Force, compliance, impedance and interaction control

Summer School
Dynamic Walking and Running with Robots
ETH Zürich, July 12, 2011

Jonas Buchli

ISTITUTO ITALIANO
DI TECNOLOGIA
Advanced Robotics

Goals

- Understand basics of force control, impedance, admittance
- Understand forces in kinematic and RBD models
- Understand some examples of force control
- Understand some of the issues of actuation for force and position control in robotics (SEA, motors, hydraulics etc)
- Understand need for torque source (and velocity source)
- Keep math at minimum, develop intuition and understanding

Motivation:
Let’s discuss a few control concepts

High gain position control

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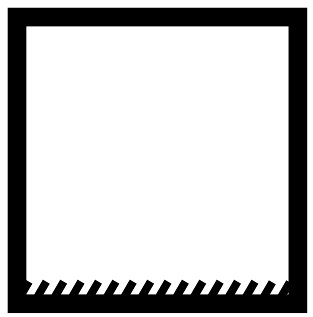

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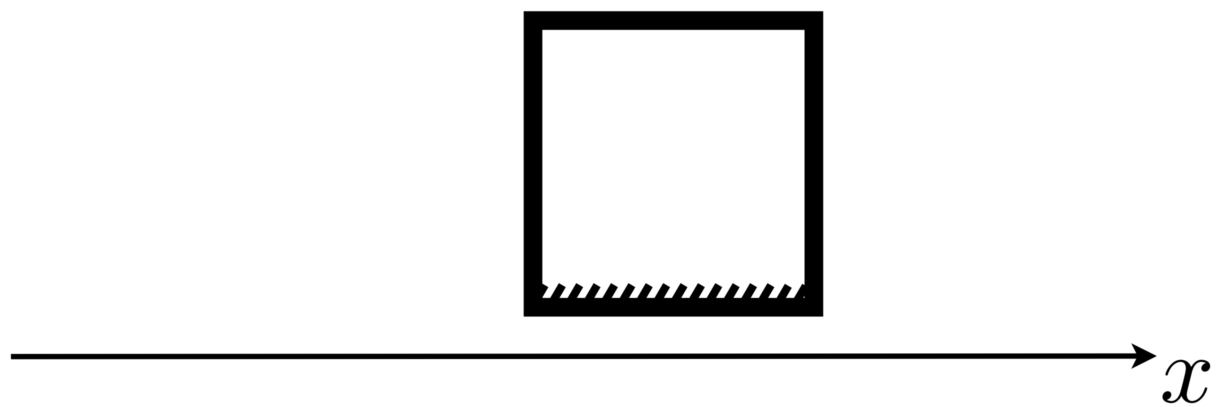

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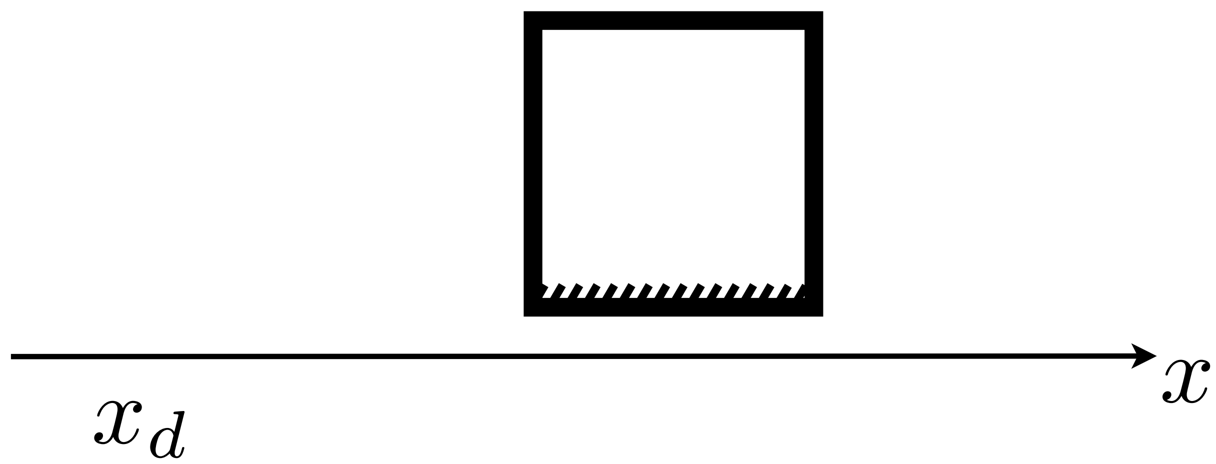

