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Port-Based Robotics

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- Control by Interconnection
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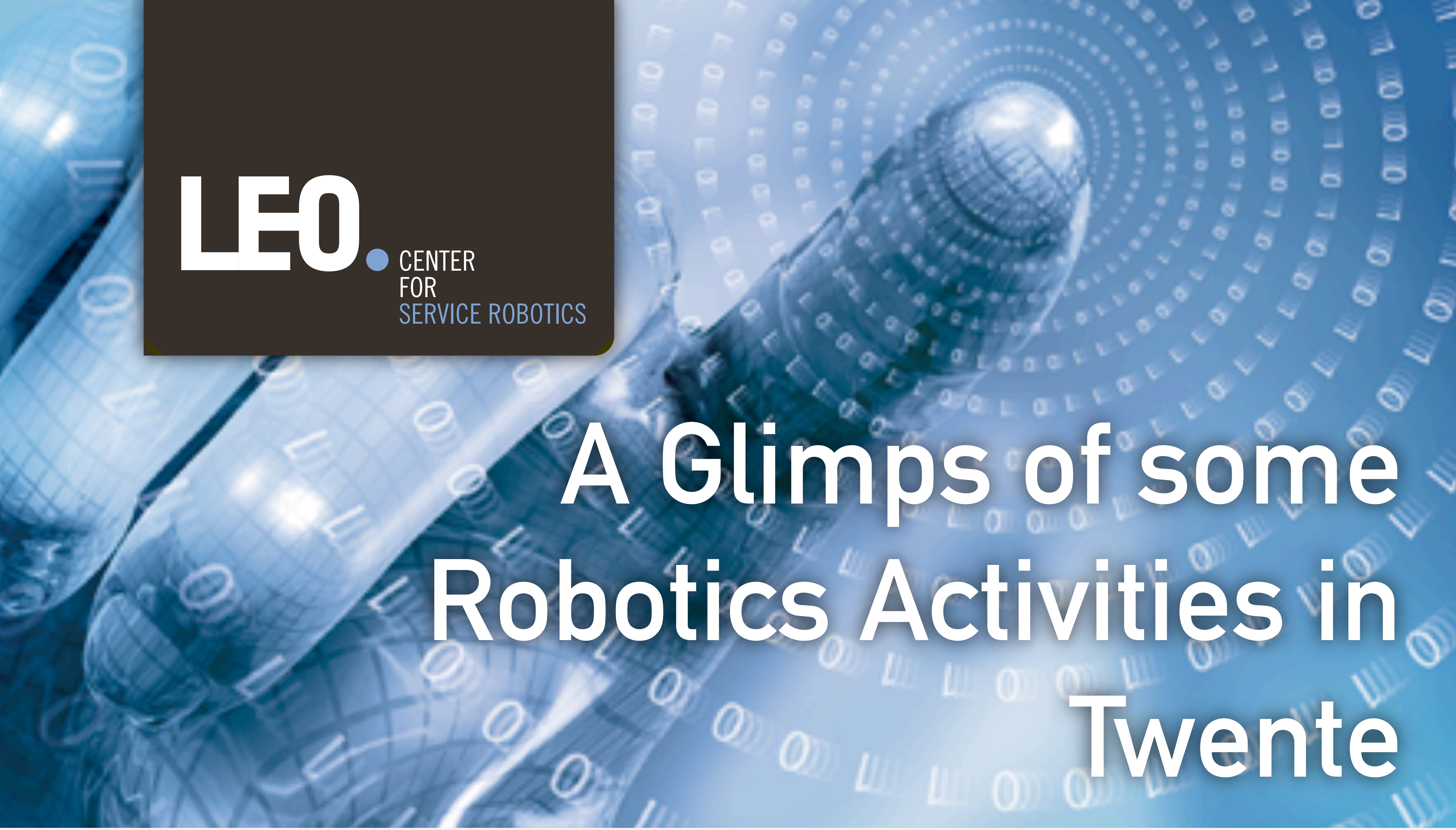

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A Glimps of some Robotics Activities in Twente

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Netherlands

UNIVERSITEIT VAN AMSTERDAM

TU Delft Delft University of Technology

LELY

TU/e Technische Universiteit Eindhoven University of Technology

3TU.

PHILIPS sense and simplicity

PHILIPS sense and simplicity

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3TU.

DEMCON advanced mechatronics

Roessingh Research and Development

Het Roessingh

oost nv

european robotic institute

assistive innovations

WAGENINGEN UR For quality of life

RoboNED

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Medical Robotics

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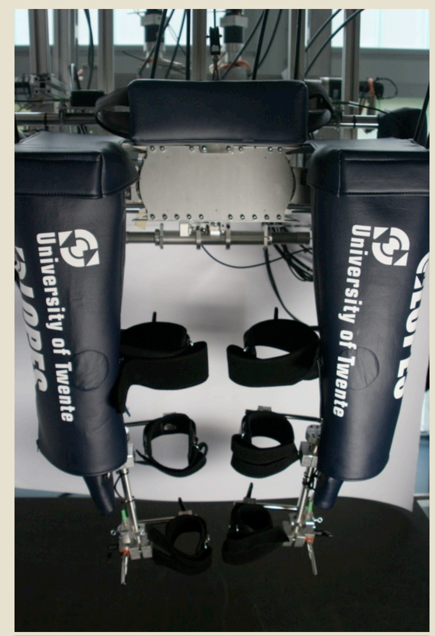
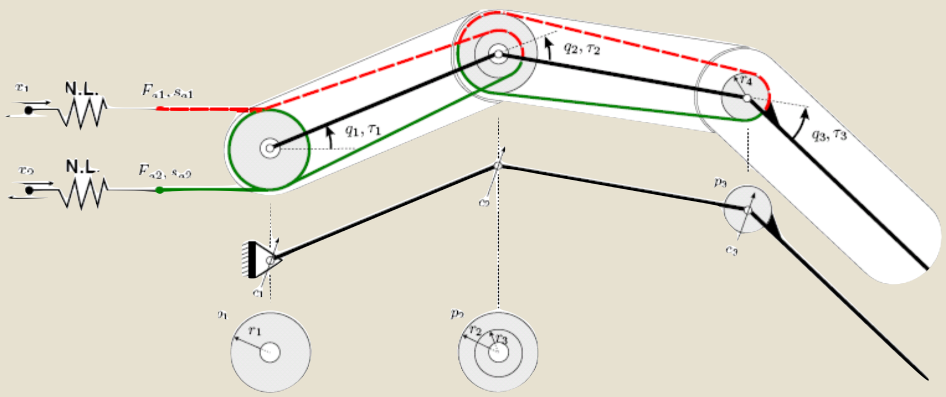
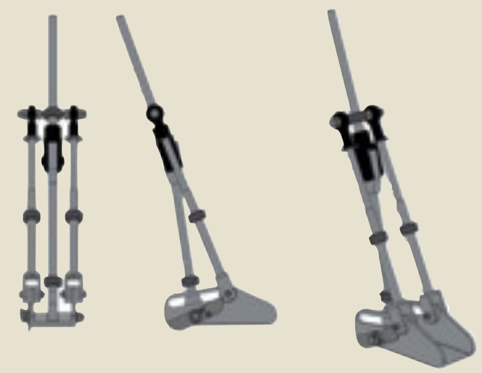
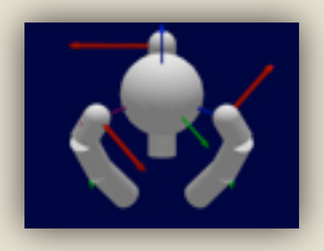
Rehabilitation Robotics



Prosthetics







Myopro

Robotics Surgery

- NOTES Master
- Brain Assisted Surgery
- Epiduroscopy
- Robotised Endoscopes
- MRI compatible devices

TeleFLEX

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Inspection Robotics

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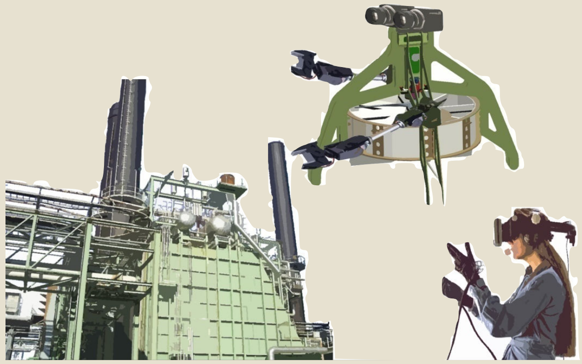
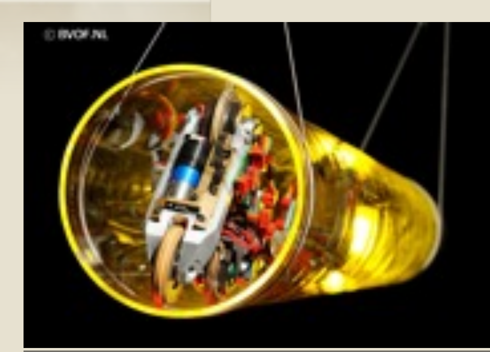
Inspection Robotics





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Humanoid Robotics

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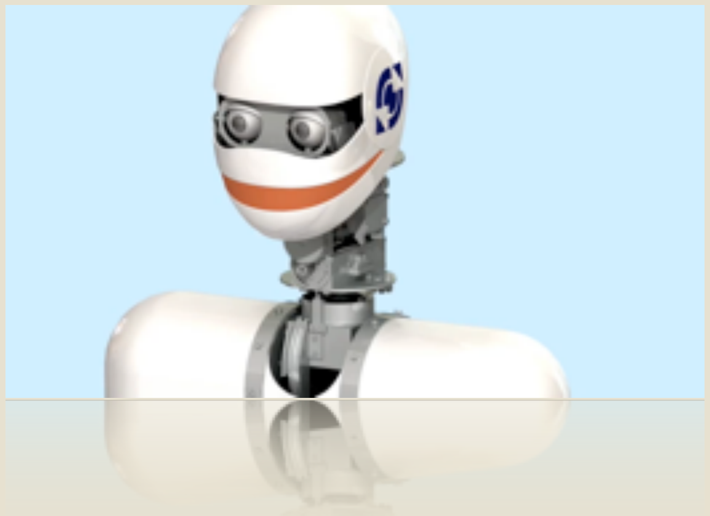
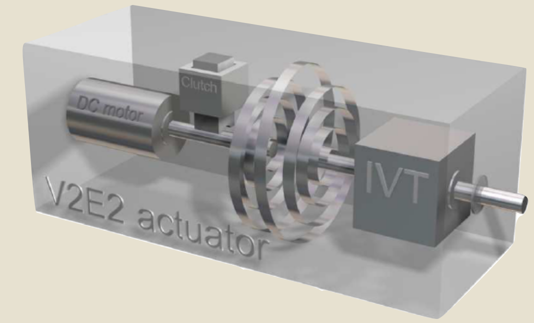
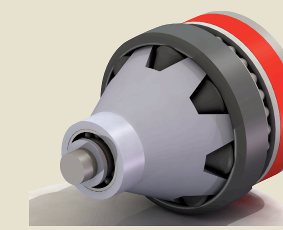
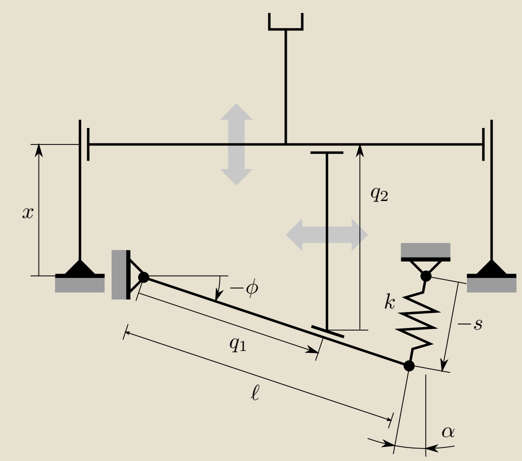
Humanoid Robotics









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20sim Package

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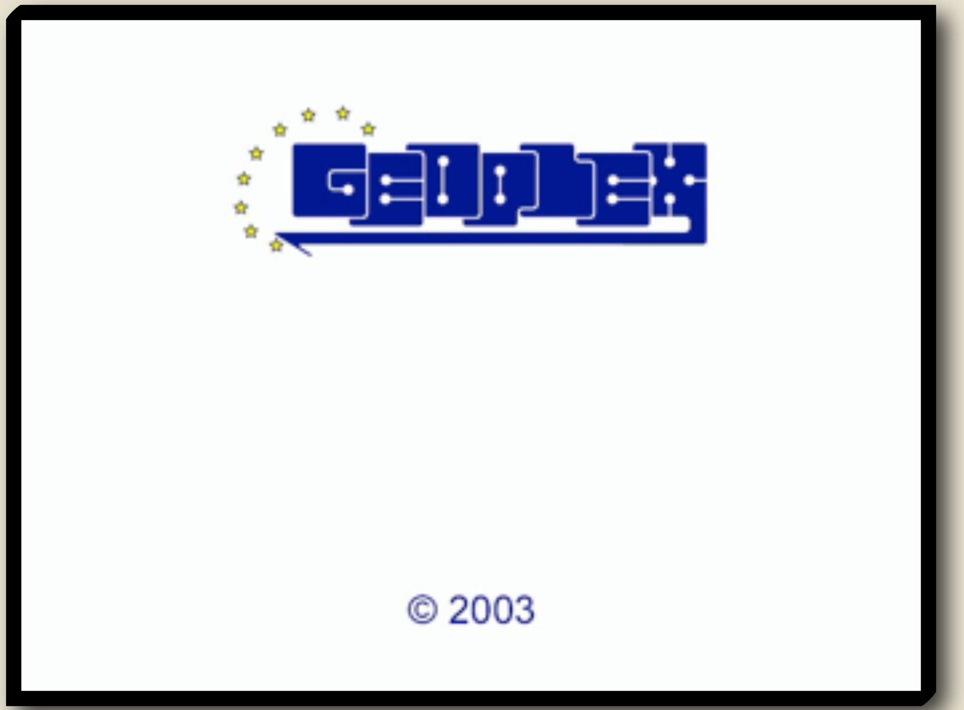
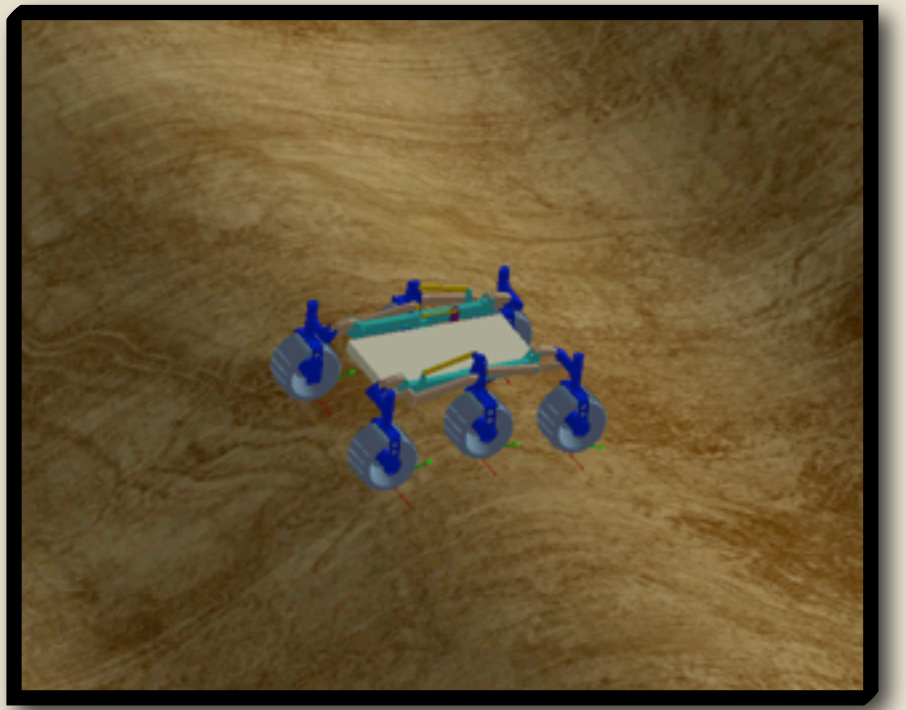
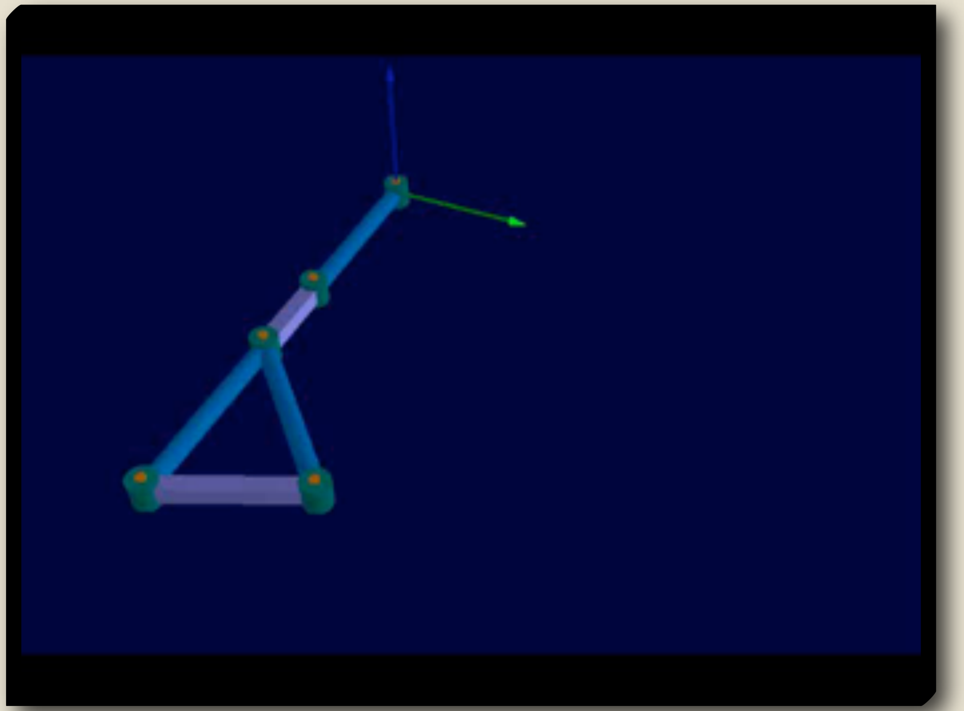
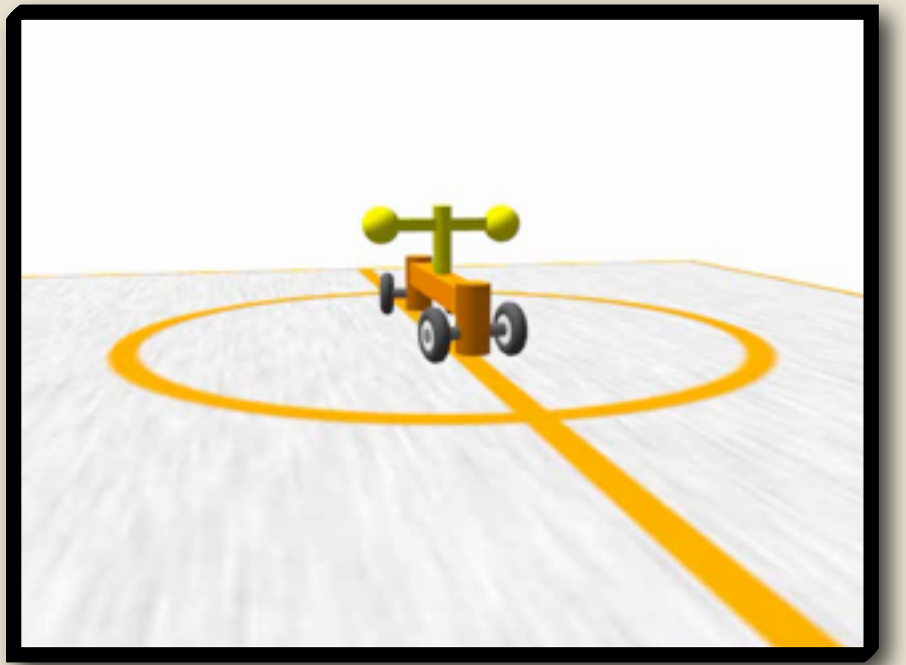
Port Based Modeling and simulation package

