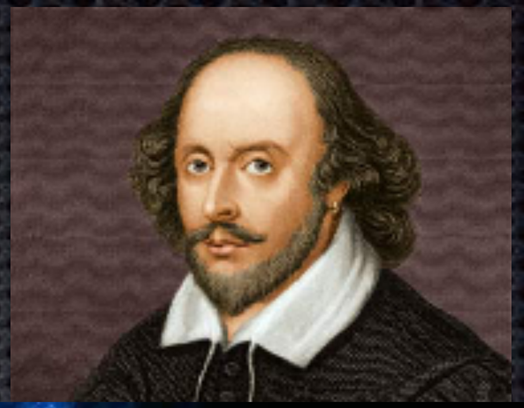
Energy (and Geometrical) Aware Robotics

Robots follow the laws of physics!

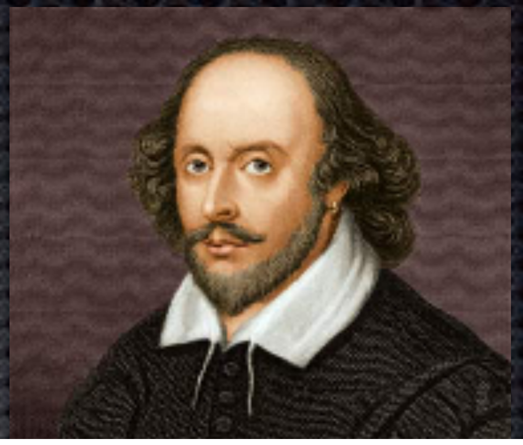
Energy or **no Energy**, that is the question

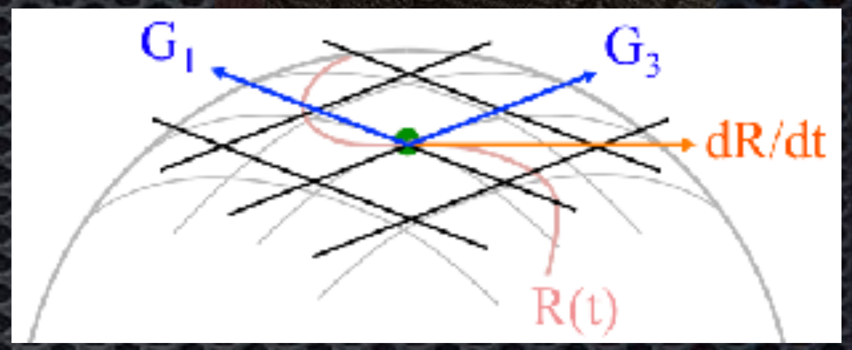


- **No relation with energy**
  - No way to work in all situations during interaction
  - No robustness
  - Environment cannot be “properly modeled”!
  - Unespected behaviour
  - …

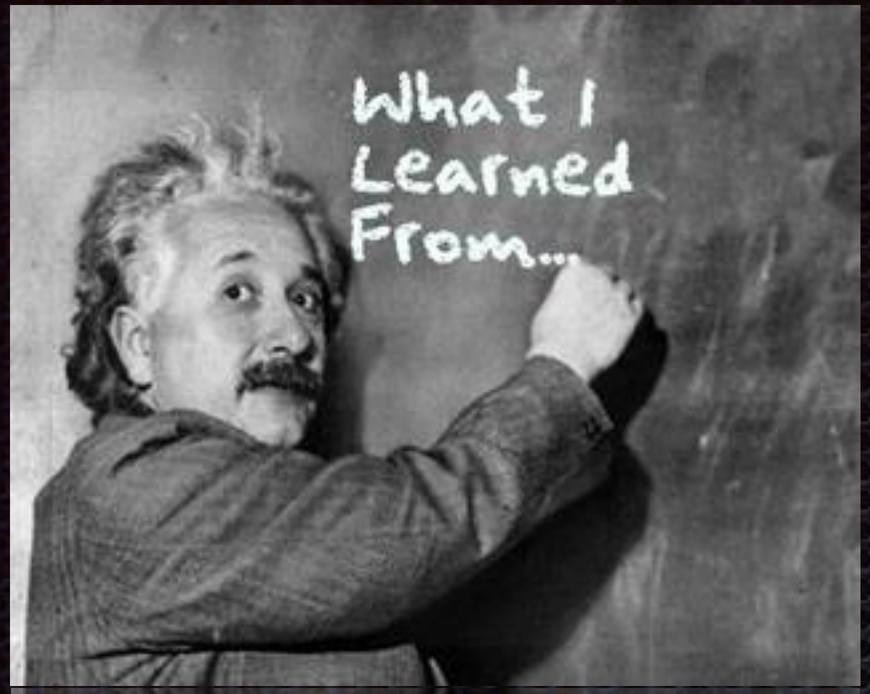
- **Passivity or better: Energy Awareness**
  - Track and Control Energy flows
  - Never problems with stability
  - Robust
  - Can Couple Digital-Continuos World
  - Handle Time delays
  - ….

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

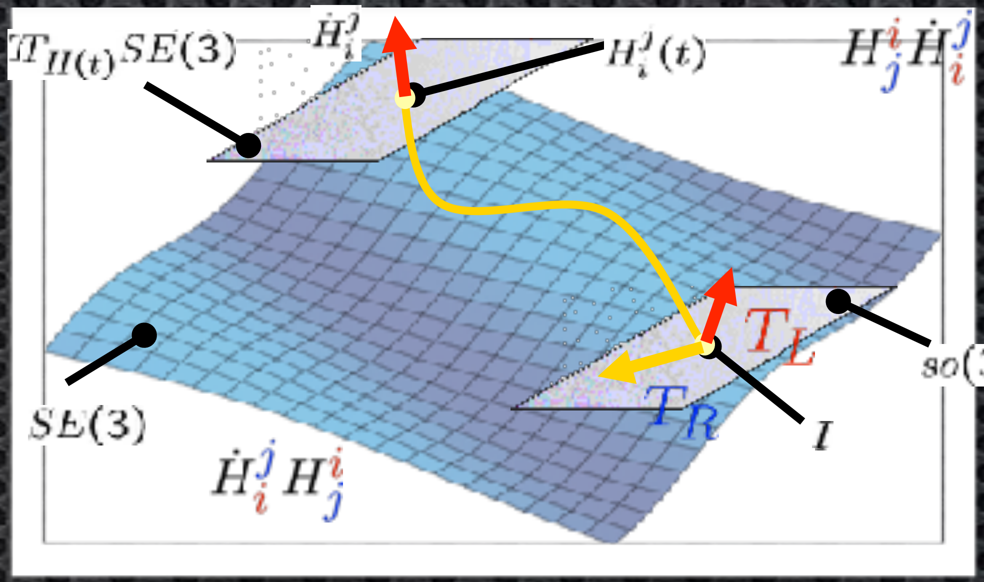




- **No Geometry**
  - Complicated equations
  - Solutions dependent on coordinates
  - Non physical nonsense: eigenvalues of Inertias, random ortogonality, projections, non invariant indeces,…
  - Singularity
  - Unexpected instabilities
  - ..
- **Geometry**
  - Simple descrpition
  - Coordinate Invariant
  - Physical
  - No singularity
  - Directly see if something is wrong: inverses, projections, error measurement
  - ….



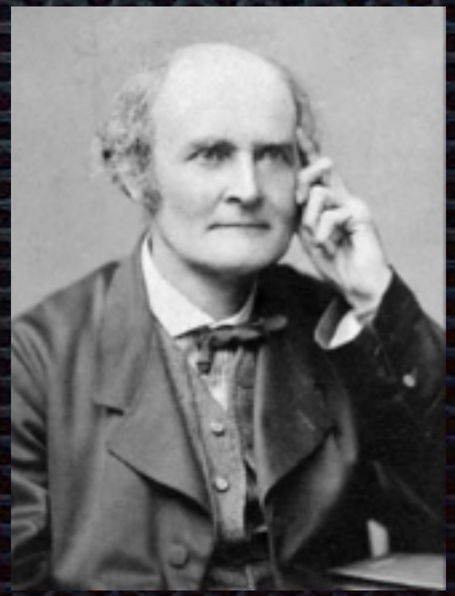
Take Home Message



Sophus Lie

- **Learn Geometry**: Lie Groups
- **Respect Physics**: Thinks **physical** (using geometry), not mathematics alone

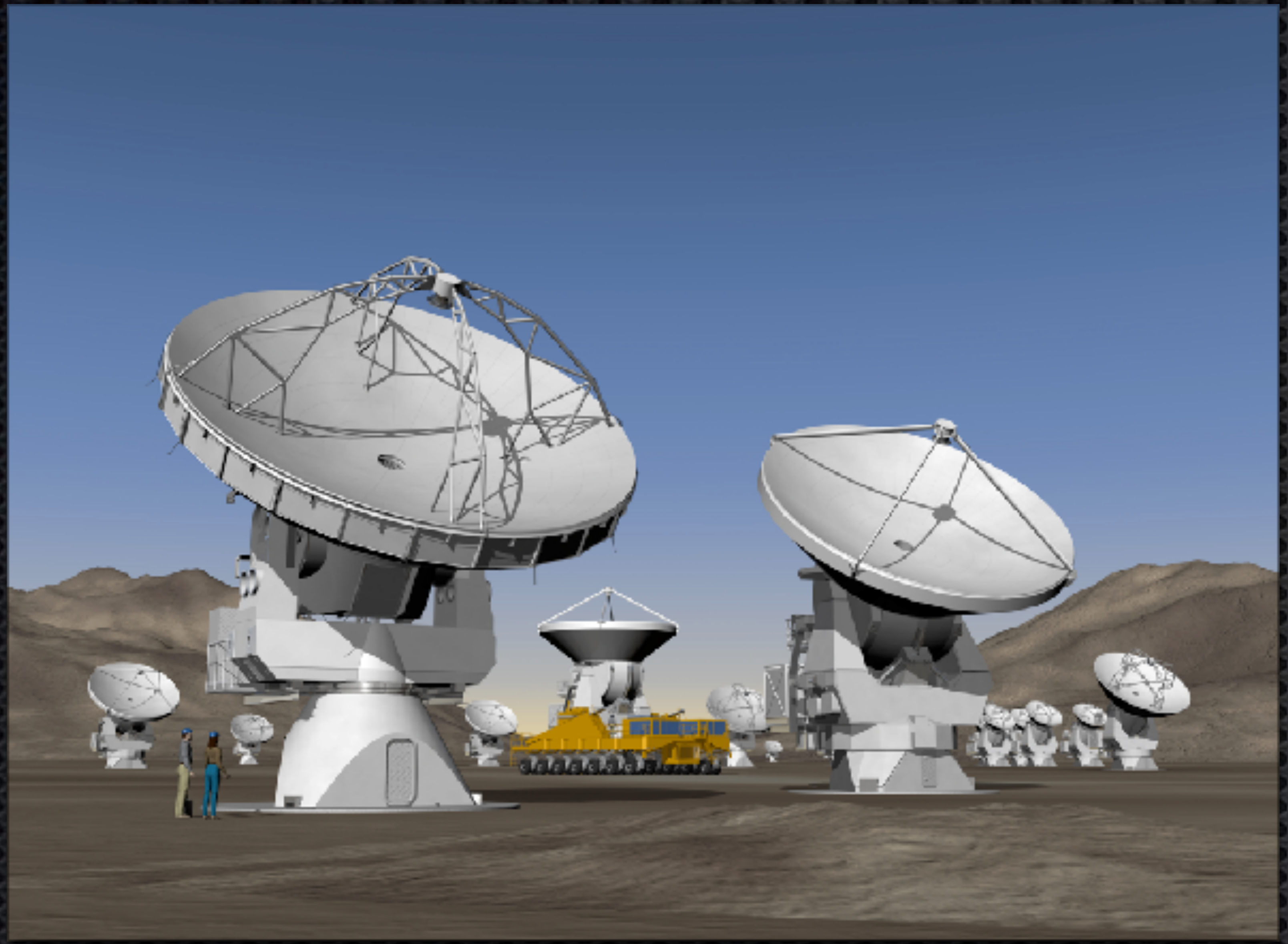
Visser, M., Stramigioli, S., & Heemskerk, C. (2006). Cayley-Hamilton for roboticists. In Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on (Vol. 1, pp. 4187–4192). Beijing: IEEE Robotics and Automation Society. doi:10.1109/IROS.2006.281911



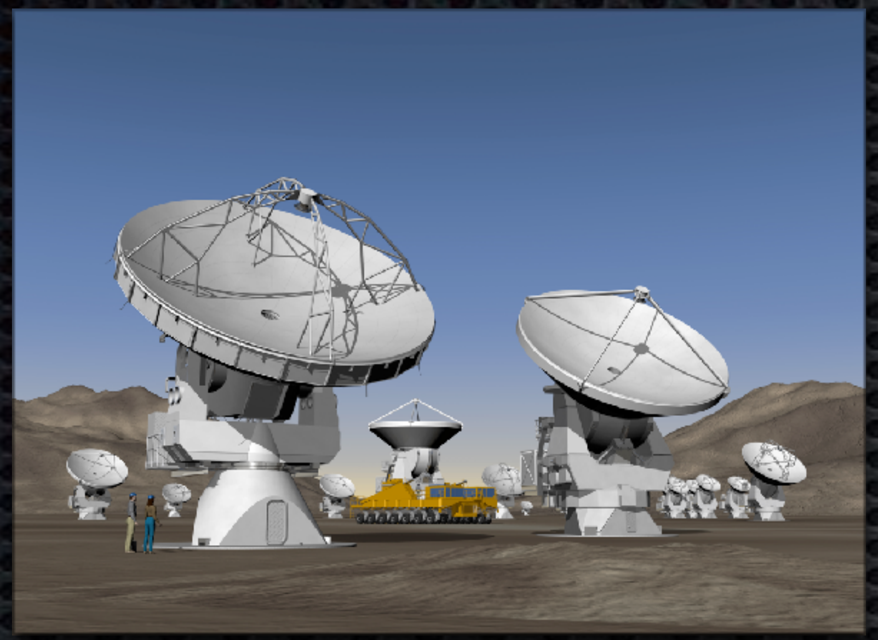
Arthur Cayley

William Hamilton

What is the Difference ?



What is the Difference ?

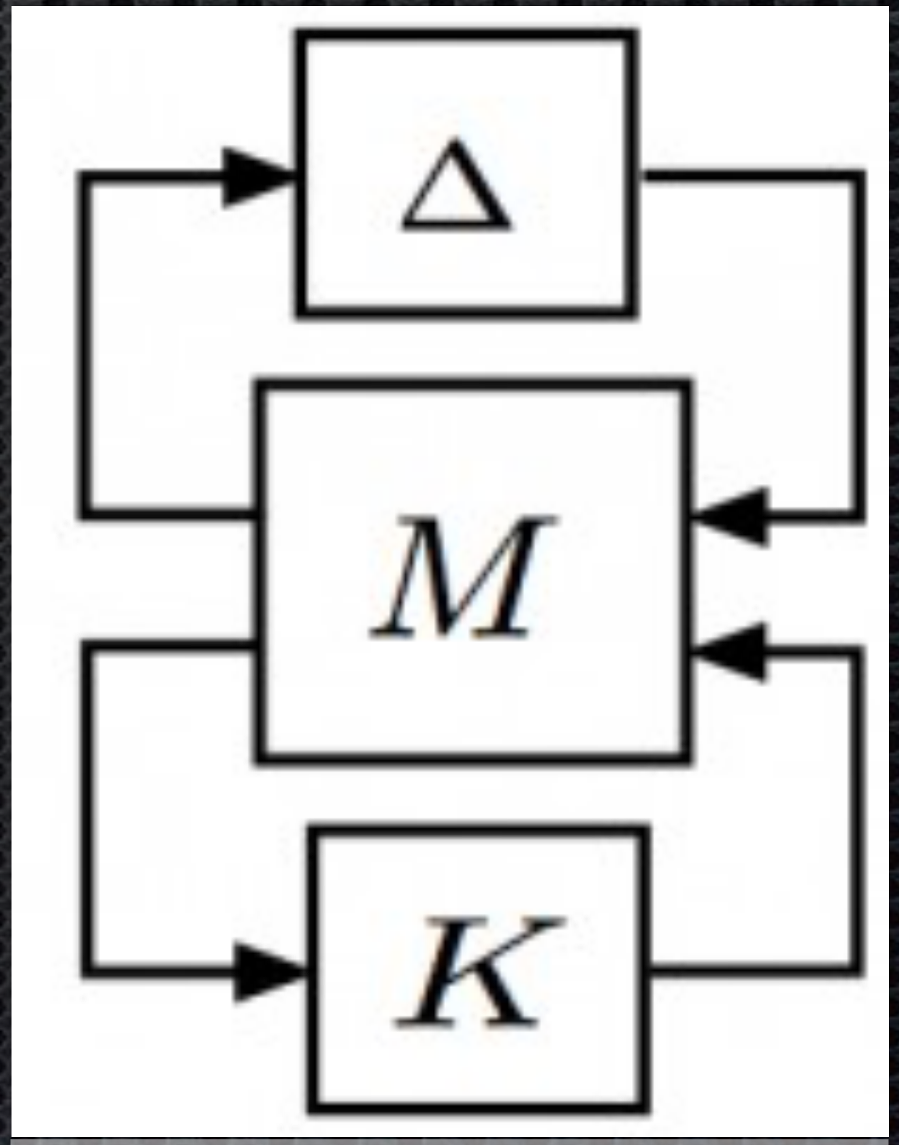


- Practically no interaction with environment
- Stiff
- Precise
- Control a signal

- Interaction IS the goal
- Compliant Behavior
- Not Precise
- Control an interaction, NOT a signal

Different Than Robust Control!

