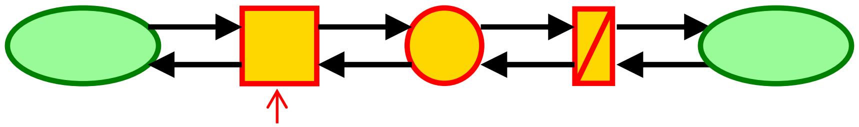
Polytech' Paris Sud
June 2014



« ENERGETIC MACROSCOPIC REPRESENTATION (EMR) »

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(University Lille1, L2EP, MEGEVH, France)

based on the course of Master
"Electrical Engineering & Sustainable Development"
University Lille1

POLYTECH PARIS-SUD

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

Université Lille1 Sciences et Technologies

1. Representation of energetic systems

- Representation I/O
- Principles to respect

2. EMR basic elements

- Source, accumulation and conversion elements
- Coupling and adaptation elements

3. EMR of a complete system

- Action and tuning path
- Association rules

4. Conclusion: towards control organization

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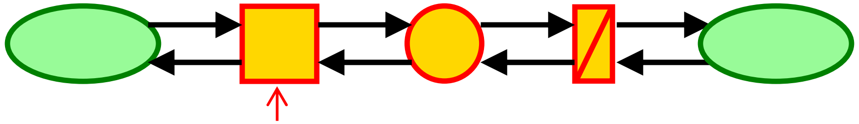
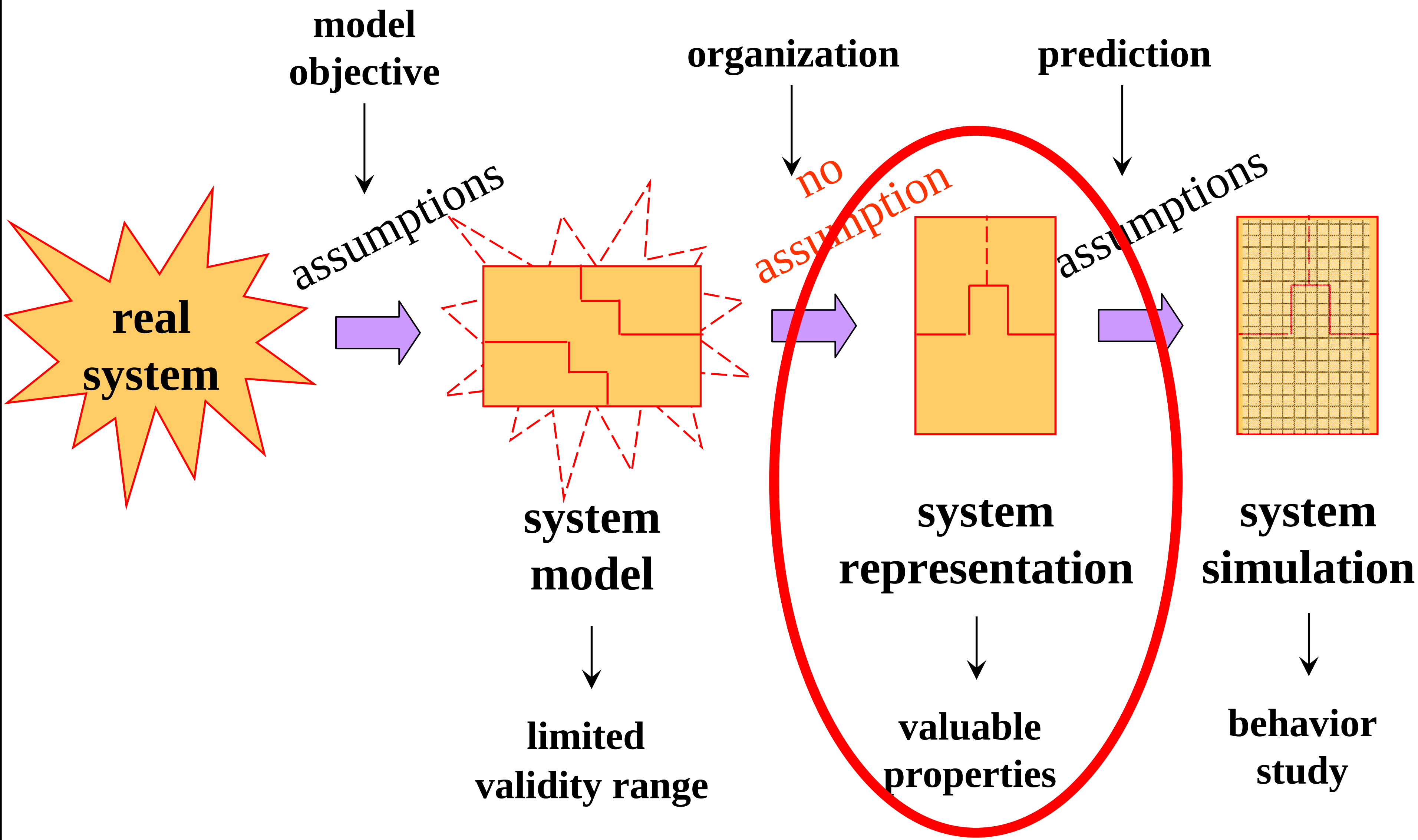
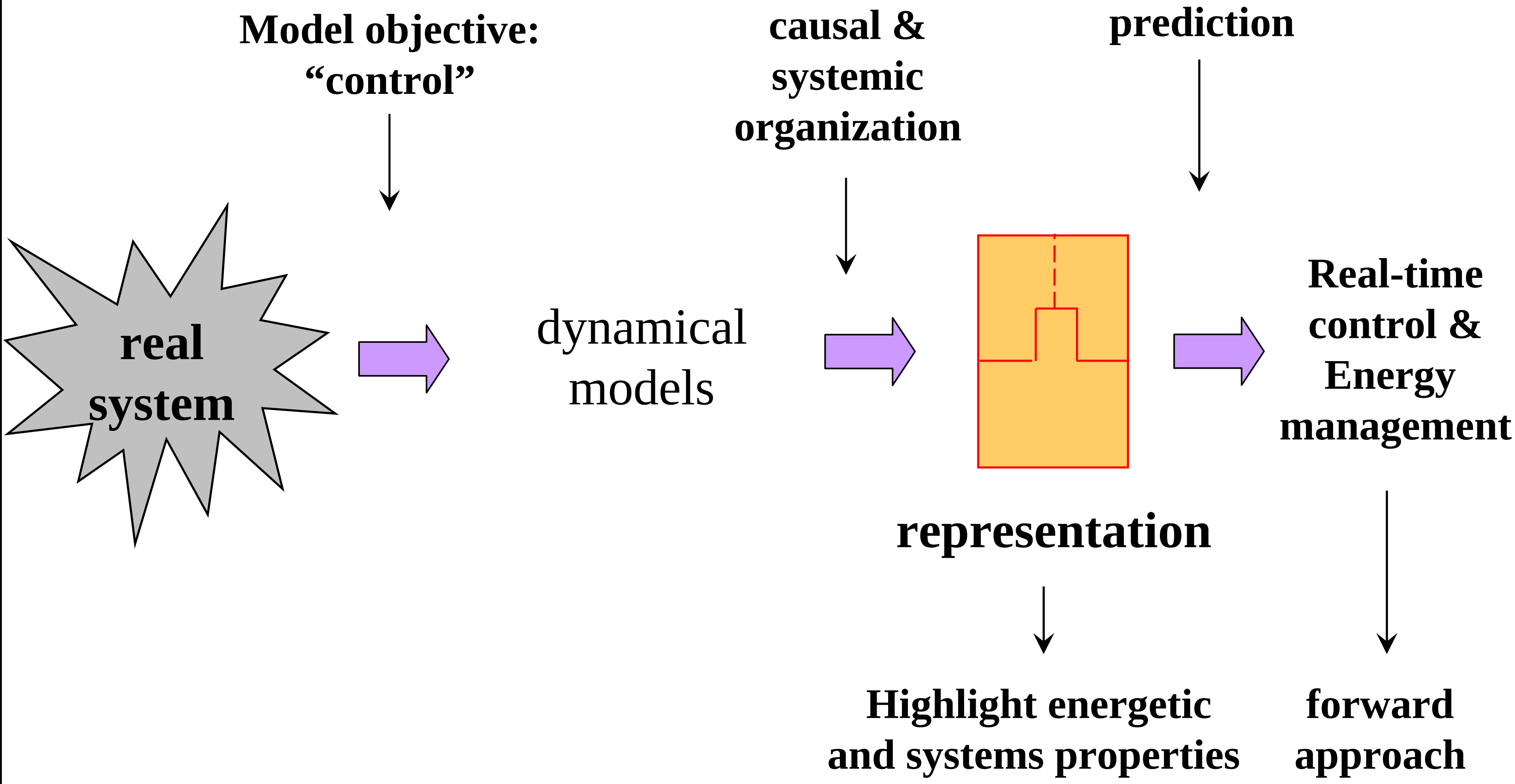


1. « Representation of energetic systems »

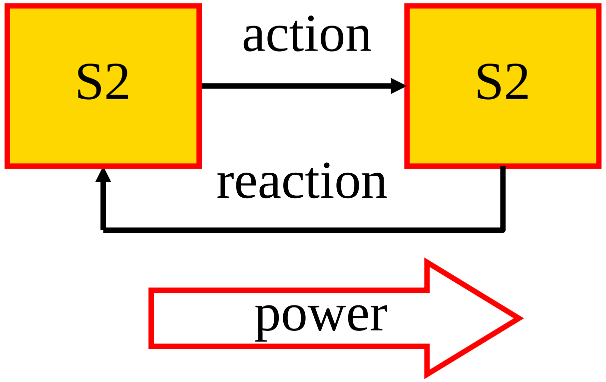
- Level of study -




Model objective:
“control”
causal &
systemic
organization
prediction
real
system
dynamical
models
Real-time
control &
Energy
management
representation
Highlight energetic
and systems properties
forward
approach

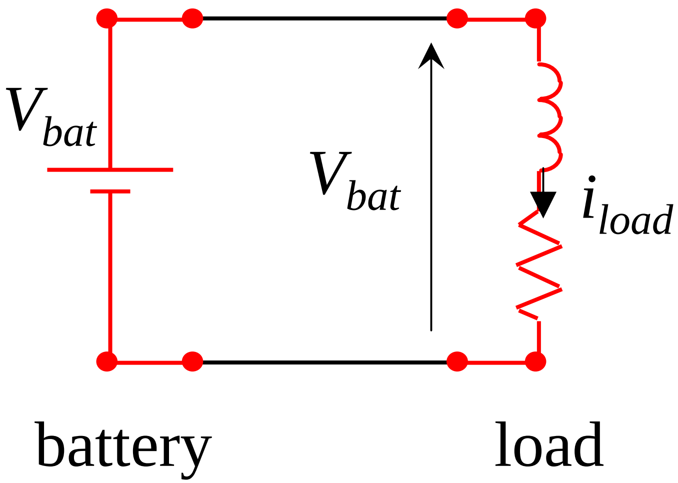
Interaction principle

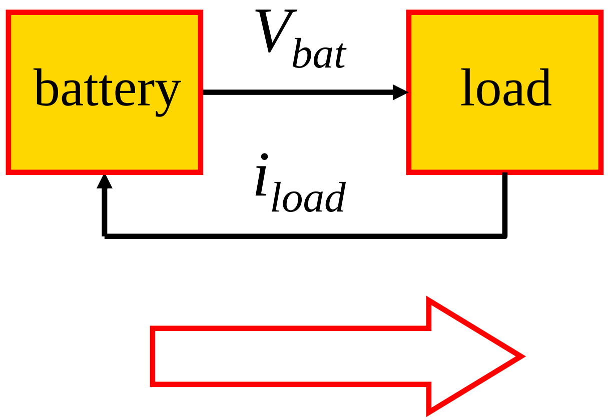
Each action induces a reaction



Power exchanged by S1and S2 = action x réaction

Example

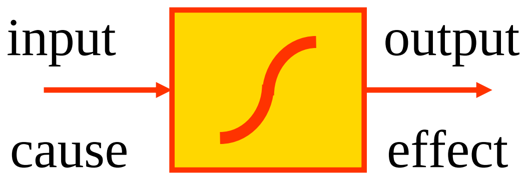


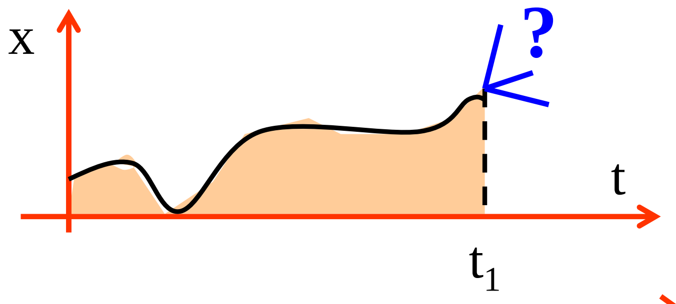


$$P = V_{bat}\, i_{load}$$

Principle of causality

physical causality is integral



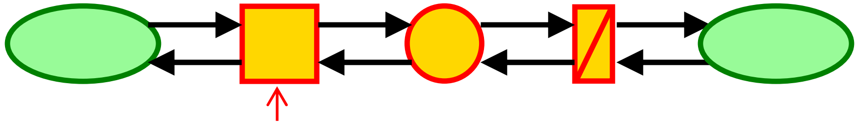


$$\int x\,dt$$ ⇨ area ⇩ knowledge of past evolution

OK in real-time

$$\frac{dx}{dt}$$ ⇨ slope ⇩ knowledge of future evolution

impossible in real-time



2. « EMR basic elements »

An energetic system:

- Energy sources
- Energy storage elements
- Energy conversion elements
- Energy distribution elements

Key elements are:

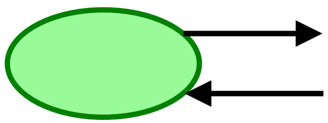
• energy storage element

(delay, state variable, closed-loop control)

