Tallinn University of Technology, May 2025

Estonian Doctoral School

# “Energetic Macroscopic Representation”

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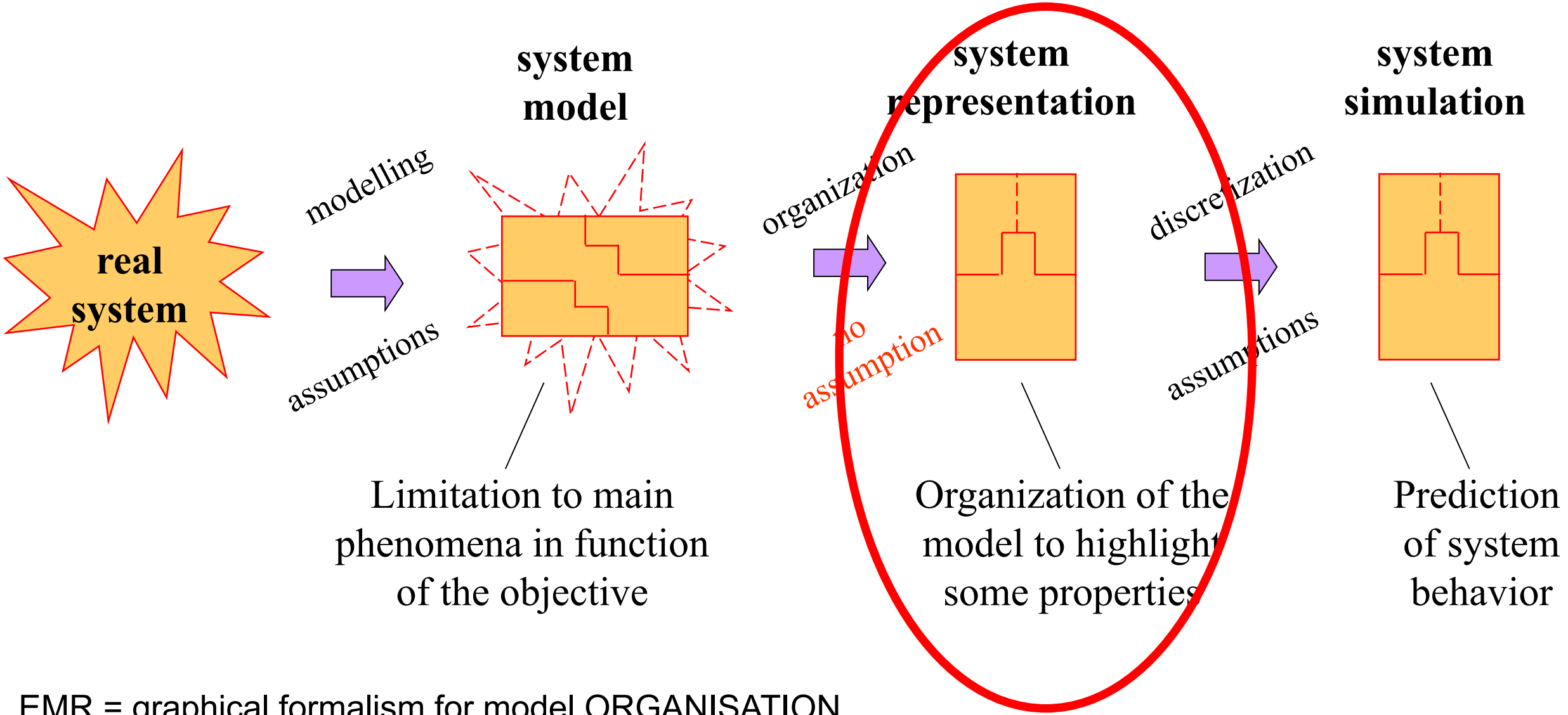
**Prof. Betty LEMAIRE-SEMAIL, Prof. Alain BOUSCAYROL,**

Based on the EMR summer school
and Master “Electrical Engineering for
sustainable development” course at Univ. Lille

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




EMR = graphical formalism for model ORGANISATION
(after the modelling step)

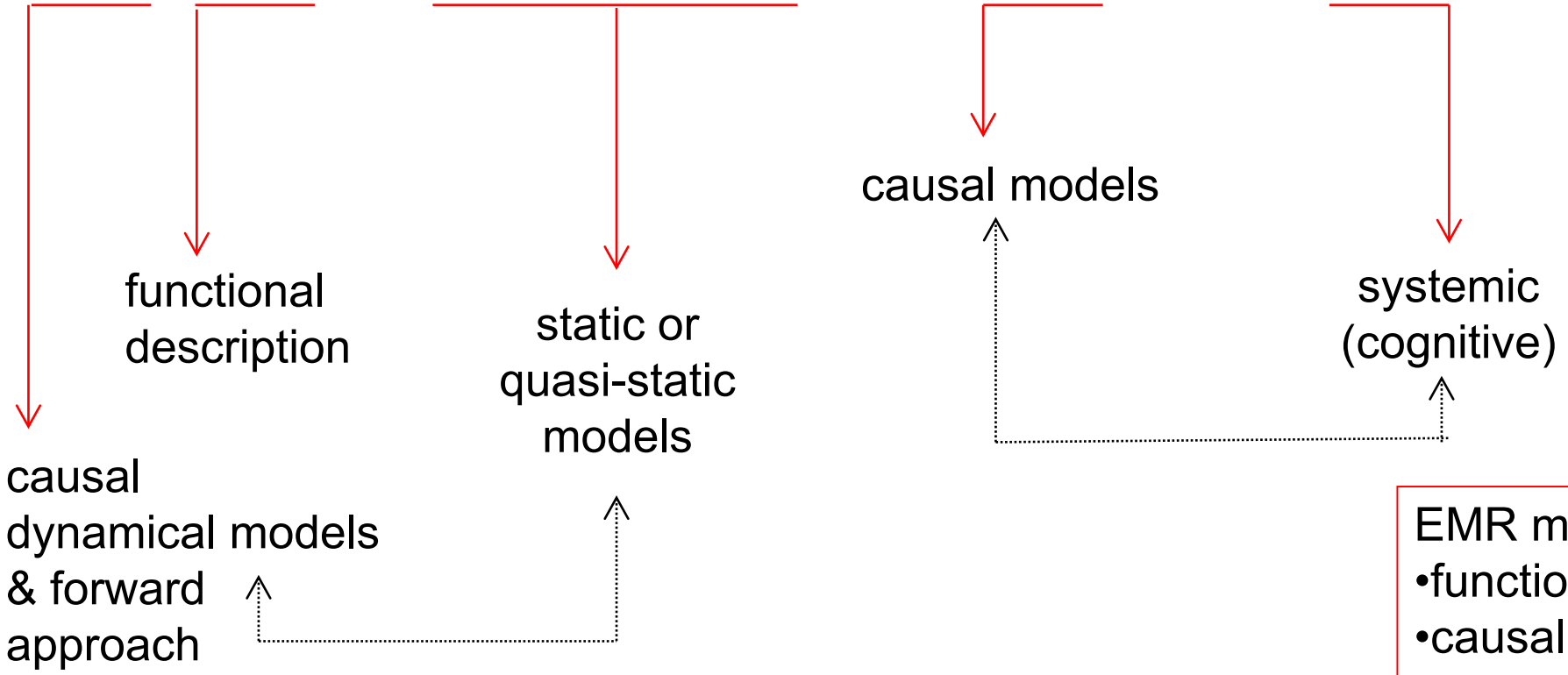
# Objective of the graphical description



A graphical description is chosen depending on objectives

EMR objective:

– real-time control and energy management of energy conversion systems




EMR must be
•functional
•causal
•systemic

1. EMR elements
2. Association rules
3. EMR of a complete system
4. Example

1. **EMR elements**
2. Association rules
3. EMR of a complete system
4. Example

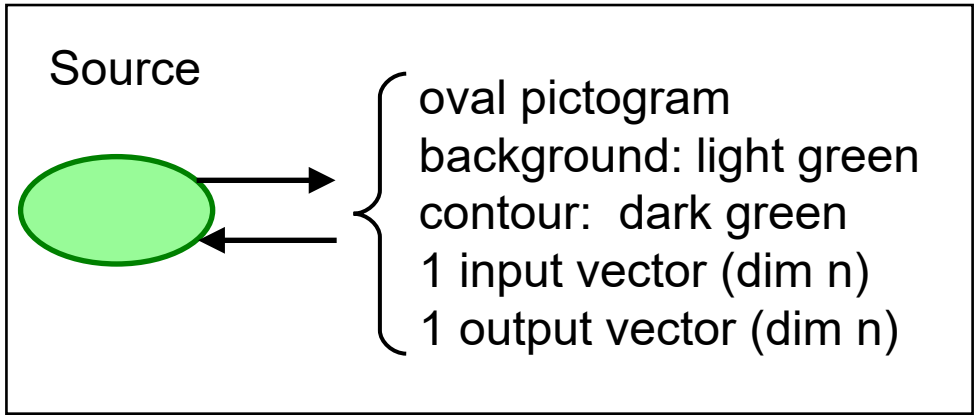
Key aspects for energy conversion systems:

- Causality principle (energy)
- Interaction principle (Systemics)

Only 4 energy functions are required to describe energy conversion systems

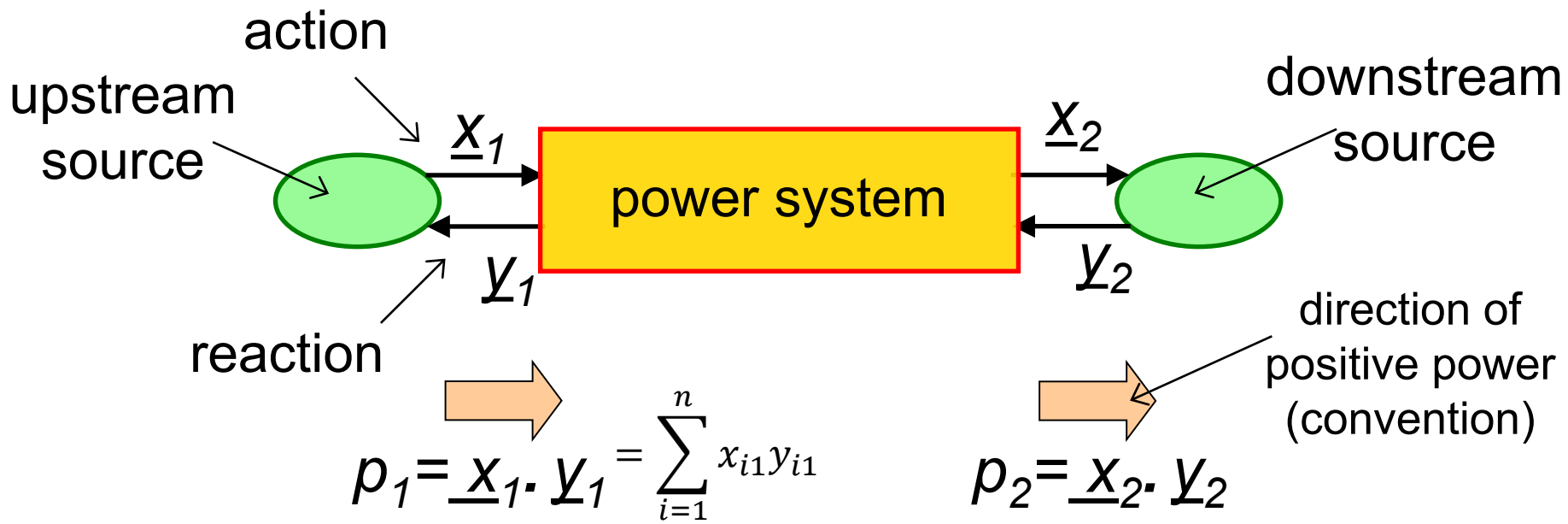
- Energy sources
- Energy storage
- Energy conversion
- Energy distribution

EMR = 4 graphical elements associated with the 4 energy functions




**terminal elements** which represent the environment of the studied system

generator and/or receptor of energy

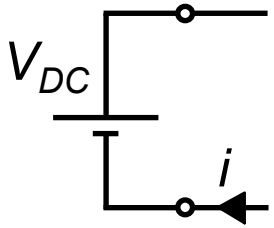


# Example of source elements

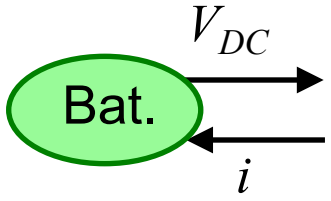


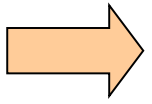
## Battery

structural description



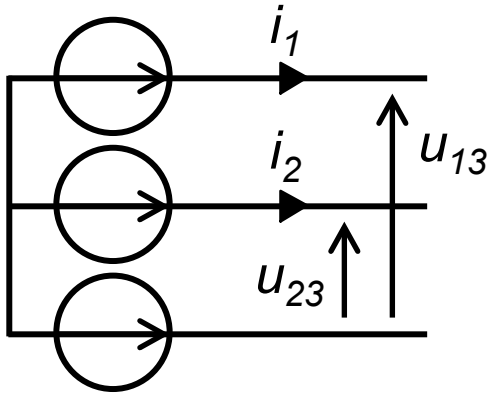

EMR (functional description)



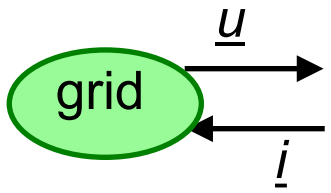



$p(t)=V_{DC}(t)i(t)$

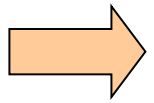
## Electrical grid




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




2 independent currents!



