Why Energy in Robotics?

Stefano Stramigioli

15:45-16:00

UNIVERSITY OF TWENTE. Chair Robotics And Mechatronics Lab, The Netherlands

ITMO UNIVERSITY (Co)head Bio-mechatronics and Energy-Efficient Robotics Lab, Russia

Happy Birthday Alessandro!!!

Let’s Start with some memories..

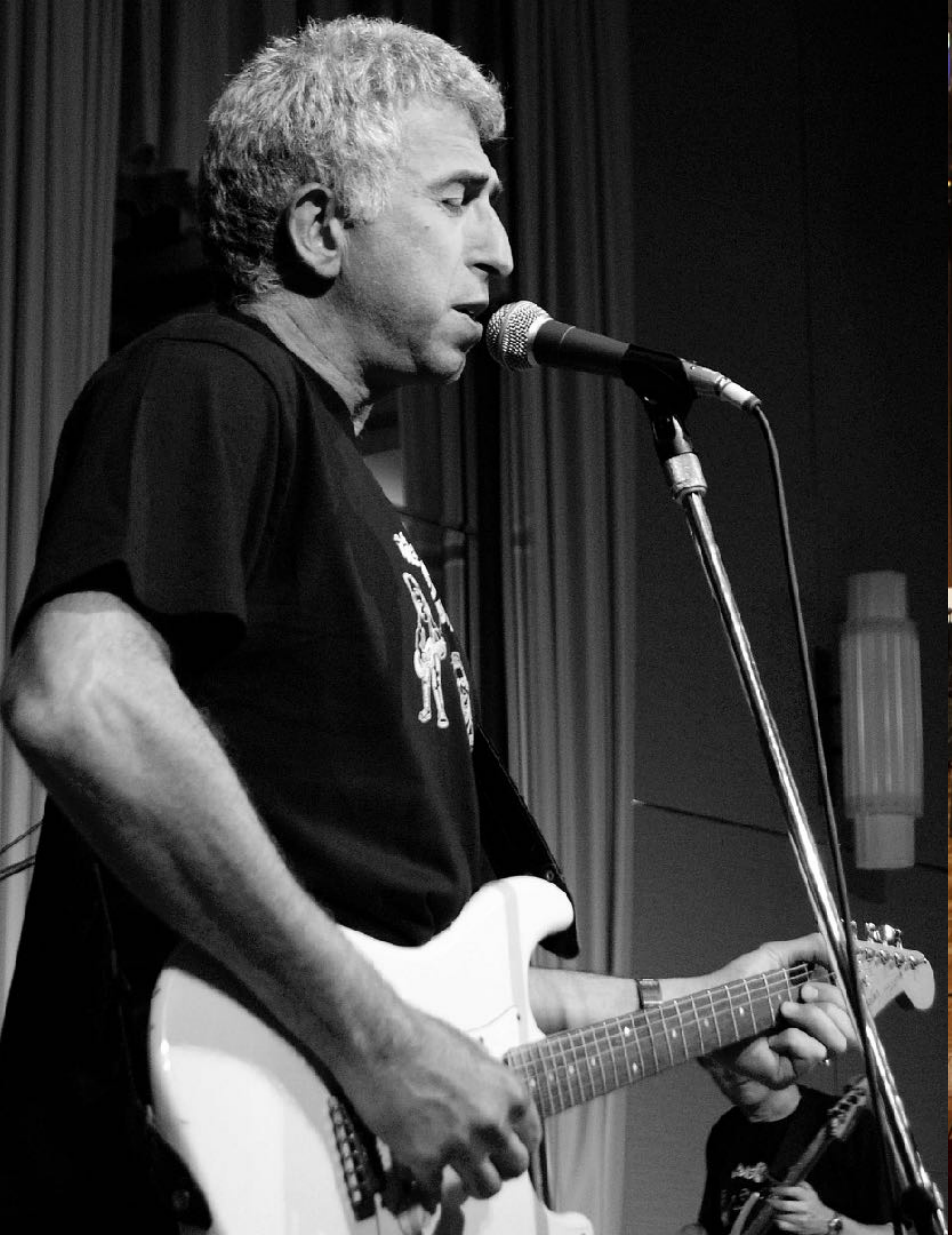
ICRA 2006, Orlando (18th of May)

ICRA 2006, Orlando (21st of May)

IROS 2006, Beijin, (13th of October)

ICRA 2007, Roma, (12th of April)

ICRA 2008, Pasadena, (22nd of May)



ICRA 2009, Kobe, (20th of May)

IROS 2009, St. Louis, (11th of October)

ICRA 2011, Shanghai, (11th of May)

IROS 2011, San Francisco, (29th of September)

ICRA 2012, St. Paul, (18th of May)

IROS 2012, Vilamoura, (8th of October)


I am so young! Only 55 years old!!
IROS 2012, Vilamoura, (11th of October)


ICRA 2013, Karlsruhe, (10th of May)

IROS 2014, Chicago, (20th of September)

ICRA 2015, Seattle, (27th of May)

(The Music Lovers)

Content

- About Paradigm Shifts
- Why EXPLICITLY using energy methods in robotics
- Example of a “difficult problem” made simple
- Conclusions & Future Work

Casimir Function for Control

S. Stramigioli, B. Maschke, and A. J. van der Schaft, “Passive output feedback and port interconnection,” in In Proceedings of 4th IFAC NOLCOS, 1998, pp. 613–618.

The Energy Router (DSER)

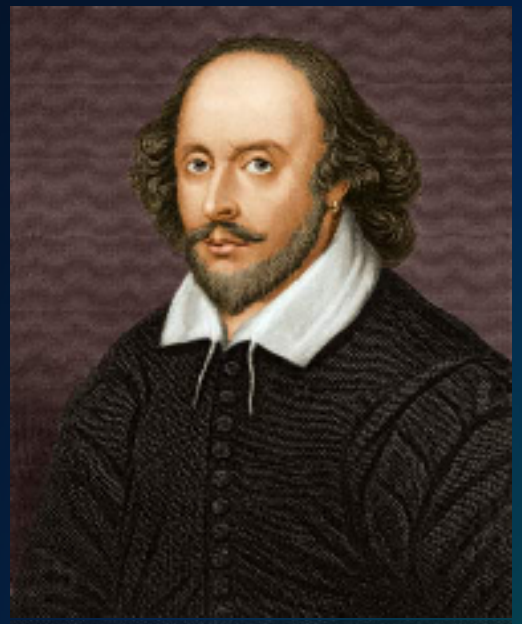
V. Duindam and S. Stramigioli, “Port-based asymptotic curve tracking for mechanical systems,” Eur. J. Control, vol. 10, no. 5, pp. 411–420, Dec. 2004.

- The DSER has been used to buffer, control in an energy continuous way:
  - Energy tanks,
  - Energy continuous tracking of n.l. systems,
  - Novel Actuators design,
  - Power continuous v.d. Pol oscillator etc.
  - Power Continuous change of parameters
  - Synchronisation of Limit Cycles
  - Passivation of Projection-Based Null Space Compliance Control
  - …

Energy (and Geometrical) Aware Robotics

Robots and Interaction follow the laws of physics!

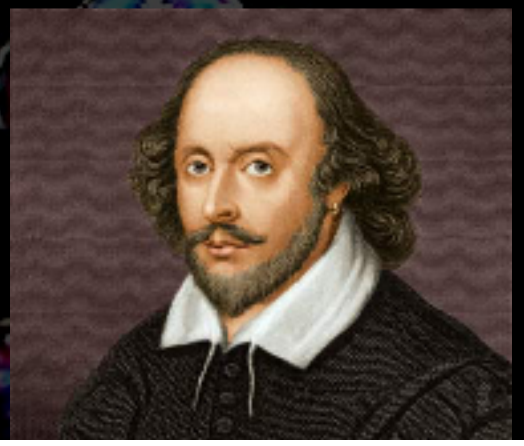
Energy or **no Energy**, that is the question

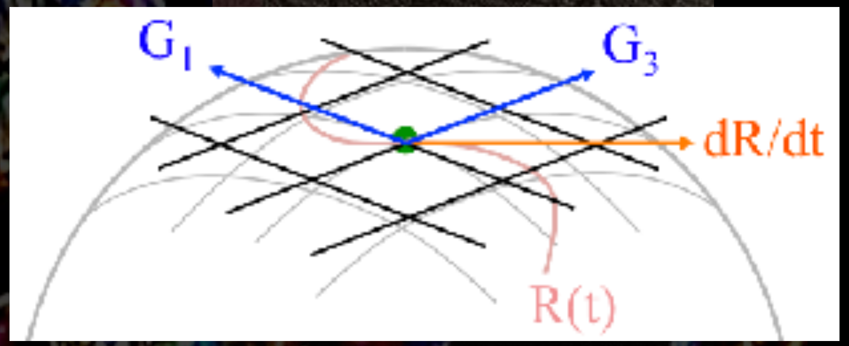


- **No relation with energy**
  - No way to work in all situations during interaction
  - No robustness
  - Environment cannot be “properly modeled”!
  - Unespected behaviour
  - …

- **Passivity or better: Energy Awareness**
  - Track and Control Energy flows
  - Never problems with stability
  - Robust
  - Can Couple Digital-Continuos World
  - Handle Time delays
  - ….

