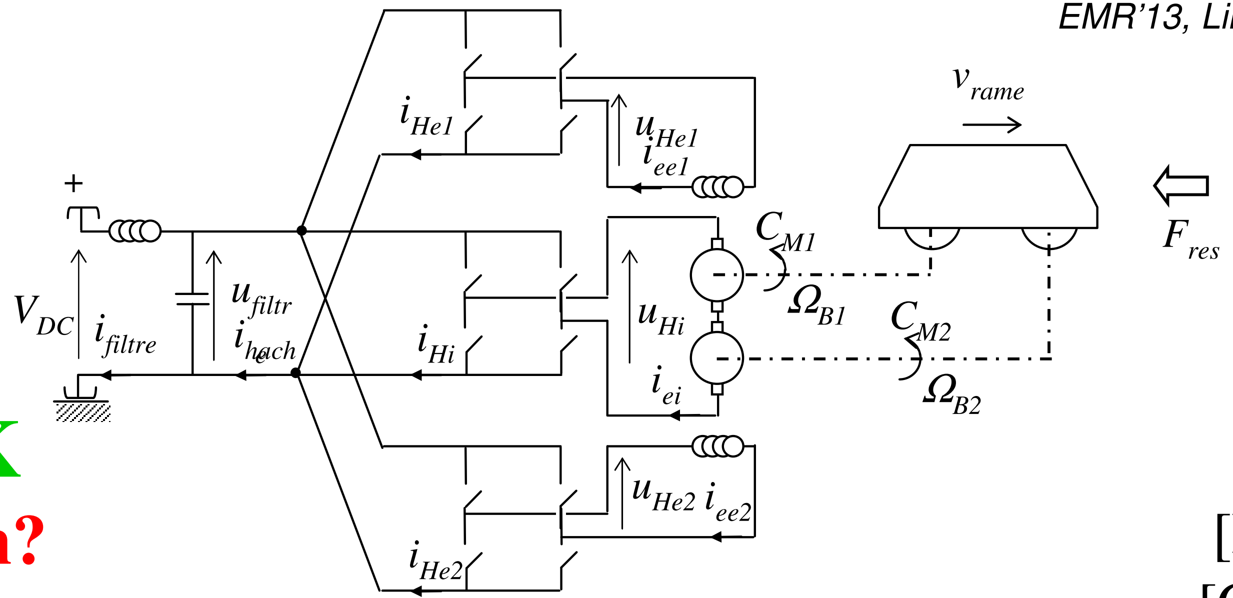


causality?
action/reaction?