• energy distribution element

(power flow coupling, control with criteria)

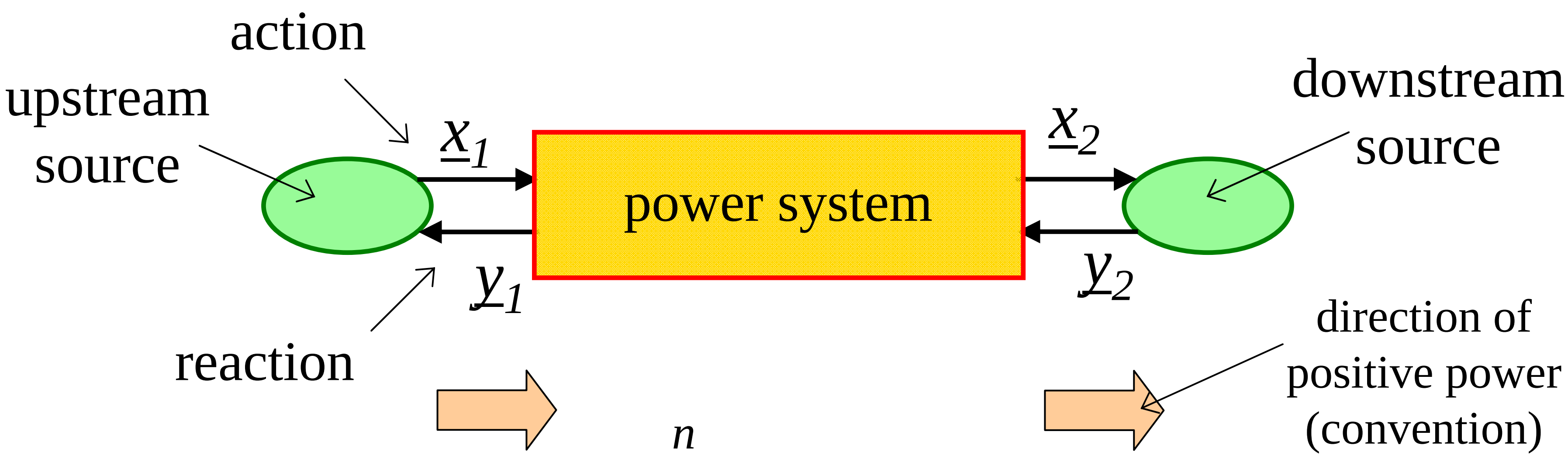
Source



- oval pictogram
- background: light green
- contour: dark green
- 1 input vector (dim n)
- 1 output vector (dim n)

terminal elements which represent the environment of the studied system

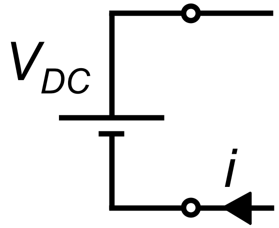
generator and/or receptor of energy

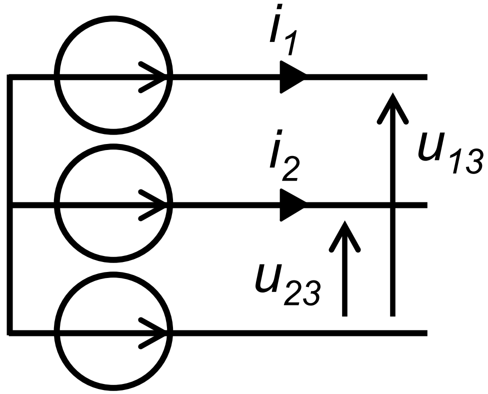


$$p_1 = \underline{x}_1 \cdot \underline{y}_1 = \sum_{i=1}^{n} x_i y_i \qquad p_2 = \underline{x}_2 \cdot \underline{y}_2$$

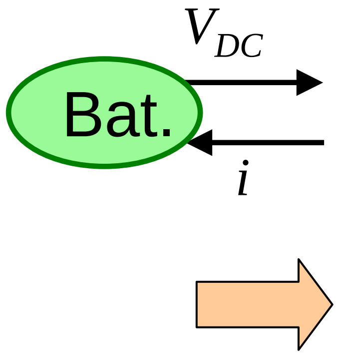
Battery — **Electrical grid**

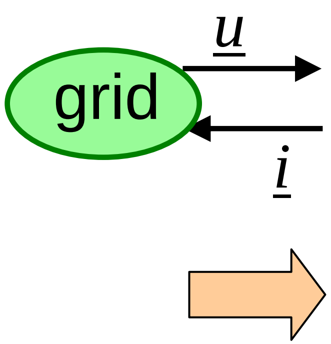
structural description





EMR (functional description)





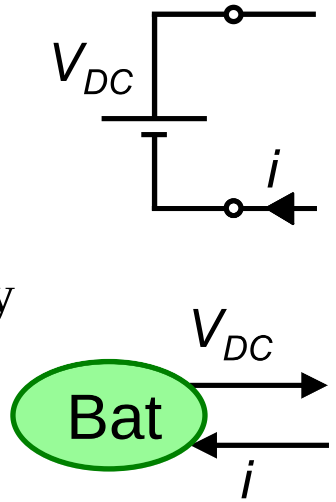
$$\underline{u} = \begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} \quad \underline{i} = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

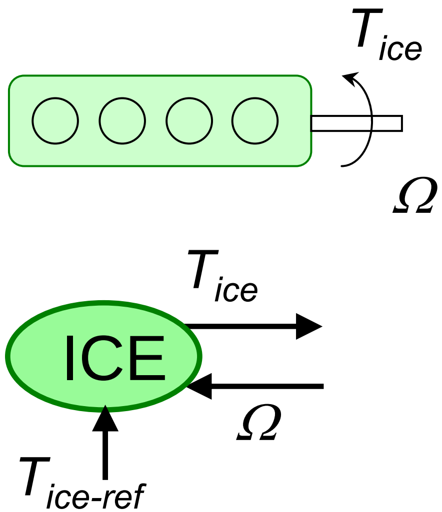
2 independent currents!

2 independent voltages!

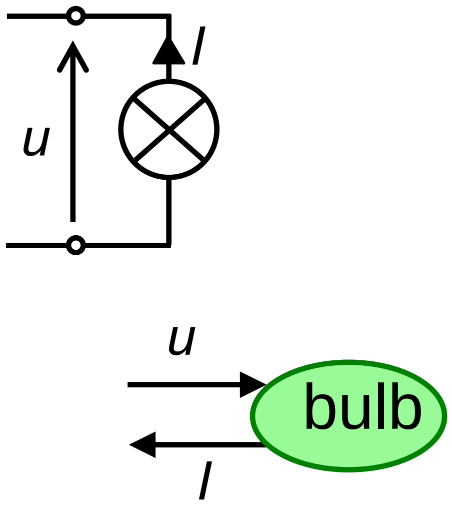
$$p = V_{DC}\, i \qquad\qquad p = \underline{u}\, \underline{i}$$

Battery
(voltage source)
generator and
receptor of energy

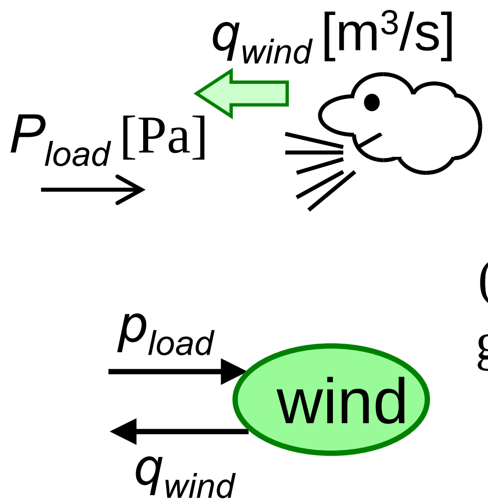




IC engine
(torque source)
generator
of energy

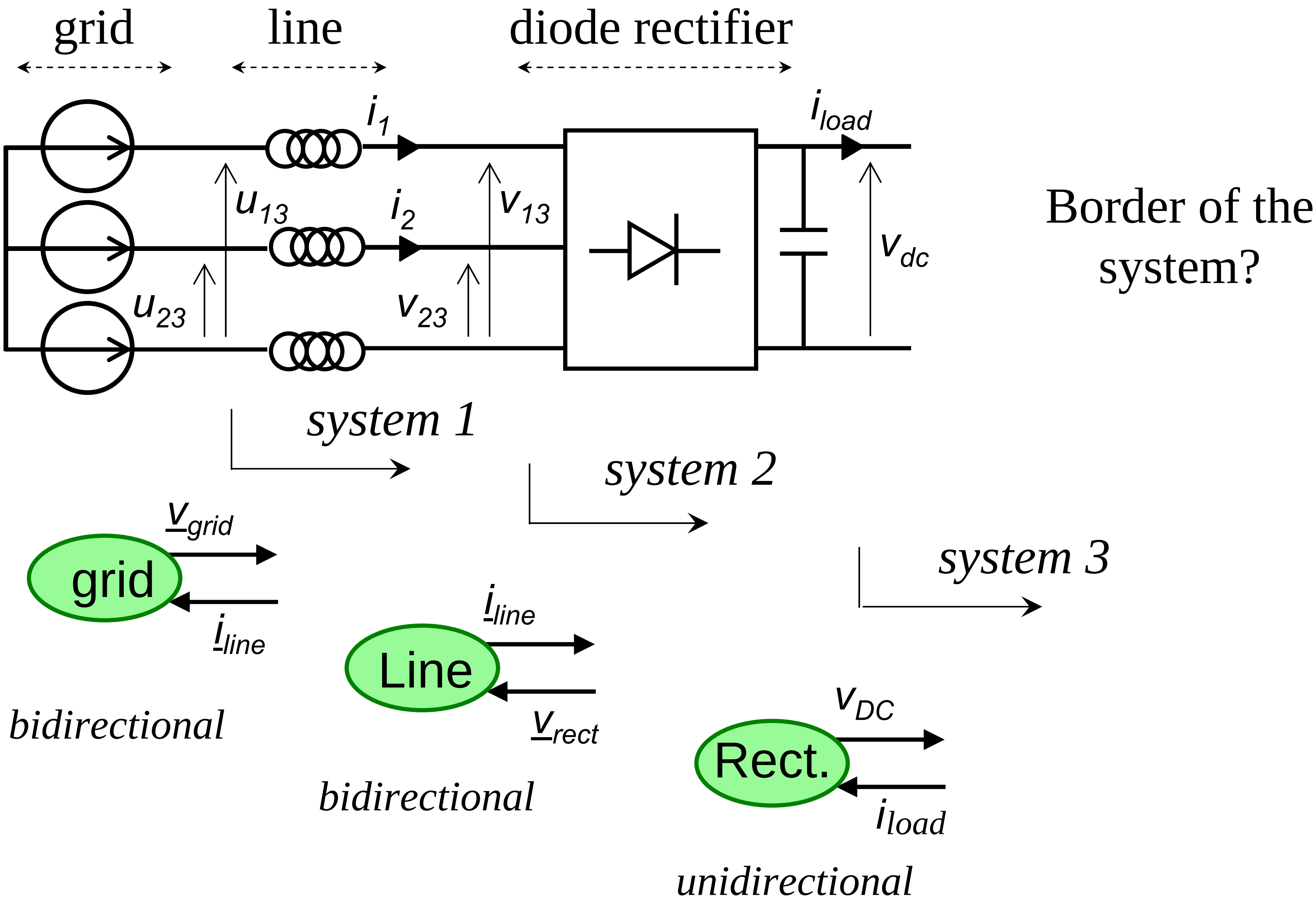


Ligthing bulb
receptor of energy



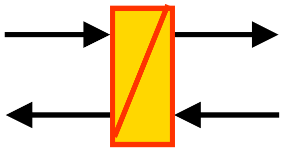
Wind
(air flow source)
generator energy

- Definition of environment -



- Accumulation elements -

Accumulator



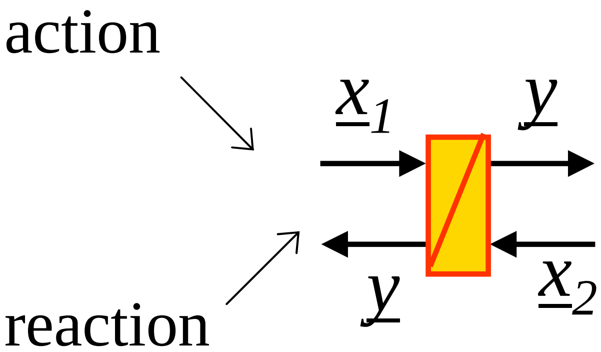
- rectangle with an oblique bar
- background: orange
- contour: red
- upstream I/O vectors (dim n)
- downstream I/O vectors (dim n)

internal accumulation of energy (with or without losses)

↓

causality principle

output(s) = ∫ input(s)

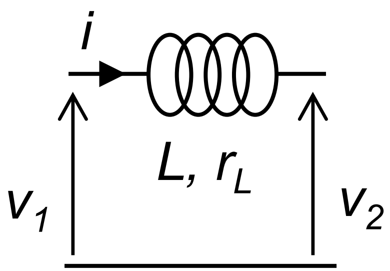
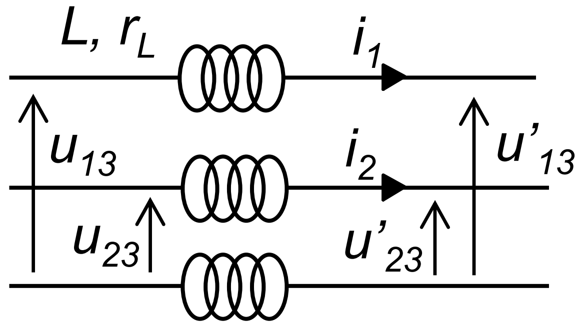
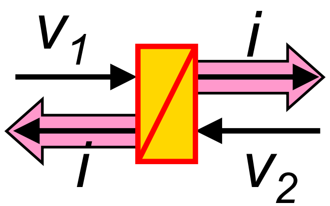
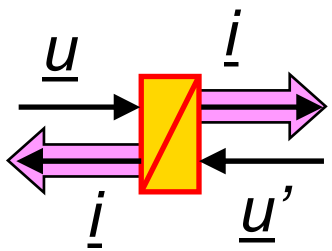


