ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UBA
Universidad de Buenos Aires

DEPARTAMENTO DE COMPUTACION
Facultad de Ciencias Exactas y Naturales - UBA

CIFASIS
CONICET
UNR | AMU

ECO-BOND GRAPHS

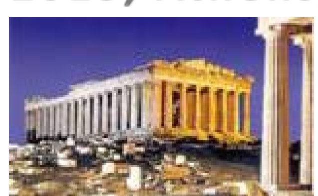
An Energy-Based Modeling and Simulation Framework for Complex Dynamic Systems

with a focus on ***Sustainability*** *and* ***Embodied Energy*** *Flows*

Dr. Rodrigo Castro
ETH Zürich, Switzerland.
University of Buenos Aires & CIFASIS-CONICET, Argentina.

Sept. 27, 2013, Athens, Greece

The 10th International Multidisciplinary Modelling & Simulation Multiconference

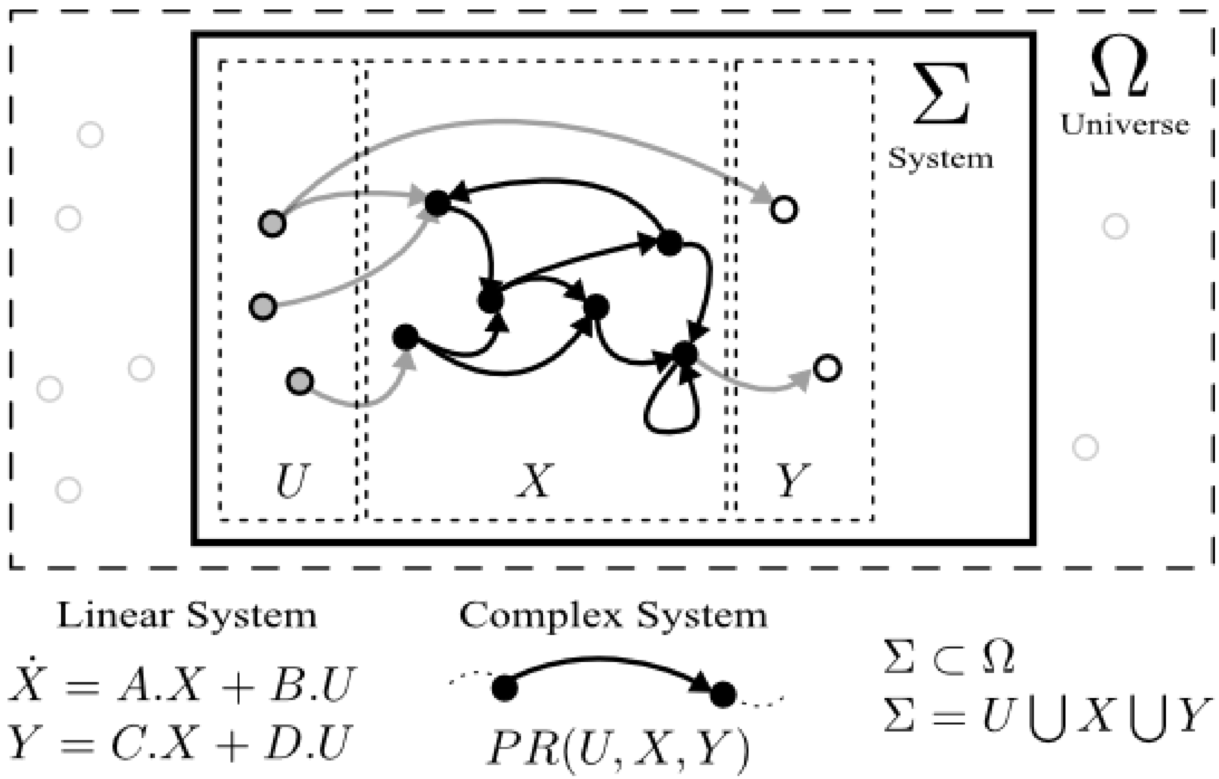


SESDE
The 1st Int'l. Workshop on Simulation for Energy, Sustainable Development & Environment

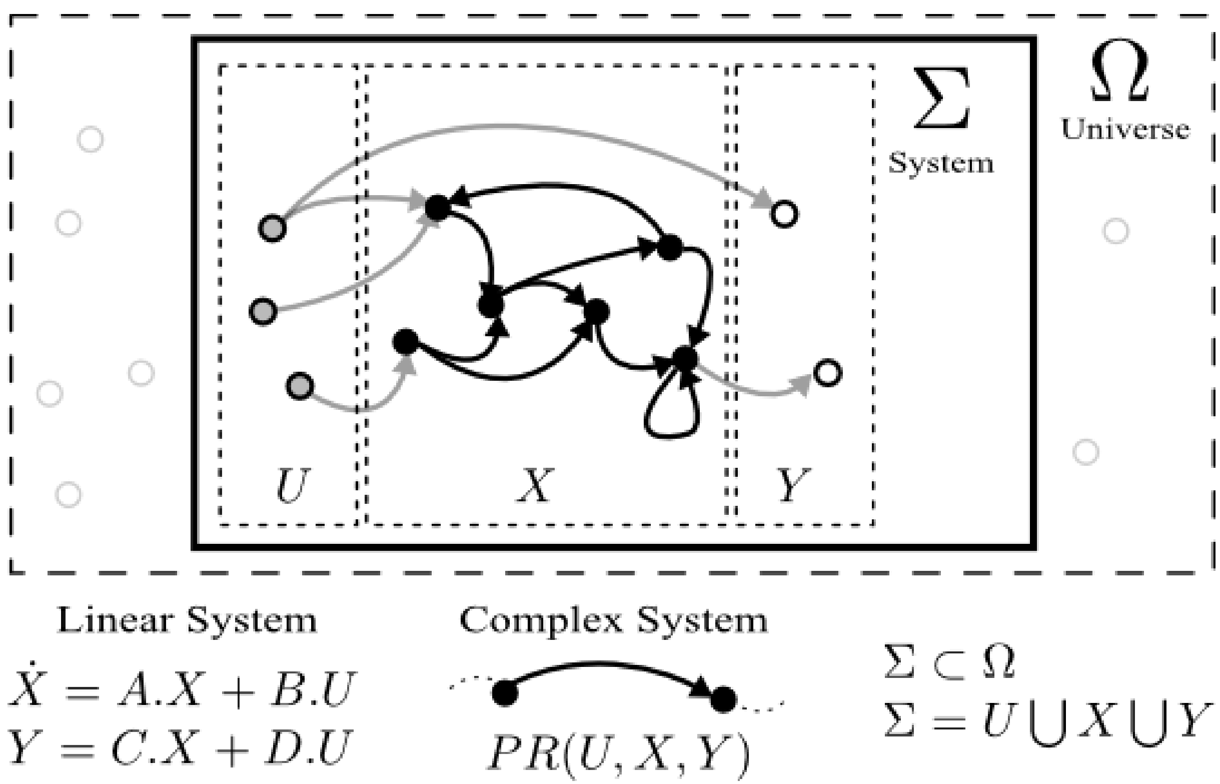
Agenda

- Problem formulation
  - Emergy tracking & Complex Dynamics Systems
- Possible approaches
- Our approach
  - Networked Complex Processes
  - 3-faceted representation of energy flows
- The Bond Graph formalism
- The new Eco Bond Graphs
  - Definition
  - Examples
  - Simulation results
- Conclusions

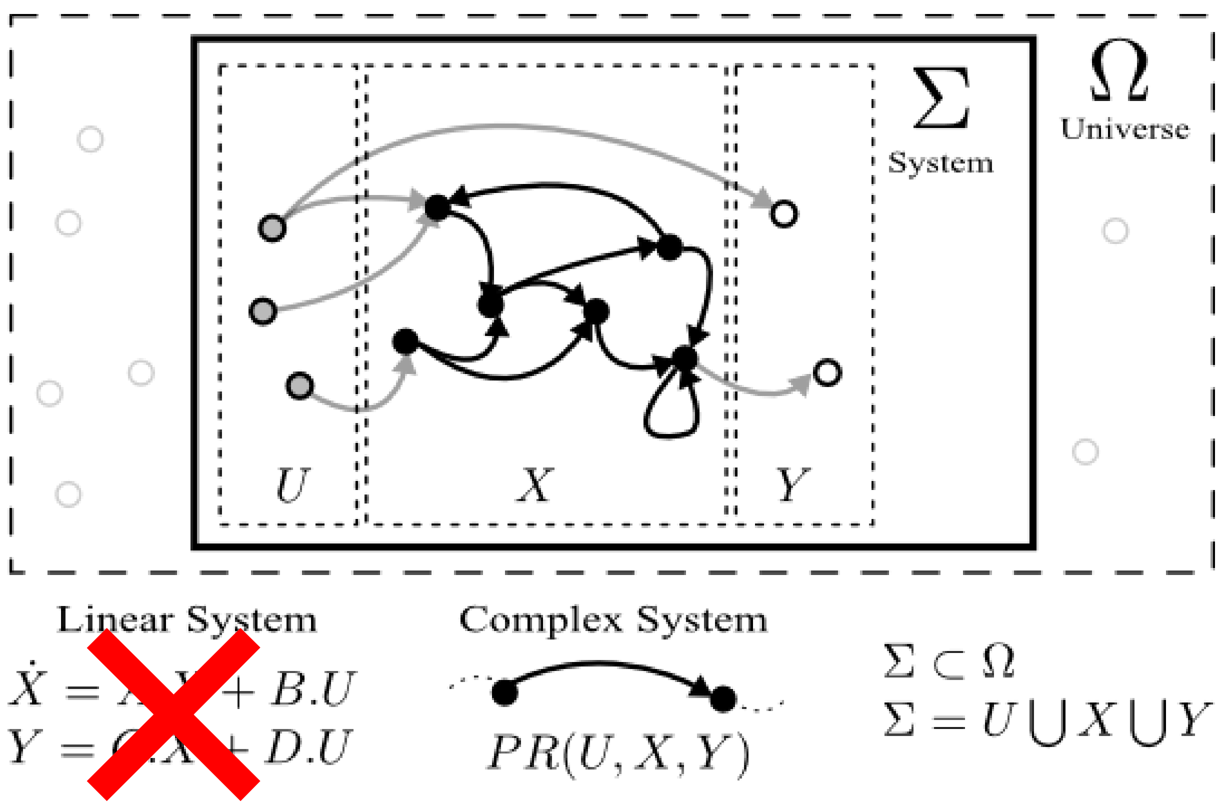
- Complex Dynamics Systems
  - Global scale socio-natural processes



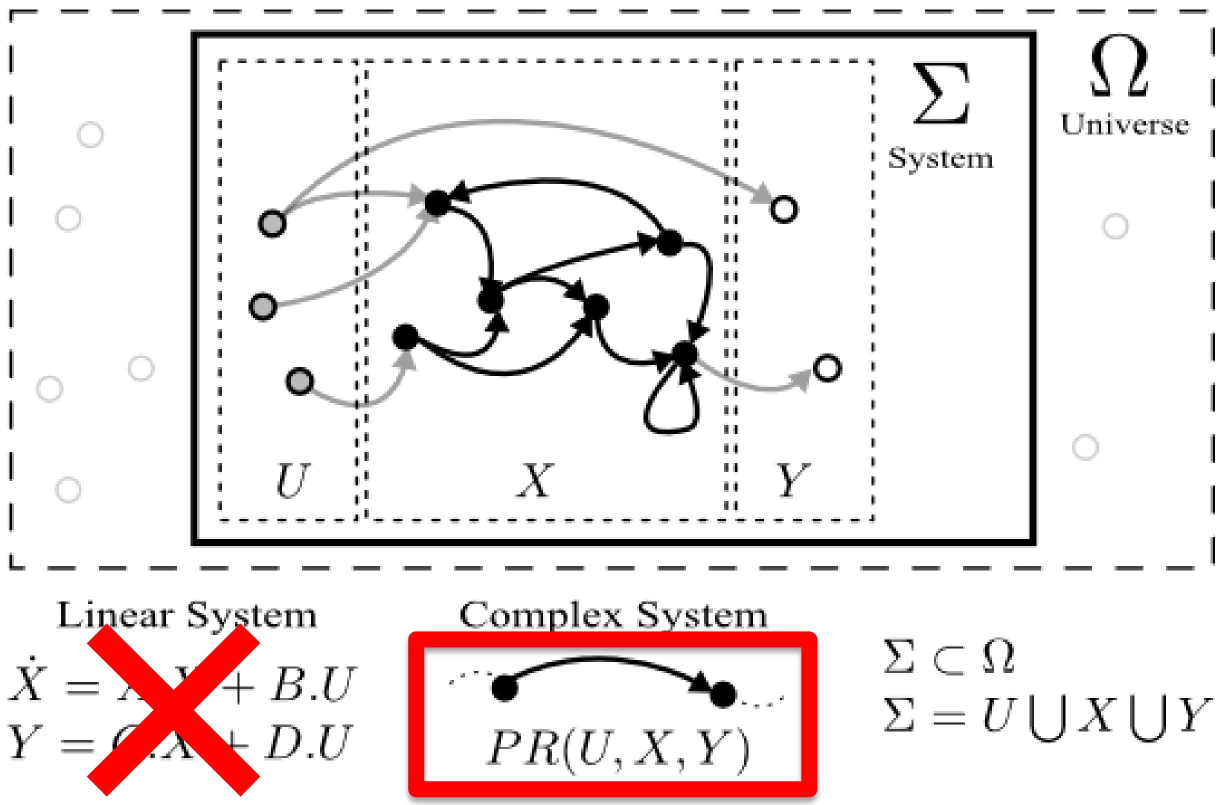
- Complex Dynamics Systems
  - Global scale socio-natural processes
    - We live in a nonlinear world, mostly away from equilibrium



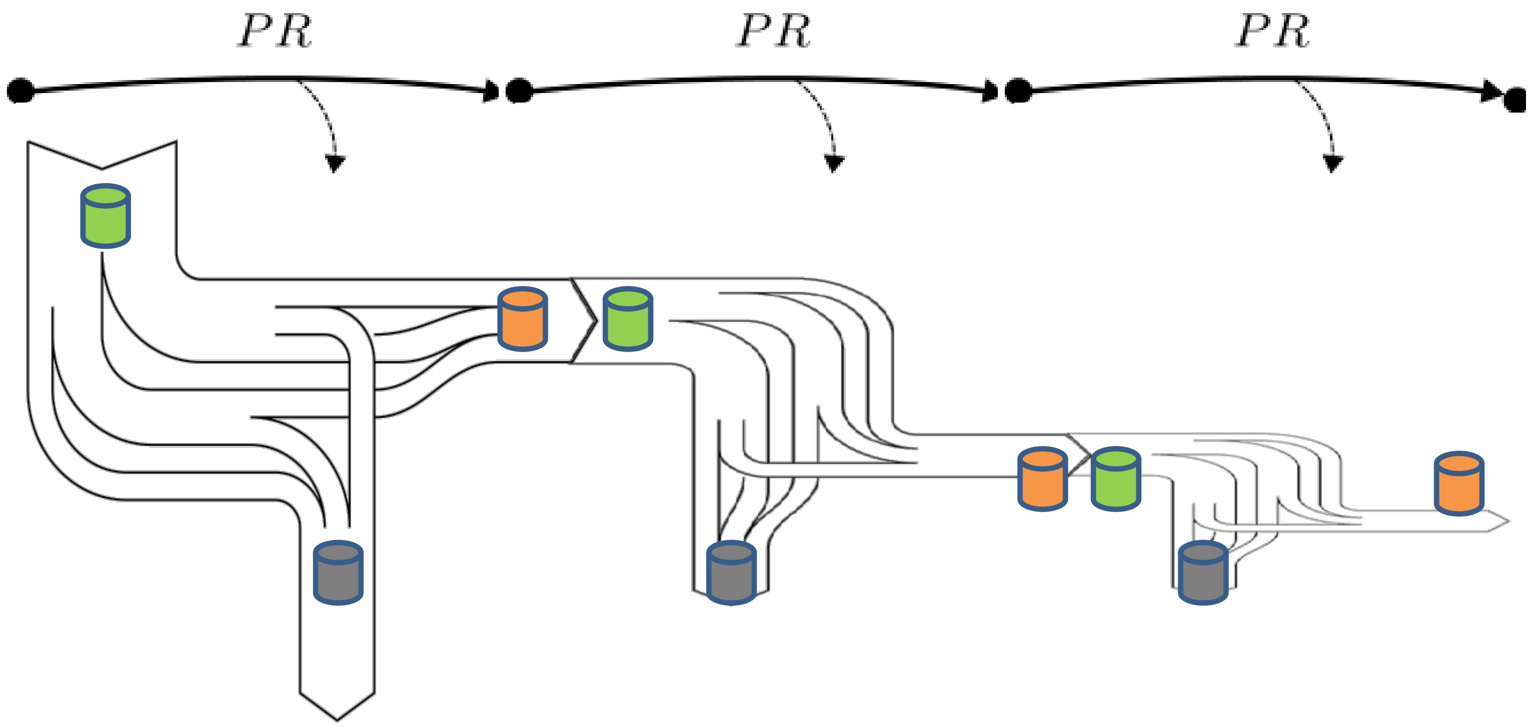
- Complex Dynamics Systems
  - Global scale socio-natural processes
    - We live in a nonlinear world, mostly away from equilibrium



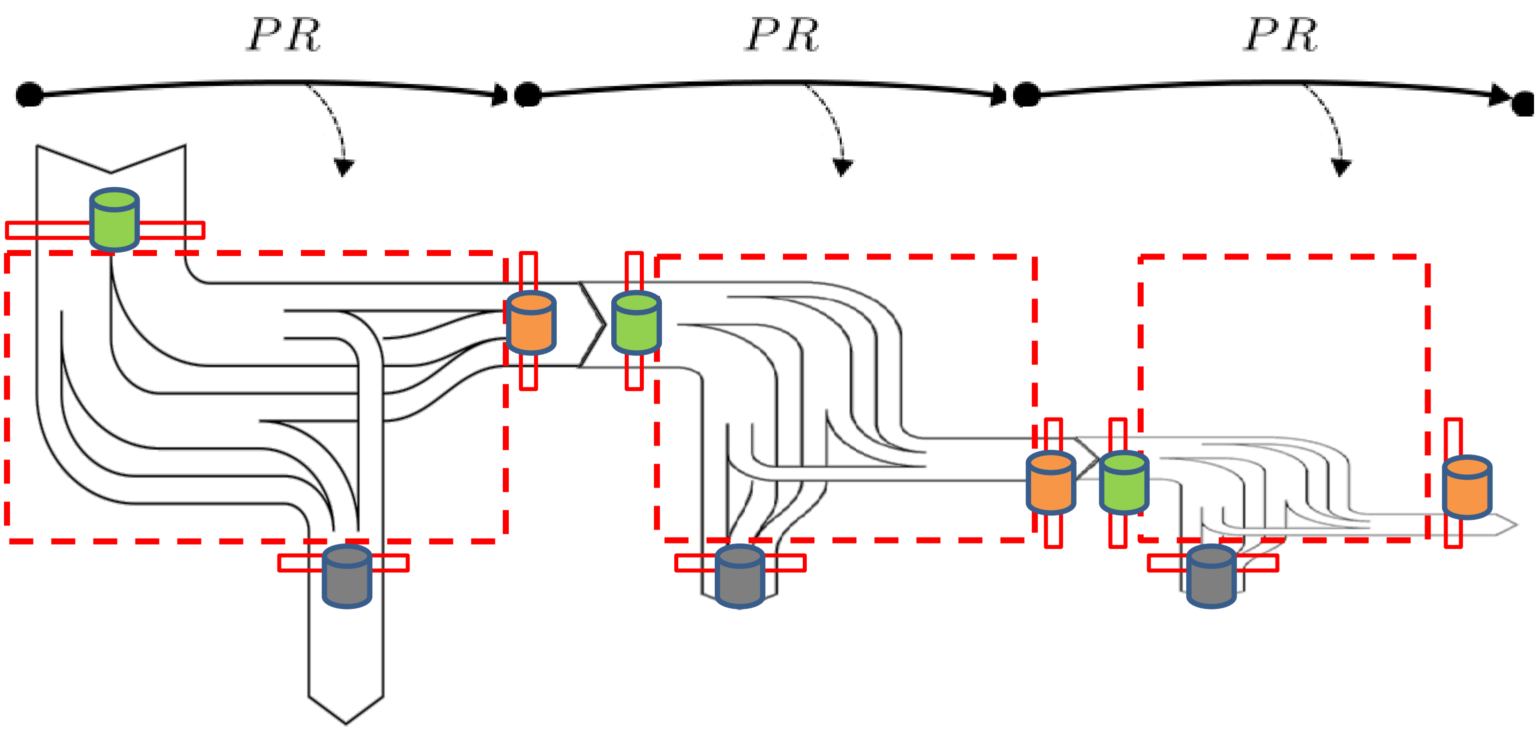
- # Complex Dynamics Systems
  - Global scale socio-natural processes
    - We live in a nonlinear world, mostly away from equilibrium



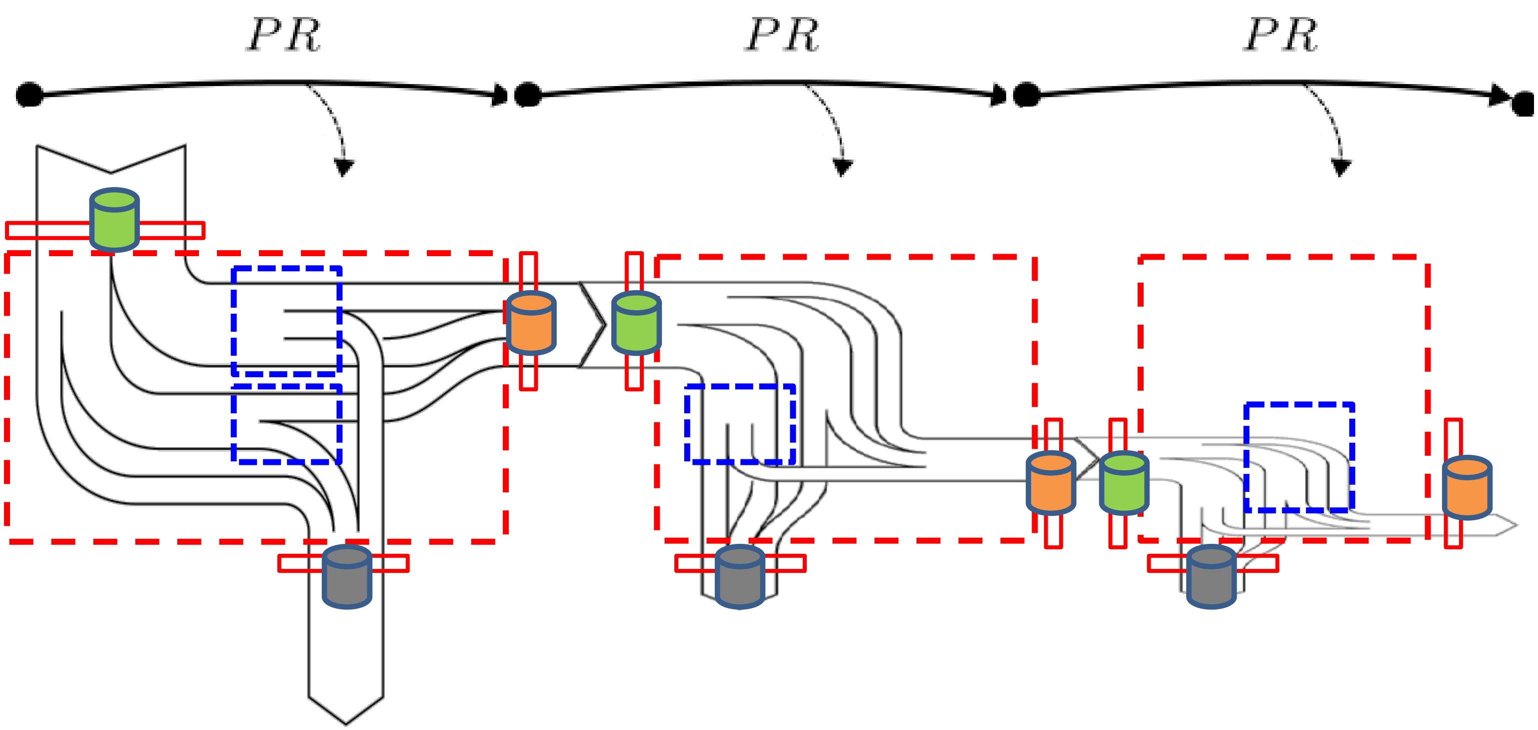
- Flows of Mass and Energy
  - Each process can abstract several internal sub processes



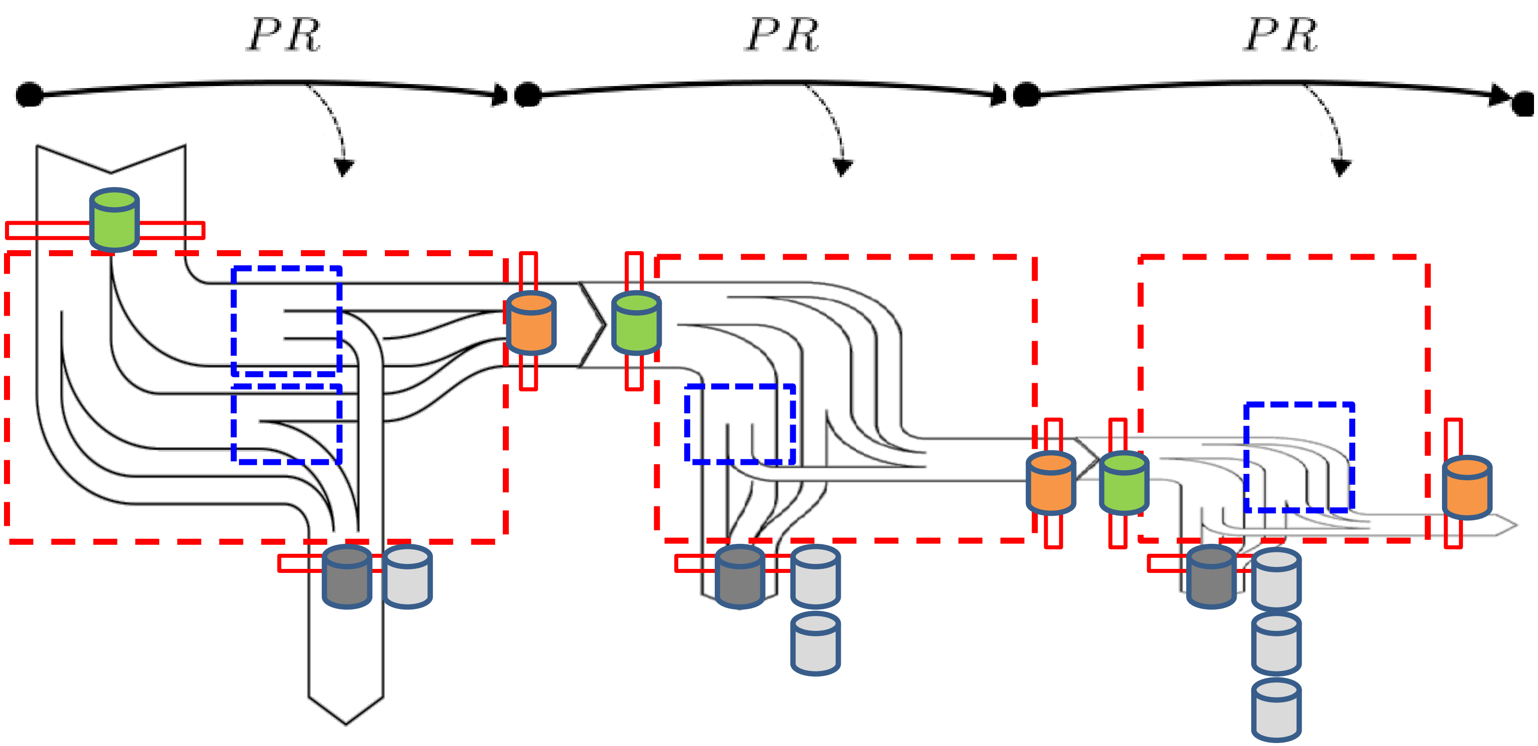
- Flows of Mass and Energy
  - Each process can abstract several internal sub processes