20-sim
The power in modeling









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Port-Based Thinking

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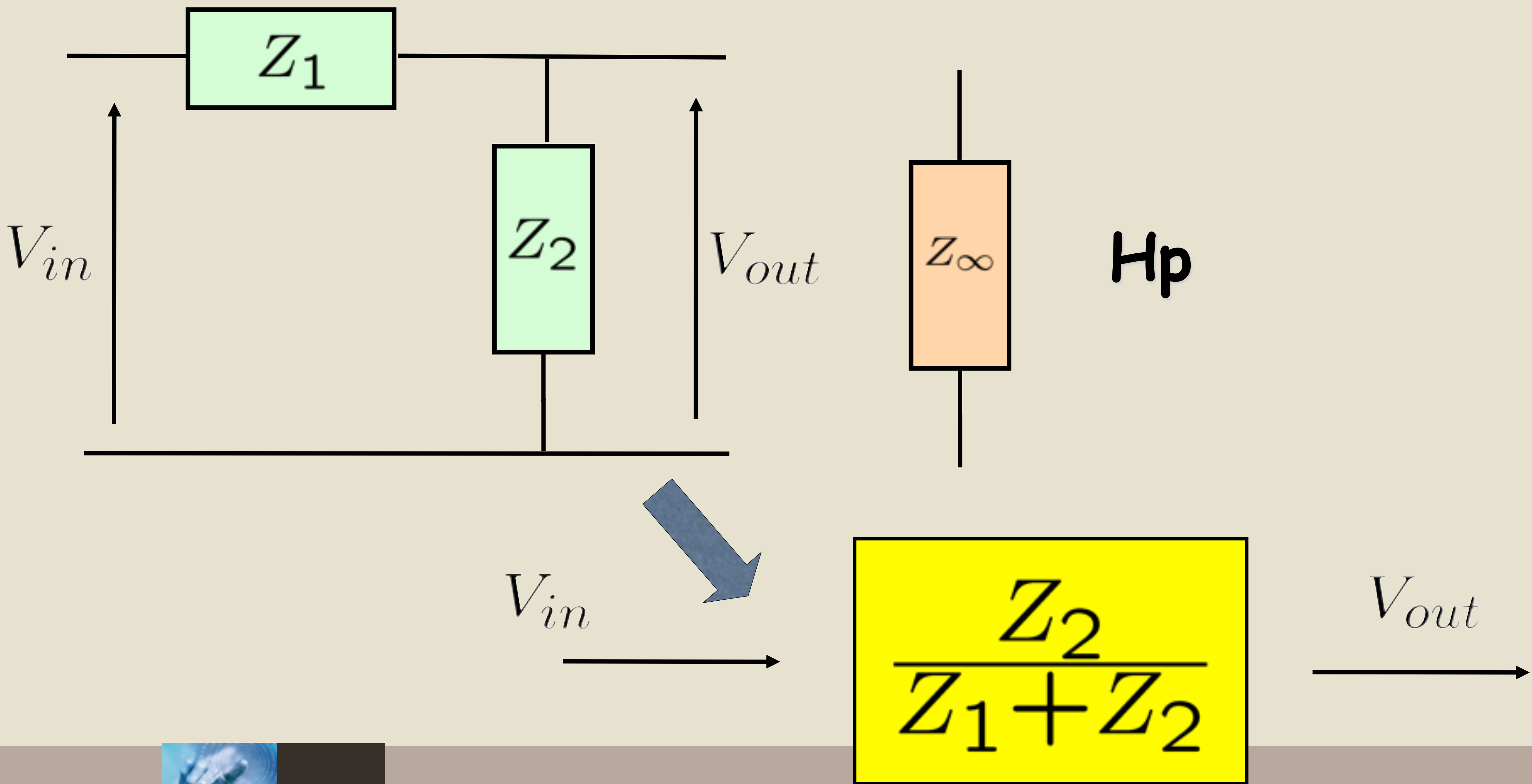
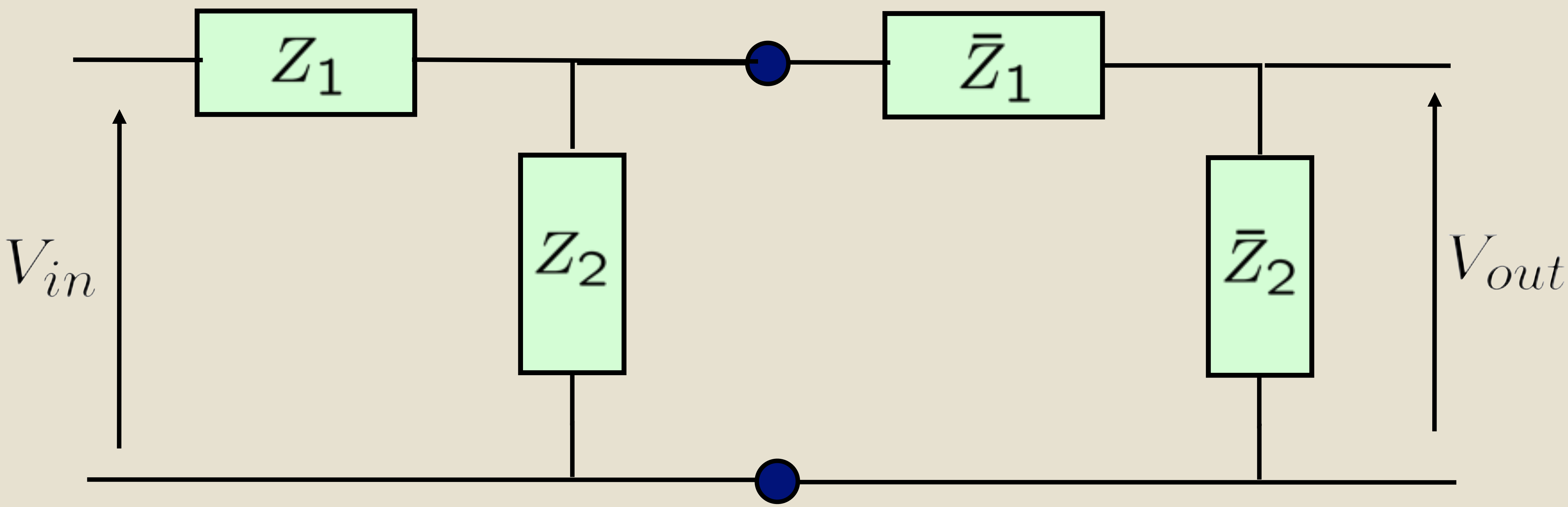
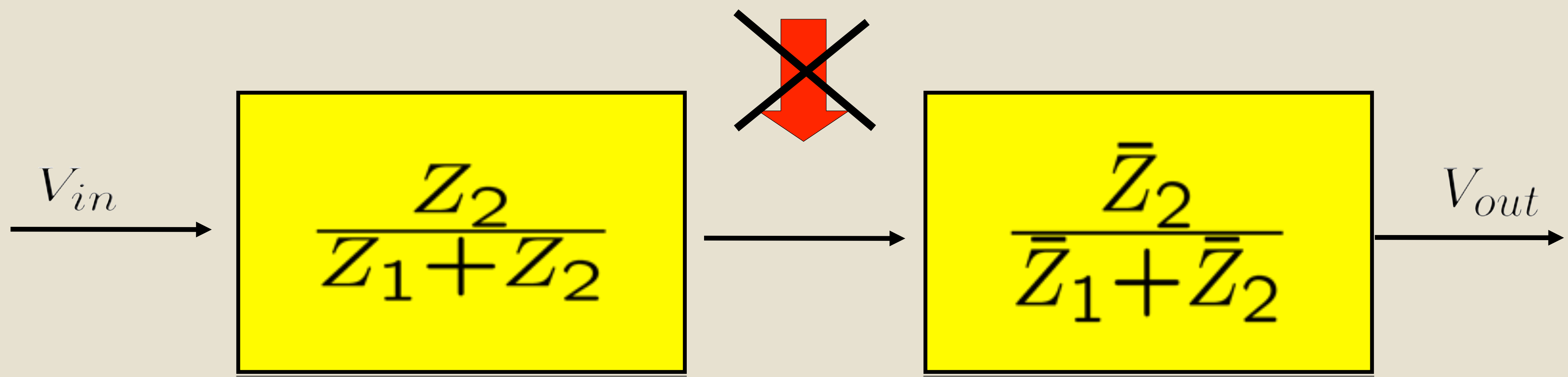
Signals versus Ports



Signals versus Ports





Conclusions on example

- With Physical Systems, **signal** modeling is often not suitable
- 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 !

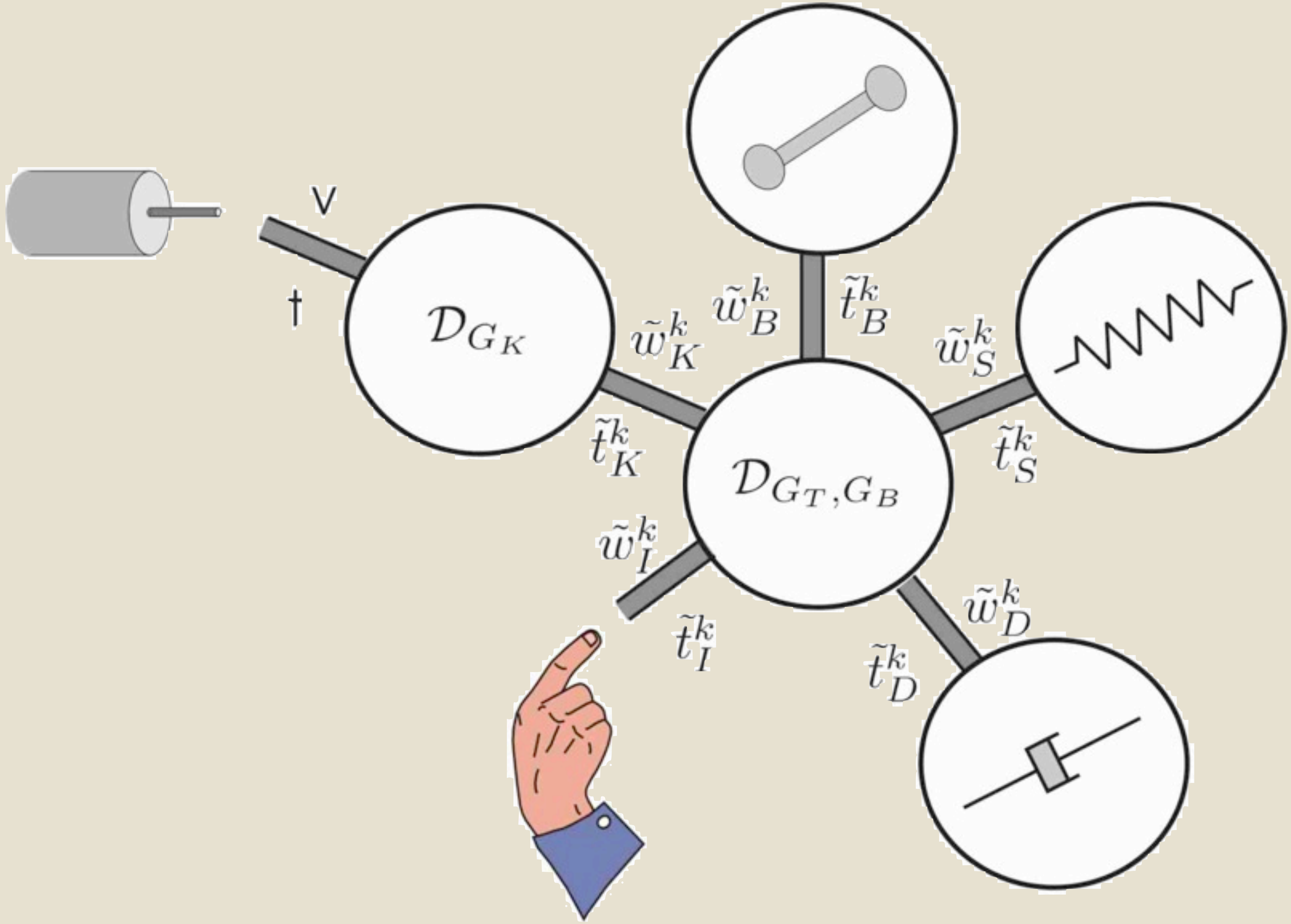
→ Port-based

Power Port

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

Examples

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



v
t
$\mathcal{D}_{G_K}$
$\tilde{w}_K^k$
$\tilde{t}_K^k$
$\tilde{w}_B^k$
$\tilde{t}_B^k$
$\tilde{w}_S^k$
$\tilde{t}_S^k$
$\mathcal{D}_{G_T,G_B}$
$\tilde{w}_I^k$
$\tilde{t}_I^k$
$\tilde{w}_D^k$
$\tilde{t}_D^k$

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The Mathematics behind the framework: Port-Hamiltonian Systems

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Autonomous, Symplectic, Hamiltonian Systems

$$\dot{q} = \frac{\partial H(q,p)}{\partial p}$$

$$\dot{p} = -\frac{\partial H(q,p)}{\partial q}$$

$$q \in \mathcal{Q},\ (q,p) \in T^*\mathcal{Q},\ H(q,p) \in C^1(T^*\mathcal{Q})$$

With ports...

$$\dot{q} = \frac{\partial H(q,p)}{\partial p}$$

$$\dot{p} = -\frac{\partial H(q,p)}{\partial q} + \tau$$

$$\dot{q} = \frac{\partial H(q,p)}{\partial p}$$

$$\Rightarrow \quad P_{in} = \dot{H} = \langle \tau, \dot{q} \rangle$$

Port Hamiltonian Systems Using the Poisson Framework

$$\dot{x} = J(x)\frac{\partial H(x)}{\partial x} + G(x)u$$

$$y = G(x)^T\frac{\partial H(x)}{\partial x}$$

$$x \in \mathcal{X},\ u \in V,\ y \in V^*,\ J^T(x) = -J(x)$$

(2,0) tensor !