$p_1 = \underline{x}_1 \cdot \underline{y}$ $p_2 = \underline{x}_2 \cdot \underline{y}$

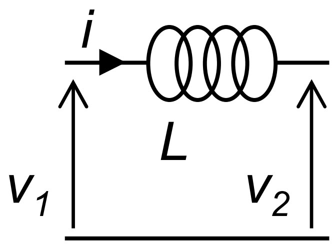
$$\underline{y} \propto \int f(\underline{x}_1, \underline{x}_2)\,dt$$

$\underline{y}$ = output, delayed from input changes

fixed I/O (causal description)

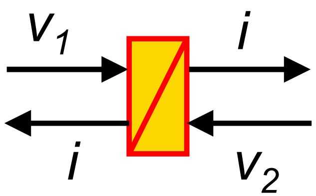
	inductor	3-phase line
structural description		
mathematical Model	$L\frac{d}{dt}\,i + r_L\, i = v_1 - v_2$	$[L]\frac{d}{dt}\underline{i} + r_L\,\underline{i} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}(\underline{u} - \underline{u}')$
EMR (causal representation)		

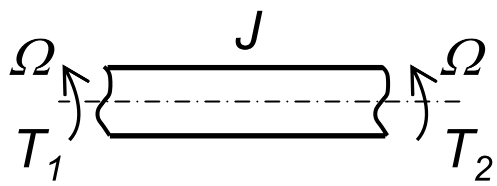
- Accumulation elements: examples (2) -



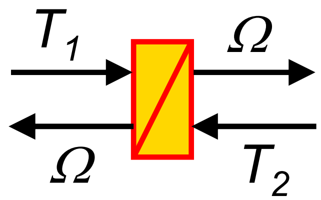
inductor

$$E = \frac{1}{2} L\, i^2$$

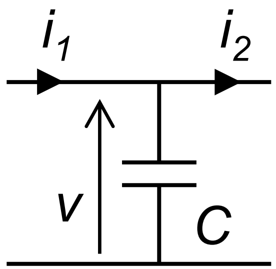




inertia

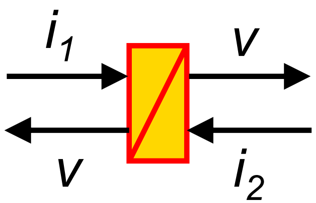


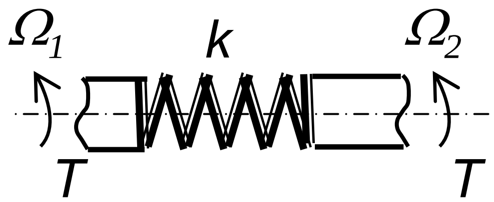
$$E = \frac{1}{2} J\, \Omega^2$$



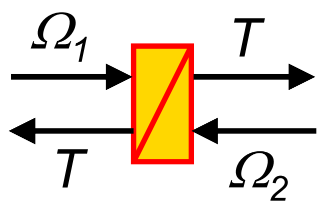
capacitor

$$E = \frac{1}{2} C\, v^2$$





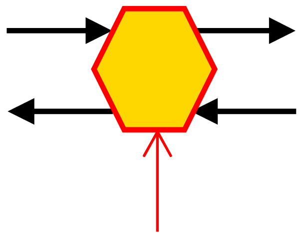
stiffness



$$E = \frac{1}{2} \frac{1}{k} T^2$$

- Conversion elements -

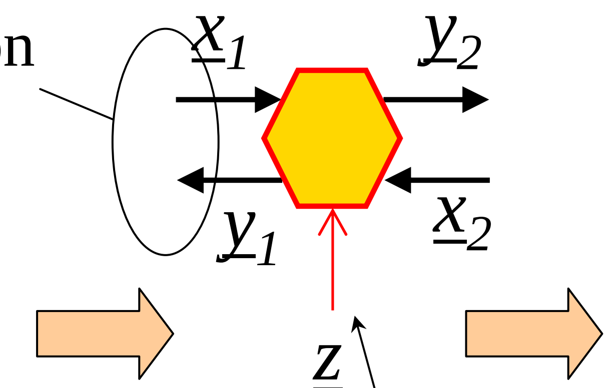
conversion element



- various pictograms
- background: orange
- contour: red
- upstream I/O vectors (dim n)
- downstream I/O vectors (dim p)
- **Possible tuning input vector** (dim q)

conversion of energy without energy accumulation (with or without losses)

action / reaction



$p_1 = \underline{x}_1 \cdot \underline{y}_1$

$p_2 = \underline{x}_2 \cdot \underline{y}_2$

tuning vector

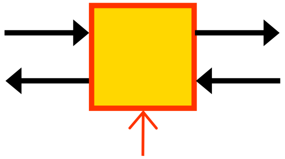
$$\begin{cases} \underline{y}_2 = f(\underline{x}_1, \underline{z}) \\ \underline{y}_1 = f(\underline{x}_2, \underline{z}) \end{cases}$$

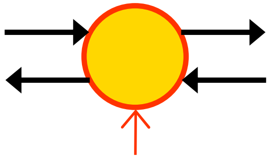
no delay!

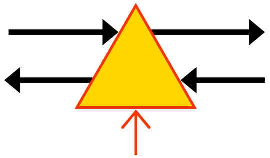
⇩

upstream and downstream I/O can be permuted (floating I/O)

- Conversion element pictograms -

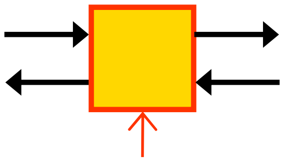

Square = electrical conversion

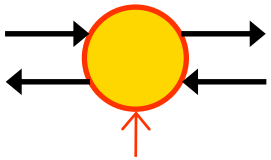

Circle = electromechanical conversion


Triangle = mechanical conversion

More general pictograms

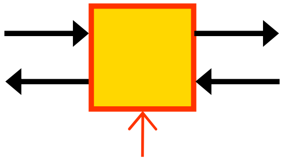
For multiphysical systems


Square = monophysical conversion

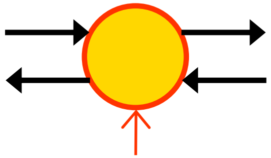

Circle = multiphysical conversion

« Energetic Macroscopic Representation (EMR) »

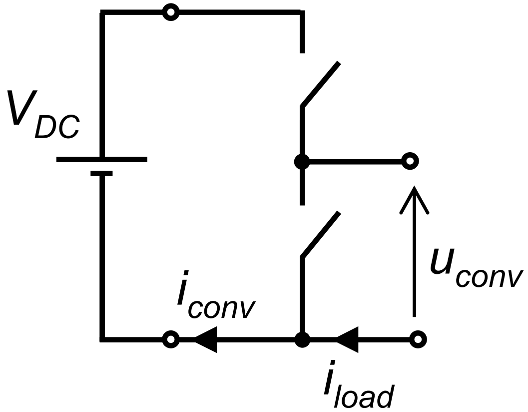
- Conversion element pictograms -

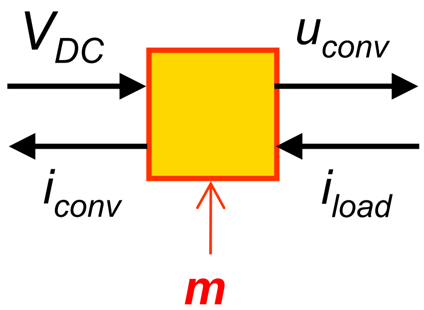


Square = monophysical conversion



Circle = multiphysical conversion

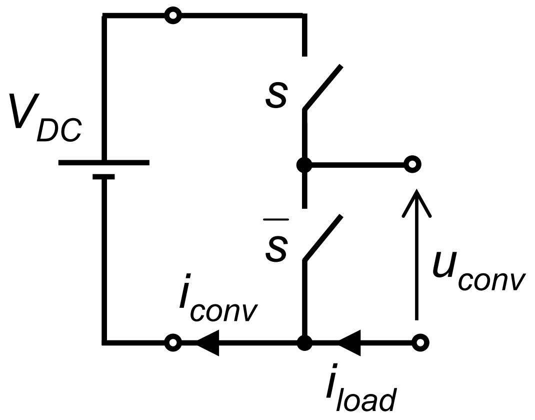


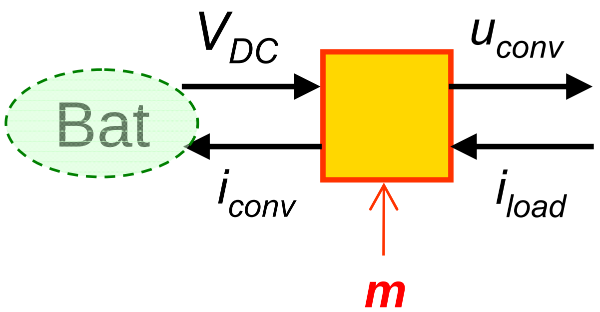


$$\begin{cases} u_{conv} = m \quad V_{DC} \\ i_{conv} = m \quad i_{load} \end{cases}$$

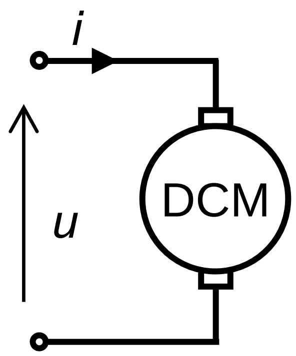
m: modulation function of the converter

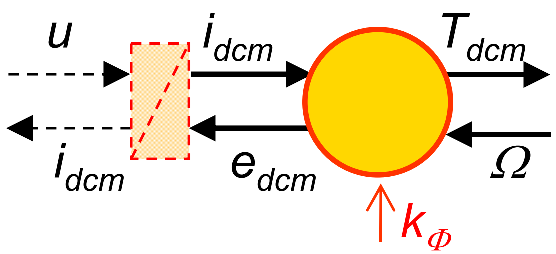
$\langle m \rangle = D =$ duty cycle





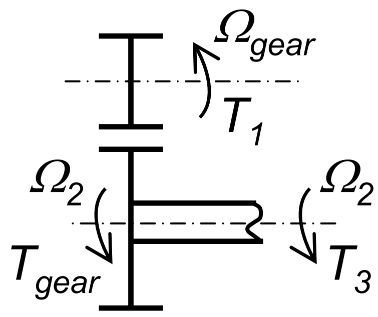
$$\begin{cases} u_{conv} = m \;\; V_{DC} \\ i_{conv} = m \;\; i_{load} \end{cases}$$

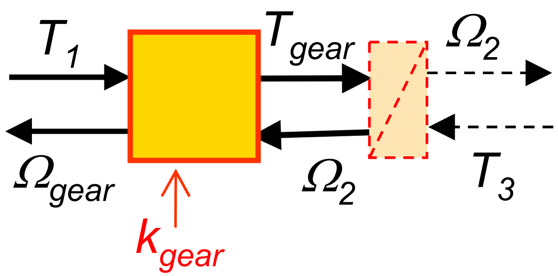




$$L \frac{d}{dt} i_{dcm} + r \; i_{dcm} = u - e_{dcm}$$

$$\begin{cases} T_{dcm} = k_\Phi \;\; i_{dcm} \\ e_{dcm} = k_\Phi \; \Omega \end{cases}$$



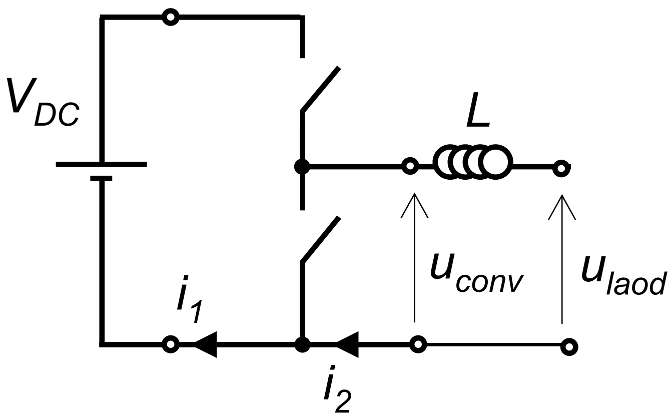


$$\begin{cases} T_{gear} = k_{gear} \;\; T_1 \\ \Omega_{gear} = k_{gear} \; \Omega_2 \end{cases}$$

$$J \frac{d}{dt} \Omega_2 = T_{gear} - T_3$$

« Energetic Macroscopic Representation (EMR) »