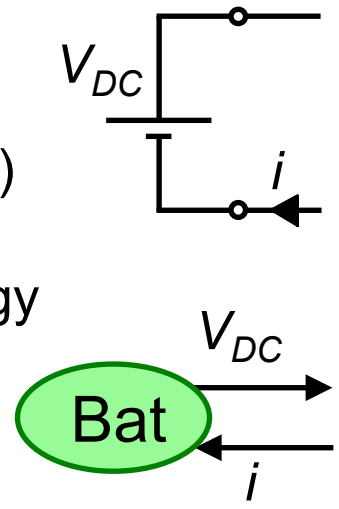
2 independent voltages!

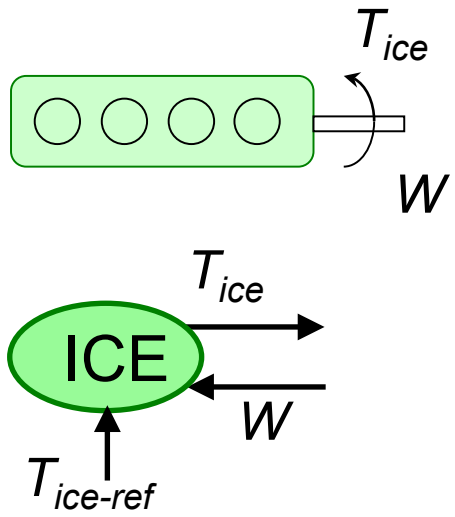
$p(t)=\underline{u}(t)\,\underline{i}(t)=u_{13}(t)i_1(t)+u_{23}(t)i_2(t)$

# Example of source elements

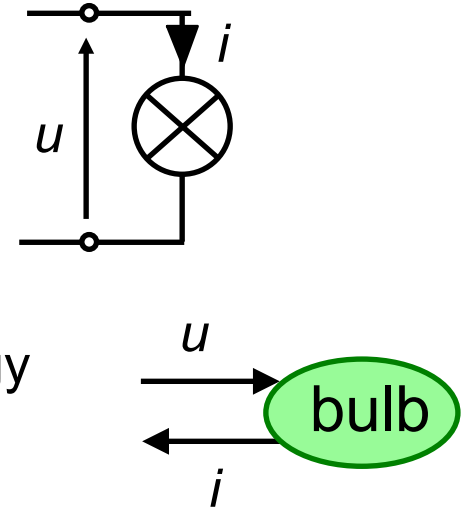


**Battery**
(voltage source)
generator and
receptor of energy

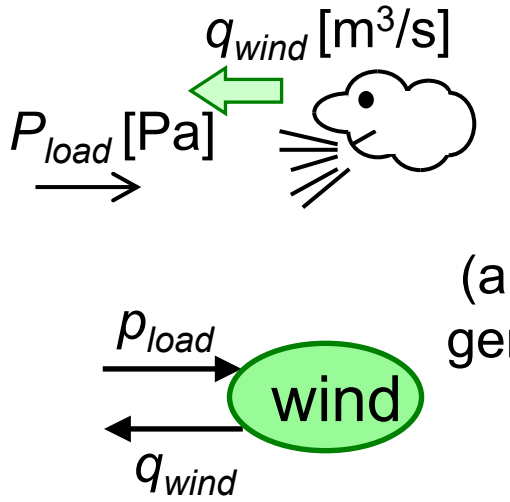


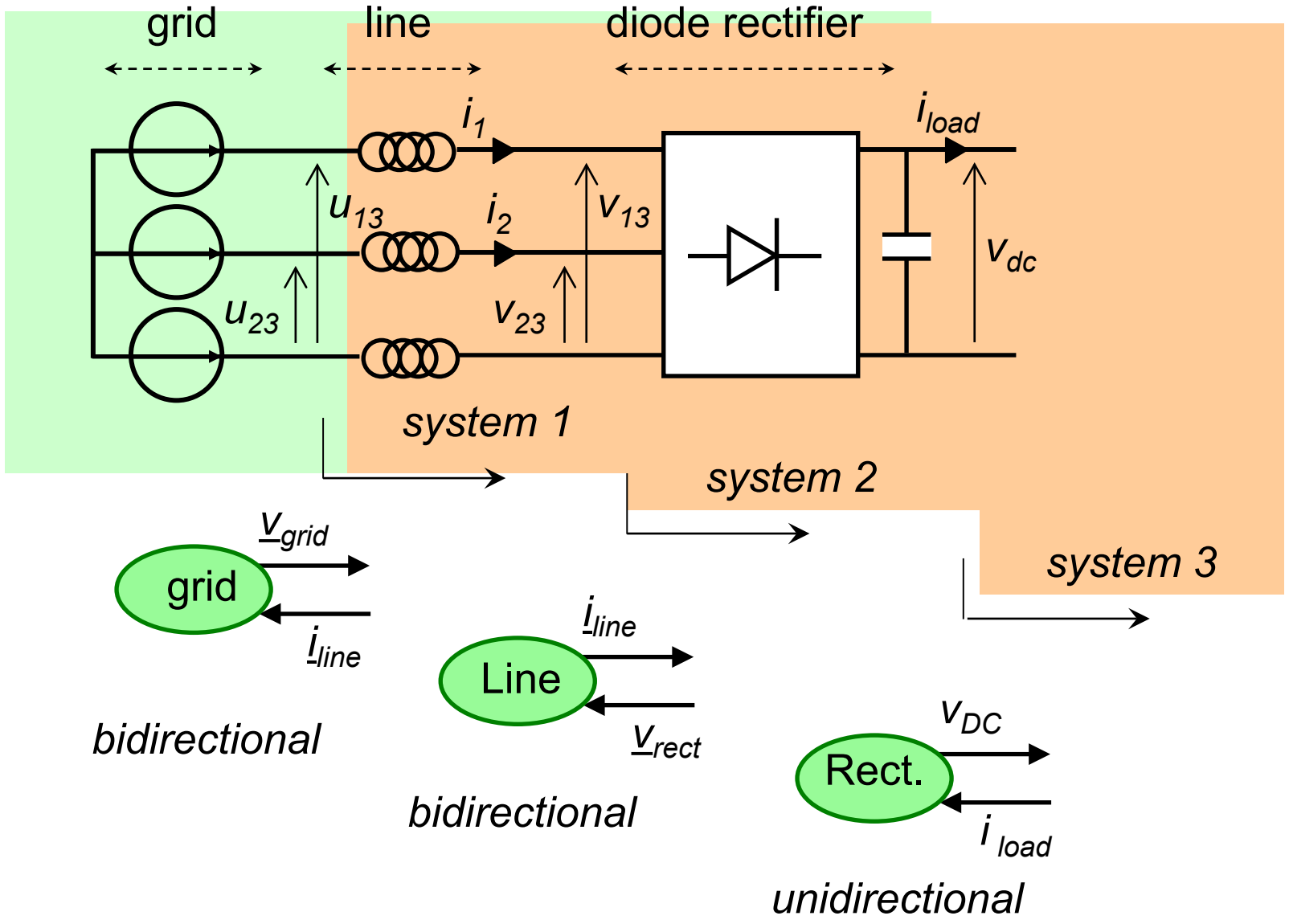

**IC engine**
(torque source)
generator
of energy




**Ligthing bulb**
receptor of energy

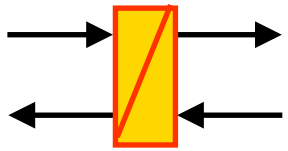



**Wind**
(air flow source)
generator energy




Border of the system?

Accumulator



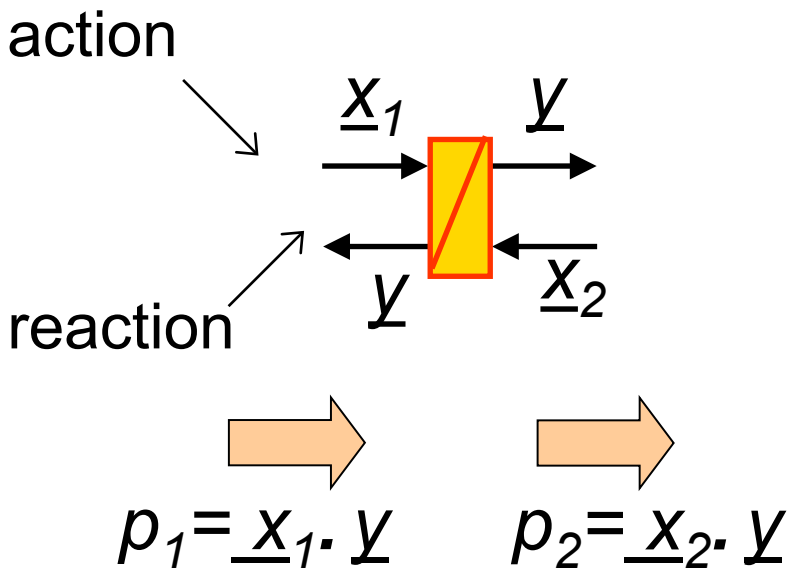
rectangle with an oblique bar
background: orange
contour: red
upstream I/O vectors (dim n)
downstream I/O vectors (dim n)

**internal accumulation of energy** (with or without losses)

**causality principle**

**Output variable = Energetic variable**

$$\text{output(s)} = \int \text{input(s)}$$




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

$\underline{y}$ = output, delayed with regard to input changes

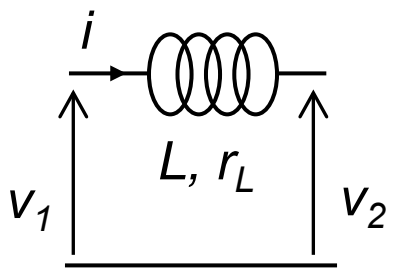
fixed I/O (causal description)

# Example of accumulation elements



inductor

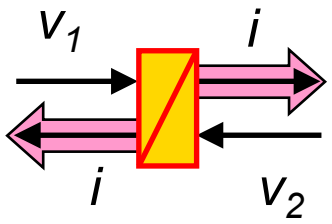
structural description




functional mathematical Model

$$L\frac{d}{dt}i + r_L\, i = v_1 - v_2$$

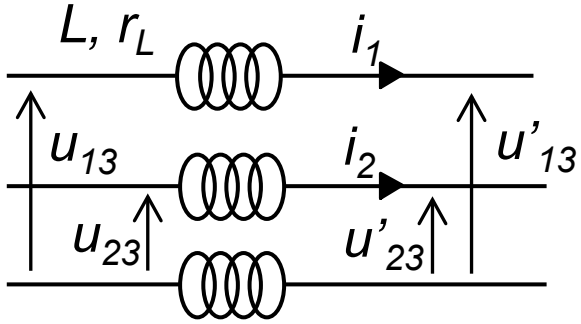
EMR (causal functional representation)



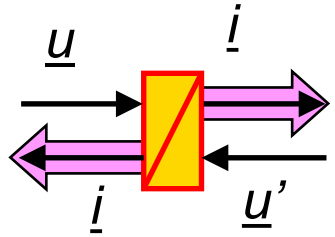

$$i = \frac{1}{L}\int_0^t (v_1 - v_2 - ri)dt$$

output = integral function of inputs
output delayed from inputs

3-phase line



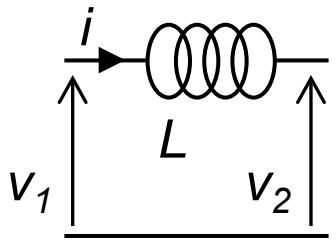

$$[L]\frac{d}{dt}\underline{i} + r_L\,\underline{i} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}(\underline{u} - \underline{u'})$$




output = current vector (dimension 2)