Simplified block diagram



- Example of a railway traction system -

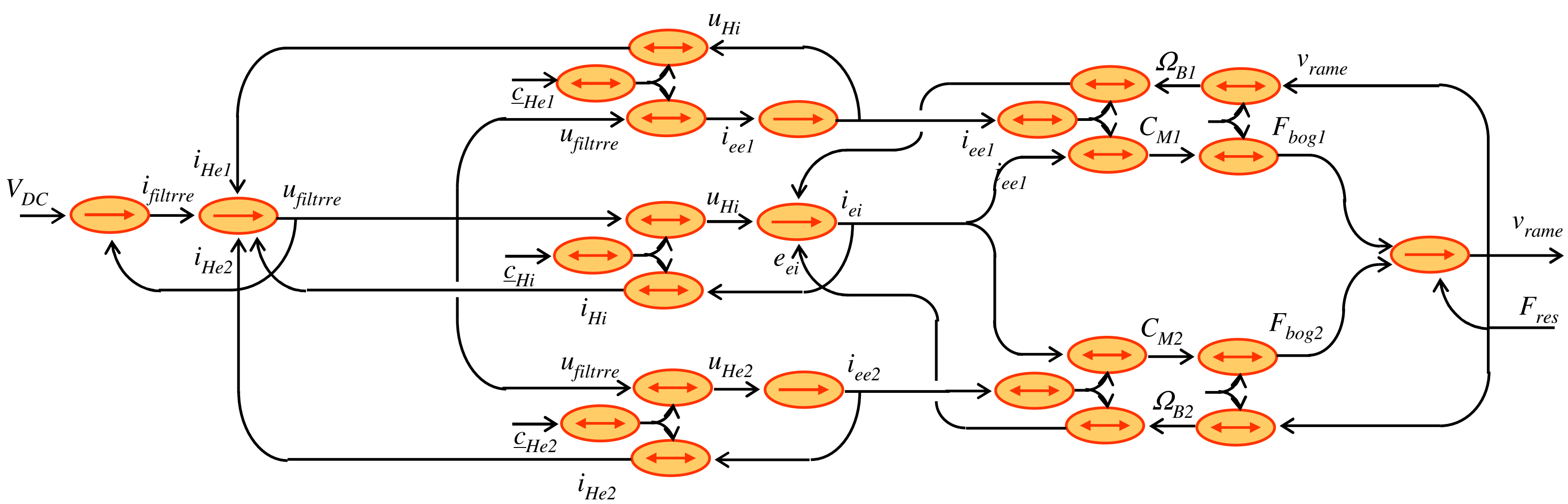


causality OK

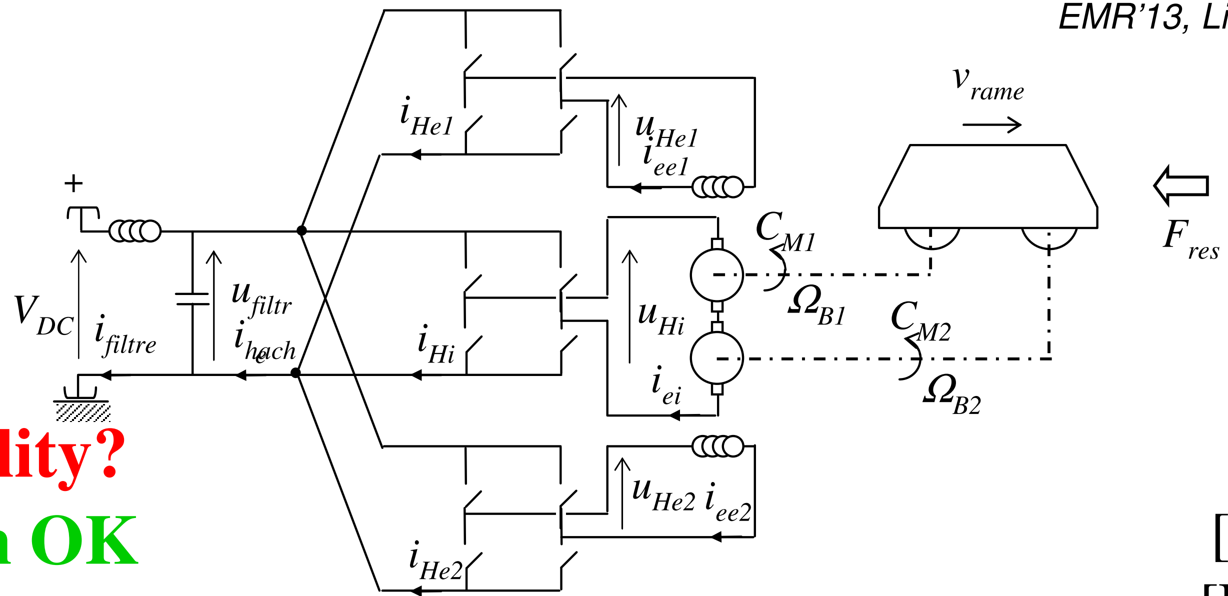
action/reaction?

[Hautier 96]
[Guillaud 01]

Causal Ordering Graph (COG)