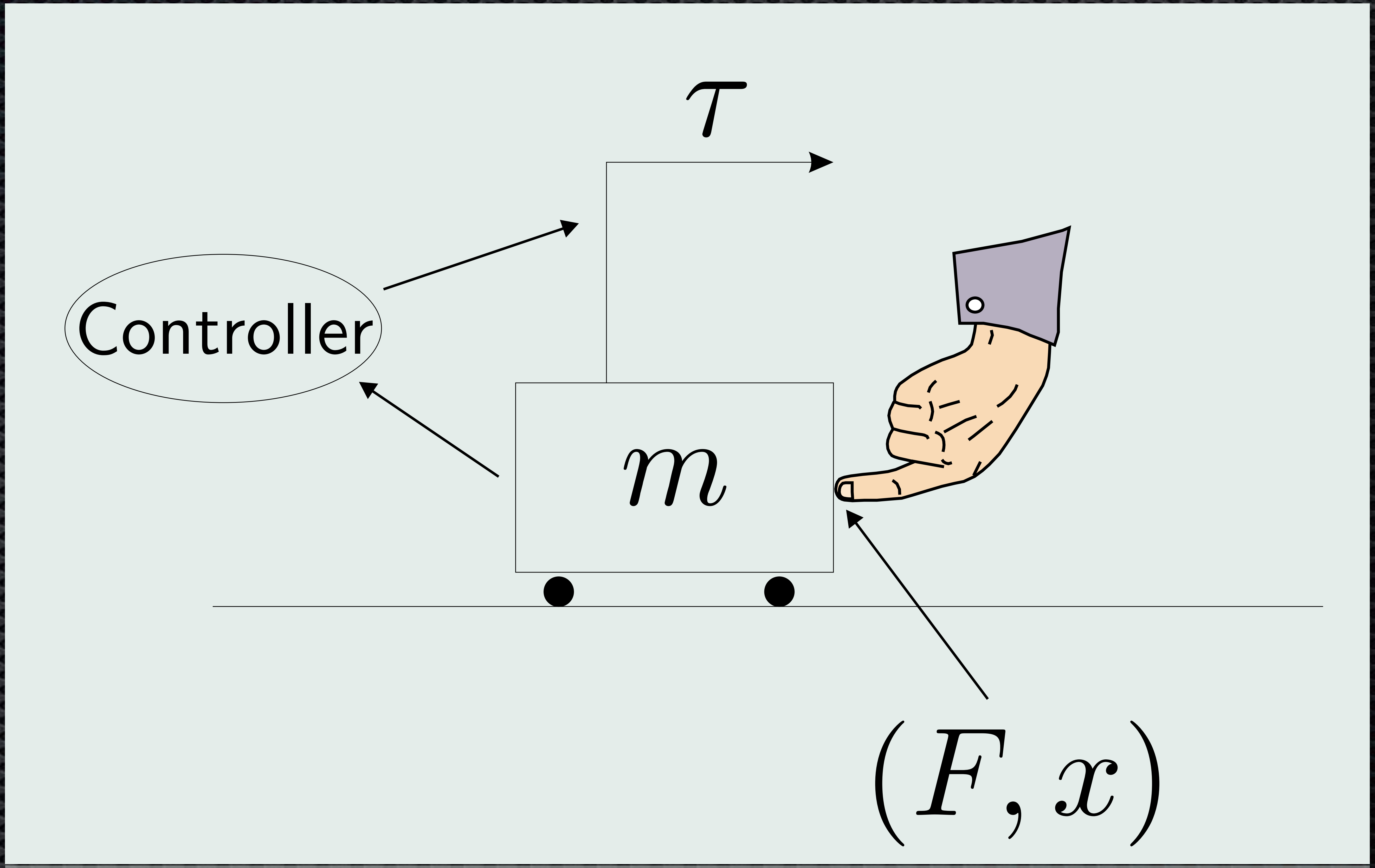
- Environment completely unpredictable
- Environment intrinsically non linear and not always present
- Goal NOT TO CONTROL A SIGNAL
- System to be controlled can continuously change depending on environment
- ….



In Interactive Robotics

- Disturbances are NOT small and ARE completely umpredictable
- Bidirectional interaction ALL the times
- Energy plays a role for stability and safety

About Mechanical Interaction



Stramigioli, S. (2001). Modeling and IPC control of interactive mechanical systems — A coordinate-free approach (Vol. 266). London: Springer London. doi:10.1007/BFb0110400

Interaction: relation of F and x

- By means of control, we can achieve a certain robot dynamics:

$$R(s)\begin{pmatrix} F(s) \\ x(s) \end{pmatrix} = 0, \qquad R(s) \in \mathbb{R}^{1\times 2}[s]$$

- and the environment will have its own behavior:

$$R_E(s)\begin{pmatrix} F(s) \\ x(s) \end{pmatrix} = 0, \qquad R_E(s) \in \mathbb{R}^{1\times 2}[s]$$

Position Control

Properly speaking we can talk about position control in the case in which the Robot is Isolated which means

$$F(t) = 0, \forall t$$

$x(t)$ only dependent on the robot $R(s)$

Force Control

- Properly speaking we can talk about force control in the case in which the Robot is "Glued" to a fixed point, which means

$$\dot{x}(t) = 0, \forall t$$

$F(t)$ only dependent on the robot $R(s)$

All other situations

In ALL other cases, BOTH F(t) and x(t) depend on BOTH the **robot** and the **environment**

$$\begin{pmatrix} R(s) \\ R_E(s) \end{pmatrix} \begin{pmatrix} F(s) \\ x(s) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

results in a unique solution for F(t) and x(t)

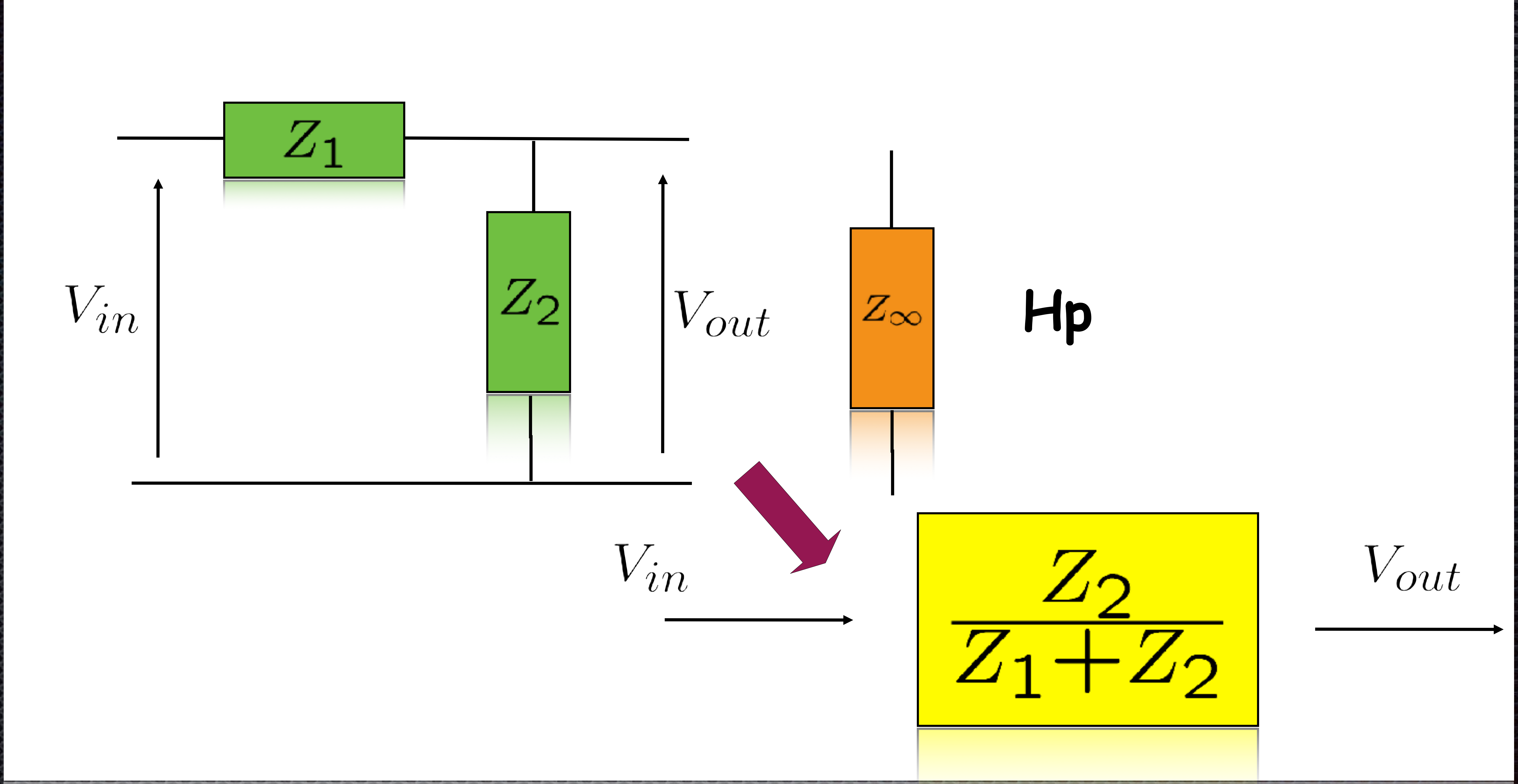
Conclusion

For an interacting system

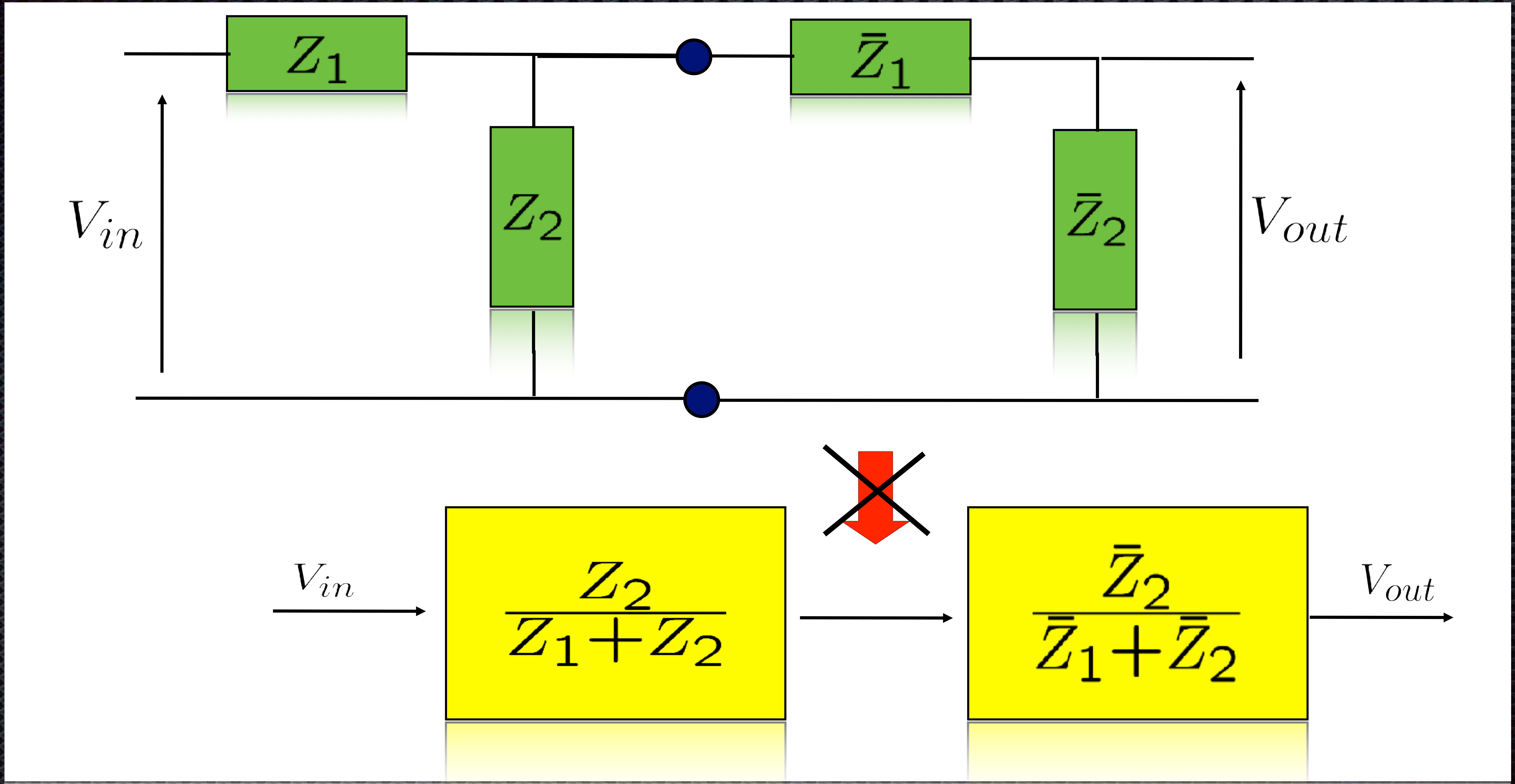
- We **CANNOT** intrinsically control $F(t)$ and/or $x(t)$ **INDEPENDENTLY** of the environment
- We **CAN** control $R(s)$ intrinsically and **INDEPENDENTLY** of the environment

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

Signals versus Ports



Signals versus Ports

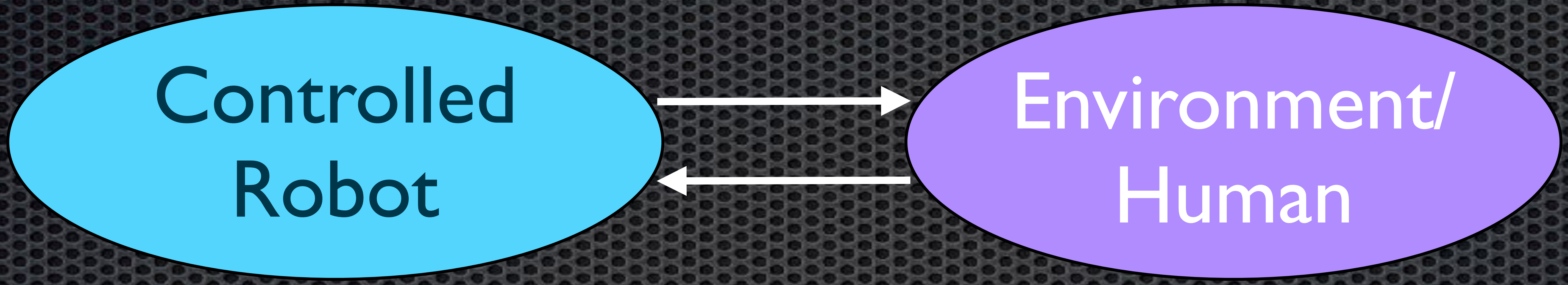


Conclusions on example

- With Physical Systems, **signal** modeling is often not suitable
- **Physical** Energy governs dynamics
- Always a bi-directional effect
- To model/control real ***OPEN systems*** signal modeling is NOT the solution
- This is true also between domains: typical example DC motor gyration
- Robotics IS interconnection of multi-domain parts, we need something more !
- In Haptics and Telemanipulation even more so!!

→ Port-based

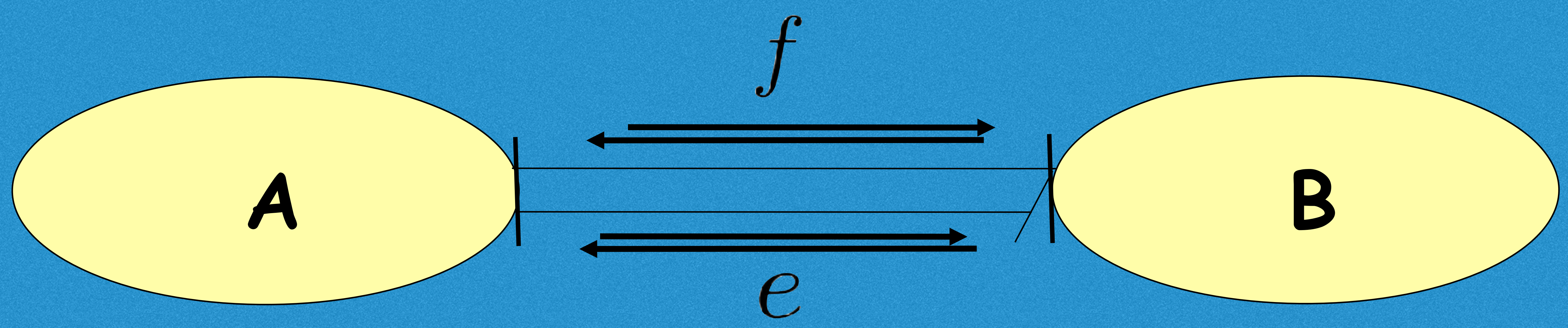
About Mechanical Interaction



Forces, Velocities

Environment is Non-linear, Unpredictable, greatly varying...

Power Bond



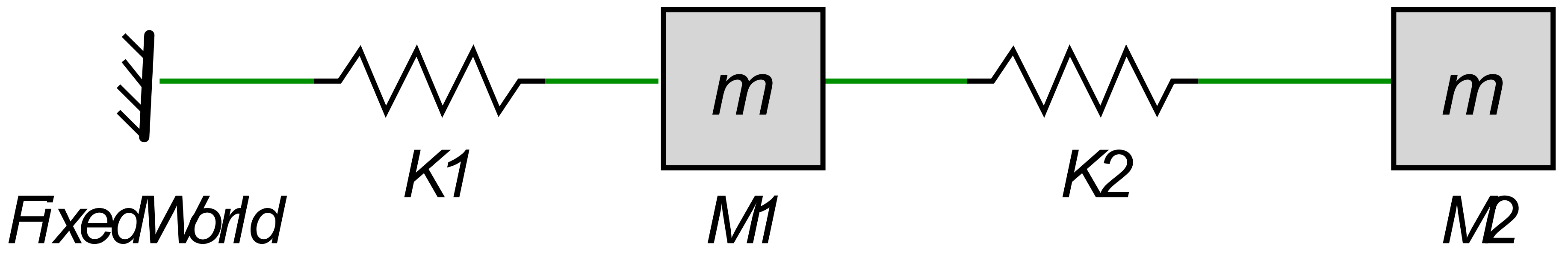
- e, f belong to vector spaces in duality
- $e(f) = e^T f$ represents the instantaneous power flowing from A to B
- In general an a-causal description !!