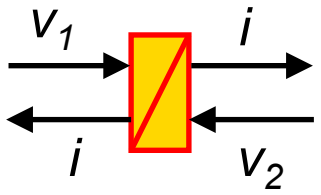
# Example of accumulation elements

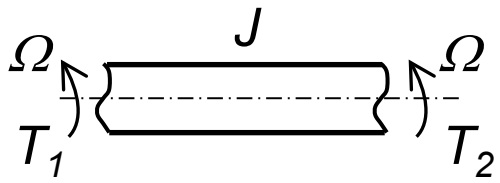




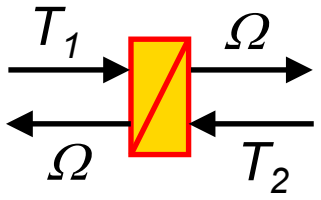

inductor

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

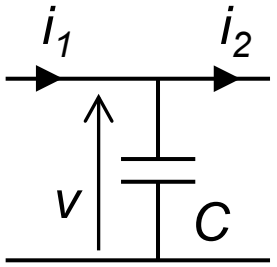



inertia

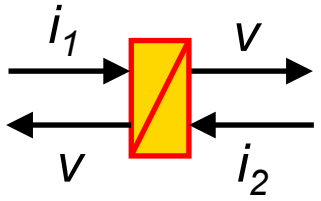


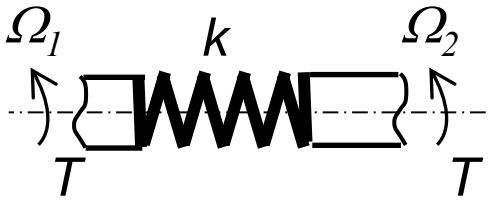

$$E = \frac{1}{2} J \Omega^2$$



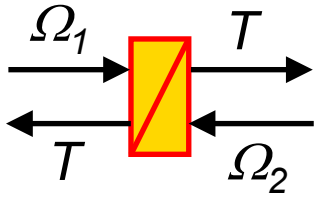

capacitor

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




stiffness

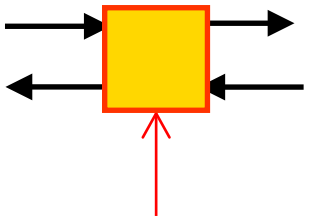



$$E = \frac{1}{2} \frac{1}{k} T^2$$

# Conversion elements



conversion element



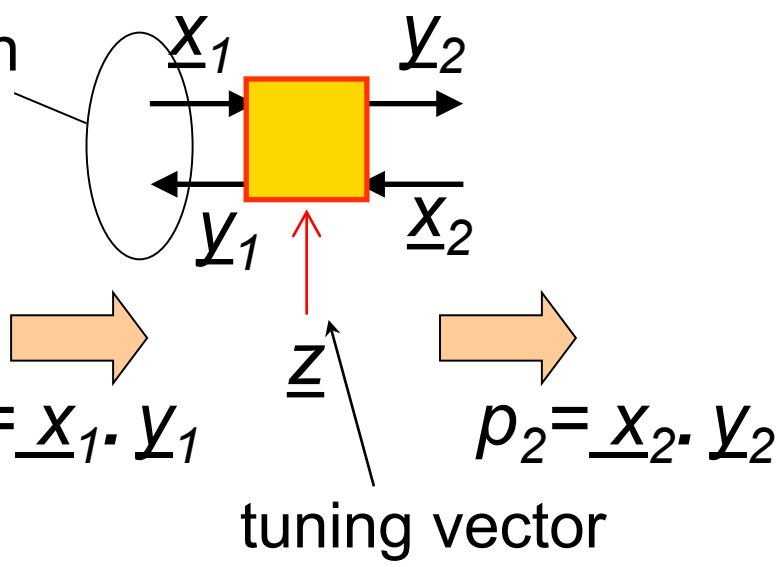
various pictograms
background: orange
contour: red
upstream I/O vectors (dim n)
downstream I/O vectors (dim p)
**Possible tuning input vector** (dim q)

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

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

no delay!

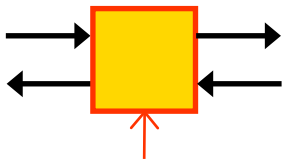
action / reaction



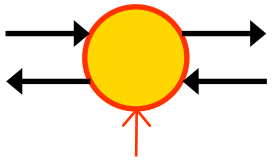

upstream and downstream I/O can be permuted (floating I/O)

# Mono and multi-domain Conversion elements

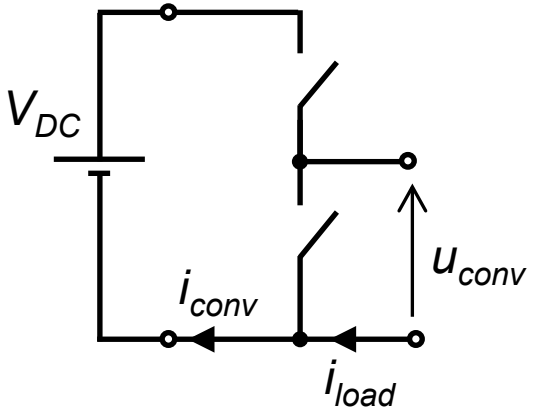


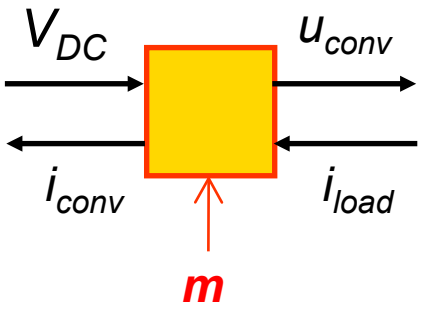


Square = mono-domain conversion



Circle = multil-domain conversion



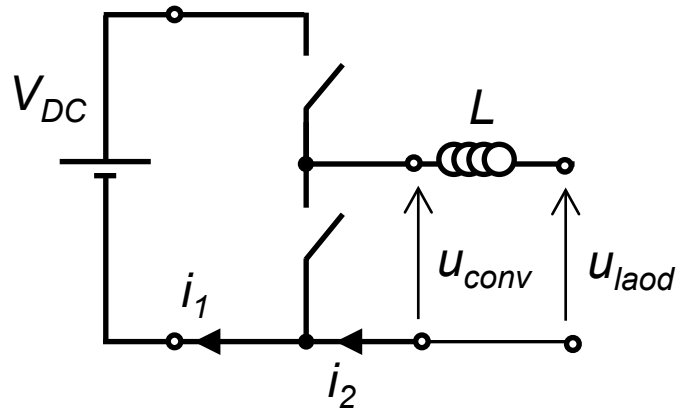




$$\begin{cases} u_{conv} = m\, V_{DC} \\ i_{conv} = m\, i_{load} \end{cases}$$

*m*: modulation function of the converter

$\langle m \rangle = D$

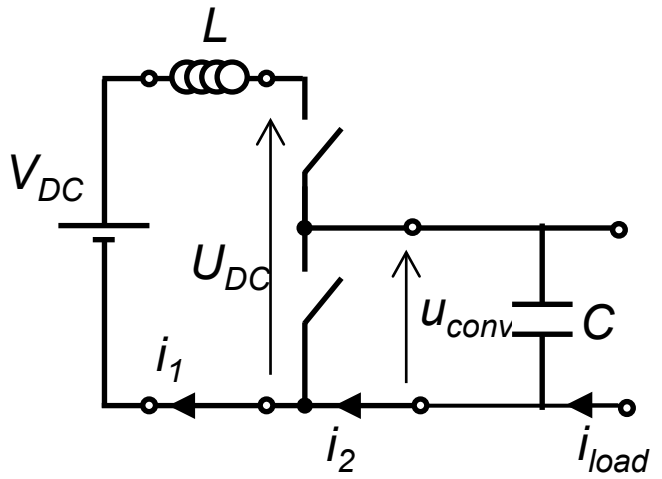
= duty cycle

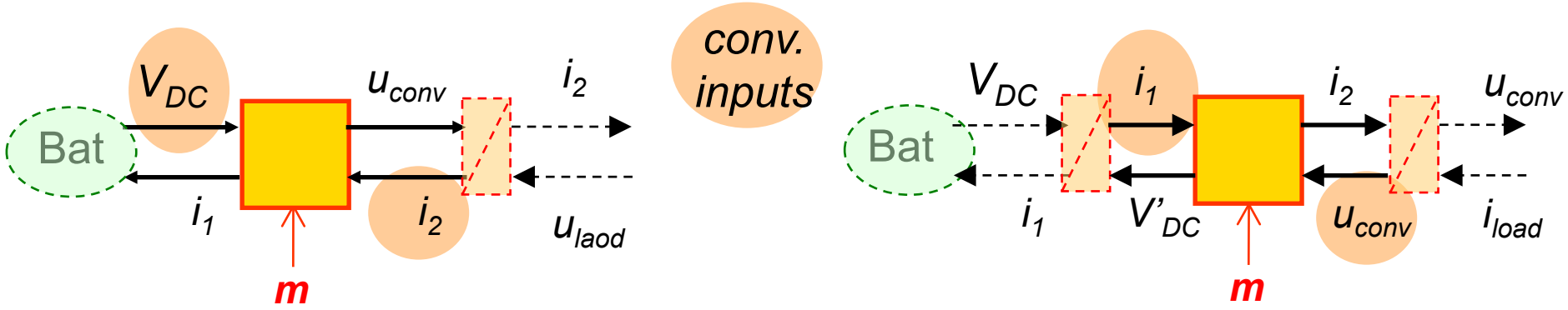



$$\begin{cases} u\text{conv} = m\, V\text{DC} \\ i_1 = m\, i_2 \end{cases}$$

or

$$\begin{cases} U\text{DC} = \dfrac{1}{m} u\text{conv} \\ i_2 = \dfrac{1}{m}\, i_1 \end{cases}$$

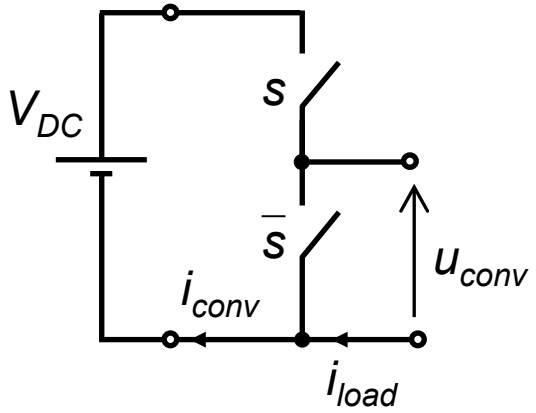


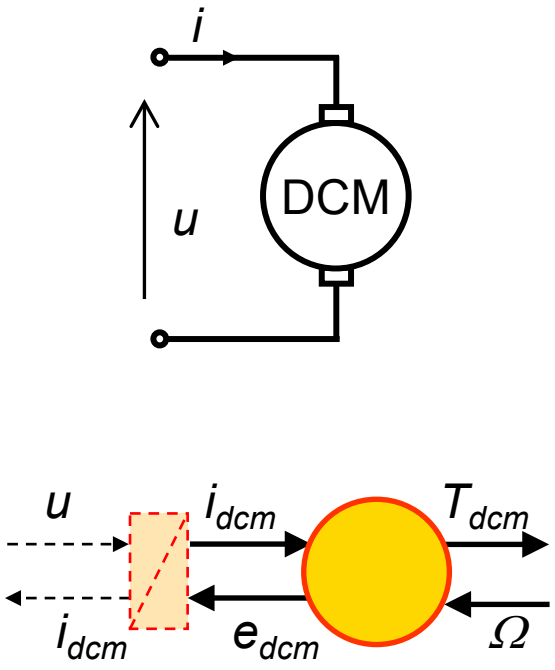

I/O are defined by accumulation elements

# Example of conversion elements



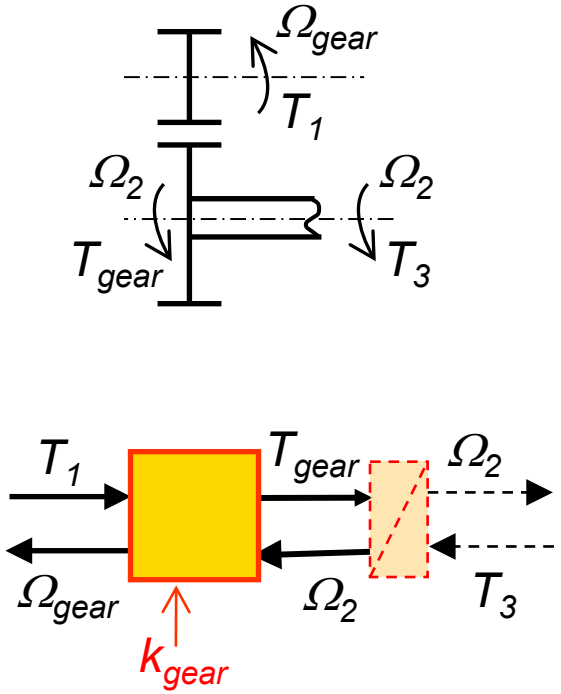



$$\begin{cases} u_{conv} = m\, V_{DC} \\ i_{conv} = m\, i_{load} \end{cases}$$




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

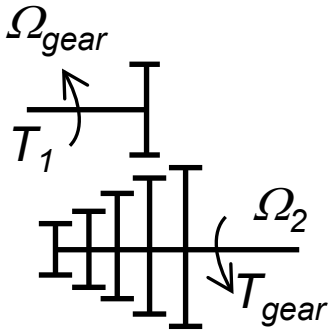
$$\begin{cases} T_{dcm} = k_\Phi\, i_{dcm} \\ e_{dcm} = k_\Phi\, \Omega \end{cases}$$