Geometry or **no Geometry**, that is the question



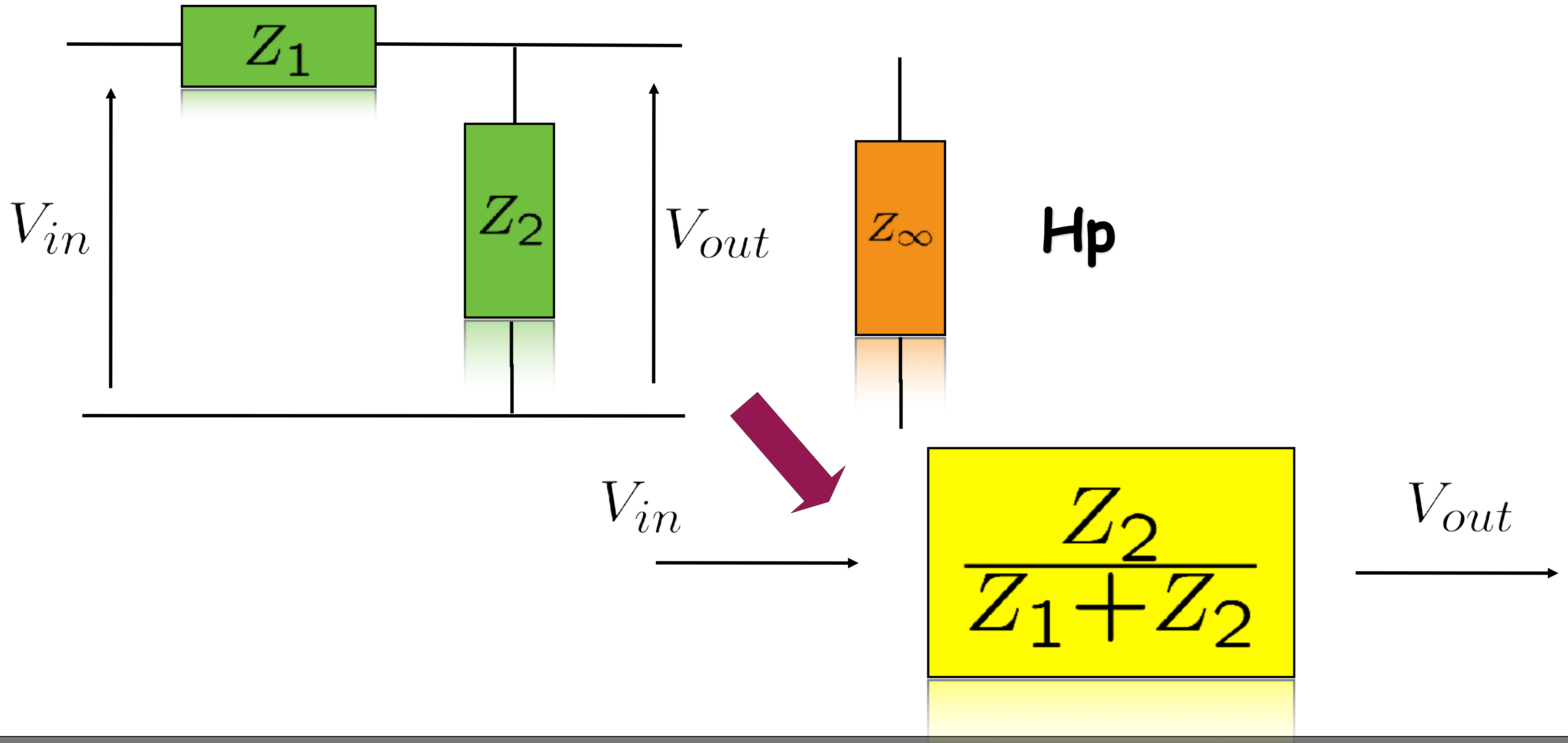


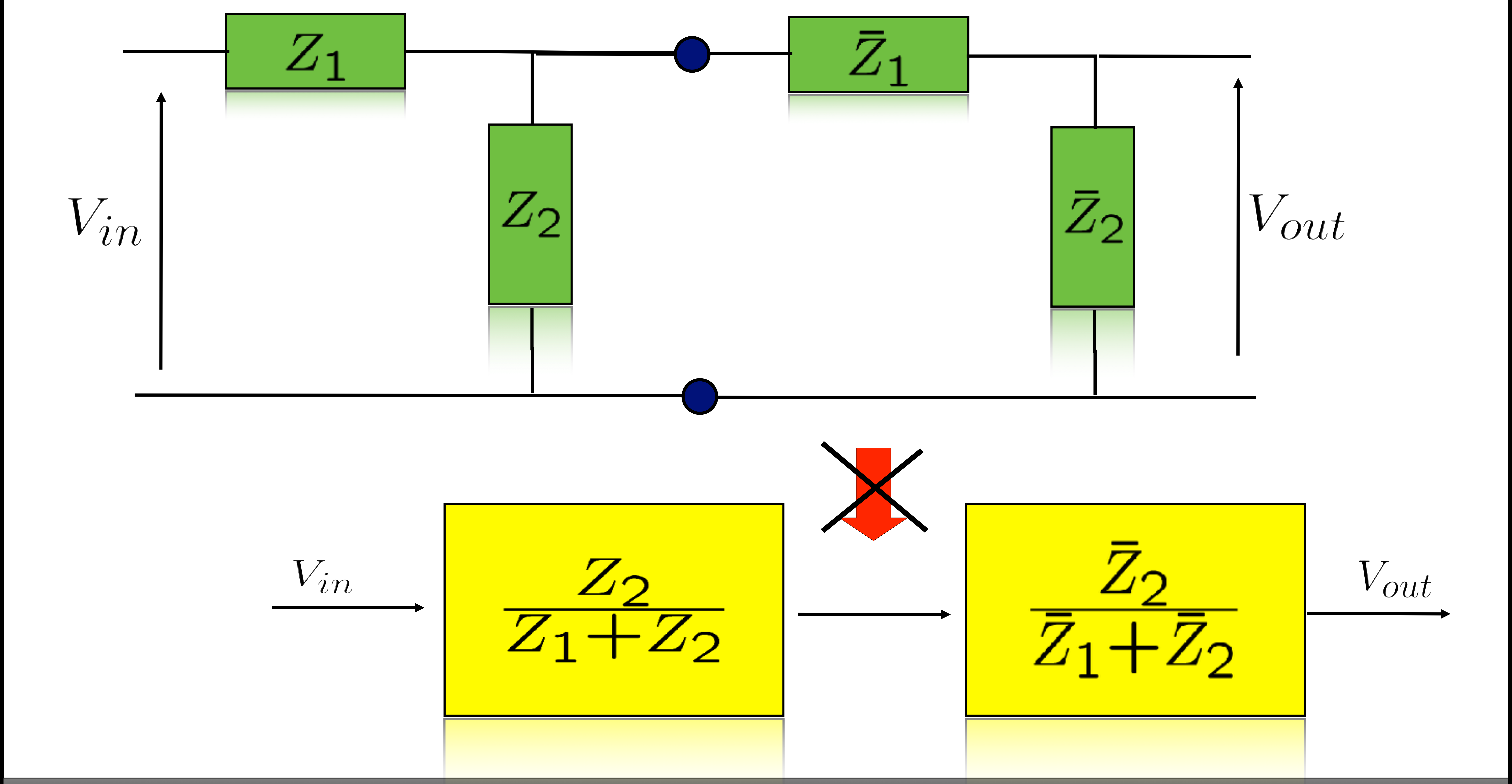
- **No Geometry**
  - Complicated equations
  - Solutions dependent on coordinates
  - Non physical nonsense: eigenvalues of Inertias, random ortogonality, projections, non invariant indeces,…
  - Singularity
  - Unexpected instabilities
  - ..

- **Geometry**
  - Simple description
  - Coordinate Invariant
  - Physical
  - No singularity
  - Directly see if something is wrong: inverses, projections, error measurement
  - ….

Modelling

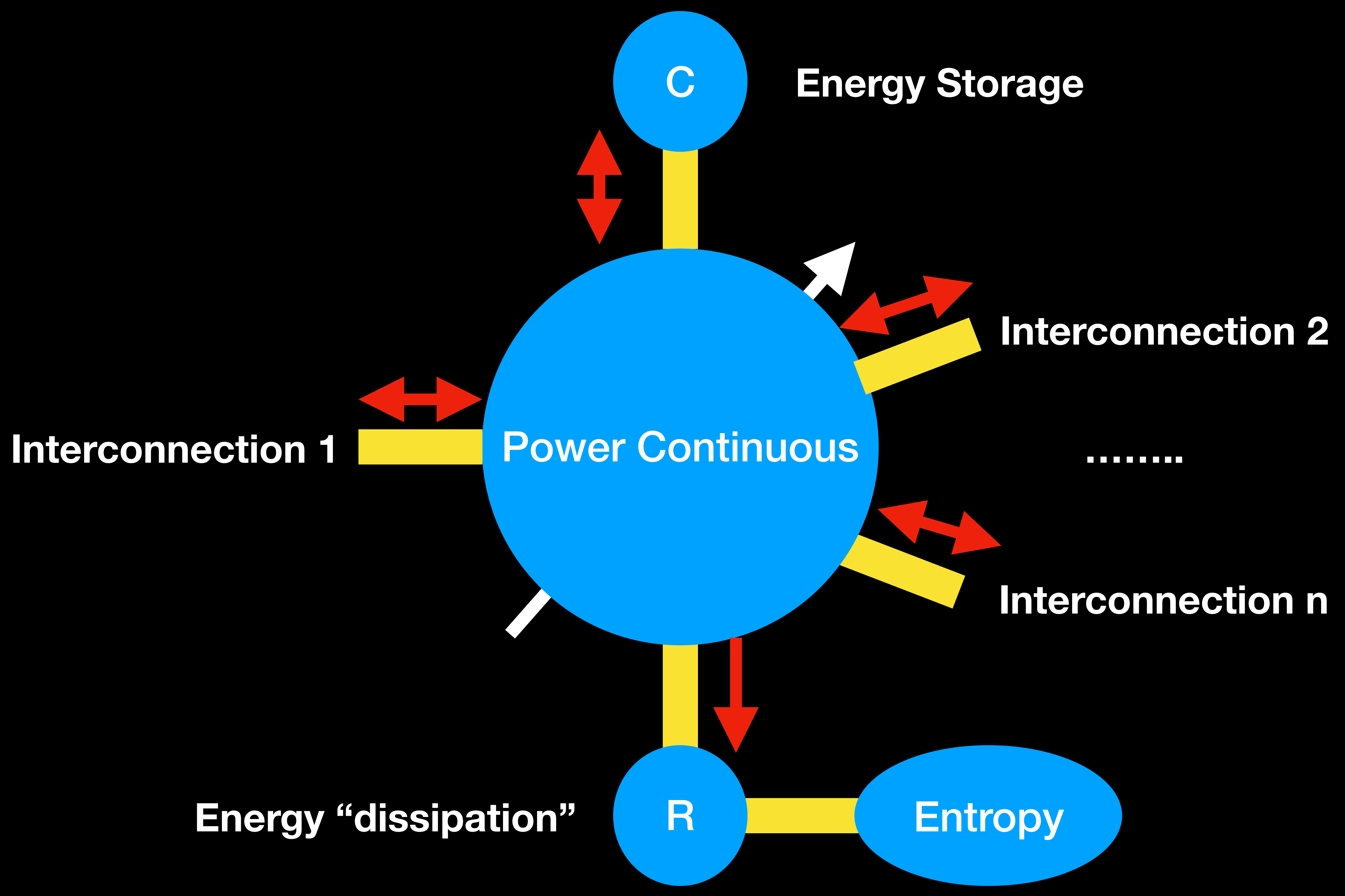
Port Based Thinking
What is it and why is this useful?

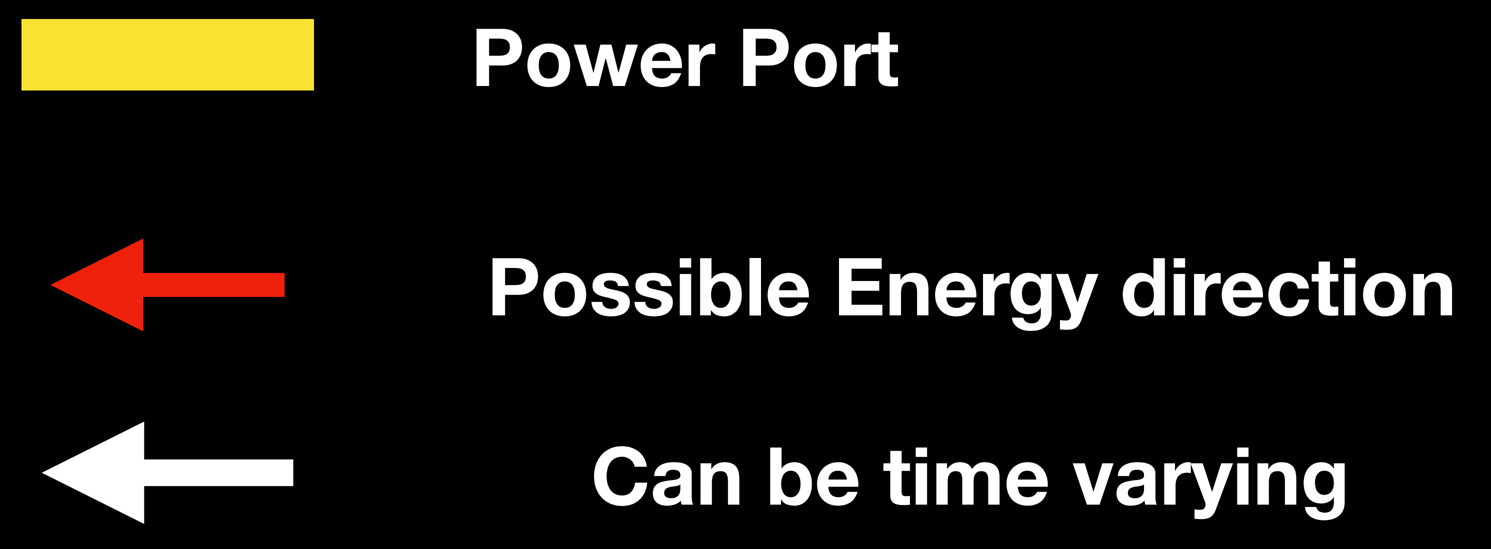

Z_1
Z_2
V_{in}
V_{out}
Z_∞
Hp
V_{in}
$\frac{Z_2}{Z_1+Z_2}$
V_{out}

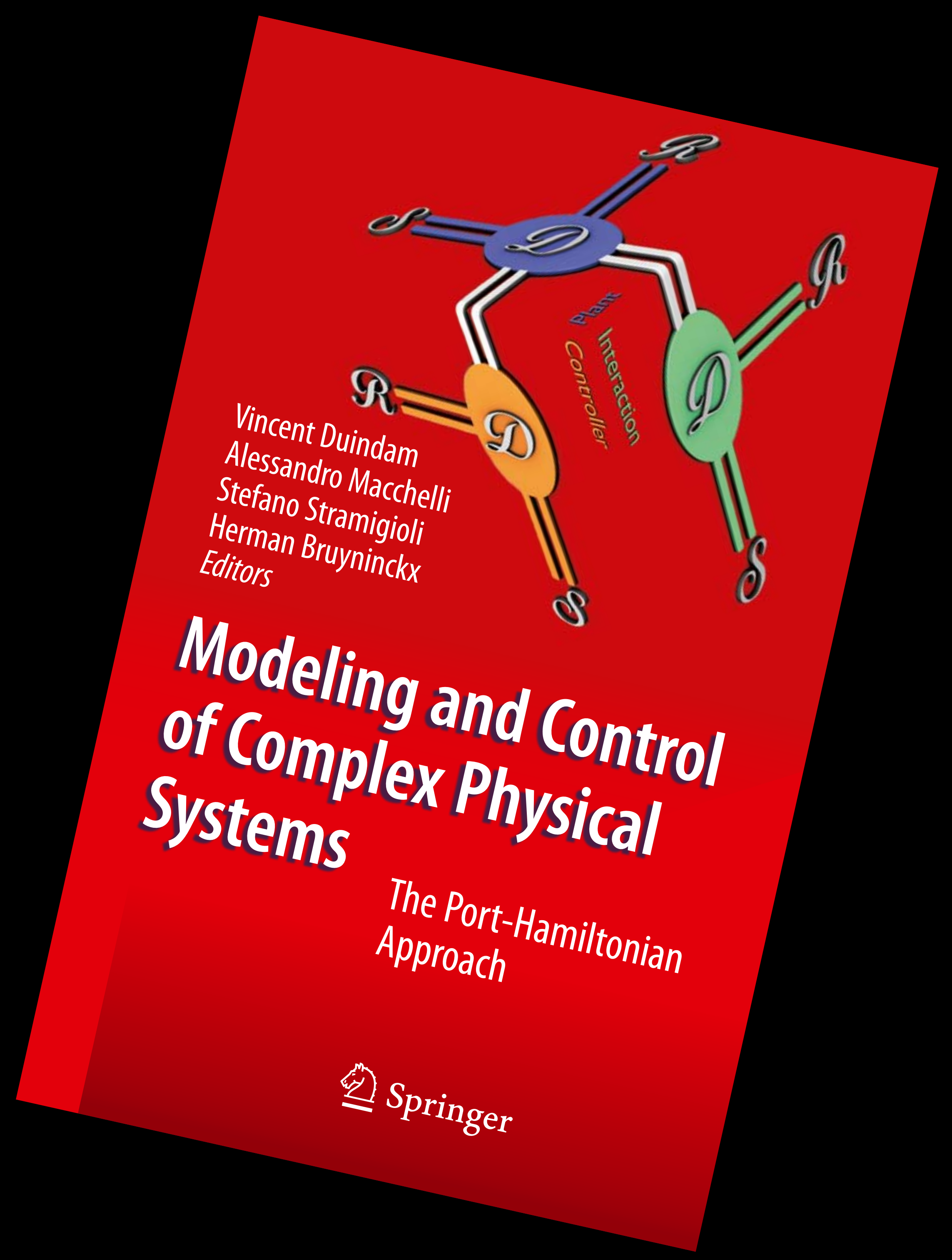


Z_1
$\bar{Z}_1$
Z_2
$\bar{Z}_2$
V_{in}
V_{out}
V_{in}
$\frac{Z_2}{Z_1+Z_2}$
$\frac{\bar{Z}_2}{\bar{Z}_1+\bar{Z}_2}$
V_{out}