Examples

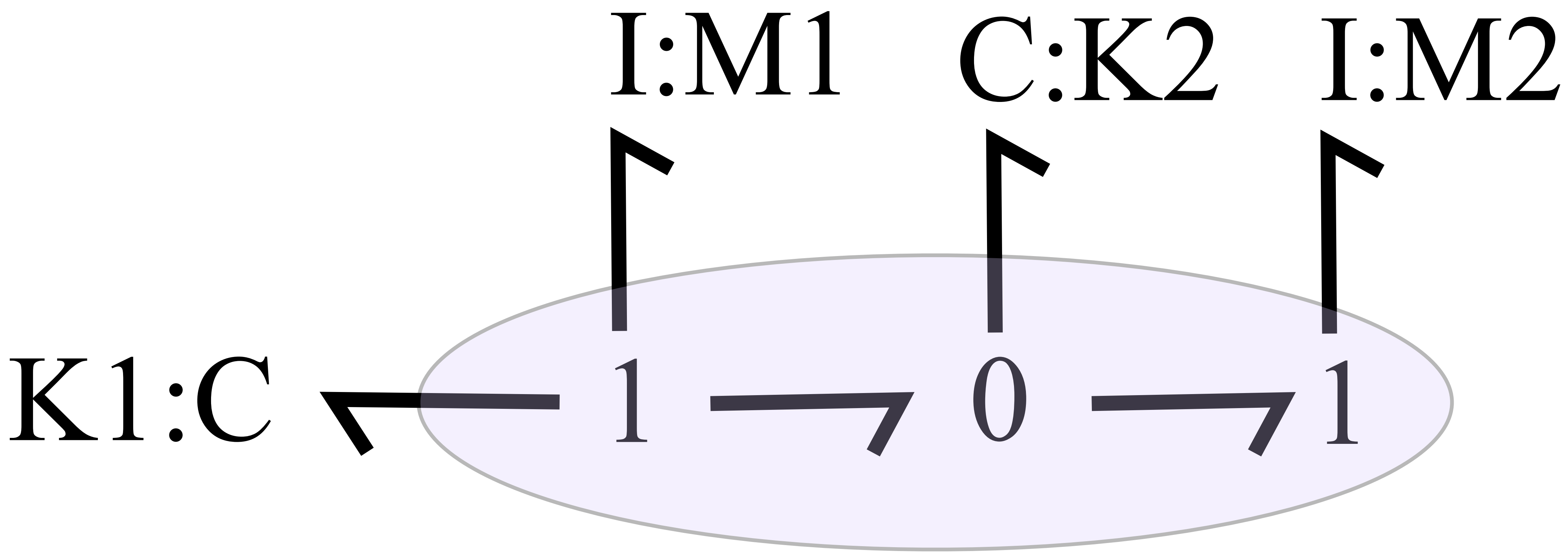
Domain	flow	effort	flow geometry
Electrical	current	voltage	$\Re$
1D mechanical	velocity	force	$\Re$
Rotational mechanics	Ang.vel.	torque	$so(3)$
rigid 3D mechanics	twist	wrench	$se(3)$
⋮	⋮	⋮	⋮

Lie Groups
Geometry

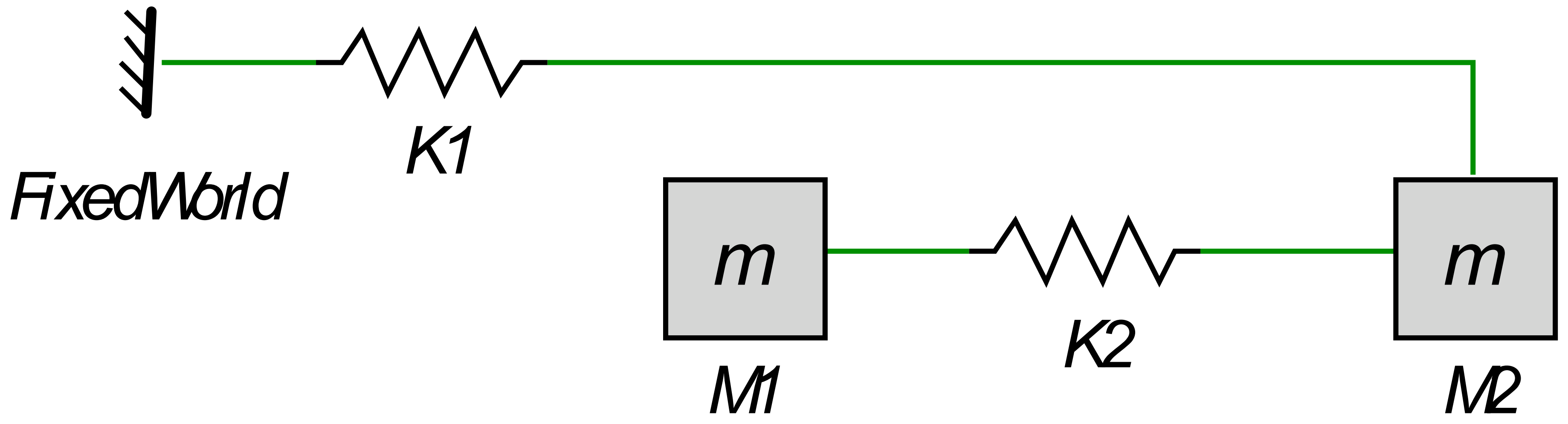
Interconnection 1



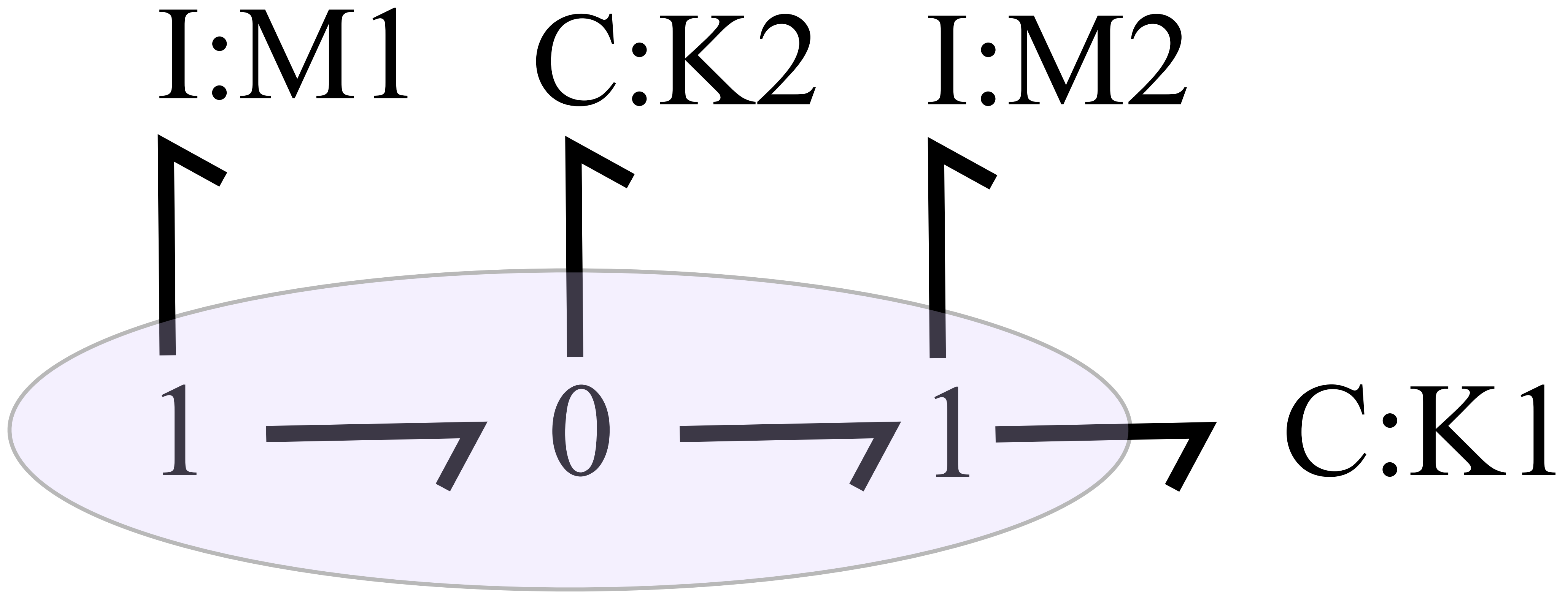
$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{p}_1 \\ \dot{p}_2 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ -1 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_1} \\ \frac{\partial H}{\partial x_2} \\ \frac{\partial H}{\partial p_1} \\ \frac{\partial H}{\partial p_2} \end{pmatrix}$$



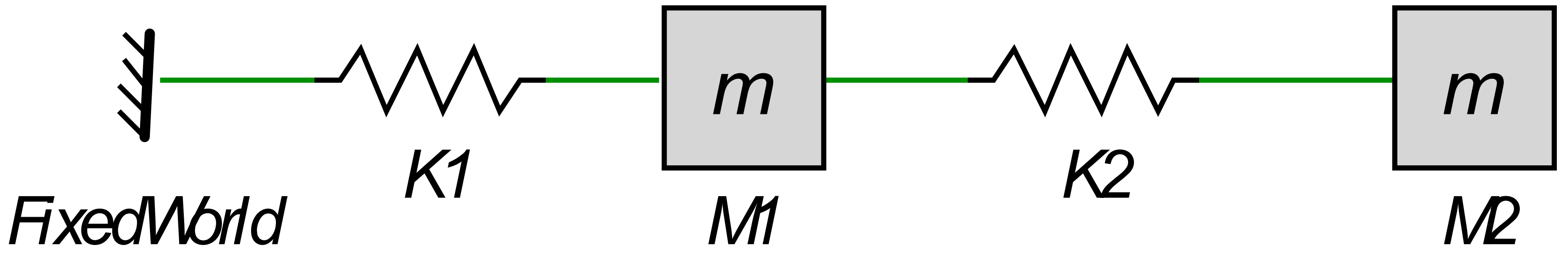
Interconnection 2



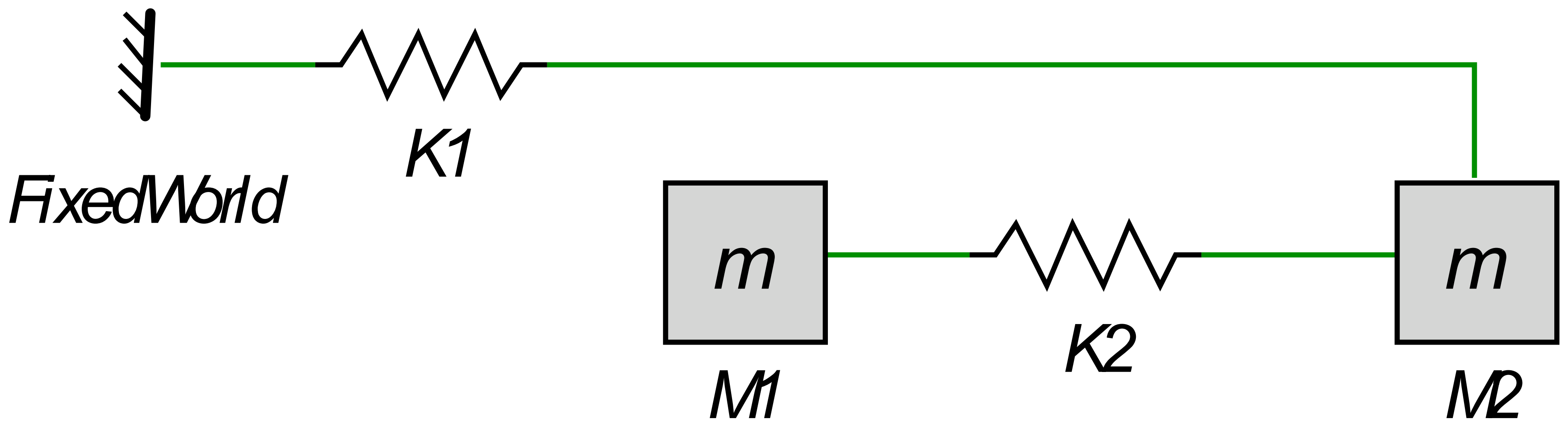
$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{p}_1 \\ \dot{p}_2 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial x_1} \\ \frac{\partial H}{\partial x_2} \\ \frac{\partial H}{\partial p_1} \\ \frac{\partial H}{\partial p_2} \end{pmatrix}$$



Network structure



$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{p}_1\\ \dot{p}_2\end{pmatrix} = \begin{pmatrix}0 & 0 & 1 & 0\\ 0 & 0 & -1 & 1\\ -1 & 1 & 0 & 0\\ 0 & -1 & 0 & 0\end{pmatrix}\begin{pmatrix}\frac{\partial H}{\partial x_1}\\ \frac{\partial H}{\partial x_2}\\ \frac{\partial H}{\partial p_1}\\ \frac{\partial H}{\partial p_2}\end{pmatrix}$$

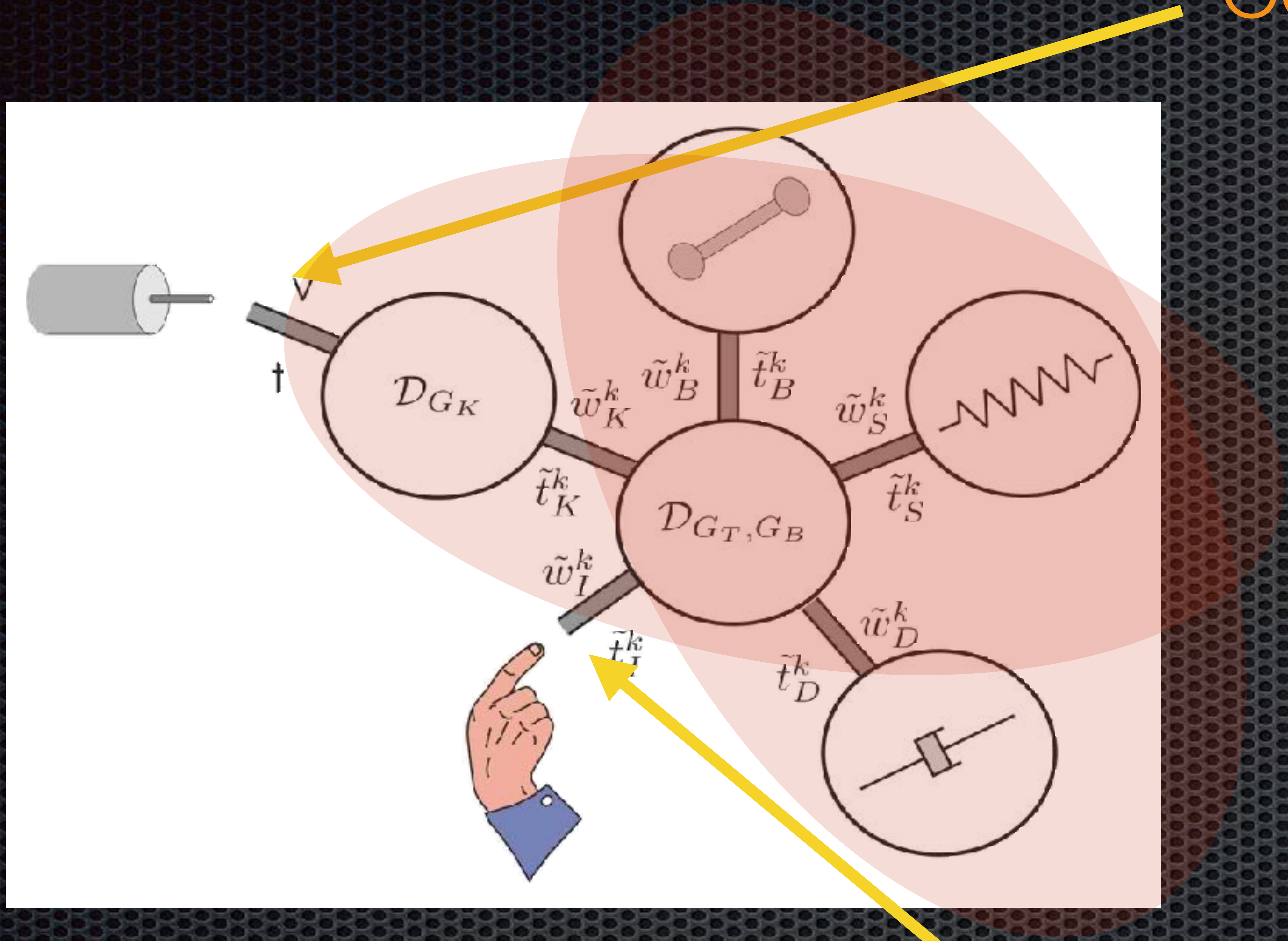


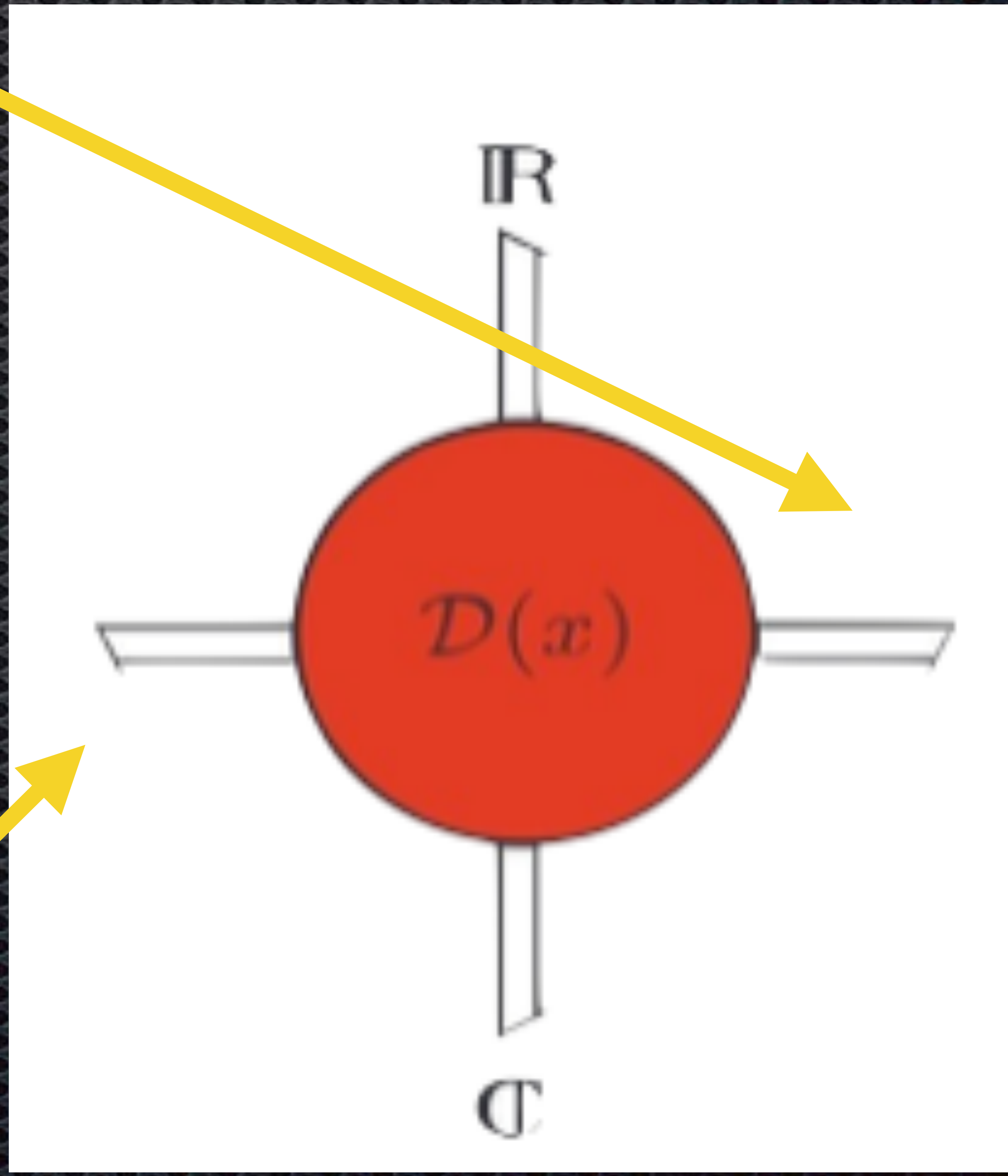
$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{p}_1\\ \dot{p}_2\end{pmatrix} = \begin{pmatrix}0 & 0 & 0 & -1\\ 0 & 0 & -1 & 1\\ 0 & 1 & 0 & 0\\ 1 & -1 & 0 & 0\end{pmatrix}\begin{pmatrix}\frac{\partial H}{\partial x_1}\\ \frac{\partial H}{\partial x_2}\\ \frac{\partial H}{\partial p_1}\\ \frac{\partial H}{\partial p_2}\end{pmatrix}$$

Same elements and Energy function but **Different Network**!