Energy Conservation

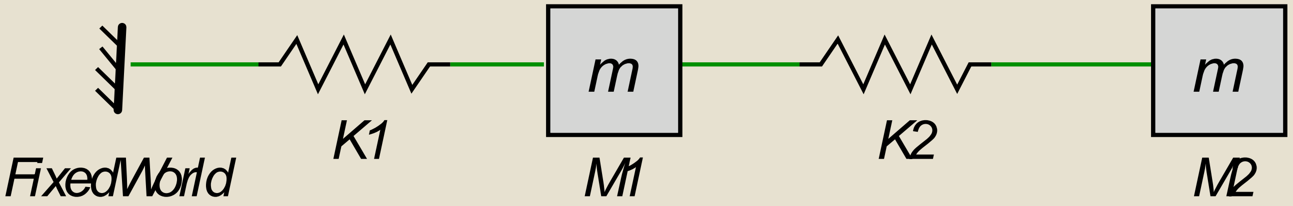
The change in stored energy is equal to the supplied power:

$$\dot{H} = \frac{\partial H}{\partial x}^T \dot{x} =$$

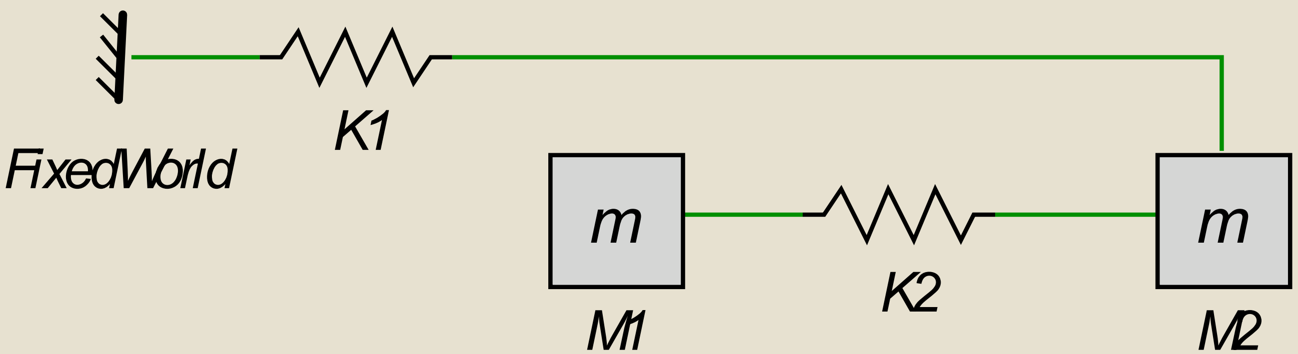
$$\underbrace{\frac{\partial H}{\partial x}^T J(x) \frac{\partial H}{\partial x}}_{0 \Leftarrow J^T(x) = -J(x)} + \underbrace{\frac{\partial H}{\partial x}^T G(x)}_{y^T} u$$

$$= y^T u$$

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!

Dirac Framework

$$\overbrace{\begin{pmatrix} I & 0 \\ 0 & I \end{pmatrix}}^{F(x)} \begin{pmatrix} \dot{x} \\ y \end{pmatrix} = \overbrace{\begin{pmatrix} J(x) & -G(x) \\ G^T(x) & 0 \end{pmatrix}}^{-E(x)} \begin{pmatrix} \frac{\partial H}{\partial x} \\ -u \end{pmatrix}$$

Of the form

$$F(x)f + E(x)e = 0$$

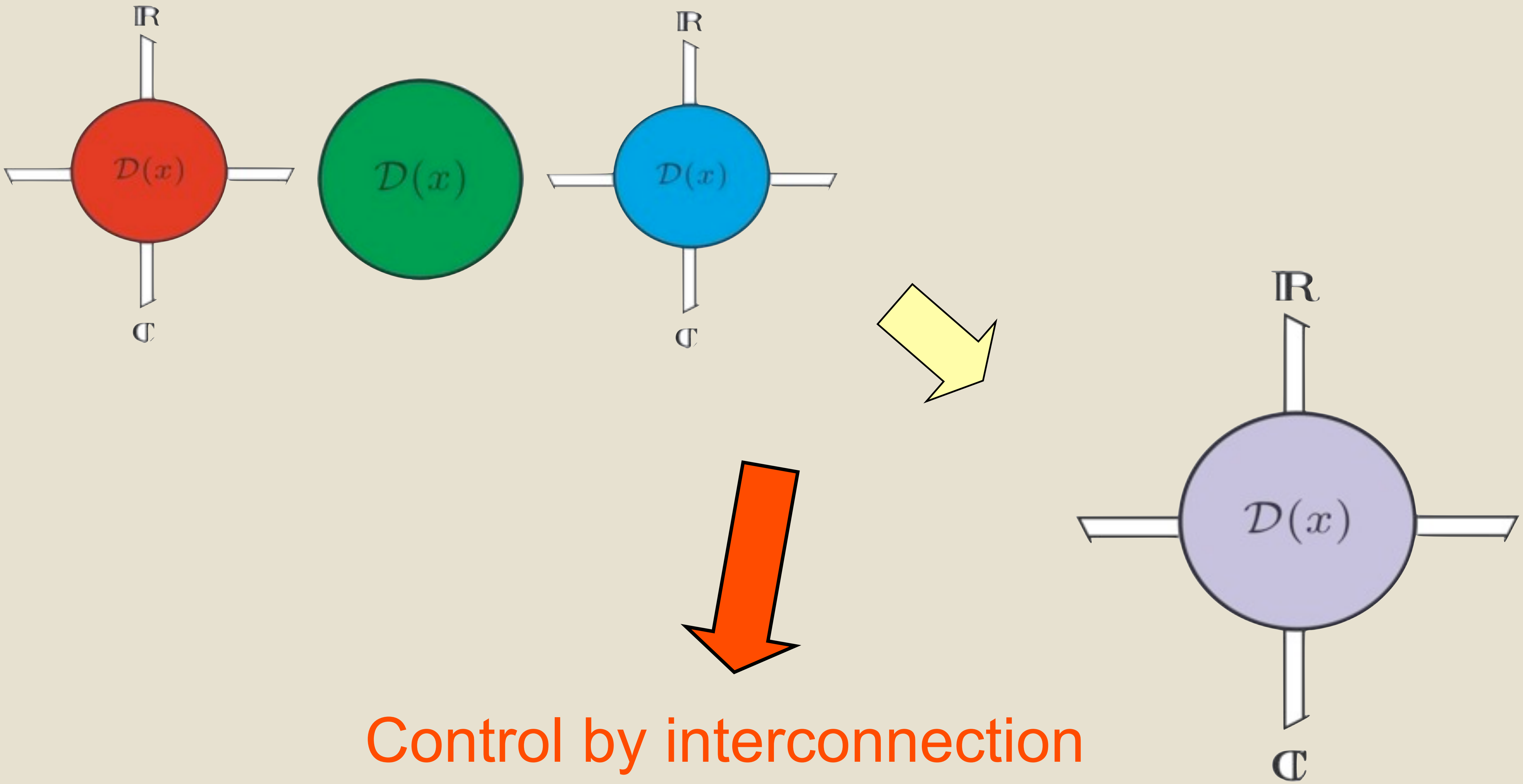
where

$$F(x)E^T(x) + E(x)F^T(x) = 0$$

Remark

- "All" physical parts can be modeled using this framework
- Interconnection of parts (and physical controllers!!) via port interconnections result in the same kind of equations (IPC)
- Looking at the network structure we get insight in the energy flows
- Delays in communication lines can be handled effectively (Passive Distributed Control)

System composition in general



Control by interconnection

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Control by Interconnection

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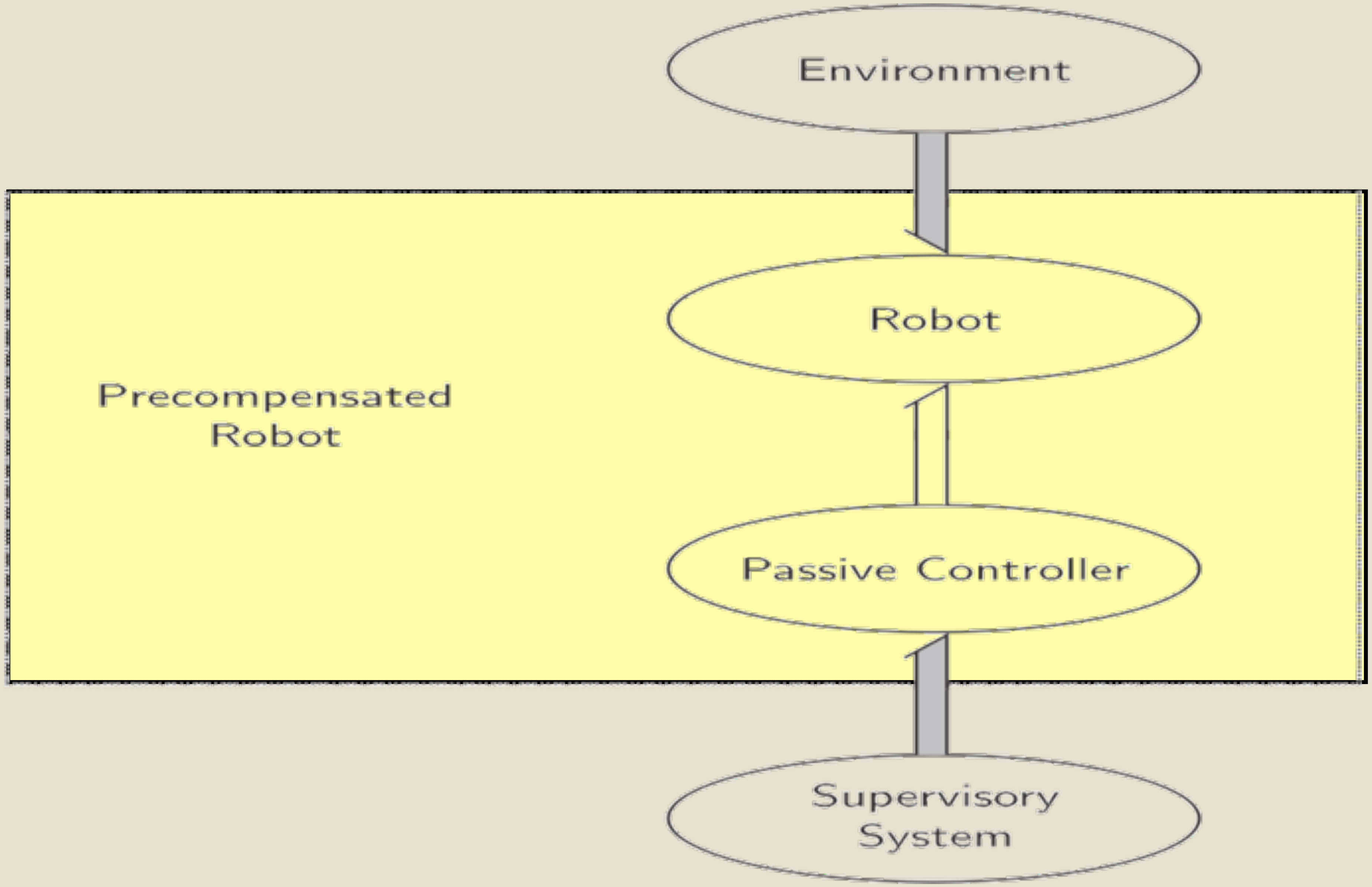
Proposed Controller Structure



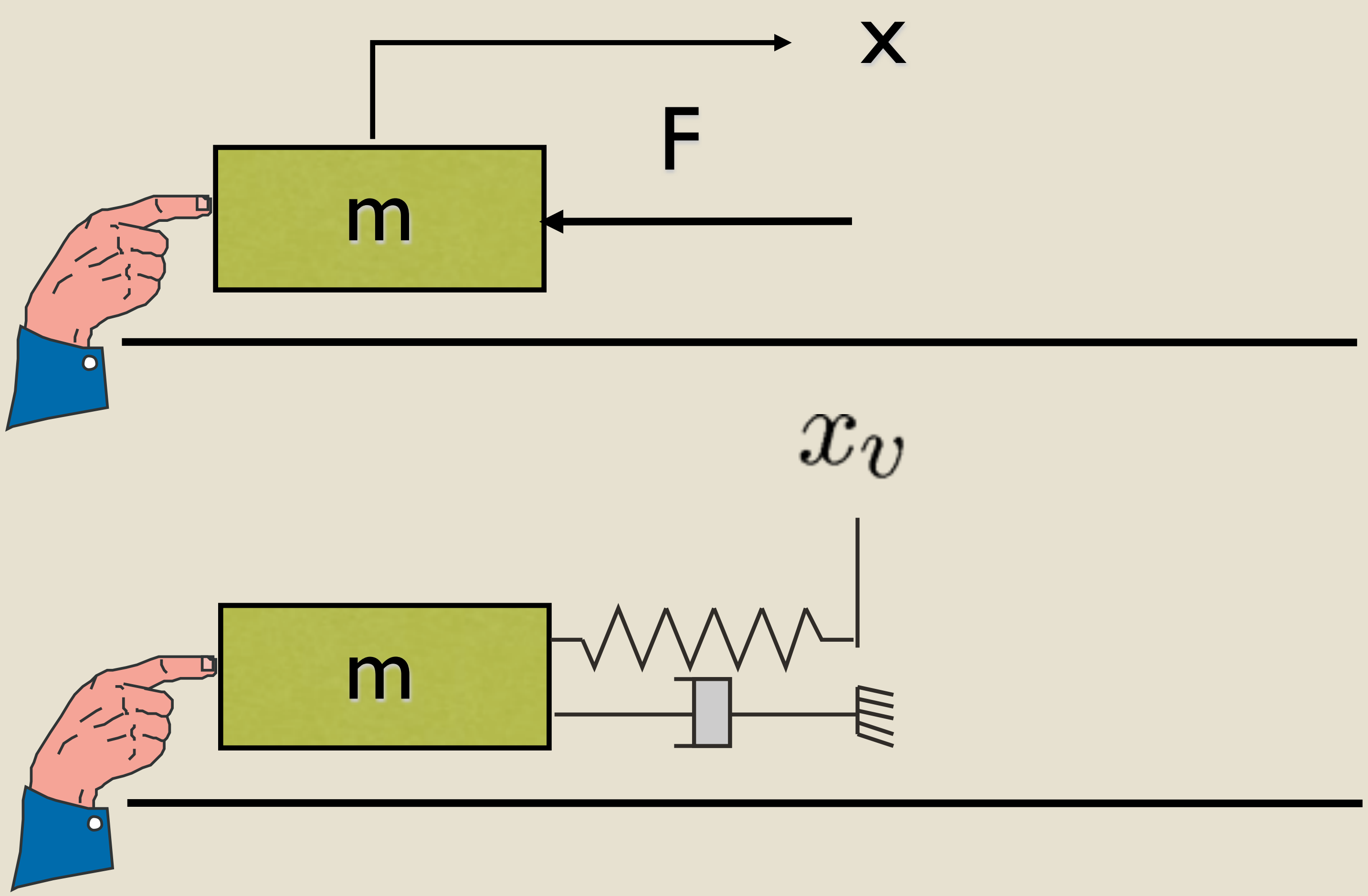
Intrinsically Passive Control

- 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 multi-bodies, spatial springs…, all using ports and Port Controlled Hamiltonian Systems representation
- More general structures are also possible