Any physical system has this structure



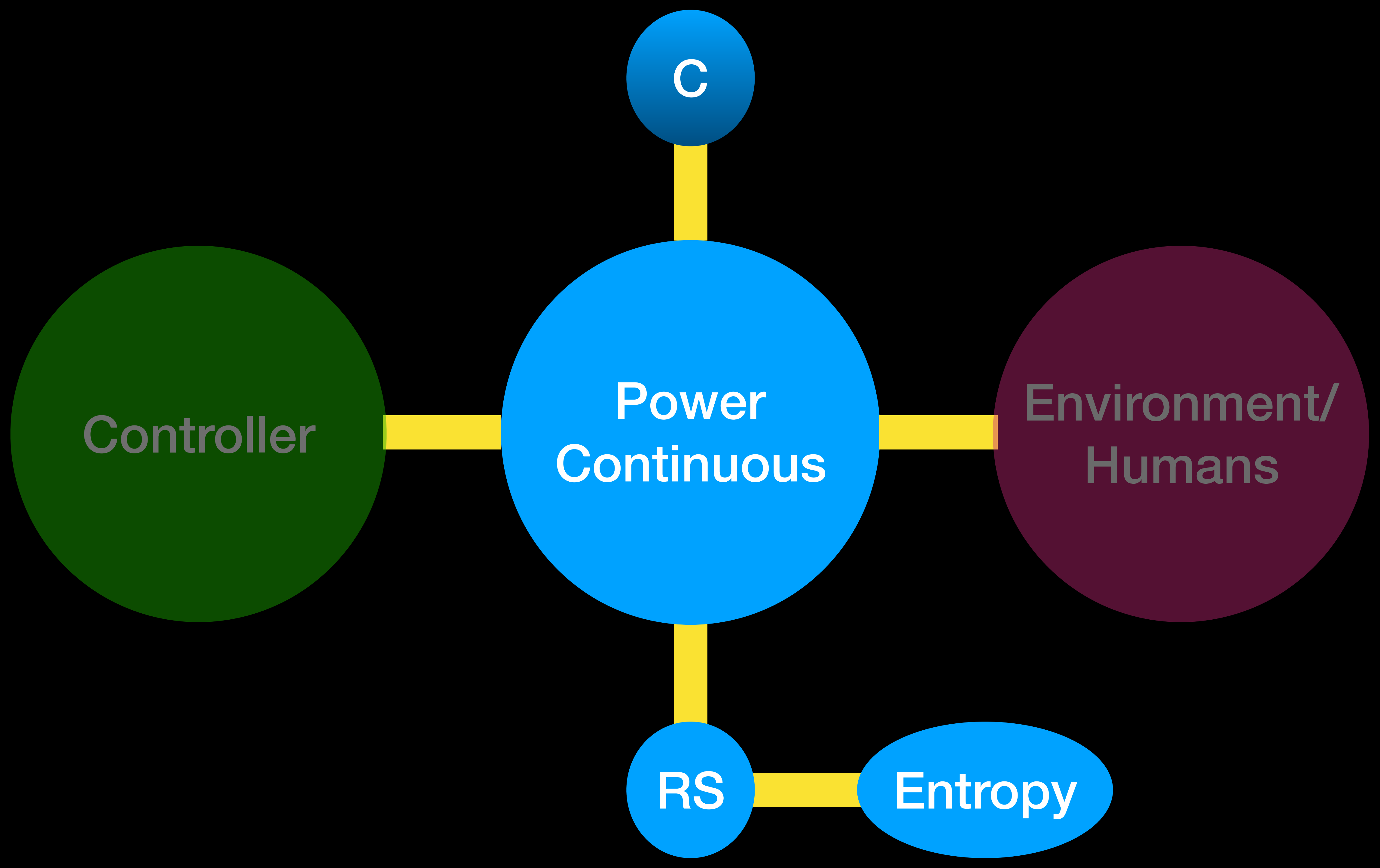




Conjecture

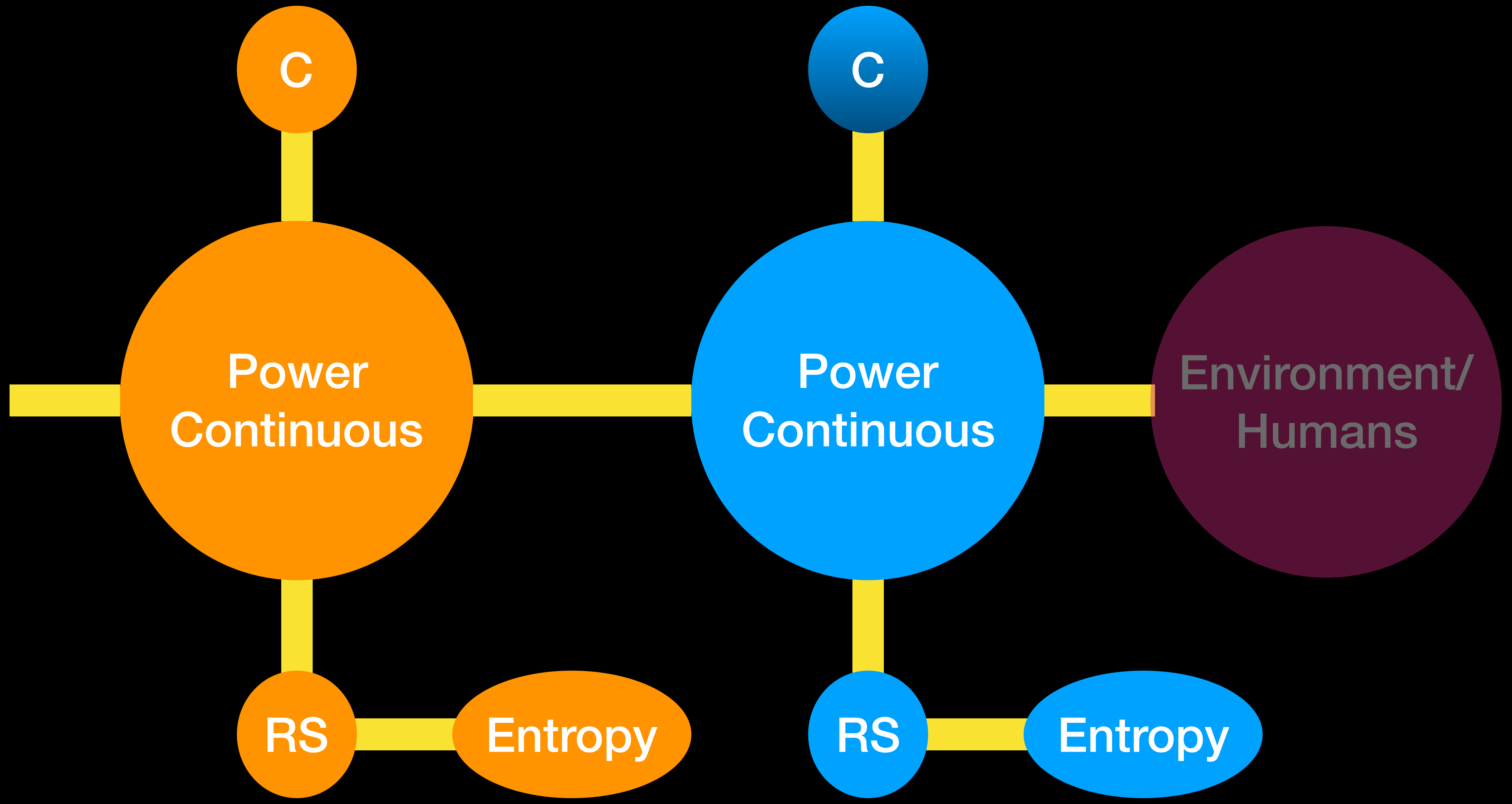
To ensure stability ***during any interaction*** *control needs to be implemented by Interconnection either physically or by control*

Control by Design or Control by Interconnection



Control by Design or Control by Interconnection

Modify the design:
- **Adding elements**
- **Change how they are connected**



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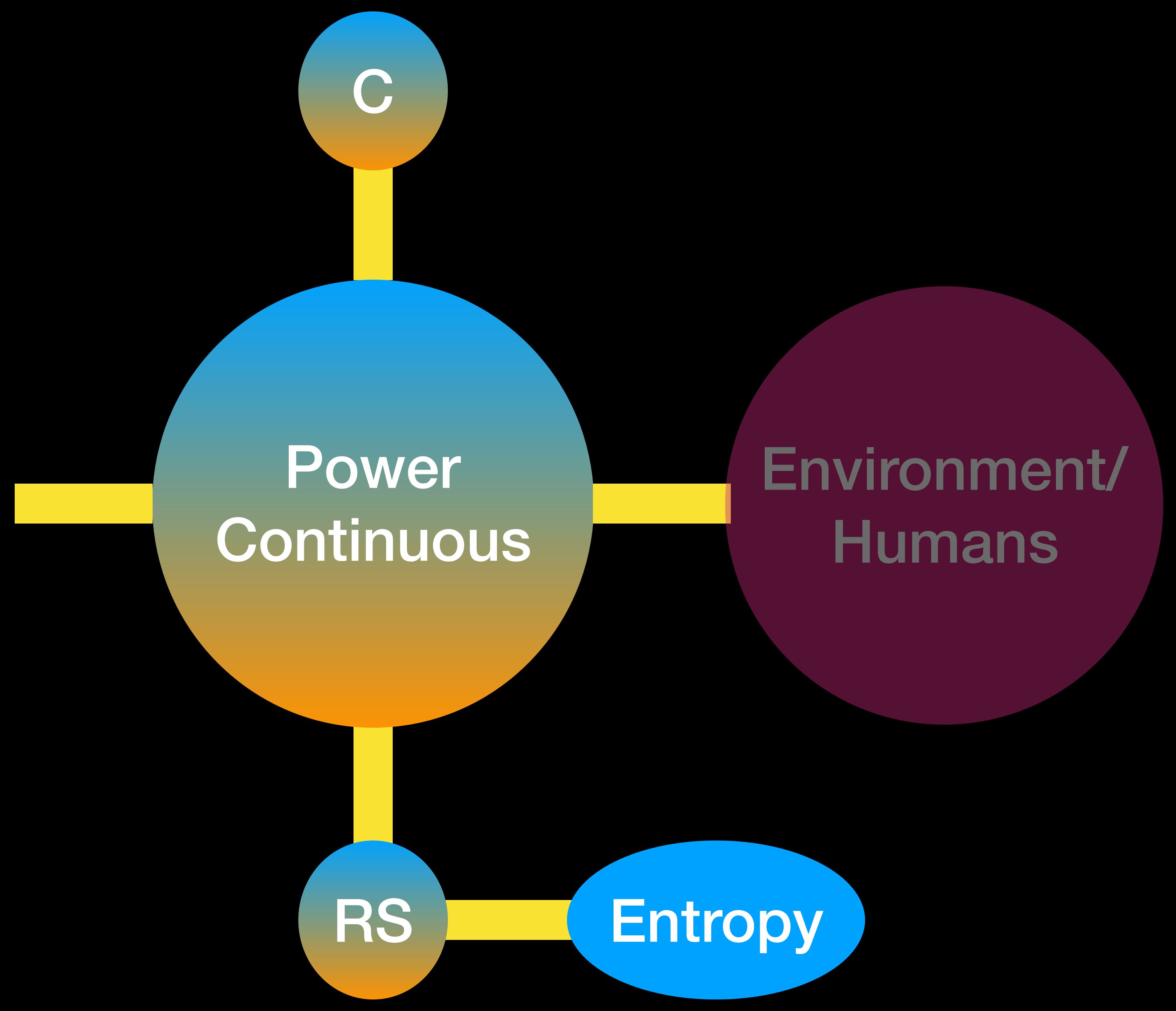
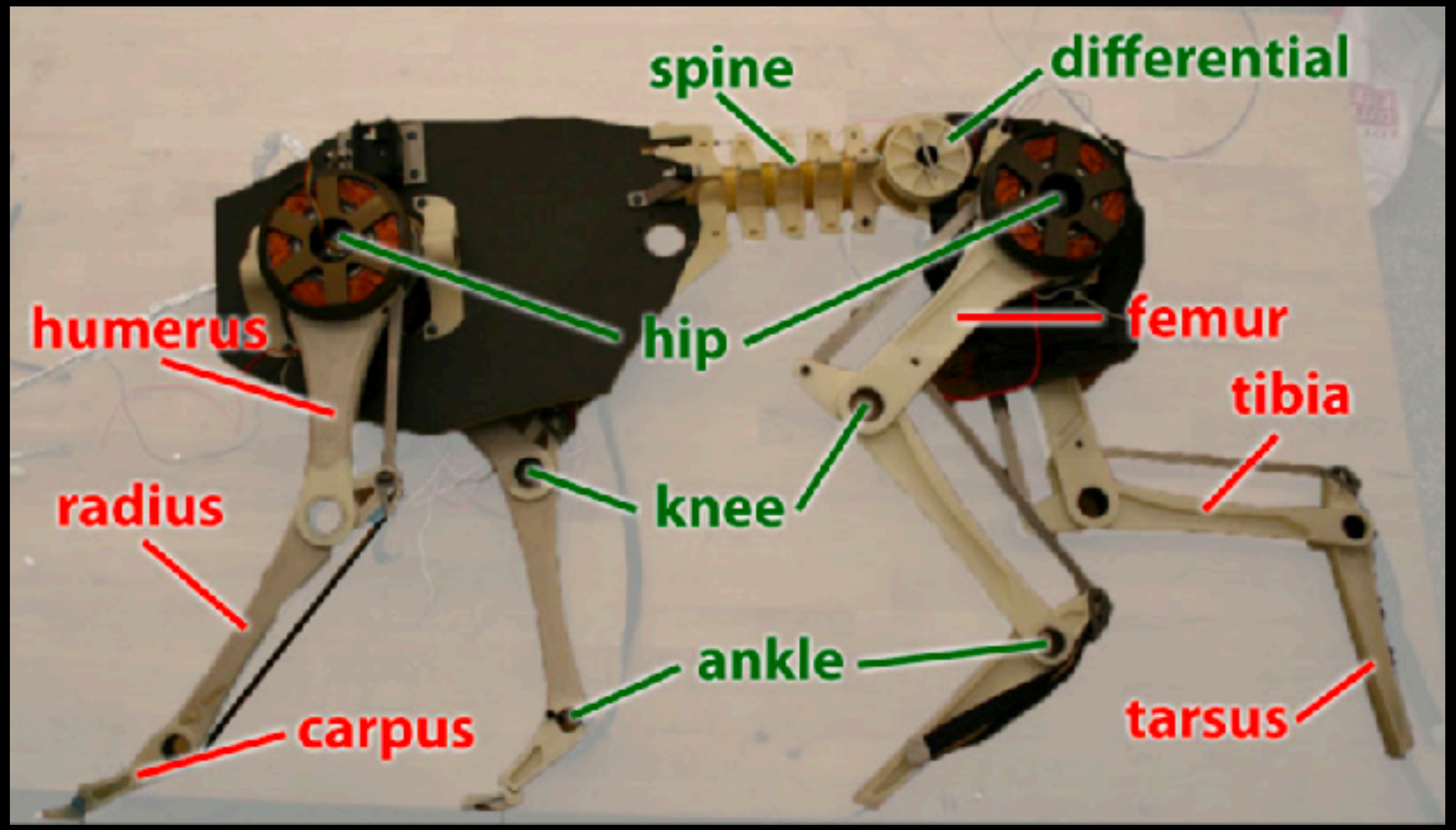