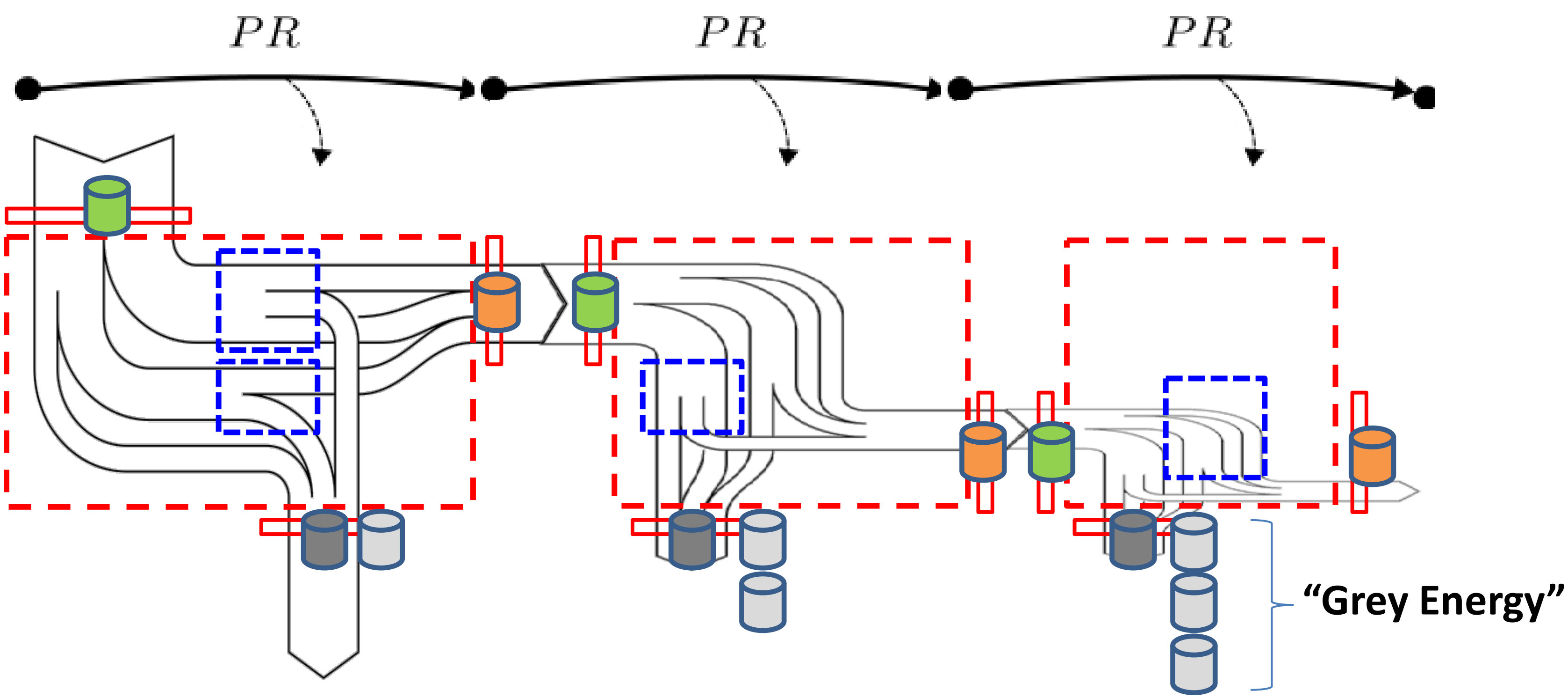
- Flows of Mass and Energy
  - Each process can abstract several internal sub processes



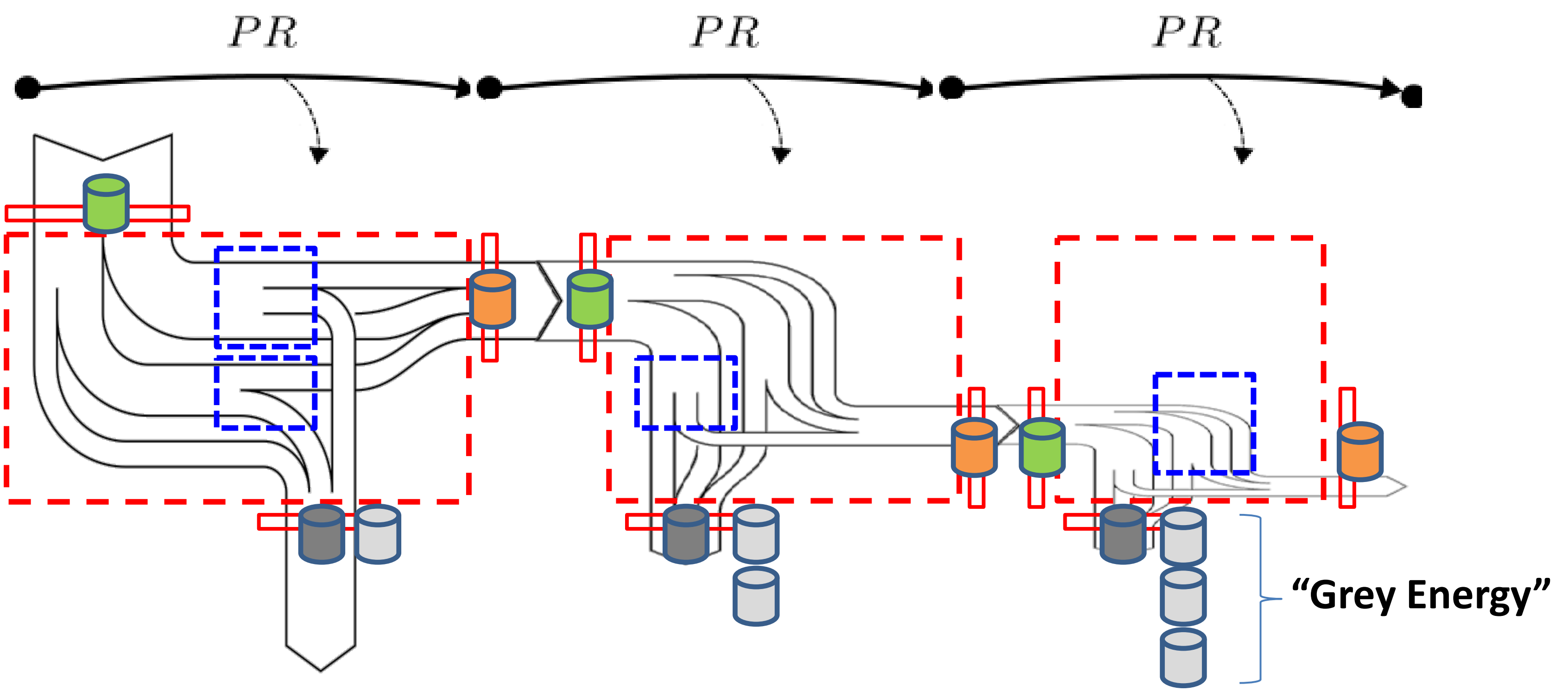
- Flows of Mass and Energy
  - Each process can abstract several internal sub processes



- Flows of Mass and Energy
  - Each process can abstract several internal sub processes

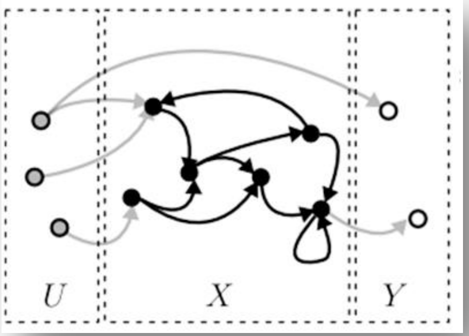


- Flows of Mass and Energy
  - Each process can abstract several internal sub processes

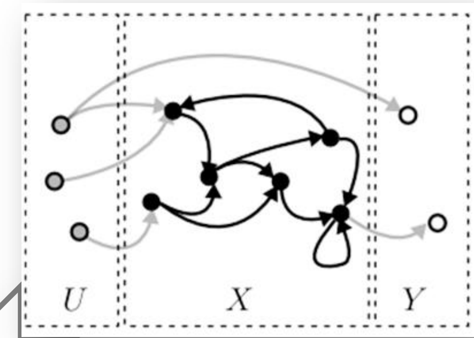


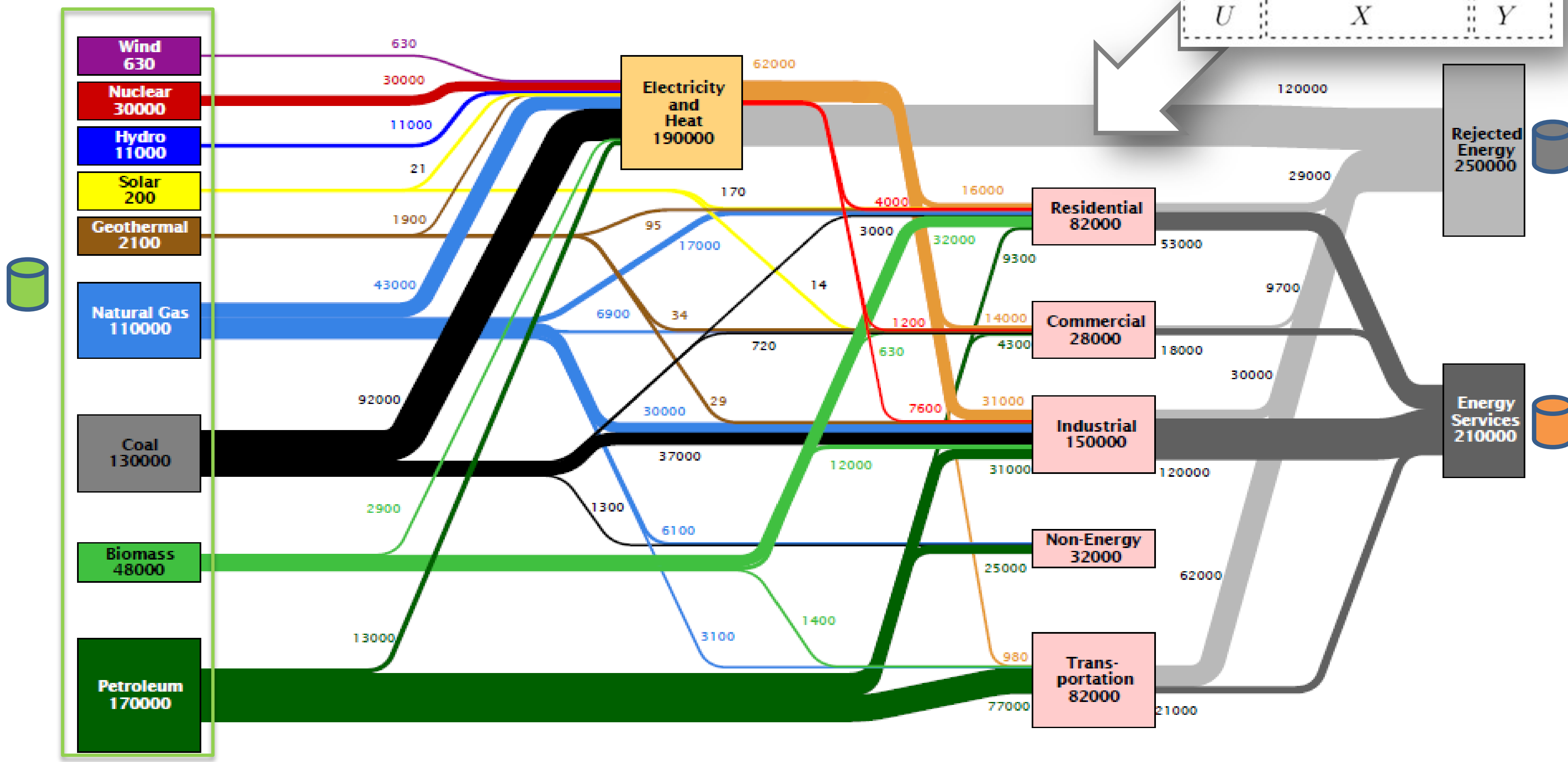
  - We want to model **systematically** this type of systems
  - Structural approach ➡ Sustainability properties

- Sankey Diagrams
  - Static (snapshot-like) World Energy Flow.

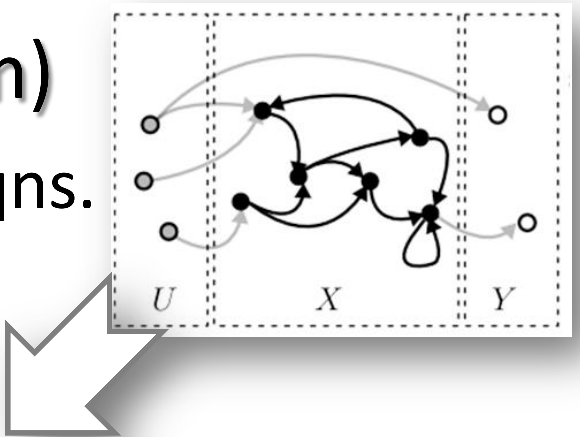


- Sankey Diagrams
  - Static (snapshot-like) World Energy Flow.

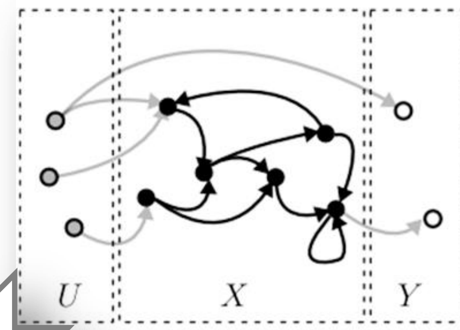


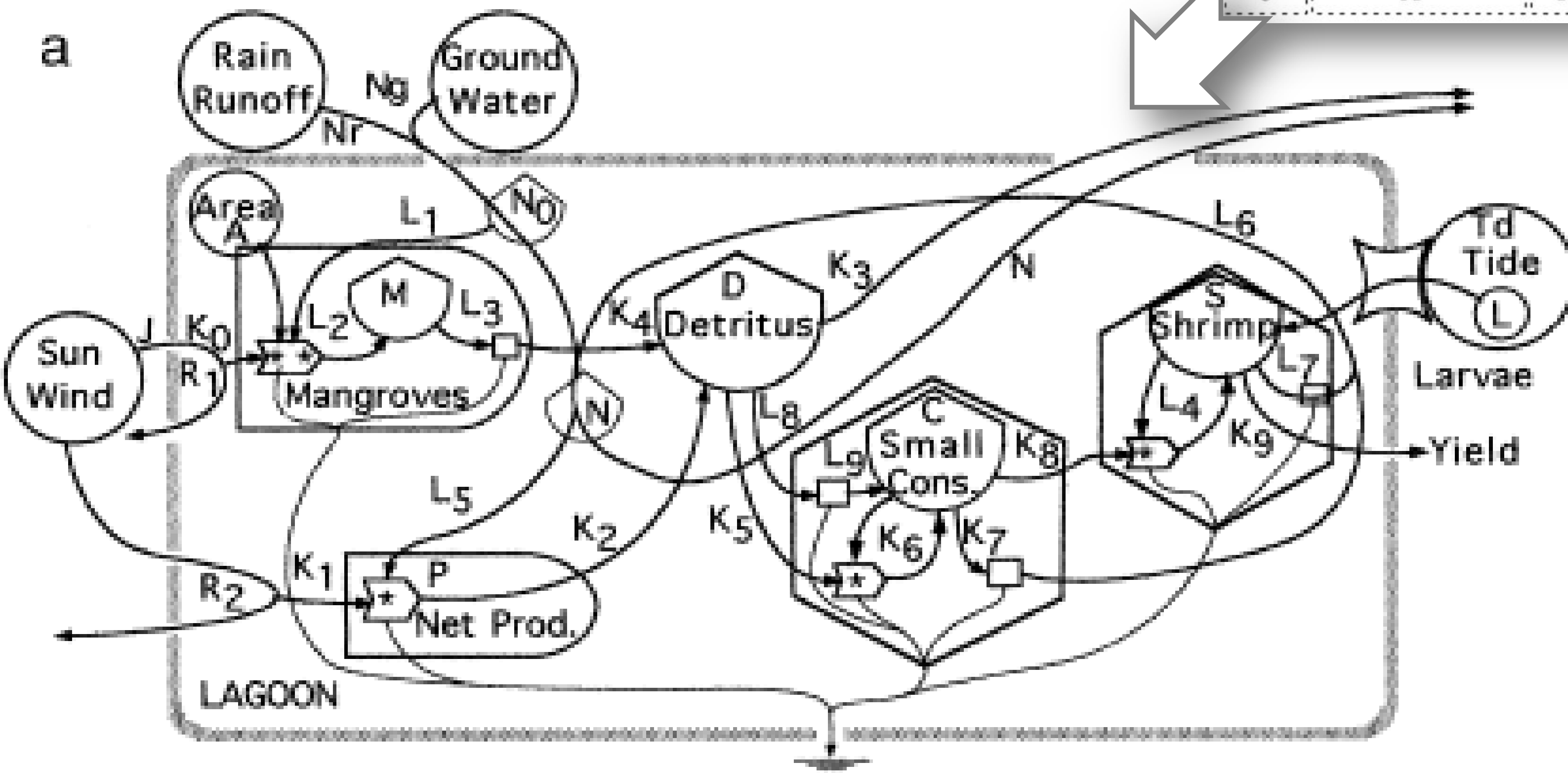


- Energy System Language (H.T. Odum)
  - Account for dynamics ➡ Differential Eqns.

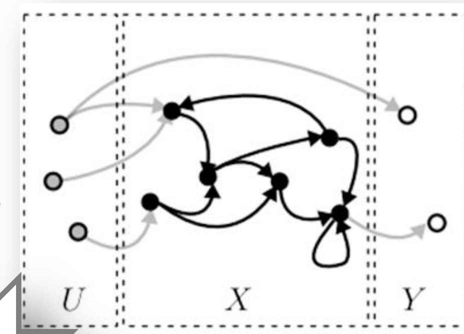


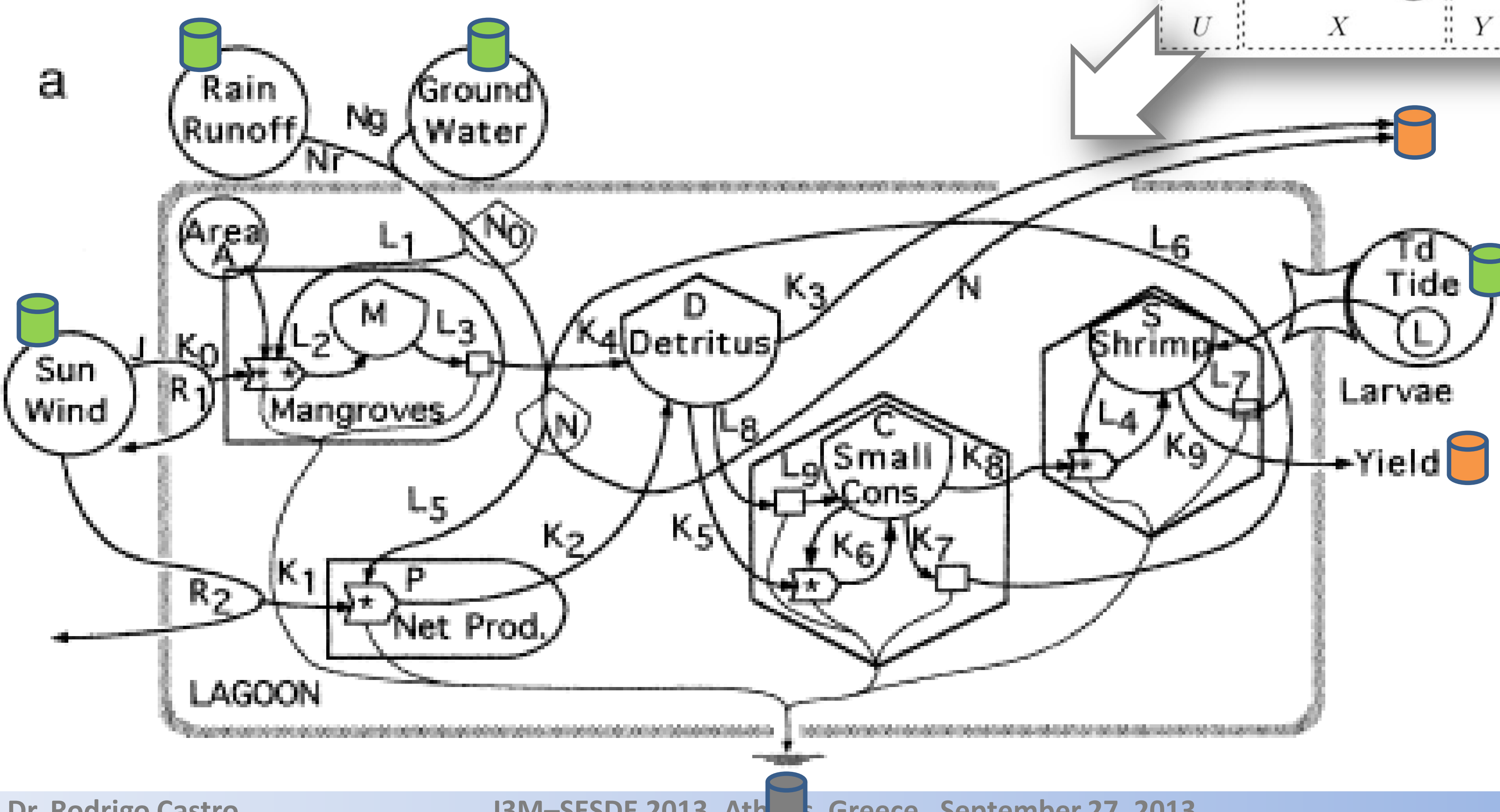
- **Energy System Language (H.T. Odum)**
  - Account for dynamics ➡ Differential Eqns.



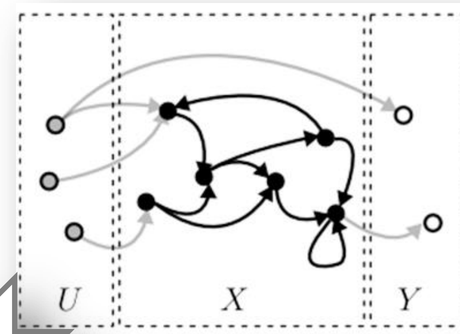


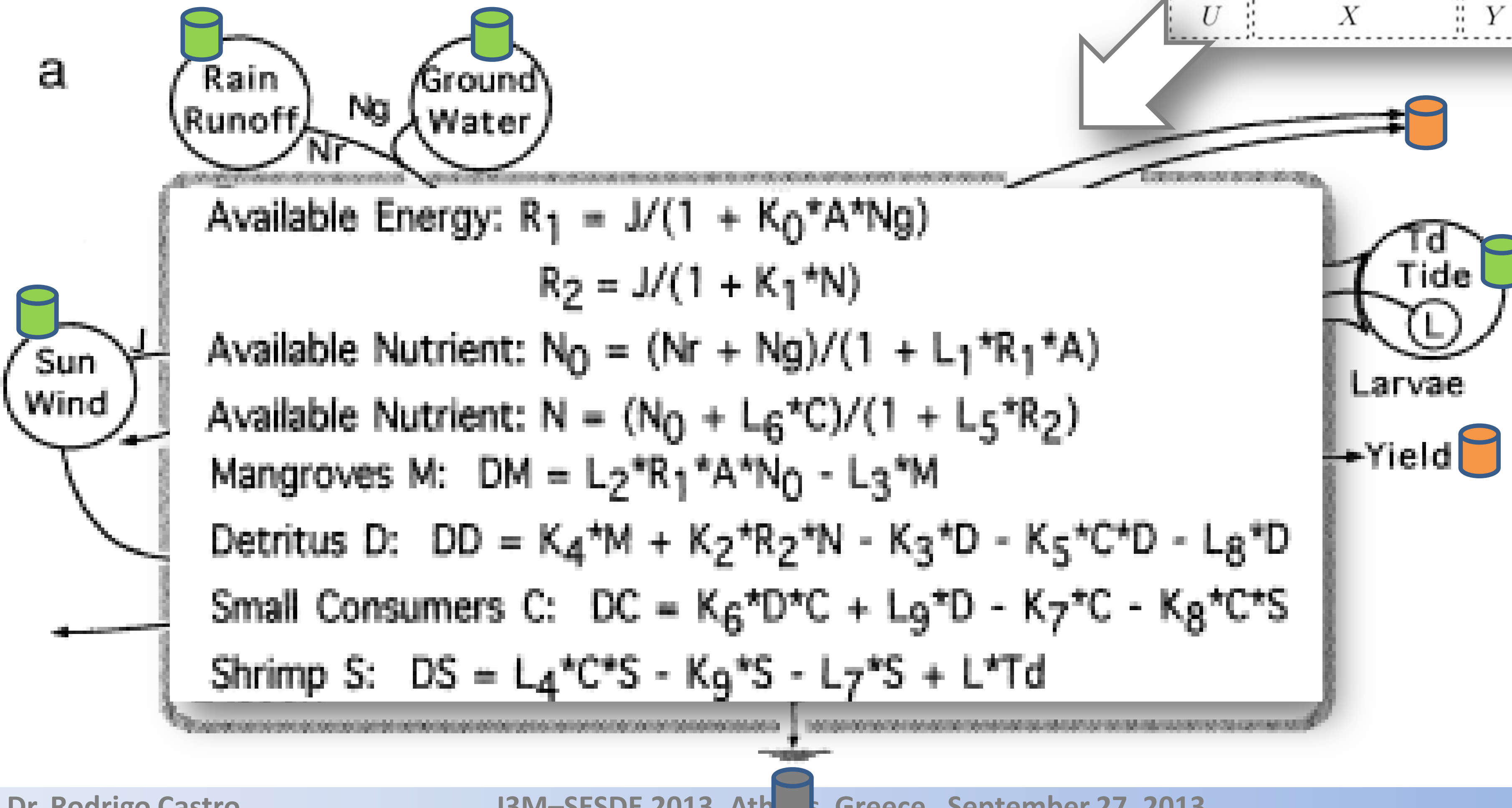
- Energy System Language (H.T. Odum)
  - Account for dynamics ➡ Differential Eqns.





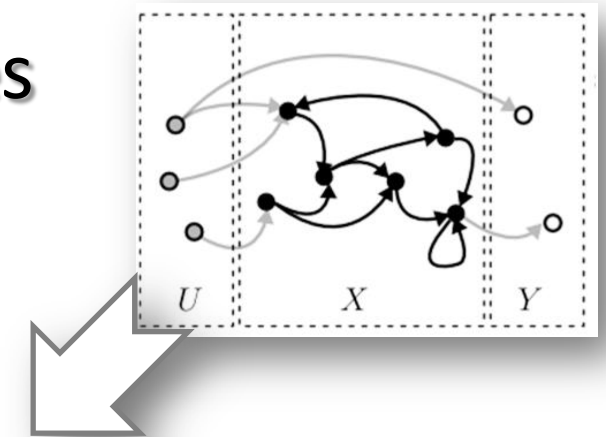
- Energy System Language (H.T. Odum)
  - Account for dynamics ➡ Differential Eqns.