Impedance Control

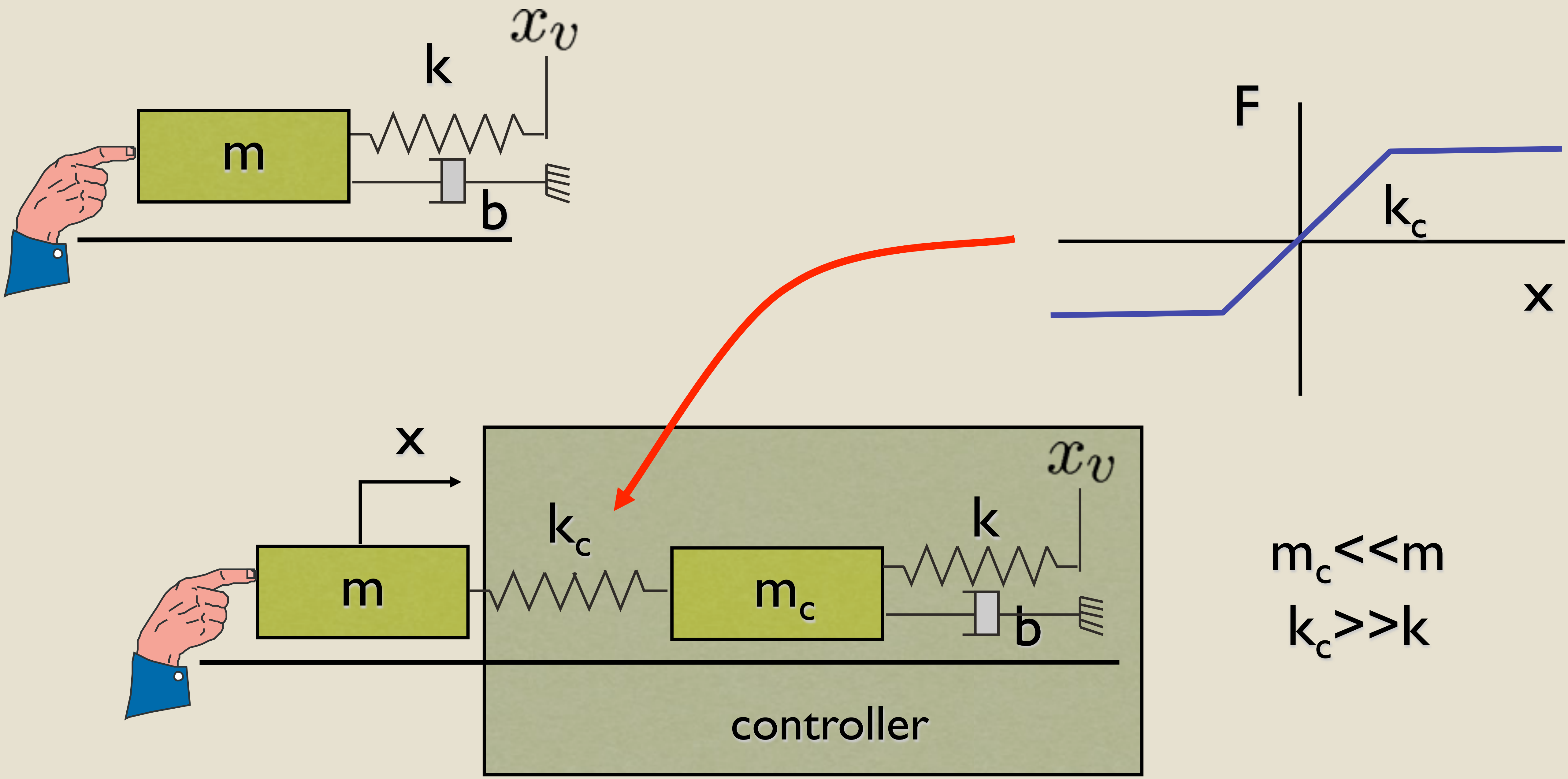
System

Desired Behavior



Note: 1.only position measurement available, 2. saturation F

Solution using interconnection ideas



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Examples

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Oscillations and Locomotion

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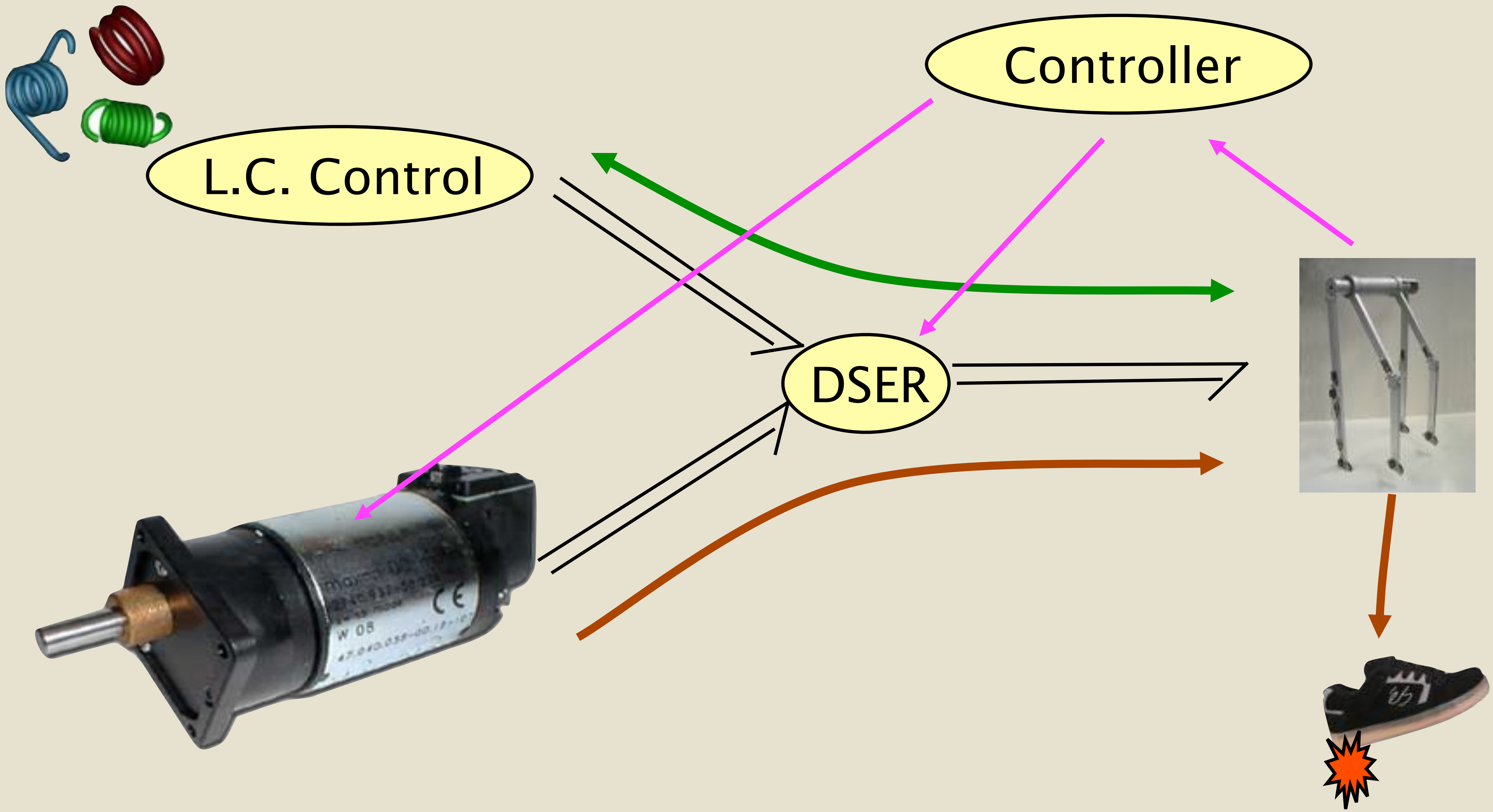
The goal



Our vision in Locomotion

3D robust and energetical walking

??

Oscillations with discontinuous Dynamics

Oscillations Multidimensional

Oscillations Synchronizations with communications delays

Oscillations Syncronisations

Phase lag/lead control with dynamic extension

L.C. shaping in 2D p.s.

Energetically continues oscillation

What do we need?

Theory

-Able to address directly power flows
(network-theory)

-Keep track of energy flows and control them
(control by interconnection)

-Multidimensional oscillations, synchronizations, 3D mechanics.. (l.c. and synchronizations)

Practice

-new actuators (VIACTORS), new transmissions (CVTs)

-reversible amplifiers

-passive handling of delays

Limit cycles

- Limit Cycle: periodic solution of a differential equation with the additional property that it is isolated. (only for N.L. systems)

- Basin of Attraction (for a stable L.C.): set of points in the state space which asymptotically converge to the L.C.

What do we want?

- Be able to shape a Limit Cycle (Performance)
- Make the Basin of attraction as big as possible (Robustness)

and

No waste of Energy

NL oscillator with globally attractive limit cycle

Van der Pol Oscillator

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

Rayleight Oscillator

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

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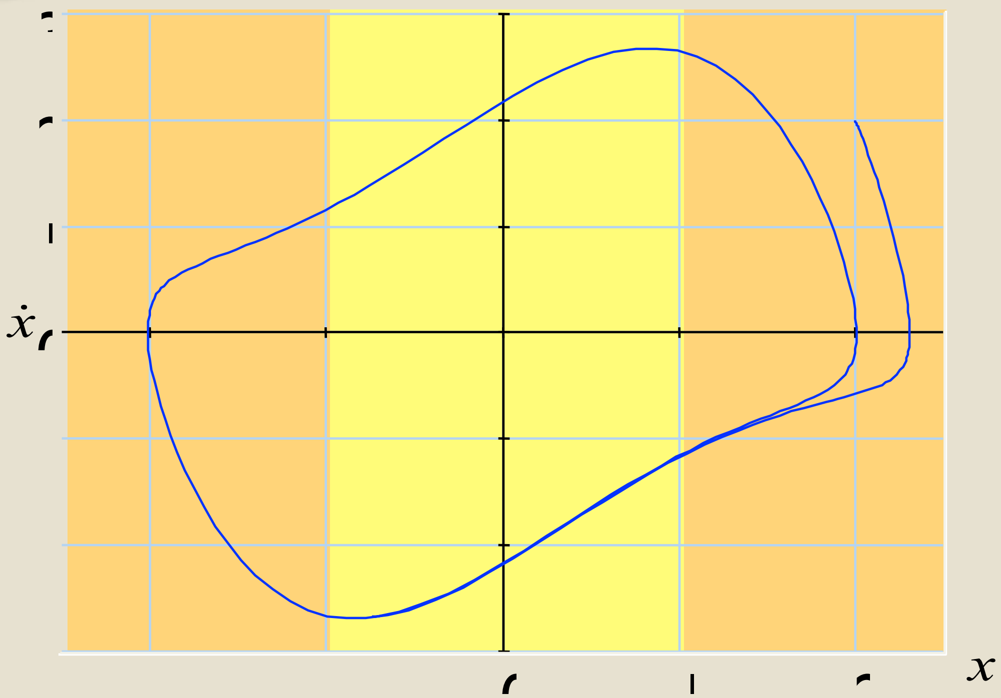
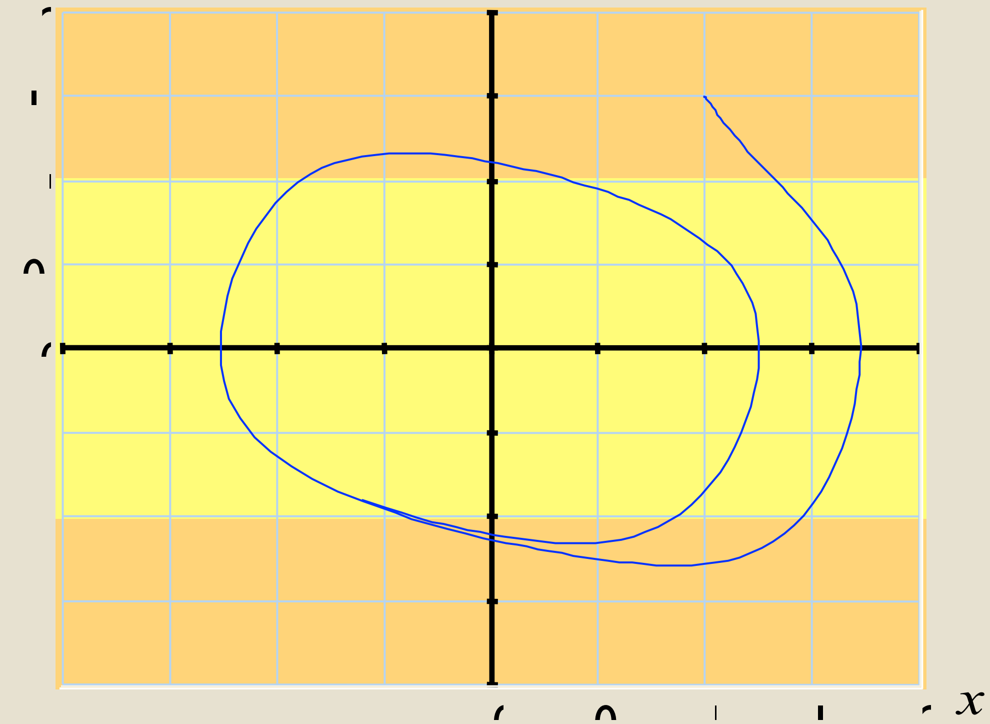
Van der Pool

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



Rayleight



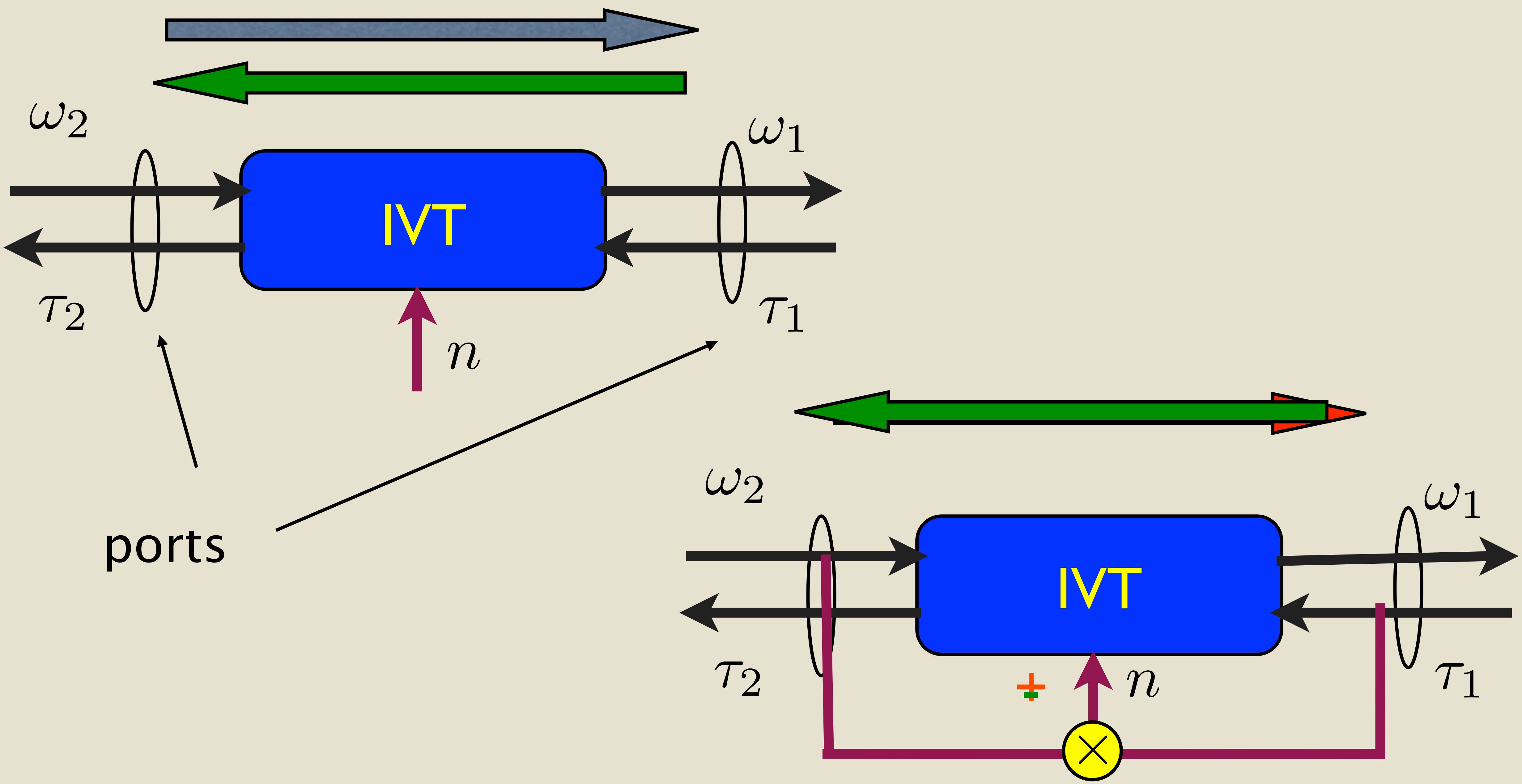
$$\ddot{x} + (\dot{x}^2 - 1)\,\dot{x} + x = 0$$

Remarks

- Extremely stable oscillation, but it dissipates and sometimes require energy
- Can we make it completely conservative?

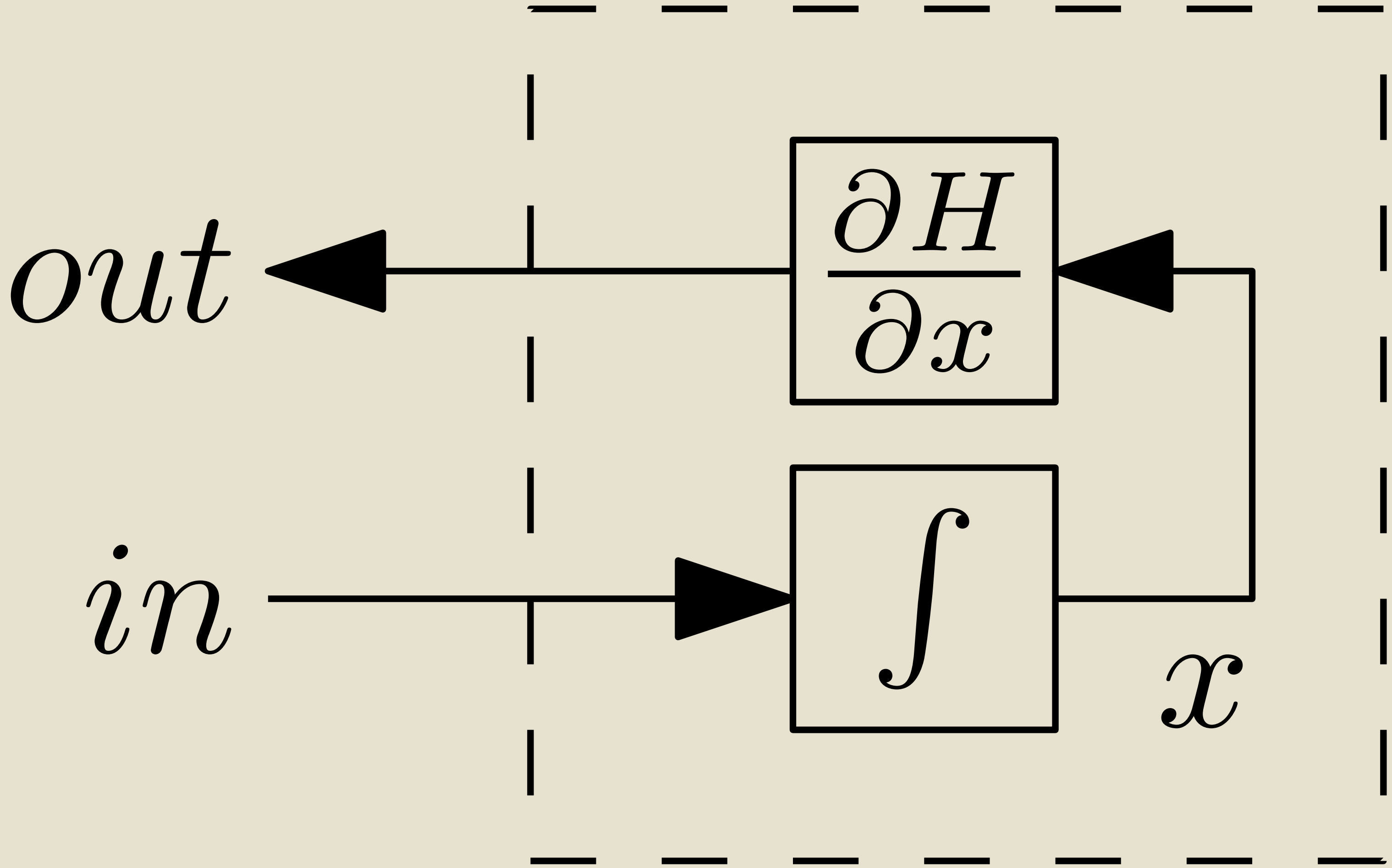
YES!