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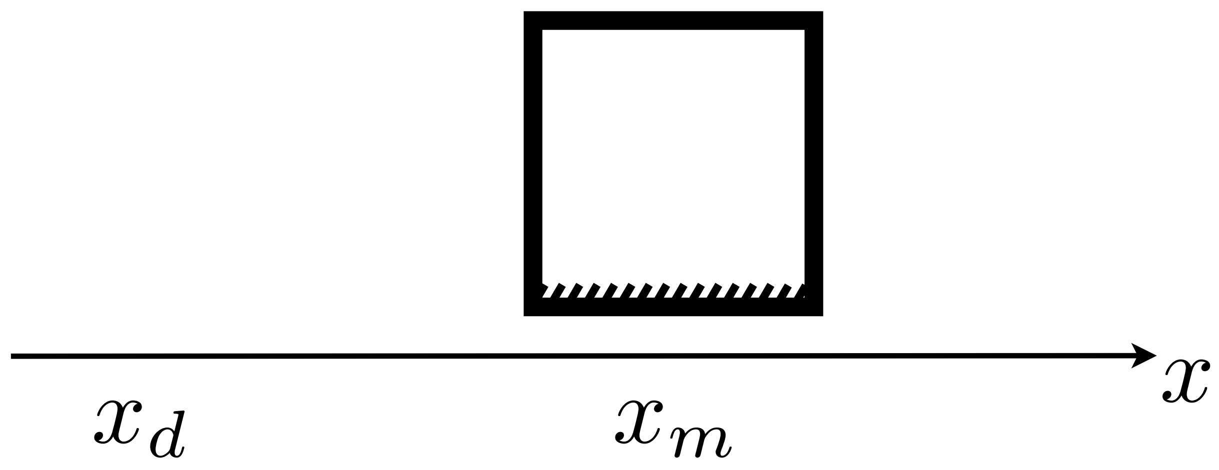

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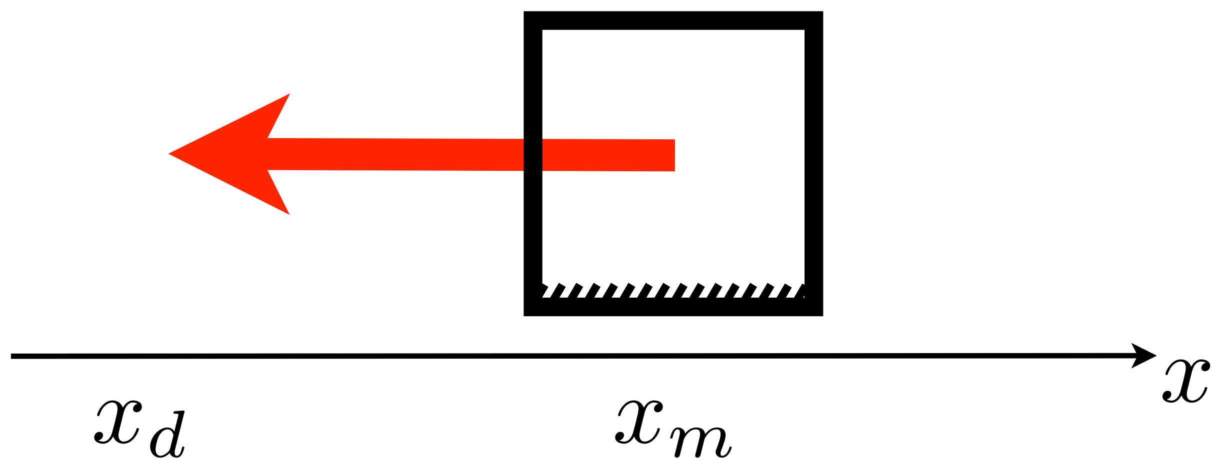