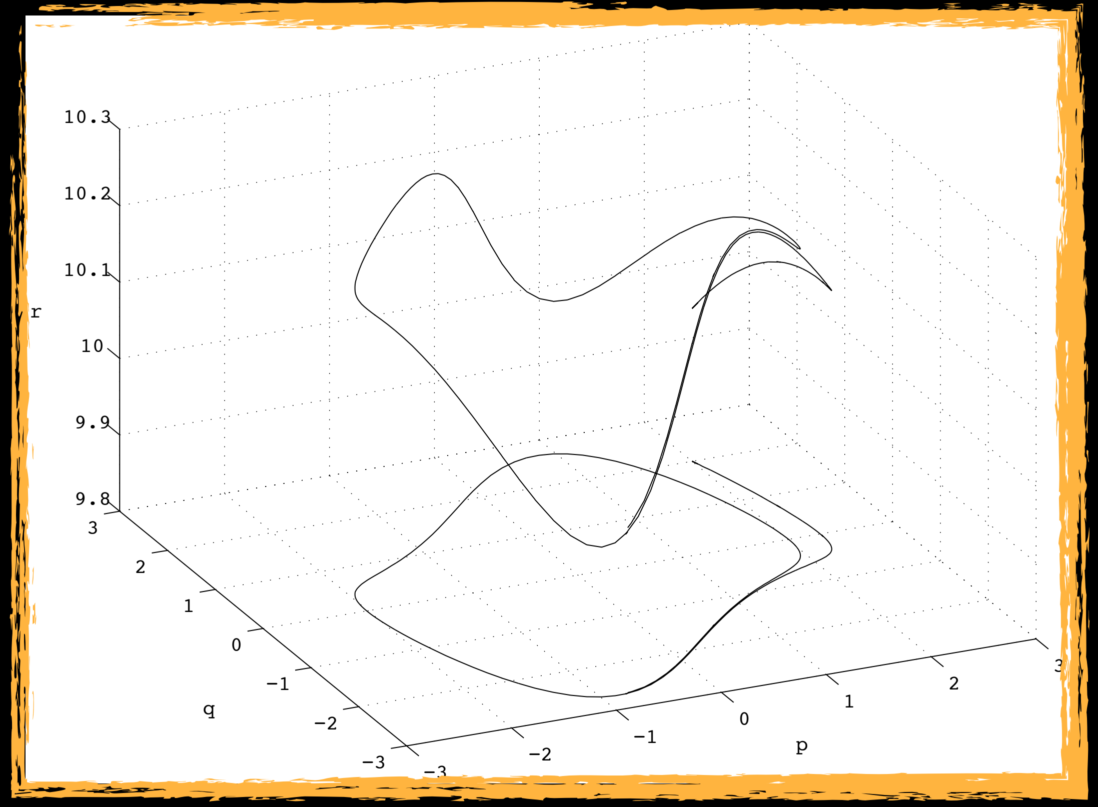
Examples

- Change “Resonance” by parallel springs

- Generate Forces needed elastically to avoid dissipation and irreversibility in drive chains



Folkertsma, G. A., Kim, S., & Stramigioli, S. (2012). Parallel stiffness in a bounding quadruped with flexible spine. In Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on (pp. 2210–2215).



Stramigioli, S., & van Dijk, M. (2008). Energy Conservative Limit Cycle Oscillations. In Proceedings of the 17th World Congress, The International Federation of Automatic Control (pp. 15666–15671). Seoul, Korea: IFAC. doi: 10.3182/20080706-5-KR-1001.2560

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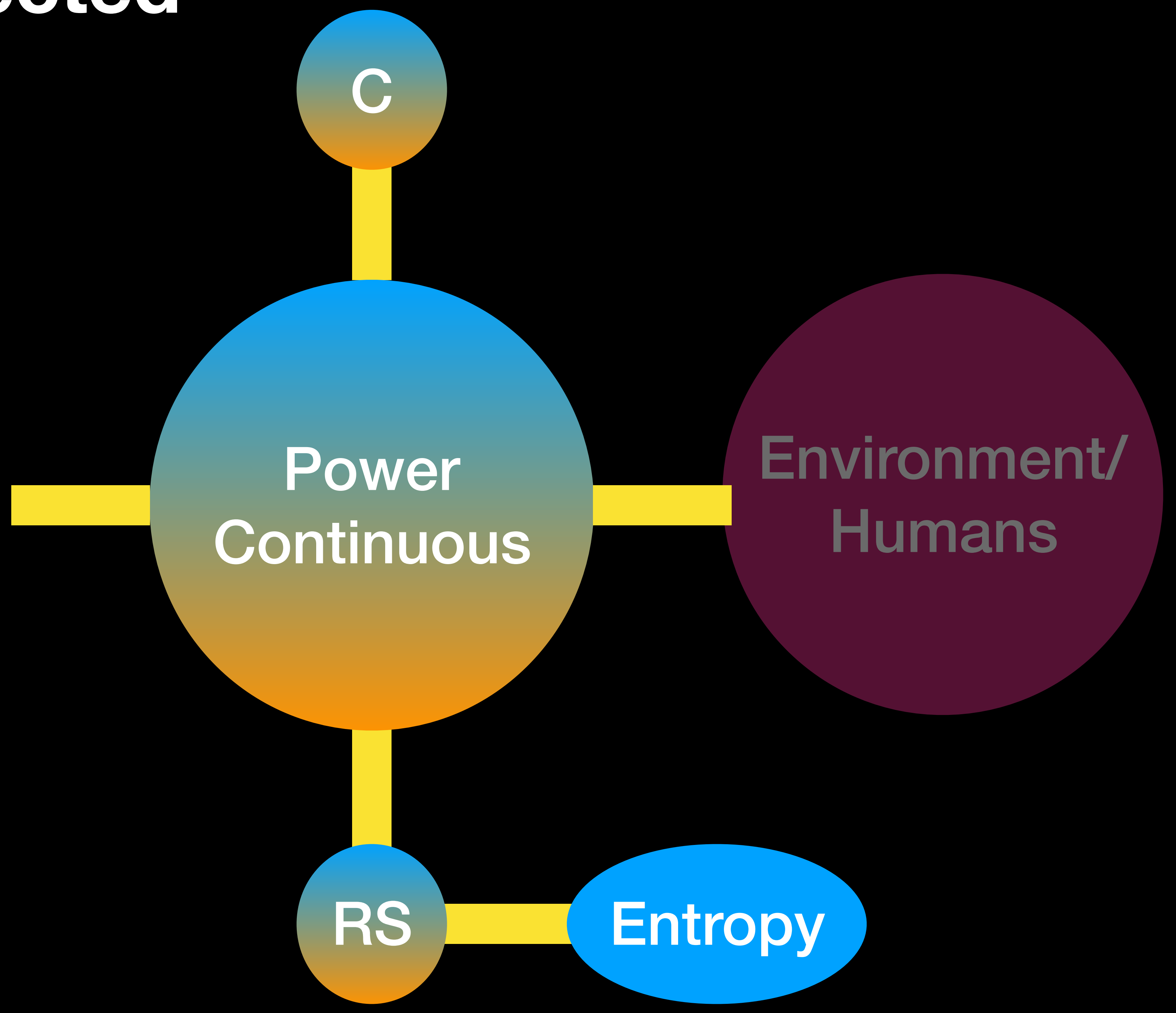

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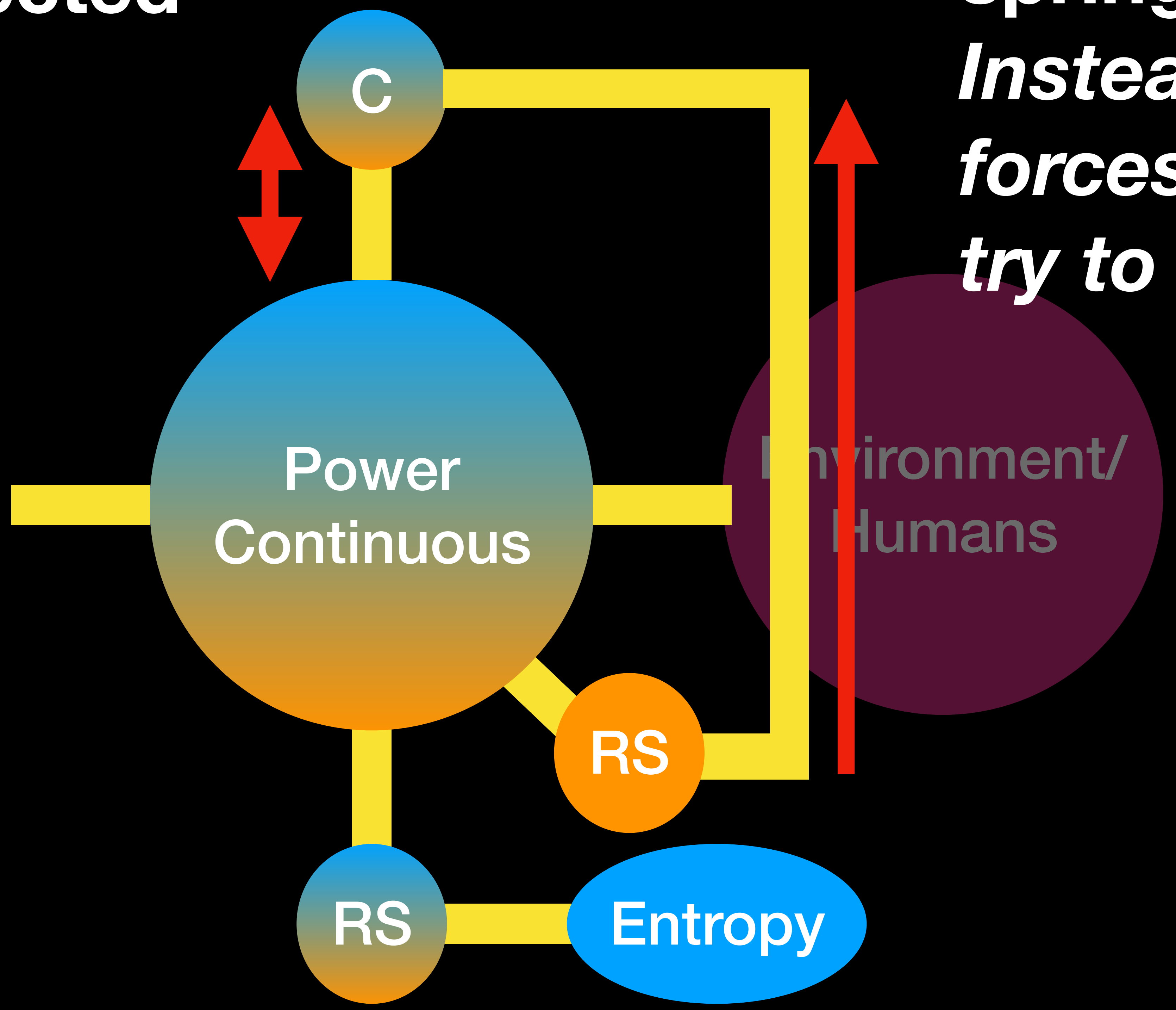

Implement "Dampers with springs”:

Instead of implementing damping forces with dissipating elements, try to do it with elastic elements