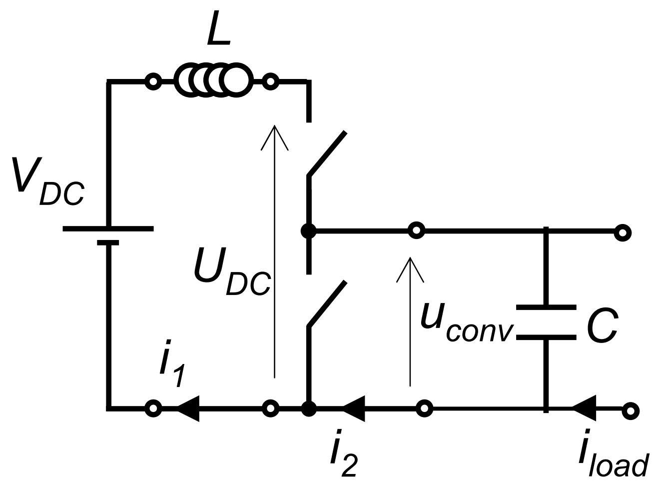
- I/O of conversion elements -

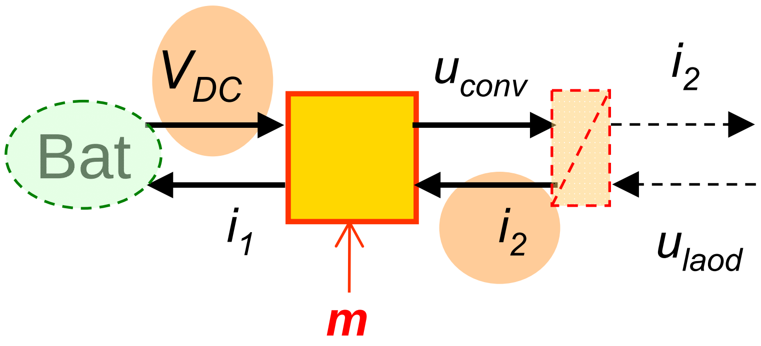


$$\begin{cases} u_{conv} = m \;\; V_{DC} \\ i_1 = m \;\; i_2 \end{cases}$$

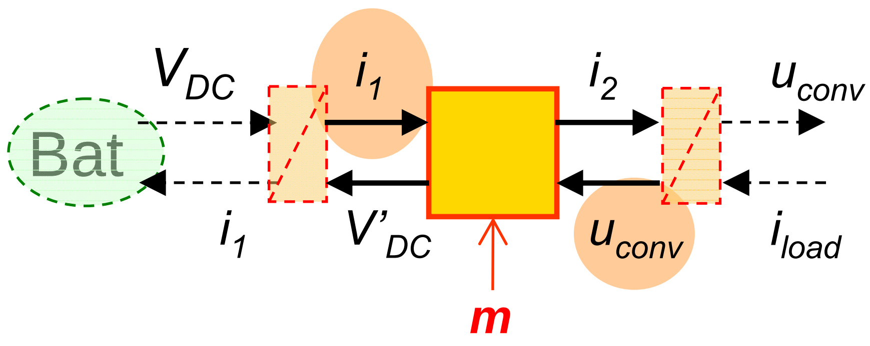
or

$$\begin{cases} U_{DC} = \frac{1}{m} u_{conv} \\ i_2 = \frac{1}{m} i_1 \end{cases}$$



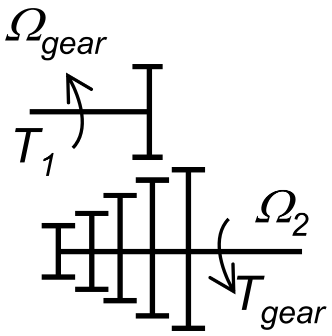


conv. inputs

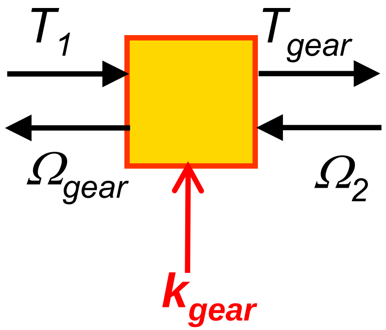


I/O are defined by accumulation elements

5-speed gearbox

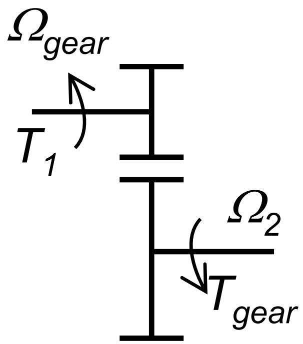


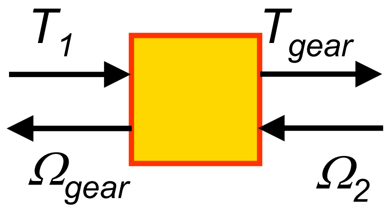
$$\begin{cases} T_{gear} = k_{gear}\, T_1 \\ \Omega_{gear} = k_{gear}\, \Omega_2 \end{cases}$$



$$k_{gear} \in \{k_1, k_2, k_3, k_4, k_5\}$$

fixed gear

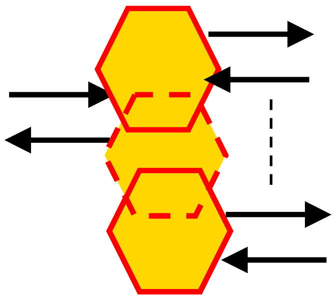




(no tuning input)

$$k_{gear} = \text{constant}$$

coupling element



- various overlapped pictograms
- background: orange
- contour: red
- pairs of I/O vectors
- N pairs, N-1 pictograms

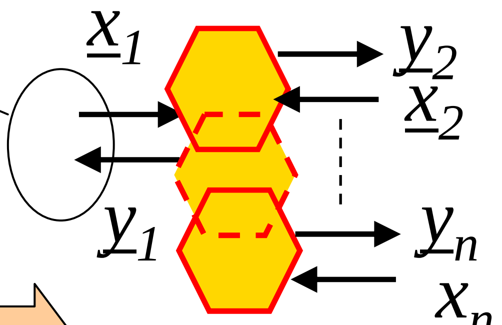
distribution of energy

without energy accumulation → no delay!

without tuning

(with or without losses)

action / reaction



$$\begin{cases} \underline{y}_1 = f_1(\underline{x}_1, .. \underline{x}_n) \\ \ldots \\ \underline{y}_n = f_n(\underline{x}_1, .. \underline{x}_n) \end{cases}$$

$$p_1 = \underline{x}_1 \cdot \underline{y}_1$$

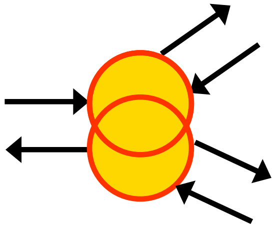
$$p_n = \underline{x}_n \cdot \underline{y}_n$$

$$\sum_{j=1}^{j=n} P_j = P_{losses}$$

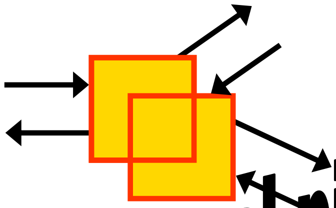
(N=2: conversion element)

- Coupling elements -

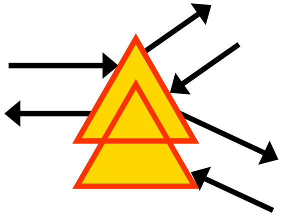
coupling elements
- overlapped pictograms
- background: orange
- contour: red



electro mechanical coupling



electrical coupling

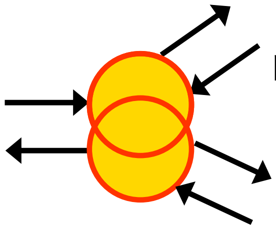


mechanical coupling

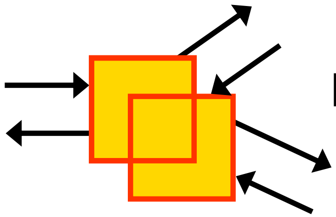
distribution of energy

More general pictograms

coupling elements
- overlapped pictograms
- background: orange
- contour: red

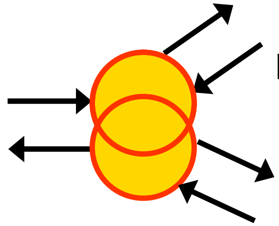


multiphysical coupling

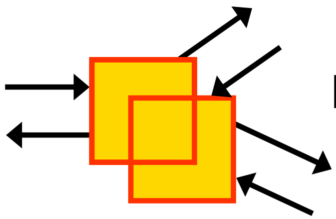


Monophysical coupling

coupling elements
- overlapped pictograms
- background: orange
- contour: red



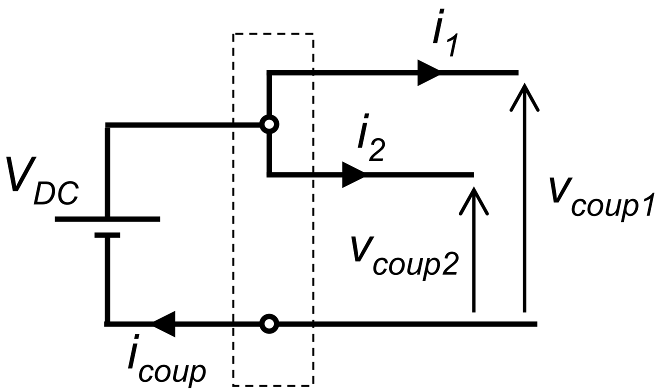
multiphysical coupling



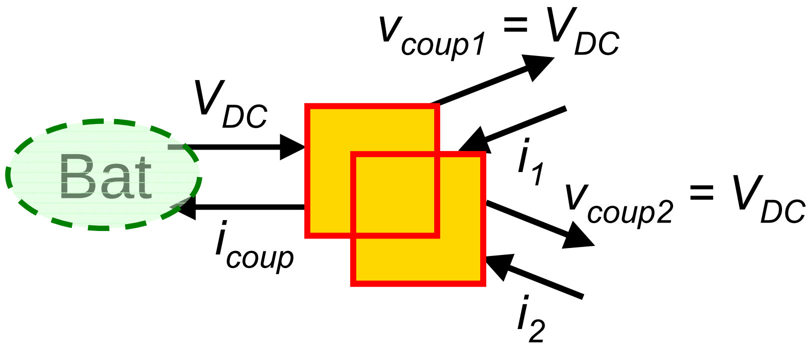
Monophysical coupling

distribution of energy

no tuning vector

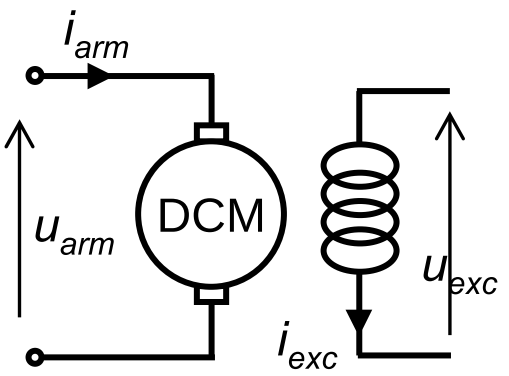


parallel connexion

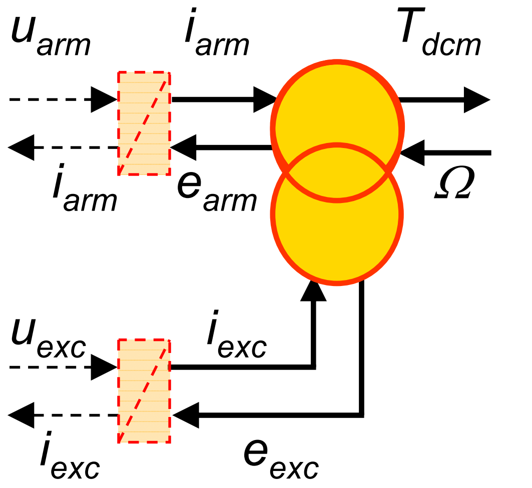


$$\begin{cases} V_{DC} \ \text{common} \\ i_{coup} = i_1 + i_2 \end{cases}$$

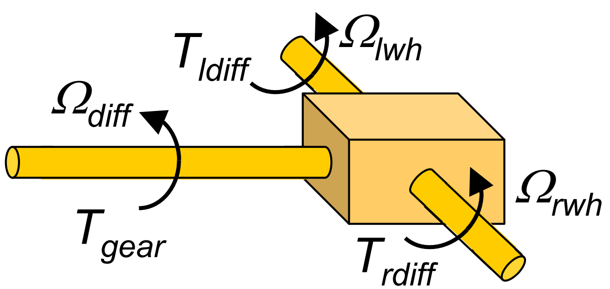
Field winding DC machine



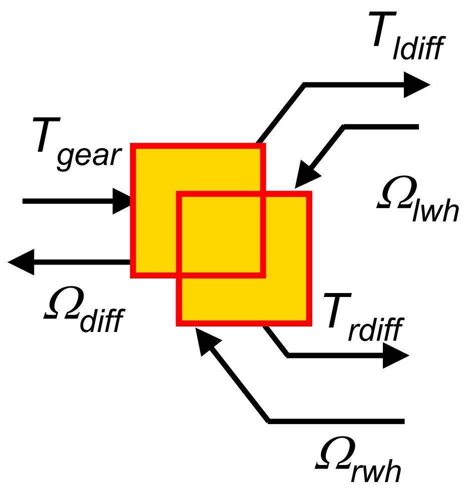
$$\begin{cases} T_{dcm} = k\, i_{exc}\, i_{arm} \\ e_{dcm} = k\, i_{exc}\, \Omega \end{cases}$$



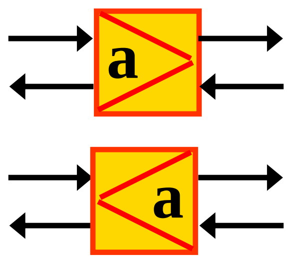
Mechanical differential



$$\begin{cases} T_{ldif} = T_{rdif} = \dfrac{T_{gear}}{2} \\ \Omega_{diff} = \dfrac{\Omega_{lwh} + \Omega_{rwl}}{2} \end{cases}$$

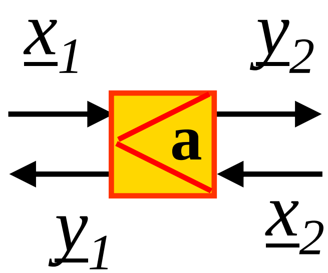


adaptation element



- Square with > or <
- background: orange
- contour: red
- upstream I/O vectors (dim n)
- downstream I/O vectors (dim n)

conversion with amplification without energy accumulation
(with or without losses)



$$\begin{cases} \underline{y}_2 = f(\underline{x}_1, \underline{z}) \\ \underline{y}_1 = f(\underline{x}_2, \underline{z}) \end{cases}$$

no delay!