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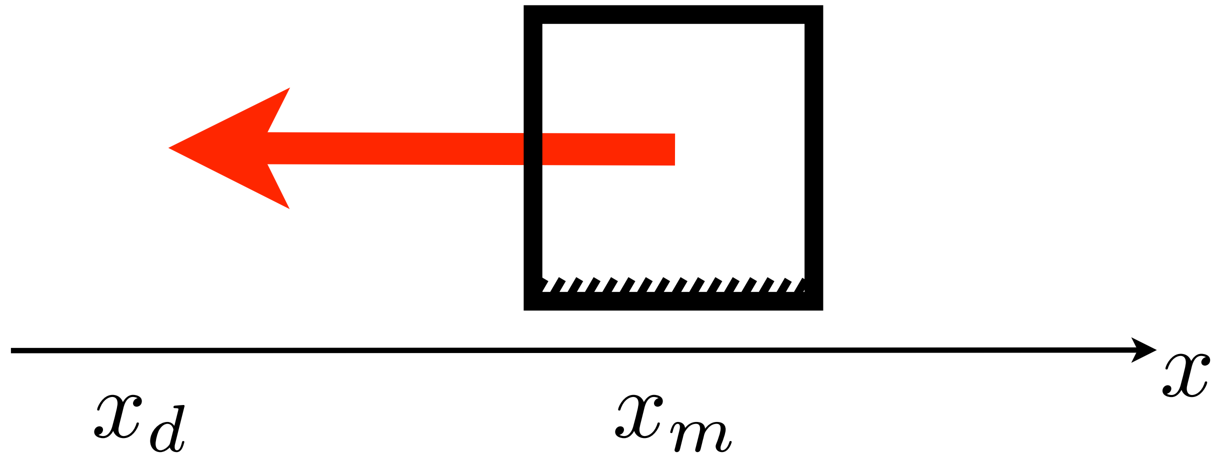

$$F = -K(x_m - x_d)$$

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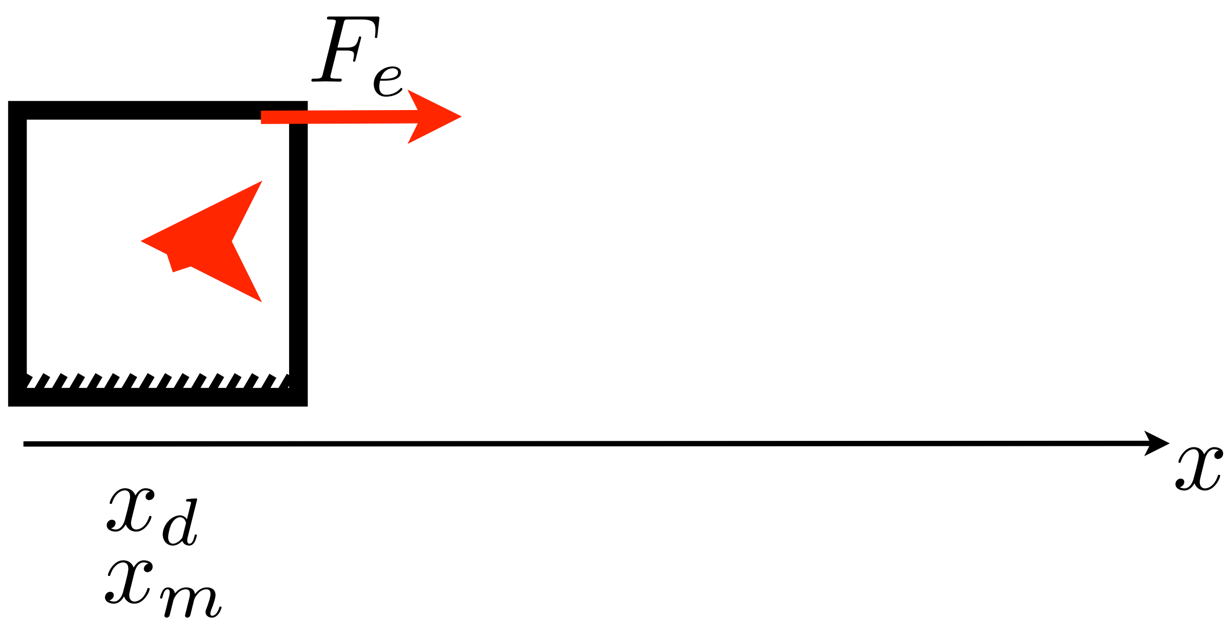