Control by Design or Control by Interconnection

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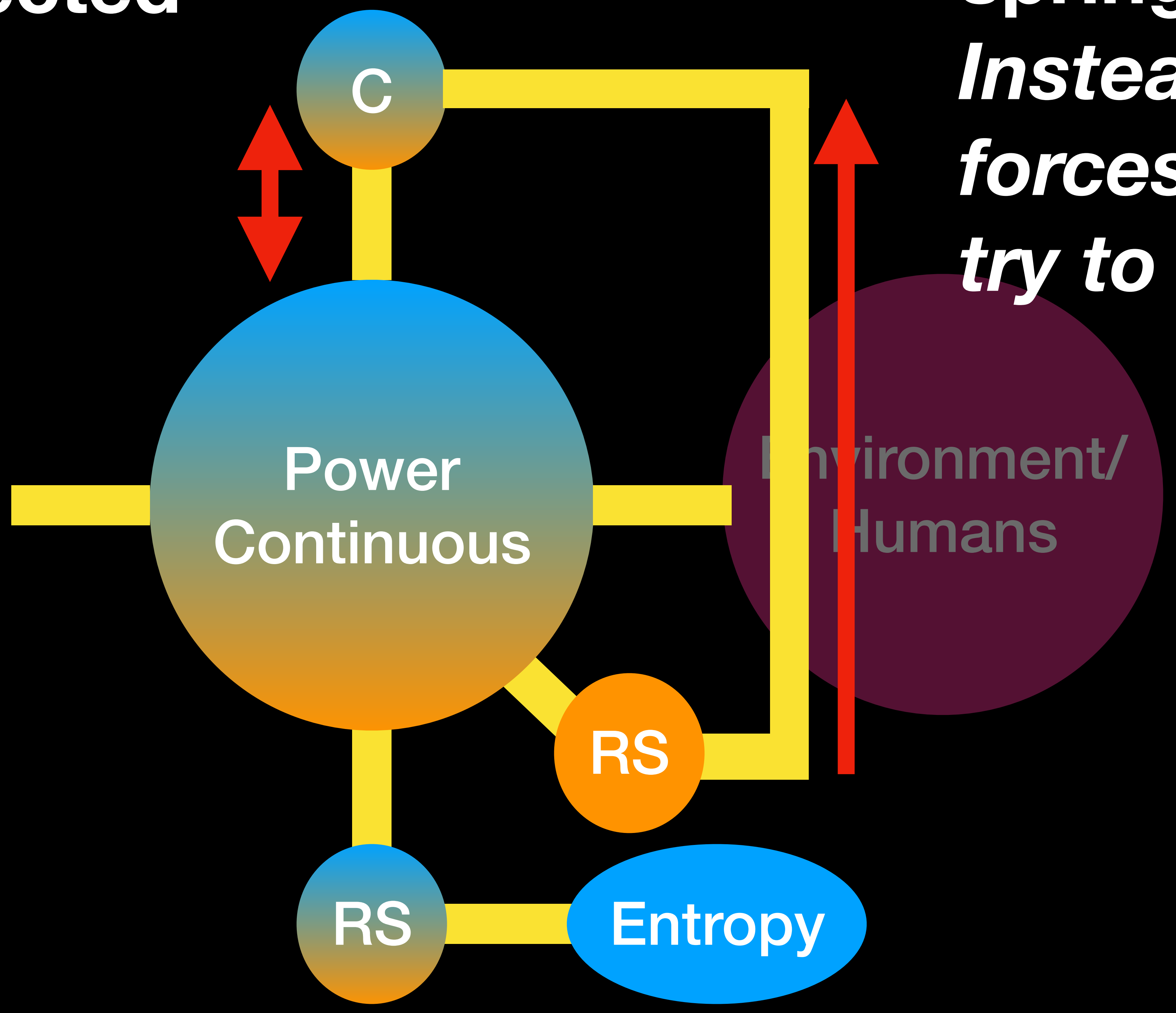

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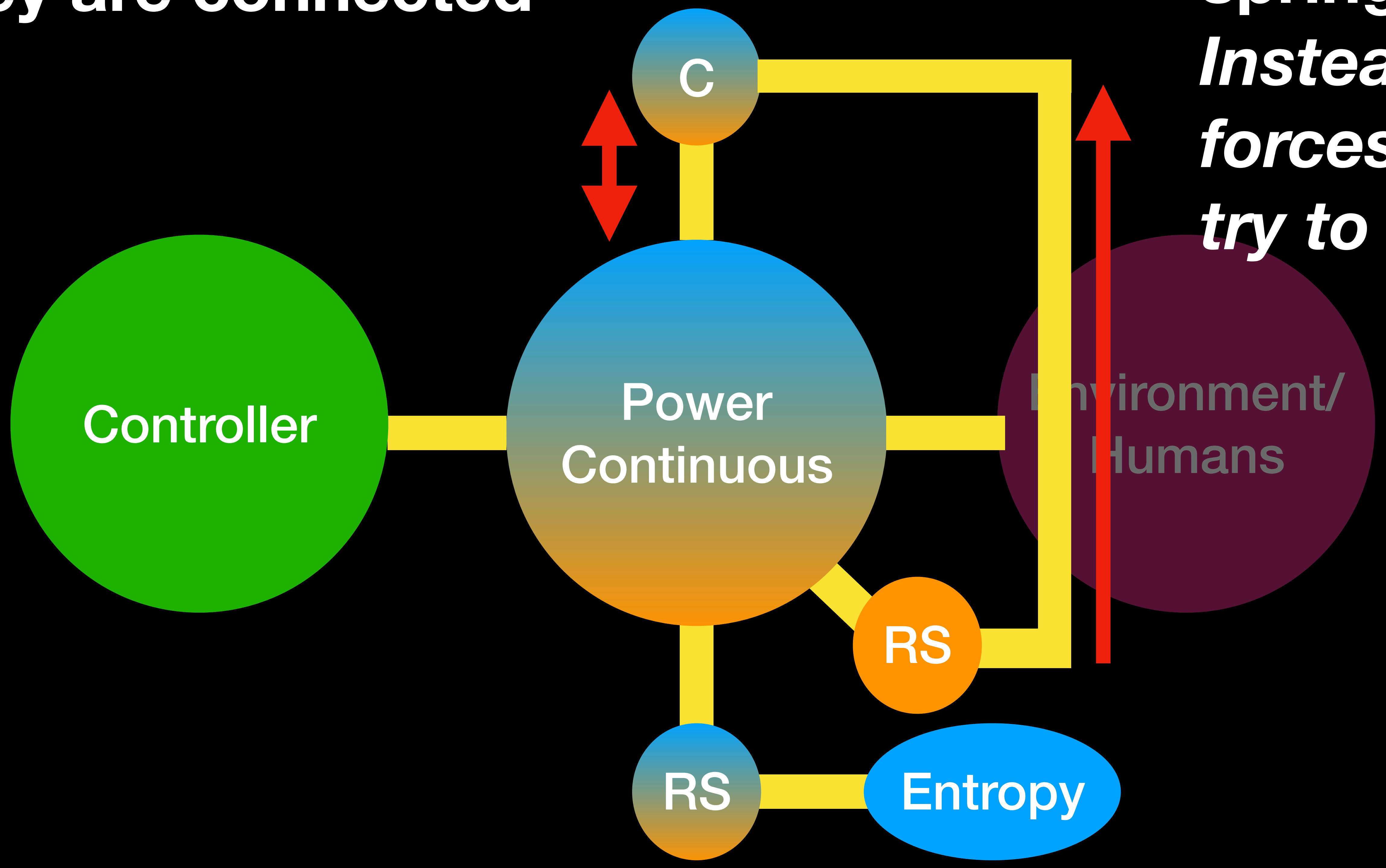
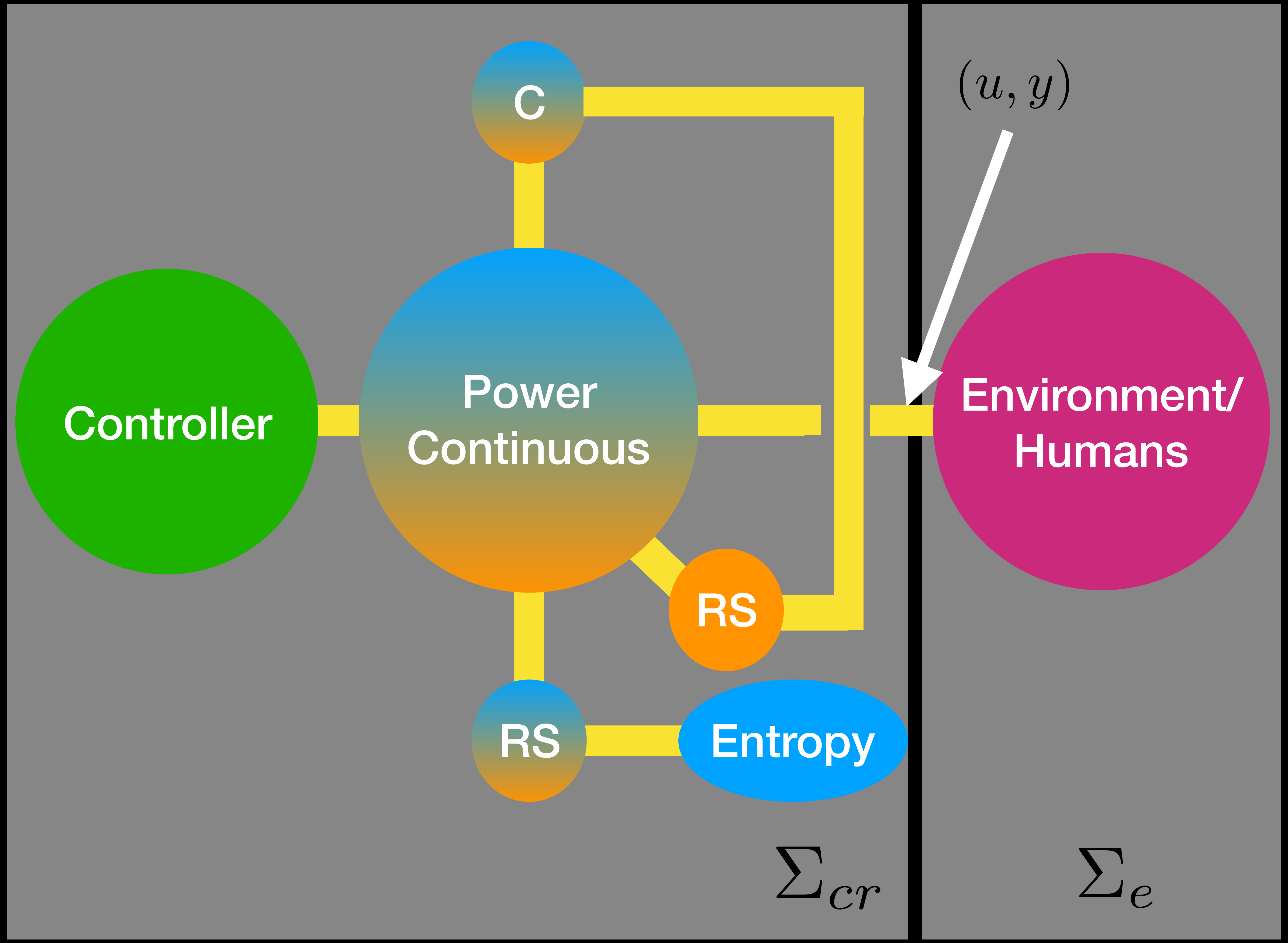


Theorem: Passivity Control Robot (PCR)

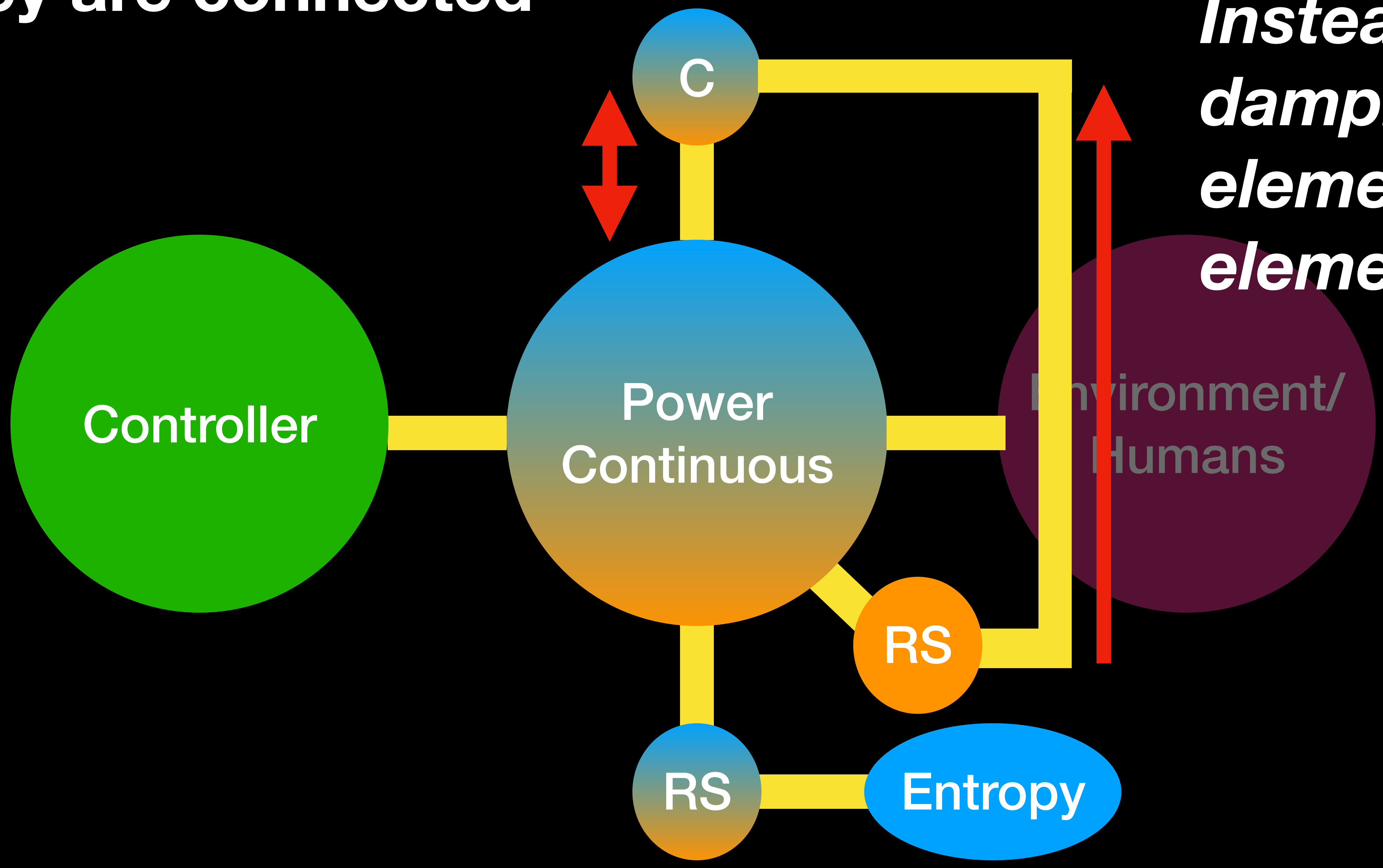


Given a non-passive system Σ_{cr} (controlled robot) with input output pair (u, y) (representing the interaction with the environment), **there exists always** a **passive system** Σ_e (environment) which connected to the Σ_{cr} will give rise to an unstable behaviour of the interconnection of Σ_e and Σ_{cr}