$p_1 = \underline{x}_1 \cdot \underline{y}_1$

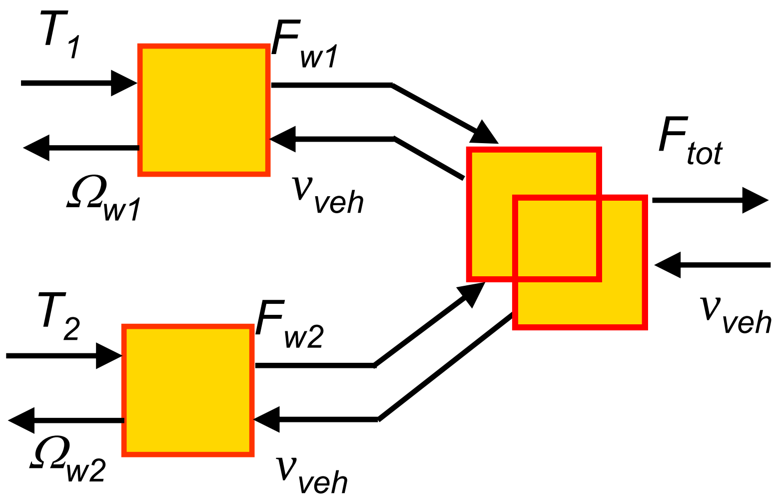
$p_2 = \underline{x}_2 \cdot \underline{y}_2$

$p_1 = a.\ p2$

$p_1 < p2$

Power amplification
(i.e. coupling element with Equi-distribution)

2 wheels
+ chassis

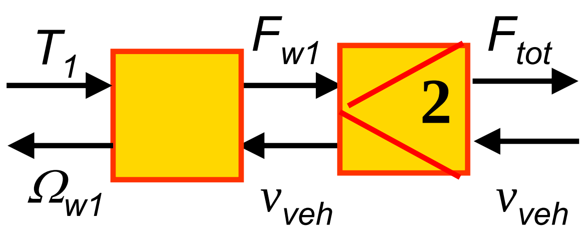


$F_{tot}=F_1+F_2$

v_{veh} common

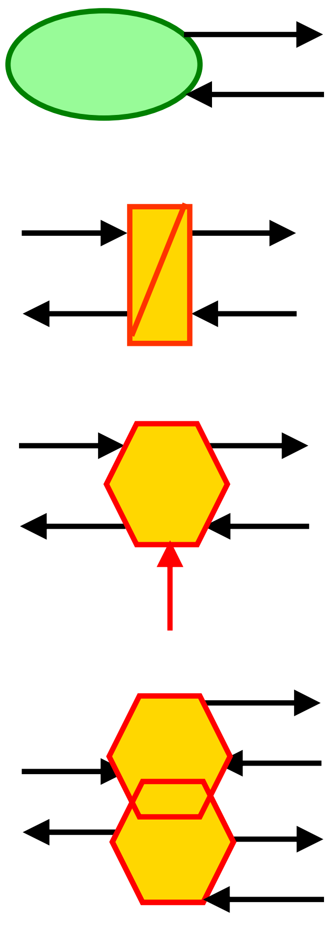
Assumption: no curve, no slip between the wheels and the road

1 equivalent wheel
+ adaptation



$F_{tot}=2F_1$

v_{veh} common



Energy source

Energy accumulation

Energy conversion (potential tuning)

Energy distribution

highlight energetic functions

all elements are connected by action/ reaction (power link) (systemic)

all power I/O are defined by accumulation elements (causality)

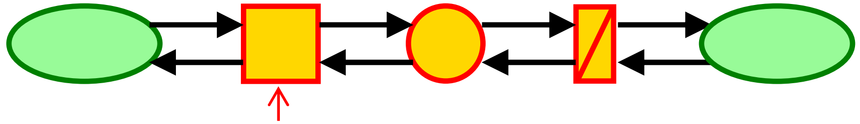
only conversion elements can have tuning inputs

⇩

valuable for control design

Polytech' Paris Sud

June 2014



3. « EMR of a complete system »

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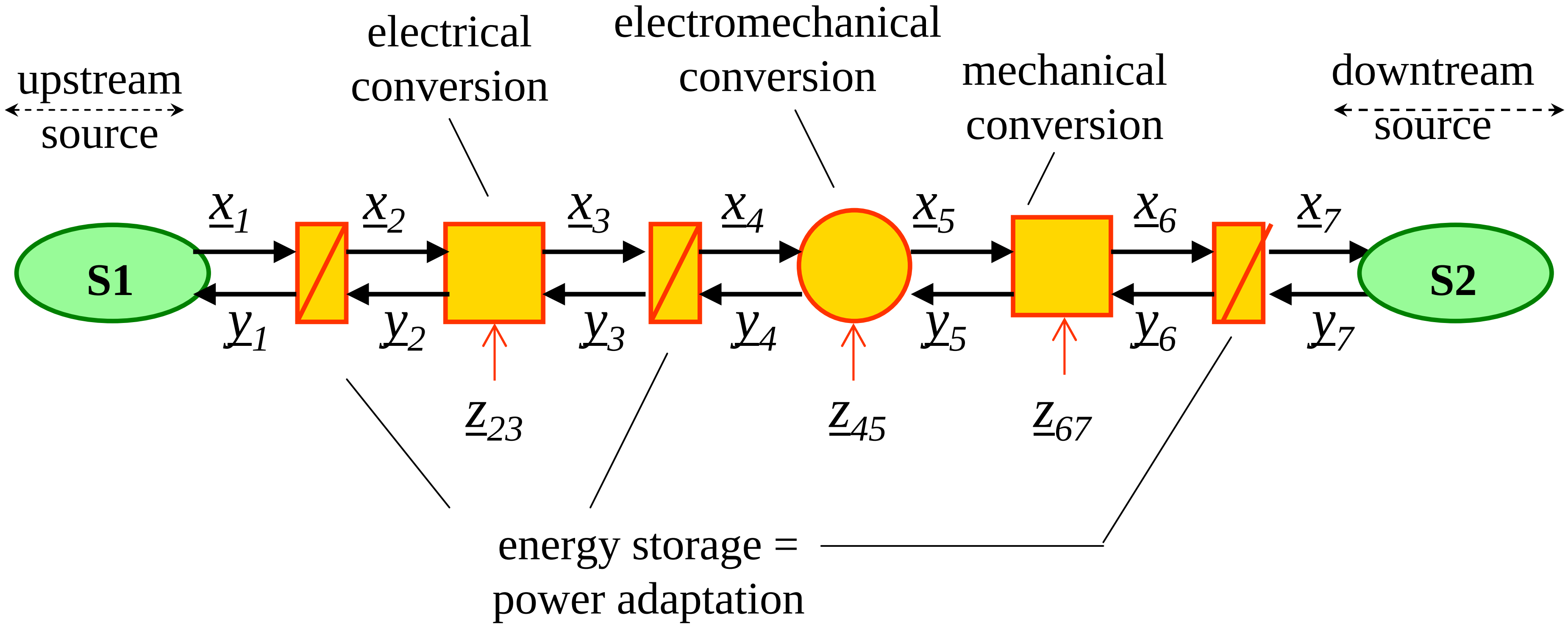
(University Lille1, L2EP)

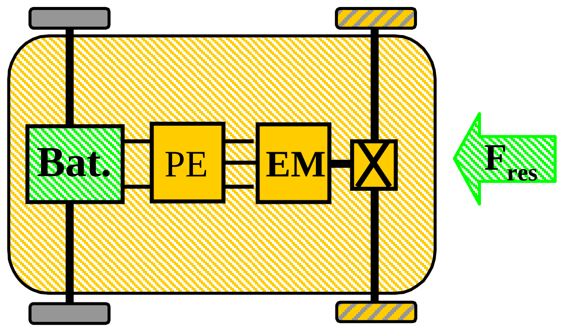
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Université Lille1 Sciences et Technologies

« Energetic Macroscopic Representation (EMR) »

- Example of an electromechanical conversion system -





upstream source → downstream source

Convention: direction of positive power flow
(could be negative for bidirectional system)

« Energetic Macroscopic Representation (EMR) »

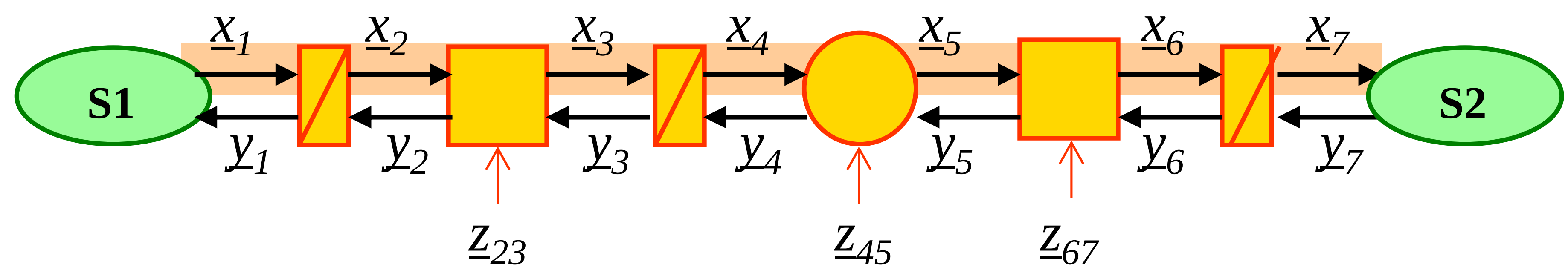
- Action and reaction paths -

Bidirectional system if:

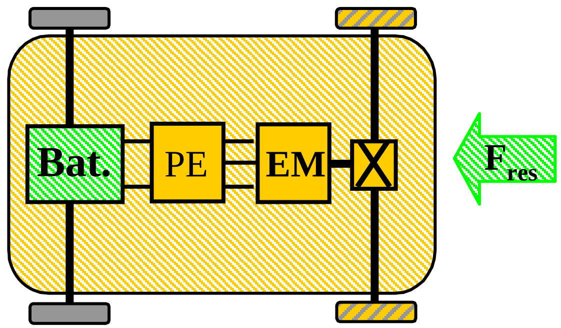
- bidirectional sources
- bidirectional conversion elements

upstream source

downstream source



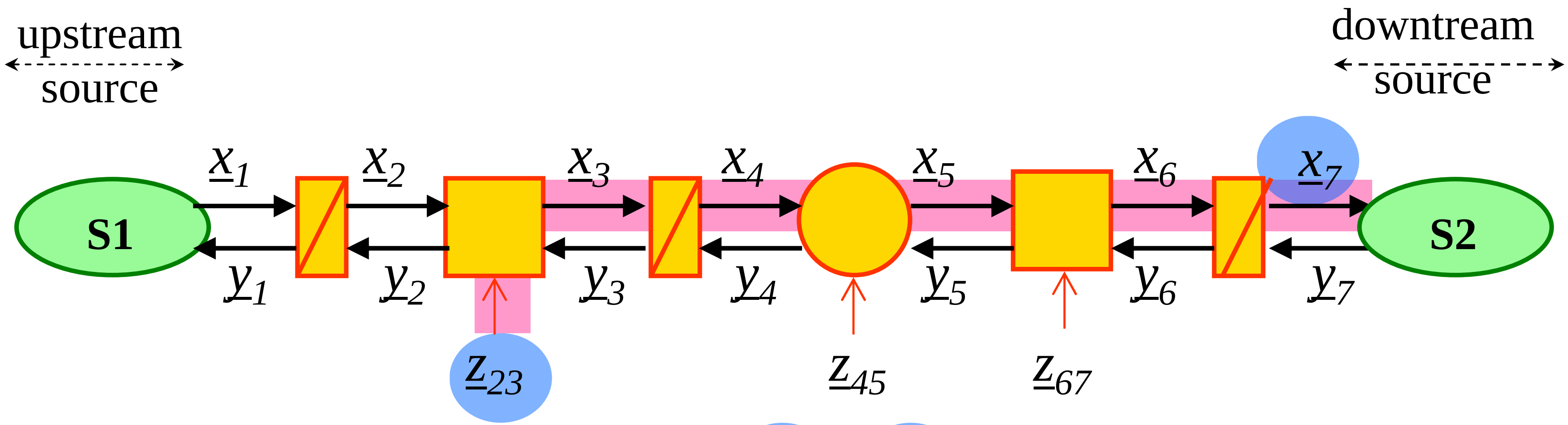
P > 0 (e.g. acceleration)
action path: $\underline{x}_1 \rightarrow \underline{x}_2 \rightarrow \underline{x}_3 \rightarrow \underline{x}_4 \rightarrow \underline{x}_5 \rightarrow \underline{x}_6 \rightarrow \underline{x}_7$
reaction path: $\underline{y}_1 \leftarrow \underline{y}_2 \leftarrow \cdots \leftarrow \underline{y}_7$



P < 0 (e.g. braking)
action path: $\underline{y}_1 \leftarrow \underline{y}_2 \leftarrow \cdots \leftarrow \underline{y}_7$
reaction path: $\underline{x}_1 \rightarrow \underline{x}_2 \rightarrow \cdots \rightarrow \underline{x}_7$

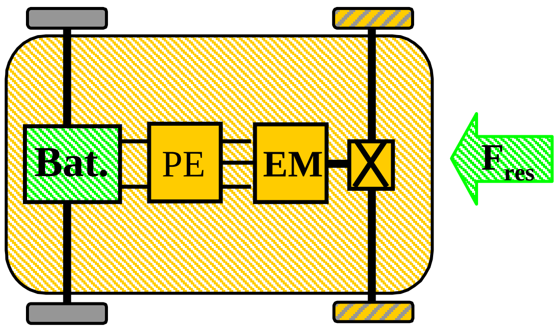
I/O independent of power flow direction
action/reaction dependent of power flow direction

- Tuning path -



Technical requirements: action on $\underline{z}_{23}$ and $\underline{x}_7$ to be controlled