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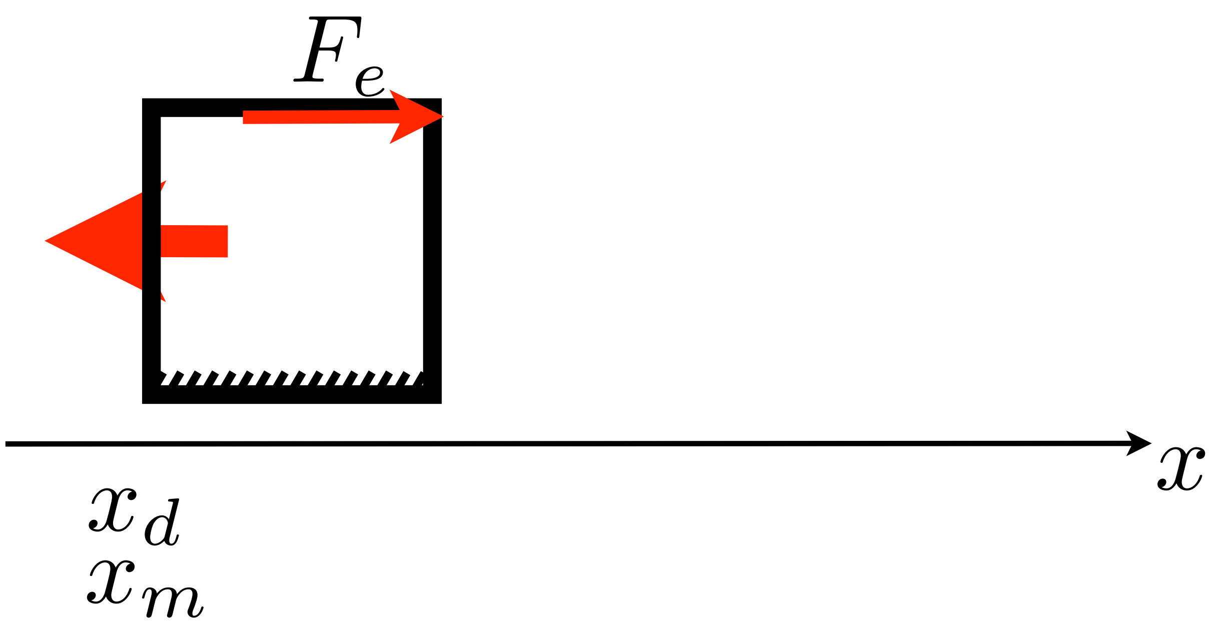

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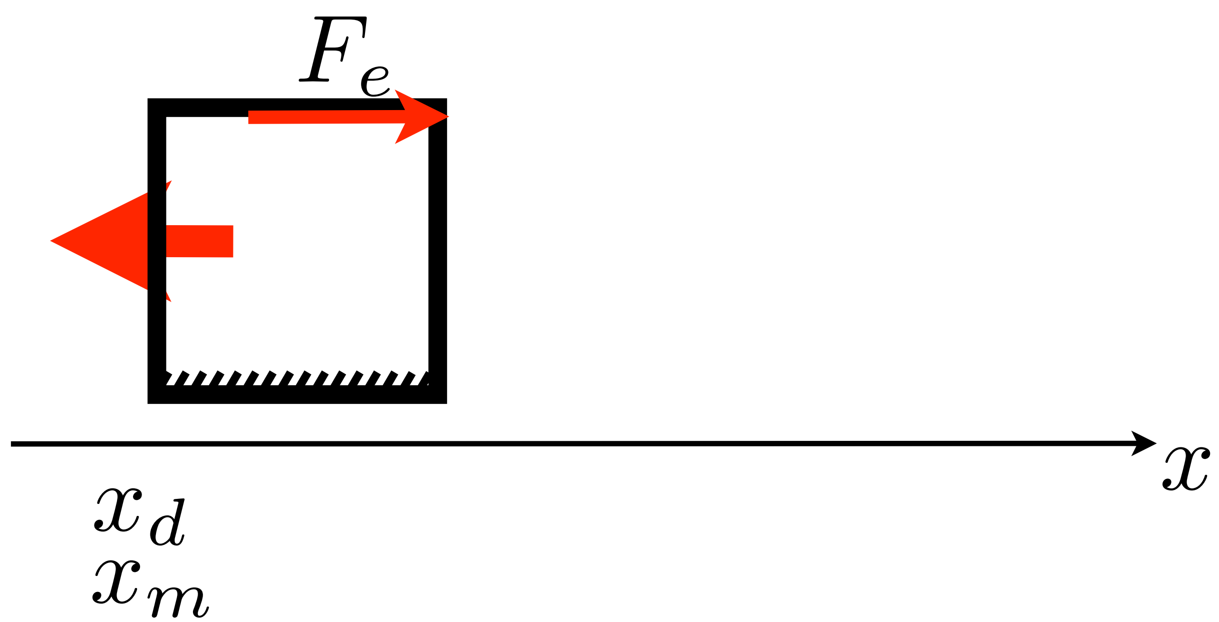