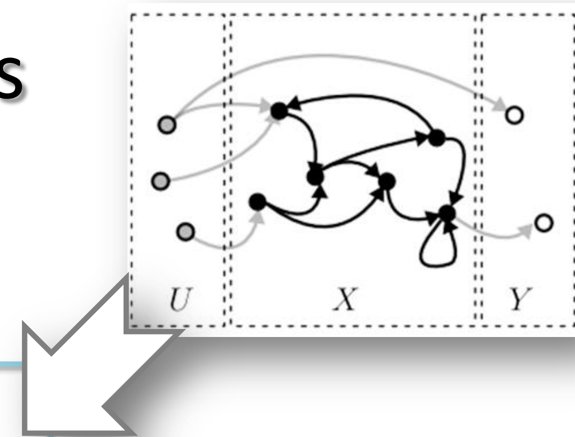


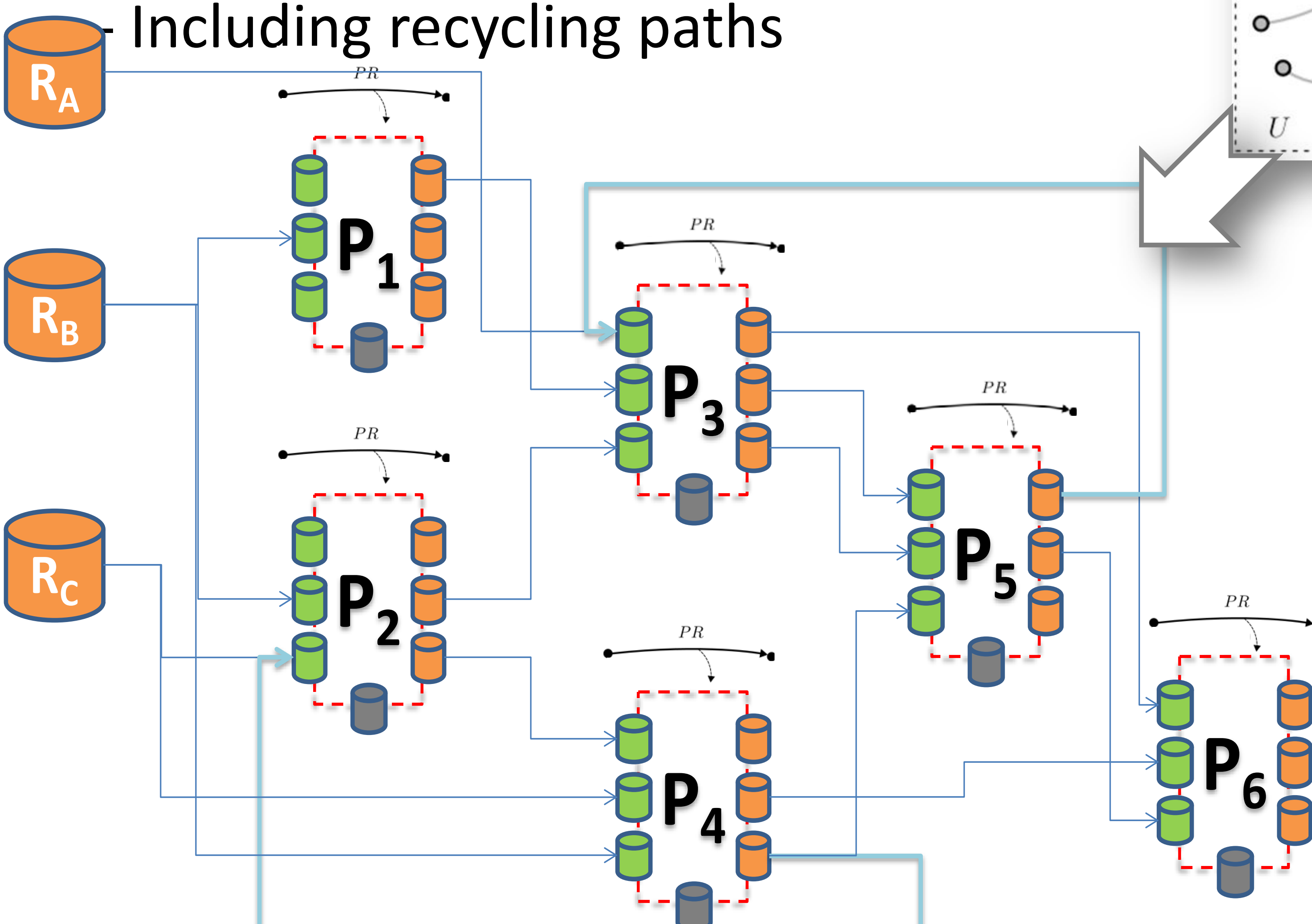
- Multi Input/Multi Output Processes
  - Including recycling paths

- Multi Input/Multi Output Processes
  - Including recycling paths

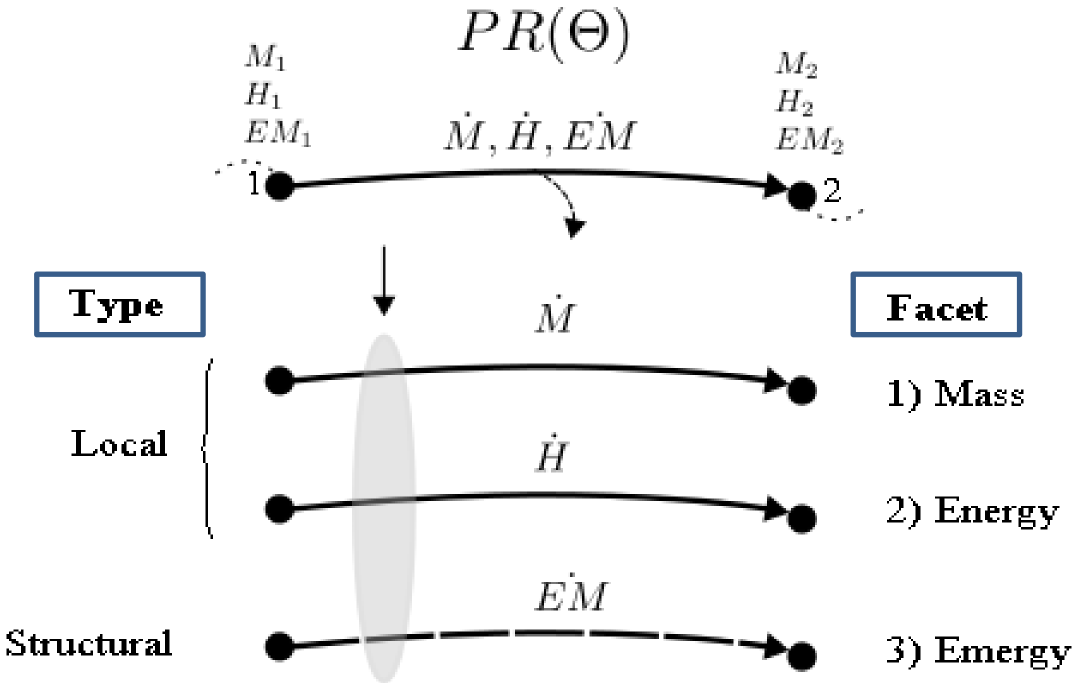


- Multi Input/Multi Output Processes
  - Including recycling paths





- 3-Faceted representation



Focus on mass flows

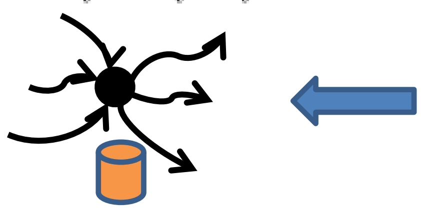
Our approach

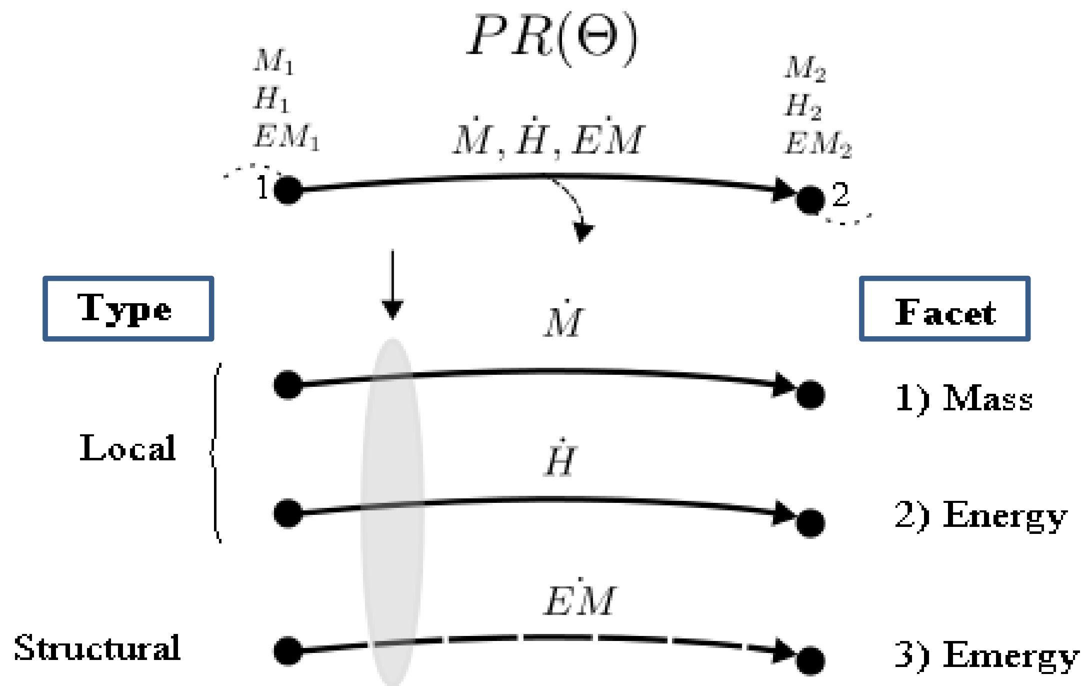
- 3-Faceted representation

Balance: Mass and Energy

$$\dot{M}_i = \sum \dot{M}_{i\,in} - \dot{M}_{i\,out}$$

$$H_i = h_i . M_i$$



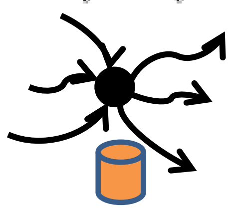


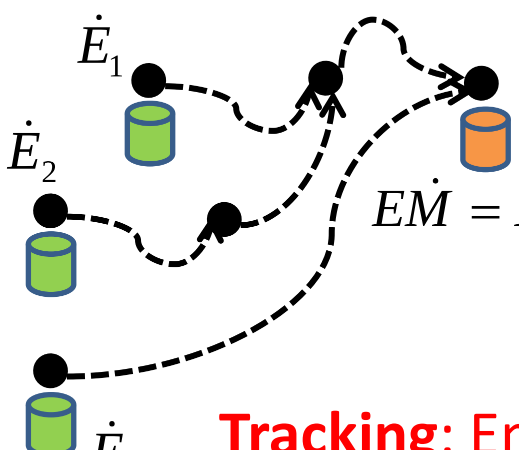
- 3-Faceted representation

Balance: Mass and Energy

$$\dot{M}_i = \sum \dot{M}_{i\,in} - \dot{M}_{i\,out}$$

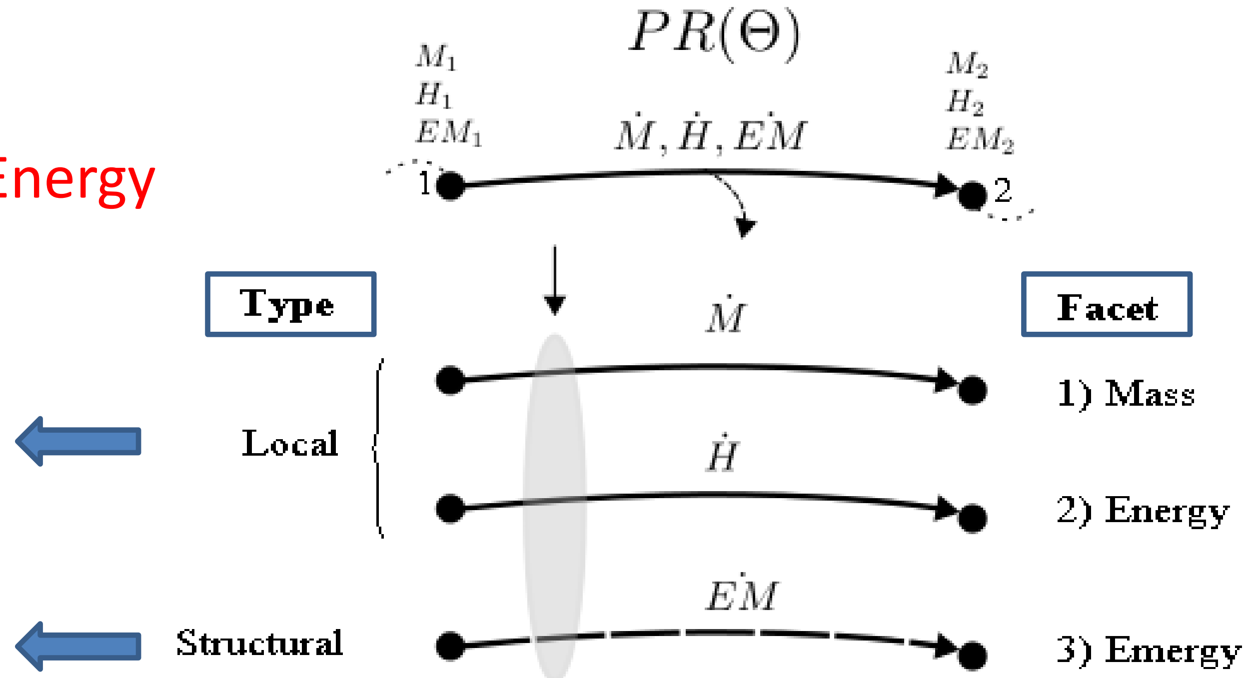
$$H_i = h_i . M_i$$





$$E\dot{M} = \dot{E}_1 + \dot{E}_2 + \dot{E}_3$$

Tracking: Emergy

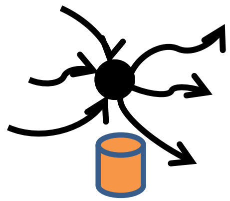


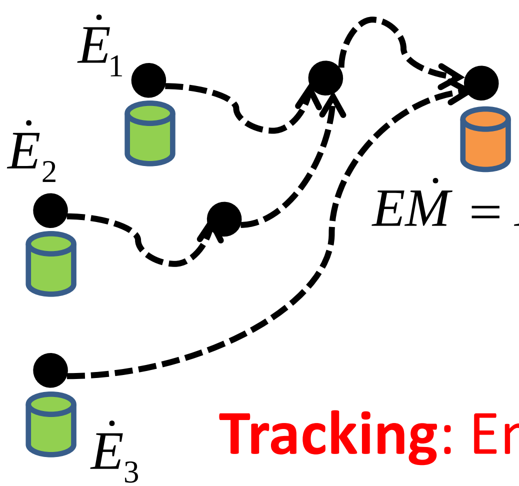
- 3-Faceted representation

Balance: Mass and Energy

$$\dot{M}_i = \sum \dot{M}_{i\,in} - \dot{M}_{i\,out}$$

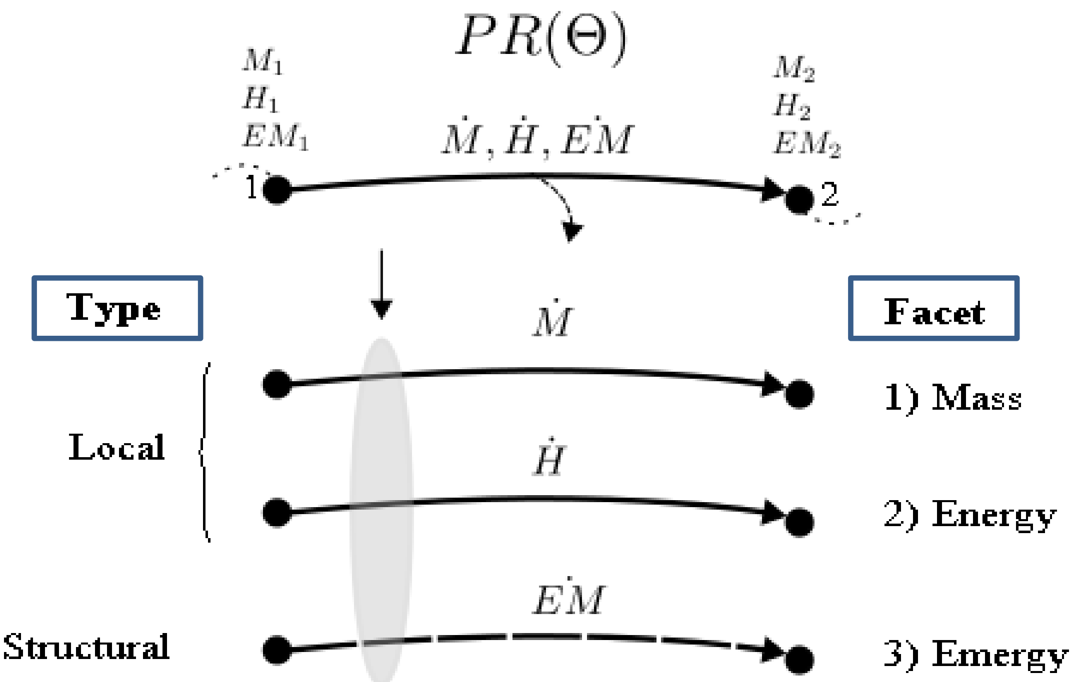
$$H_i = h_i . M_i$$





$$E\dot{M} = \dot{E}_1 + \dot{E}_2 + \dot{E}_3$$

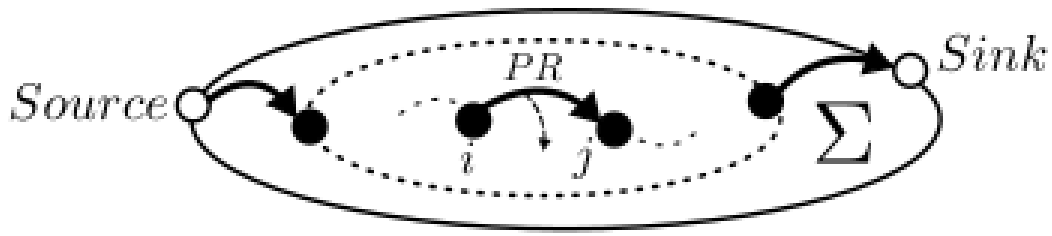
Tracking: Emergy

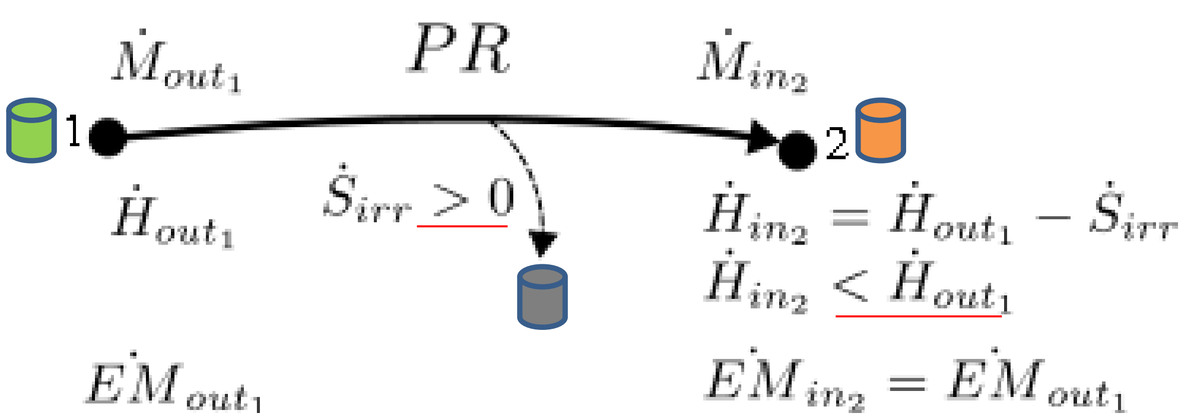


At a Process	At a Node
$\dot{M} = f_M(M_1, M_2, \Theta)$	$\dot{M}_i = \sum \dot{M}_{i\,in} - \dot{M}_{i\,out}$
$\dot{H} = f_H(H_1, H_2, \Theta)$	$H_i = h_i . M_i$
$E\dot{M} = f_{EM}(EM_1, EM_2, \Theta)$	$EM_i = em_i . M_i$

Basic formulation

- Minimum required formulation
  - To achieve the modeling goal <u>systematically</u>

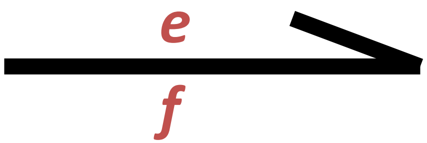




- How do we formalize and generalize this structure ?

Bondgraphic approach

- Bondgraph is a graphical modeling technique
  - Rooted in the tracking of power [Joules/sec=Watt]
  - Represented by effort variables (e) and flow variables (f)

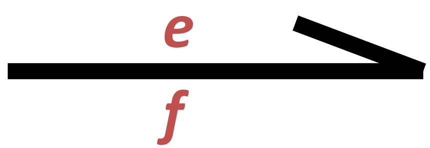


$$Power = e \cdot f$$

e: ***Effort***

f: ***Flow***

- Bondgraph is a graphical modeling technique
  - Rooted in the tracking of power [Joules/sec=Watt]
  - Represented by effort variables (e) and flow variables (f)



Power = e · f

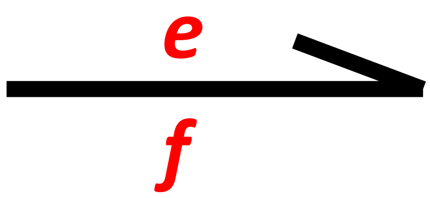
e: Effort

f: Flow

- **Goal:**
  - Sound physical modeling of generalized flows of energy
  - Self checking capabilities for thermodynamic feasibility
- **Strategy**:
  - Bondgraphic modeling of phenomenological processes
  - Including emergy tracking capabilities

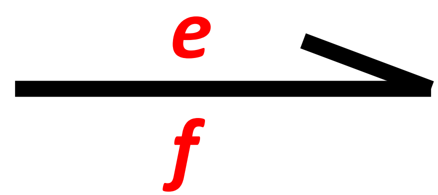
Energy domains

- Bondgraph is multi-energy domain



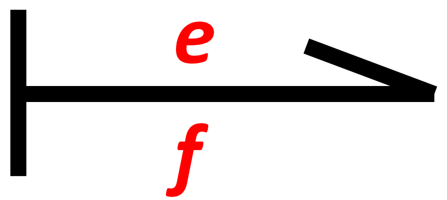
Energy domains

- **Bondgraph** is multi-energy domain

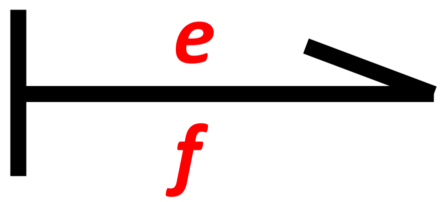


***Energy* Domain**	***e*** ***Effort variable***	***f*** ***Flow variable***
Mechanical, translation	Force	Linear velocity
Mechanical, rotation	Torque	Angular velocity
Electrical	Electromotive force	Current
Magnetic	Magnetomotive force	Flux rate
Hydraulic	Pressure	Volumetric flow rate
Thermal	temperature	entropy flow rate

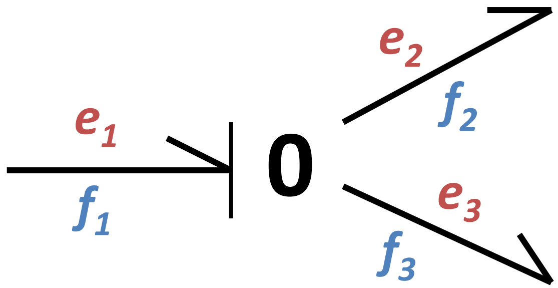
- As every bond defines two **separate variables**
  - The ***effort e*** and the ***flow f***
  - We need two equations to compute values for these two variables
- It is always possible to compute one of the two variables at each side of the bond.



- As every bond defines two **separate variables**
  - The ***effort e*** and the ***flow f***
  - We need two equations to compute values for these two variables
- It is always possible to compute one of the two variables at each side of the bond.
- A ***vertical bar*** symbolizes the side where the ***flow*** is being computed.