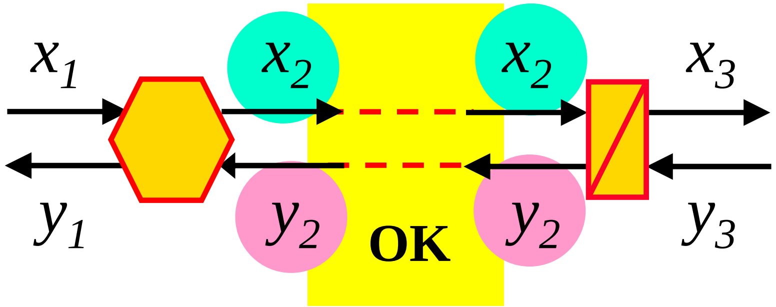
Tuning path: $\underline{z}_{23} \rightarrow \underline{x}_3 \rightarrow \underline{x}_4 \rightarrow \underline{x}_5 \rightarrow \underline{x}_6 \rightarrow \underline{x}_7$



The tuning path is **independent of the power flow direction**

(e.g. velocity control in acceleration AND regenerative braking)

- Association rules: direct connection -



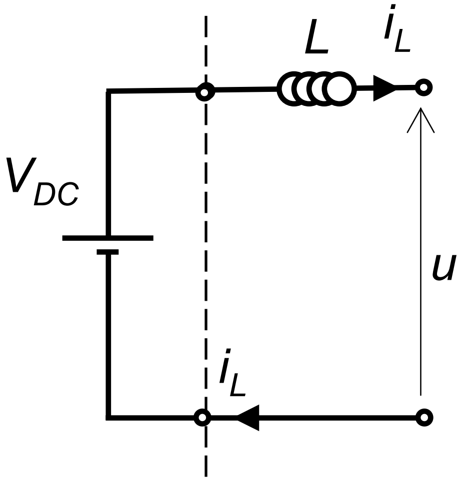
direct connection if:

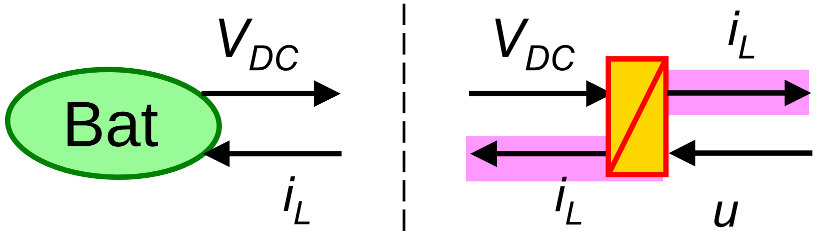
Out(S1) = In (S2)

In(S1) = Out(S2)

S1 and S2 any sub-systems

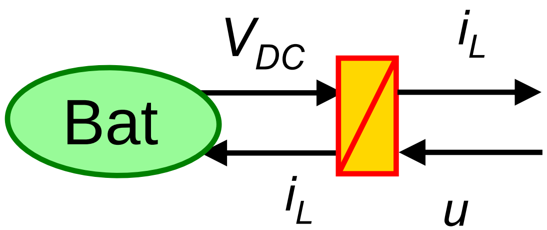
Example



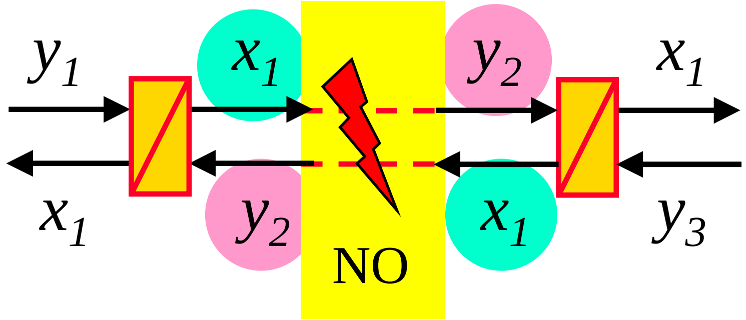


$$L\frac{d}{dt}i_L = V_{DC} - u$$

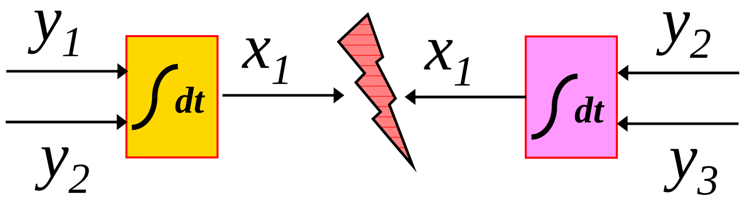
i state variable



- Merging rule -



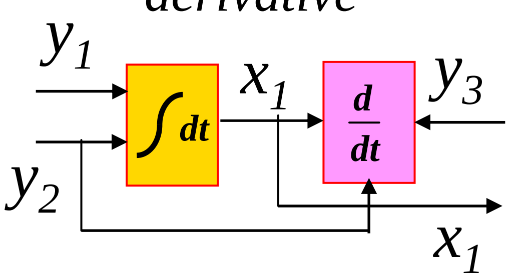
2 accumulation elements would impose the same state variable x_1



Conflict of association

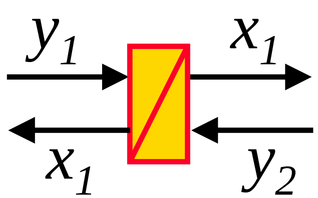
solutions

derivative



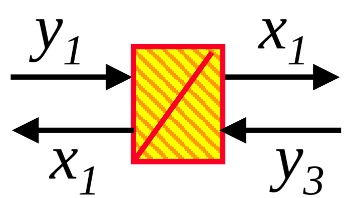
Structural / mathematical solution / non physical

simplification



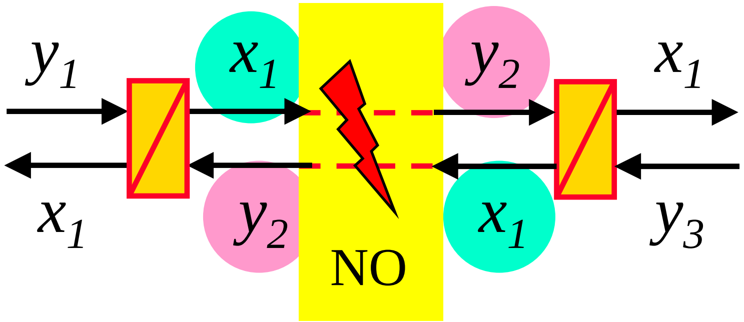
Cartesian approach / non physical

merging



1 equivalent function for 2 elements / systemic

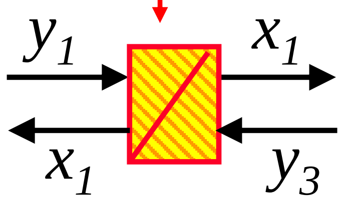
- Association rules: merging rule -



2 accumulation elements would impose the same state variable x_1

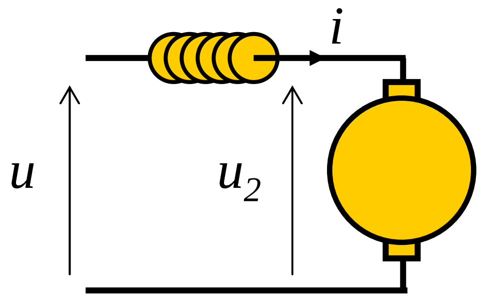
Conflict of association

merging

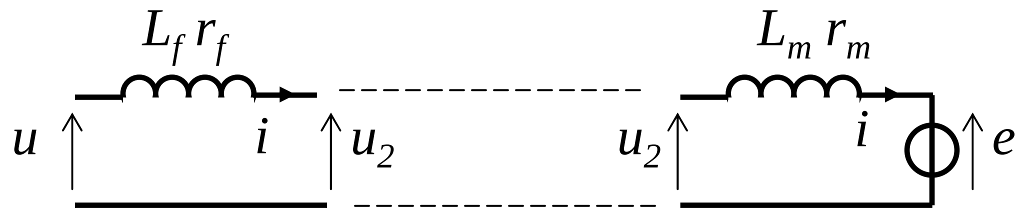


1 equivalent function for 2 elements / systemic

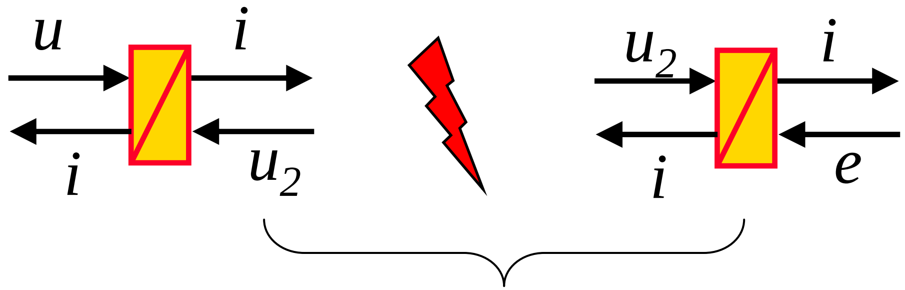
DC machine and smoothing inductor



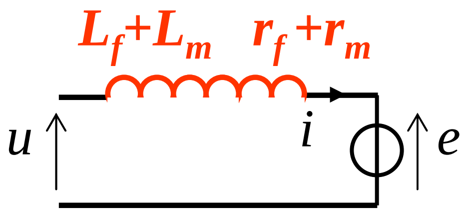
<u>Assumption</u>: L_f, L_m constant

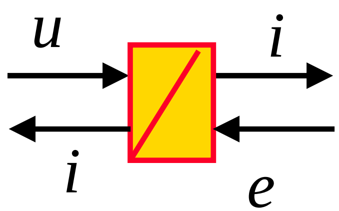


$$L_f \frac{di}{dt} = u - u_2 - r_f i \qquad L_m \frac{di}{dt} = u_2 - e - r_m i$$



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





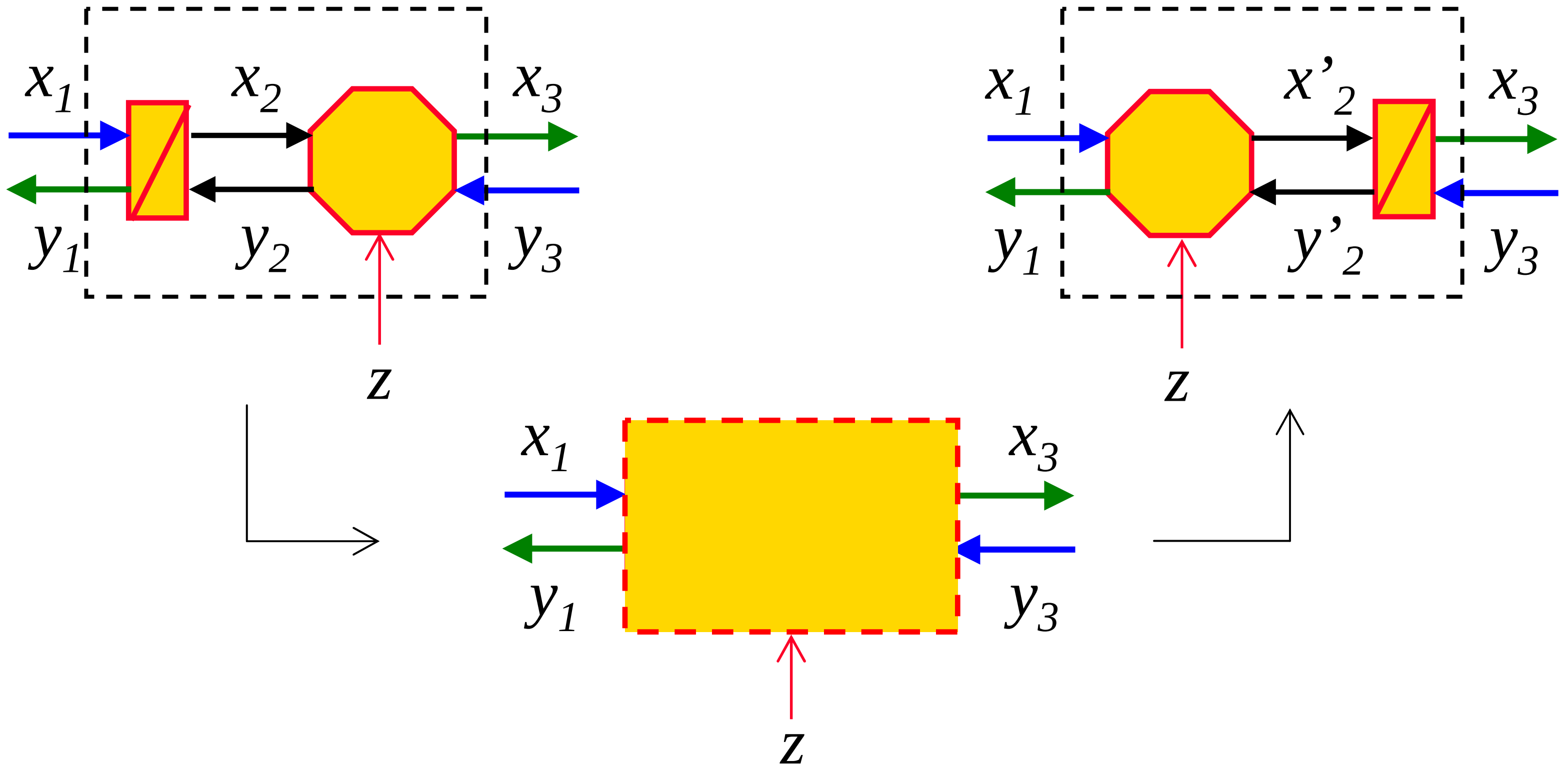
<u>Remark:</u>

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

↓ merging (systemic)

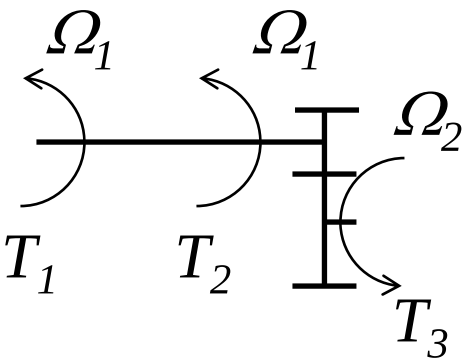
↓ Structural (Cartesian)