A General Interactive and Controllable Robot

Control Port

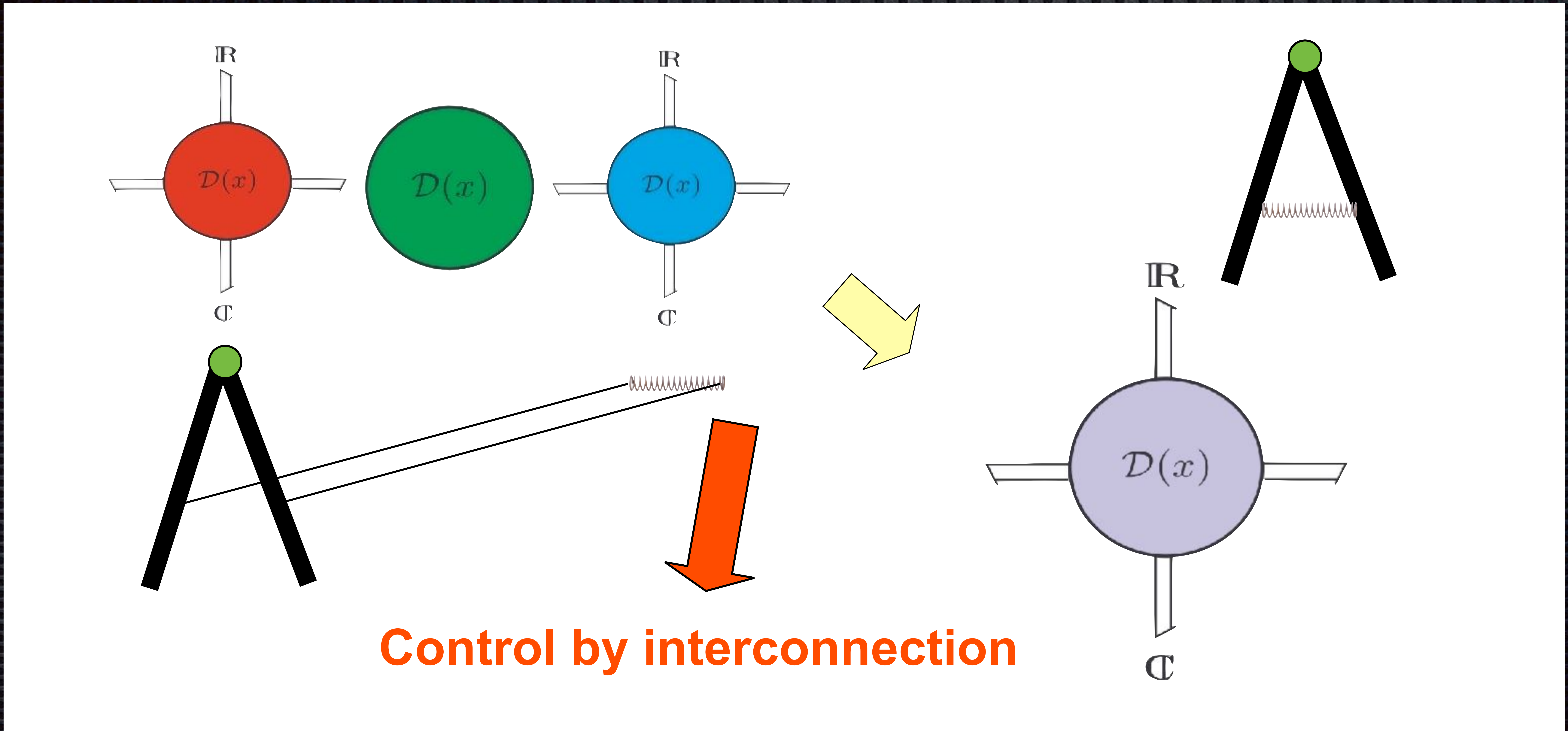




Interaction Port

Control by Interconnection

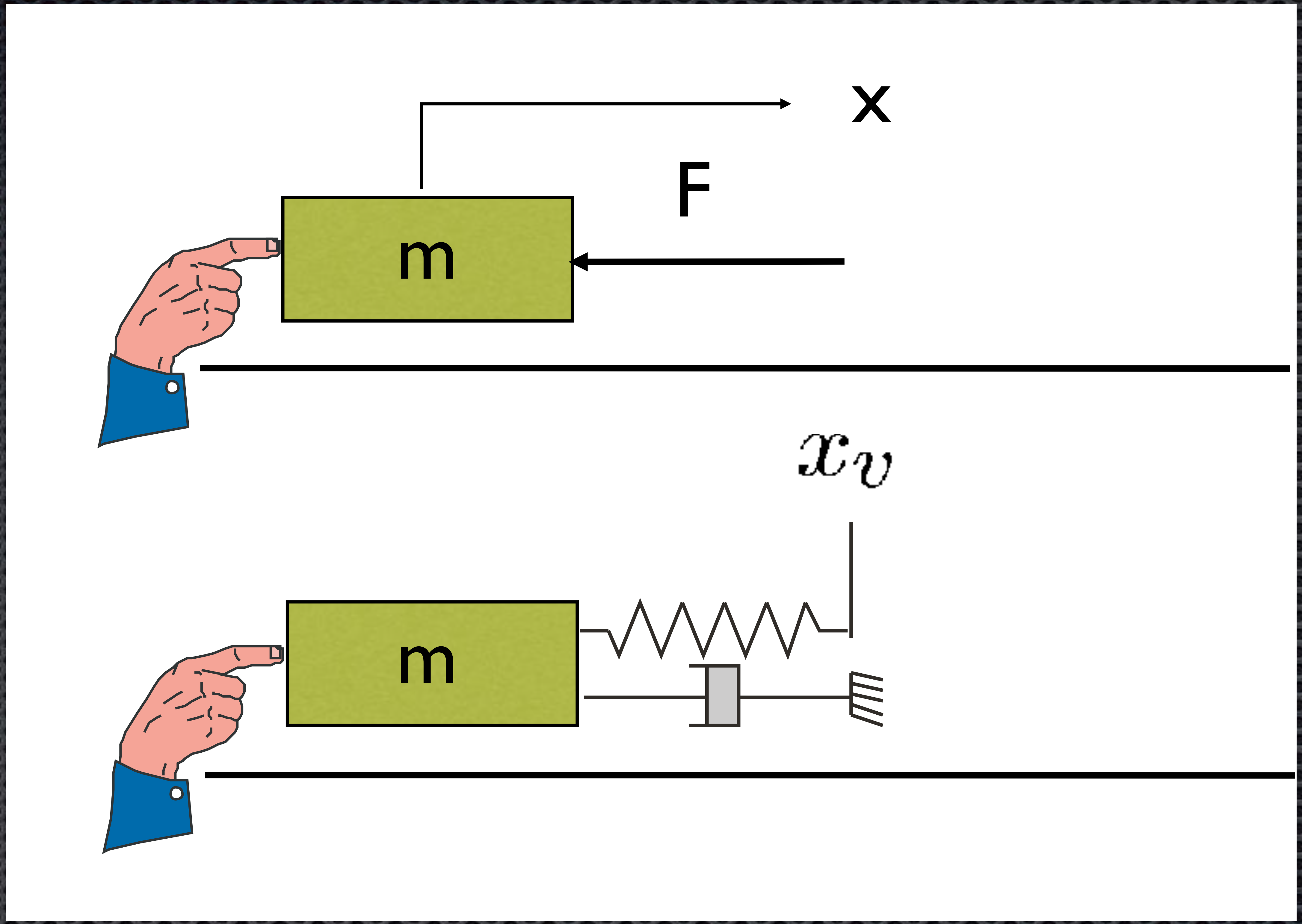
System composition in general



Impedance Control

System

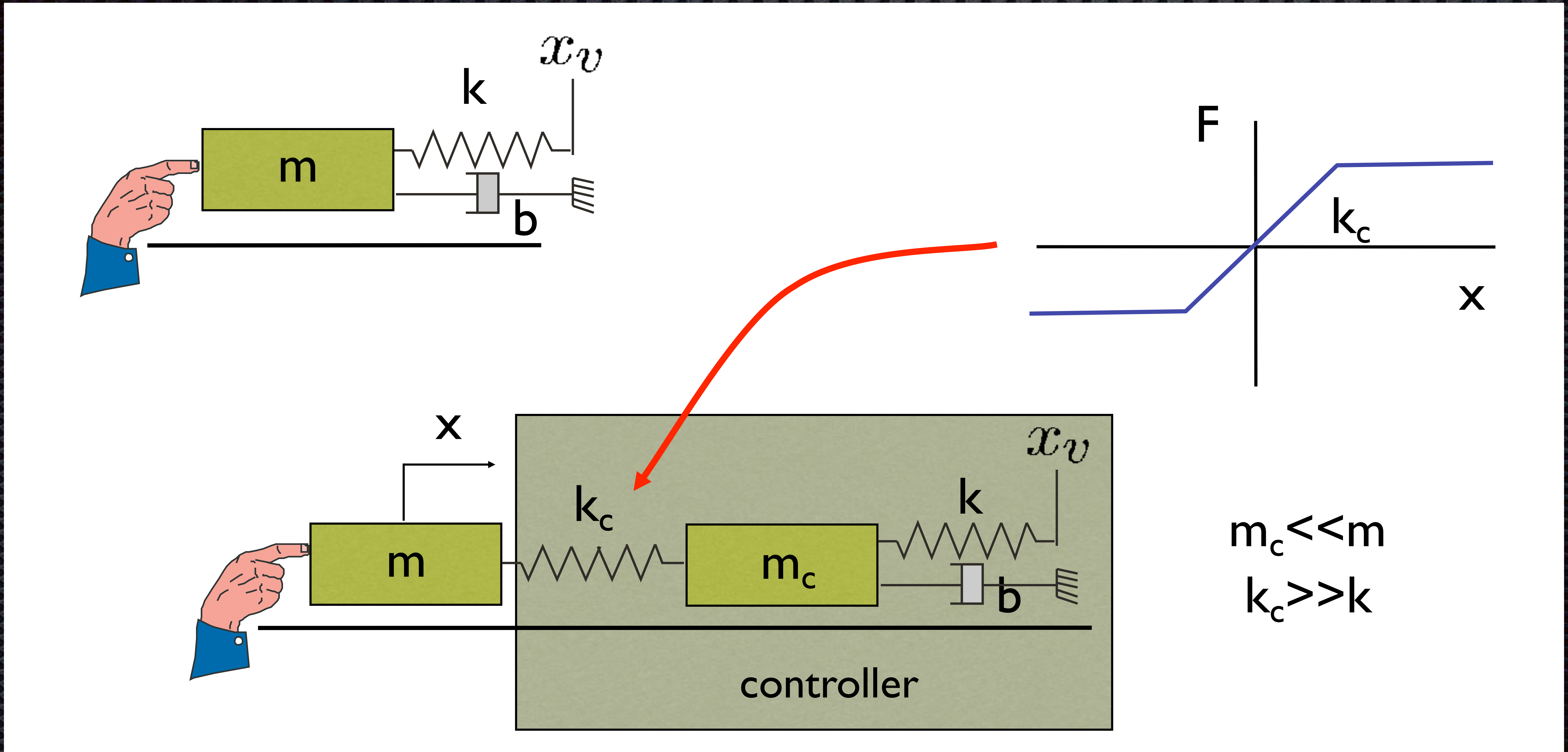
Desired Behavior



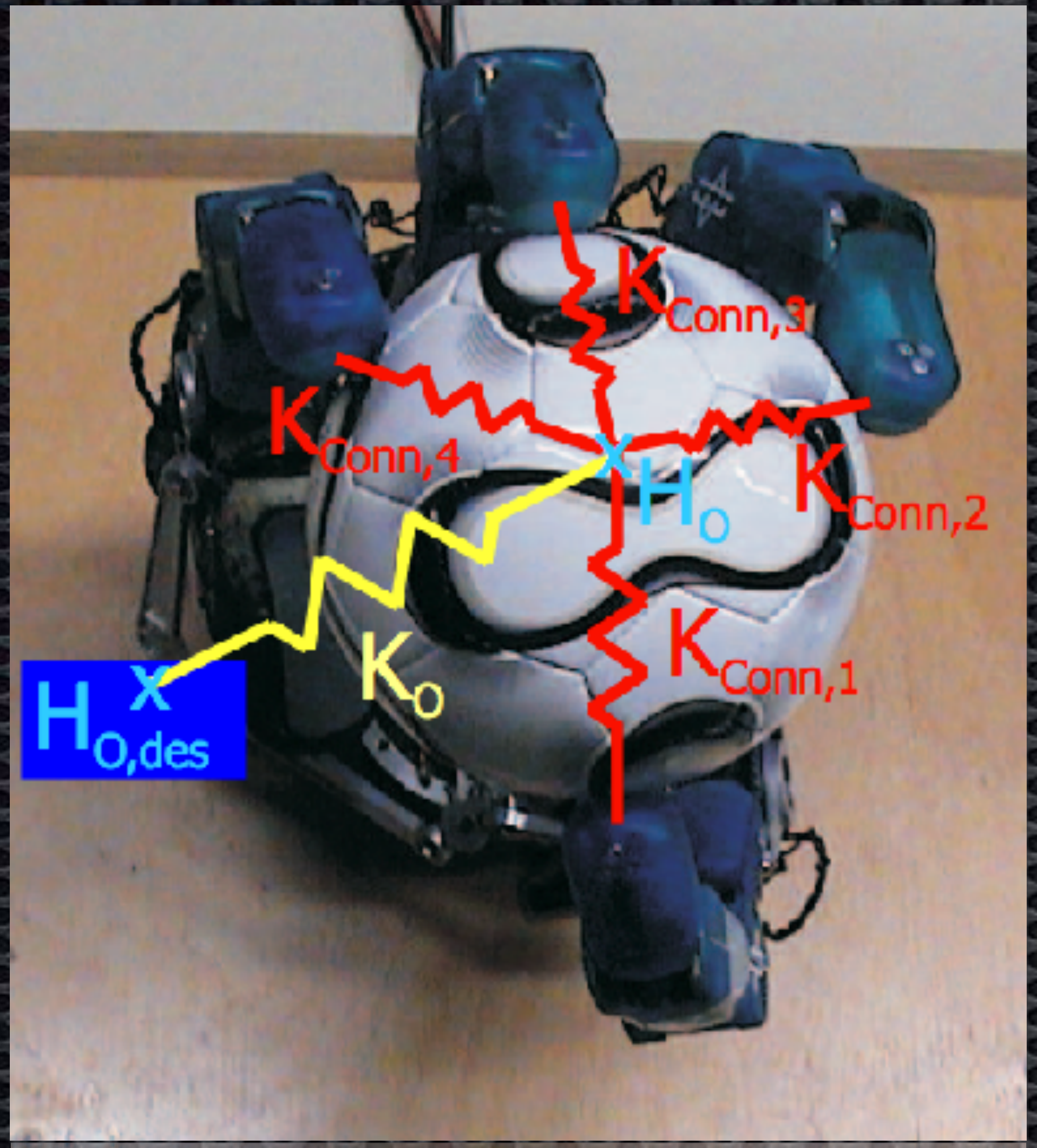
Stramigioli, S. (1996). CREATING ARTIFICIAL DAMPING BY MEANS OF DAMPING INJECTION. In K.Danai (Ed.), Proceedings of the ASME Dynamic Systems and Control Division (Vol. DSC.58, pp. 601–606). Atlanta, (GE).