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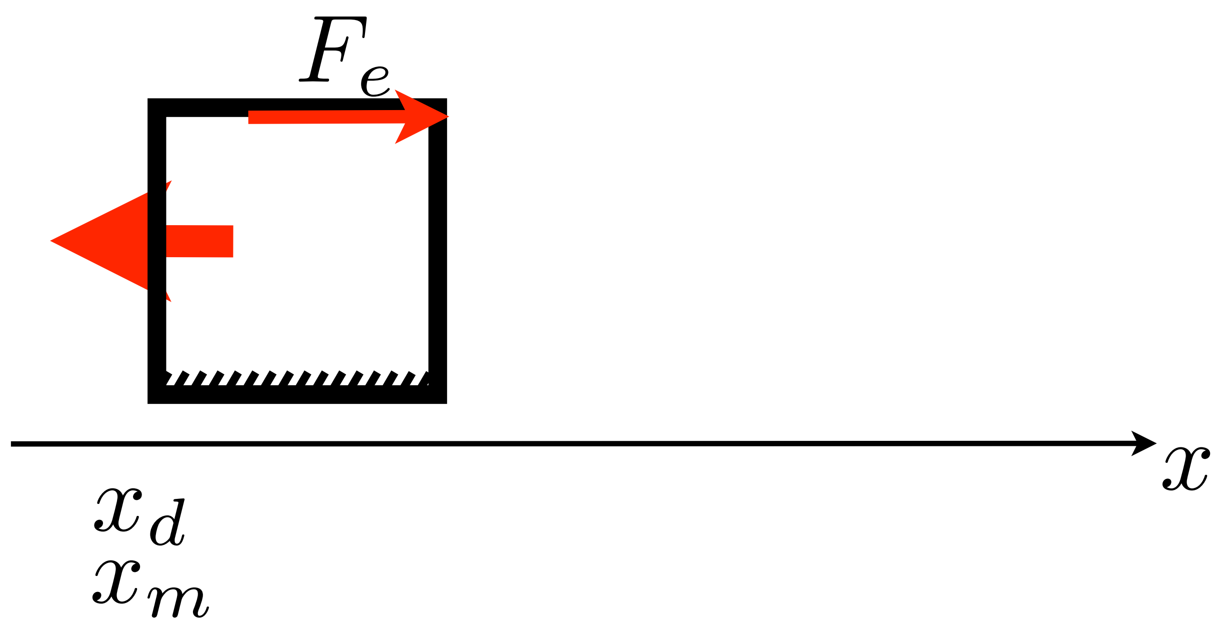