↓ simplification



permutation possible if same global behavior:
strictly the same effects (y_1 and x_3) from the same causes (x_1 , y_3 and z)

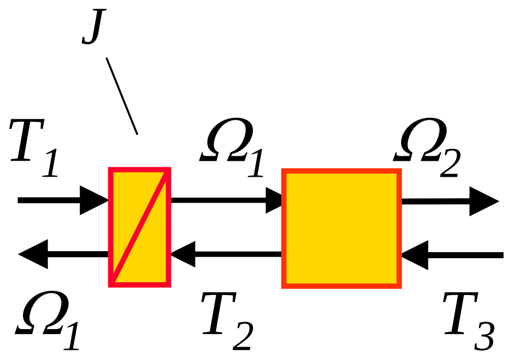
- Permutation rule: example -



Shaft + gearbox

$$J\frac{d}{dt}\Omega_1 = T_1 - T_2$$

$$\begin{cases} T_2 = k\,T_3 \\ \Omega_2 = k\Omega_1 \end{cases}$$

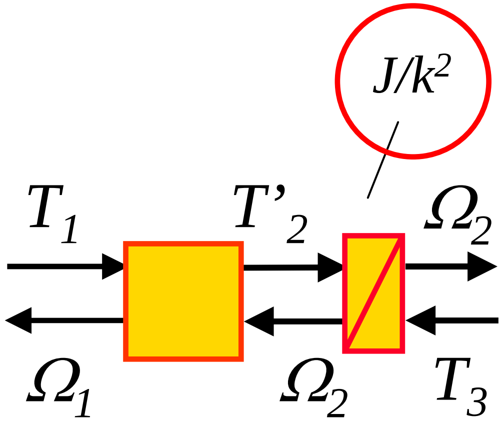


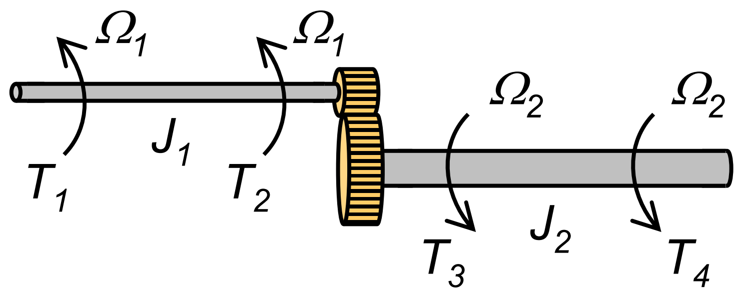
variable change

$$\frac{J}{k^2}\frac{d}{dt}\Omega_2 = T'_2 - T_3$$

$$\begin{cases} T'_2 = \dfrac{1}{k}T_1 \\ \Omega_1 = \dfrac{1}{k}\Omega_2 \end{cases}$$

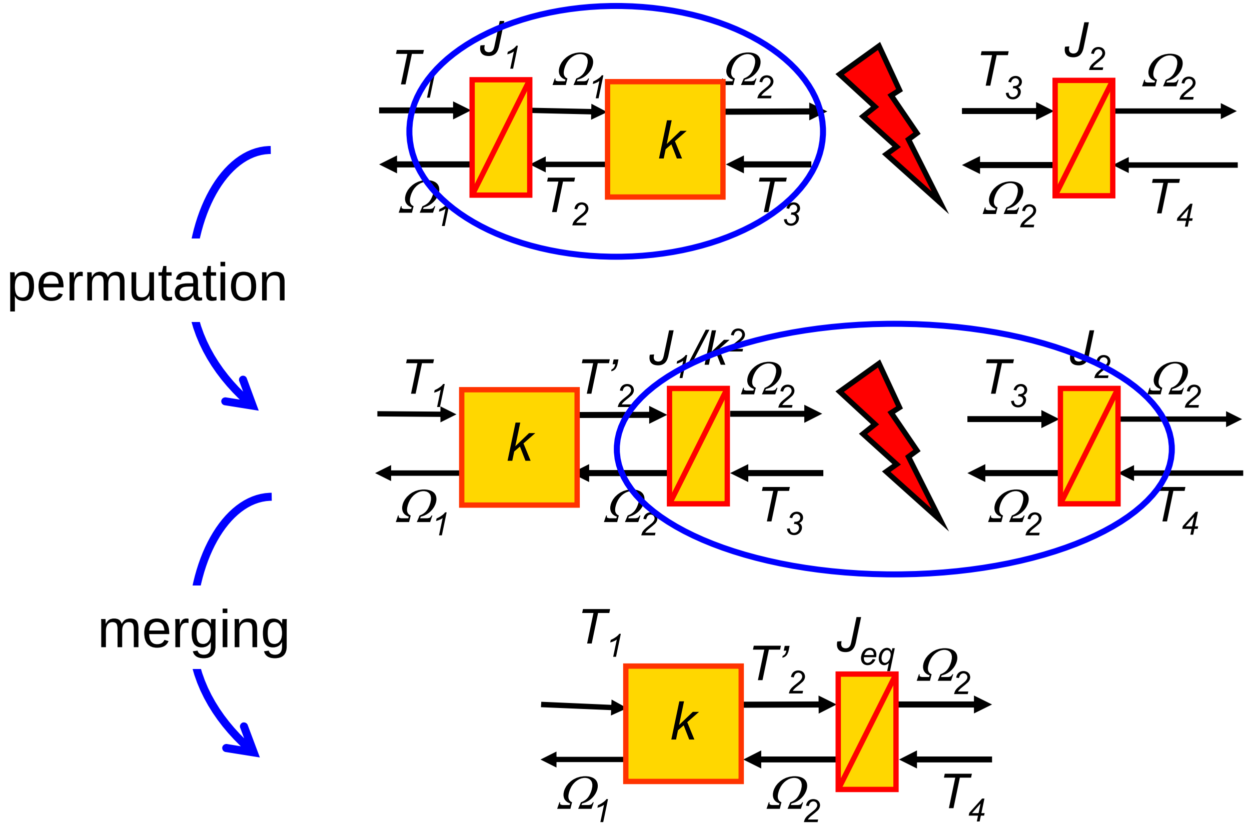
no assumption
strict equivalence
(same model)





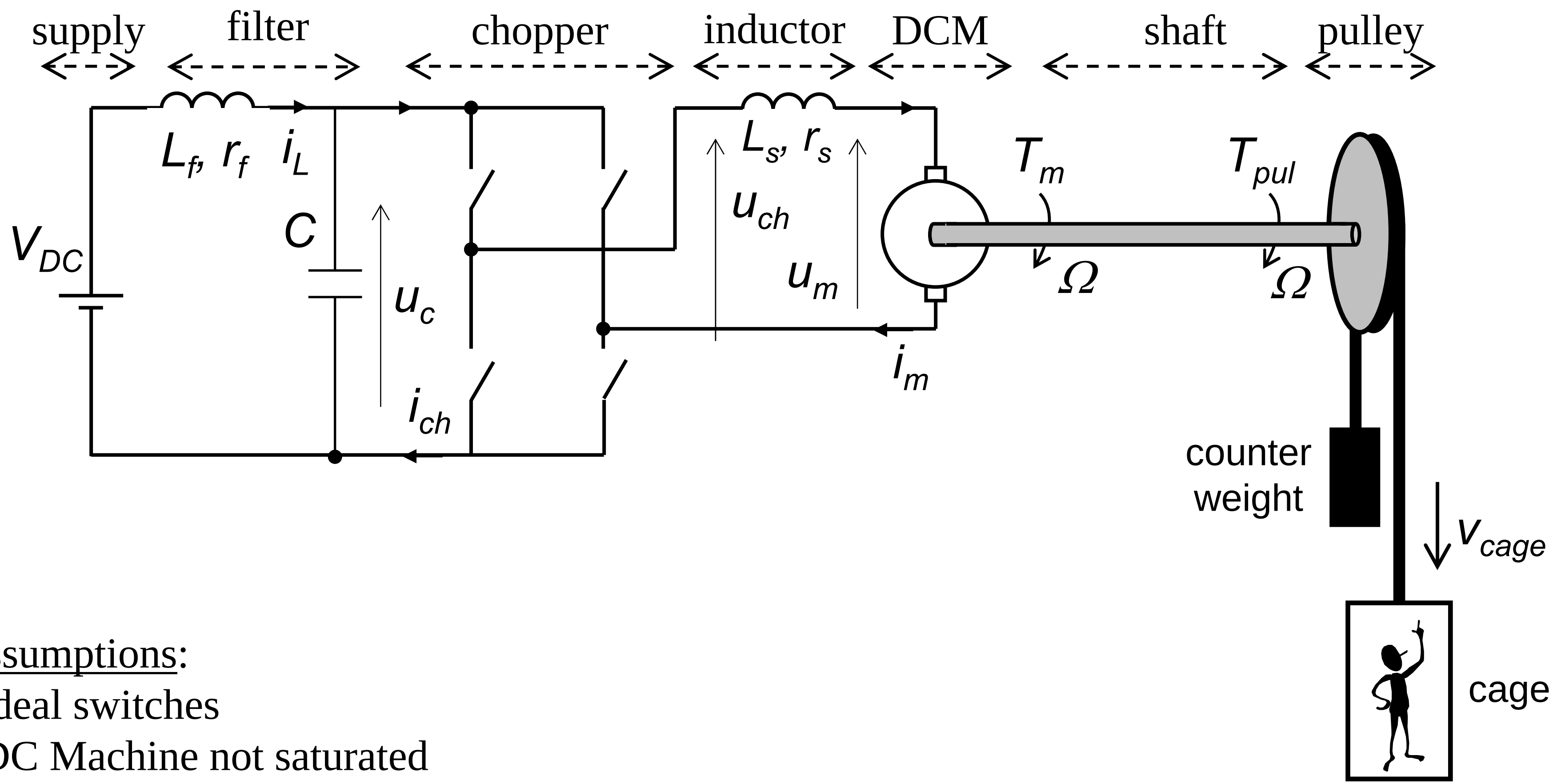
<u>Assumptions</u>:
J_1 , J_2 constant
no backslash