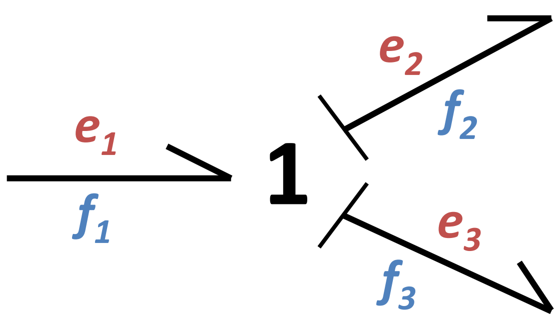


- Local balances of energy



$\Leftrightarrow$

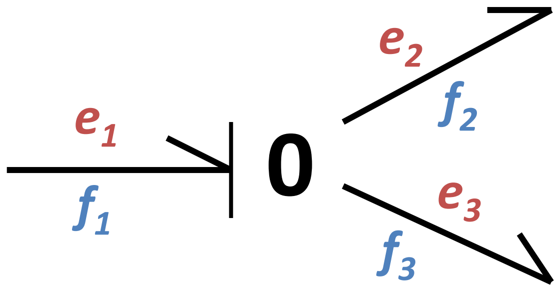
$$e_2 = e_1$$
$$e_3 = e_1$$
$$f_1 = f_2 + f_3$$



$\Leftrightarrow$

$$f_2 = f_1$$
$$f_3 = f_1$$
$$e_1 = e_2 + e_3$$

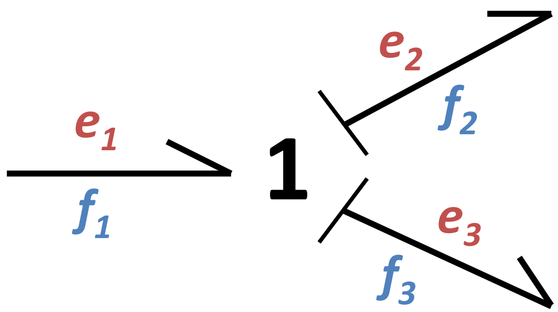
- Local balances of energy



$\Leftrightarrow$

$$e_2 = e_1$$
$$e_3 = e_1$$
$$f_1 = f_2 + f_3$$

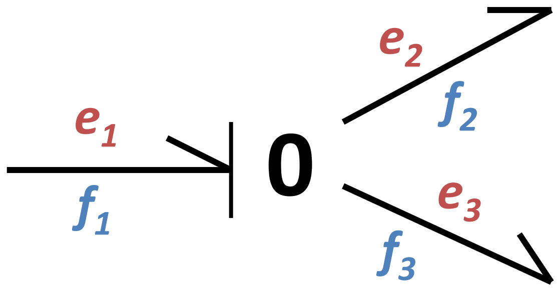
*Junctions of type **0** have only one flow equation, and therefore, they must have exactly one causality bar.*



$\Leftrightarrow$

$$f_2 = f_1$$
$$f_3 = f_1$$
$$e_1 = e_2 + e_3$$

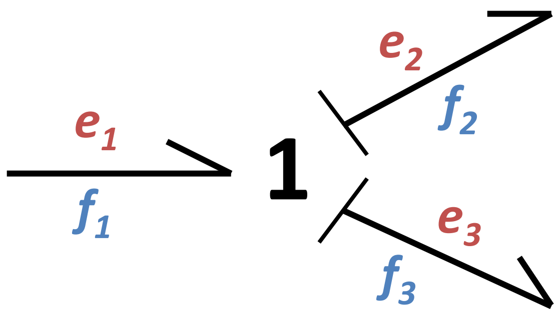
- Local balances of energy



$\Leftrightarrow$

$$e_2 = e_1$$
$$e_3 = e_1$$
$$f_1 = f_2 + f_3$$

*Junctions of type **0** have only one flow equation, and therefore, they must have exactly one causality bar.*



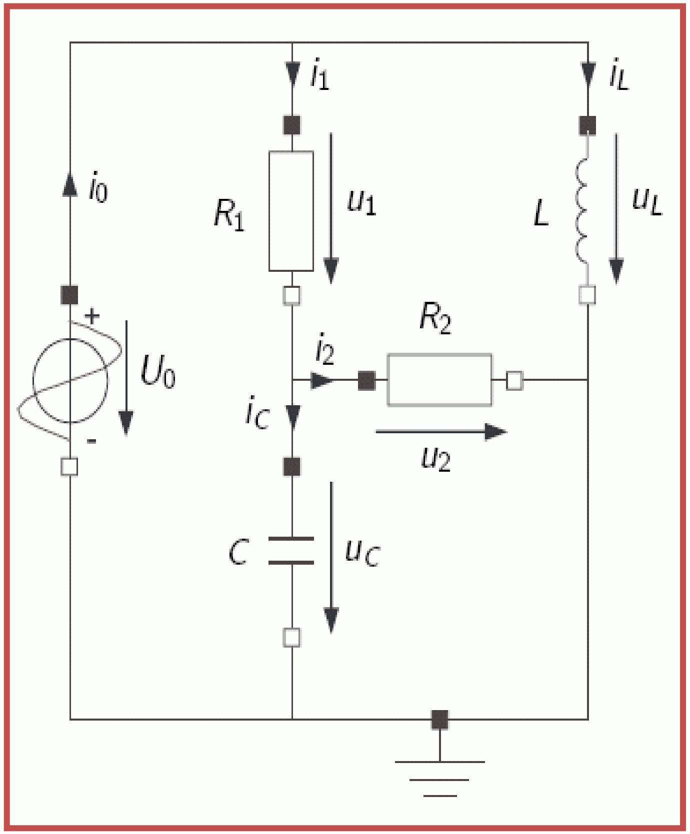
$\Leftrightarrow$

$$f_2 = f_1$$
$$f_3 = f_1$$
$$e_1 = e_2 + e_3$$

*Junctions of type **1** have only one effort equation, and therefore, they must have exactly (n-1) causality bars.*