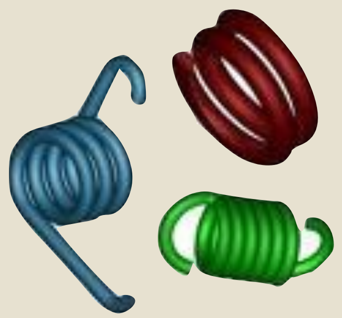
Modulated



ω_2
ω_1
IVT
τ_2
τ_1
n
ports
ω_2
ω_1
IVT
τ_2
τ_1
n
+

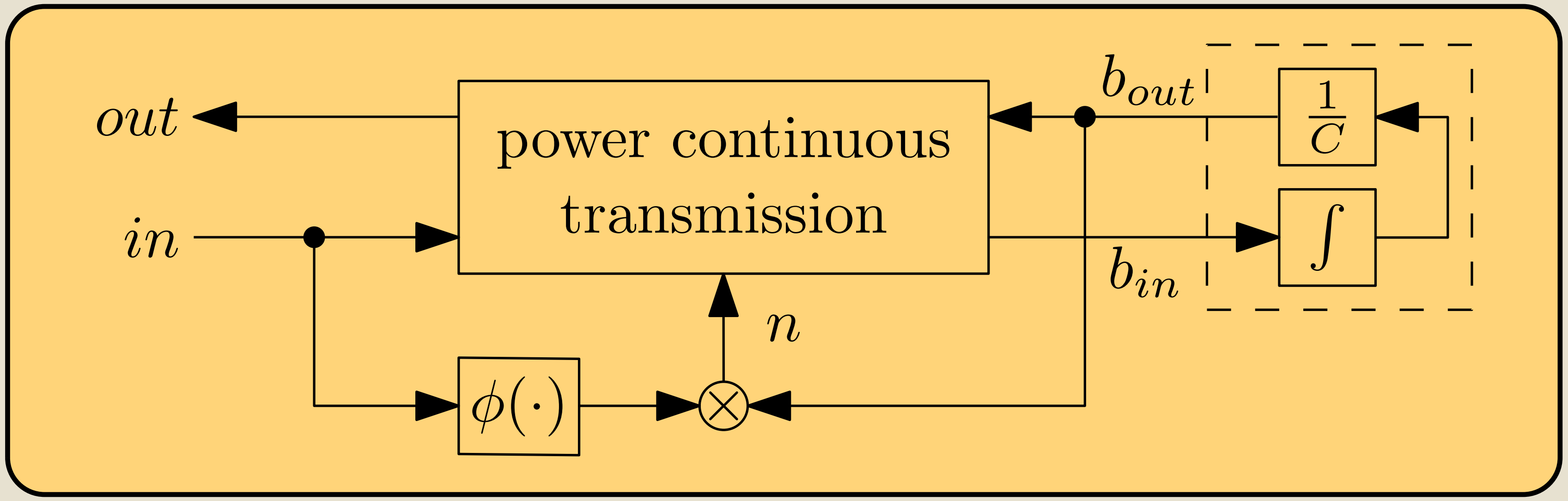
Energy Storage





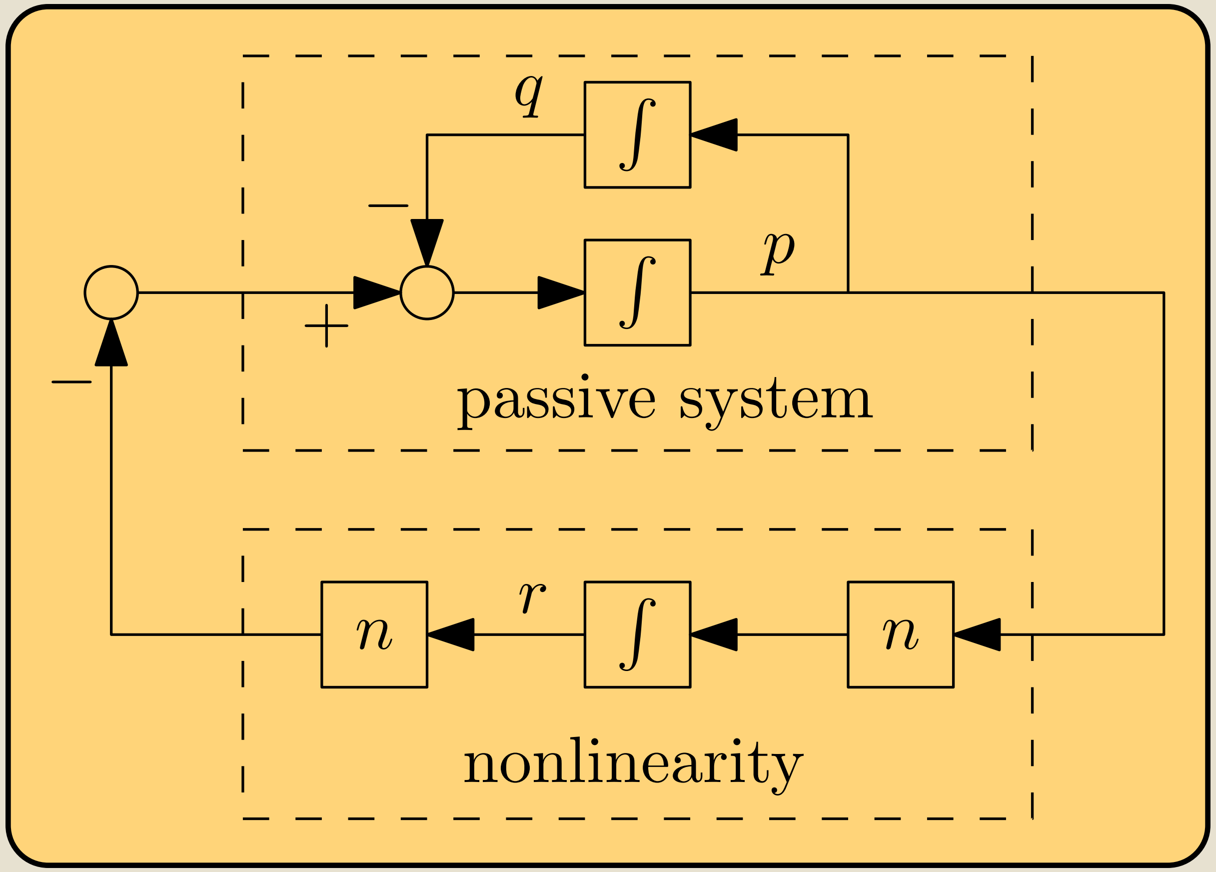
Realizing “reversible” damping

$$out = \phi(in) \qquad v = Ri, \qquad F = Bv \qquad \dots$$



$$\left.\begin{aligned} out &= n \cdot b_{out} = n \cdot \frac{\partial H}{\partial x} \\ out &= \phi(in) \end{aligned}\right\} \qquad n = \frac{\phi(in)}{\frac{\partial H}{\partial x}}$$

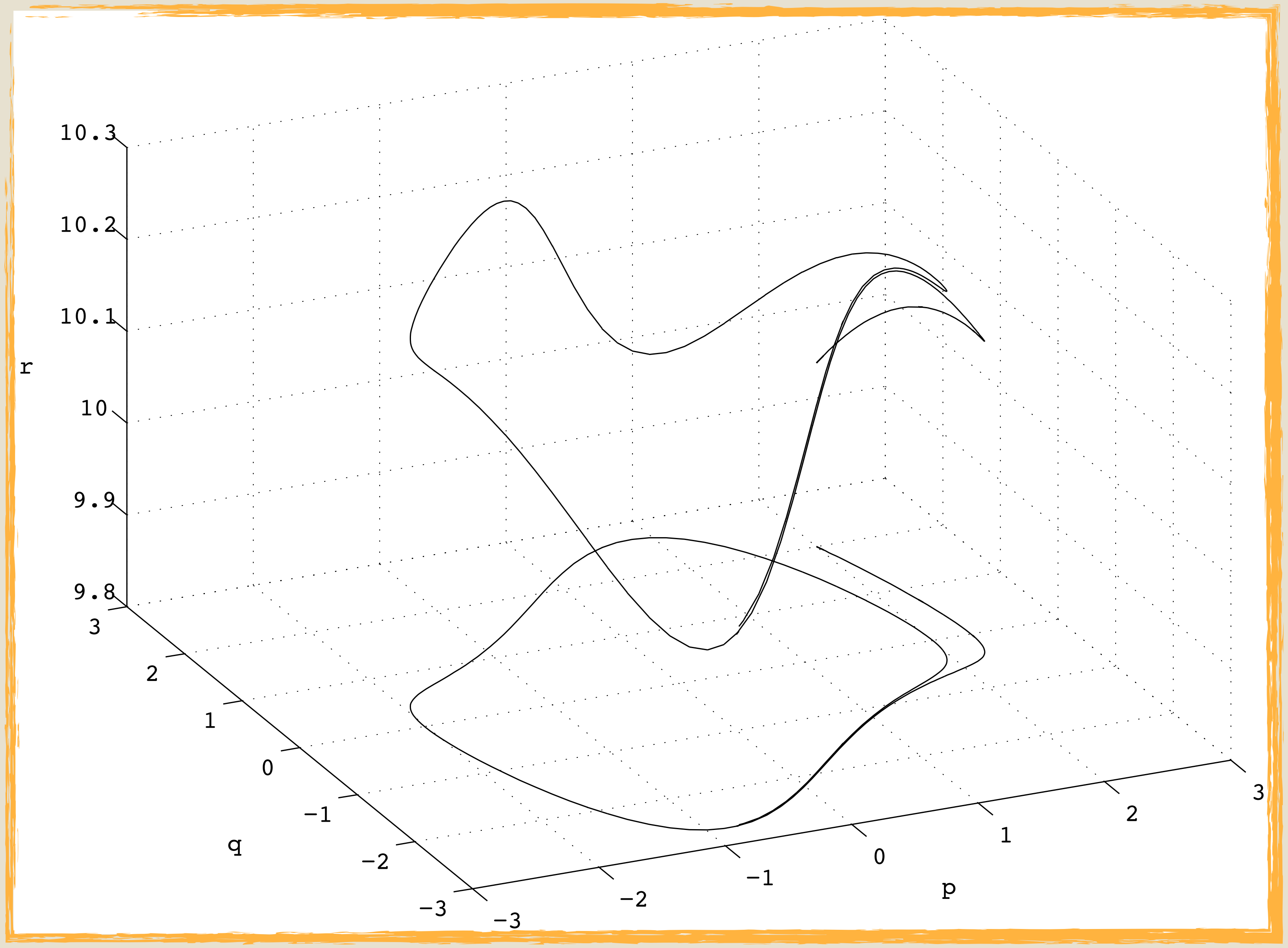
Conservative V.d.Pol



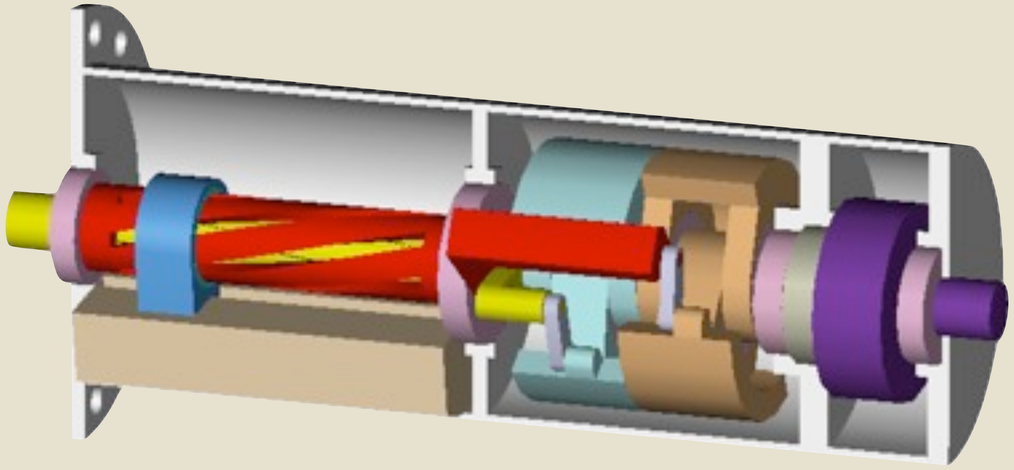
$$\begin{bmatrix} \dot{q} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & -n \\ 0 & n & 0 \end{bmatrix} \begin{bmatrix} q \\ p \\ r \end{bmatrix}.$$

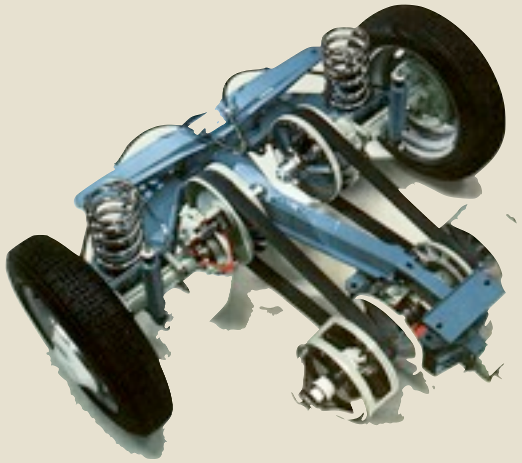
$$H(x) = \frac{1}{2} x^T \cdot x = \frac{1}{2} q^2 + \frac{1}{2} p^2 + \frac{1}{2} r^2.$$

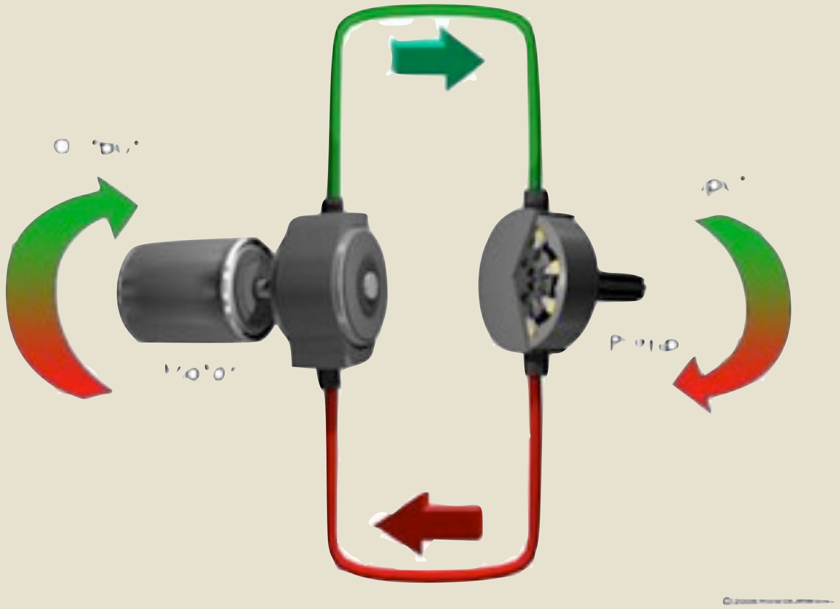
State Space Plot

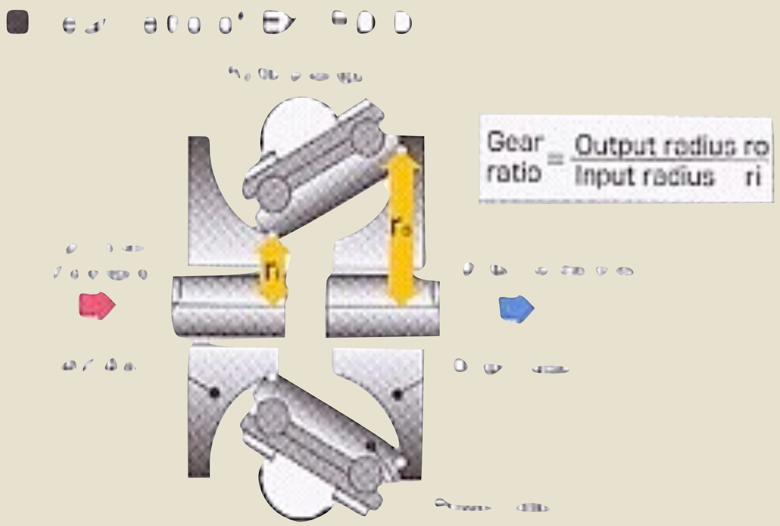


Continuous Variable Transmission





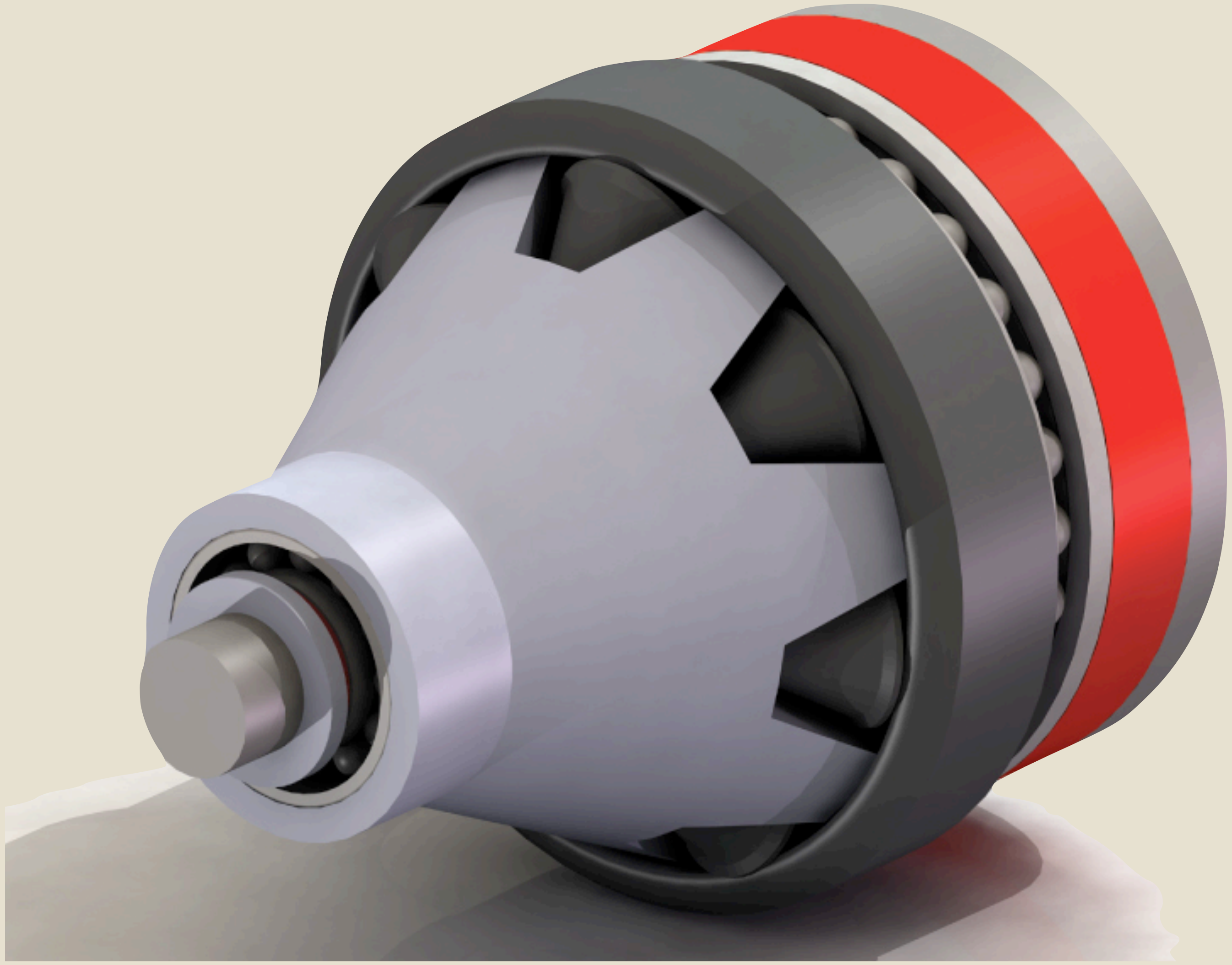




Conclusions

- If we manage to make a decent CVT we can design and shape globally stable oscillators!
- We can also synchronize them by modulating transmissions
- Eventually we can create and tune oscillators online