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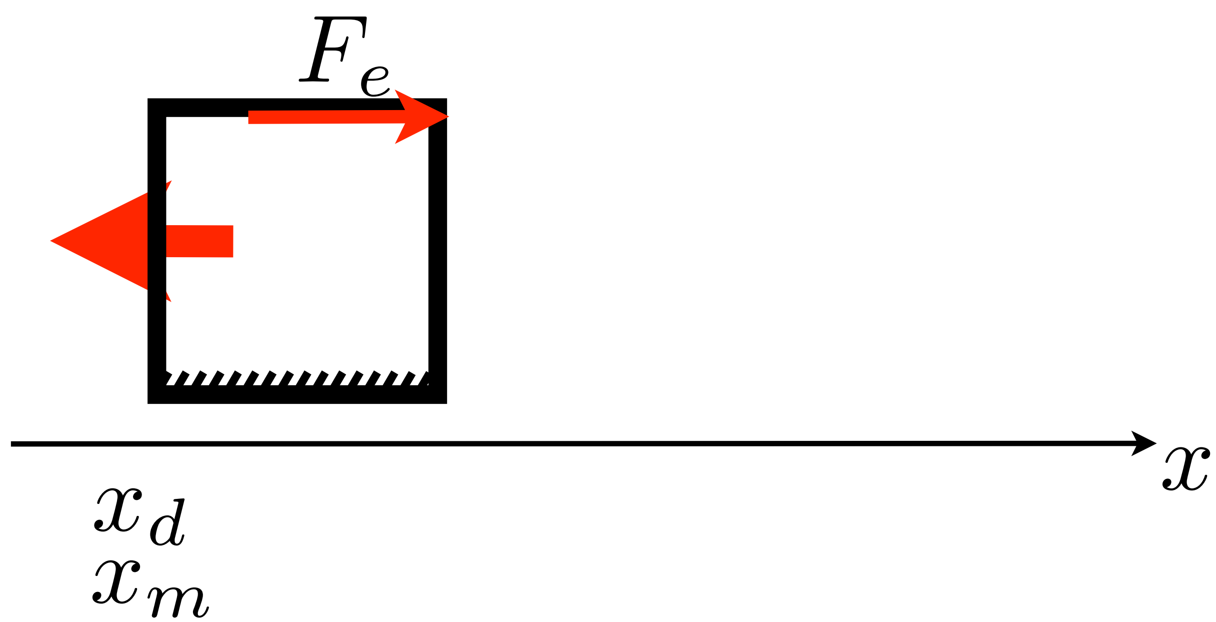
High gain position control



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The higher the gain, the less dependent on external forces and uncertainties!

Position control & contact

Is position control always a good choice?

Contact: Environment imposes position, Controller wants to impose position... what happens?

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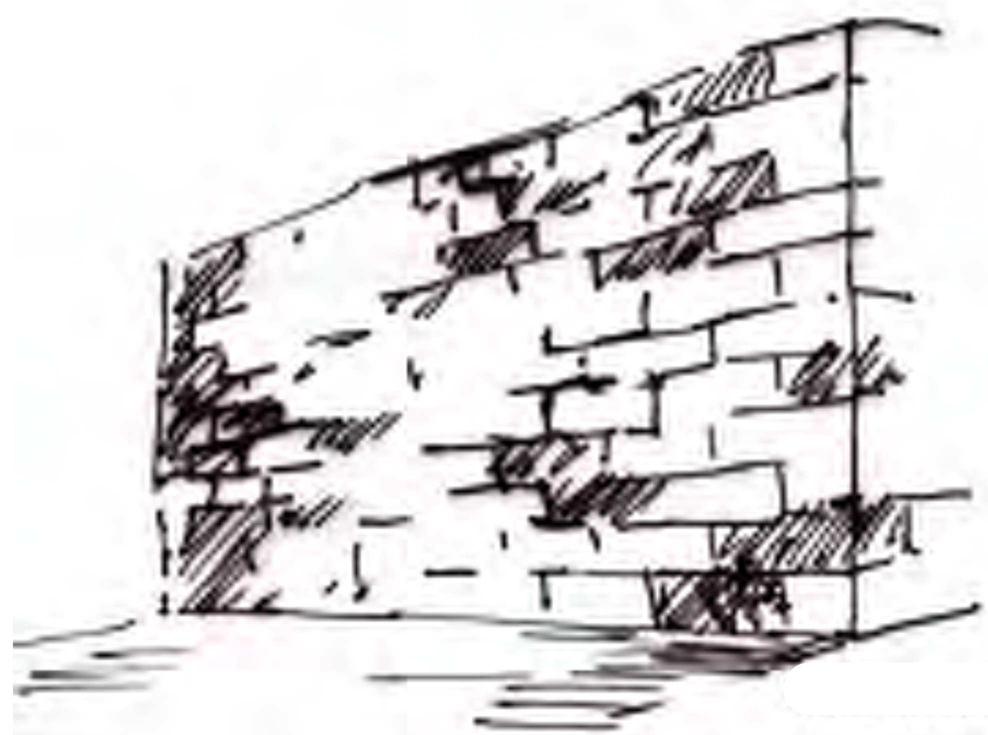

Why high gain control sometimes might be a bad idea!

[DLR: Haddadin, Albu-Schäffer, Frommberger, Rossmann, Hirzinger]

Compliance control

Compliance is widely exploited in natural systems!

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It can be controlled & changed!

Complian

Lots of active control!

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It can be controlled & changed!