- Example of a railway traction system -

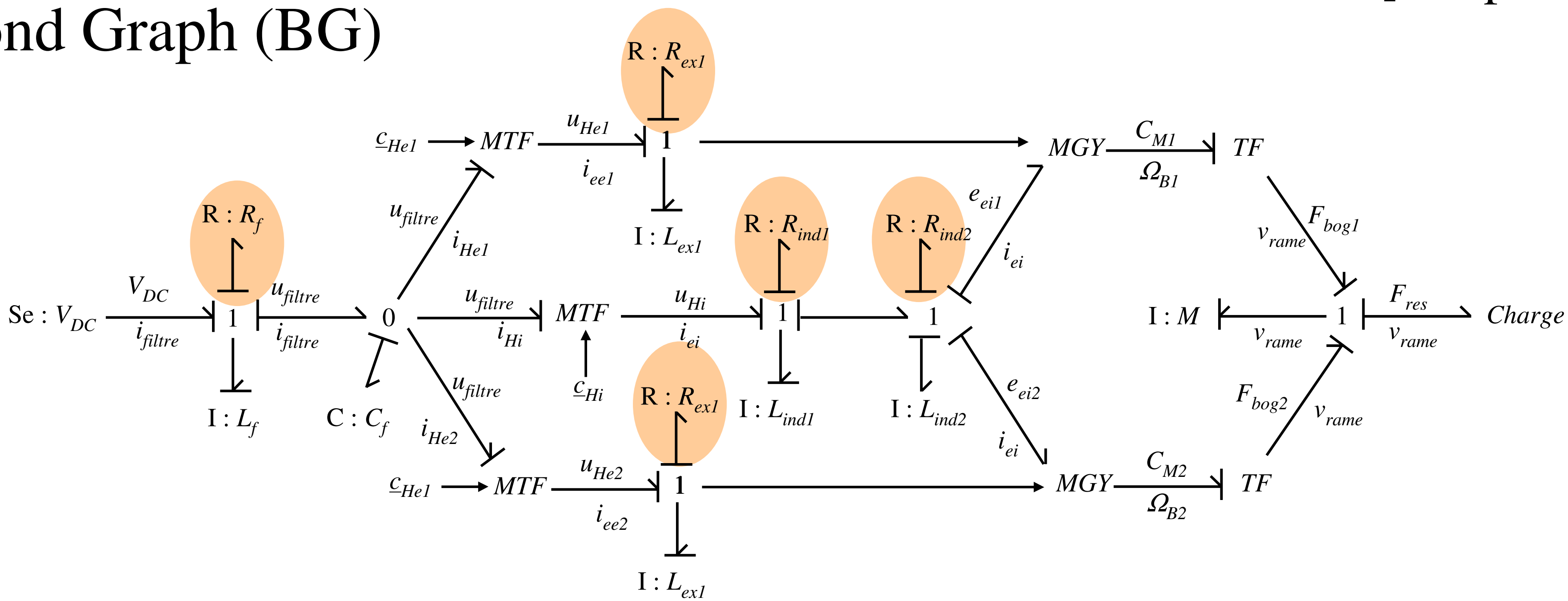


physical causality?