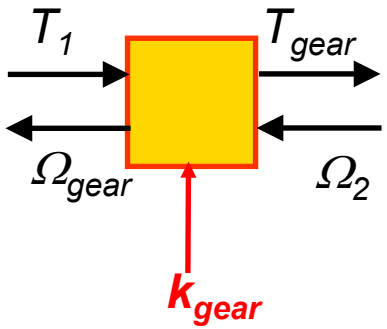

$$\begin{cases} T_{gear} = k_{gear}\, T_1 \\ \Omega_{gear} = k_{gear}\, \Omega_2 \end{cases}$$

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

## 5-speed gearbox

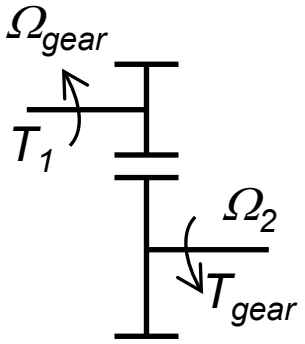


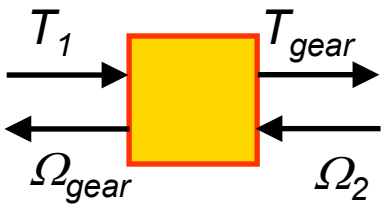

$$\begin{cases} T\text{gear} = k\text{gear}\, T_1 \\ \Omega\text{gear} = k\text{gear}\, \Omega_2 \end{cases}$$




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

## fixed gear

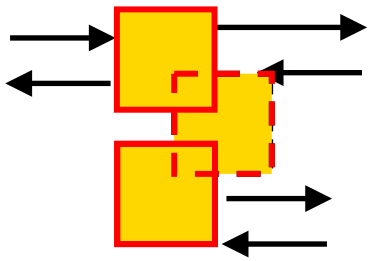



(no tuning input)

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

coupling element



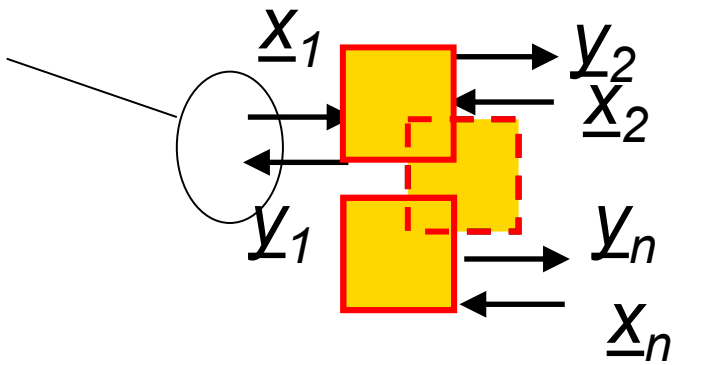
various overlapped pictograms
background: orange
contour: red
pairs of I/O vectors
N pairs, N-1 pictograms

**distribution of energy**
**without energy accumulation**
**without tuning**
(with or without losses)

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

no delay!

action / reaction




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

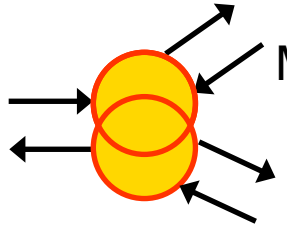
$$P_s = \sum_{i=2}^{n} \underline{x}_i \ \underline{y}_i$$

N elements connected
(N-1) overlapped pictograms

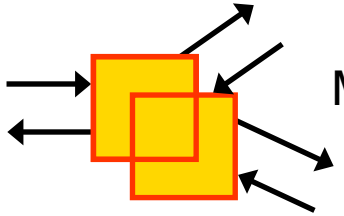
# Mono and multi-domain coupling elements



coupling elements { overlapped pictograms
background: orange
contour: red



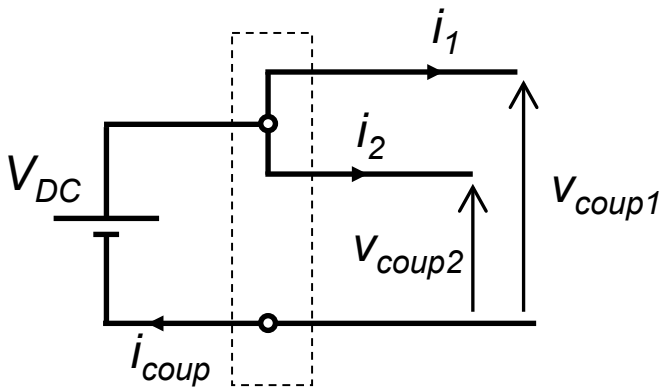
Multi-domain coupling



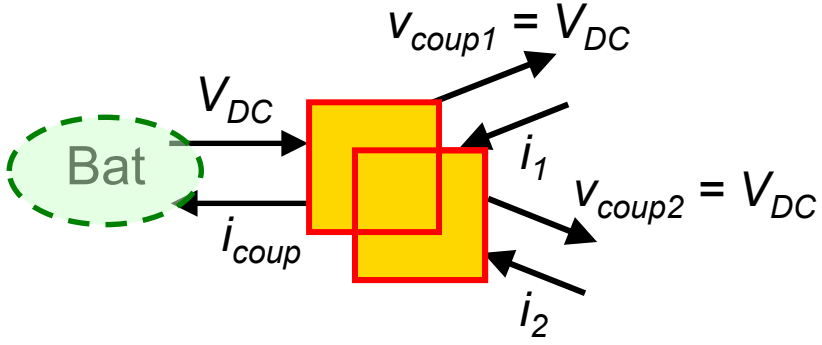
Mono-domain coupling

distribution of energy

no tuning vector




parallel connexion

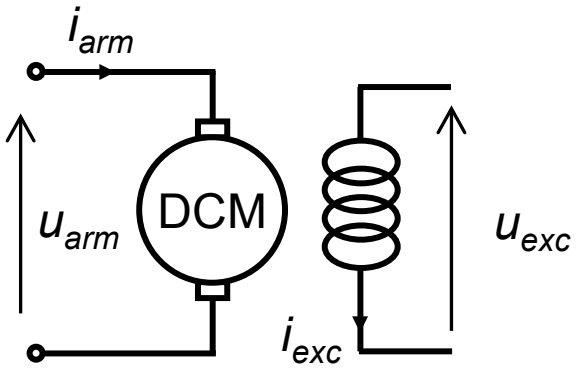



$\begin{cases} V_{DC} \text{ common} \\ i_{coup} = i_1 + i_2 \end{cases}$

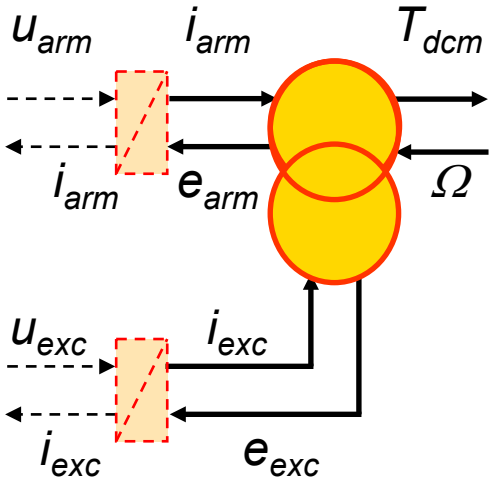
3 electrical elements
Connected
(battery, load 1, load 2)

2 overlapped
orange squares

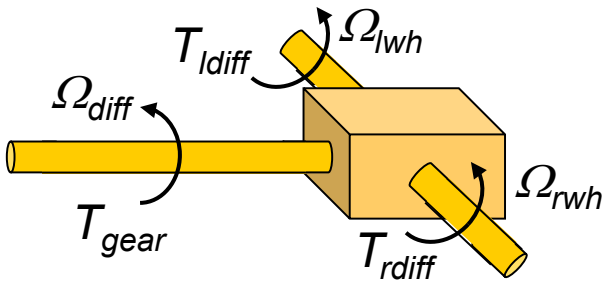
## Field winding DC machine



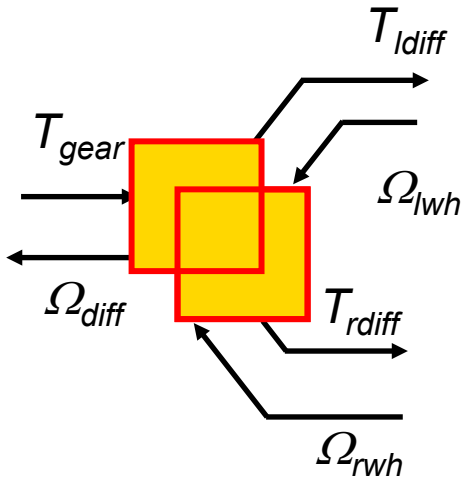

$$\begin{cases} T_{dcm} = k\, i_{exc}\, i_{arm} \\ e_{arm} = k\, i_{exc}\, \Omega \end{cases}$$




## Mechanical differential

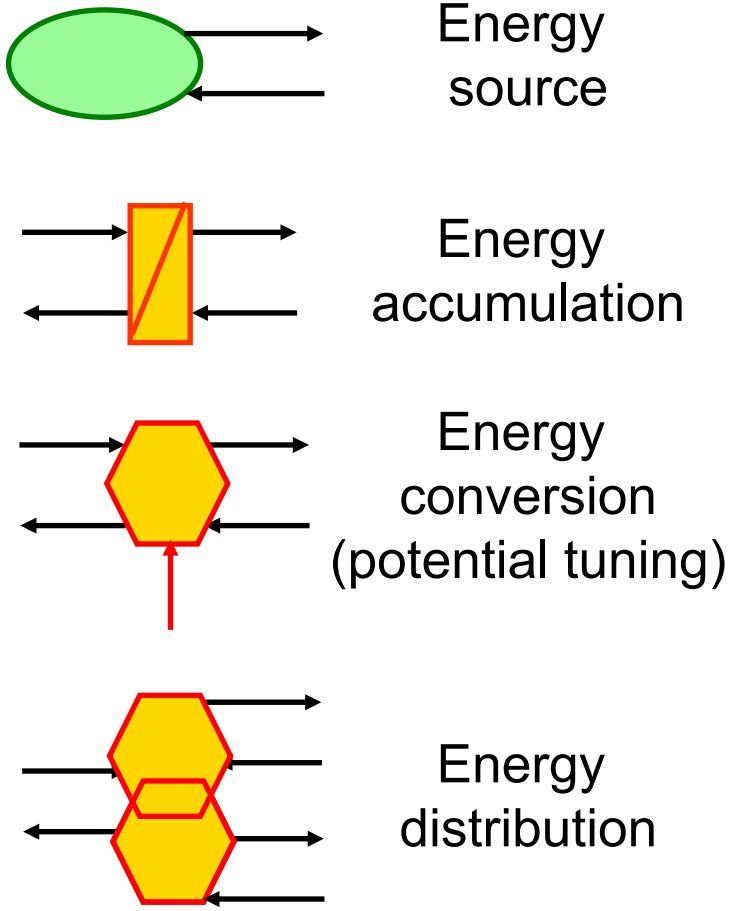



$$\begin{cases} T_{ldif} = T_{rdif} = \dfrac{T_{gear}}{2} \\ \Omega_{diff} = \dfrac{\Omega_{lwh} + \Omega_{rwh}}{2} \end{cases}$$



# Summary on EMR elements





Energy source

Energy accumulation

Energy conversion (potential tuning)

Energy distribution

all elements connected
by action/ reaction (Systemics)