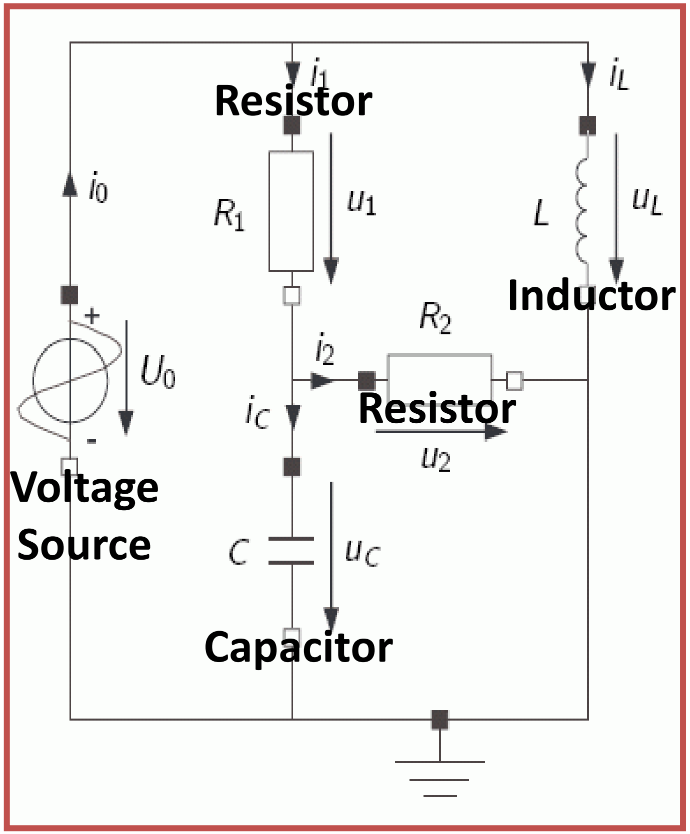
- An electrical energy domain model

Electrical Circuit



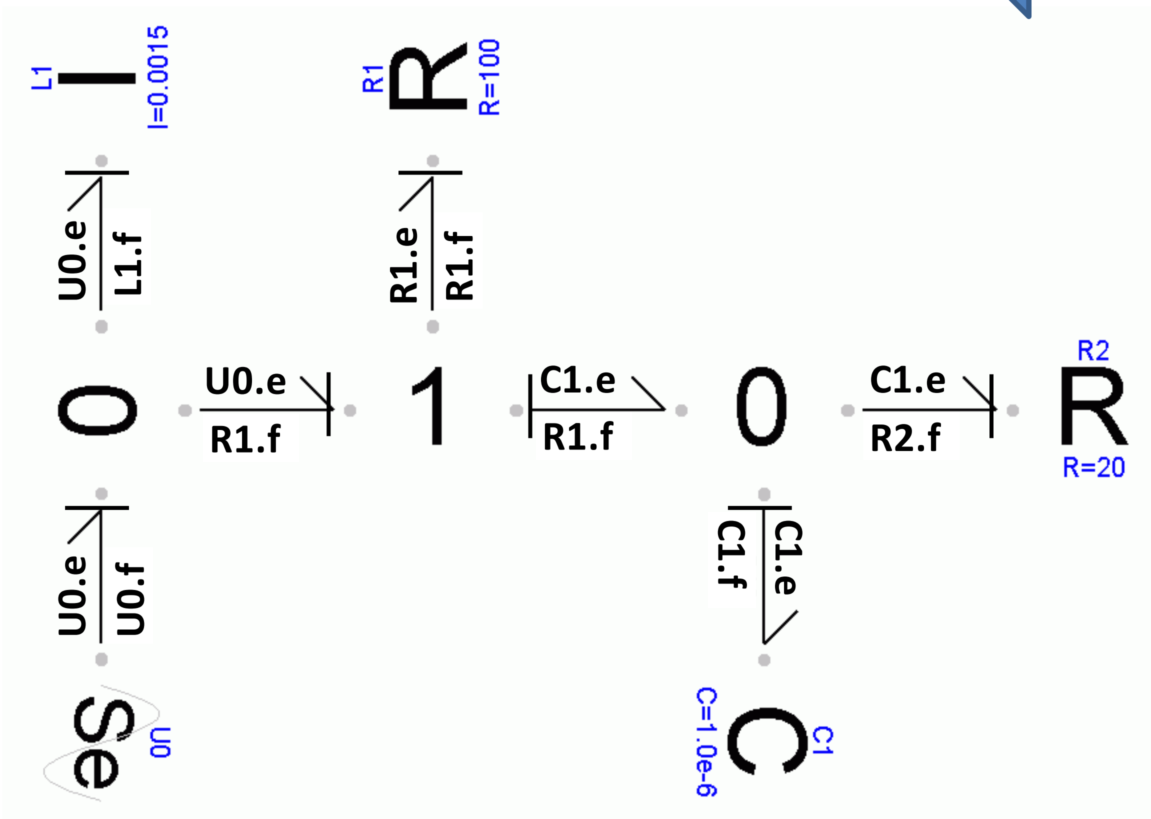
- An electrical energy domain model

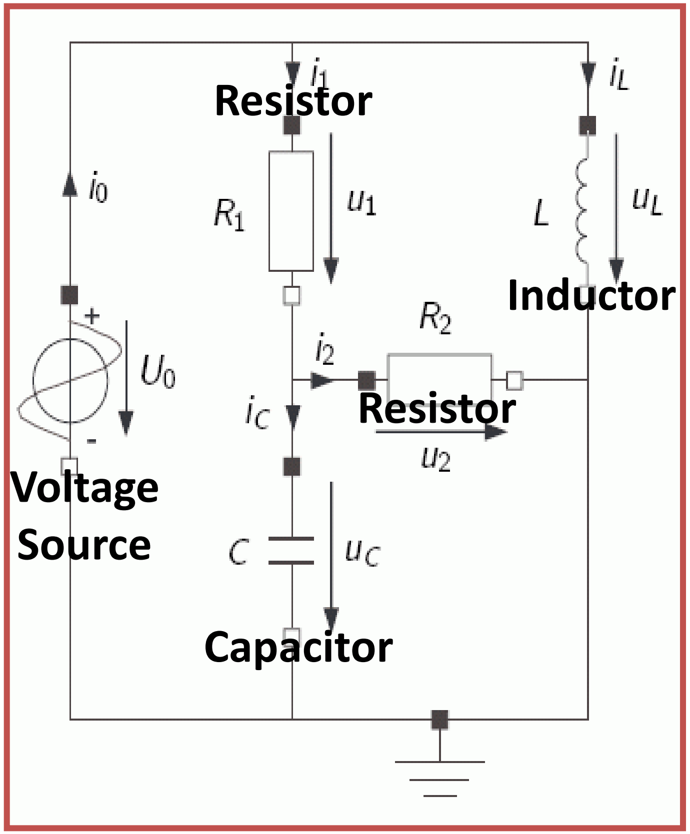
Electrical Circuit



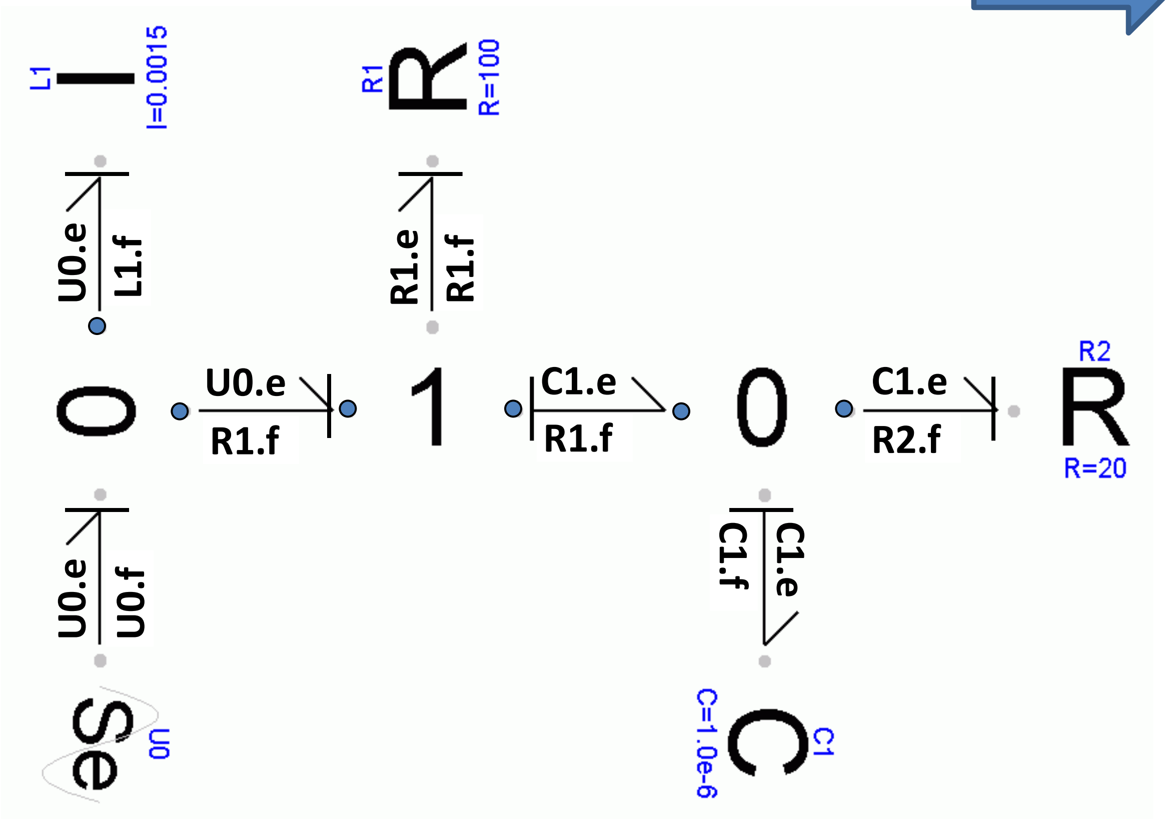
- An electrical energy domain model

Bondgraphic equivalent ← **Electrical Circuit**

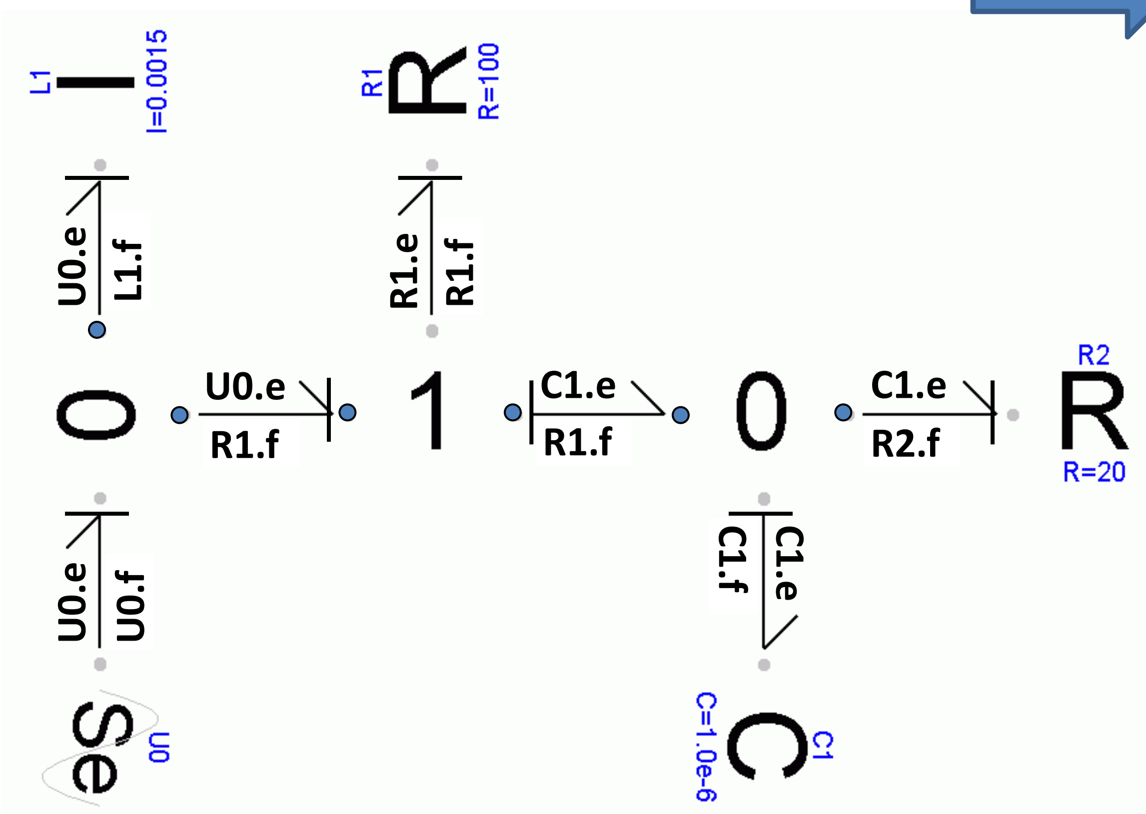




Bondgraphic model

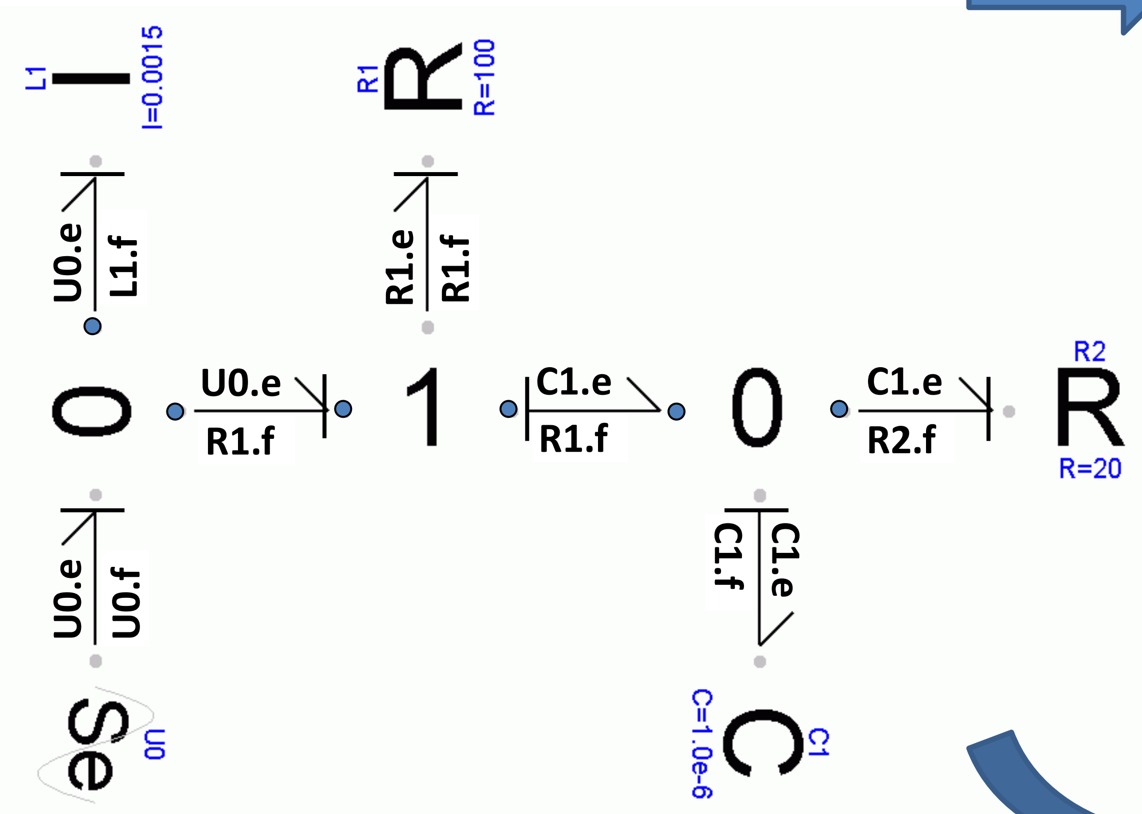


Bondgraphic model

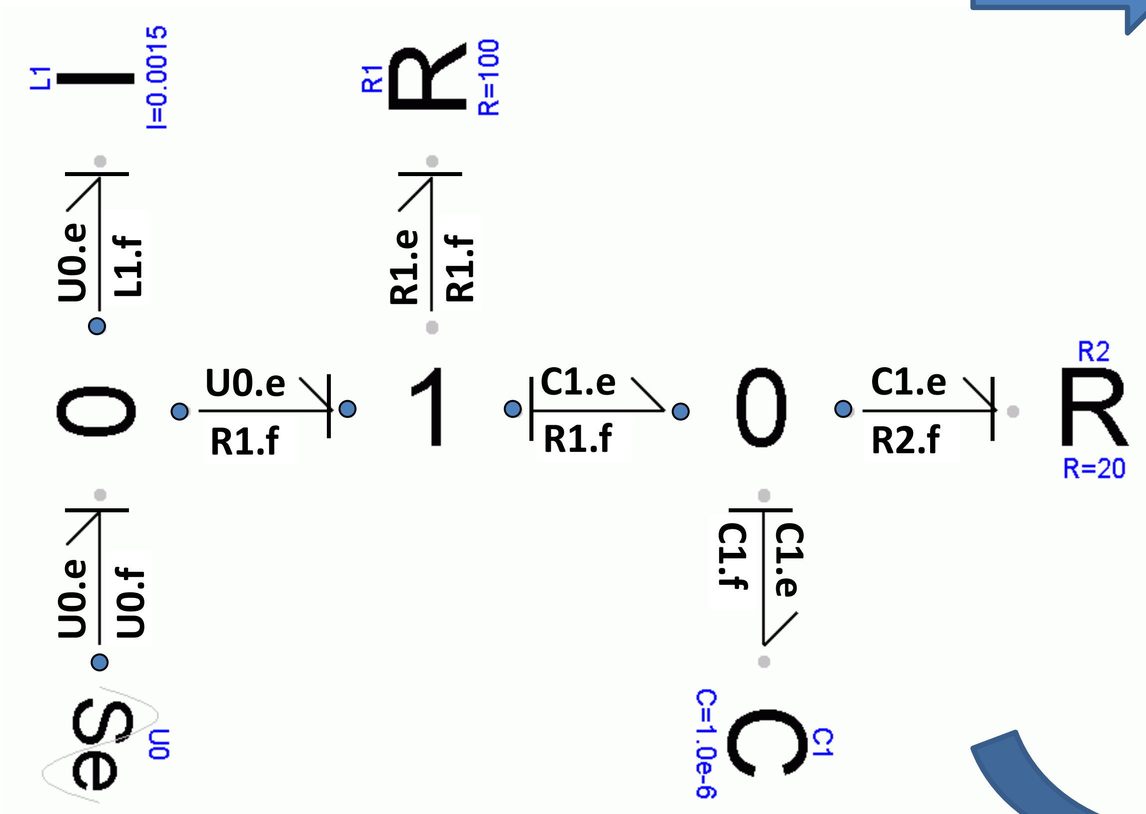


Systematic derivation of equations

Bondgraphic model



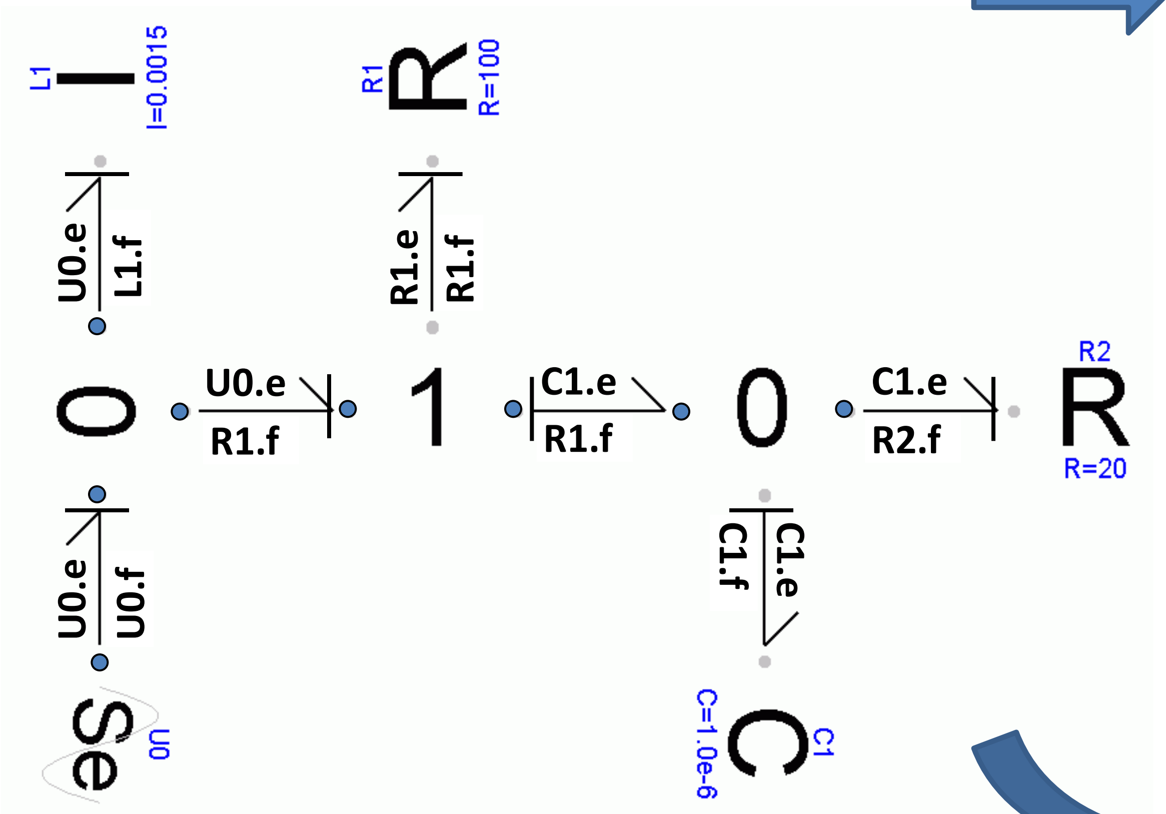
Bondgraphic model



Systematic derivation of equations

$U0.e = f(t)$

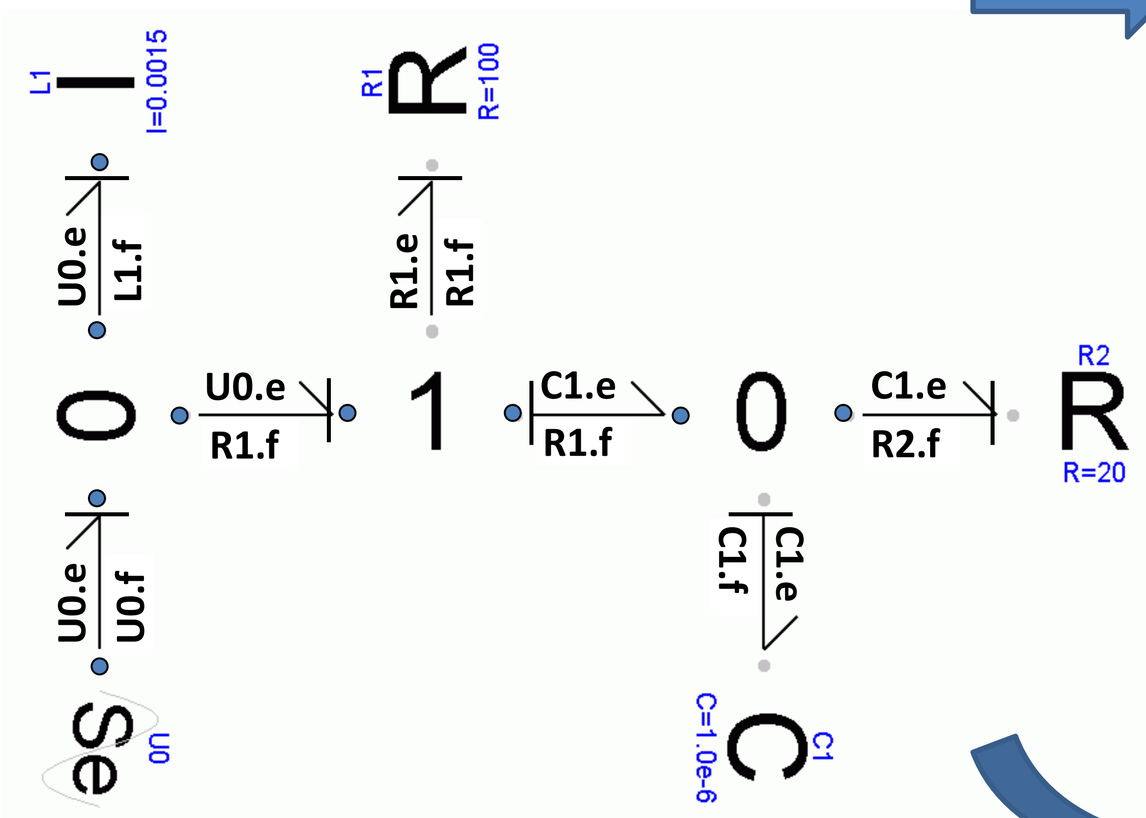
Bondgraphic model



Systematic derivation of equations

U0 .e = f(t)
U0 .f = L1 .f + R1 .f

Bondgraphic model



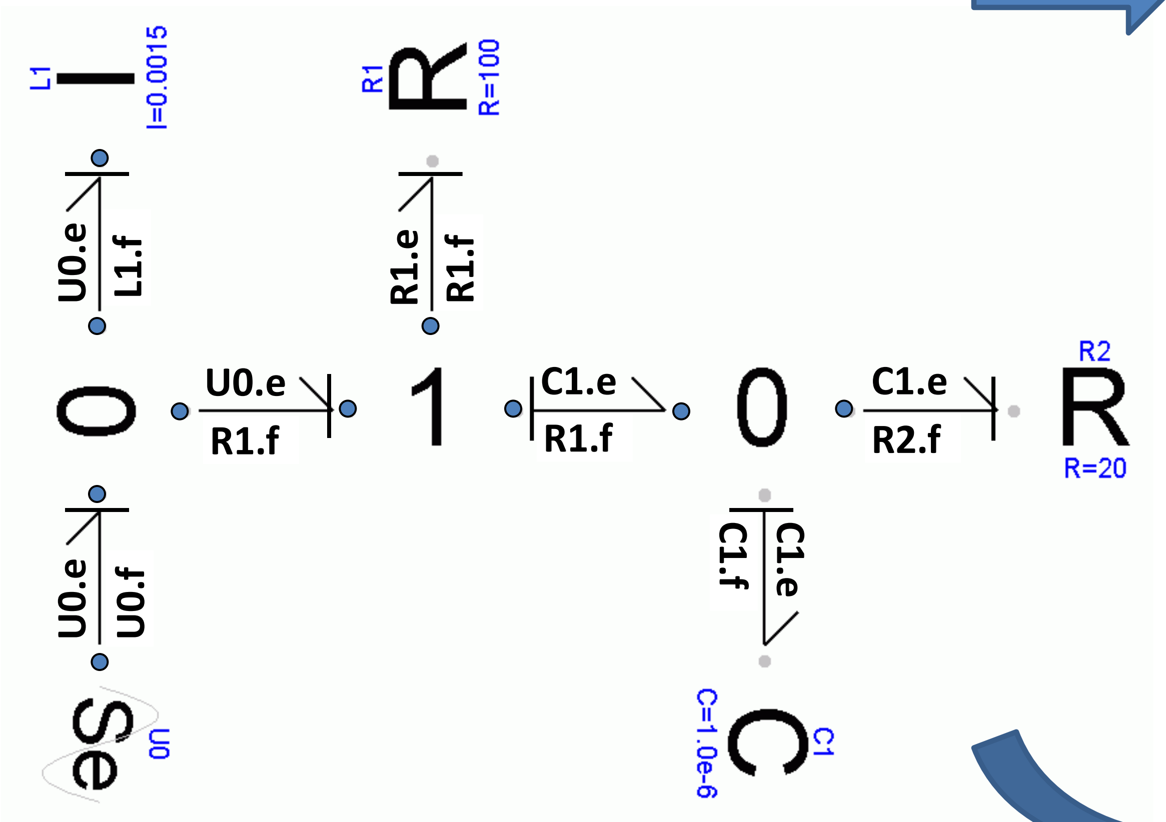
Systematic derivation of equations

$U0.e = f(t)$

$U0.f = L1.f + R1.f$

$d/dt\ L1.f = U0.e\ /\ L1$

Bondgraphic model



Systematic derivation of equations

$U0.e = f(t)$

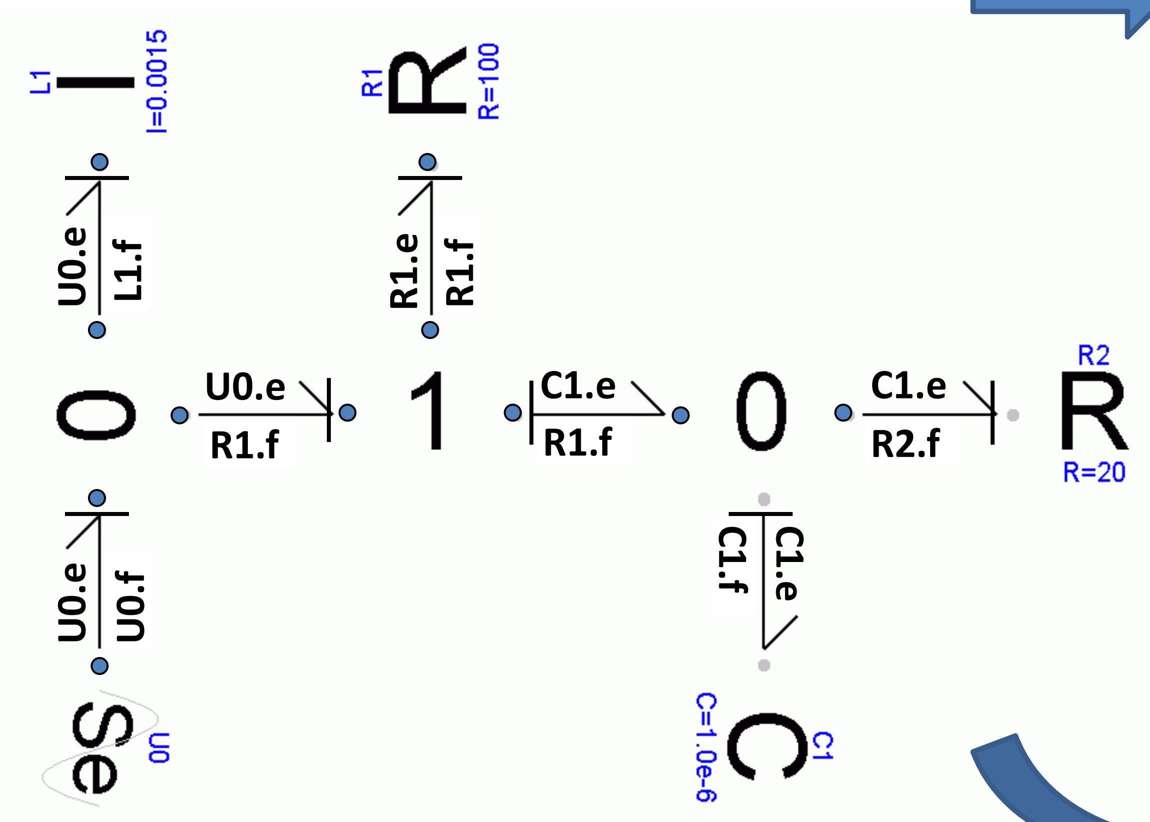
$U0.f = L1.f + R1.f$

$d/dt\ L1.f = U0.e \,/\, L1$

$R1.e = U0.e - C1.e$

The Bond Graph Formalism

Bondgraphic model



Systematic derivation of equations

$$U0.e = f(t)$$

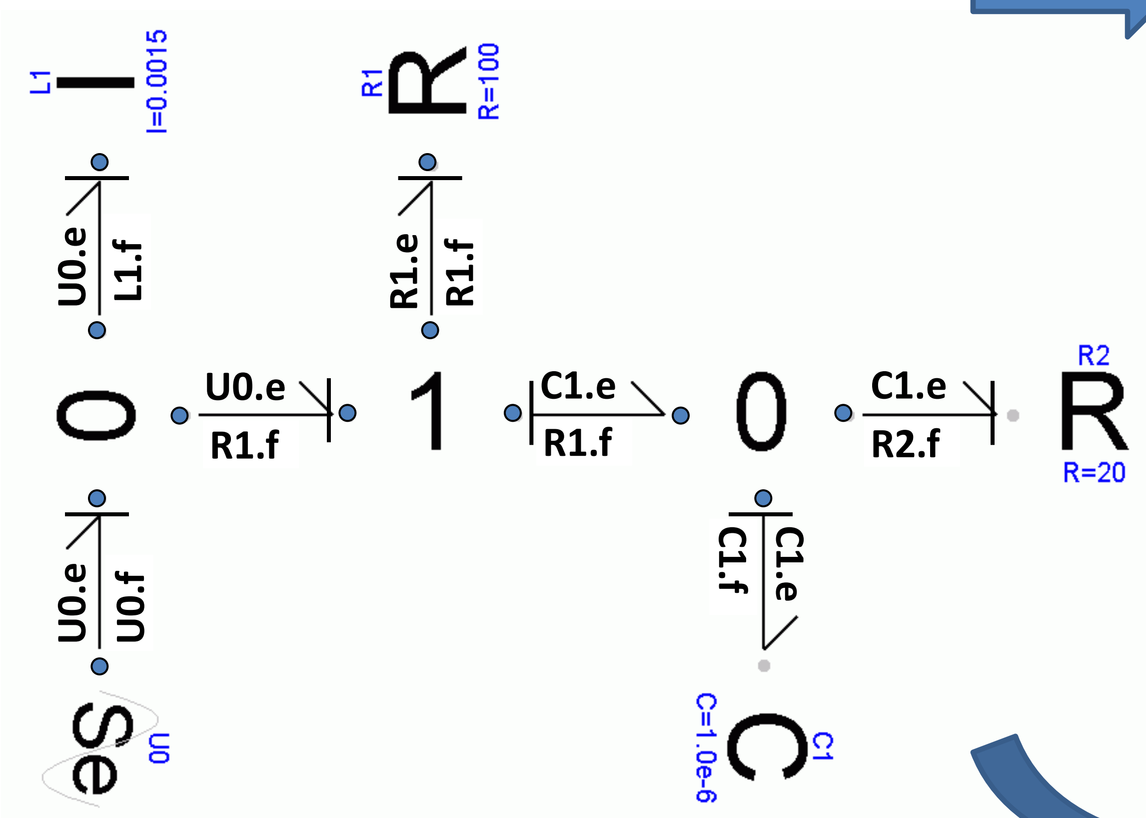
$$U0.f = L1.f + R1.f$$

$$d/dt\ L1.f = U0.e \,/\, L1$$

$$R1.e = U0.e - C1.e$$

$$R1.f = R1.e \,/\, R1$$

Bondgraphic model



Systematic derivation of equations

$$U0.e = f(t)$$

$$U0.f = L1.f + R1.f$$

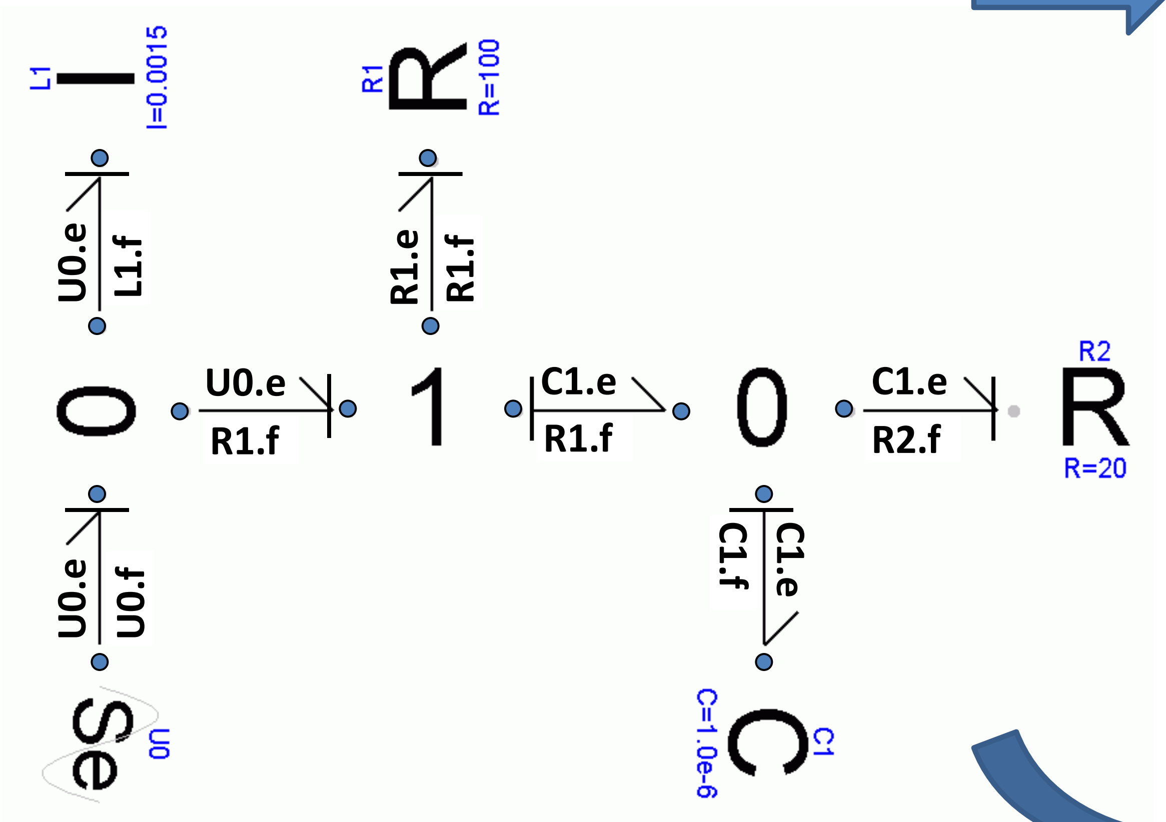
$$\frac{d}{dt} L1.f = U0.e \,/\, L1$$

$$R1.e = U0.e - C1.e$$

$$R1.f = R1.e \,/\, R1$$

$$C1.f = R1.f - R2.f$$

Bondgraphic model



Systematic derivation of equations

$U0.e = f(t)$

$U0.f = L1.f + R1.f$

$d/dt\ L1.f = U0.e / L1$

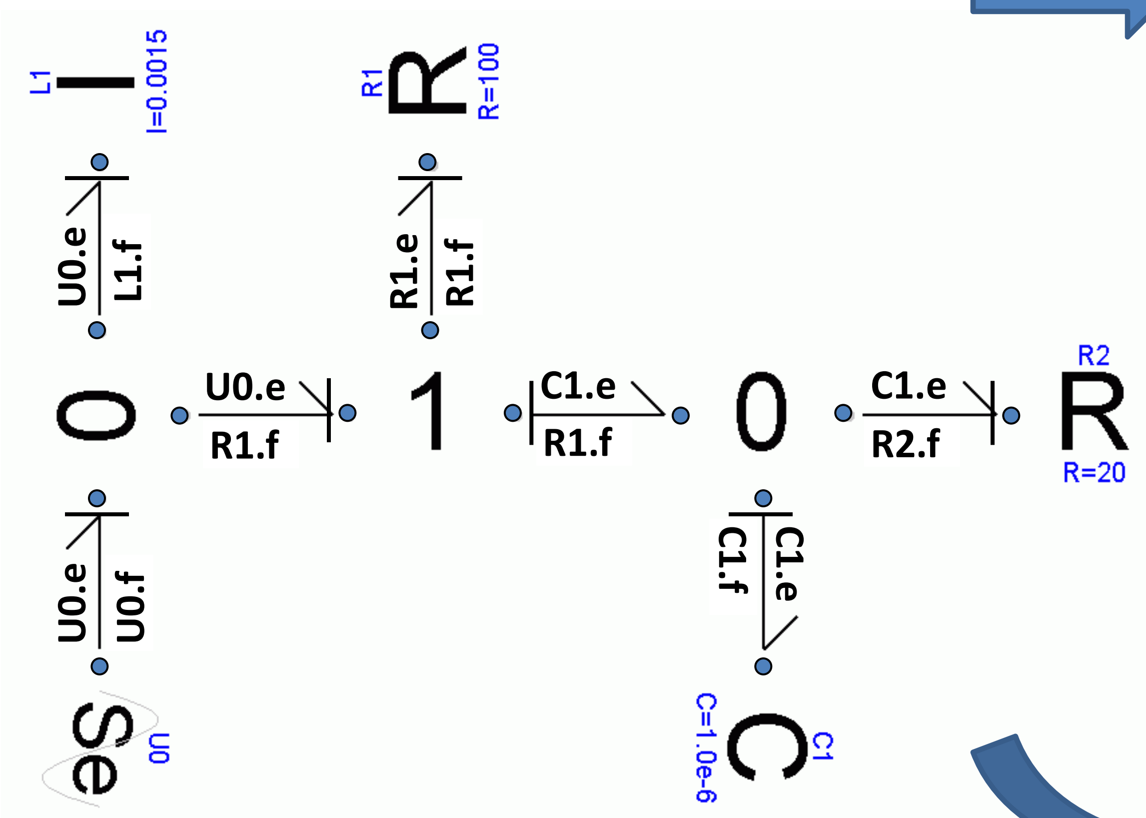
$R1.e = U0.e - C1.e$

$R1.f = R1.e / R1$

$C1.f = R1.f - R2.f$

$d/dt\ C1.e = C1.f / C1$

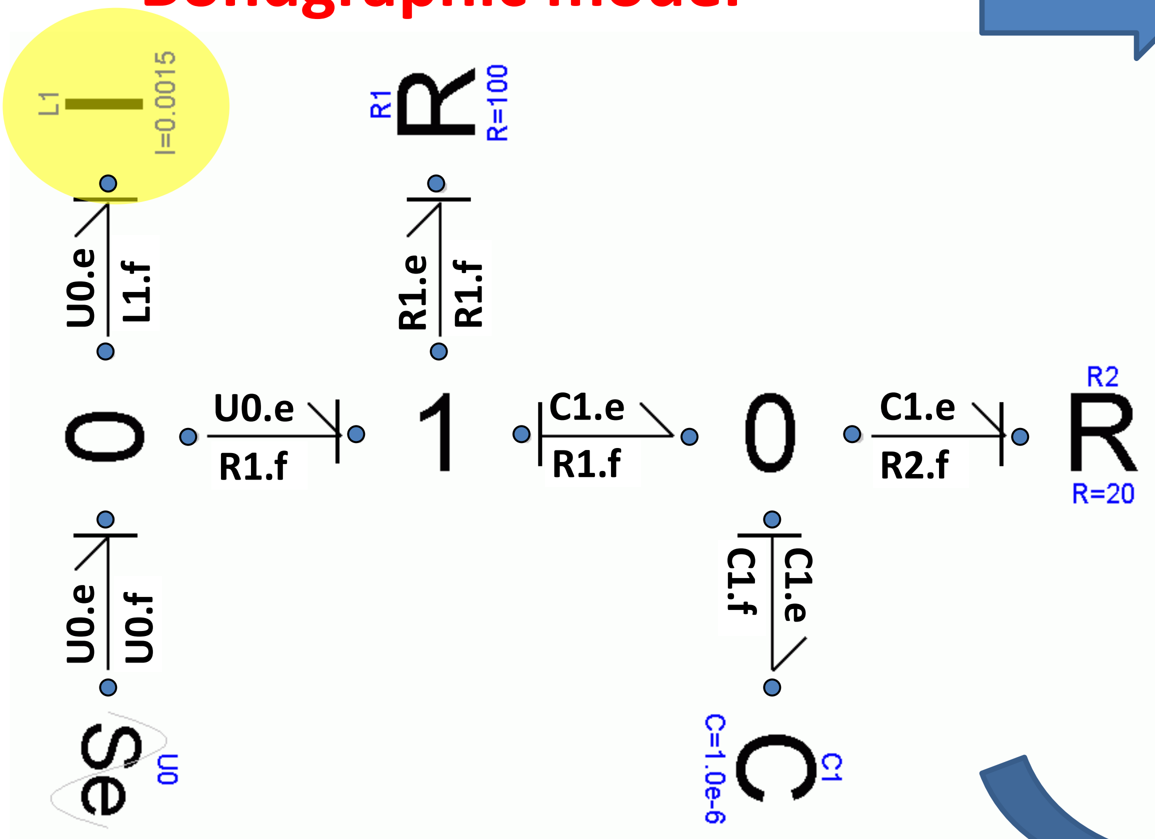
Bondgraphic model



Systematic derivation of equations

$$U0.e = f(t)$$
$$U0.f = L1.f + R1.f$$
$$d/dt\ L1.f = U0.e \,/\, L1$$
$$R1.e = U0.e - C1.e$$
$$R1.f = R1.e \,/\, R1$$
$$C1.f = R1.f - R2.f$$
$$d/dt\ C1.e = C1.f \,/\, C1$$
$$R2.f = C1.e \,/\, R2$$

Bondgraphic model



Systematic derivation of equations

$U0.e = f(t)$

$U0.f = L1.f + R1.f$

$\frac{d}{dt} L1.f = U0.e \,/\, L1$

$R1.e = U0.e - C1.e$

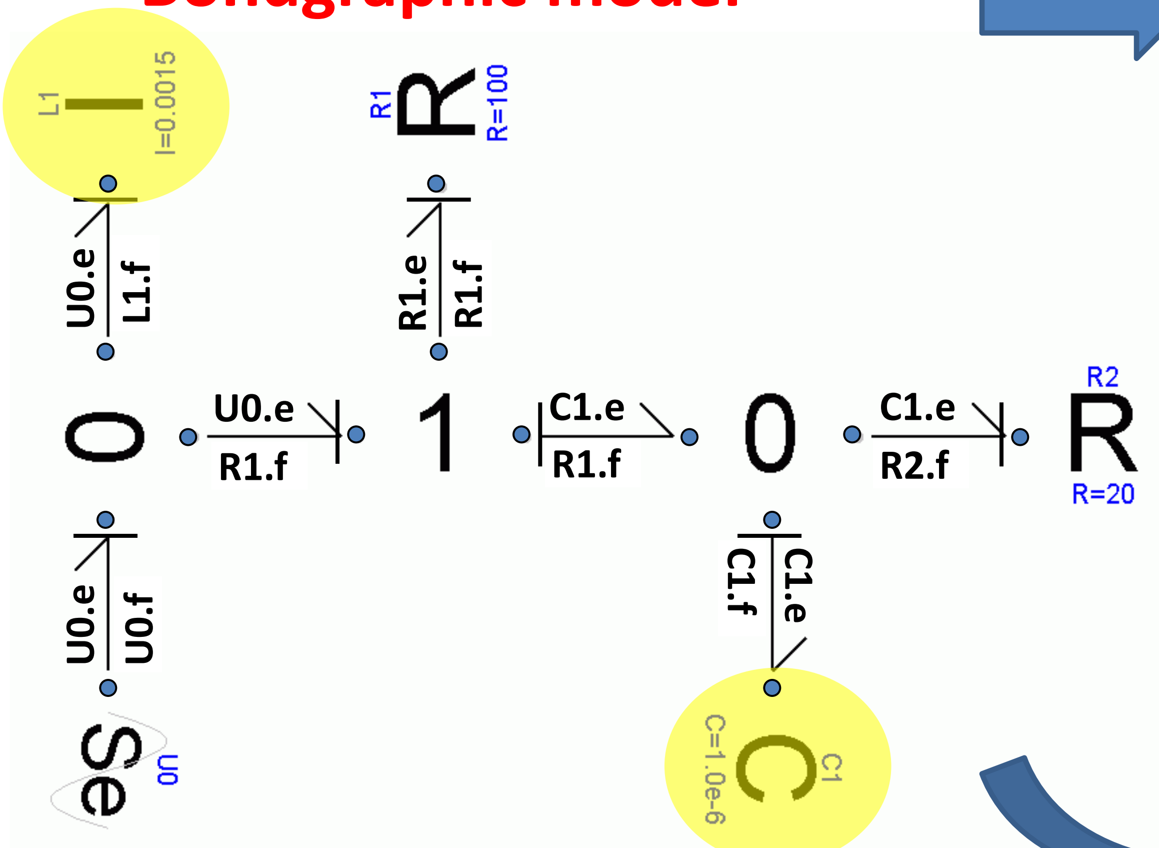
$R1.f = R1.e \,/\, R1$

$C1.f = R1.f - R2.f$

$\frac{d}{dt} C1.e = C1.f \,/\, C1$

$R2.f = C1.e \,/\, R2$

Bondgraphic model



Systematic derivation of equations

$U0.e = f(t)$

$U0.f = L1.f + R1.f$

$d/dt\ L1.f = U0.e / L1$

$R1.e = U0.e - C1.e$

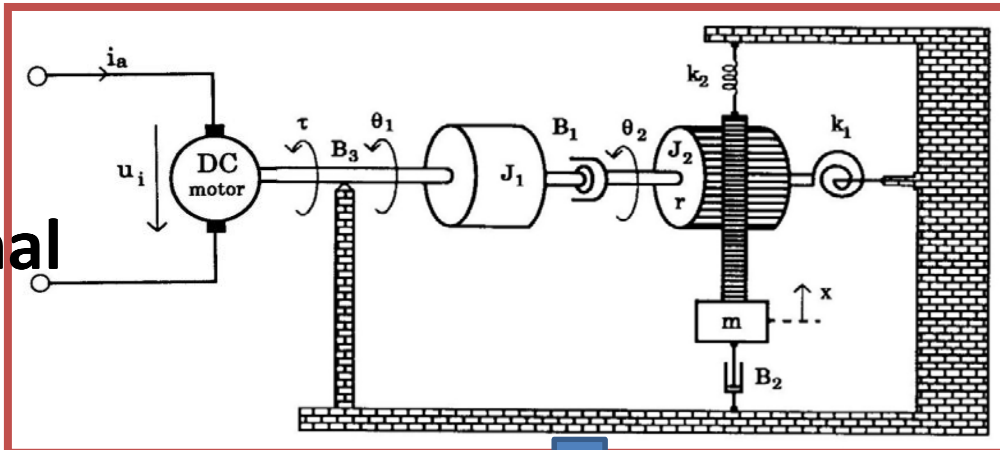
$R1.f = R1.e / R1$

$C1.f = R1.f - R2.f$

$d/dt\ C1.e = C1.f / C1$

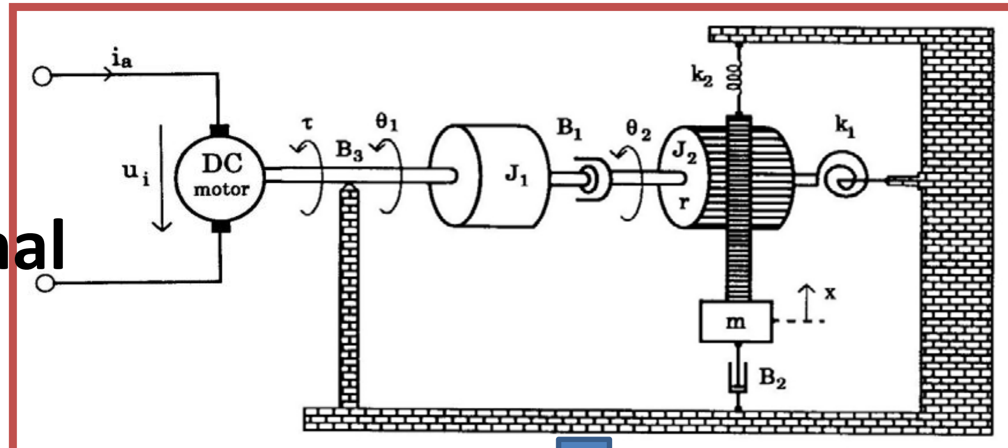
$R2.f = C1.e / R2$

- A multi-energy domain model
  - **Electricity**
  - **Mechanical rotational**
  - **Mechanical translational**