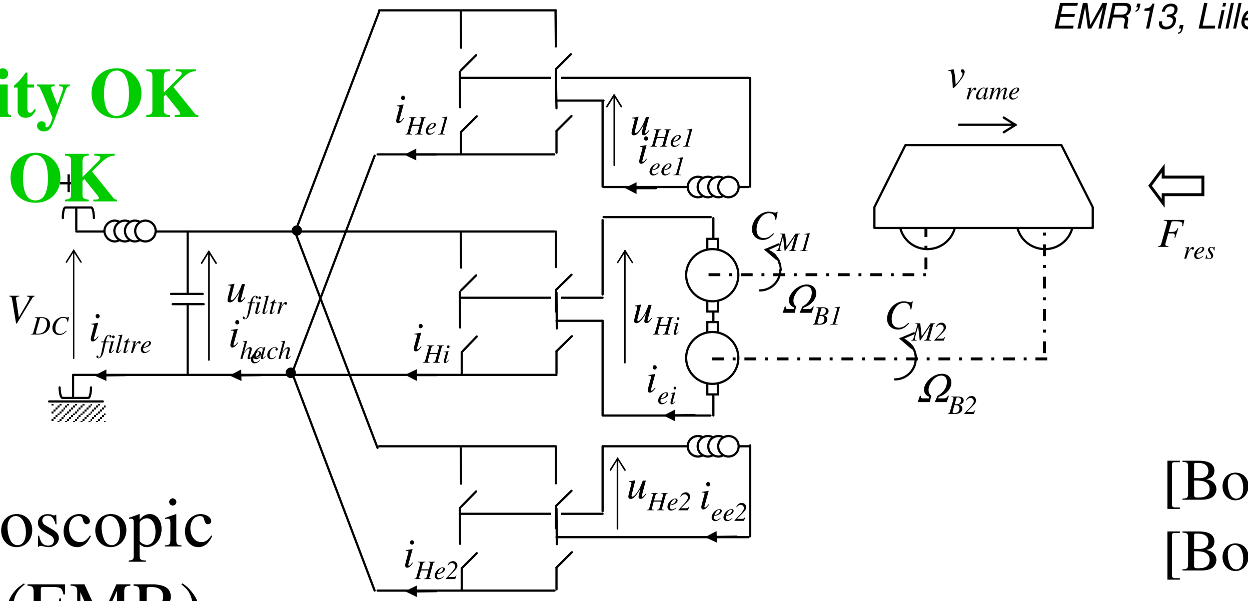
action/reaction OK

[Paynter 61]
[Dauphin 99]

Bond Graph (BG)

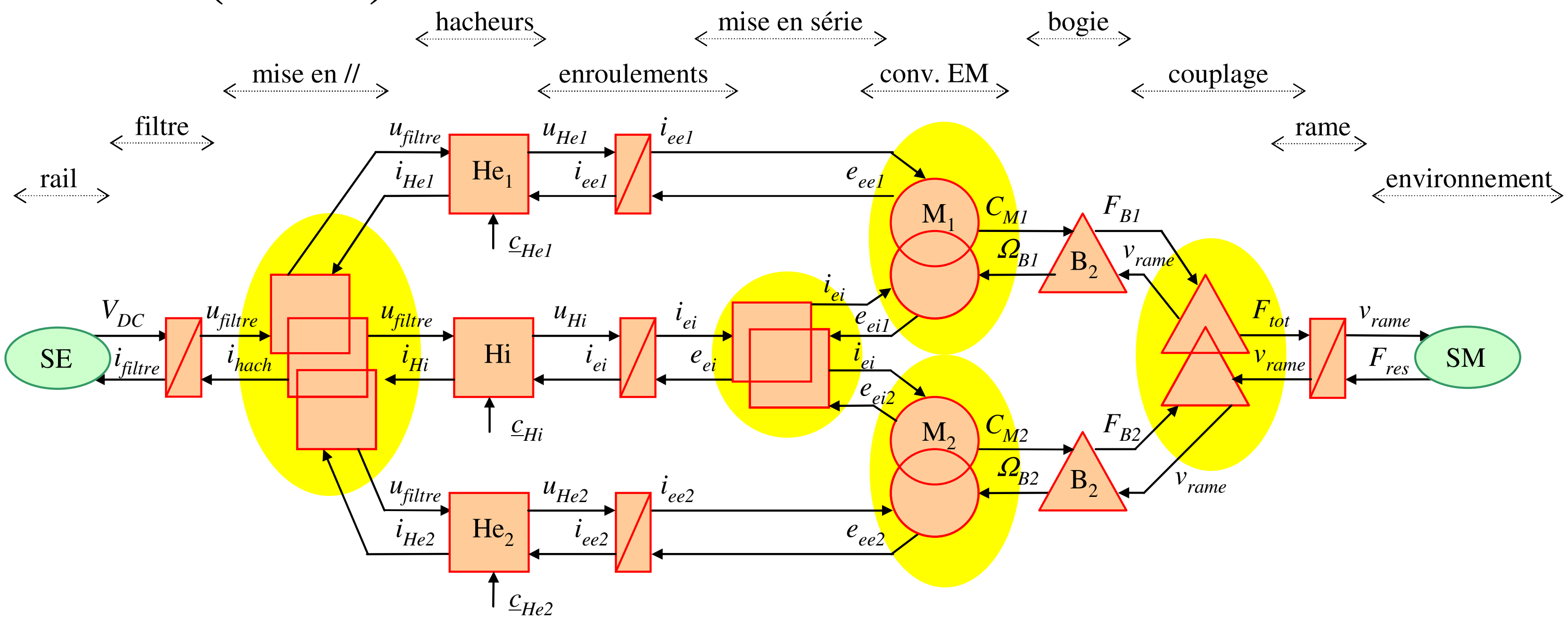


physical causality OK
action/reaction OK



Energetic Macroscopic Representation (EMR)