The Twente CVT



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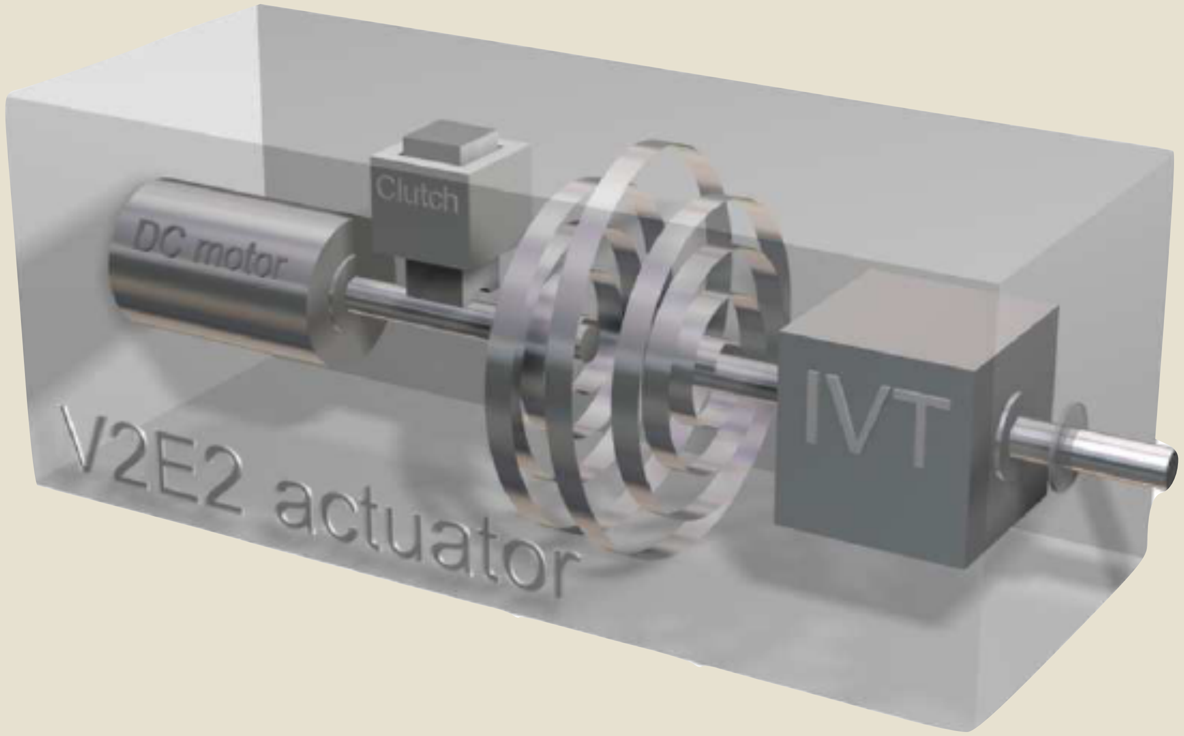
Very Versatile Energy Efficient Actuator

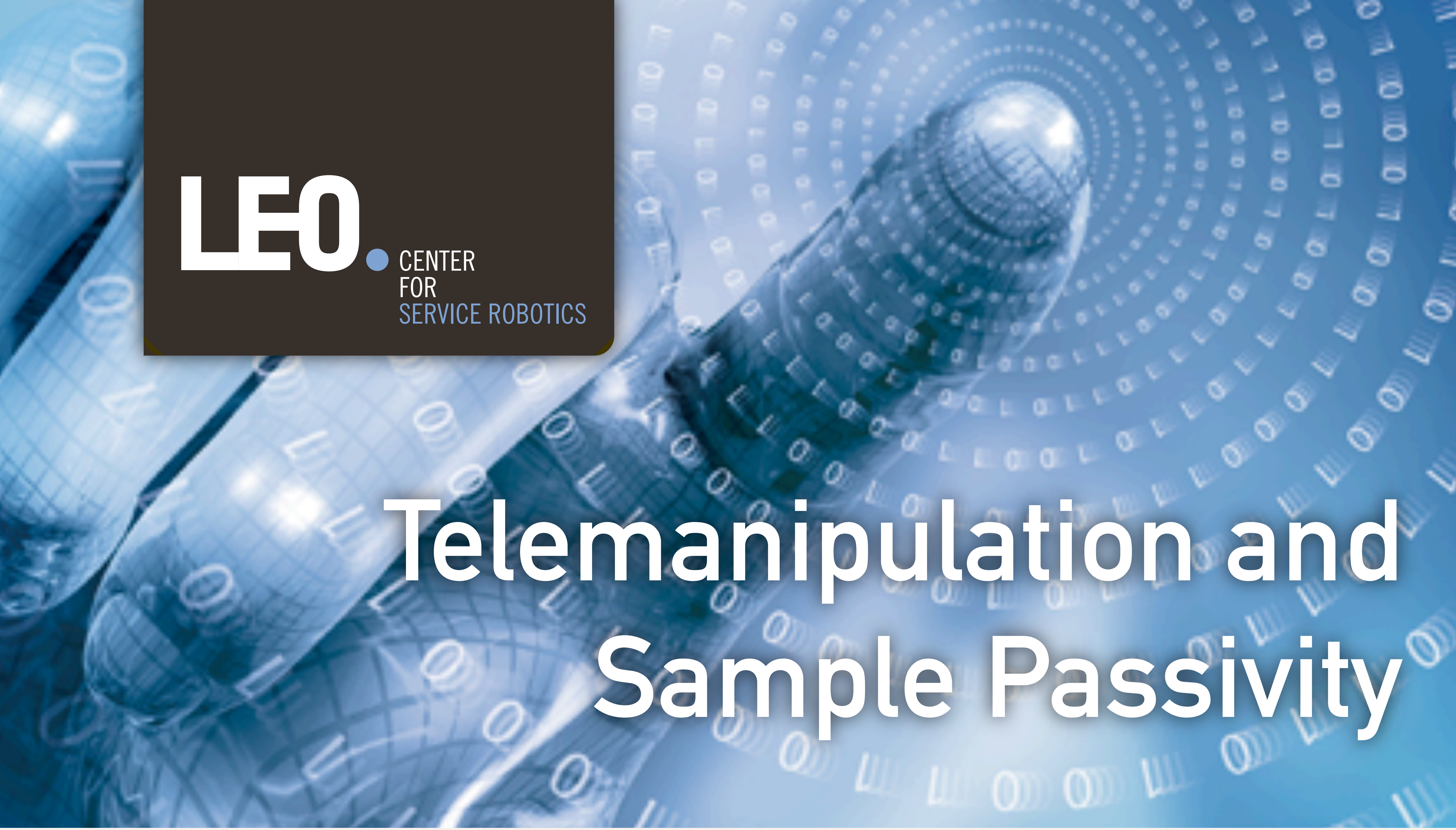
- Torque Servoing
- Stores any negative work applied on load
- Zero dissipation for constant force
- Ideal for periodic motions



Variable Impedance Actuators

- Energy Efficiency
- Safety
- Passive behaviour in all conditions
- Embedding Intelligence

VIACTORS



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Telemanipulation and Sample Passivity

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Rationale

- Explicitly handle energy exchanged with the environment/human
- Handle the coupling between the real, continuous time world and energy and virtual, descrete time, computer generated world
- Take care of the two energy leakages: sample-hold and integration
- Based on network theory and port-Hamiltonian systems

Stramigioli, S., Secchi, C., van der Schaft, A.J., Fantuzzi, C.,, "Sampled Data Systems Passivity and Discrete Port-Hamiltonian Systems", IEEE transactions on robotics and automation, IEEE, vol. 21, nr. 4, pp. 574-587, 2005

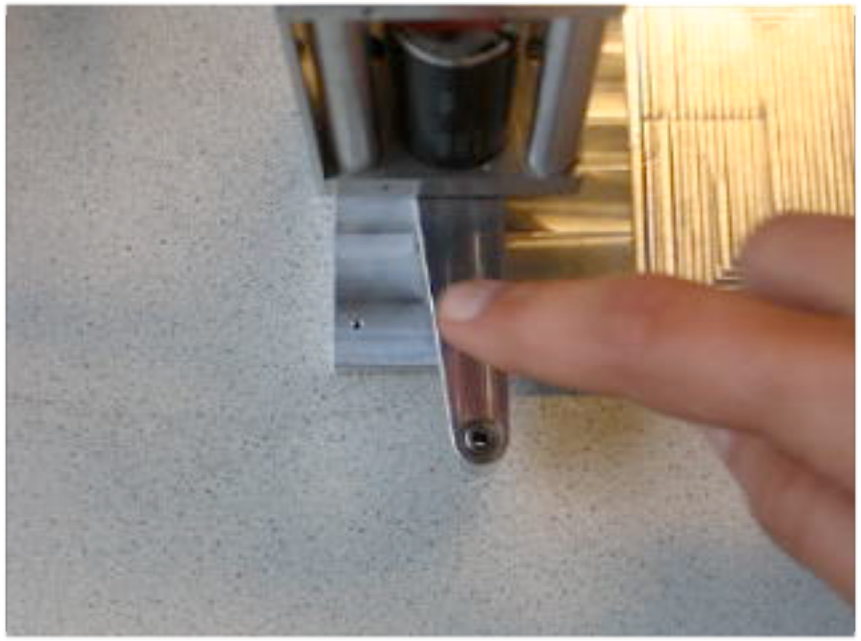
Sampled Passivity

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

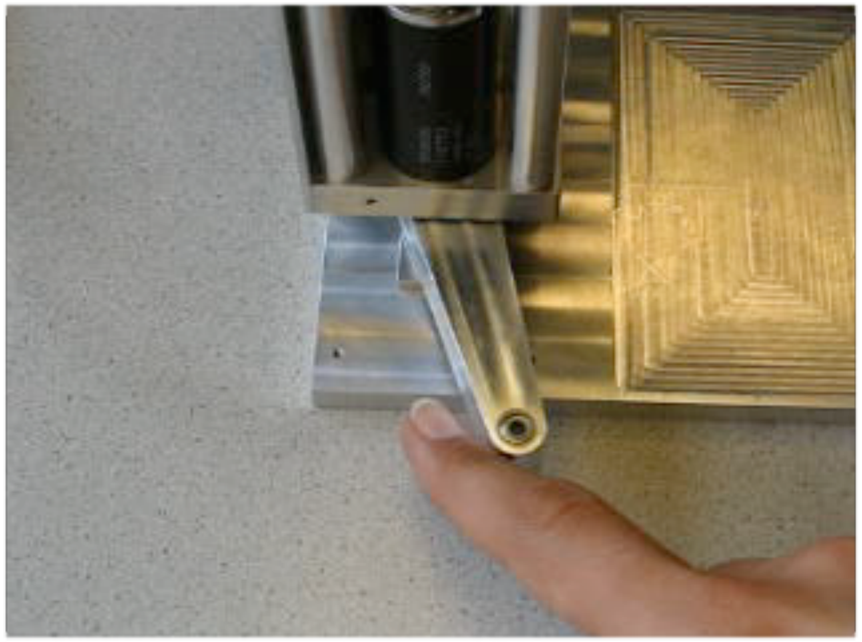
$$\Delta E_C^{in} = \int_{kT}^{(k+1)T} \bar{e}_D^T f_D(s)ds = \bar{e}_D(k) \int_{kT}^{(k+1)T} f_D(s)ds$$

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

Intrinsically Passive Control (IPC)



Standard PD



IPC PD

30 Hz sample rate

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Conclusions

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Conclusions

- Phisical ALWAYS involve bidirectional interaction
- Energy is the glue of physics
- In interactive tasks, energy flows are important for passivity and safety
- Port-based based robotics treats energy flows explicitly
- Novel concepts have been achieved using this paradigm

Thanks for Listening

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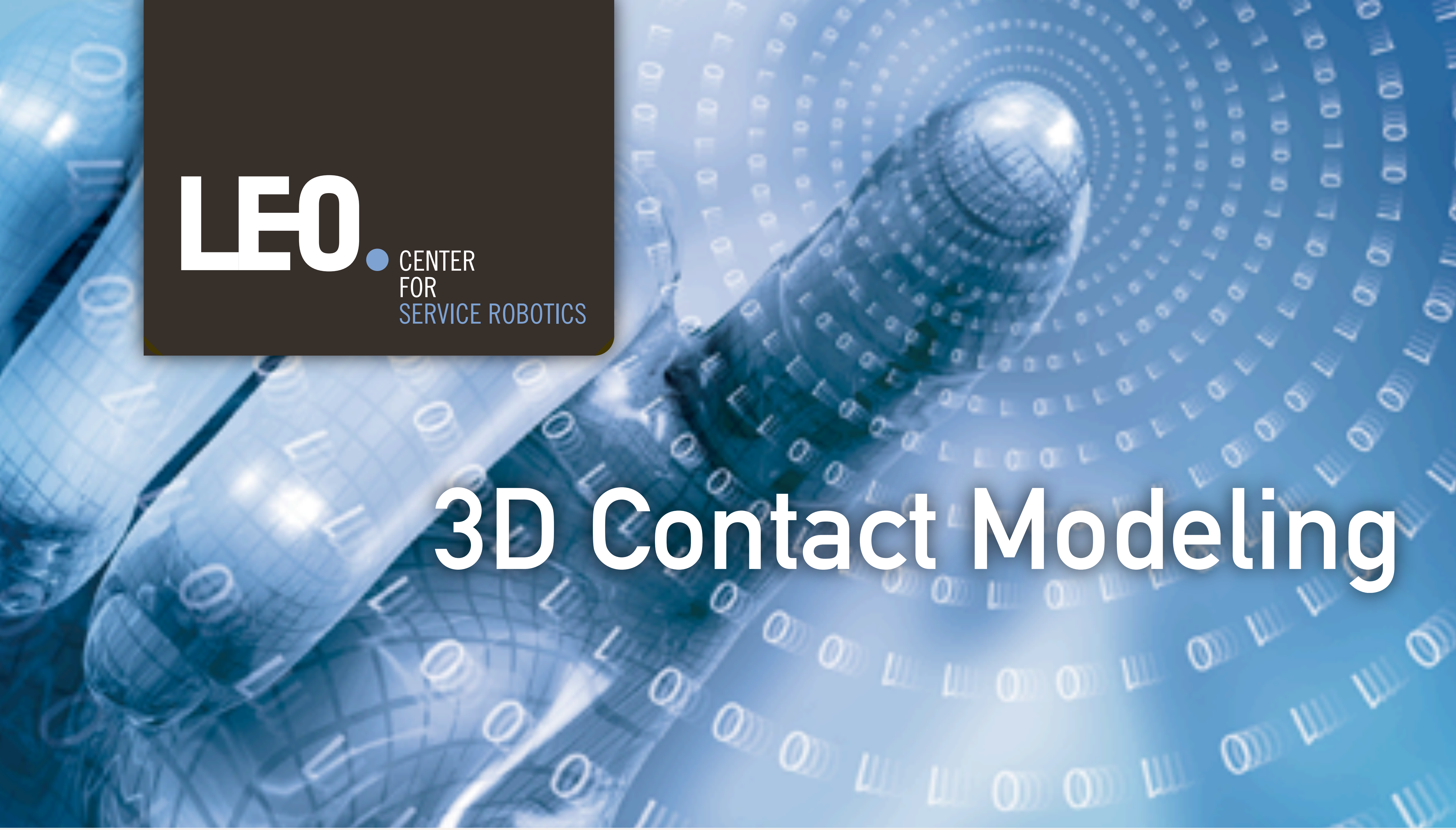