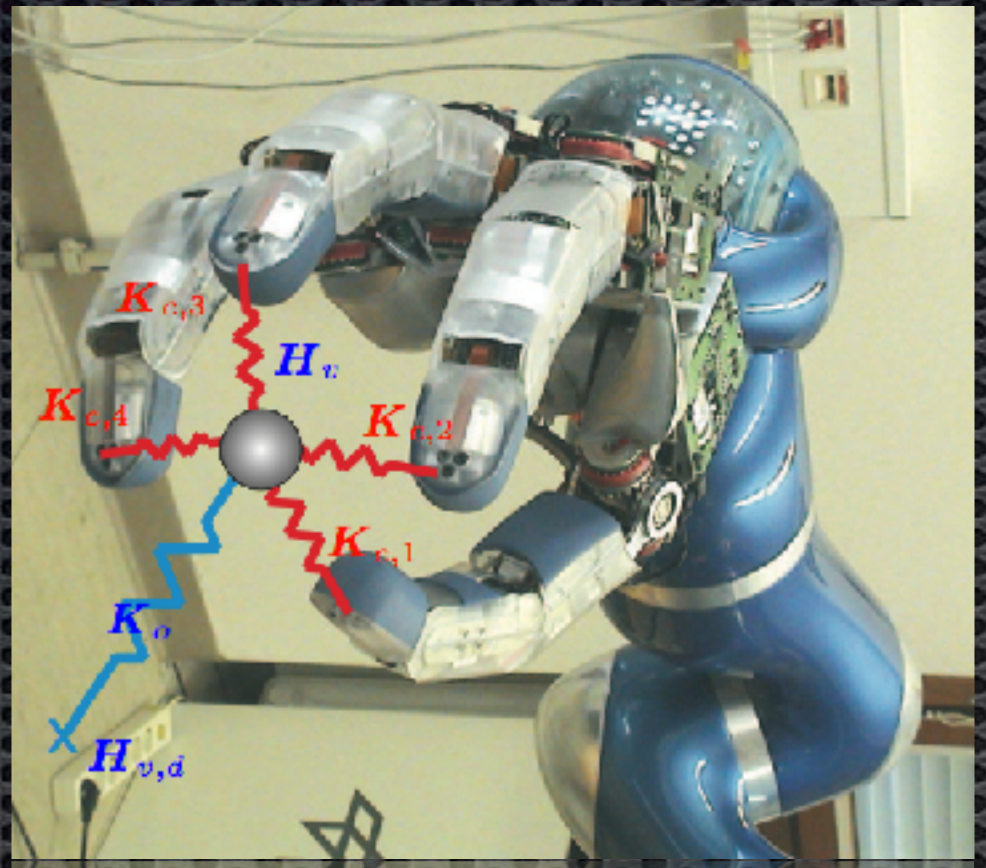
Note:
1. Only position measurement available,
2. Saturation F

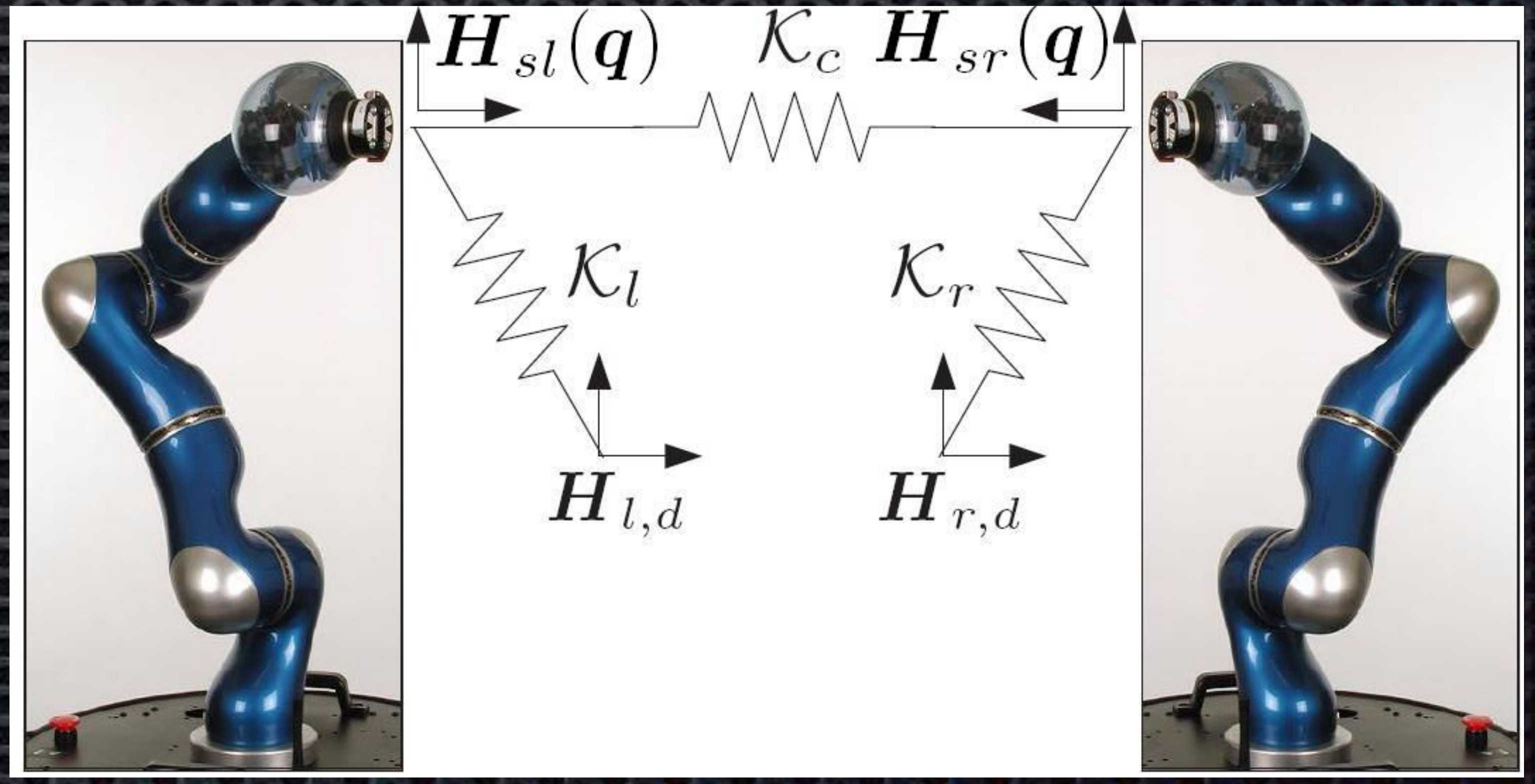
Solution using interconnection ideas



Other Examples







DLR Hand and Dual Arm System

Stramigioli, S. (1999). A novel impedance grasping strategy as a generalized hamiltonian system. In D. Aeyels, F. Lamnabhi-Lagarrigue, & A. van der Schaft (Eds.), Stability and Stabilization of Nonlinear Systems, (Lecture Notes in Control and Information Sciences 246) (Vol. 246, pp. 293–324). London: Springer, London. Retrieved from http://www.springerlink.com/index/YV6077556306V032.pdf

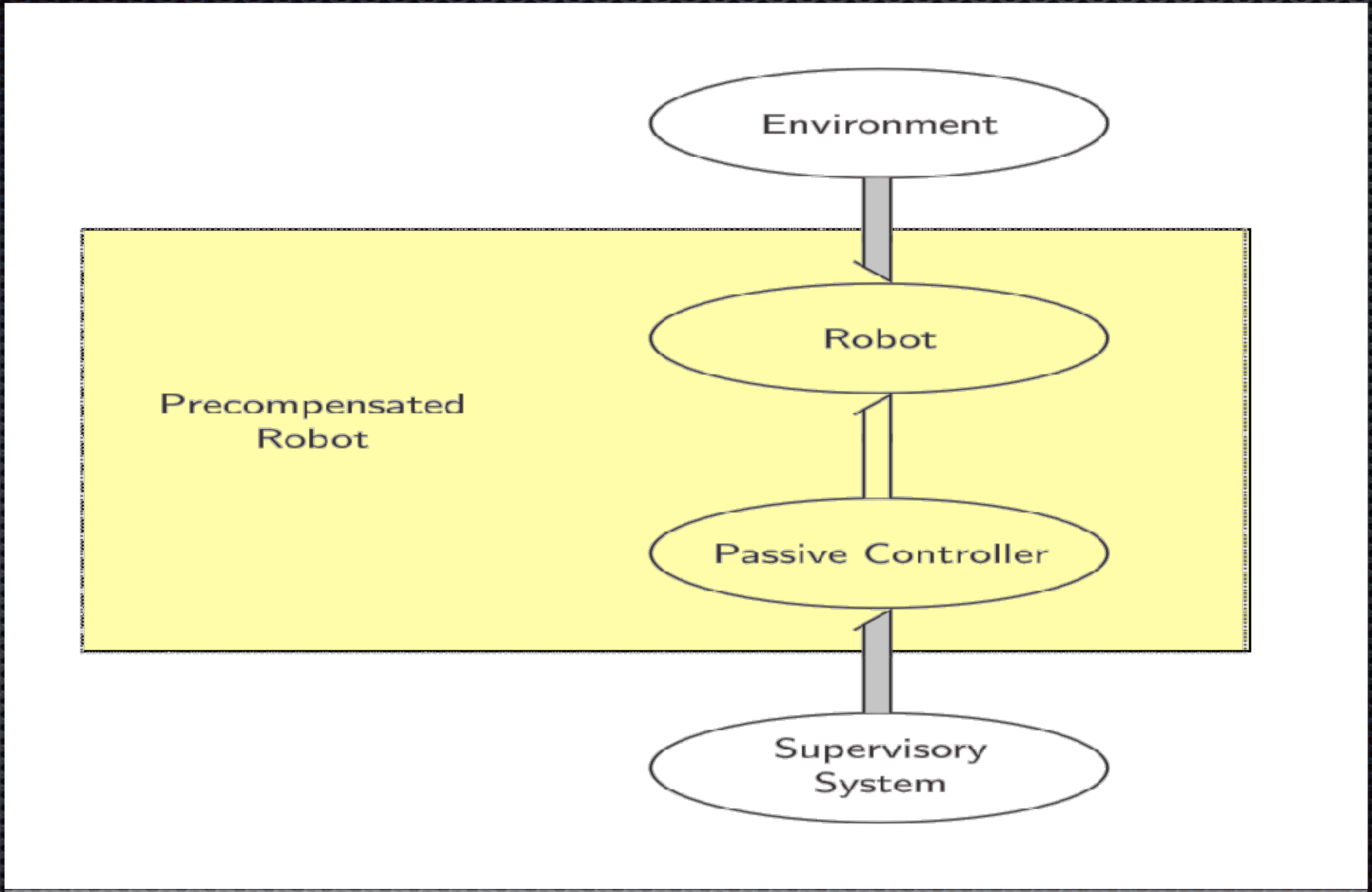
Stramigioli, S., Melchiorri, C., & Andreotti, S. (1999). A passivity-based control scheme for robotic grasping and manipulation. In Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No.99CH36304) (Vol. 3, pp. 2951–2956). Phoenix: IEEE. doi:10.1109/CDC.1999.831385

Remarks

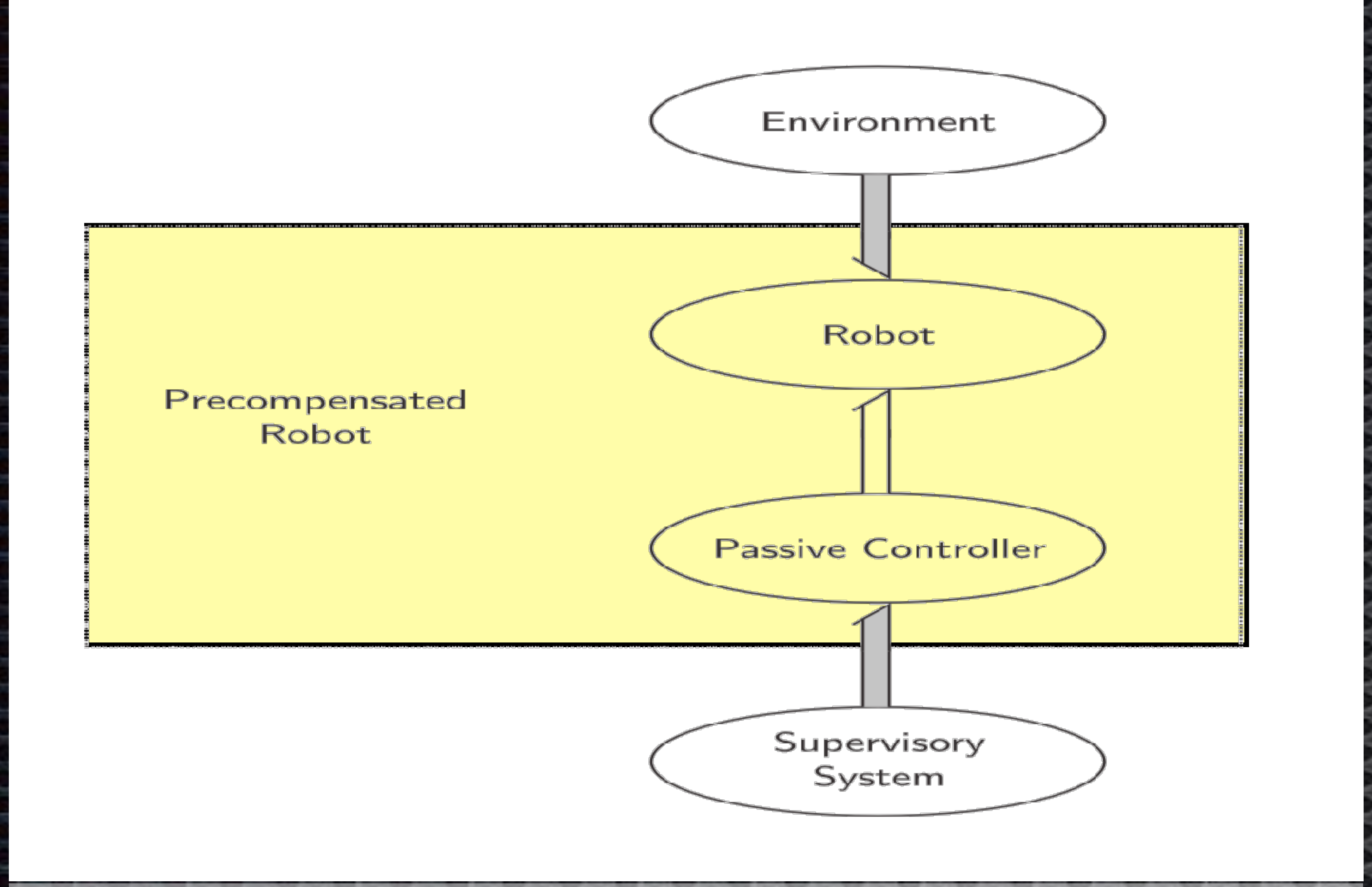
- A REALLY Passive Controller coupled with a robot in a power continuous way will behave passively with ANY environment
- With Control by interconnection, model uncertainty can decrease “performance” but never compromise PASSIVITY and SAFETY
- Possible with physically interpretable controllers and NOT.
- Active behaviour is possible and supervised

IPC-Supervisor Architecture

Proposed Controlled Structure



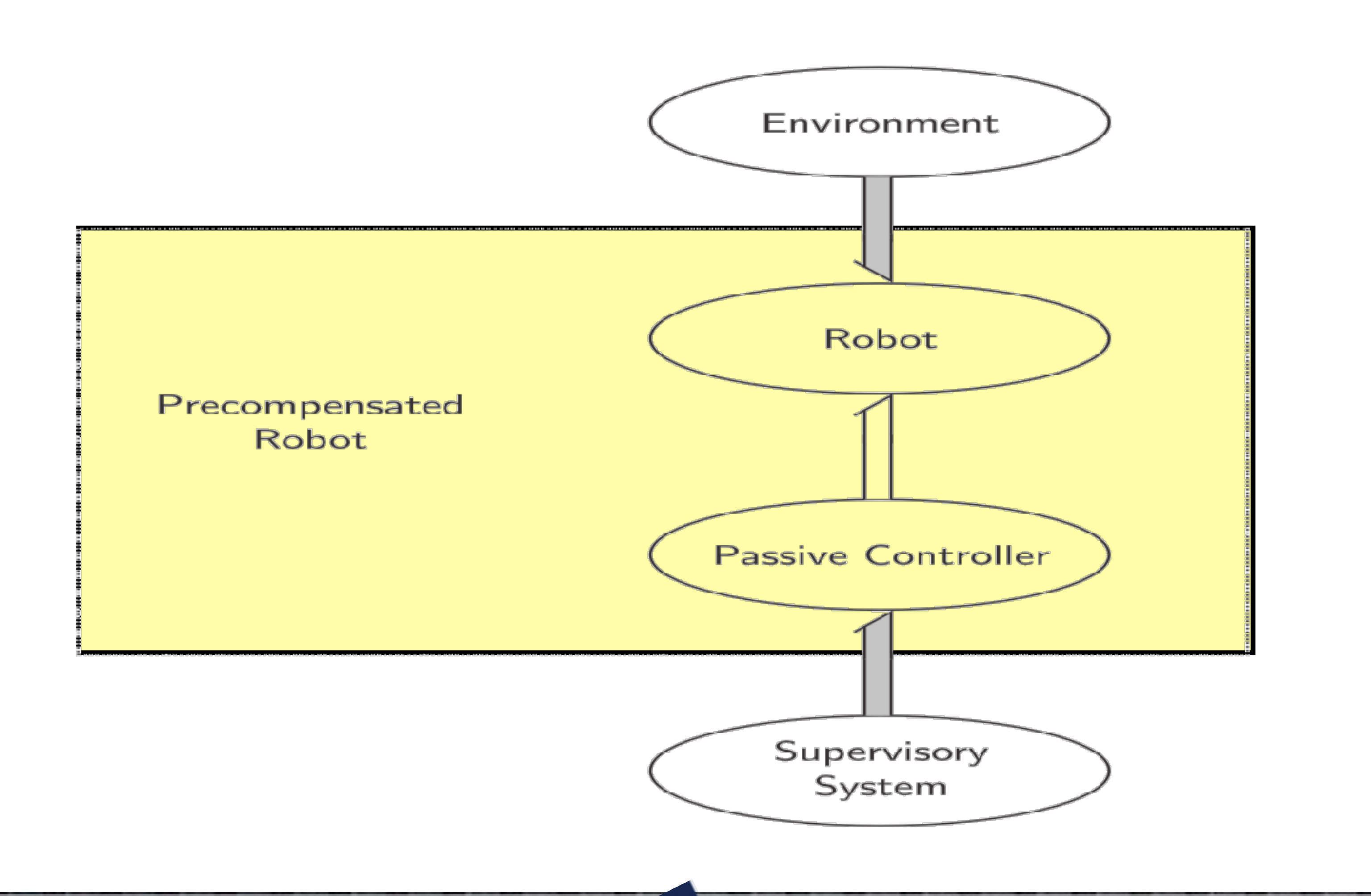
Claims (Conjectures)

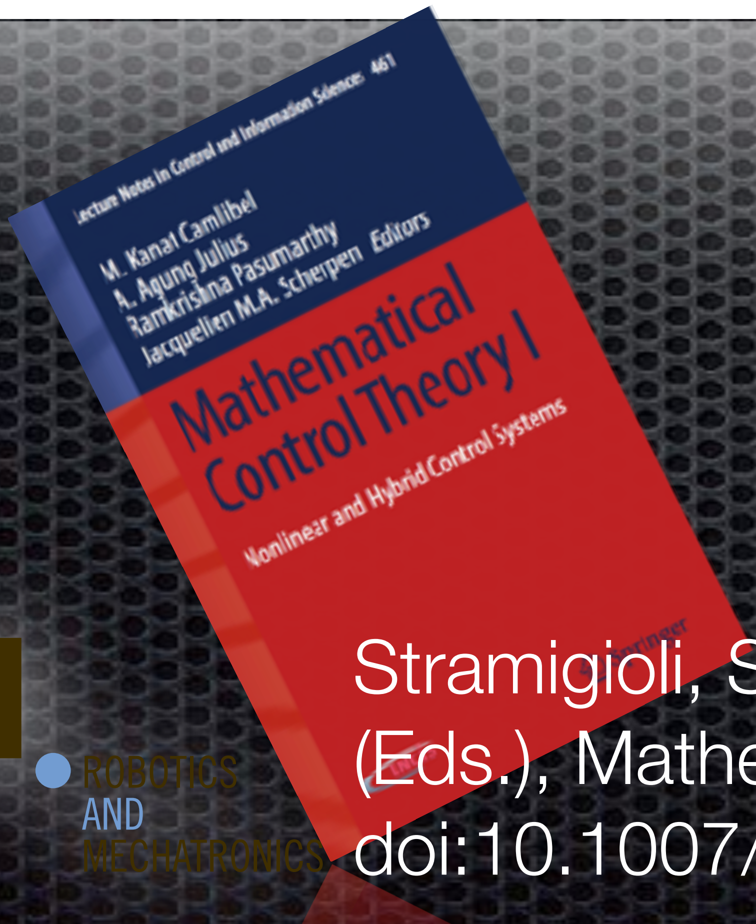


Non Passivity (NP)
A necessary condition for having stable interaction with an unknown environment is that the controlled robot should result in a passive behaviour seen from the port which interacts with the environment

Intrinsically Passive Control (IPC)
A necessary condition for achieving the previous point is that, for a physical robot, which is clearly passive, the control should be **by interconnection** and should be passive by itself following the IPC paradigm.