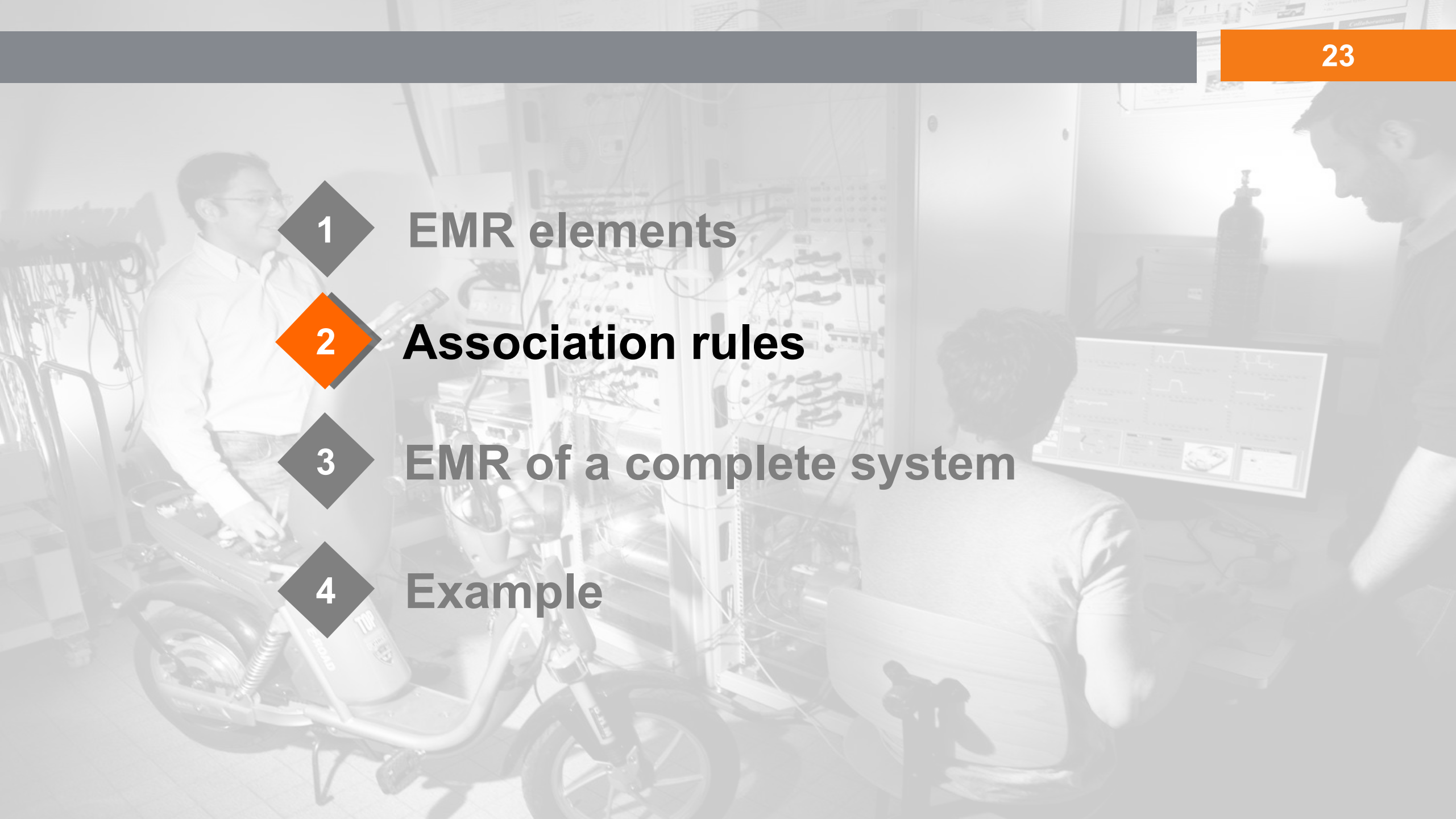
all power I/O defined
by accumulation elements
(causality)

only conversion elements
can have tuning inputs

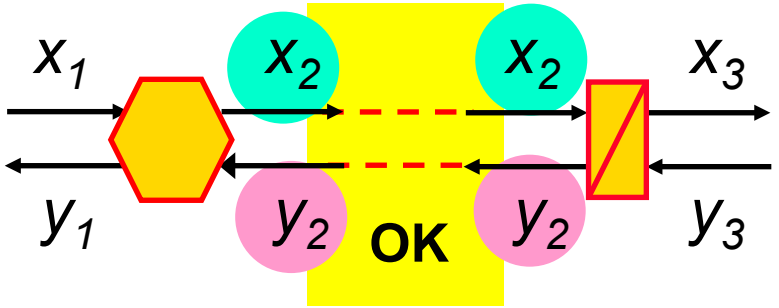
⇩

valuable for control design

[Bouscayrol 2012] [Bouscayrol 2023]

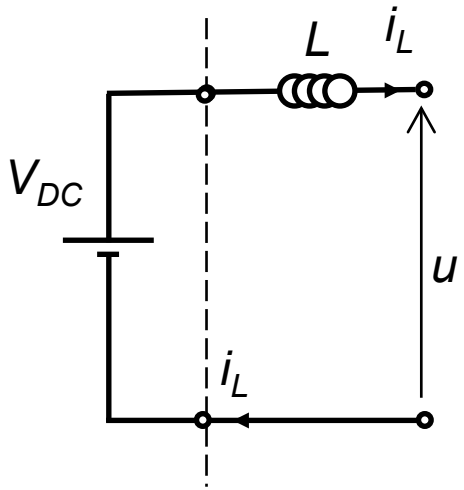


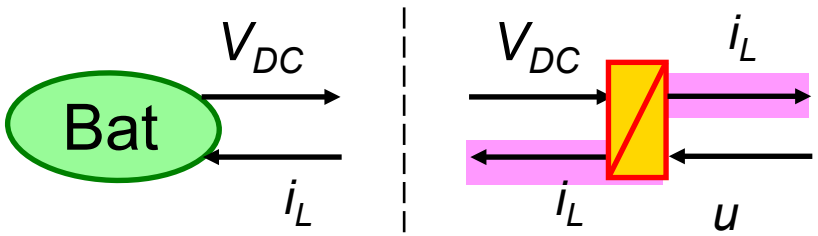
1. EMR elements
2. **Association rules**
3. EMR of a complete system
4. Example

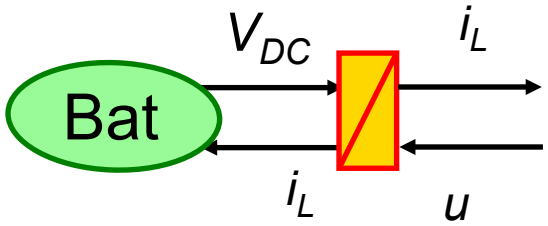



S1 and S2 any sub-systems

*Example*

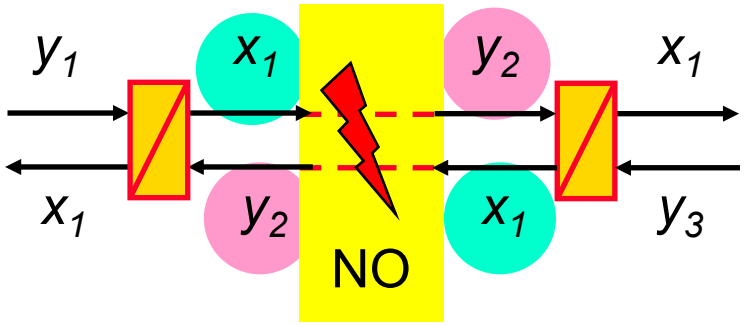


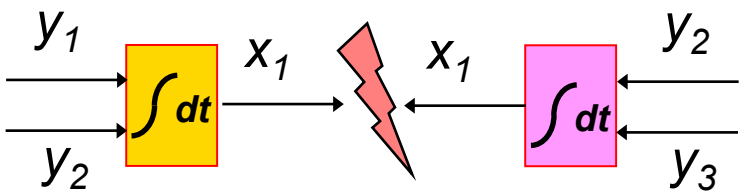




$$L\frac{d}{dt}i_L = V_{DC} - u$$

*i* energetic variable



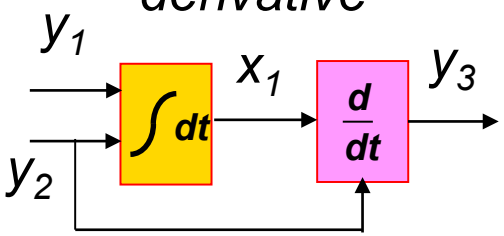

2 accumulation elements impose the same state variable $x_1$




**Conflict of association**

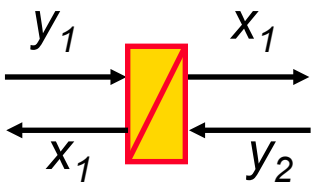
*solutions*

*derivative*



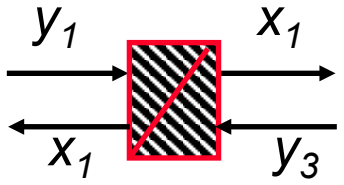

Structural / mathematical solution / non physical

*simplification*

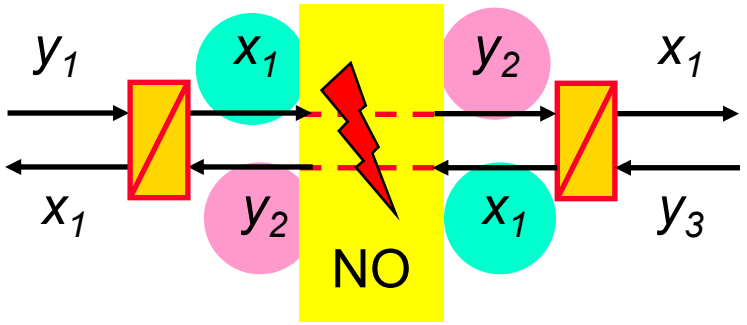



Cartesian approach / non physical

*merging*



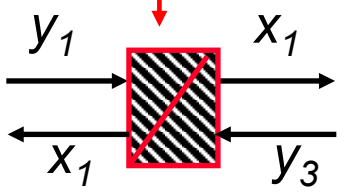

1 equivalent function for 2 elements / systemic




2 accumulation elements would impose the same state variable $x_1$

**Conflict of association**

*merging*




1 equivalent function for 2 elements / systemic

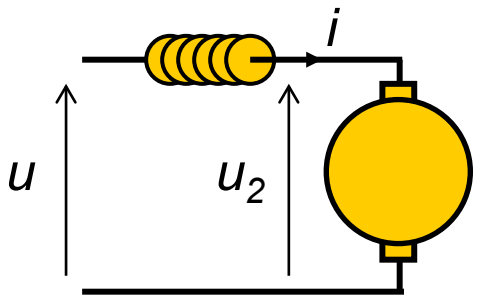
EMR only for detection of conflict of association

come back on modelling for mathematical solving

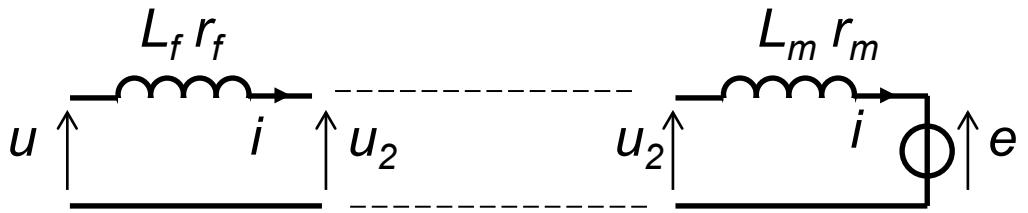
# Example of merging rule



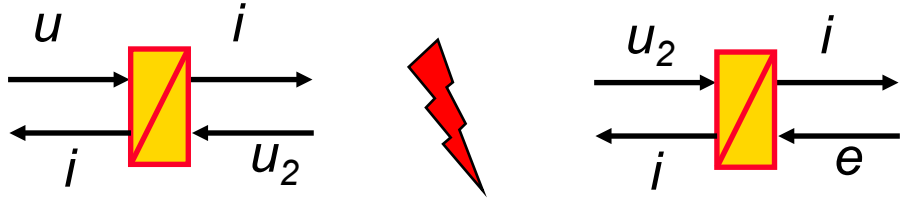
DC machine and smoothing inductor



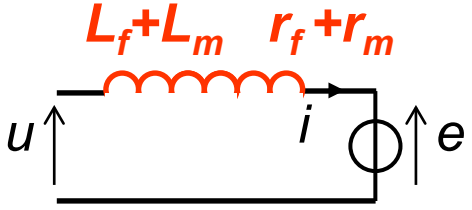

Assumption: $L_f$, $L_m$ constant

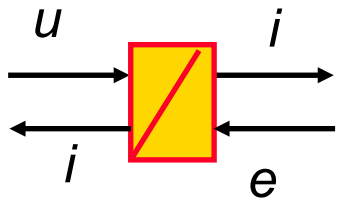



$$L_f \frac{\mathrm{di}}{\mathrm{dt}} = u - u_2 - r_f i \qquad L_m \frac{\mathrm{di}}{\mathrm{dt}} = u_2 - e - r_m i$$