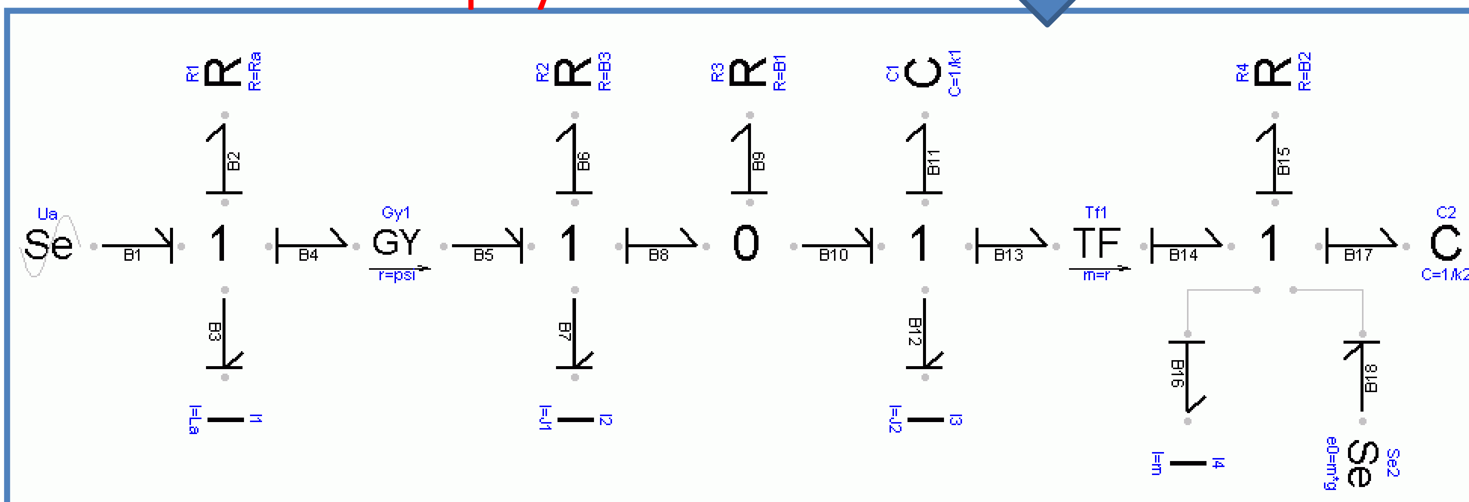


Special elements such as
Gyrator and **Transformer**
convert energy flows across diff. physical domains

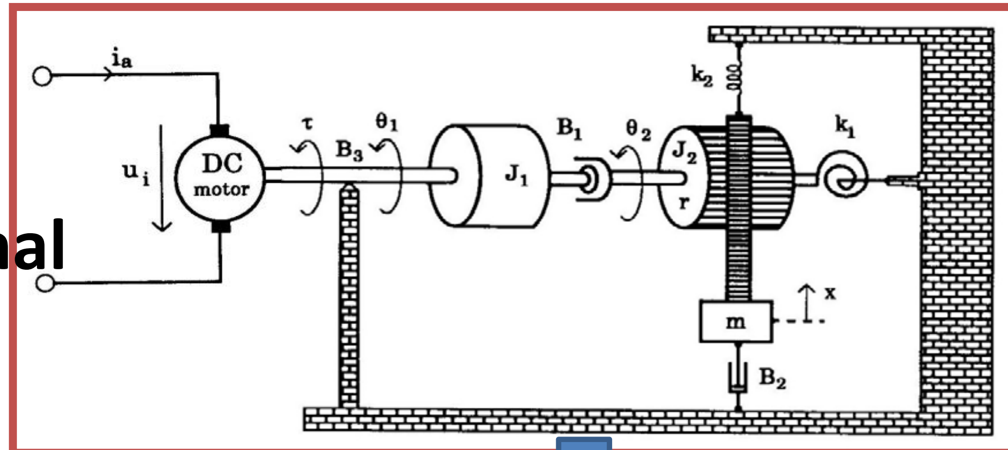
- A multi-energy domain model
  - **Electricity**
  - **Mechanical rotational**
  - **Mechanical translational**



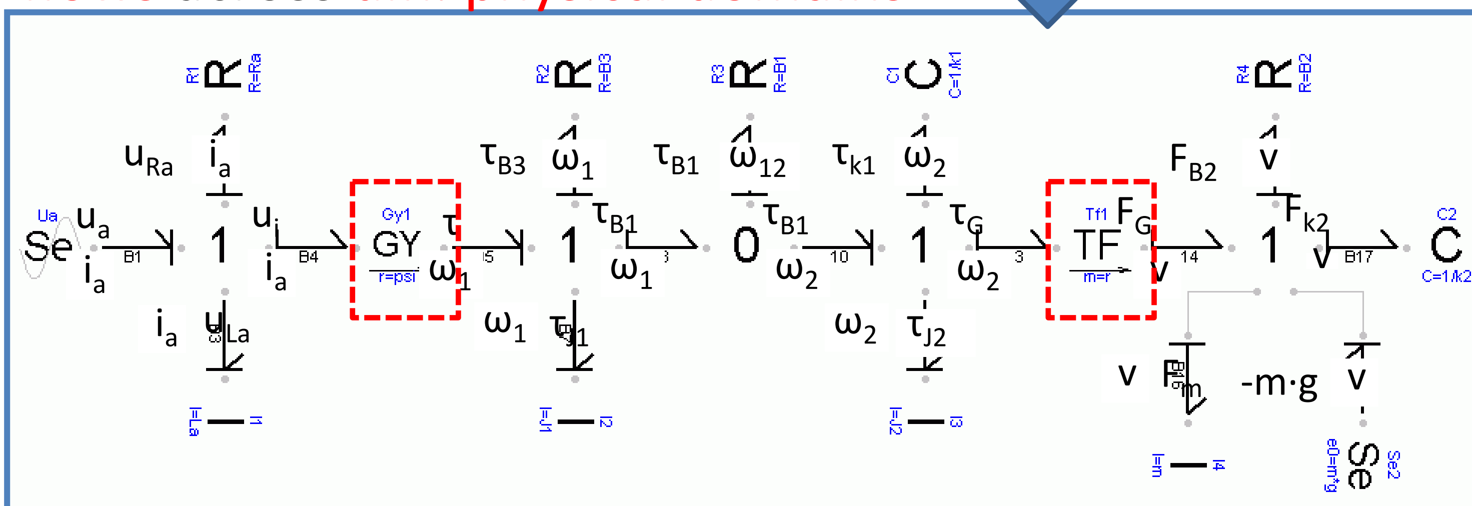
Special elements such as **Gyrator** and **Transformer** convert energy flows across diff. physical domains



- A multi-energy domain model
  - **Electricity**
  - **Mechanical rotational**
  - **Mechanical translational**



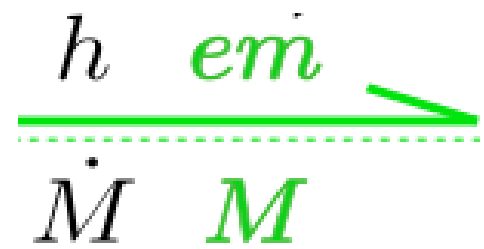
Special elements such as **Gyrator** and **Transformer** convert energy flows across diff. physical domains



- Bond Graph variables for Complex Systems
  - **Facets 1 and 2**
    - Power variables:
      - **Specific Enthalpy** [J/kg] (an *effort variable*)
      - **Mass Flow** [kg/sec] (a *flow variable*).

      [J/sec] = [J/kg] · [kg/sec] represents power
    - Information variable
      - **Mass** [Kg] (a *state* variable)
  - **Facet 3** (the e*m*ergy facet)
    - Information variable
      - **Specific E*m*ergy** [J/kg] (a *structural* variable)
      - [J/sec] = [J/kg] · [kg/sec] also denotes power

EcoBG



- # Bond Graph variables for Complex Systems

  – **Facets 1 and 2**

  - Power variables:

    – **Specific Enthalpy** [J/kg] (an *effort variable*)

    – **Mass Flow** [kg/sec] (a *flow variable*).

    [J/sec] = [J/kg] · [kg/sec] represents power

  - Information variable

    – **Mass** [Kg] (a *state* variable)

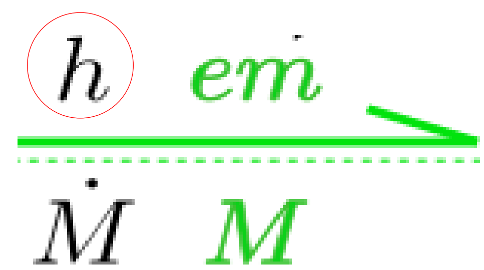
  – **Facet 3** (the e*m*ergy facet)

  - Information variable

    – **Specific Emergy** [J/kg] (a *structural* variable)

    – [J/sec] = [J/kg] · [kg/sec] also denotes power

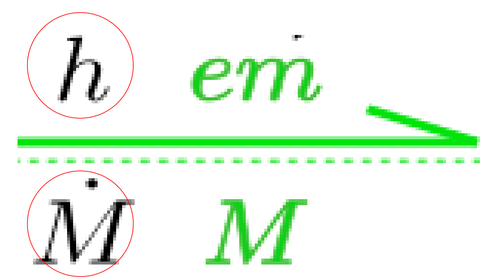
EcoBG



- Bond Graph variables for Complex Systems
  - **Facets 1 and 2**
    - Power variables:
      - **Specific Enthalpy** [J/kg] (an *effort variable*)
      - **Mass Flow** [kg/sec] (a *flow variable*).

      [J/sec] = [J/kg] · [kg/sec] represents power
    - Information variable
      - **Mass** [Kg] (a *state* variable)
  - **Facet 3** (the e*m*ergy facet)
    - Information variable
      - **Specific E*m*ergy** [J/kg] (a *structural* variable)
      - [J/sec] = [J/kg] · [kg/sec] also denotes power

EcoBG

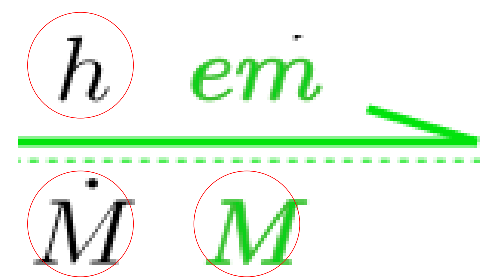


Facets and Bonds

- Bond Graph variables for Complex Systems
  - **Facets 1 and 2**
    - Power variables:
      - **Specific Enthalpy** [J/kg] (an *effort variable*)
      - **Mass Flow** [kg/sec] (a *flow variable*).

      [J/sec] = [J/kg] · [kg/sec] represents power
    - Information variable
      - **Mass** [Kg] (a *state* variable)
  - **Facet 3** (the e*m*ergy facet)
    - Information variable
      - **Specific E*m*ergy** [J/kg] (a *structural* variable)
      - [J/sec] = [J/kg] · [kg/sec] also denotes power

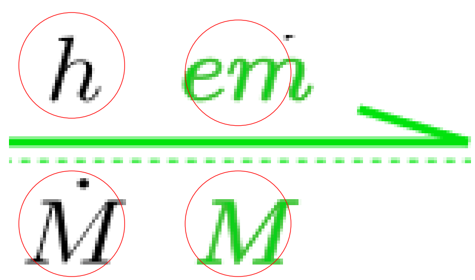
EcoBG



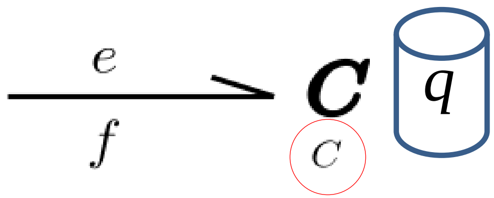
- Bond Graph variables for Complex Systems
  - **Facets 1 and 2**
    - Power variables:
      - **Specific Enthalpy** [J/kg] (an *effort variable*)
      - **Mass Flow** [kg/sec] (a *flow variable*).

      [J/sec] = [J/kg] · [kg/sec] represents power
    - Information variable
      - **Mass** [Kg] (a *state* variable)
  - **Facet 3** (the e*m*ergy facet)
    - Information variable
      - **Specific Em*ergy*** [J/kg] (a *structural* variable)
      - [J/sec] = [J/kg] · [kg/sec] also denotes power

EcoBG

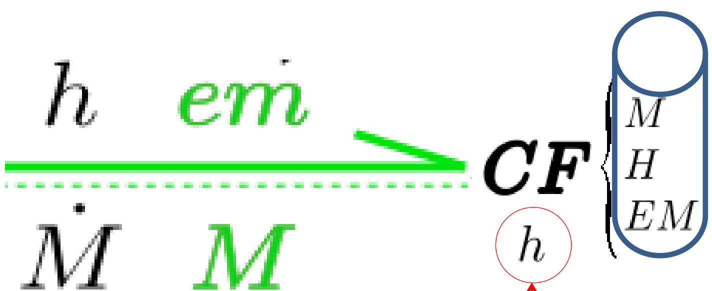


- The EcoBG Storage element
  - A **C**apacitive **Field** (**CF**) accumulates more than one quantity: Enthalpy, Mass and Emergy



$$e(t) = \frac{1}{C} \int f(t).dt$$

} BG

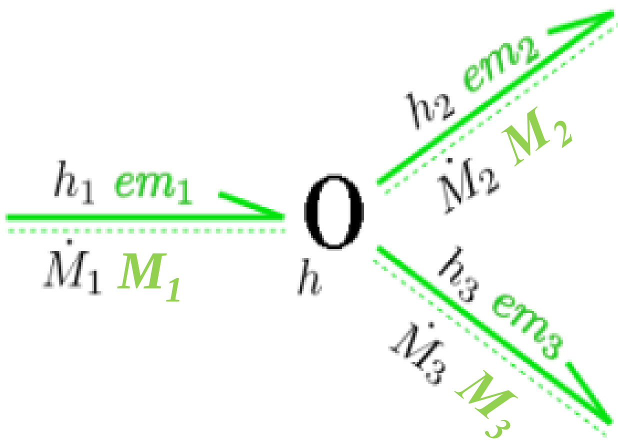


$$H(t) = h. \int \dot{M}(t).dt$$
$$M(t) = H(t)/h$$
$$EM(t) = \int em(t).\dot{M}(t).dt$$

} EcoBG

The **specific enthalpy** is
a property of the accumulated mass
Known in advance -> A parameter

- The EcoBG 0-Junction



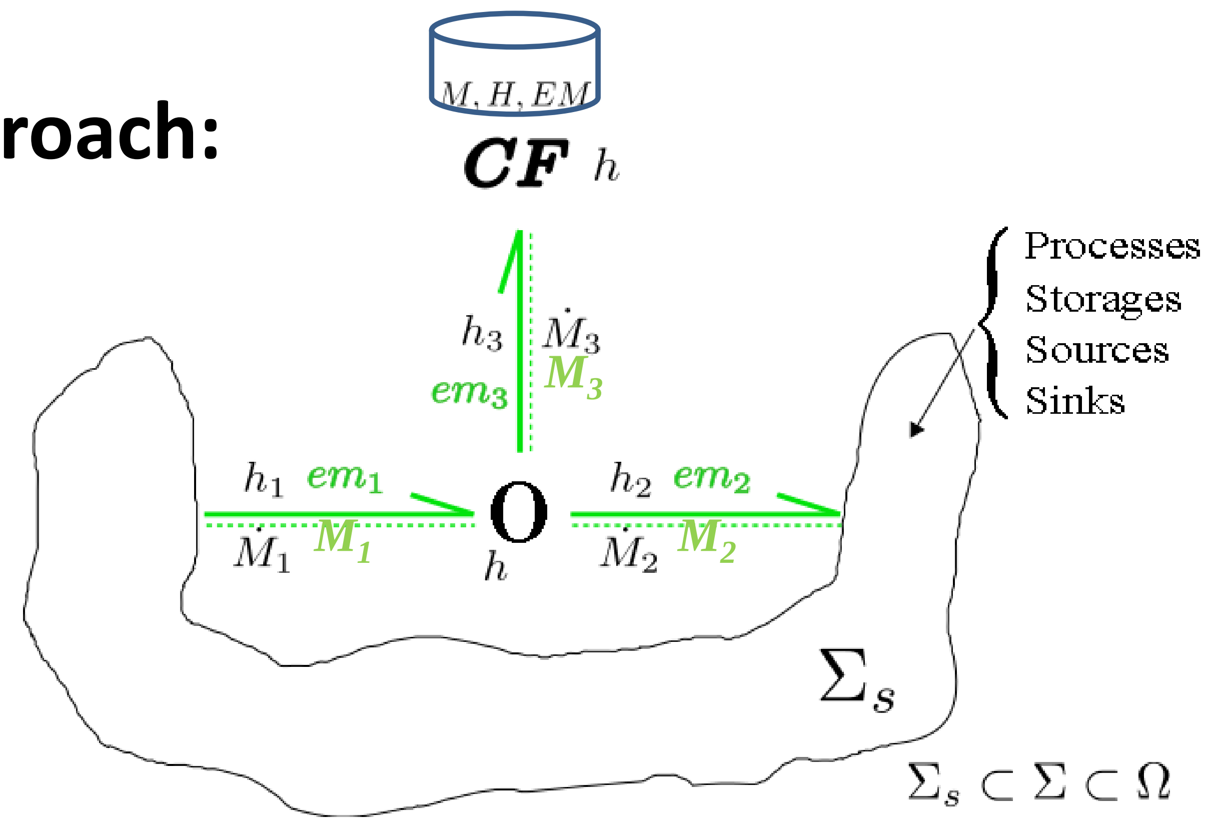
$$\left.\begin{array}{rcl} e_1 = e_2 = e_3 & = & e \\ f_1 - f_2 - f_3 & = & 0 \end{array}\right\} \text{BG}$$

$$\left.\begin{array}{rcl} h_1 = h_2 = h_3 & = & h \\ \dot{M}_1 - \dot{M}_2 - \dot{M}_3 & = & 0 \end{array}\right\} \text{EcoBG}$$

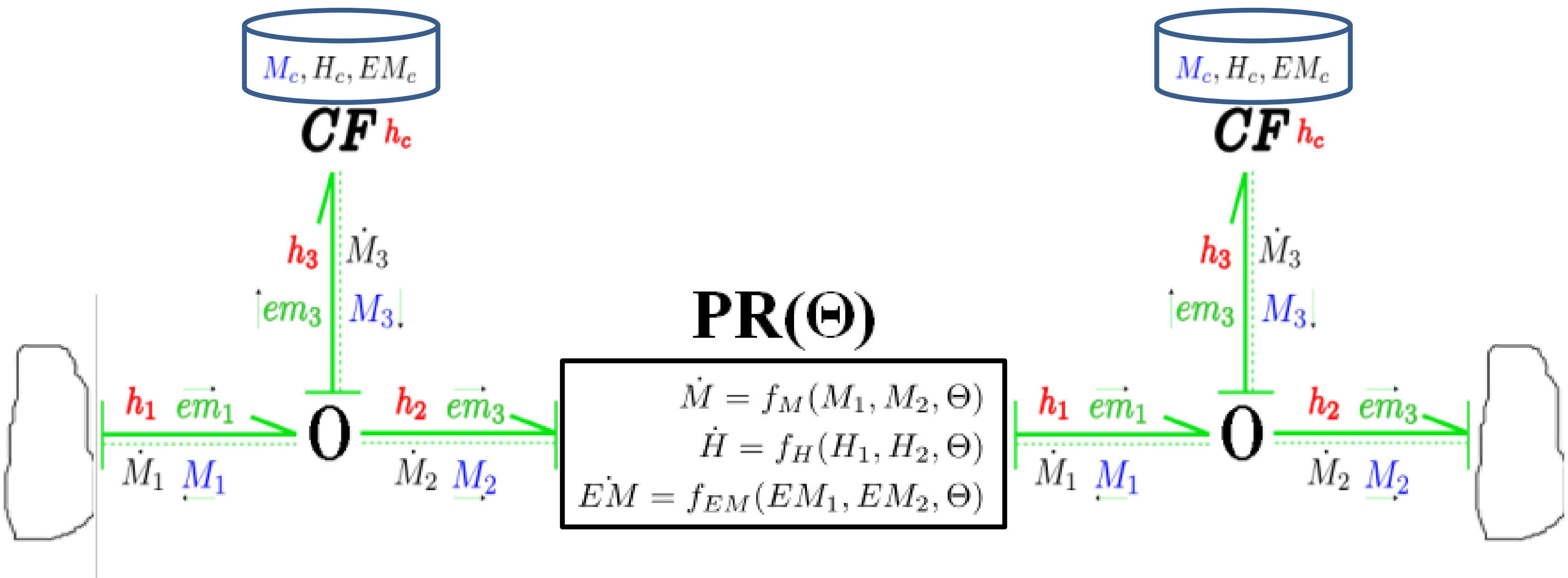
$$em_{in} = em_1 \qquad em_{out} = em_2 \;=\; em_3$$

$$\left.\begin{array}{rcl} \sum Power = \sum \dot{H}_i = h.\sum \dot{M}_i & = & 0 \\ \sum EmPower = \sum \dot{EM}_i = \sum em_i.\dot{M}_i & = & 0 \end{array}\right\} \text{Power Balances}$$

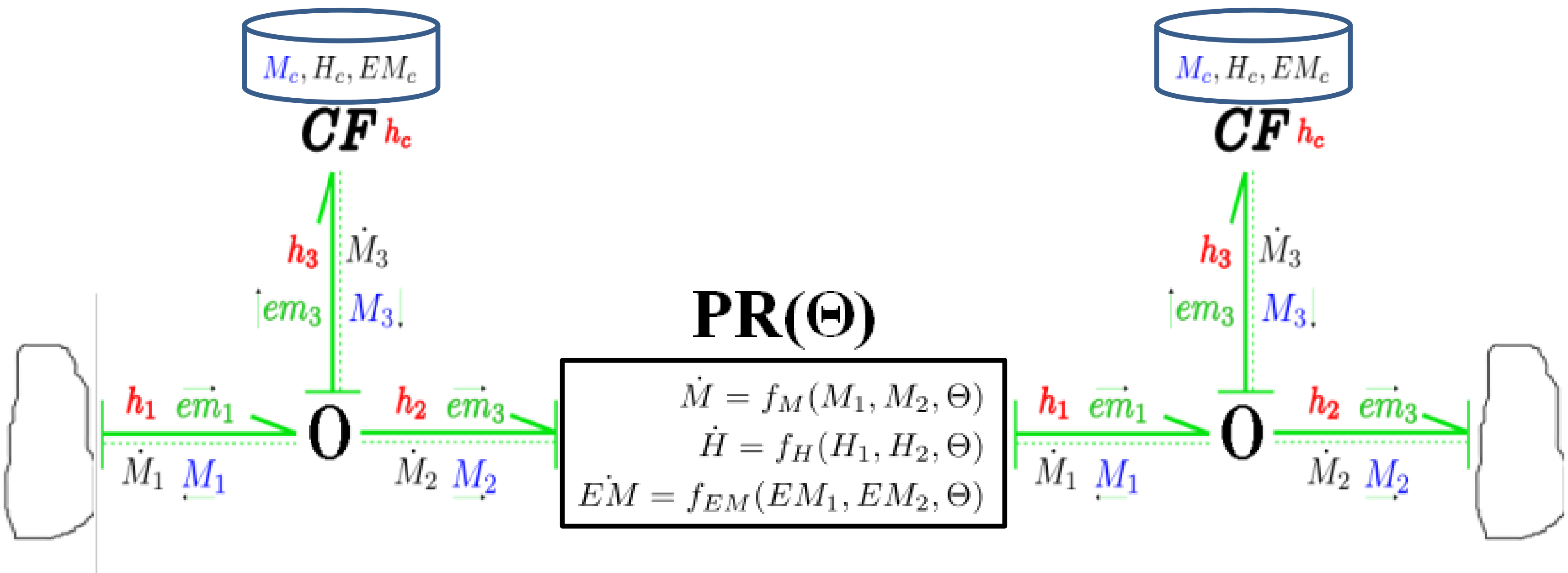
- Basic unit based on EcoBG elements
  - An important “building block”
- Storage of mass and energy adhering to the proposed
  3-Faceted approach:

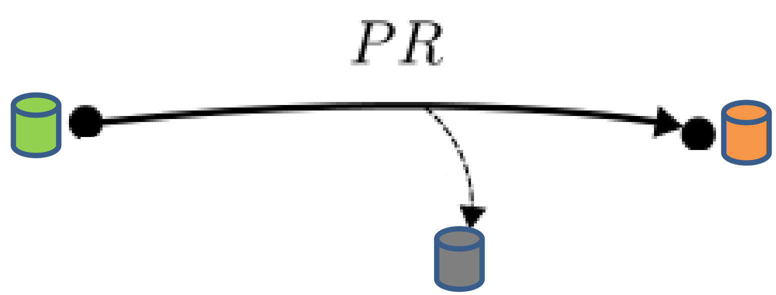


- EcoBG **Process** elements

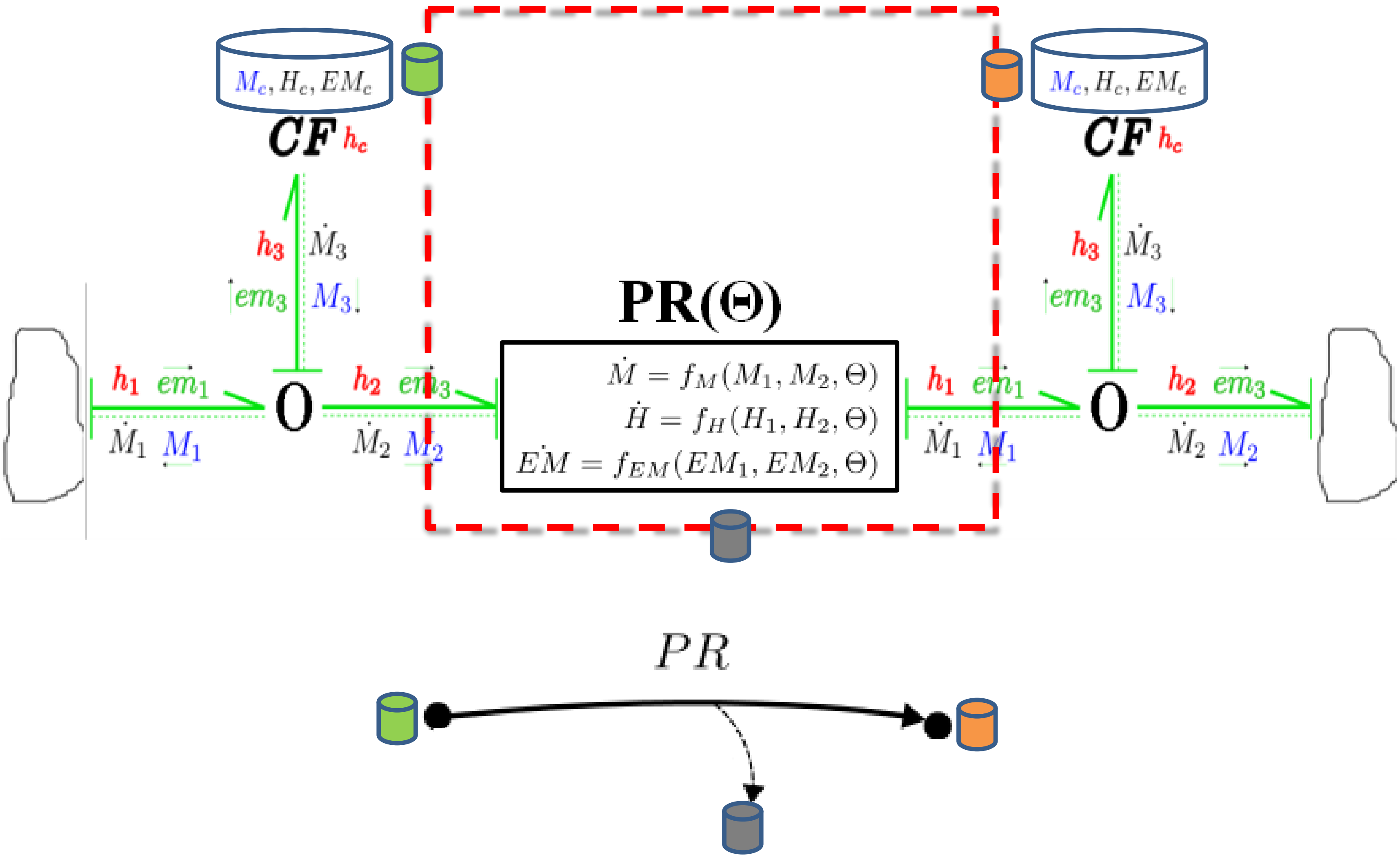


- EcoBG **Process** elements

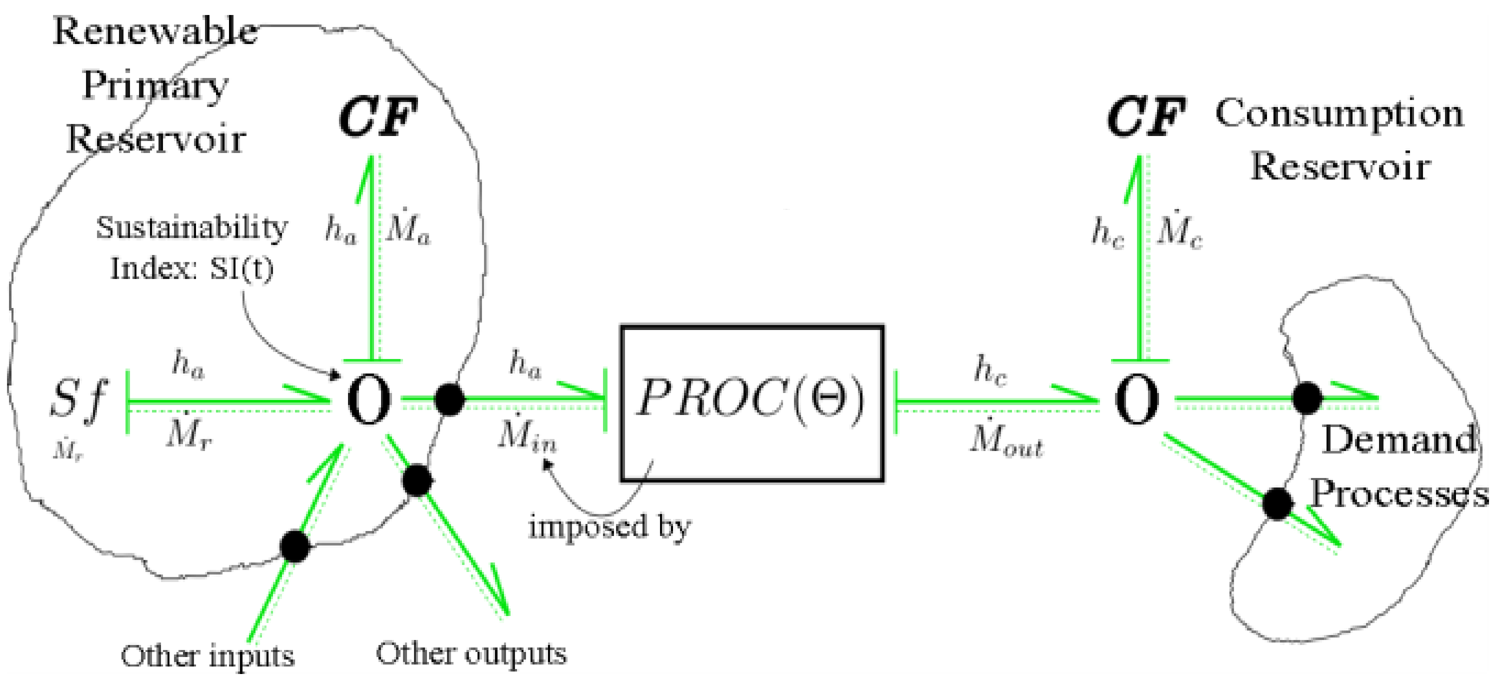




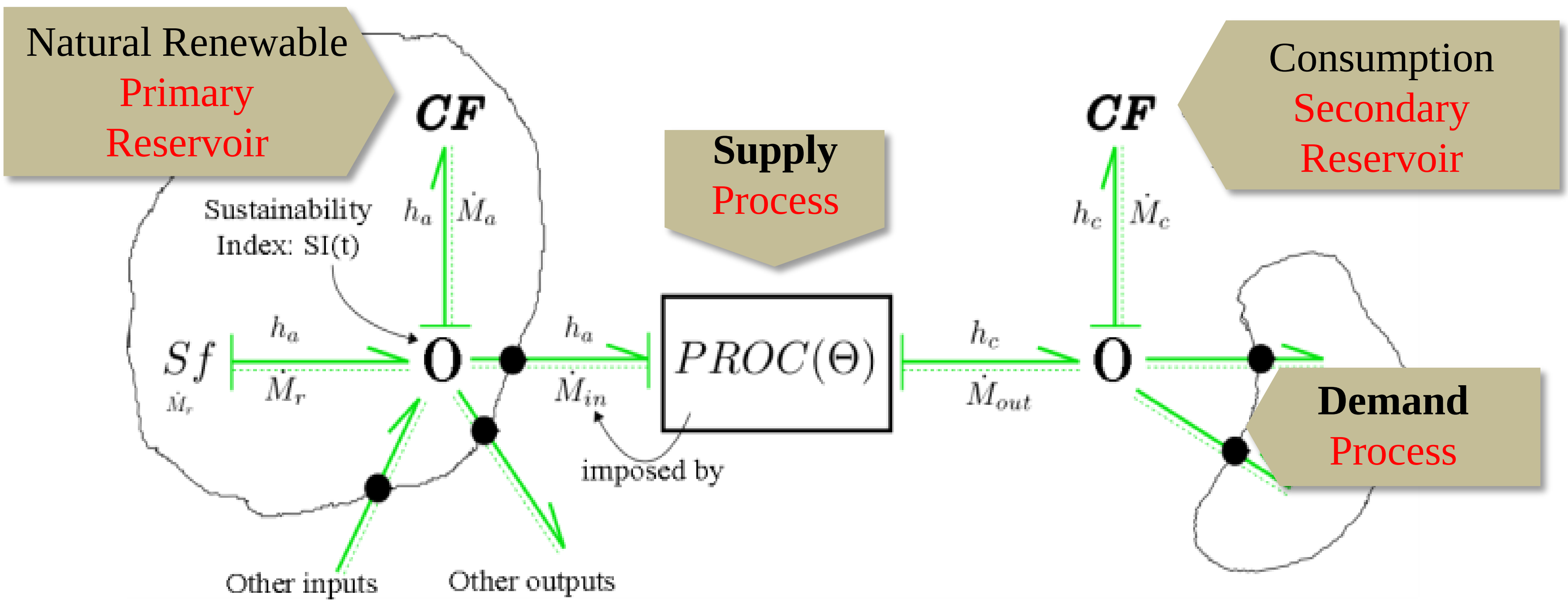
- EcoBG **Process** elements



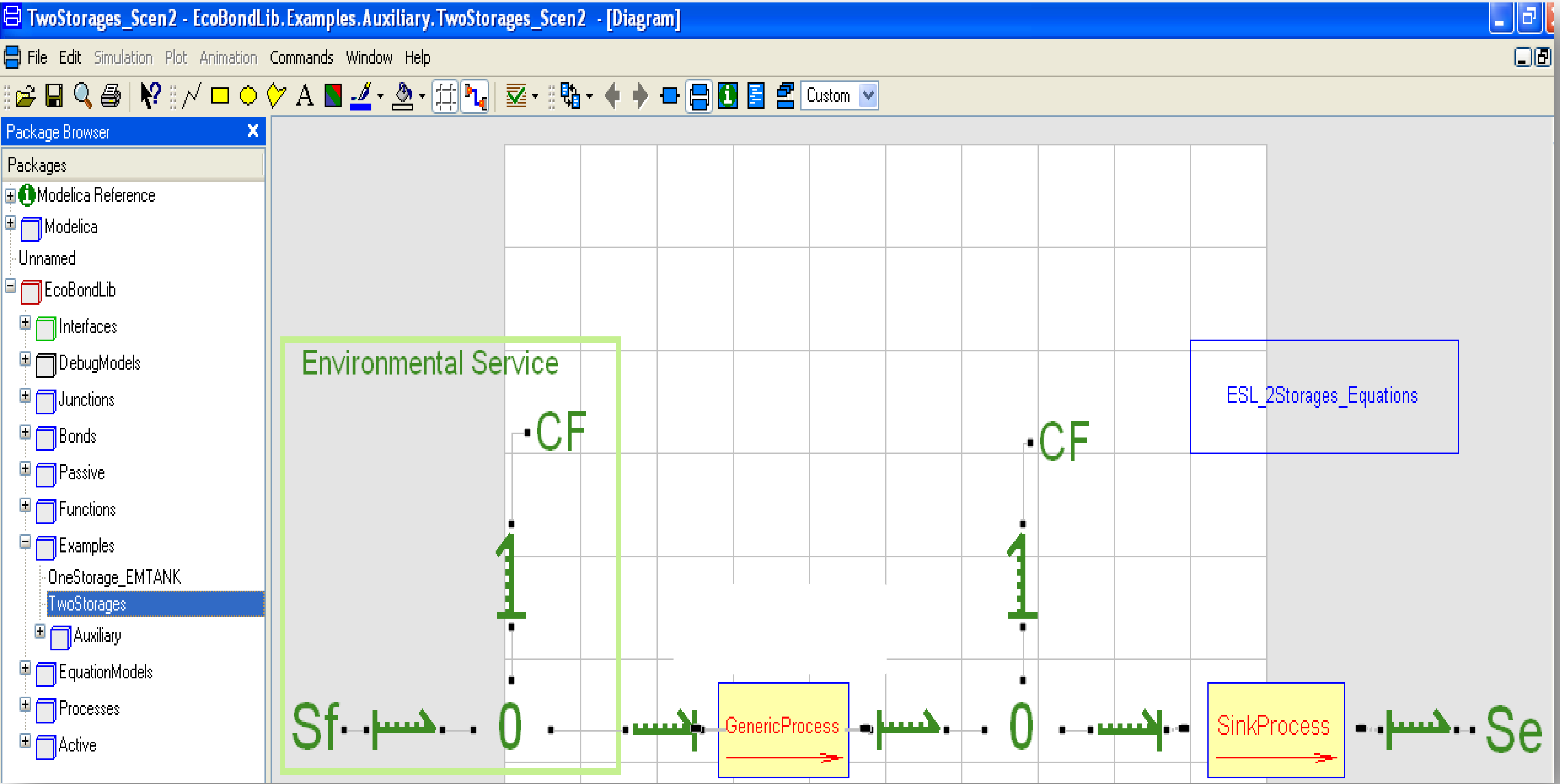
- Extraction of renewable resources for consumption



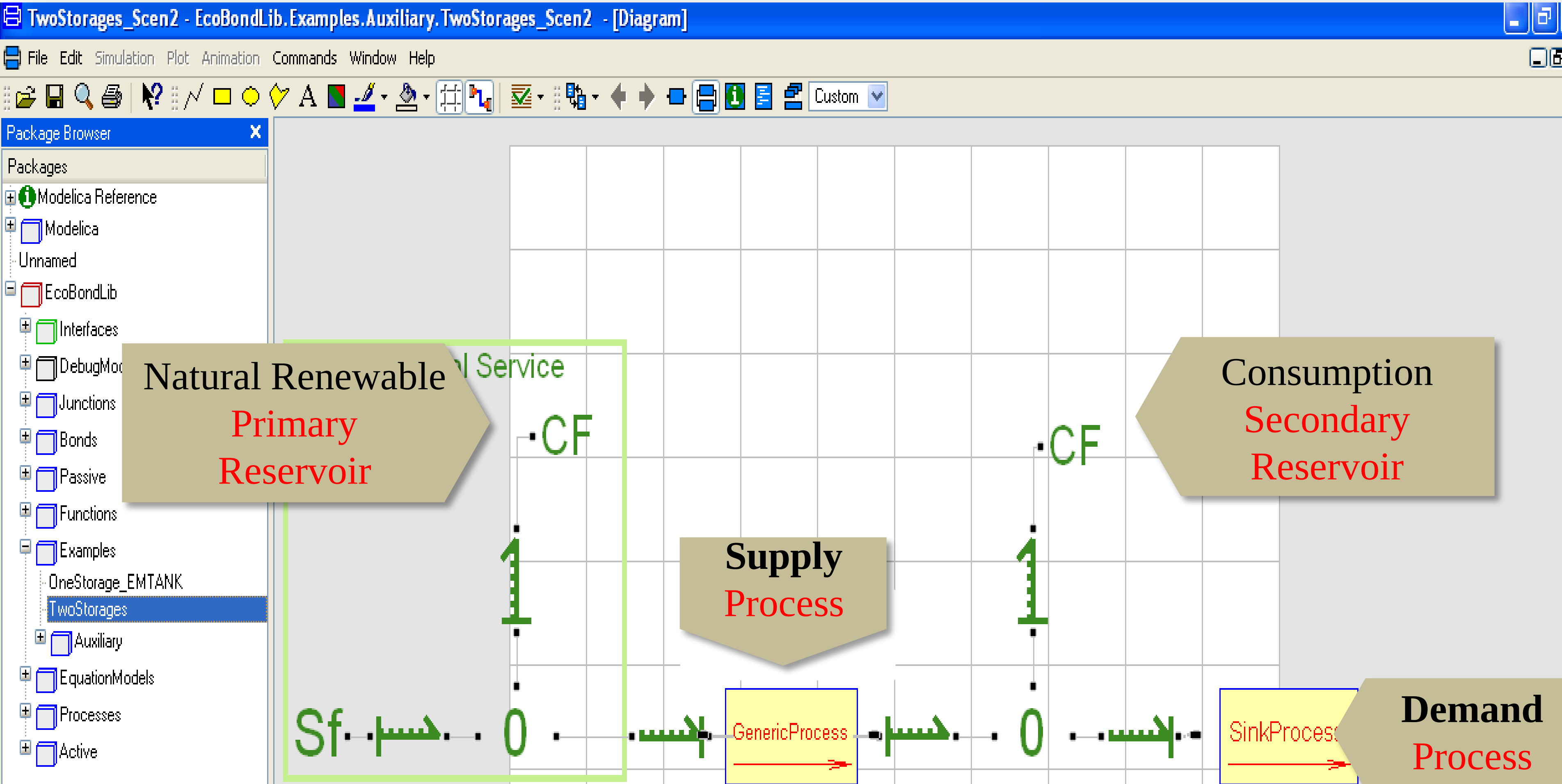
- Extraction of renewable resources for consumption

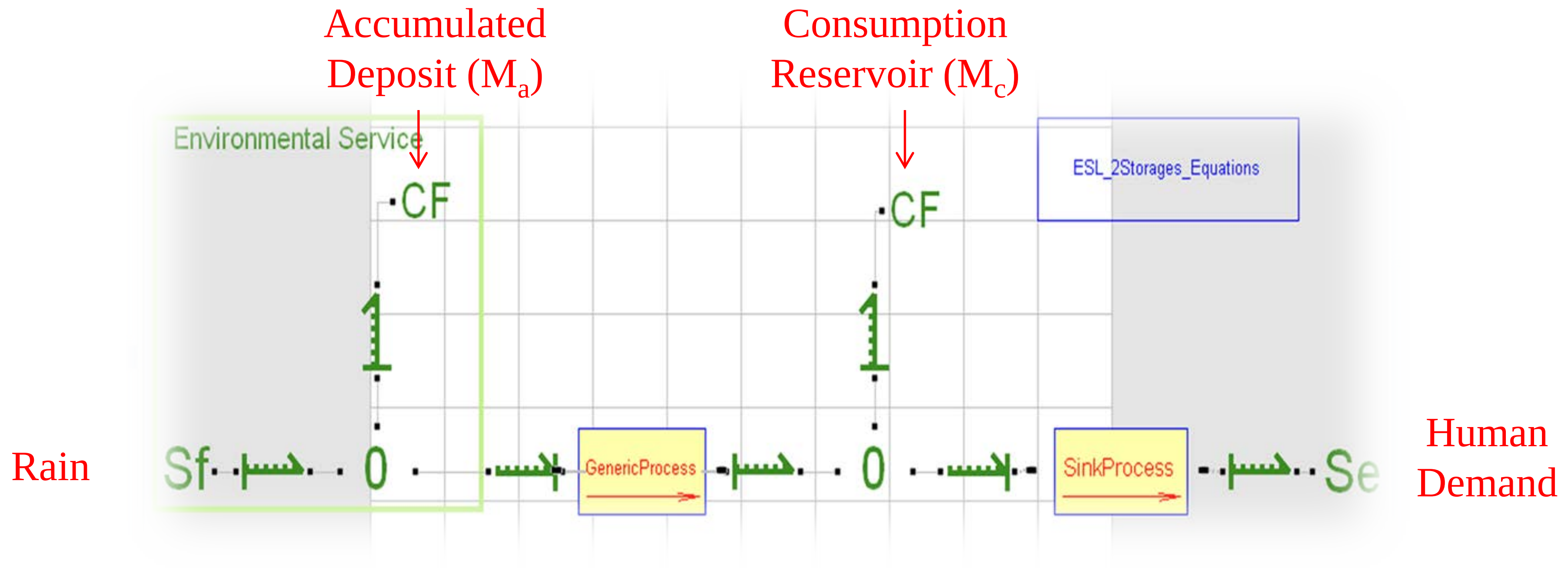


- EcoBG library implemented in the Dymola® tool.

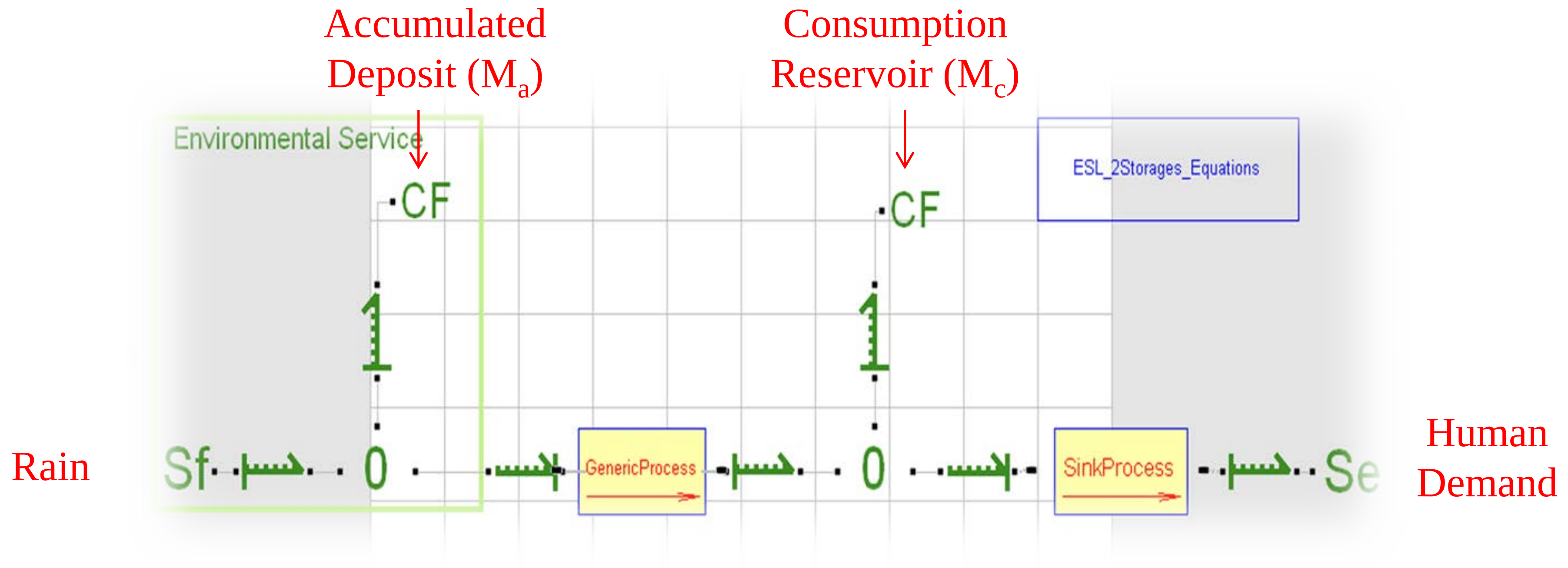


- EcoBG library implemented in the Dymola® tool.




Accumulated
Deposit (M_a)
Consumption
Reservoir (M_c)
Environmental Service
CF
CF
ESL_2Storages_Equations
1
1
Rain
Sf
0
GenericProcess
0
SinkProcess
Se
Human
Demand

$$\dot{M}_a = \dot{M}_r - K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c - \dot{M}_d$$

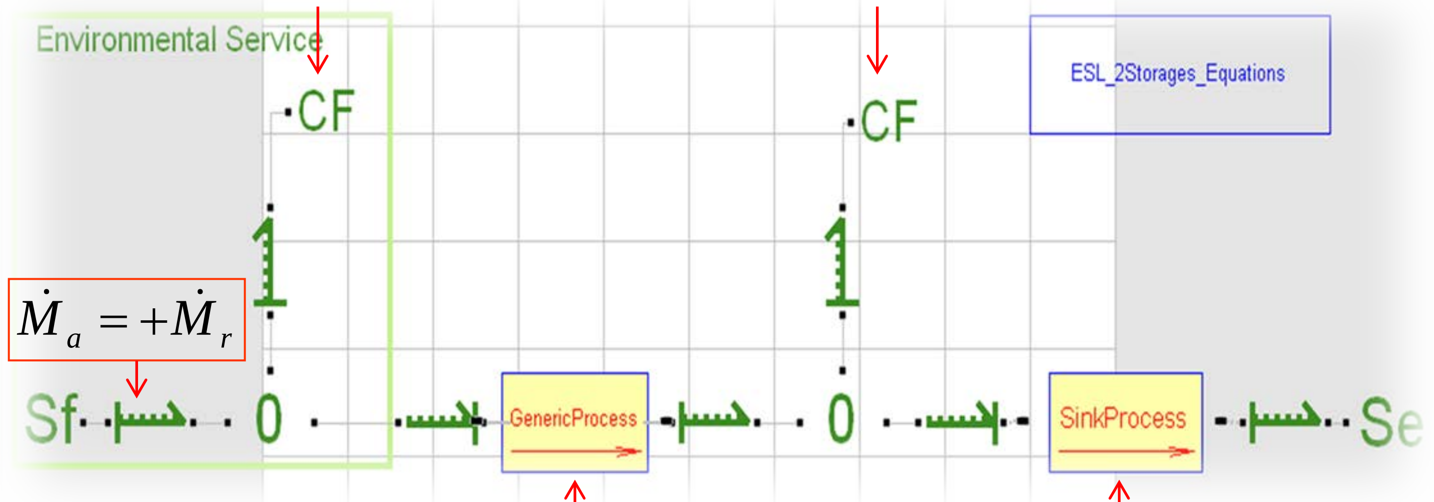


The **Mass** Layer

$$\dot{M}_a = \dot{M}_r - K_s.M_a.M_c$$
$$\dot{M}_c = \quad K_s.M_a.M_c - K_s^{irr} M_c - \dot{M}_d$$

Accumulated Deposit (M_a)

Consumption Reservoir (M_c)



$$\dot{M}_a = +\dot{M}_r$$

Rain

Human Demand

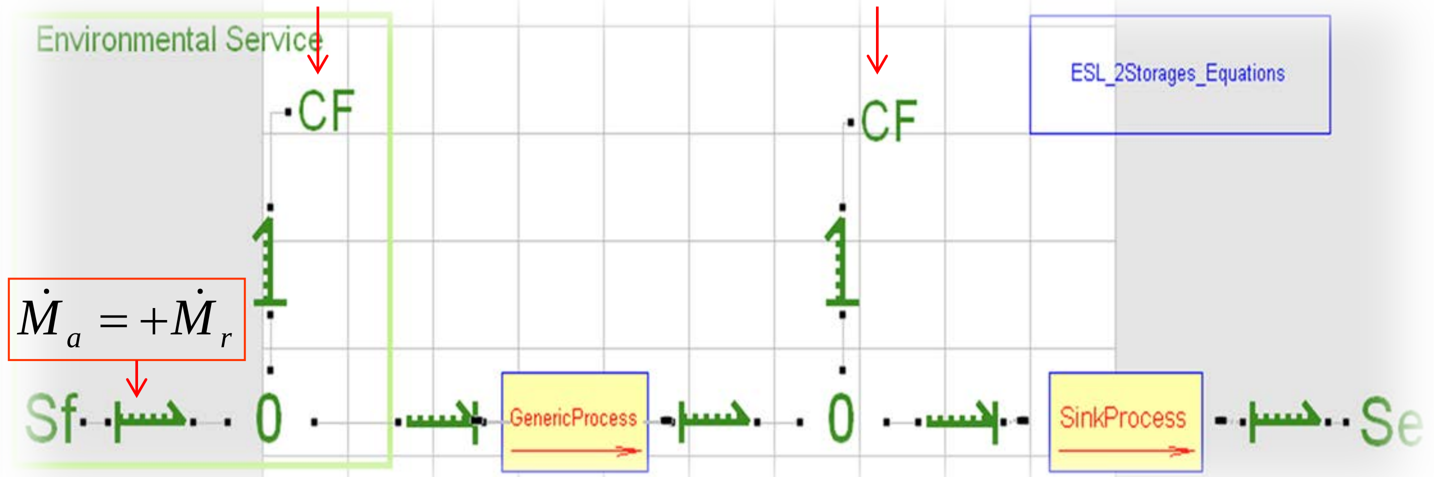
$$\dot{M}_a = K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c$$

$$\dot{M}_c = -K_d^{irr} M_c - \dot{M}_d$$

$$\dot{M}_a = \dot{M}_r - K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c - \dot{M}_d$$

Accumulated Deposit (M_a)

Consumption Reservoir (M_c)



Rain

Human Demand

$$\dot{M}_a = +\dot{M}_r$$

$$\dot{M}_a = K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c$$

$$\dot{M}_c = -K_d^{irr} M_c - \dot{M}_d$$

$$\dot{M}_a = \dot{M}_r - K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c - \dot{M}_d$$