Problem Statements (Conjectures..)





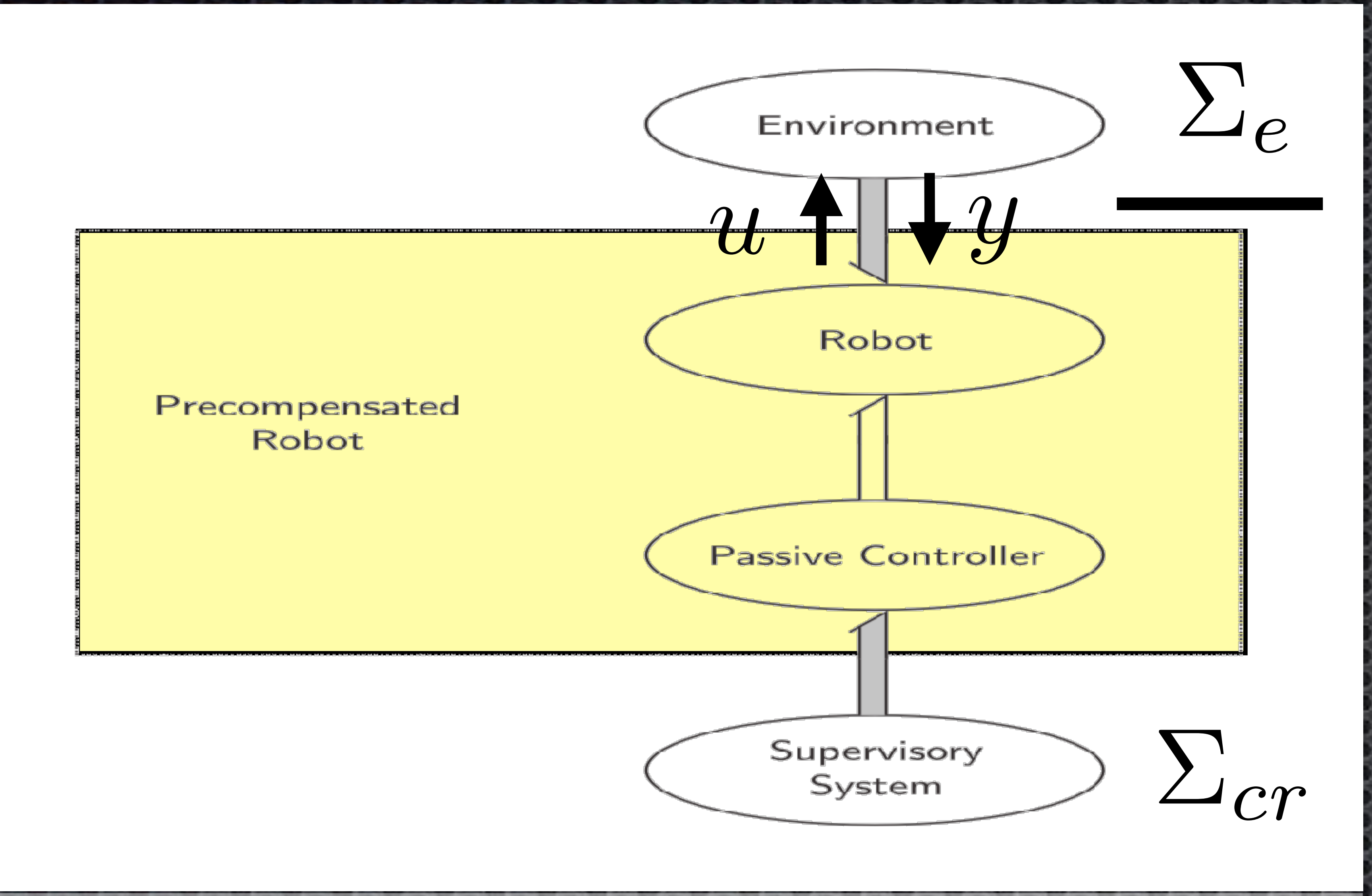
Passivity Control Robot (PCR)
If a controlled robot is not passive seen from the environment port, there is always a (passive) environment which can destabilise the interaction

Not Passive State FeedBack (NPSF)
For any passive robot, a general control which does not specifically address passivity as a port interconnection (IPC), there is always an environment which could result in an unstable interconnected behaviour as described in PCR

Characterisation of Stable Active Environment (CSAE)
Given a Robot controlled passively via interconnection (IPC), we can characterise the **active environments** which would result in a stable interconnected behaviour

Stramigioli, S. (n.d.). Energy-Aware Robotics. In K. Camlibel, J. Agung, J. Scherpen, & R. Pasumarthy (Eds.), Mathematical Control Theory I, Nonlinear and Hybrid Control Systems (pp. 37–50). SPRINGER. doi:10.1007/978-3-319-20988-3

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}

Intrinsically Passive Control

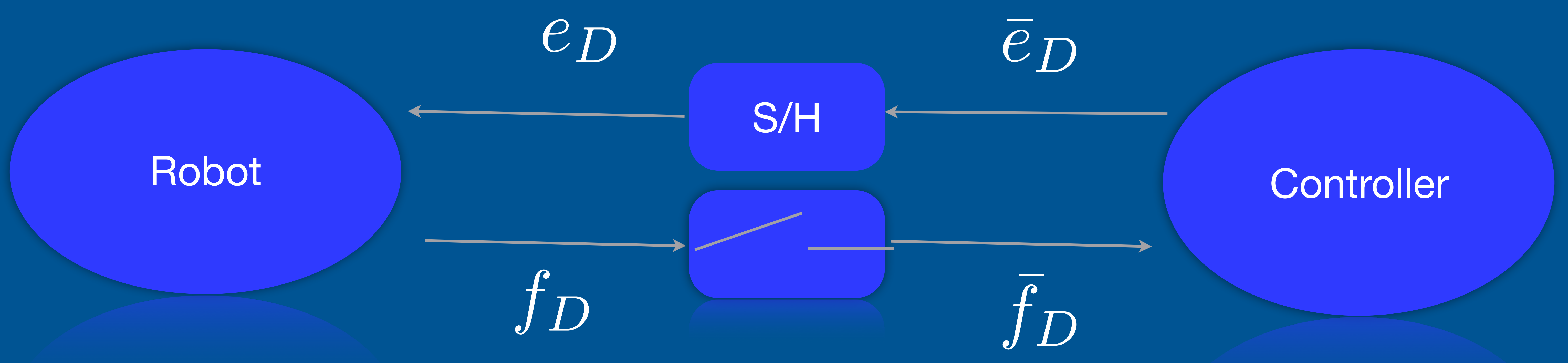
- We need to develop the interactive robot in a way which we can guarantee to be passive to **AT LEAST** be sure it will be stable with a **PASSIVE** environment.
- We can inject energy via the supervisor and if "something goes wrong" cut the energy flow and recover passivity
- We can design a controller equivalent to a 3D multi-body system interconnected to the robot to be controlled: the controller will be a set of equivalent multibodies, spatial springs…, all using ports and Port Controlled Hamiltonian Systems representation!
- More general structures are also possible and can be analysed with Port-Hamiltonian Systems Theory

Questions

1. How can we take care of the digital implementation?

2. How can we take care that we alway respect the “control by interconnection” paradigm?

Answer 1: Sample Passivity



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

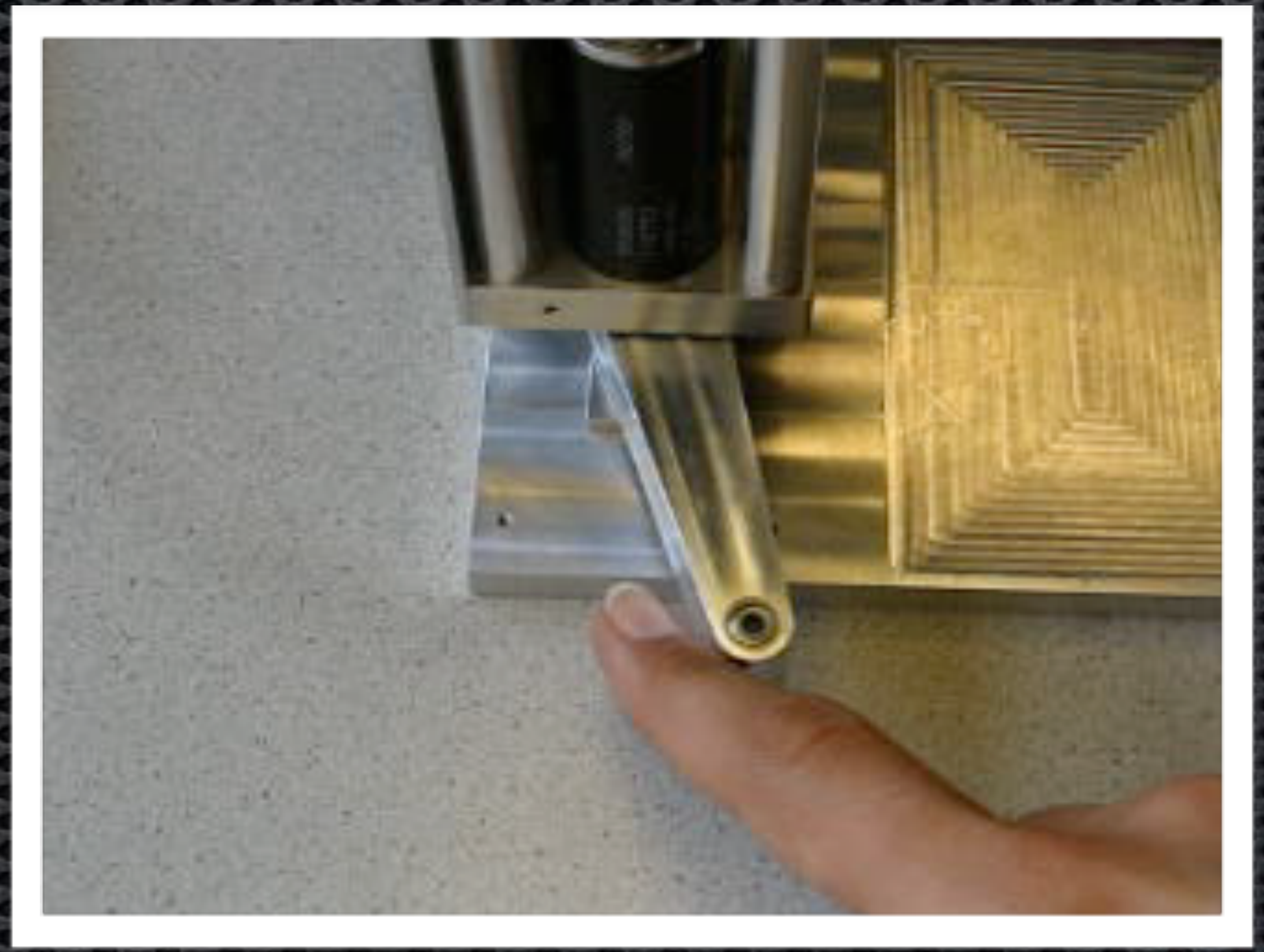
$$\Delta E_C^{in} = \int_{kT}^{(k+1)T} \bar{e}_D^T f_D(s)ds = \bar{e}_D(k) \int_{kT}^{(k+1)T} f_D(s)ds$$

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

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!