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

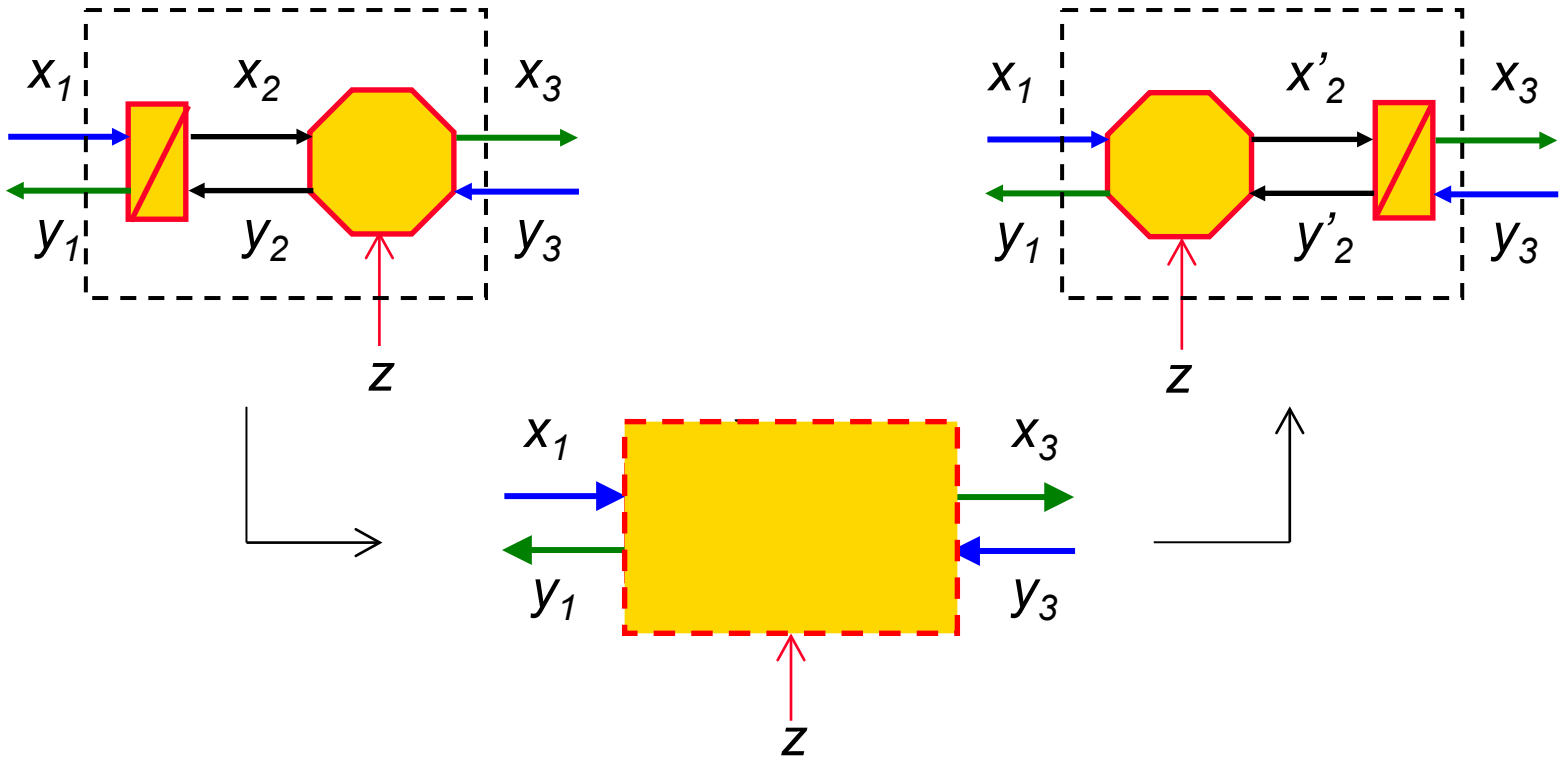



**Remark:**

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

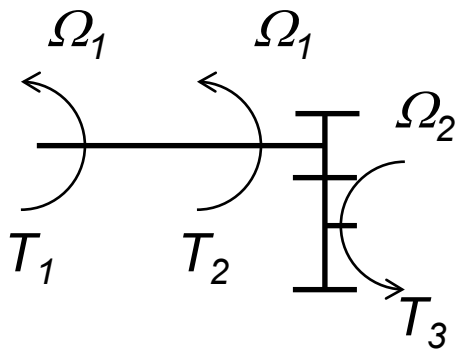
| merging (systemic) | Structural (Cartesian) | simplification |
|---|---|---|




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

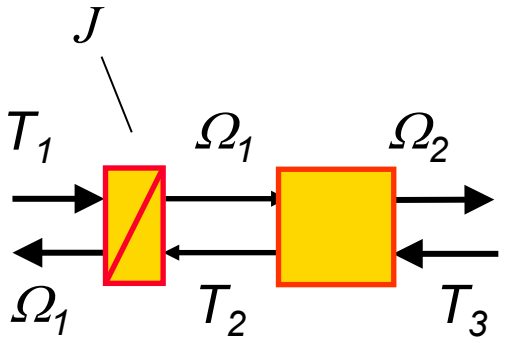
# Example of permutation rule






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

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



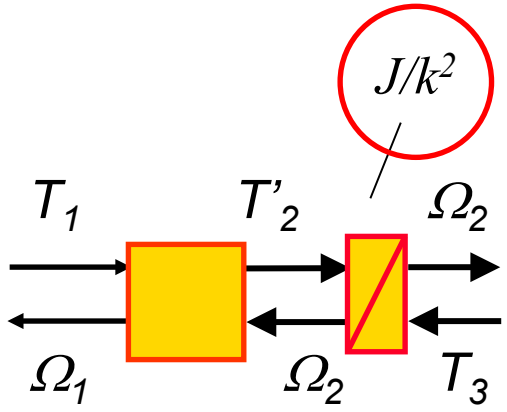

Shaft + gearbox

*variable change*

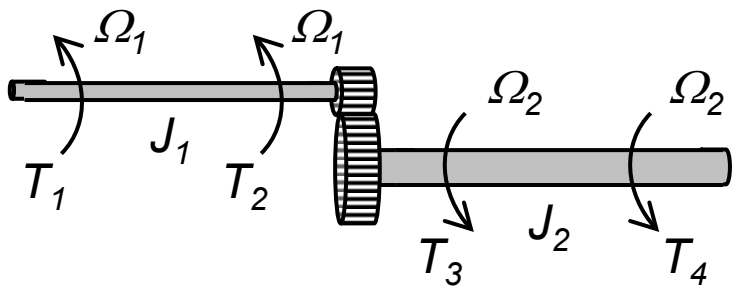
$$\frac{J}{k^2}\,\frac{d}{dt}\,\Omega_2 = T'_2 - T_3$$

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

no assumption
strict equivalence
(same model)



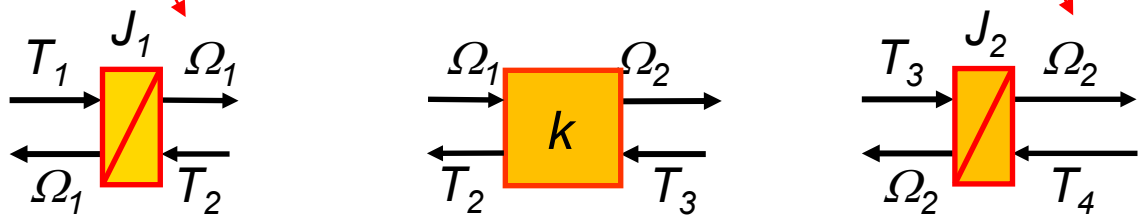
Example: two inertia linked by a fix ratio gearbox




Models

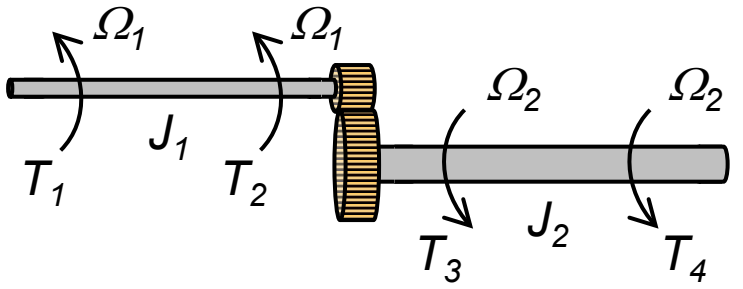
$$J_1 \frac{d\Omega_1}{dt} = T_1 - T_2 \qquad \begin{cases} \Omega_2 = K.\Omega_1 \\ T_2 = K.T_3 \end{cases} \qquad J_2 \frac{d\Omega_2}{dt} = T_3 - T_4$$

Representation



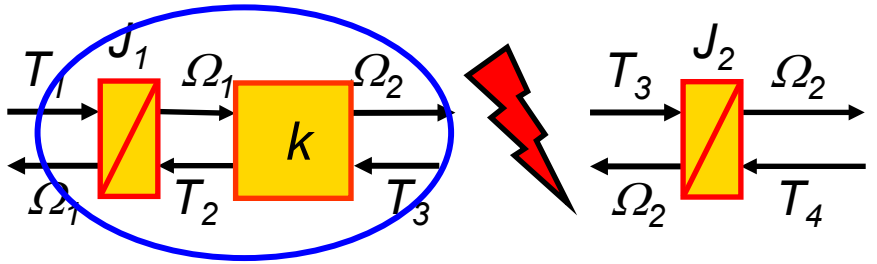

causal acausal causal

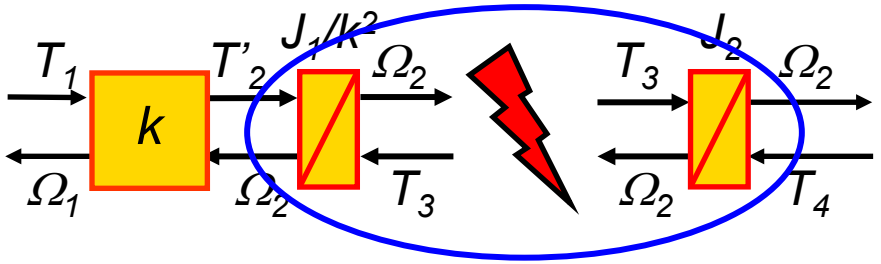
Assumptions:
$J_1$ , $J_2$ constant
no backslash



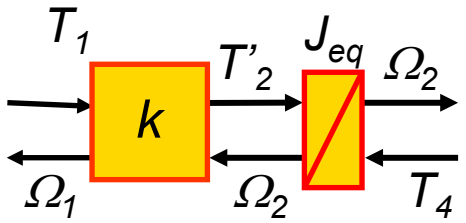

to solve conflict of association

permutation

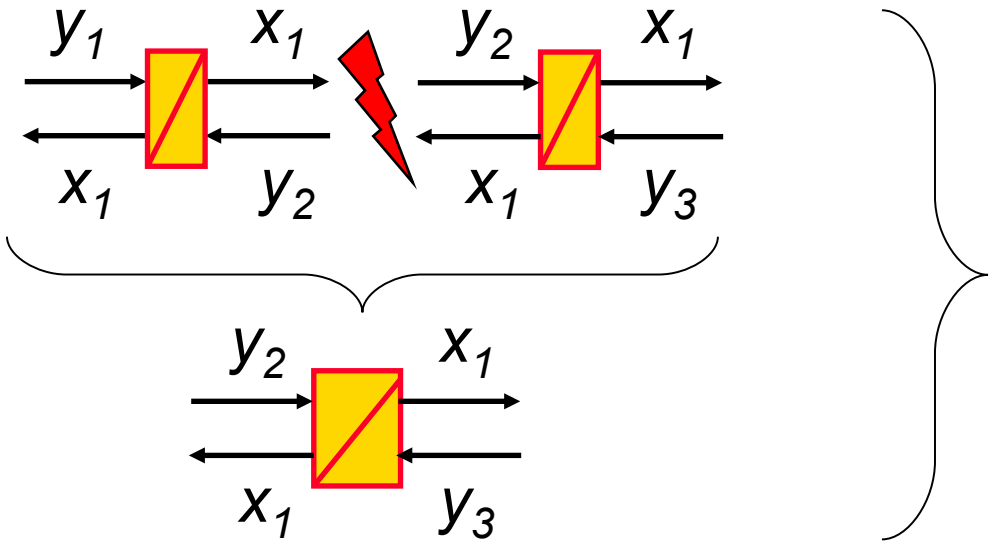



merging




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




Priority to the function
by keeping the physical causality

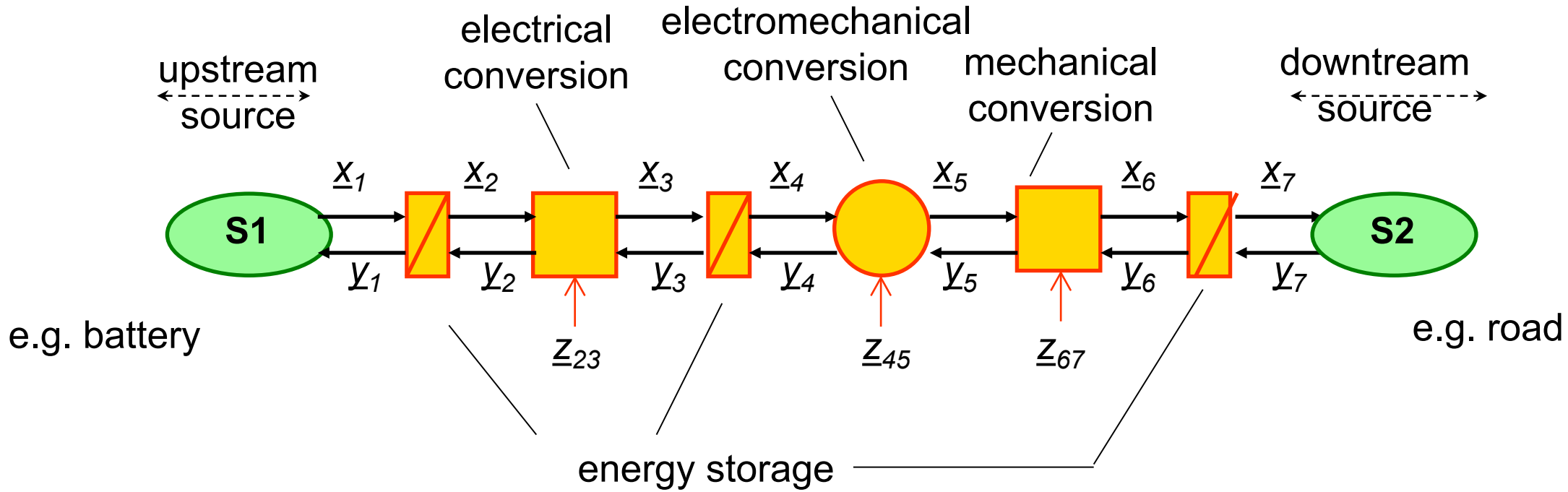
Principle of holism
(systemic)