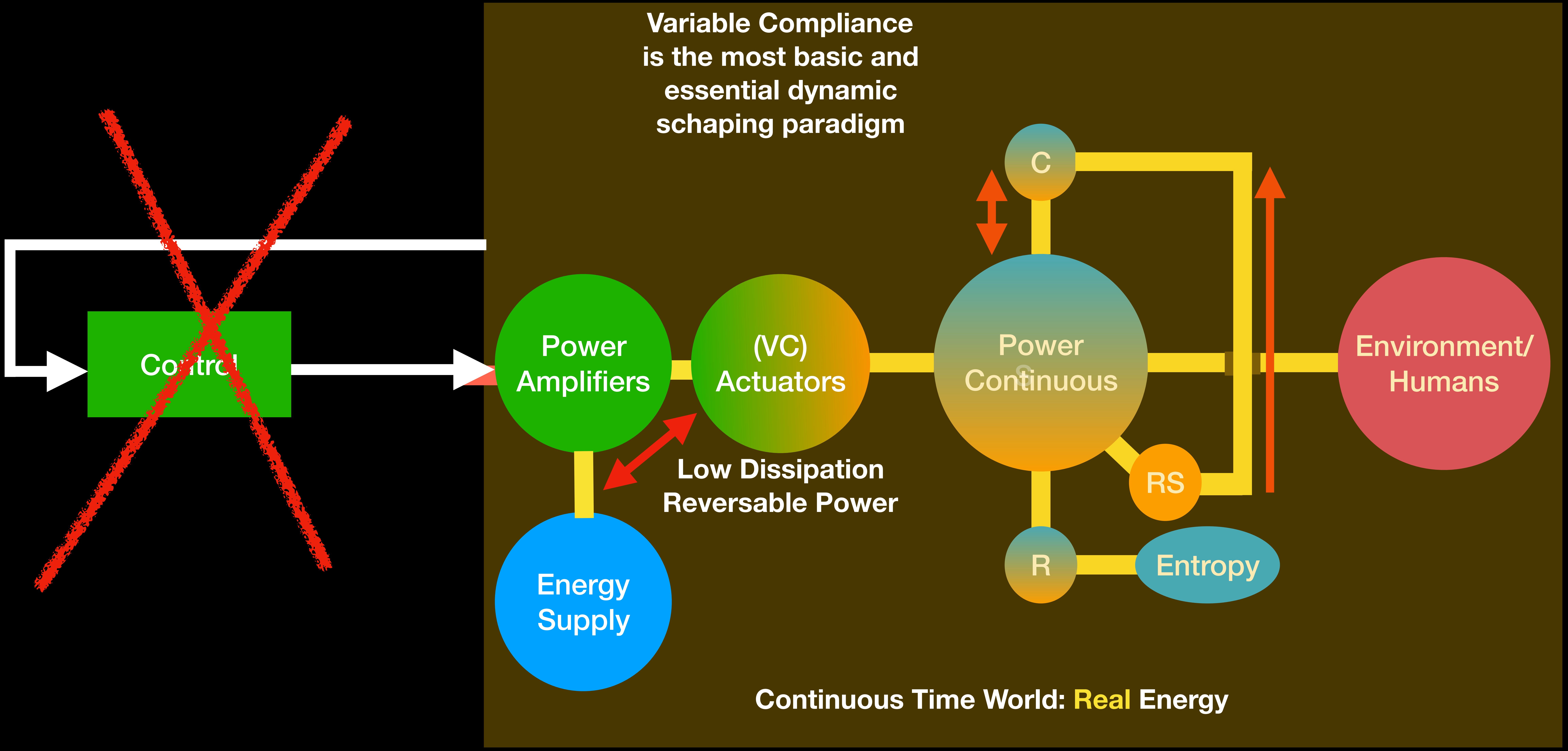
Control by Design or Control by Interconnection

Modify the design:
- Adding elements
- Change how they are connected

Implement "Dampers with springs":
Instead of implementing damping forces with dissipating elements, try to do it with elastic elements

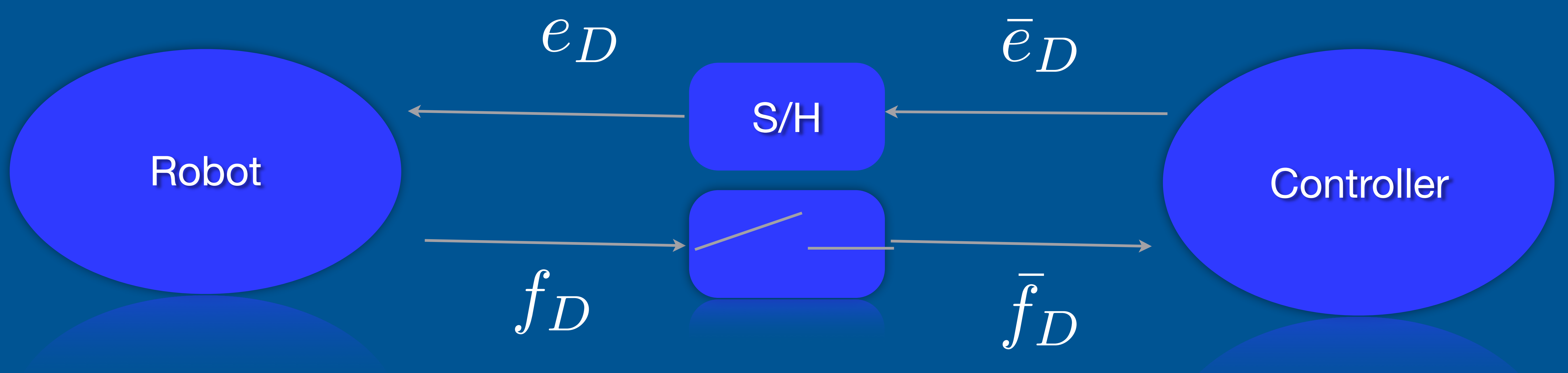


Control by Design or Control by Interconnection



Control by Design or Control by Interconnection

Passive Sampling



$$e_D(t) = \bar{e}_D(k) \quad t \in [kT, (k+1)T]$$

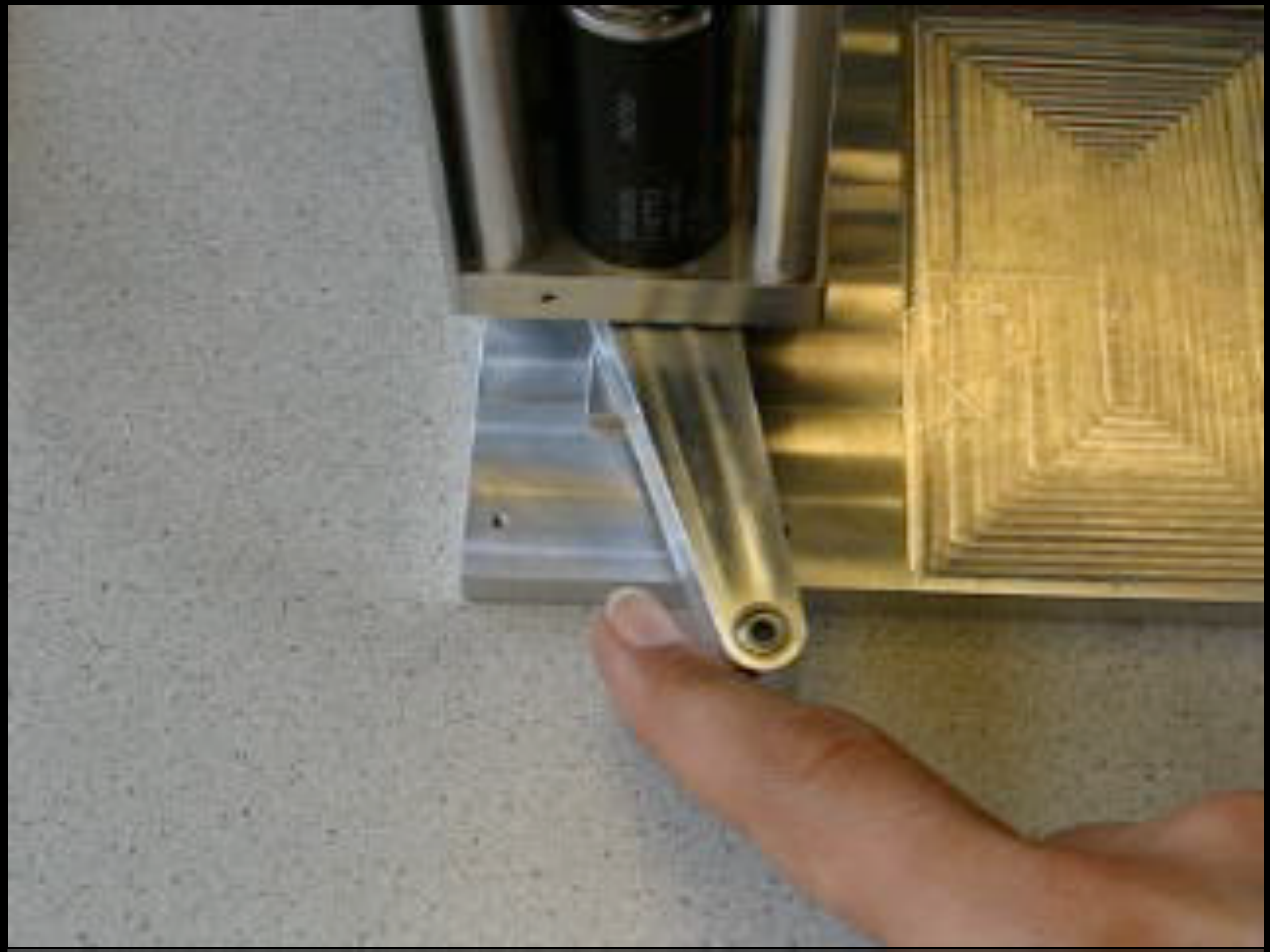
$$\Delta E_C^{in} = \int_{kT}^{(k+1)T} \bar{e}_D^T f_D(s)ds = \bar{e}_D(k) \int_{kT}^{(k+1)T} f_D(s)ds$$

$$= \bar{e}_D(k)(q((k+1)T) - q(kT))$$

S. Stramigioli, C. Secchi, A. J. van der Schaft, and C. Fantuzzi, "Sampled Data Systems Passivity and Discrete Port-Hamiltonian Systems," IEEE transactions on robotics,

This actually works!