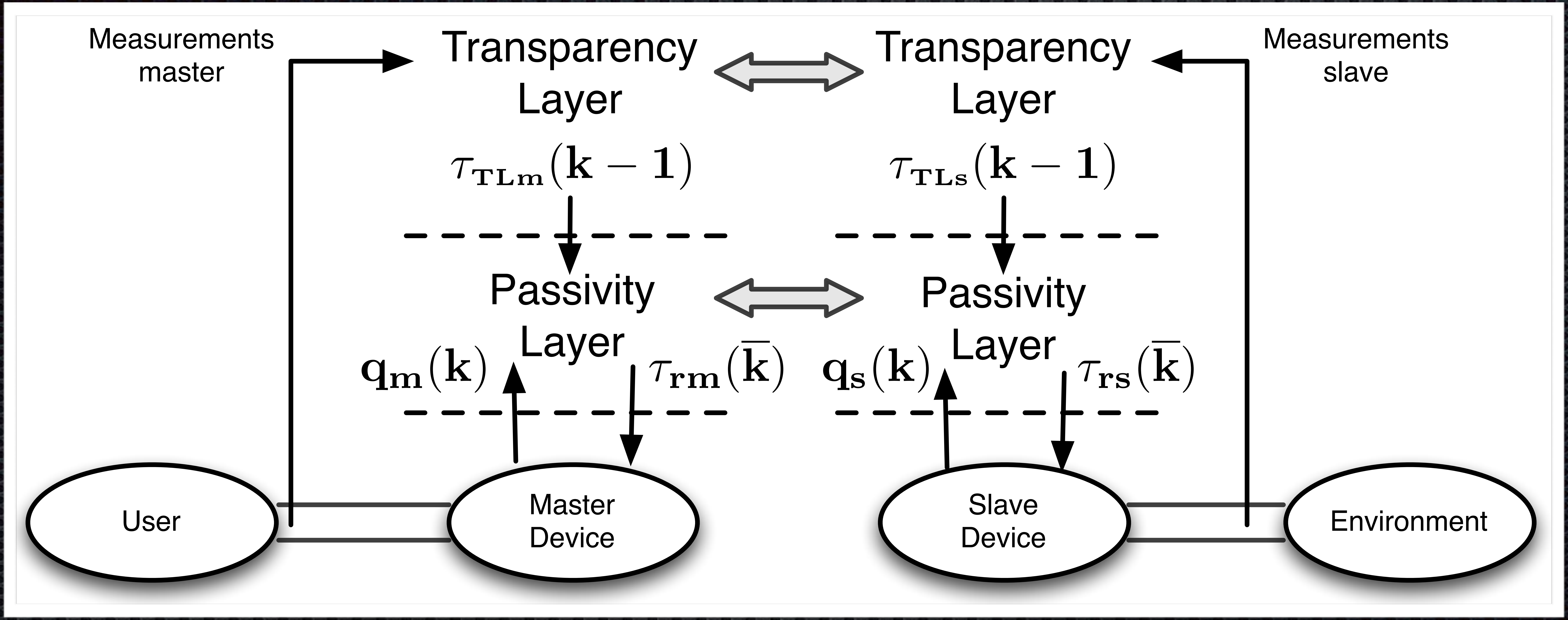
Standard PD



IPC PD

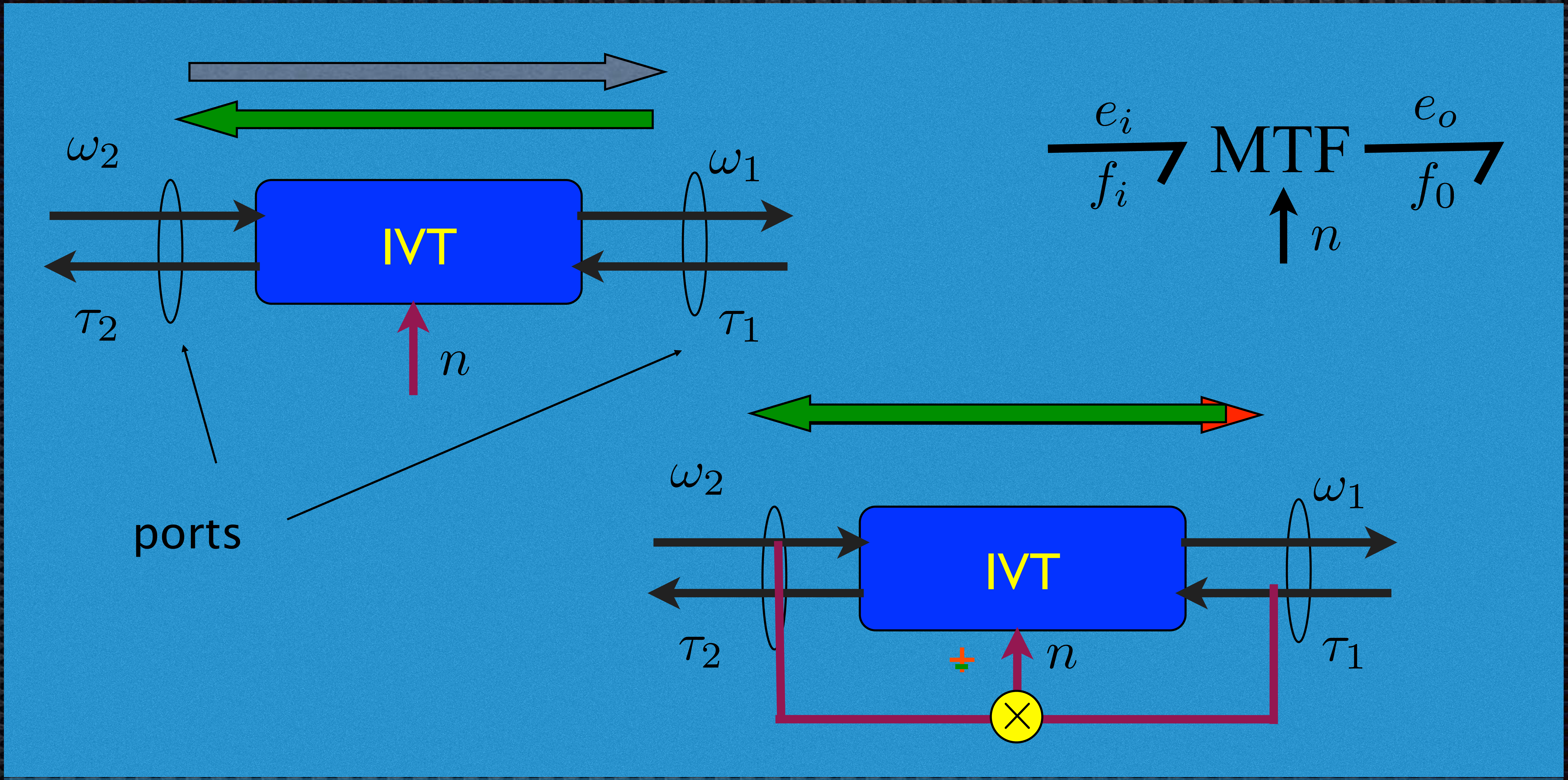
30 Hz sample rate

Solving the time delay problem in telemanipulation



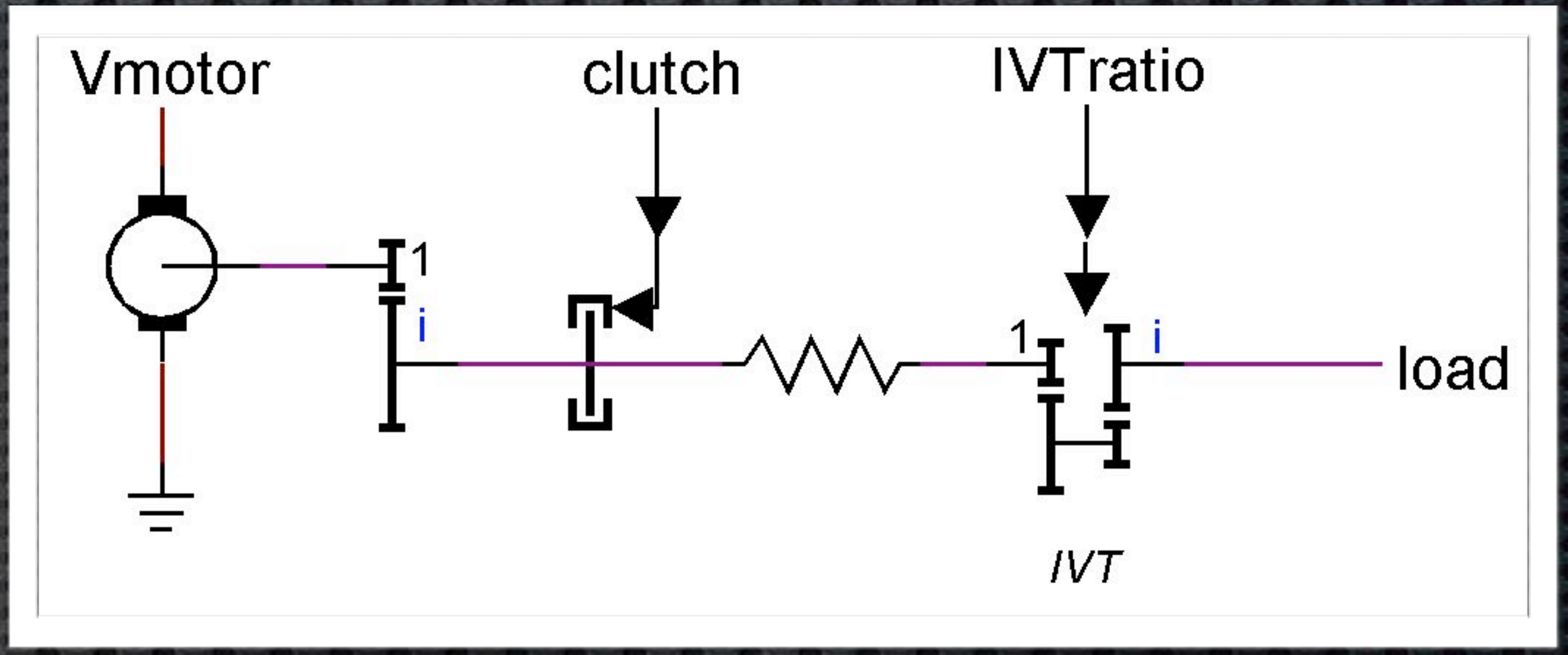
Franken, M. C. J., Stramigioli, et al. (2009). **Bridging the gap between passivity and transparency**. In Robotics: Science and Systems V, Seattle, USA (p. 36). Robotics Science and Systems.

Answer 2: Control Energy Flows



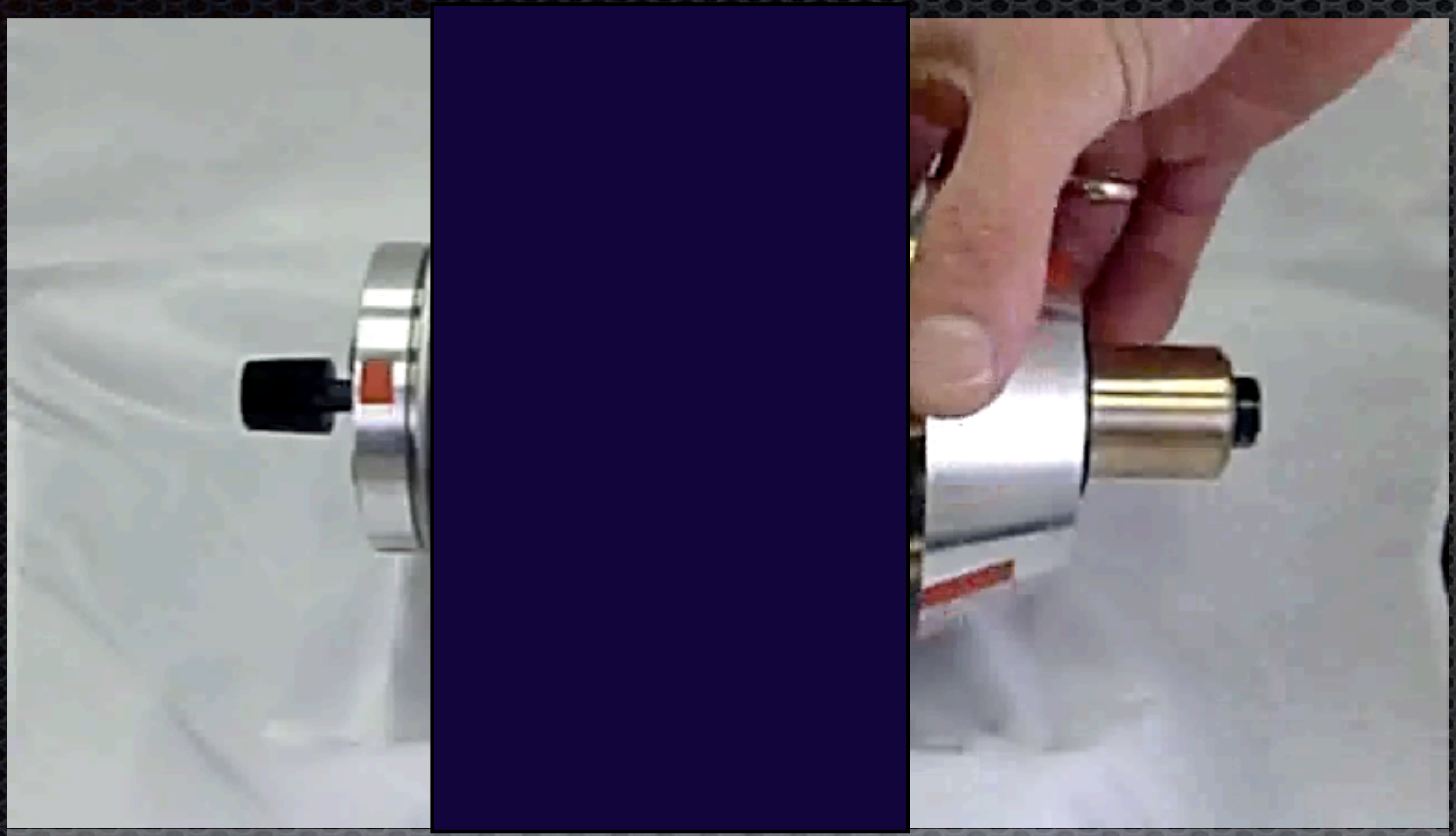
Very Versitile Energy Efficient Actuator

- Torque Servoing
- Stores any negative work applied on load
- Zero dissipation for constant force
- Ideal for periodic motions
- Can REVERSIVELY achieve damping! Advantage of damping WITHOUT loss of energy



Stramigioli, S., van Oort, G., & Dertien, E. (2008). A concept for a new Energy Efficient actuator. In 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (pp. 671–675). China: IEEE. doi:10.1109/AIM.2008.4601740

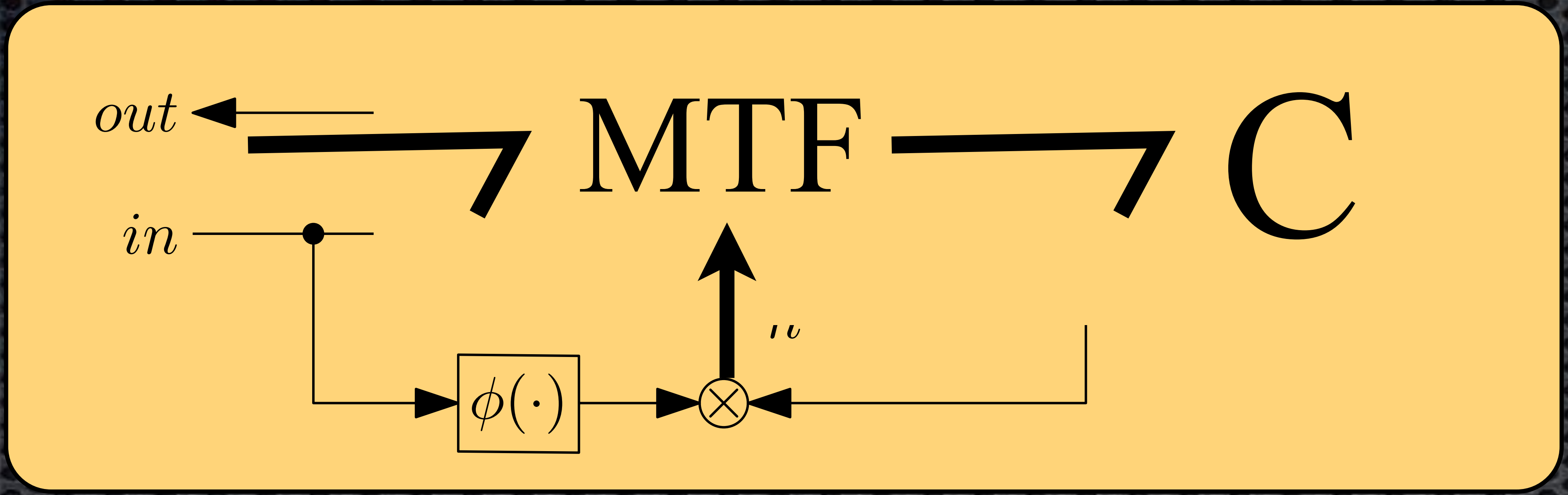
UT-IVT

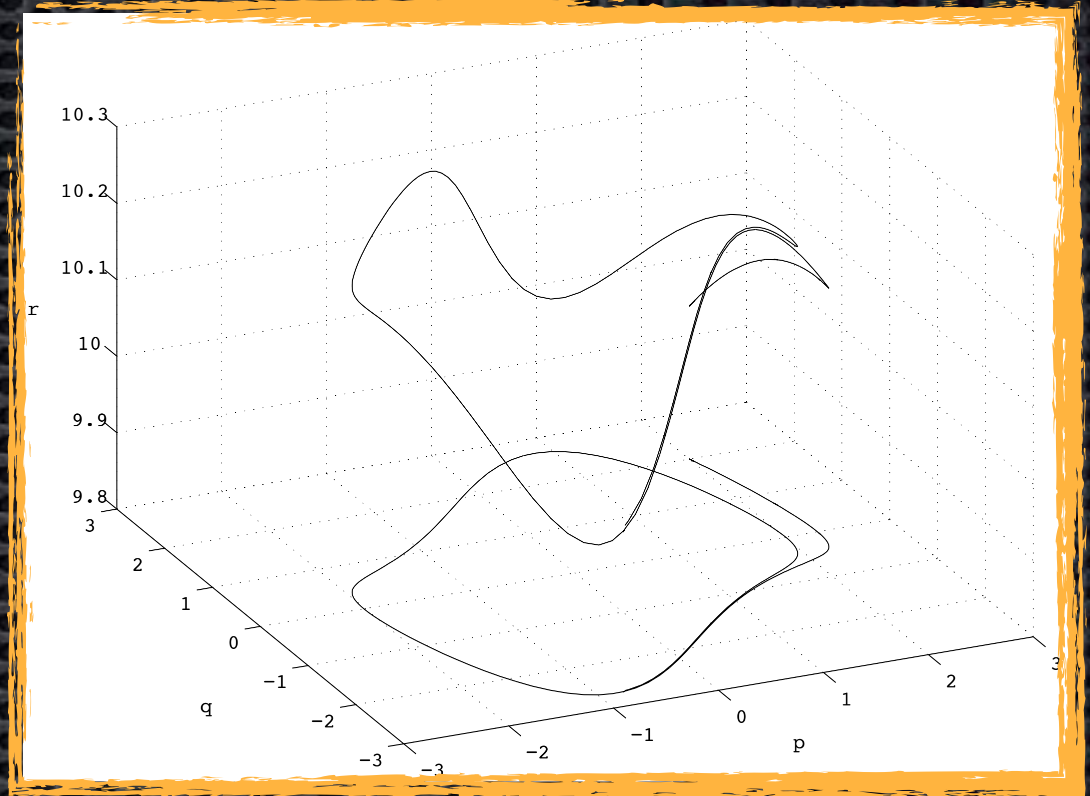


Gain >0

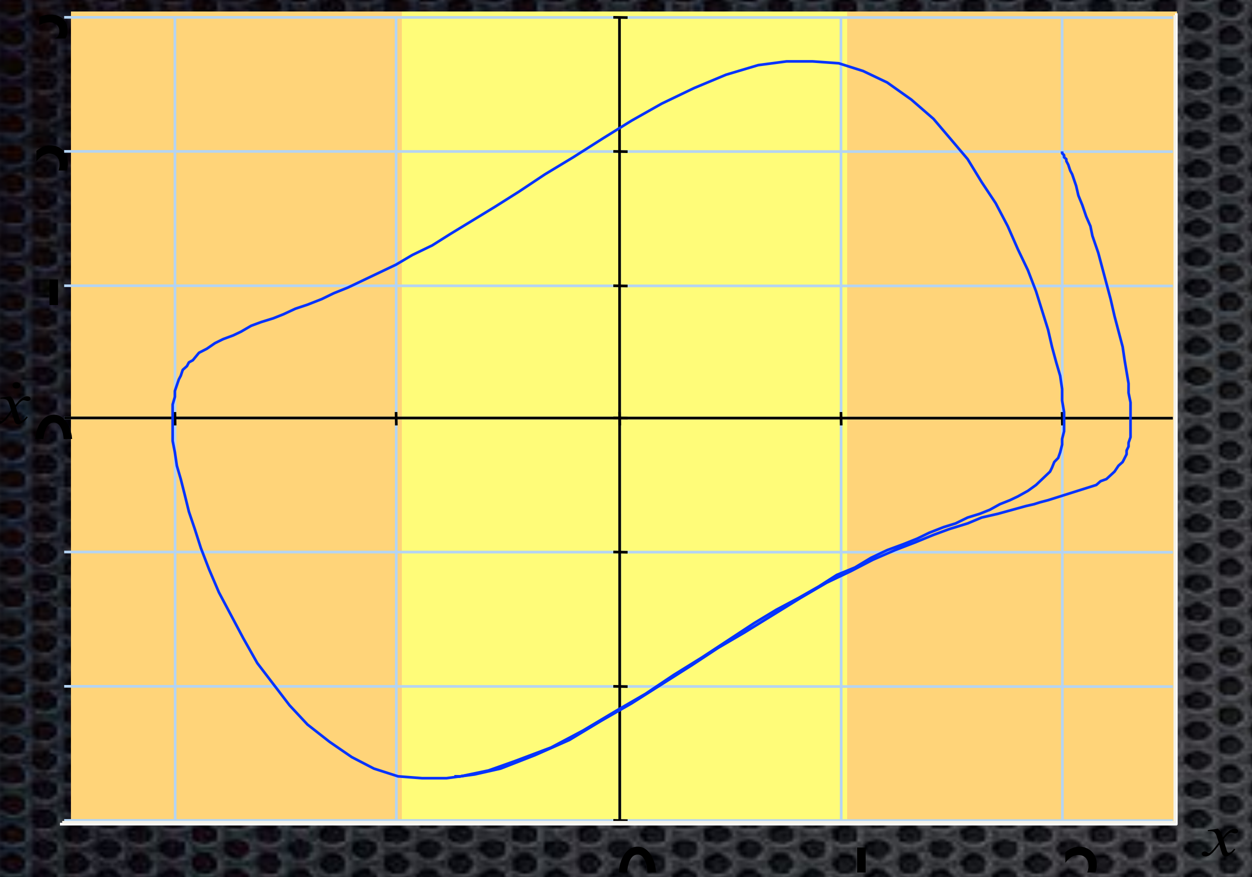
Gain =< 0

Use in Limit Cycle generations





v.d. Pol



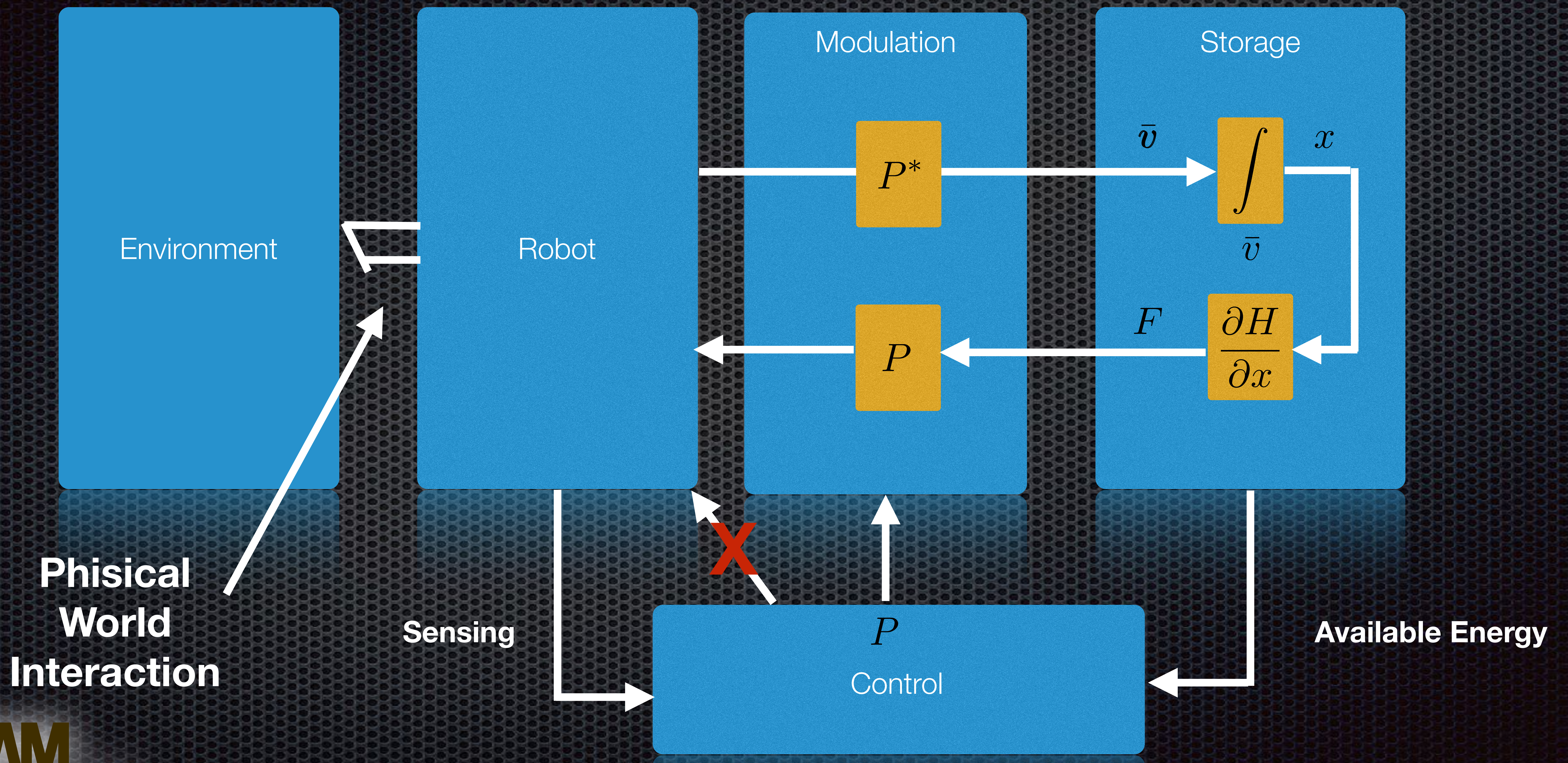
$$\begin{bmatrix} \dot{q} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & -n \\ 0 & n & 0 \end{bmatrix} \begin{bmatrix} q \\ p \\ r \end{bmatrix}.$$