**Main difference between structural and functional descriptions:**
1 physical device: maybe 2 functions (e.g. two EMR elements)
Association of several physical devices: maybe a unique function (1 EMR element)

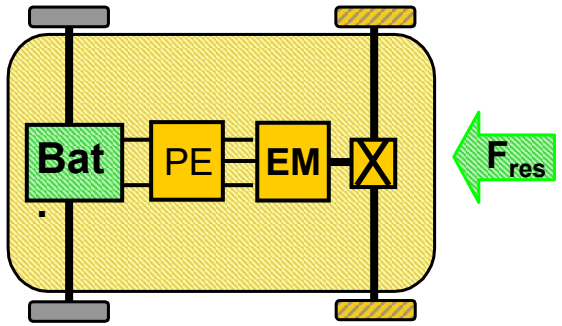
1. EMR elements
2. Association rules
3. **EMR of a complete system**
4. Example

# Example of an electromechanical conversion system






[Chen 2008]




upstream source → downstream source

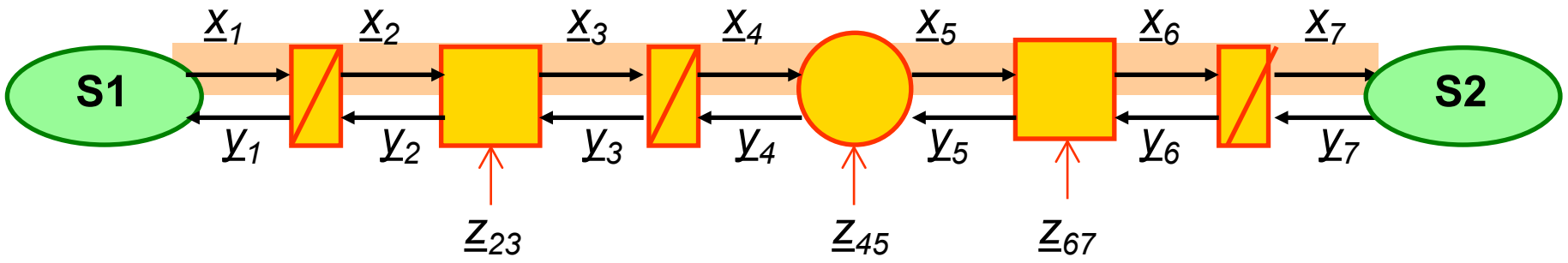
**Convention:** direction of positive power flow (could be negative for bidirectional system)

# Action and reaction paths

Bidirectional system if:
- bidirectional sources
- bidirectional conversion elements

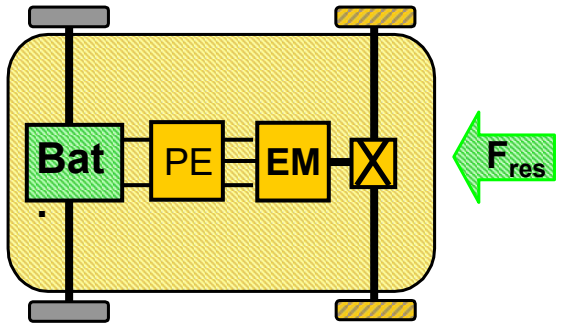
upstream source

downtream source




P > 0 action path: $\underline{x}_1 \rightarrow \underline{x}_2 \rightarrow \underline{x}_3 \rightarrow \underline{x}_4 \rightarrow \underline{x}_5 \rightarrow \underline{x}_6 \rightarrow \underline{x}_7$

(e.g. acceleration) reaction path: $\underline{y}_1 \leftarrow \underline{y}_2 \leftarrow \cdots \leftarrow \underline{y}_7$

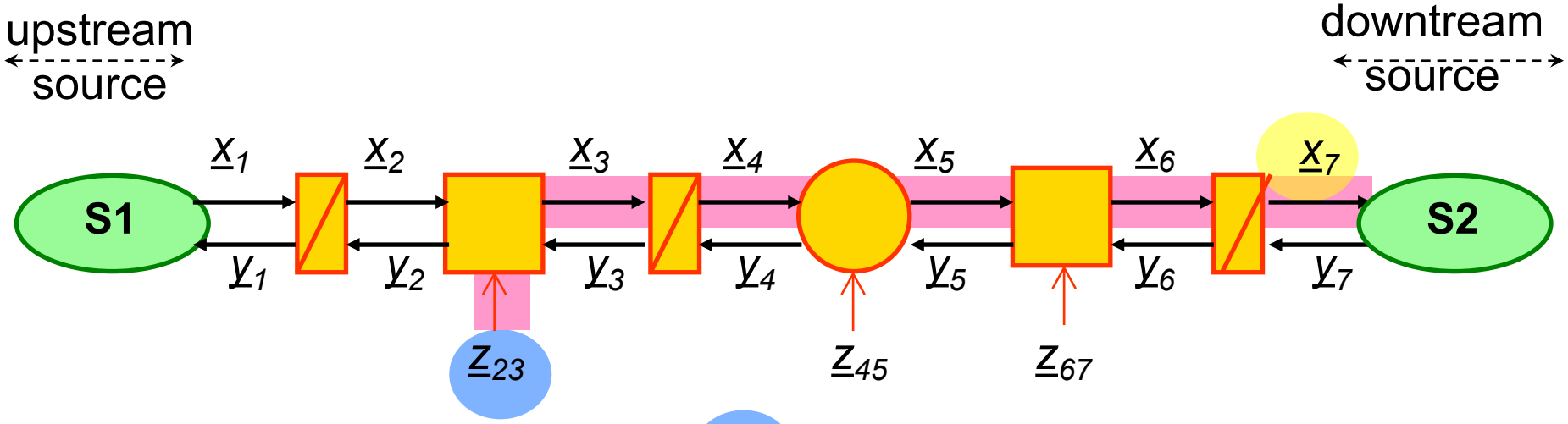



P < 0 action path: $\underline{y}_1 \leftarrow \underline{y}_2 \leftarrow \cdots \leftarrow \underline{y}_7$

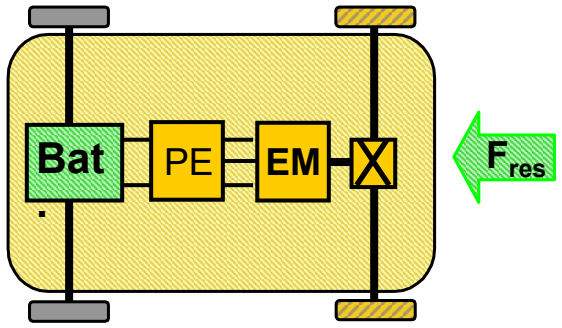
(e.g. braking) reaction path: $\underline{x}_1 \rightarrow \underline{x}_2 \rightarrow \cdots \rightarrow \underline{x}_7$

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

Tuning path: causal path from the selected tuning input to the output to be controlled




Technical requirements: action on $\underline{z}_{23}$ (e.g. converter modulation ratio) and $\underline{x}_7$ (e.g. vehicle velocity) to be controlled



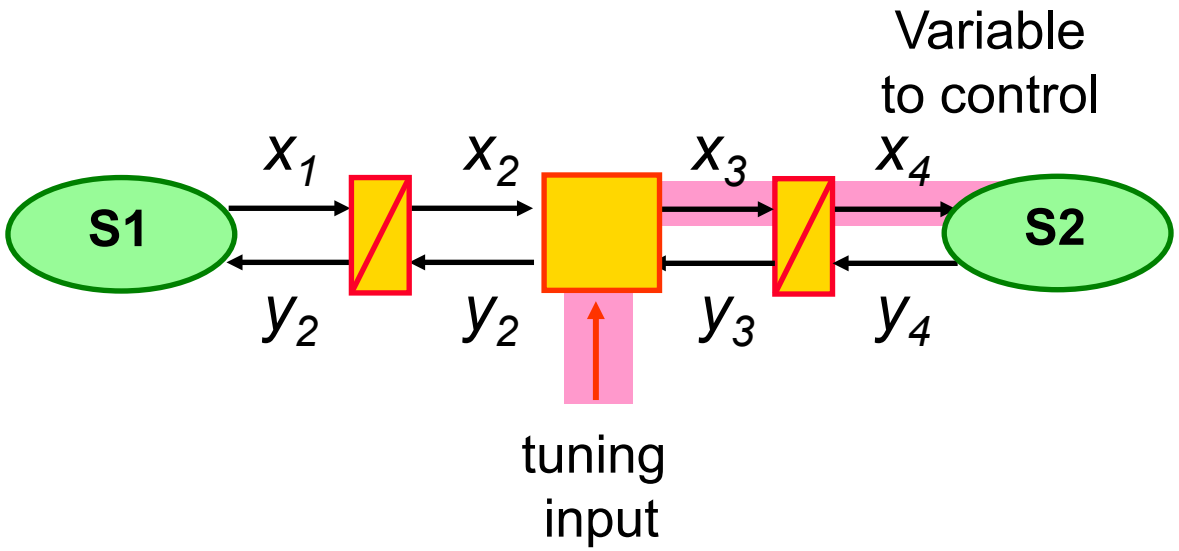

Tuning path: $\underline{z}_{23} \rightarrow \underline{x}_3 \rightarrow \underline{x}_4 \rightarrow \underline{x}_5 \rightarrow \underline{x}_6 \rightarrow \underline{x}_7$

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

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

# Summary on EMR at system level






EMR = tool for analysis before
control development

I/Os are independent
of power flows

tuning paths:
• defined by the technical requirements
• independent of the power flow direction

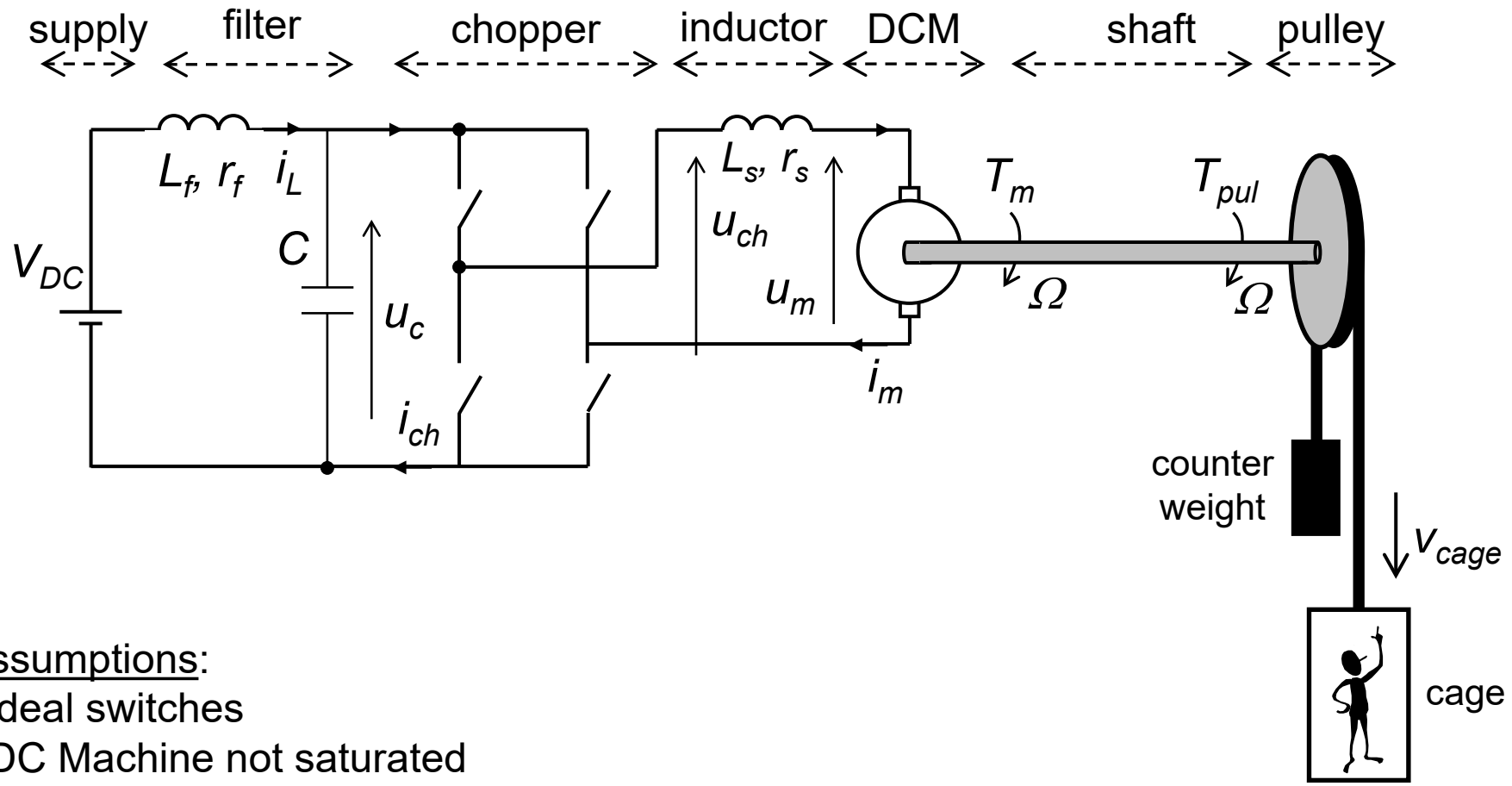
EMR is adapted for control orgnization

unique control scheme whatever
the power flow direction
(e.g. traction or generator mode)