Standard PD



IPC PD

30 Hz sample rate

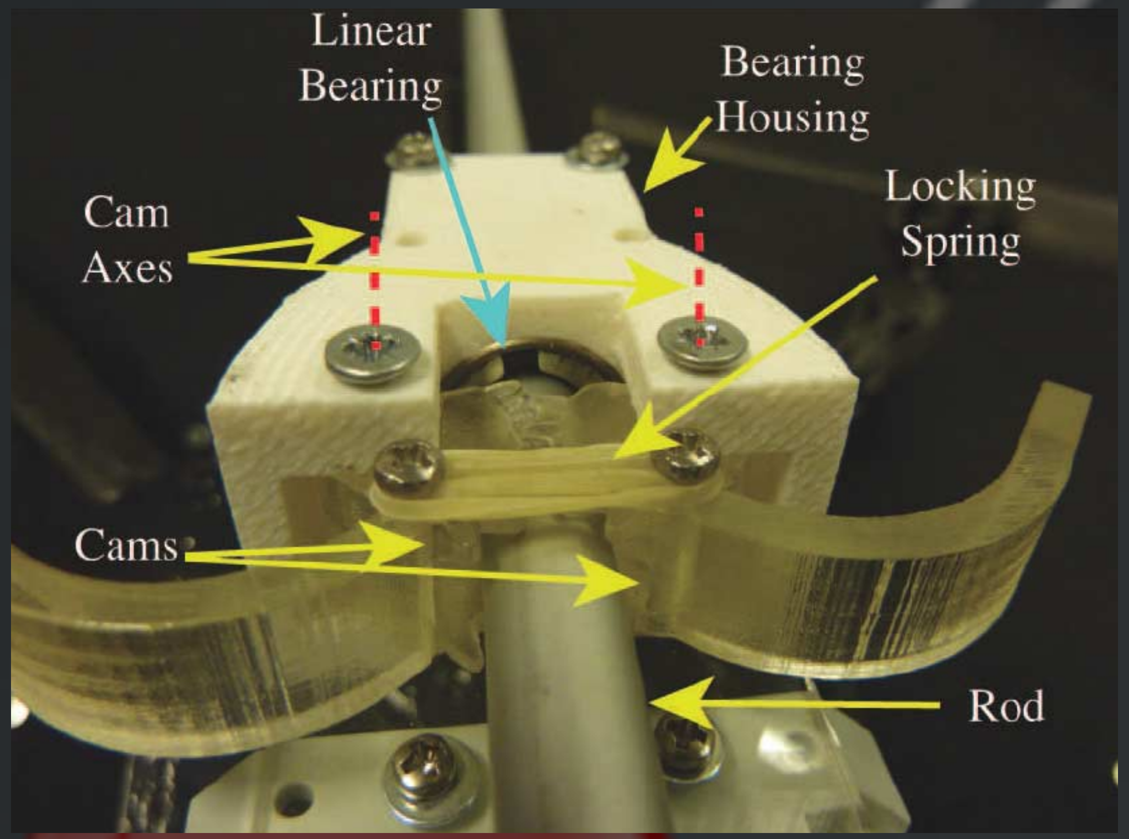
Implementation

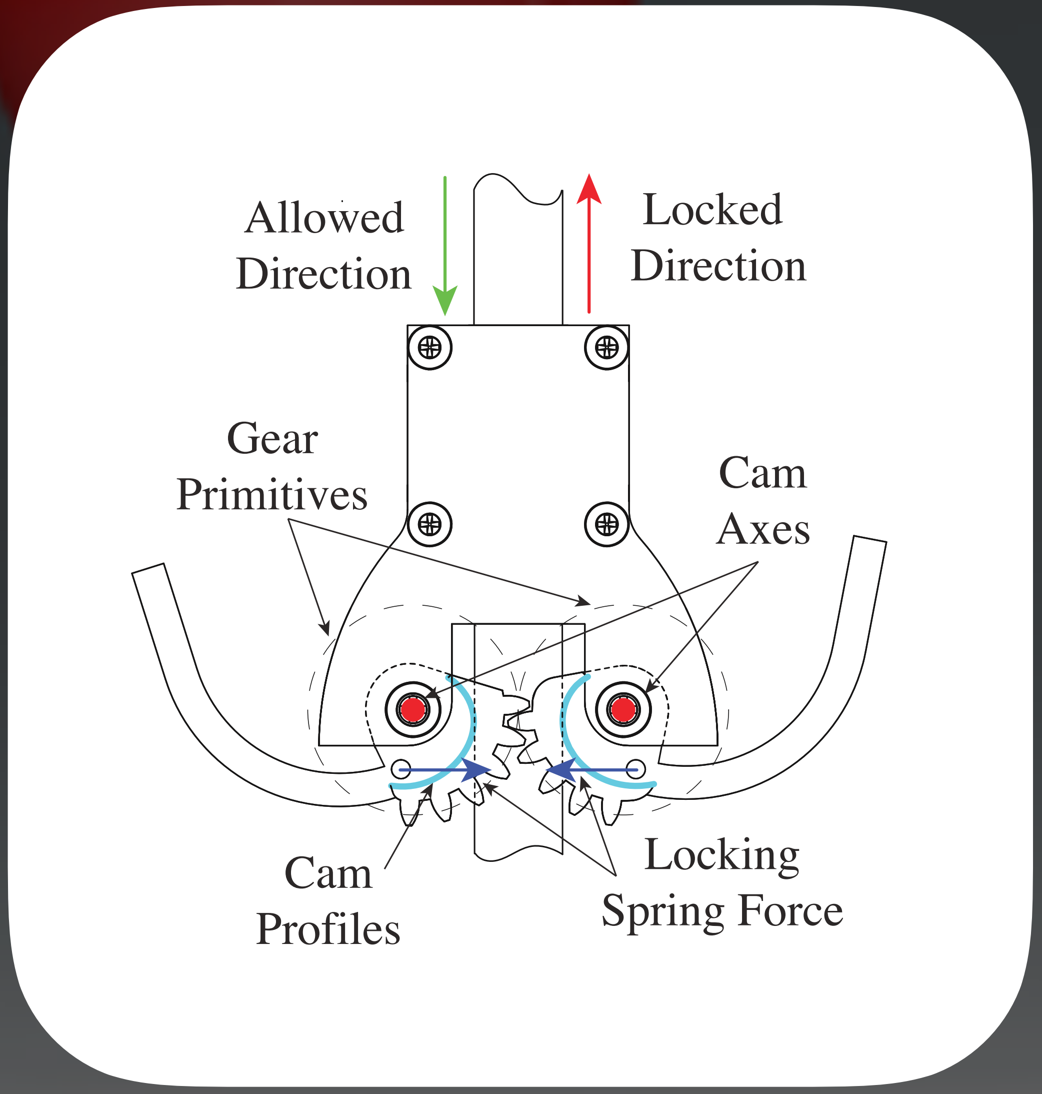
*Put Intelligence as much as possible in the mechanics: **embedded intelligence***

VIACTOR

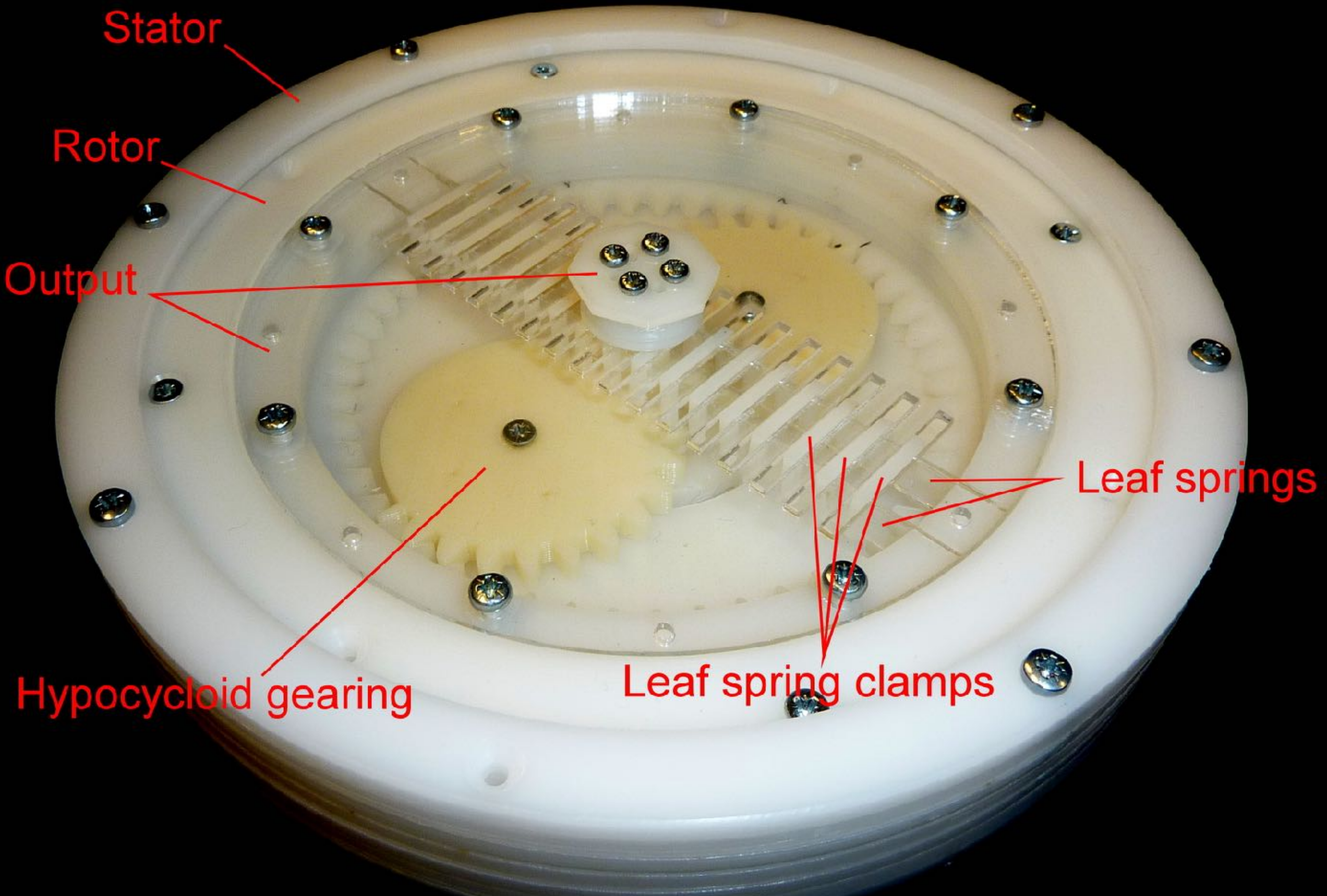
Control by Design or Control by Interconnection

Irreversible Impacts absorption





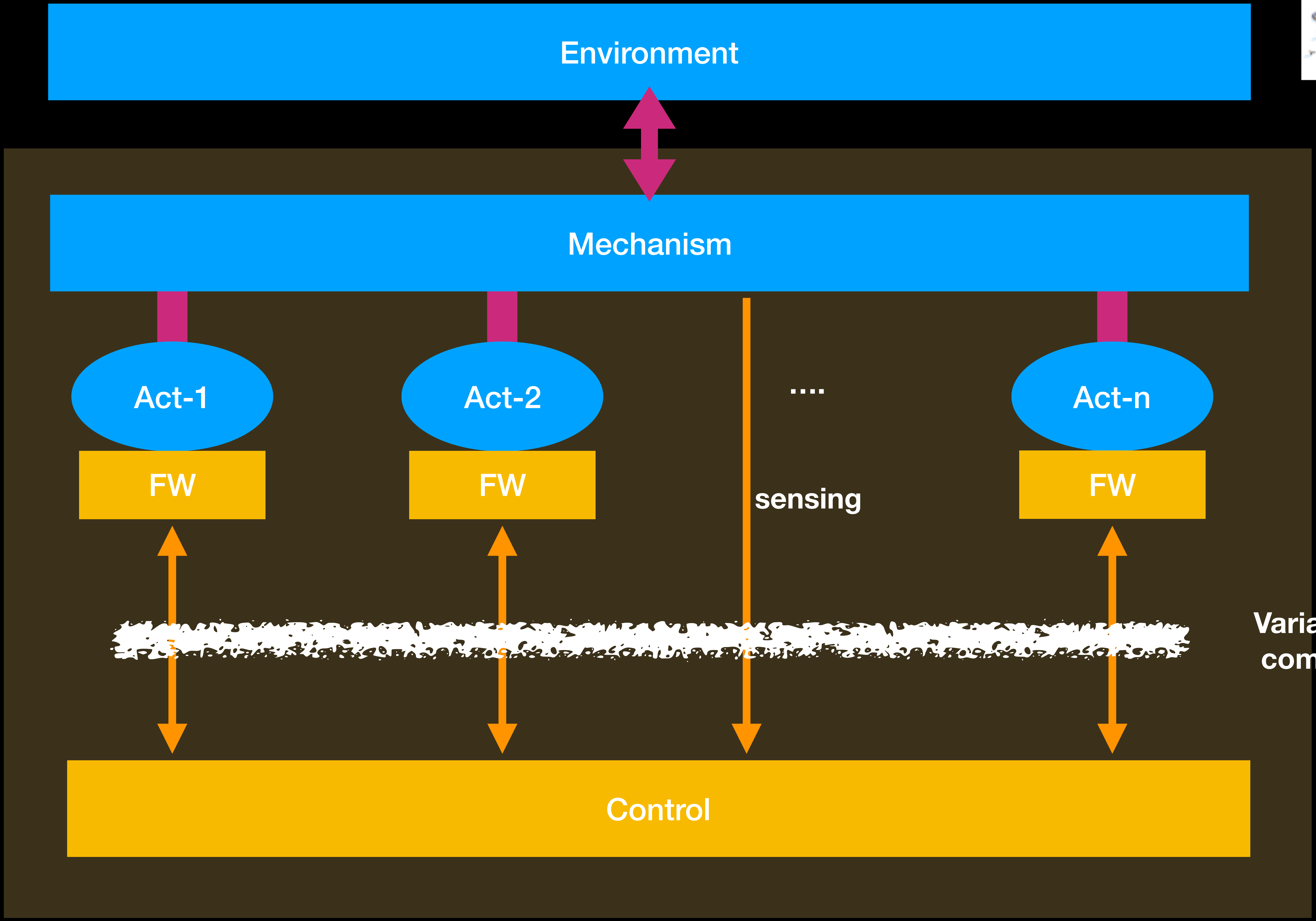

CAUTION
Contact
UNIVERSITY OF TWENTE
RAM
Then the brush is activated.


Stator
Rotor
Output
Leaf springs
Hypocycloid gearing
Leaf spring clamps

Patented

Example: A difficult problems made simple

Interactive, Distributed Architecture
with time varying delays



Variable, Different Time delays:
computation, communication..