[Bouscayrol 00]
[Bouscayrol 05]



Multi-physical system ⇨ Systemic approach

Energy management ⇨ Energetic approach
Causal modeling

System control ⇨ Functional description

Real-time control ⇨ Dynamical modeling
Causal modeling

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

Energy management of HEVs:
Energy management of local subsystems
Energy management of the whole system (co-ordination of subsystems)

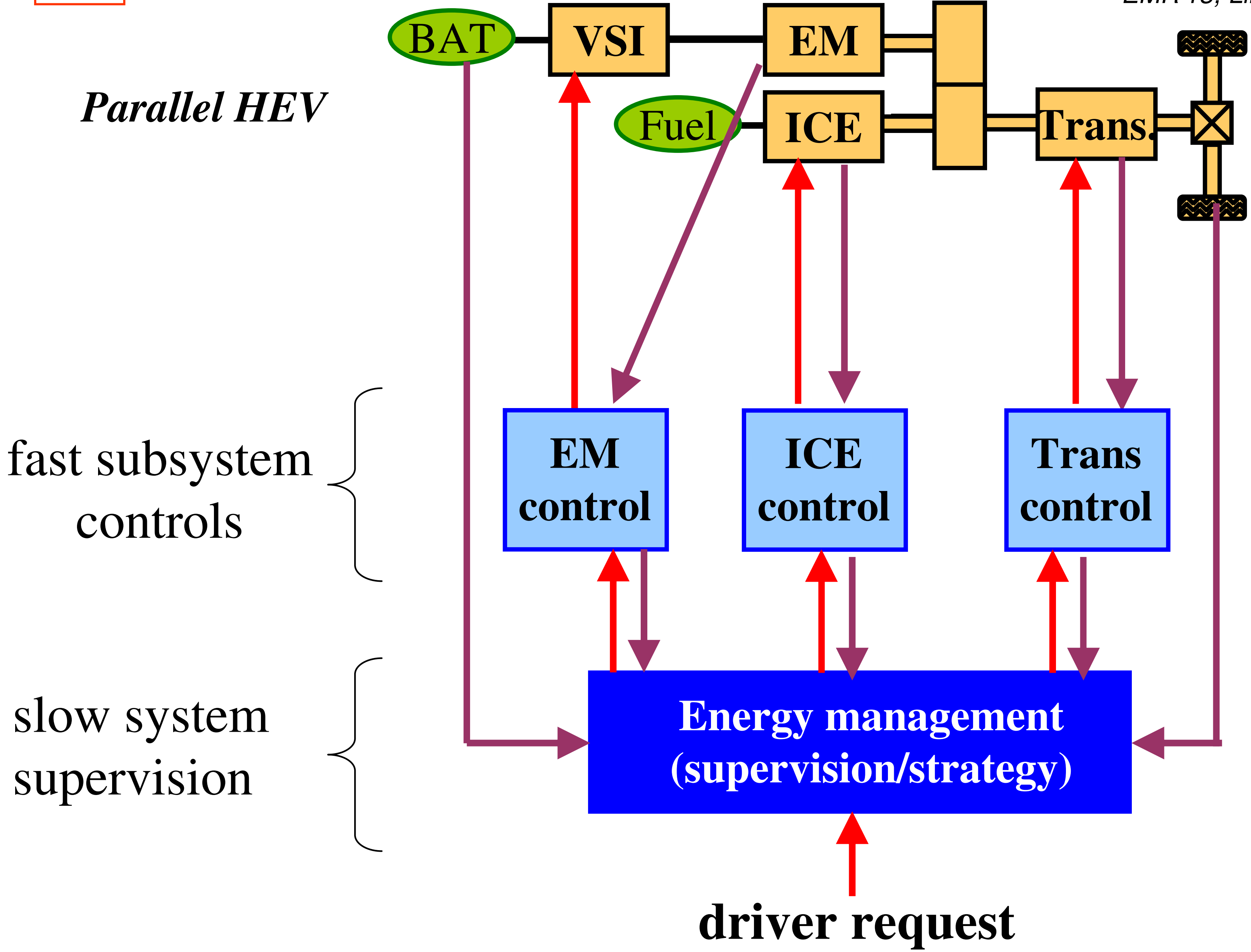
⇩

Two control levels can be organized:
- local control → Dynamic and causal models
- system supervision → Quasi-static models