3D Contact Modeling

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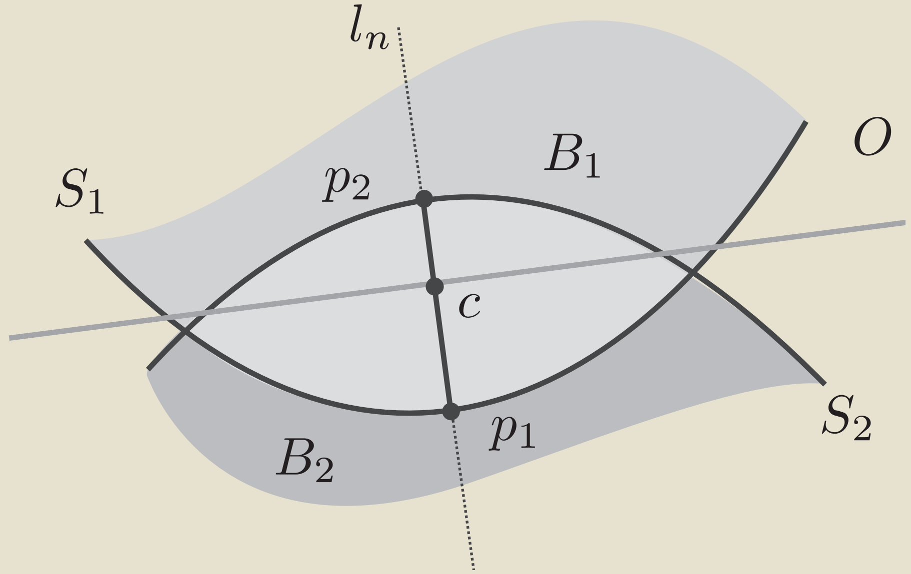
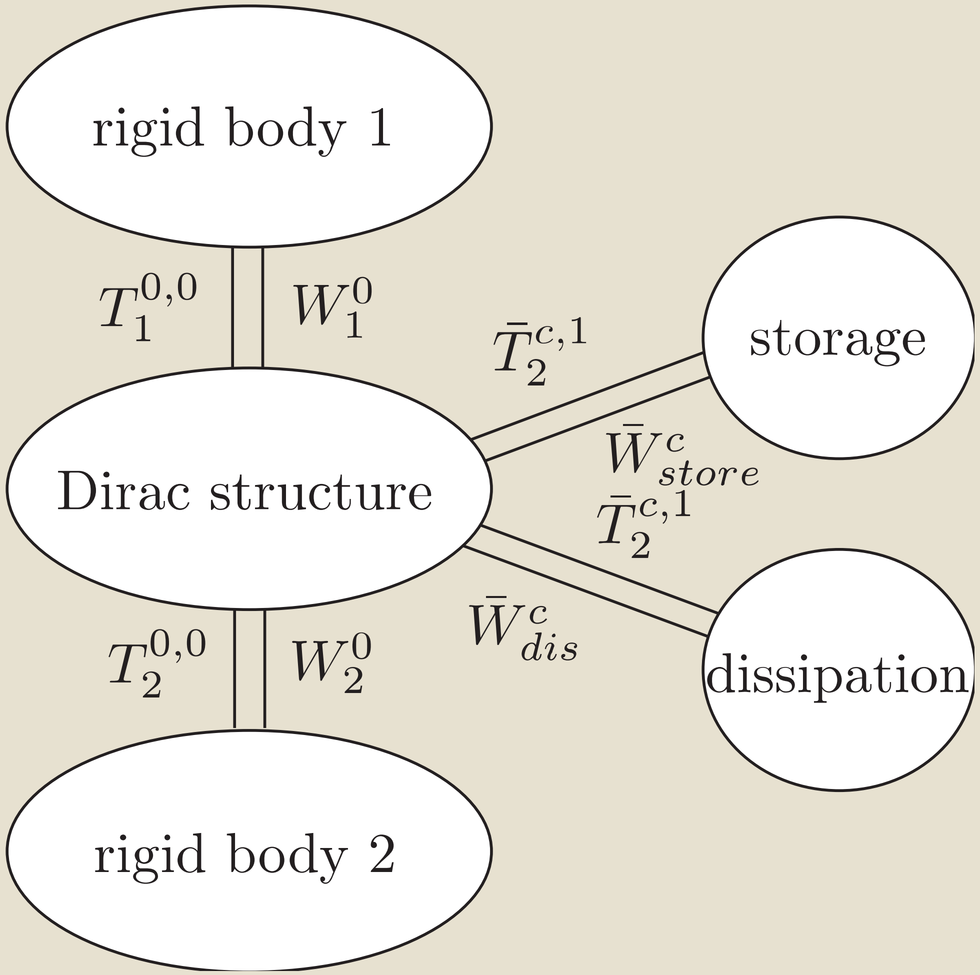
Visco-elastic contact model





European Journal of Control

Port Based Modeling of Spatial Visco-Elastic Contacts

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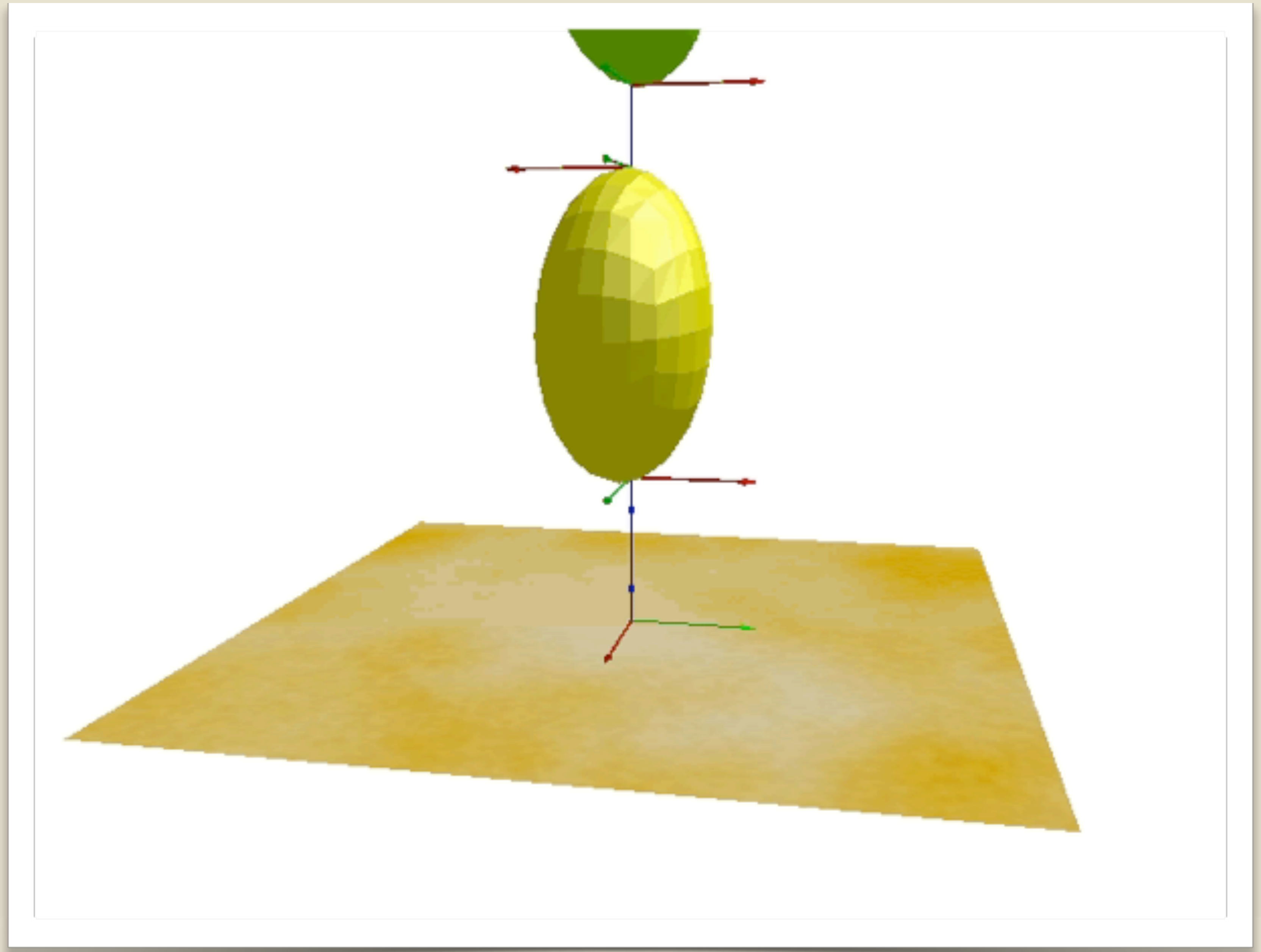
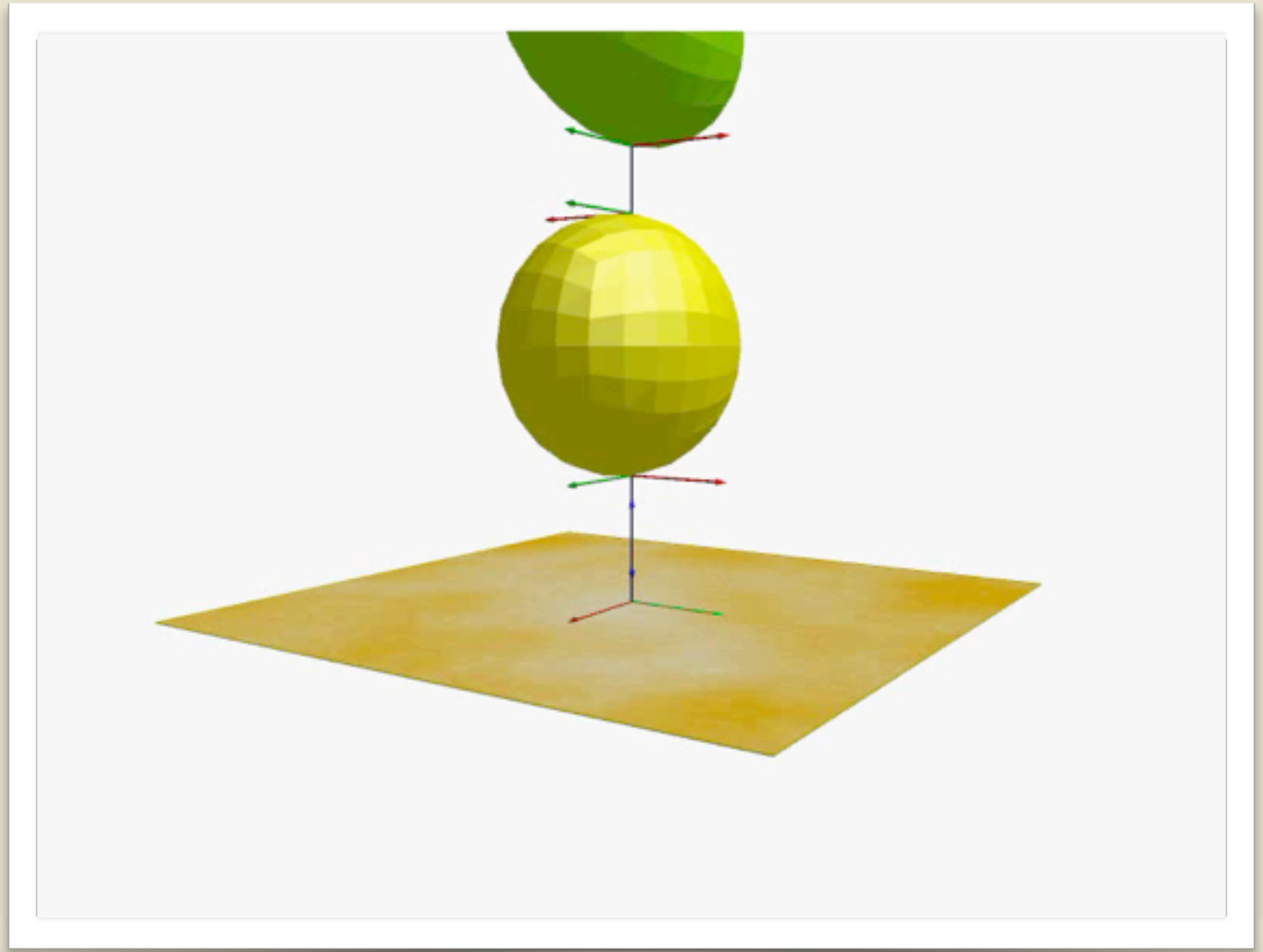
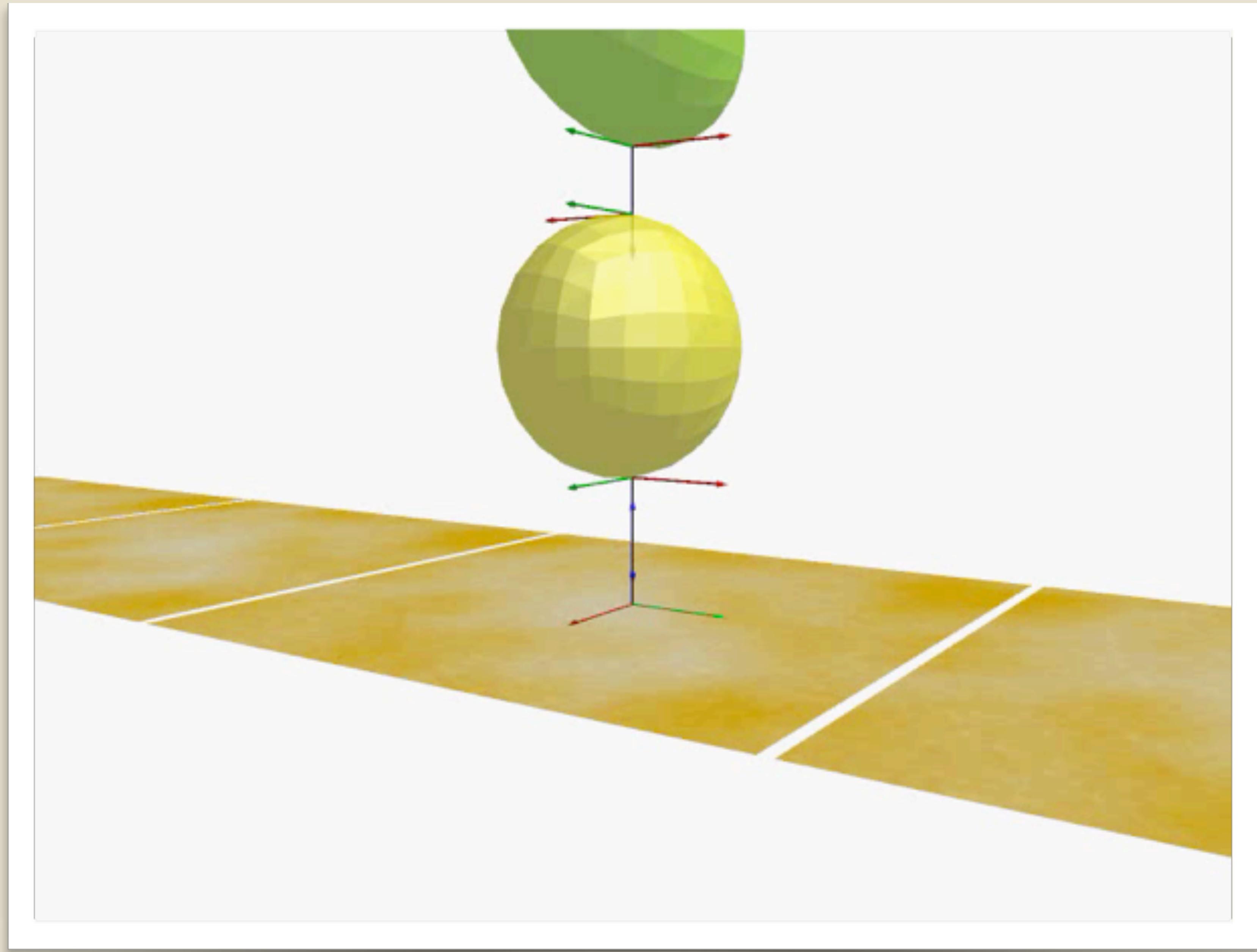
Animation of a complex situation