to solve conflict of association



$$J_{eq} = \frac{J_1}{k^2} + J_2$$

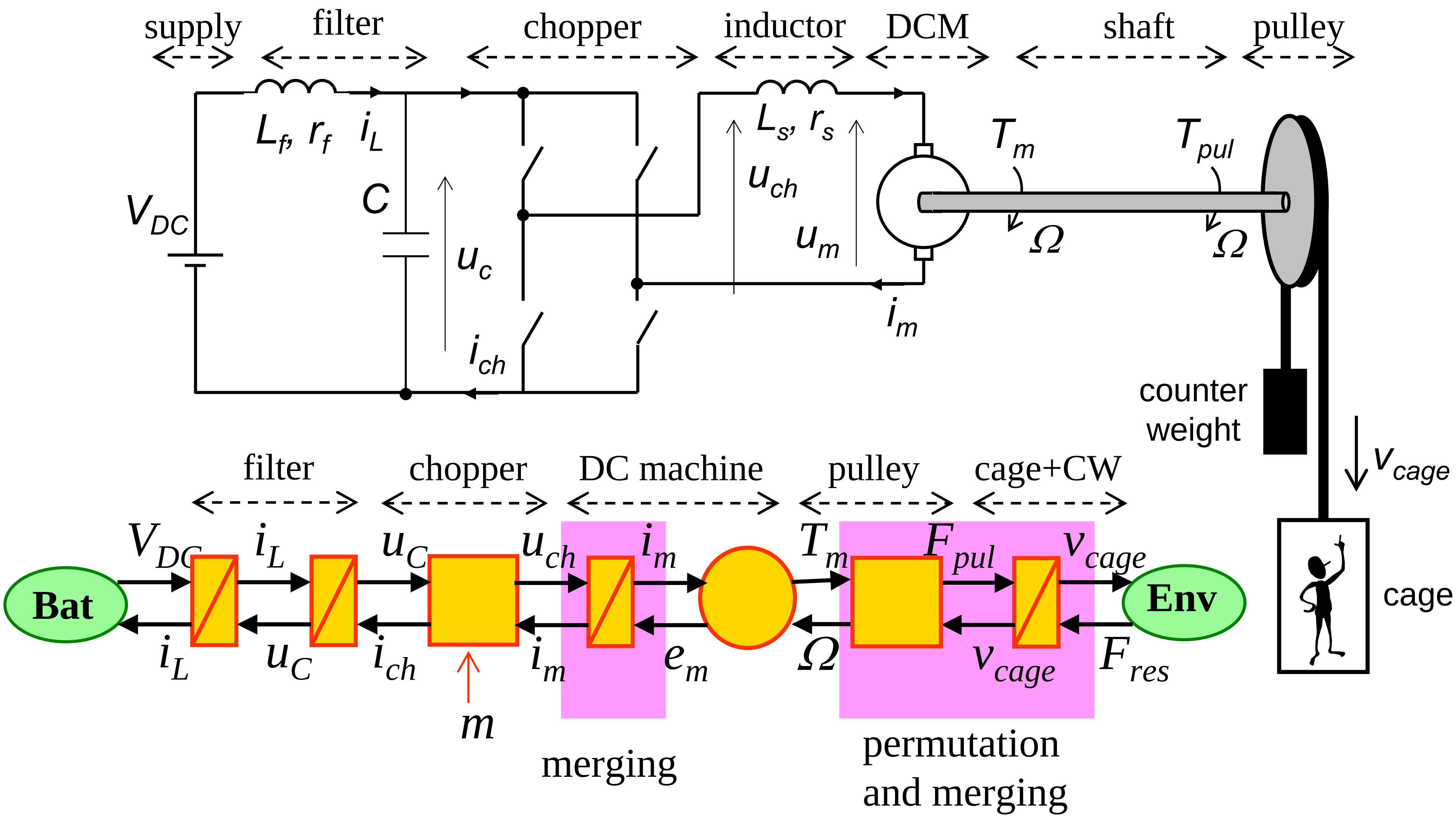
- Example: a lift -



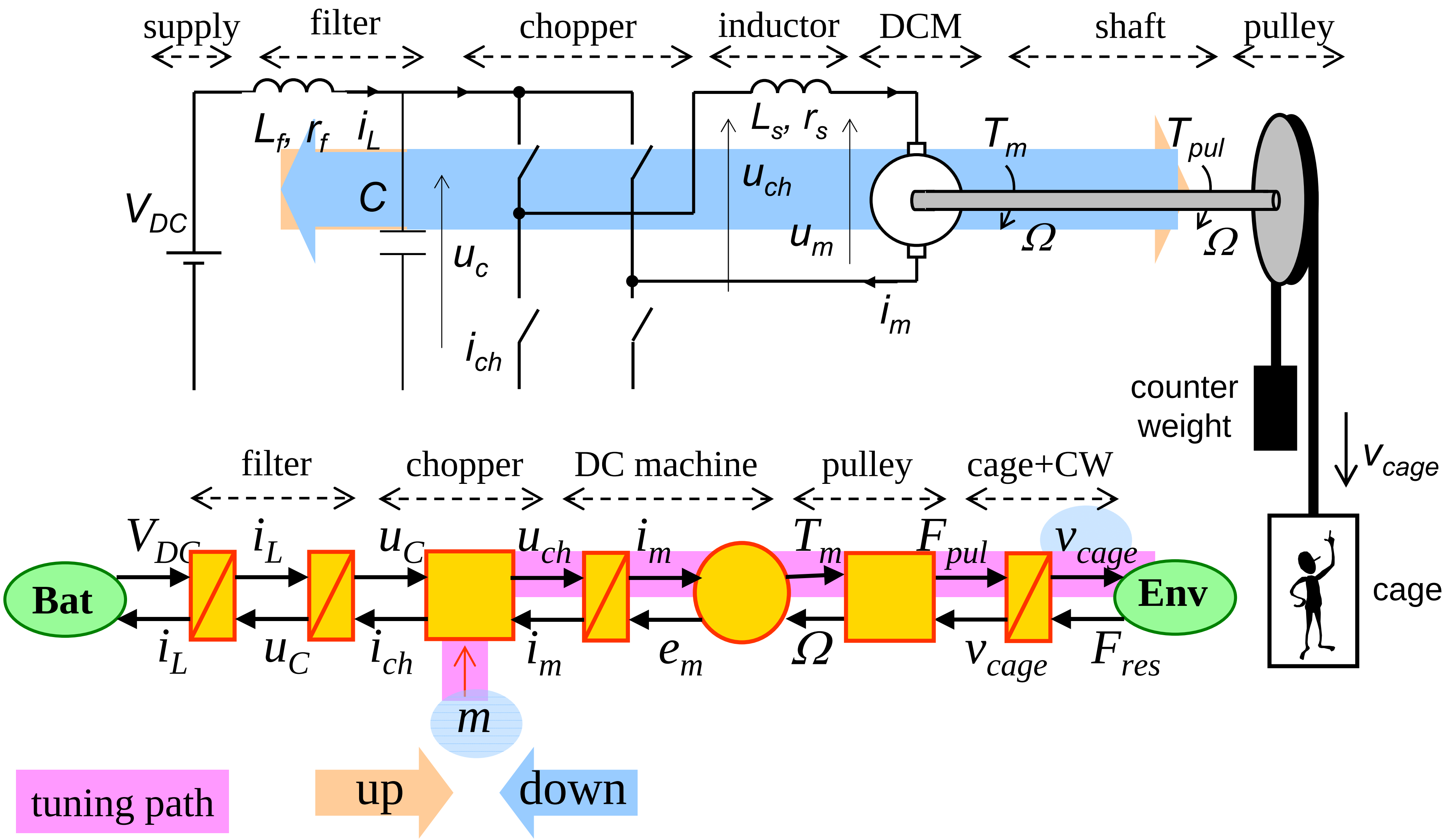
Assumptions:
- ideal switches
- DC Machine not saturated

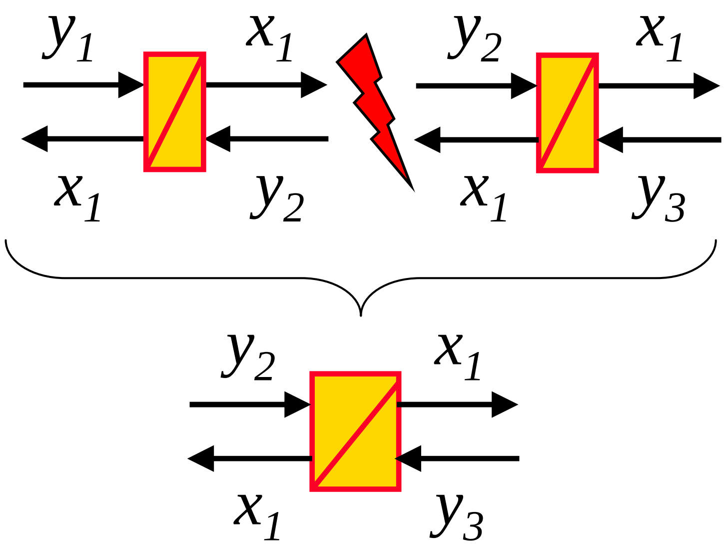
Technical requirement:
- control of velocity v_{cage}
- tuning input = modulation ratio of chopper *m*

- Lift example: EMR -



- Lift example: tuning path -





Priority to the function
by keeping the physical causality
(systemic)

EMR describes energetic functions

I/O are independent of power flows

Tuning paths:

- defined by the technical requirements
- independent of the power flow direction

⇩

EMR is adapted for control design

« Conclusion »

EMR = multi-physical graphical description

based on the interaction principle (systemic)
and the causality principle (energy)

Basic elements = energetic function

sources, accumulation, conversion and distribution of energy

Association rules = holistic property of systemic

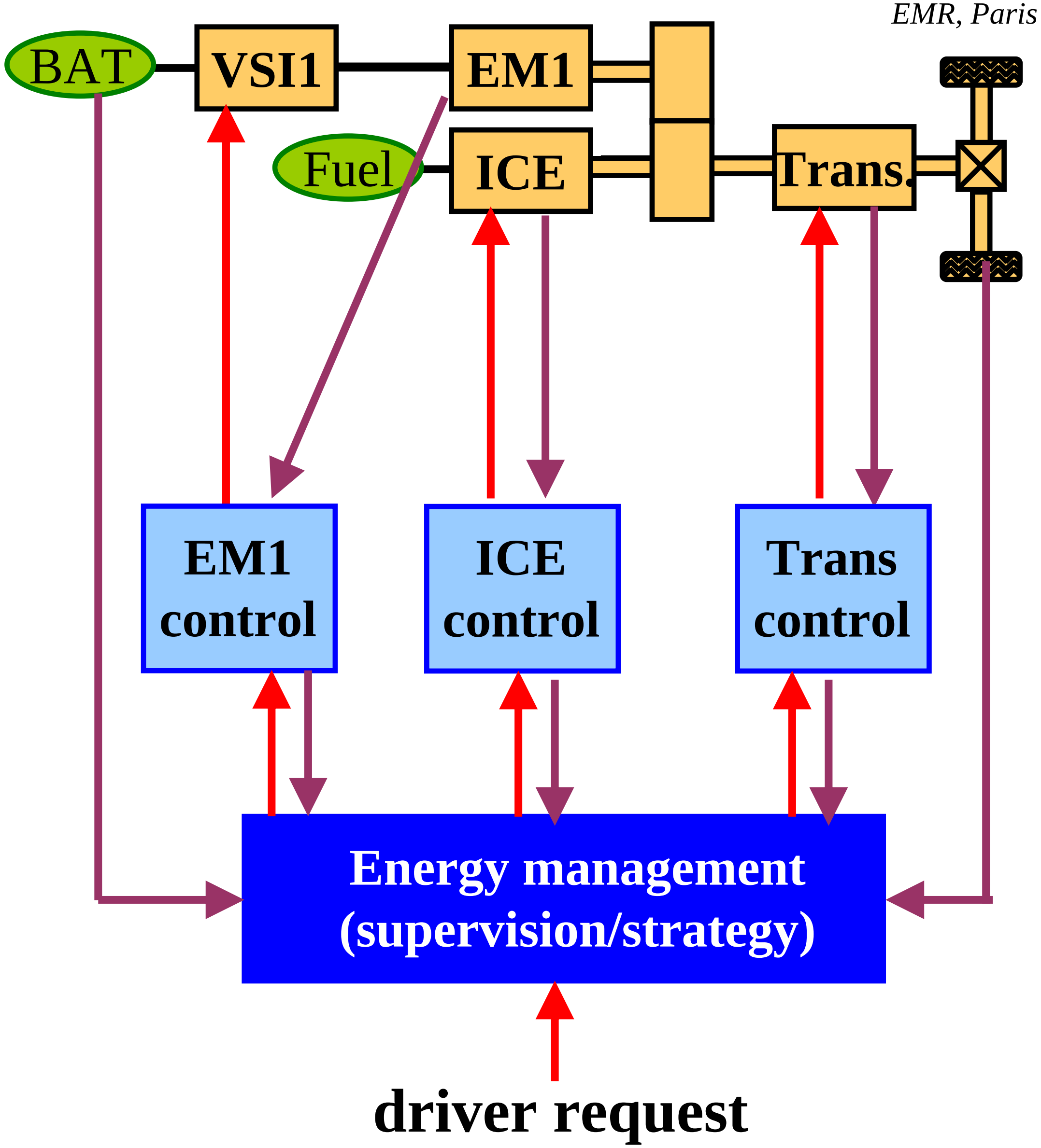
enable keeping physical causality in association conflict

Applications

analysis, simulation, control structure…

- Different control levels -

Parallel HEV

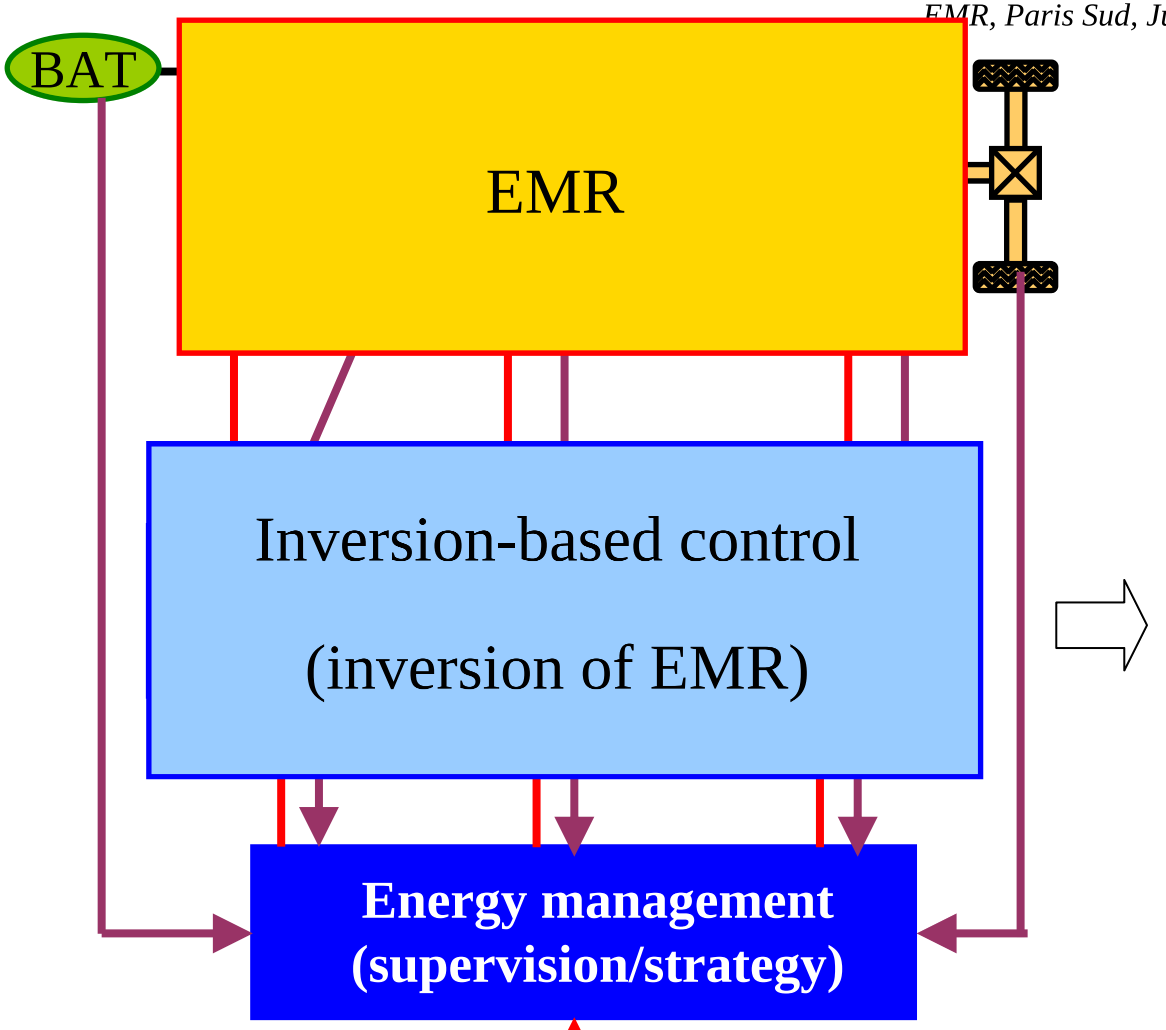


fast subsystem controls

slow system supervision

- Different control levels (2) -

Parallel HEV



fast subsystem controls

slow system supervision

Next Step

driver request

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