$M_{a,0} = 150Kg$

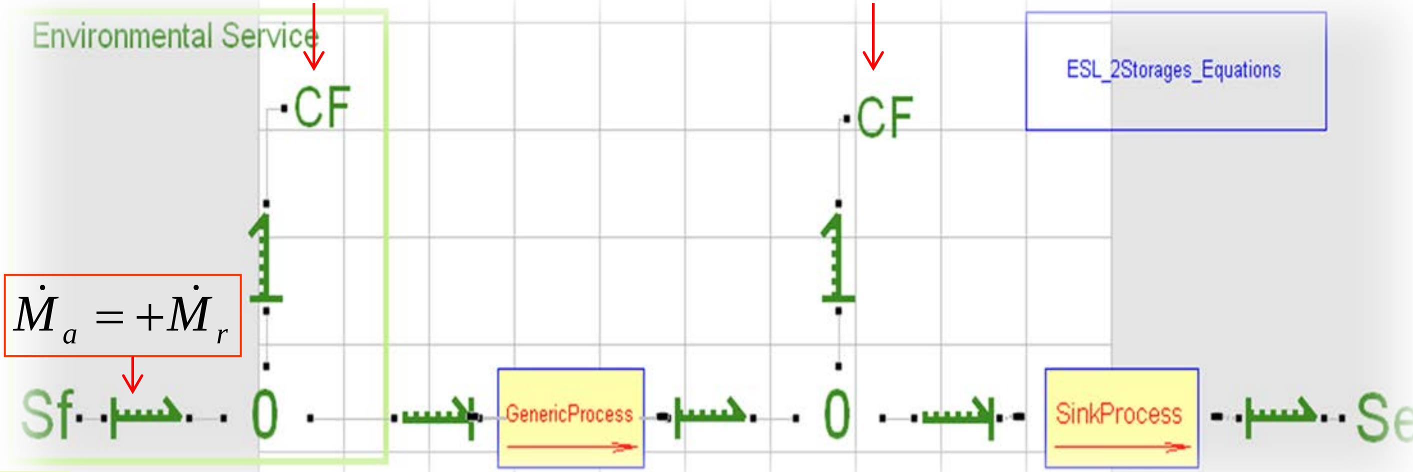
Accumulated Deposit (M_a)

Consumption Reservoir (M_c)

$M_{c,0} = 1Kg$

$\dot{M}_a = +\dot{M}_r$

Rain



Human Demand

$\dot{M}_r = 2\dfrac{Kg}{s}$

$$\dot{M}_a = K_s.M_a.M_c$$
$$\dot{M}_c = K_s.M_a.M_c - K_s^{irr} M_c$$

$\dot{M}_c = -K_d^{irr} M_c - \dot{M}_d$

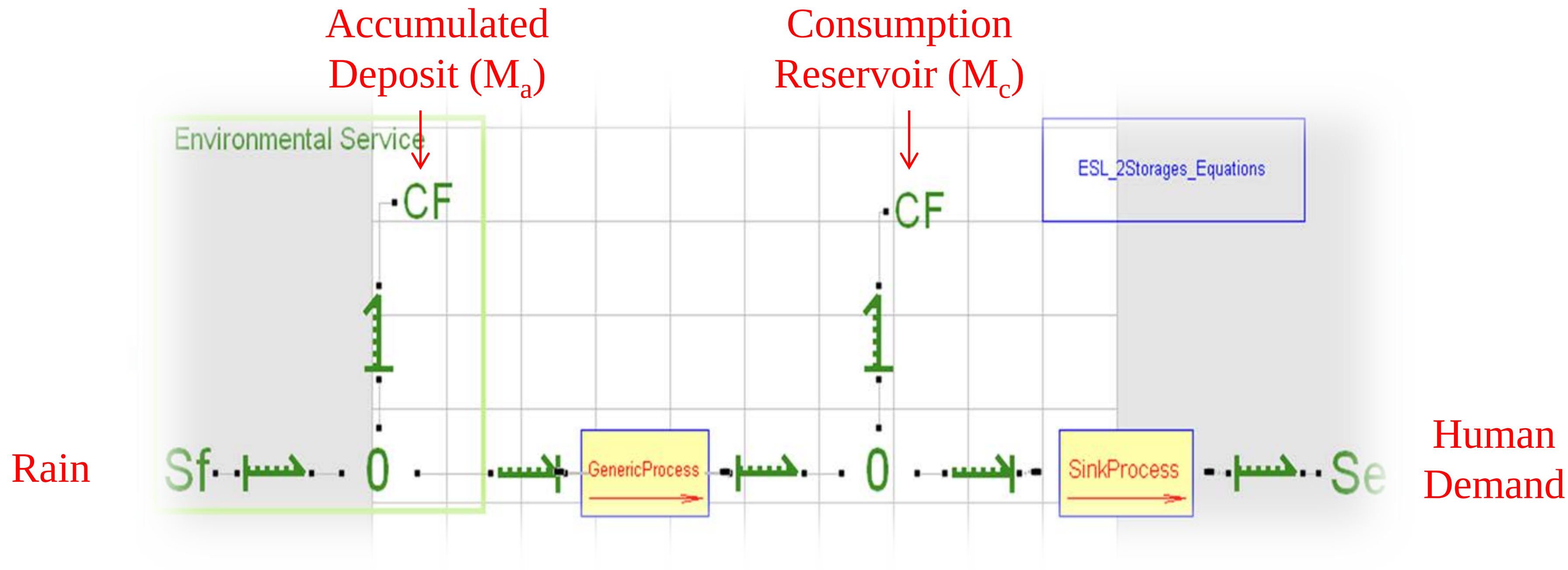
$\dot{M}_d = 0.05\dfrac{Kg}{s}$

$K_{irr}^{d} = 0$

$K_s = 0.001$

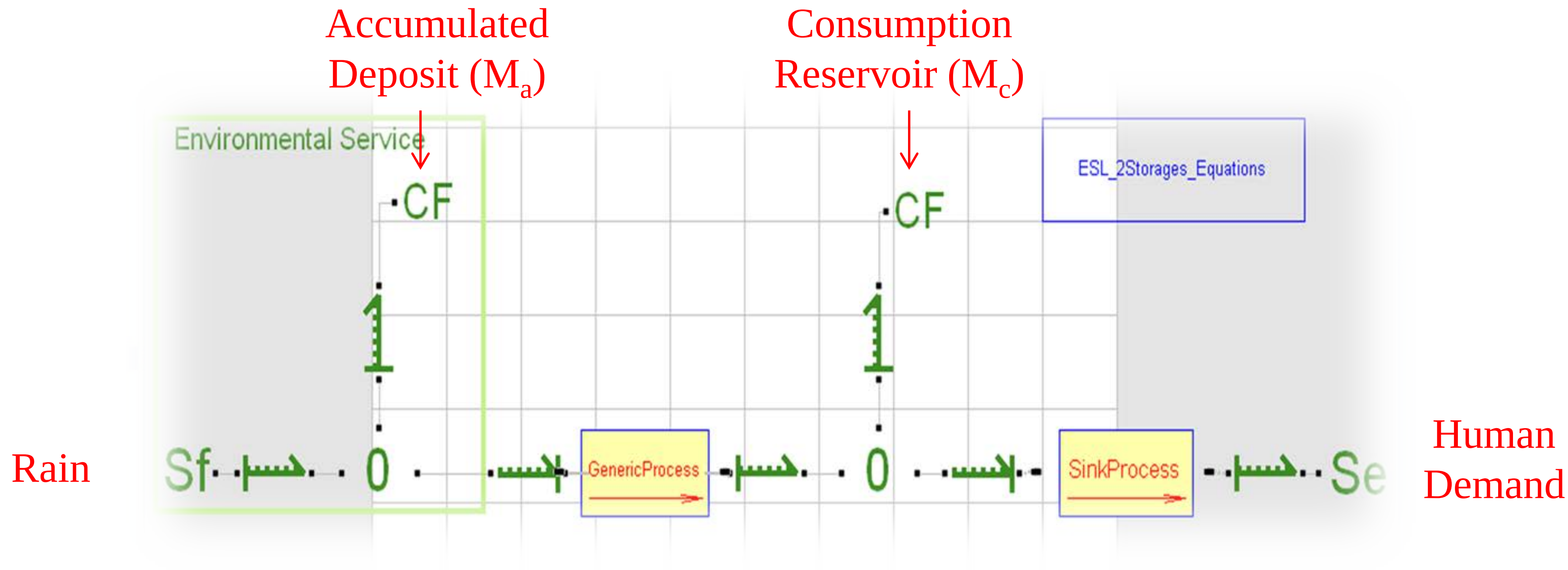
$K_s^{irr} = 0.1$

Energy and **Emergy** Layers



Energy and **Emergy** Layers

$$E\dot{M}_a = Tr_r.h_r.(\dot{M}_r) - Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = Tr_a.h_c.(K_s.M_a.M_c) - Tr_c.h_c.(\dot{M}_d)$$



Energy and **Emergy** Layers

$$E\dot{M}_a = Tr_r.h_r.(\dot{M}_r) - Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = Tr_a.h_c.(K_s.M_a.M_c) - Tr_c.h_c.(\dot{M}_d)$$

Accumulated Deposit (M_a)

Consumption Reservoir (M_c)

Rain

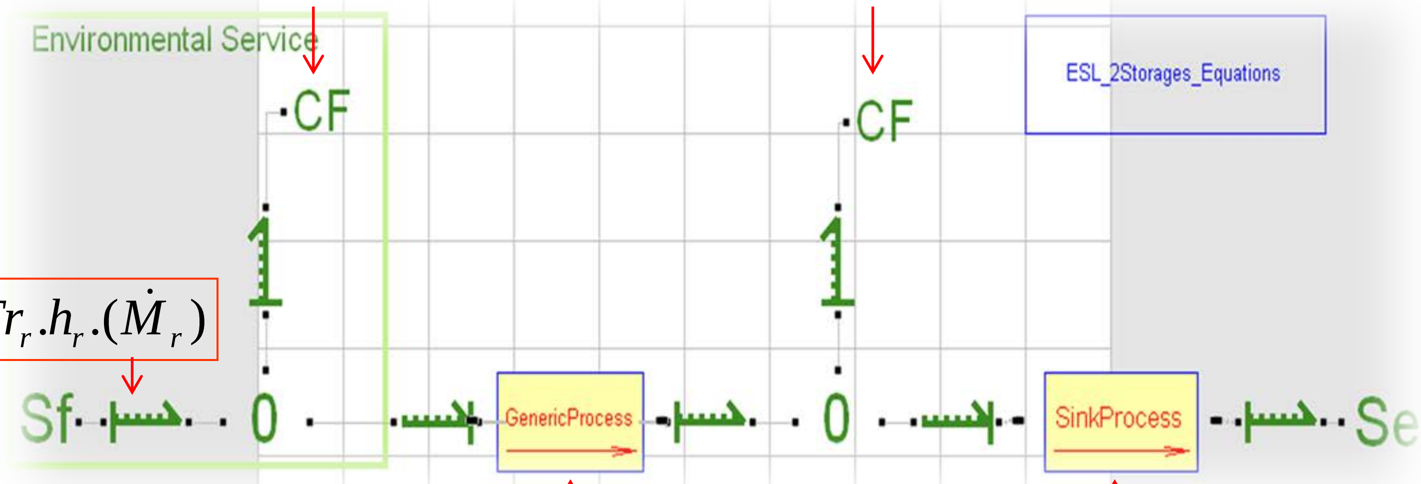
Human Demand

Energy and Emergy Layers

$$E\dot{M}_a = Tr_r.h_r.(\dot{M}_r) - Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = Tr_a.h_c.(K_s.M_a.M_c) - Tr_c.h_c.(\dot{M}_d)$$

Accumulated Deposit (M_a)

Consumption Reservoir (M_c)



$$E\dot{M}_a = +Tr_r.h_r.(\dot{M}_r)$$

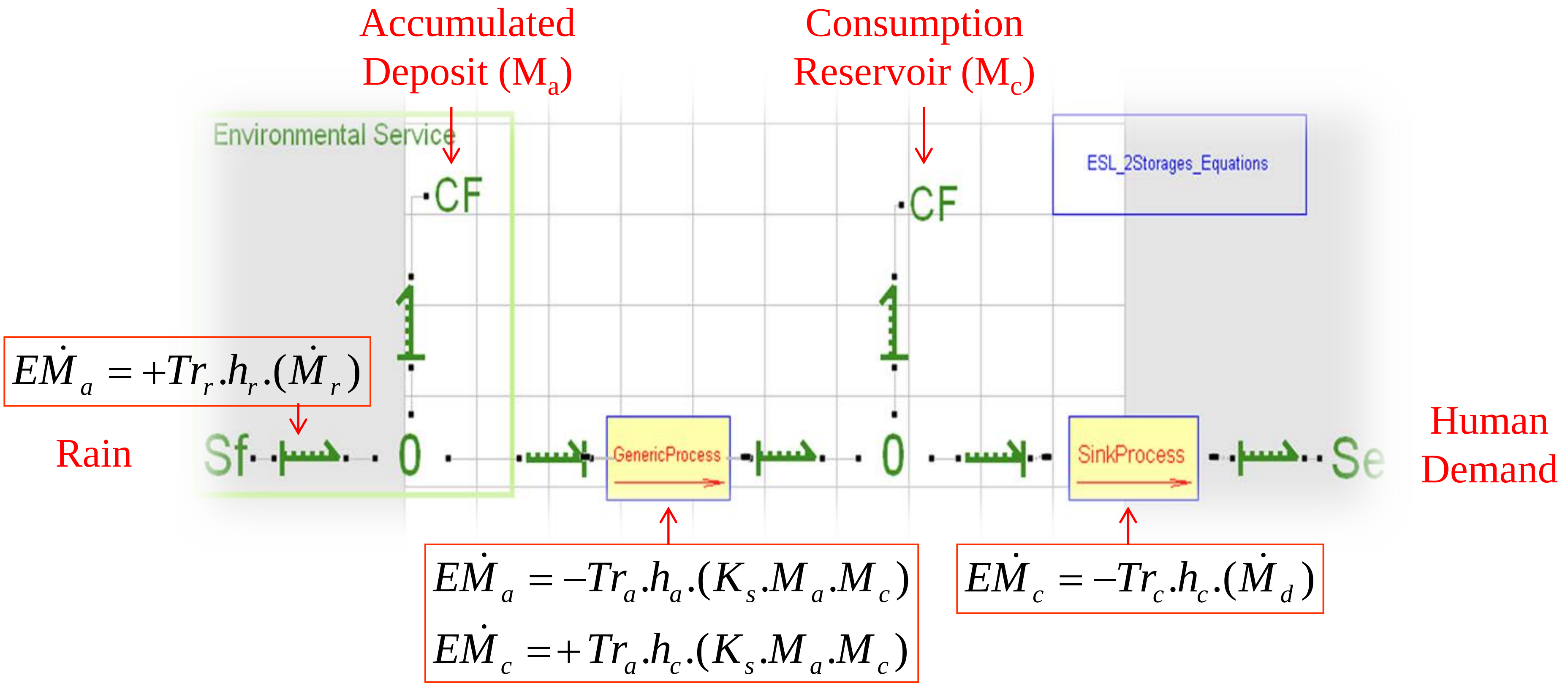
Rain

Human Demand

$$E\dot{M}_a = -Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = +Tr_a.h_c.(K_s.M_a.M_c)$$

$$E\dot{M}_c = -Tr_c.h_c.(\dot{M}_d)$$

$$E\dot{M}_a = Tr_r.h_r.(\dot{M}_r) - Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = Tr_a.h_c.(K_s.M_a.M_c) - Tr_c.h_c.(\dot{M}_d)$$



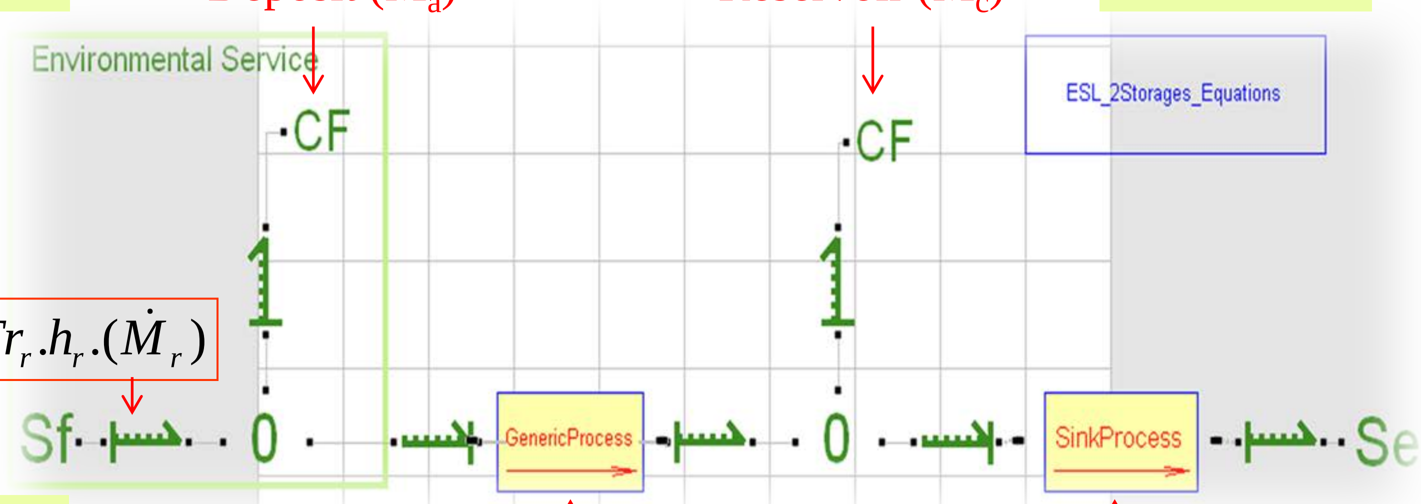
$$E\dot{M}_a = Tr_r.h_r.(\dot{M}_r) - Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = Tr_a.h_c.(K_s.M_a.M_c) - Tr_c.h_c.(\dot{M}_d)$$

$$h_a = 1\frac{J}{kg}$$

Accumulated Deposit (M_a)

Consumption Reservoir (M_c)

$$h_c = 1\frac{J}{kg}$$



$$E\dot{M}_a = +Tr_r.h_r.(\dot{M}_r)$$

Rain

Human Demand

$$h_r = 1\frac{J}{kg}$$

$$em_r = 1\frac{J}{kg}$$

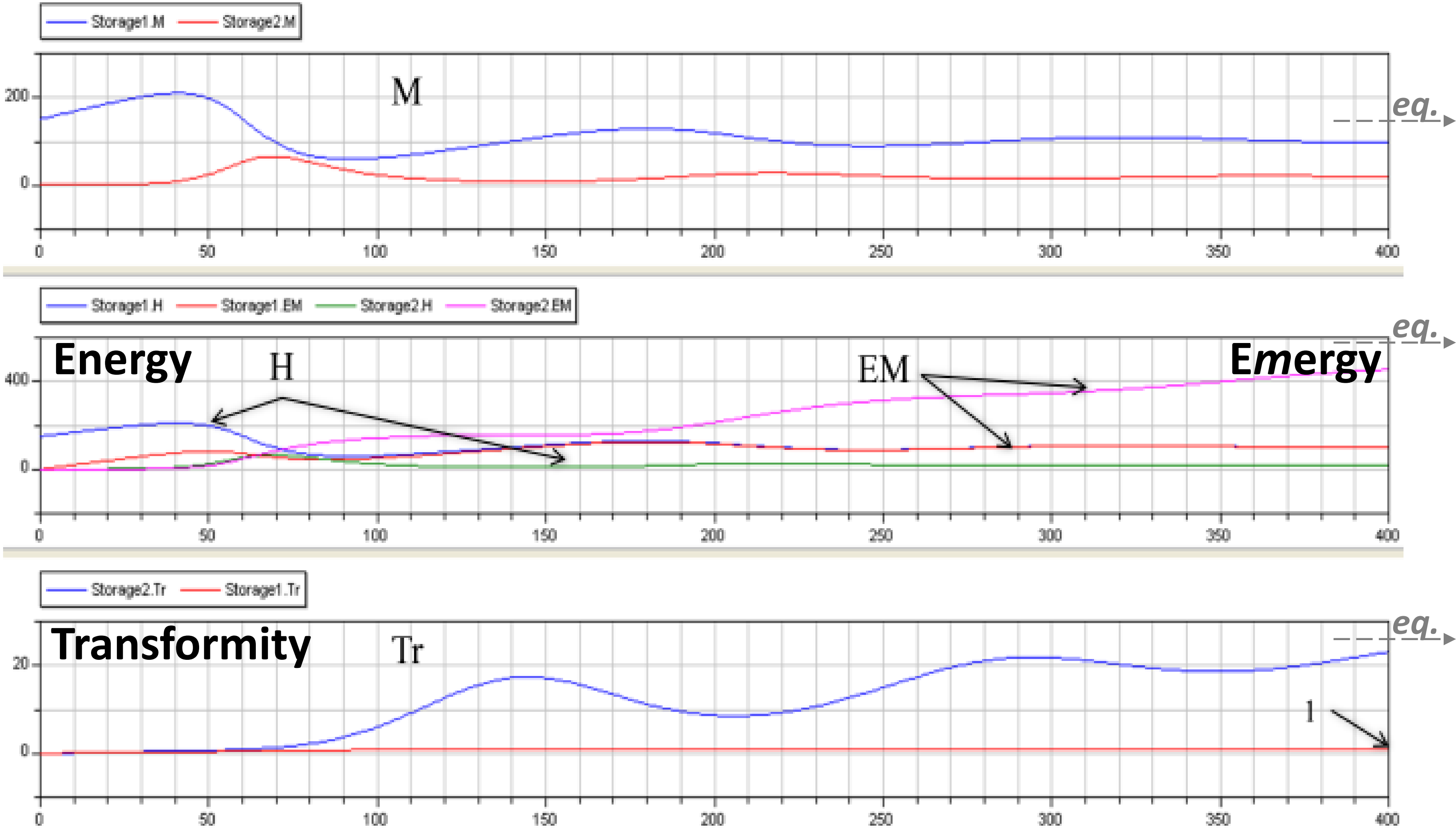
$$Tr_r = \frac{em_r}{h_r} = 1$$

$$E\dot{M}_a = -Tr_a.h_a.(K_s.M_a.M_c)$$
$$E\dot{M}_c = +Tr_a.h_c.(K_s.M_a.M_c)$$

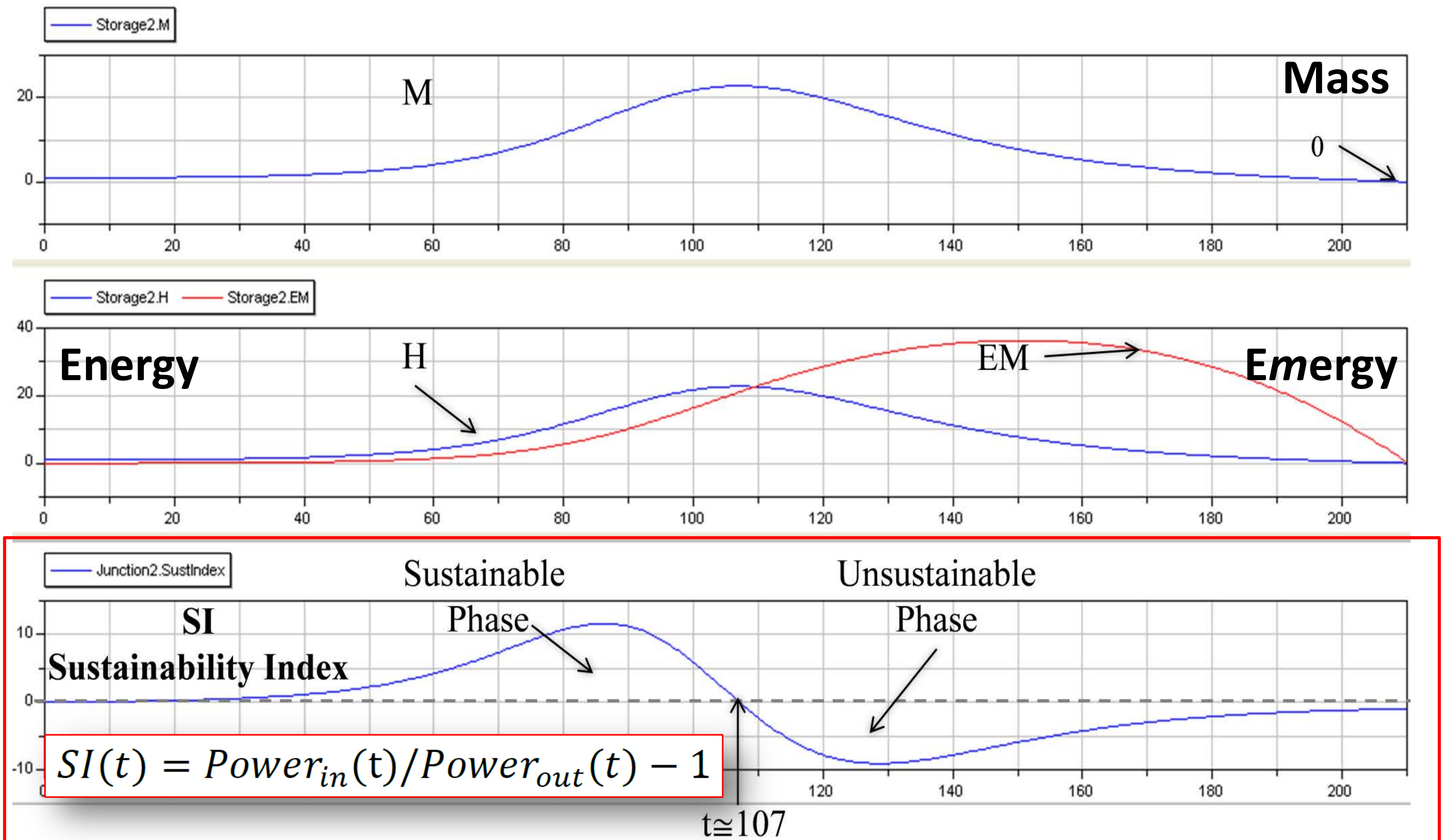
$$E\dot{M}_c = -Tr_c.h_c.(\dot{M}_d)$$

$$K_s = 0.001$$

- Accumulated quantities (Deposit and Reservoir)



- Experiment: Rain flow reduced 4x. Results for Reservoir.



$$SI(t) = Power_{in}(t)/Power_{out}(t) - 1$$

Conclusions

- Eco Bond Graphs
  - A new "Plumbing Technology" for modeling Complex Dynamics Systems
  - A low-level tool to equip other higher-level modeling formalisms
    - with the ability to track e*m*ergy flows
- Hierarchical interconnection of EcoBG subsystems
  - Automatic and systematic evaluation of sustainability:
    - global tracking of e*m*ergy and
    - local checking of energy balances
- M&S practice
  - The laws of thermodynamics are not an opinable subject
    - Every sustainability-oriented effort should -at some point- consider e*m*ergy
- We should become able to **inform** both:
    - decision makers (experts, politicians, corporations) and
    - people who express their wishes (democratic societies)
  - about which are the **feasible** physical boundaries
    - within which their -largely opinable- desires and/or plans can be **possibly implemented in a sustainable fashion**.

Thanks for your attention !

rodrigo.castro@usys.ethz.ch
rodrigo.castro@cifasis-conicet.gov.ar
rcastro@dc.uba.ar