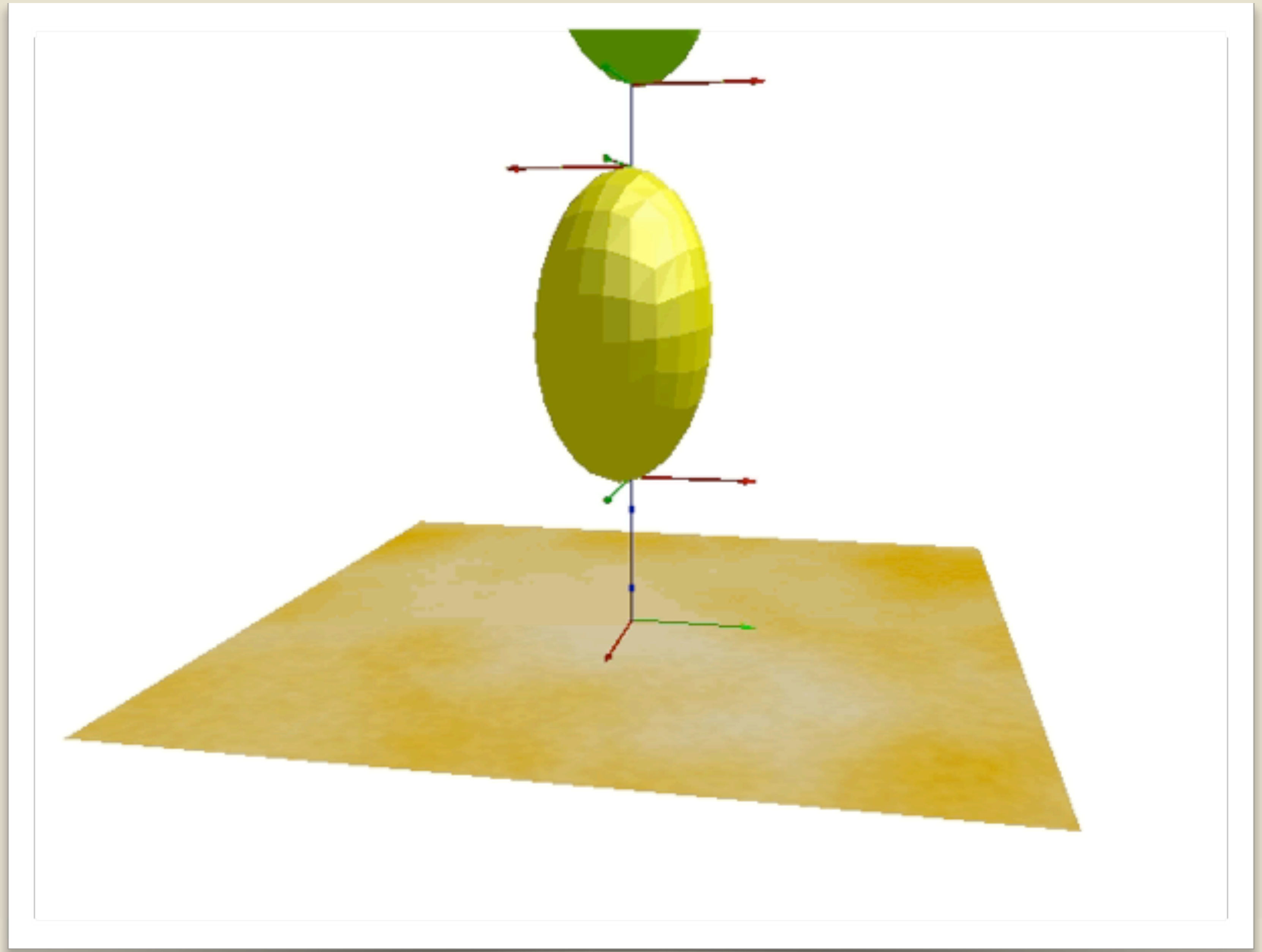
Using softer contact



Very little damping



Very soft



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Grasping

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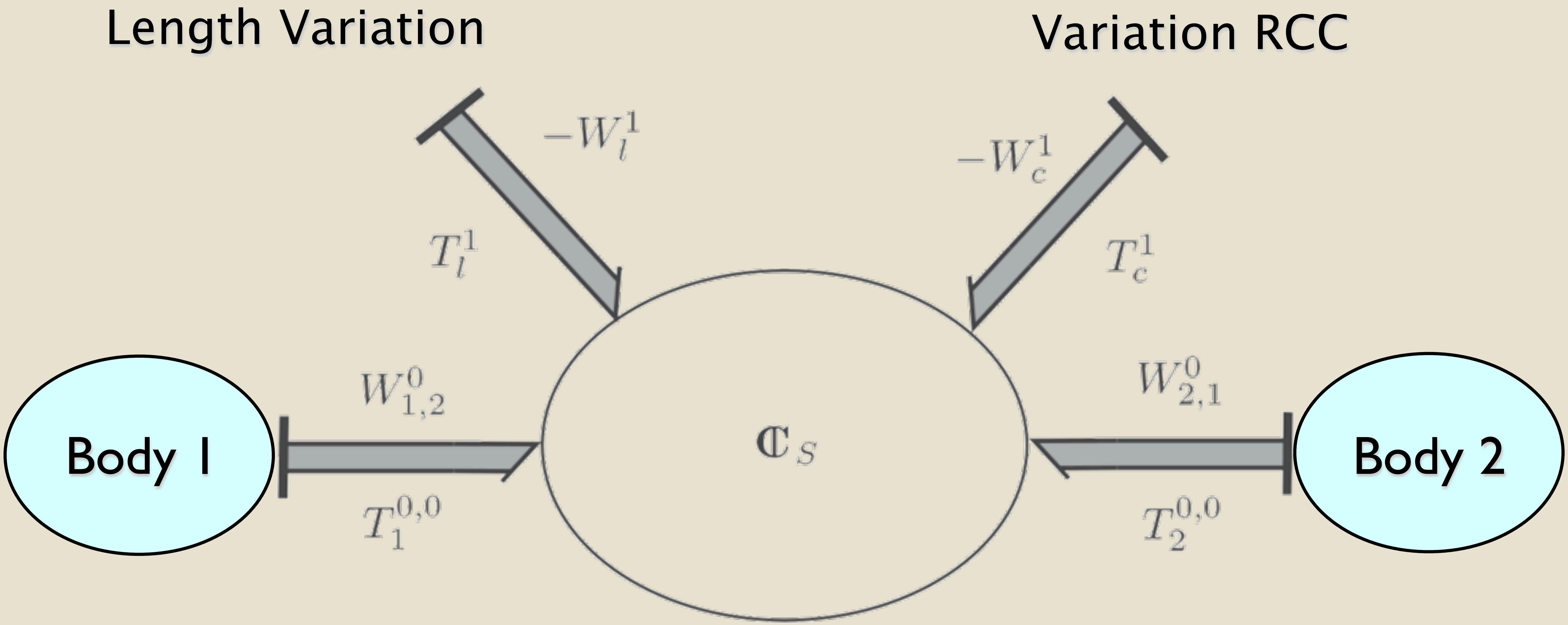
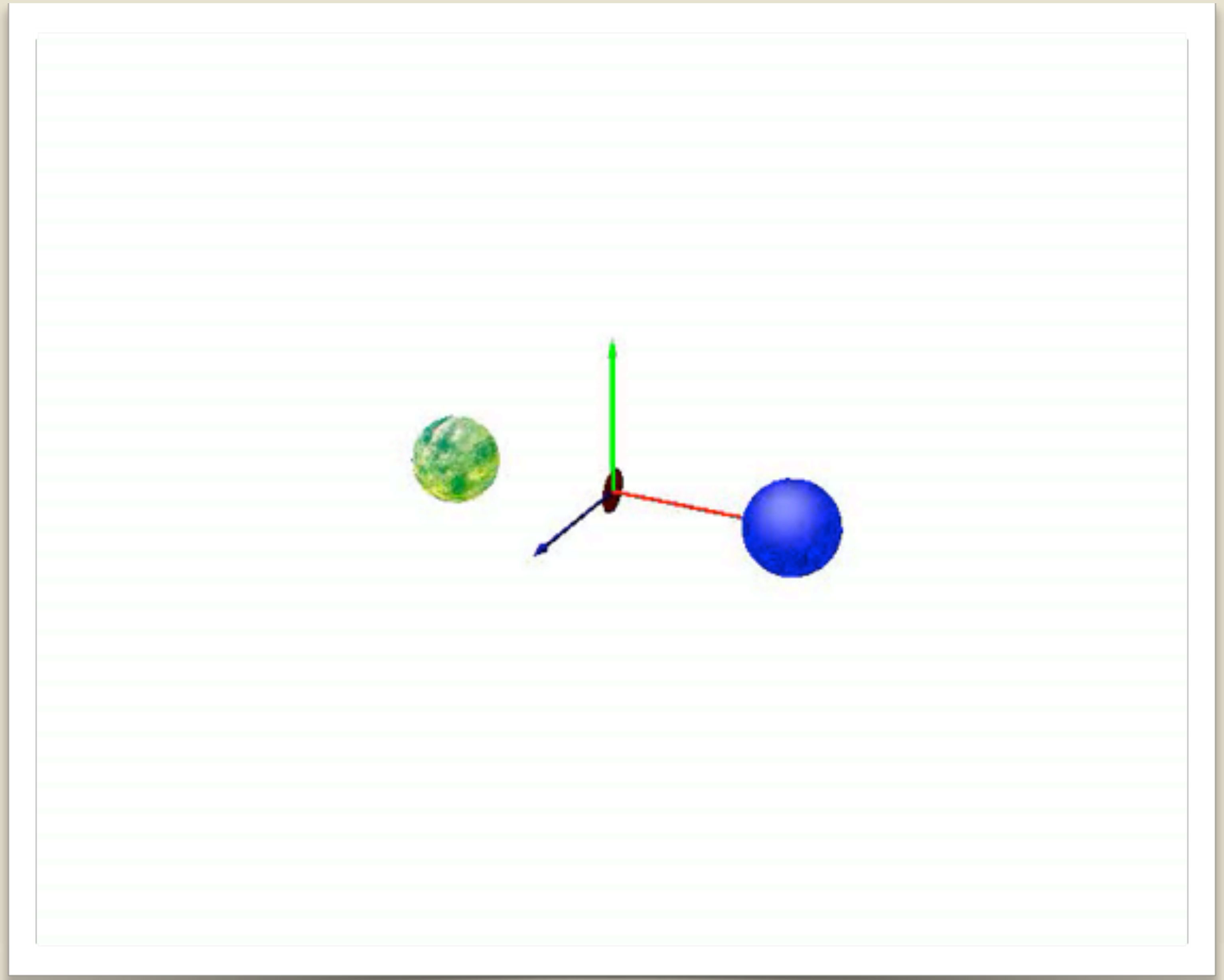
Variable Spatial Springs

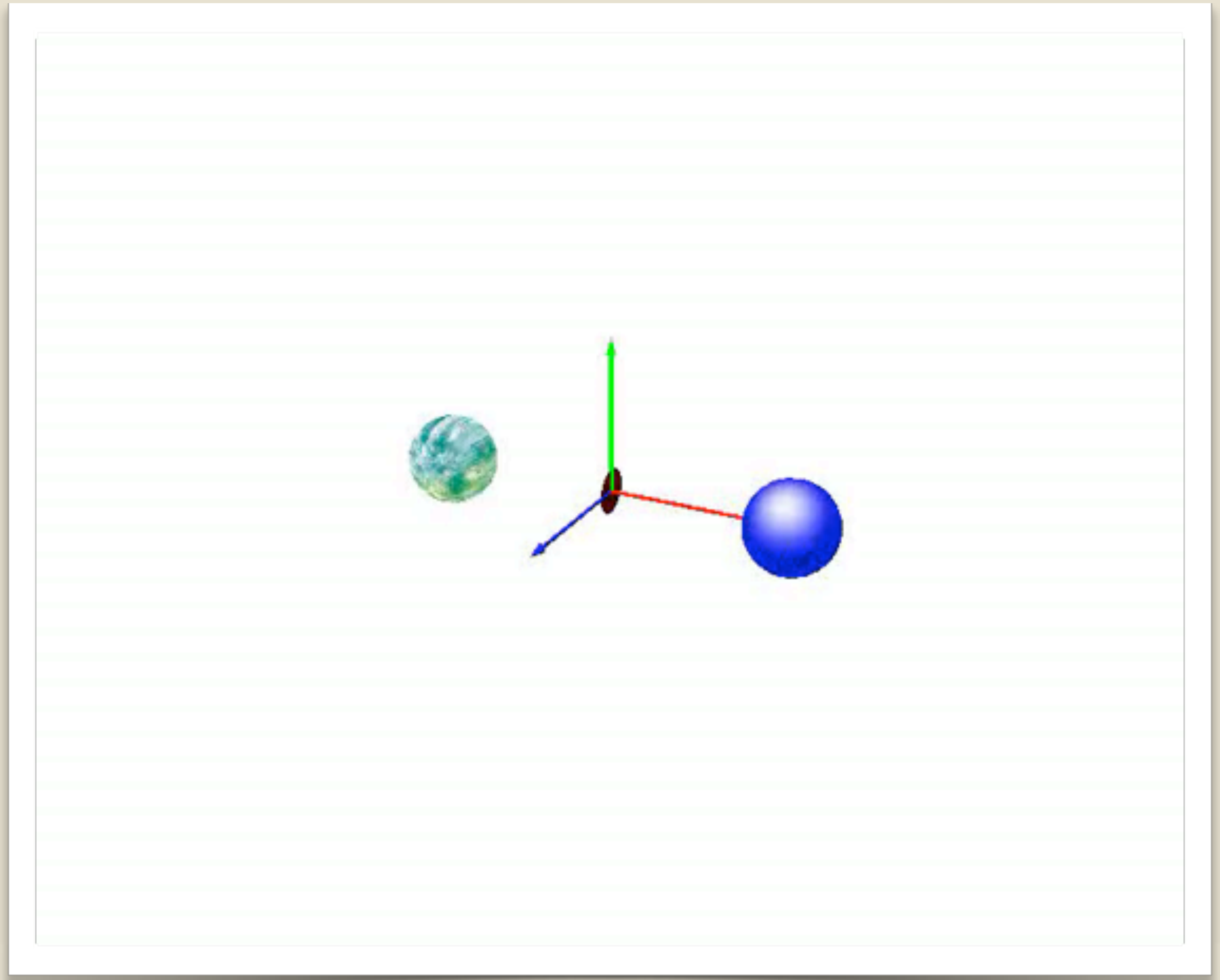


It can be shown that varying RCC does NOT exchange energy !!

Changing Length

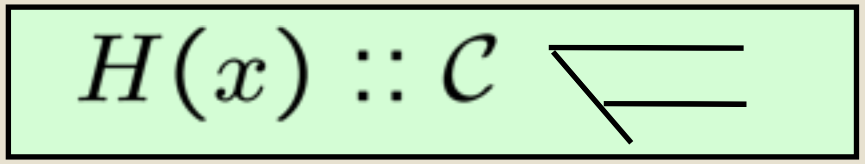


Changing the RCS (no energy supply!)

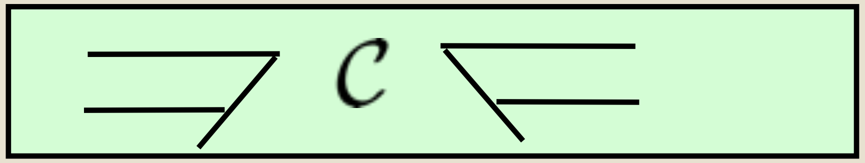


Parametric Changes (1D)

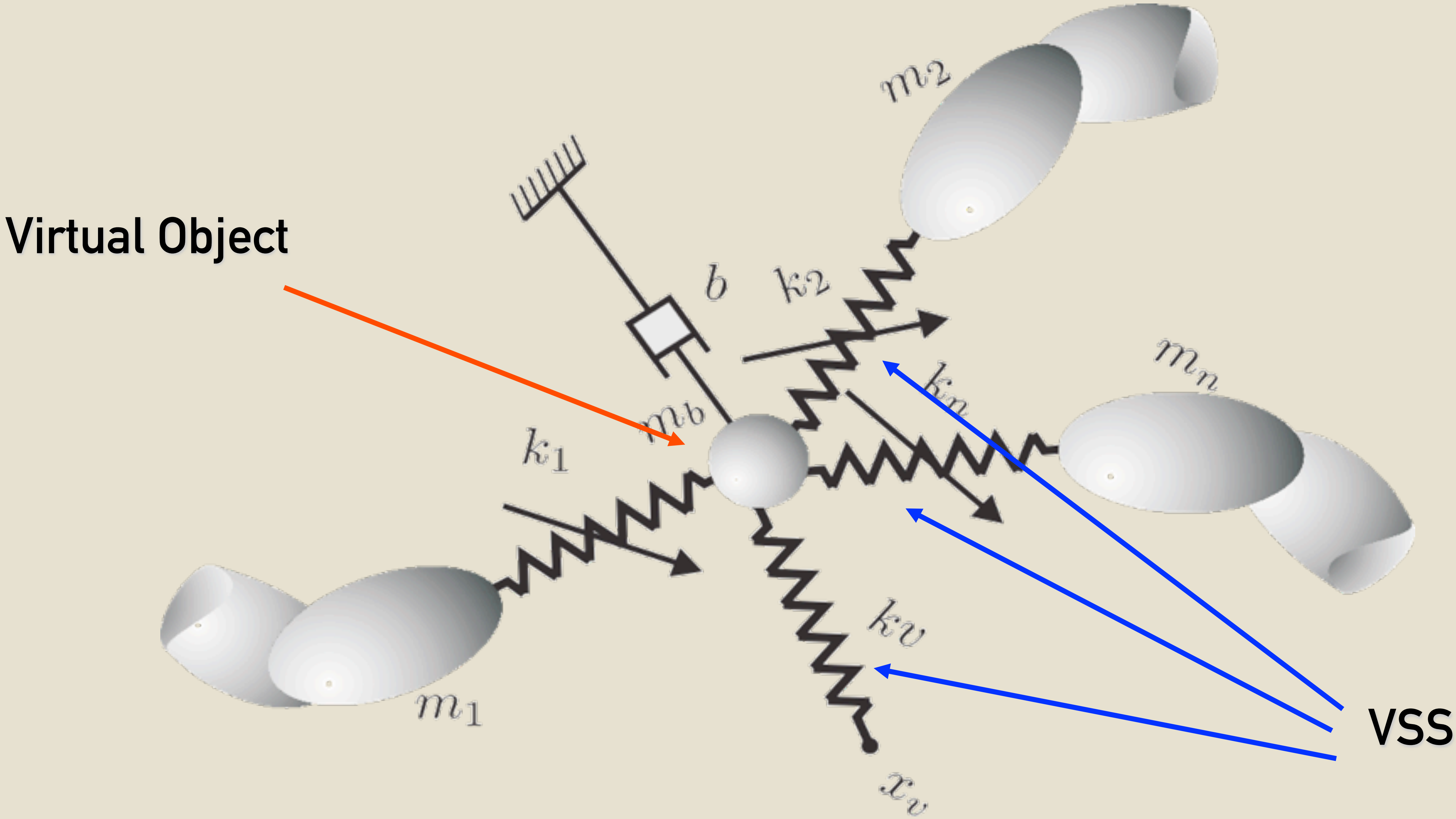
$$H(x) = \frac{1}{2}Kx^2 \rightarrow F = dH = \frac{\partial H}{\partial x} = Kx$$



$$H(x,k) = \frac{1}{2}Kx^2 \rightarrow \begin{aligned} F &= \frac{\partial H}{\partial x} = Kx \\ F_k &= \frac{\partial H}{\partial k} = \frac{1}{2}x^2 \end{aligned}$$



Example: Proposed Grasp Strategy



Animation of Algorithm