compatibility in term of inputs/outputs ⇨ compatibility of the control levels

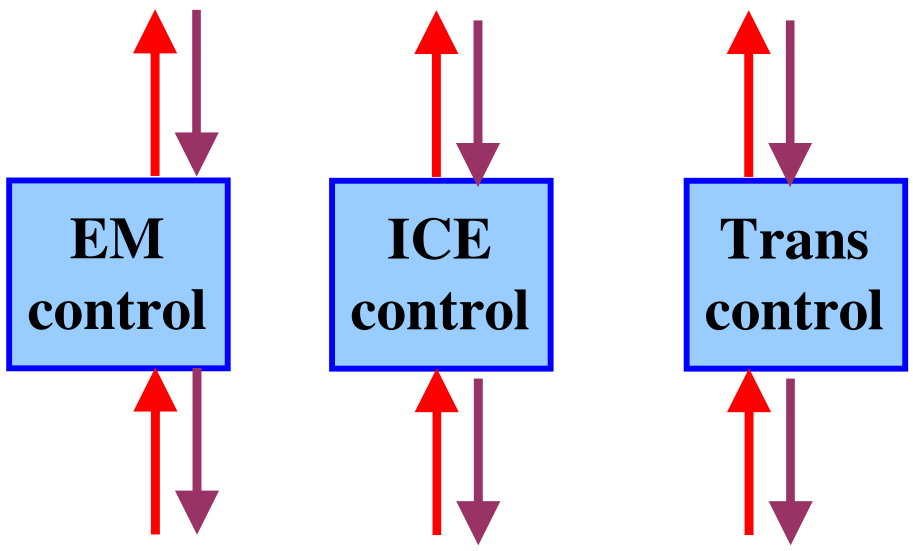
[Delarue & al 2005]

- Different control levels (example) -



Local energy management:

must take into account power flows in all parts of subsystems

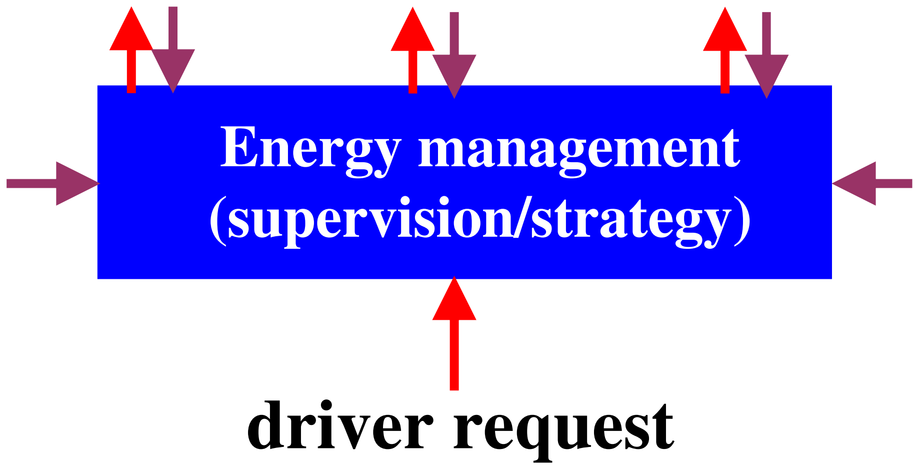


Classical controls of subsystems:

required dynamic and energetic models to manage power flows in real-time

Rule-based
- **deterministic rule-based**: state machine / power follower/ thermostat control…
- **fuzzy rule-based**: predictive / adpative / conventional…

Optimization based
- **global optimization**: Dynamic programming / stochastic DP / Game theory / Optimal control….
- **real-time optimization**: Robust control / Model predictive / decoupling control / l control…



[Salmasi 2007]