$$\ddot{x} + \left(x^2 - 1\right)\dot{x} + x = 0$$

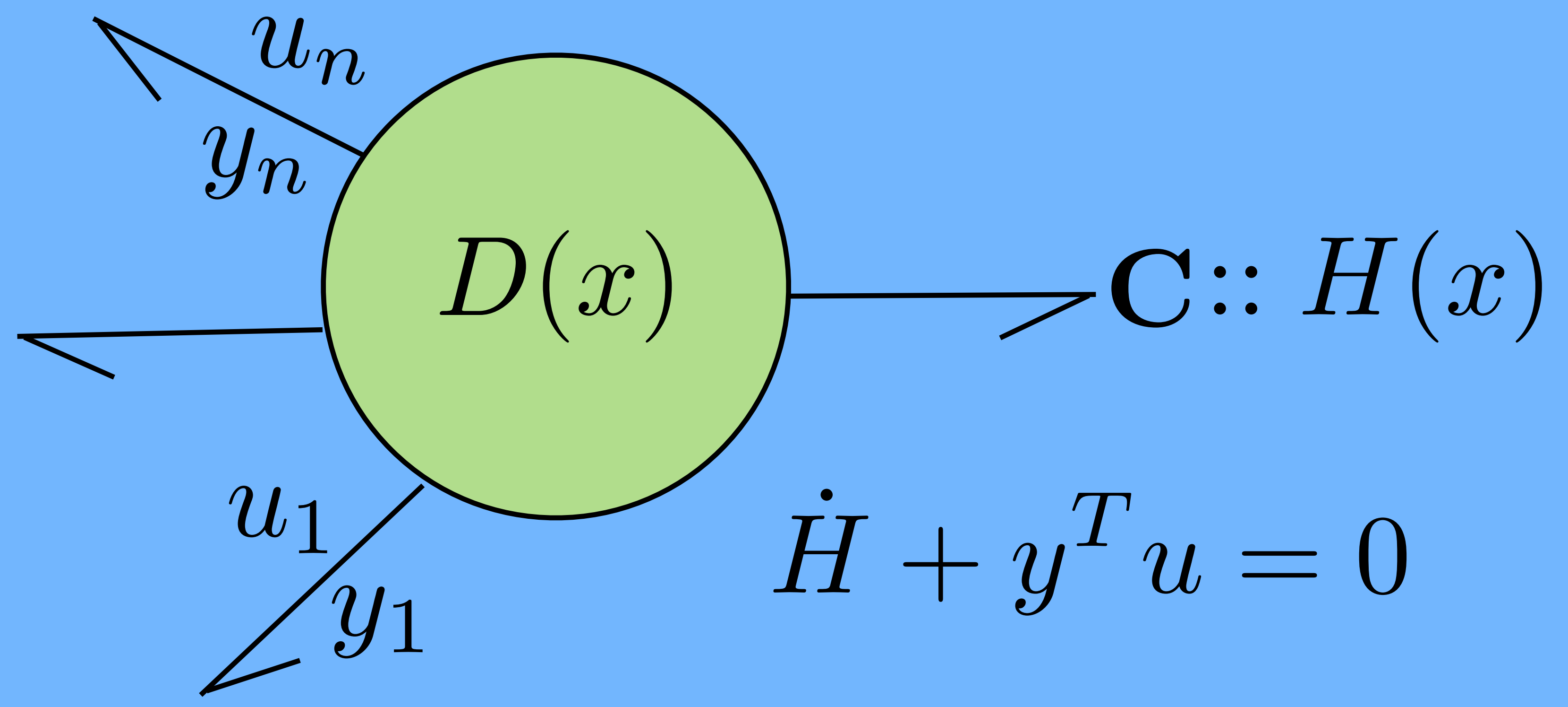
$$H(x) = \tfrac{1}{2}x^T \cdot x = \tfrac{1}{2}q^2 + \tfrac{1}{2}p^2 + \tfrac{1}{2}r^2.$$

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

Answer 2: Control Energy Awareness



Answer 2: Generalisation



$$\dot{H} + y^T u = 0$$

$$u := \begin{pmatrix} u_1 & \dots & u_n \end{pmatrix}$$
$$y := \begin{pmatrix} y_1 & \dots & y_n \end{pmatrix}$$

$$\begin{pmatrix} u_1 \\ \vdots \\ u_n \\ \dot{x} \end{pmatrix} = D \begin{pmatrix} y_1 \\ \vdots \\ y_n \\ \frac{\partial H}{\partial x} \end{pmatrix} \#$$

with $D = -D^T$

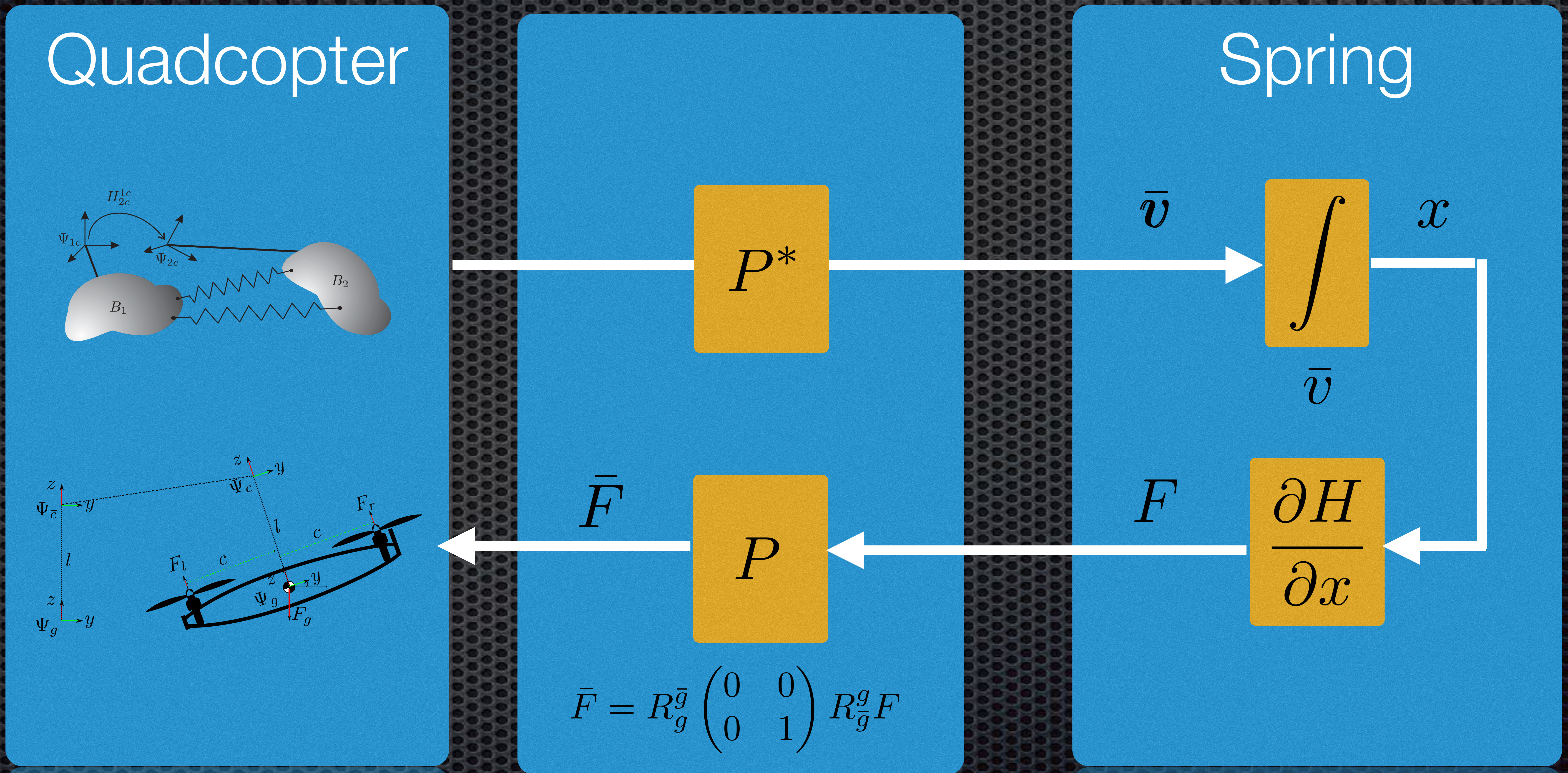
$$H(x) = \frac{x^2}{2}$$

It can be shown that

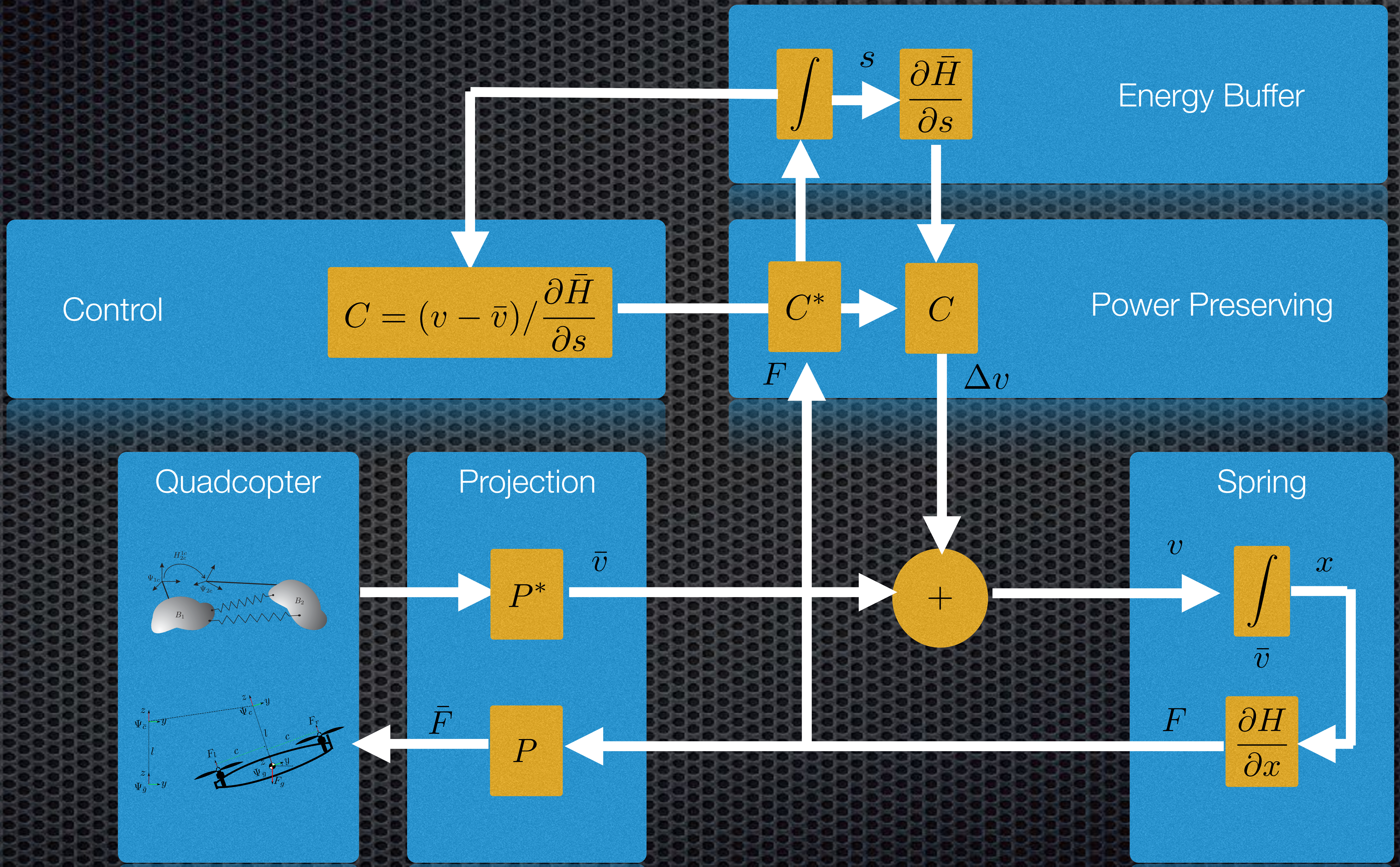
$x > 0 \Rightarrow \forall u \quad \exists D$ s.t. # holds

Damping would be automatically handled

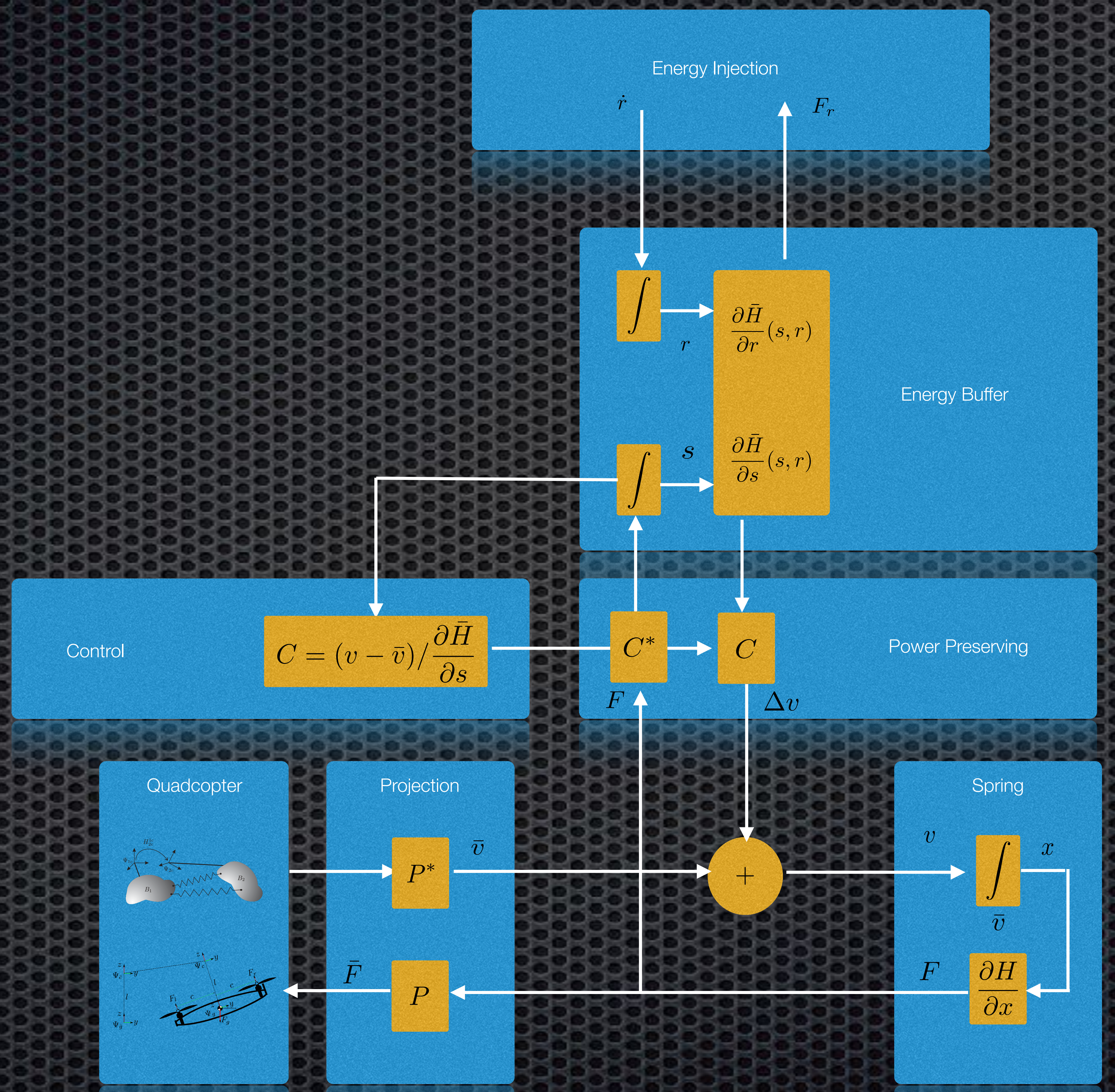
Projection Problem Example



Projection Solution



Projection Solution



Reflections

- For Robots Mechanically interacting with "the world", **energy paradigm is a must**
- It has been formally proven that if we do not do it, we risk to get instability even with some passive environment
- A formal proof that non-collocated/state fb control for passivity is not robust is being worked on
- The methods have proven to
  - be formally sound,
  - work properly in practice
  - deliver new paradigms in actuation, control, tele manipulations etc.