1. EMR elements
2. Association rules
3. EMR of a complete system
4. **Example**

# Example of a lift system

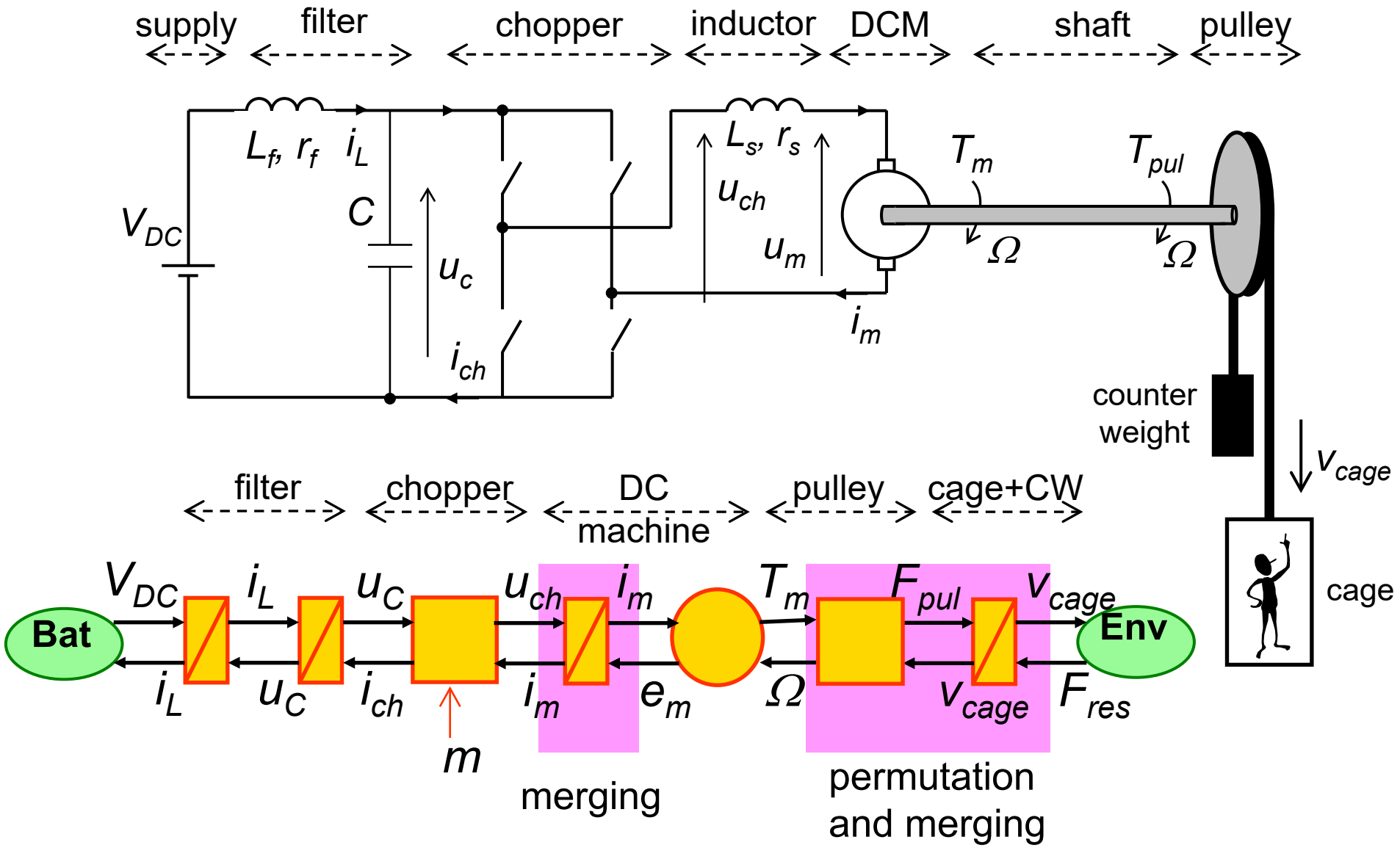




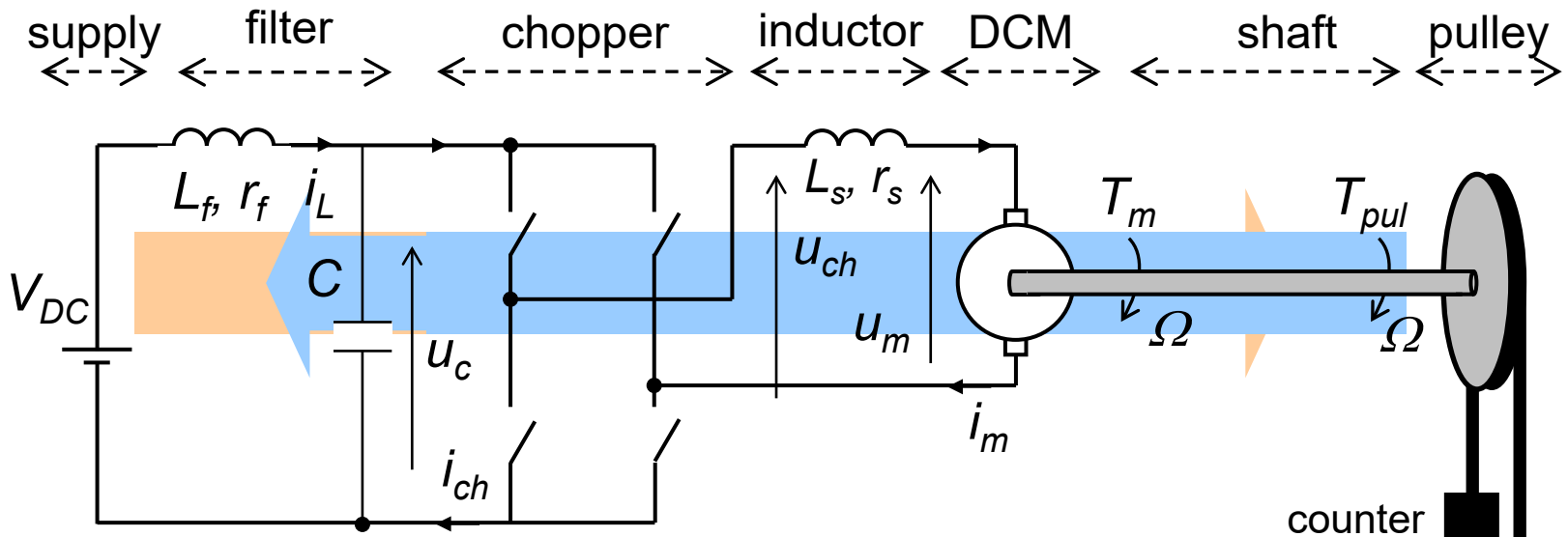

Assumptions:
- ideal switches
- DC Machine not saturated

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

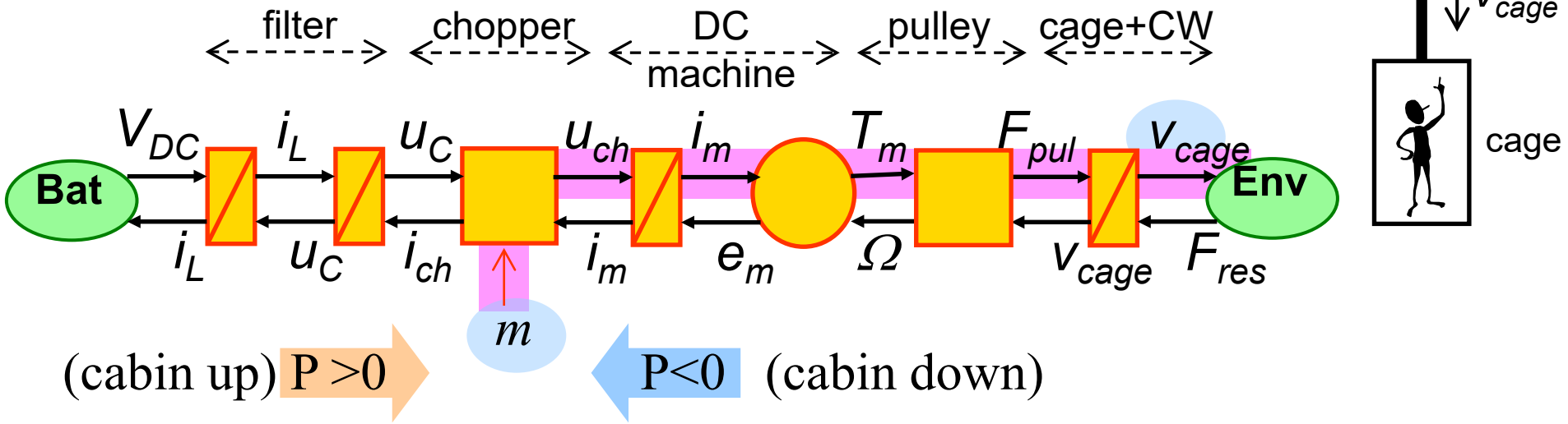
[Lhomme 2014]


supply
filter
chopper
inductor
DCM
shaft
pulley
$L_f$, $r_f$
$i_L$
$V_{DC}$
C
$u_c$
$i_{ch}$
$L_s$, $r_s$
$u_{ch}$
$u_m$
$i_m$
$T_m$
$T_{pul}$
$\Omega$
$\Omega$
counter weight
$v_{cage}$
cage
filter
chopper
DC machine
pulley
cage+CW
Bat
$V_{DC}$
$i_L$
$u_C$
$u_{ch}$
$i_m$
$T_m$
$F_{pul}$
$v_{cage}$
Env
$i_L$
$u_C$
$i_{ch}$
$i_m$
$e_m$
$\Omega$
$v_{cage}$
$F_{res}$
m
merging
permutation and merging

# Tuning path of the lift system




tuning path



# Conclusion

**EMR = multi-physical graphical description**

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

**Basic elements = energetic function**

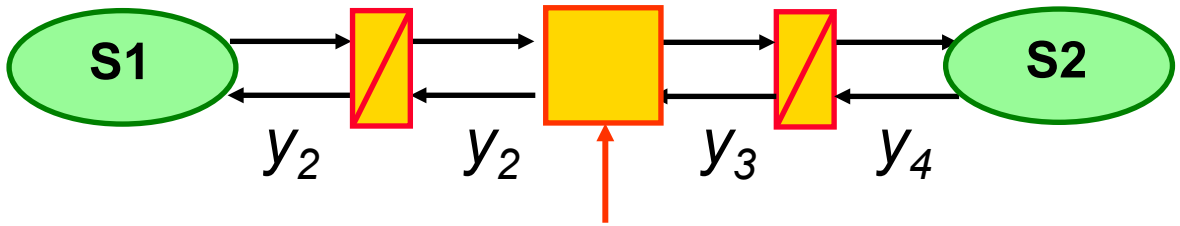
sources, accumulation, conversion and distribution of energy

**Association rules = holistic property of systemic**

enable keeping physical causality in conflict of association

**Applications of EMR**

analysis, simulation, control organization…



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# Thanks for your attention!

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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