Conclusions

Conclusions

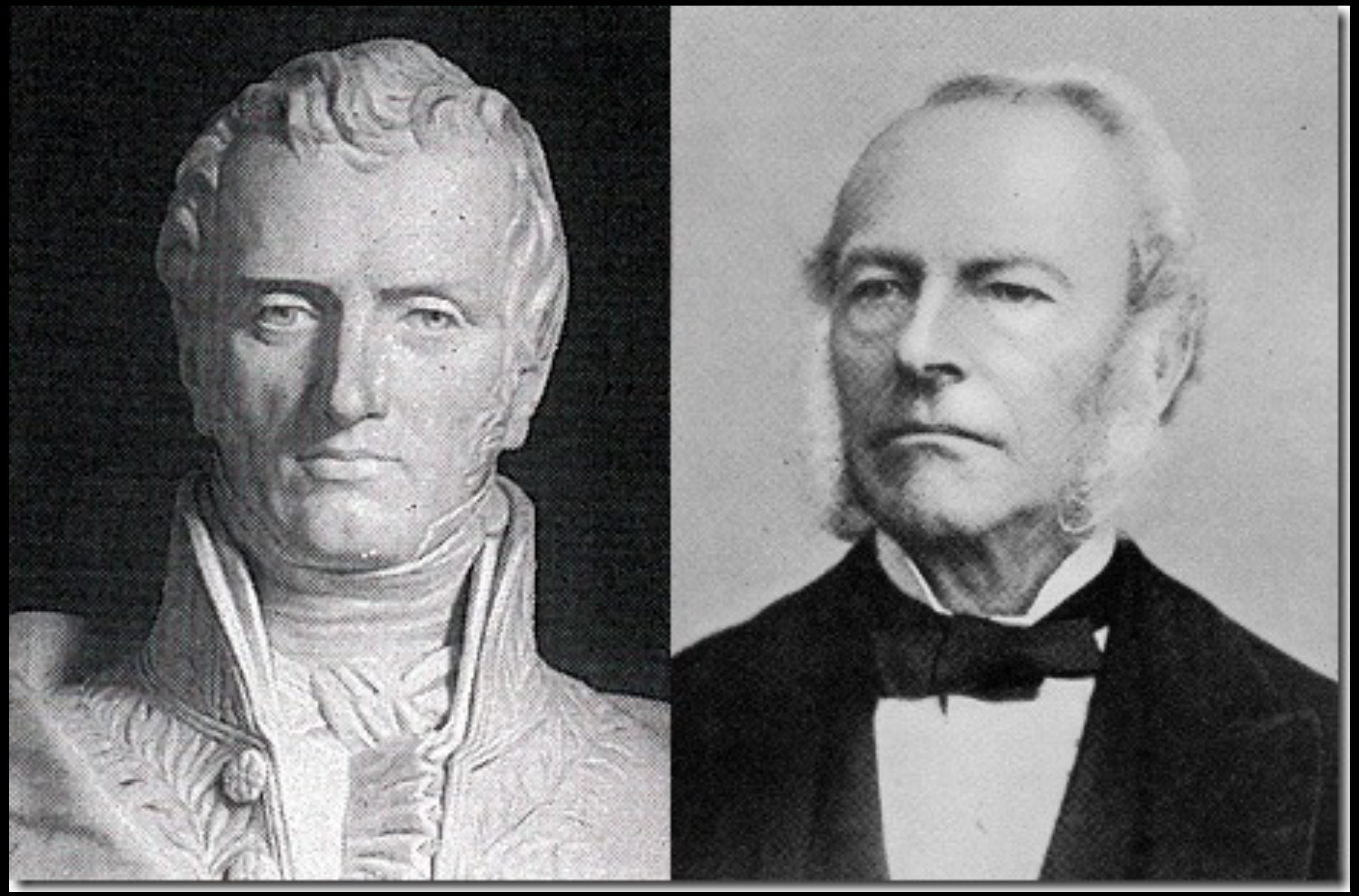
- To analyse or develop systems for the sake of optimising energy consumption, **proper tools/language** as needed or at least useful
- To ensure proper behaviour during interaction, the digital control needs to also be **energy aware**
- The coupling of the continuous and discrete part of the system can be made energy consistent: **energy consistent sample and hold**
- Port-Based / Energy Aware Robotics can help in innovative design by **giving insight in the energy flows**.

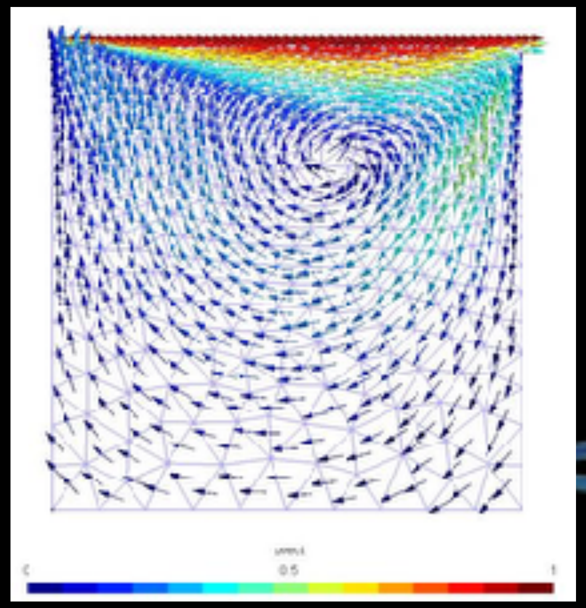
Future Work

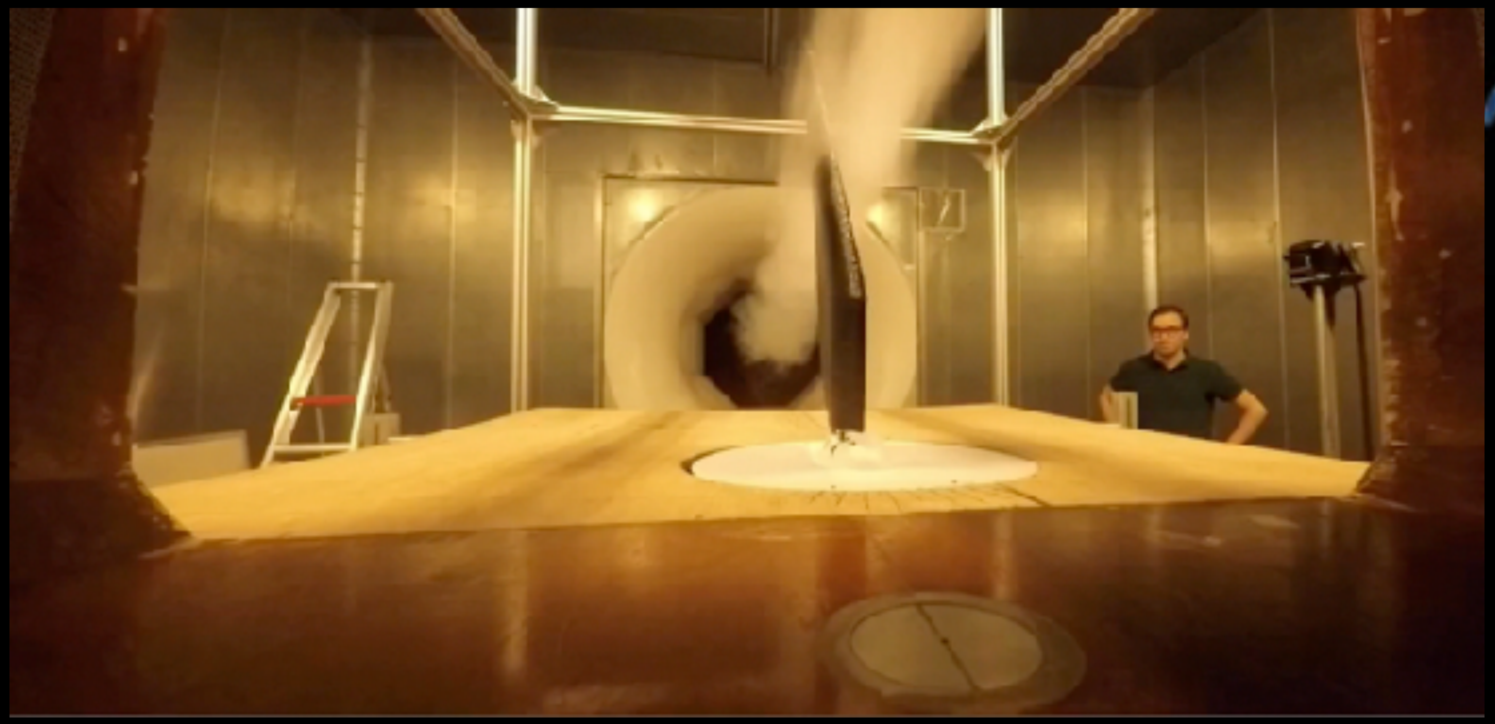
Speed up to 80 Km/h in 5 bfr wind

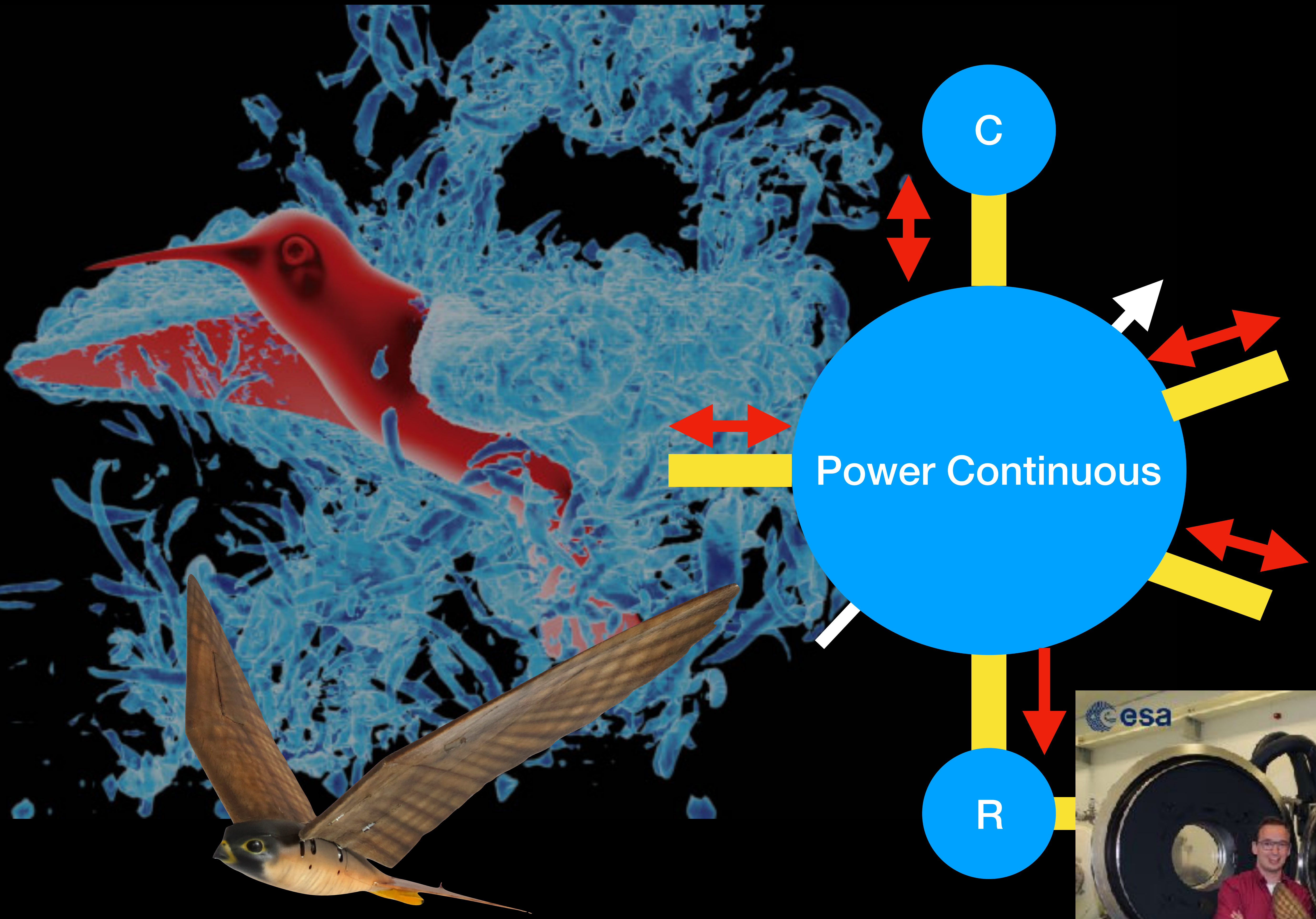

Velocity.Curl Z
fluid_unstructured symmetry 2
[s^-1]
-3.000e+000
-1.500e+000
0.000e+000
1.500e+000
3.000e+000
ANSYS
R14.5
Academic
Reversed Von Kármán sheet generation
Strouhal number (0.2 < St < 0.4)
0
1.500
3.000
(m)
0.750
2.250
X

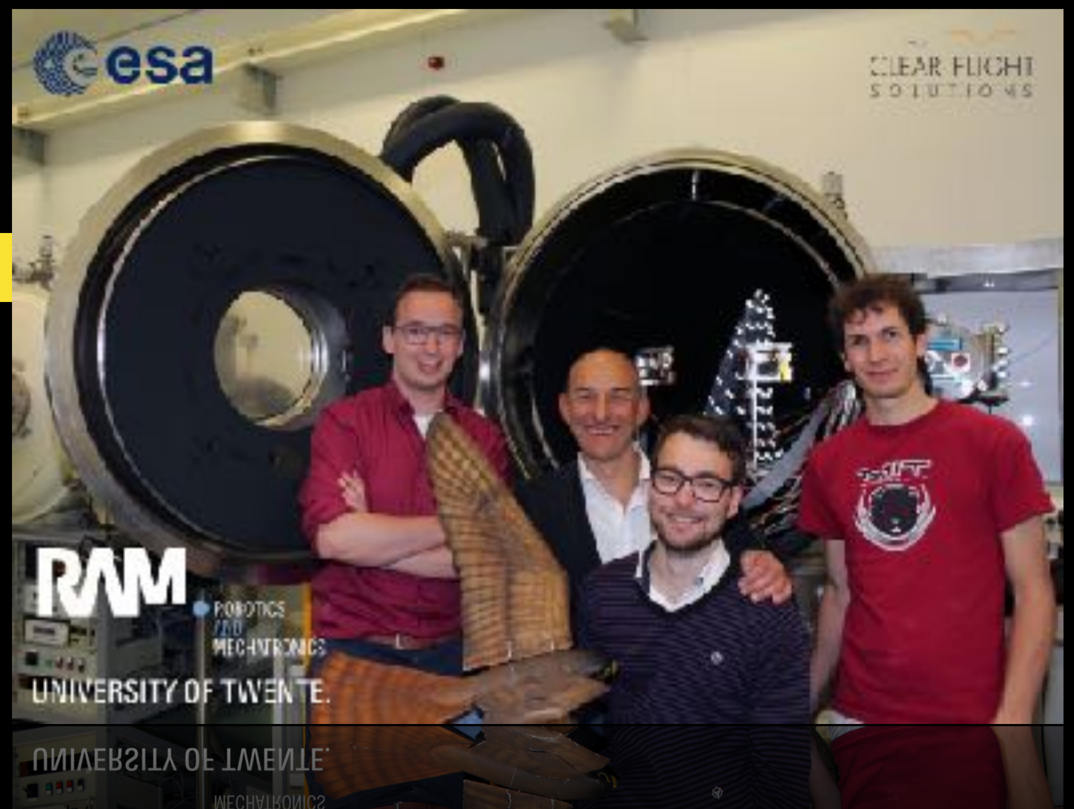
Variable boundaries, port-based Navier- Stokes











Dear Alessandro, congratulations again and thanks!

*The sky is **not** the limit,*

..but just the first layer

THANK YOU FOR YOUR ATTENTION