Compliance & Force control

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Can we use compliance and force control
for robots and what is it useful for?

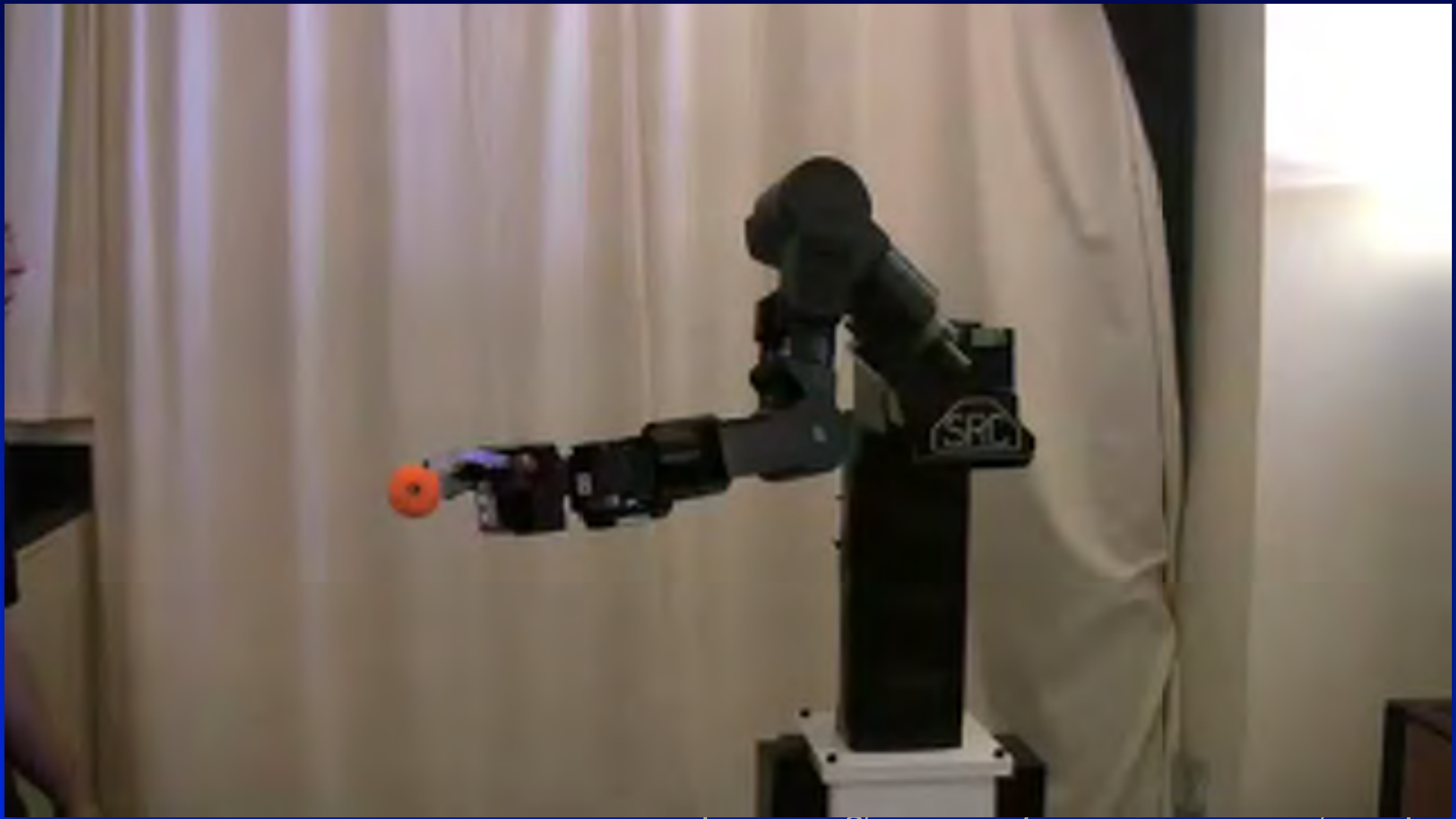
Compliance & Force control

Can we use compliance and force control
for robots and what is it useful for?
How to do this on complex robots?

Compliance & Force control

[Little Dog, Boston Dynamics/CLMC Lab , USC]

Compliance & Force control



[SARCOS Slave arm, CLMC Lab , USC]

Compliance & Force control

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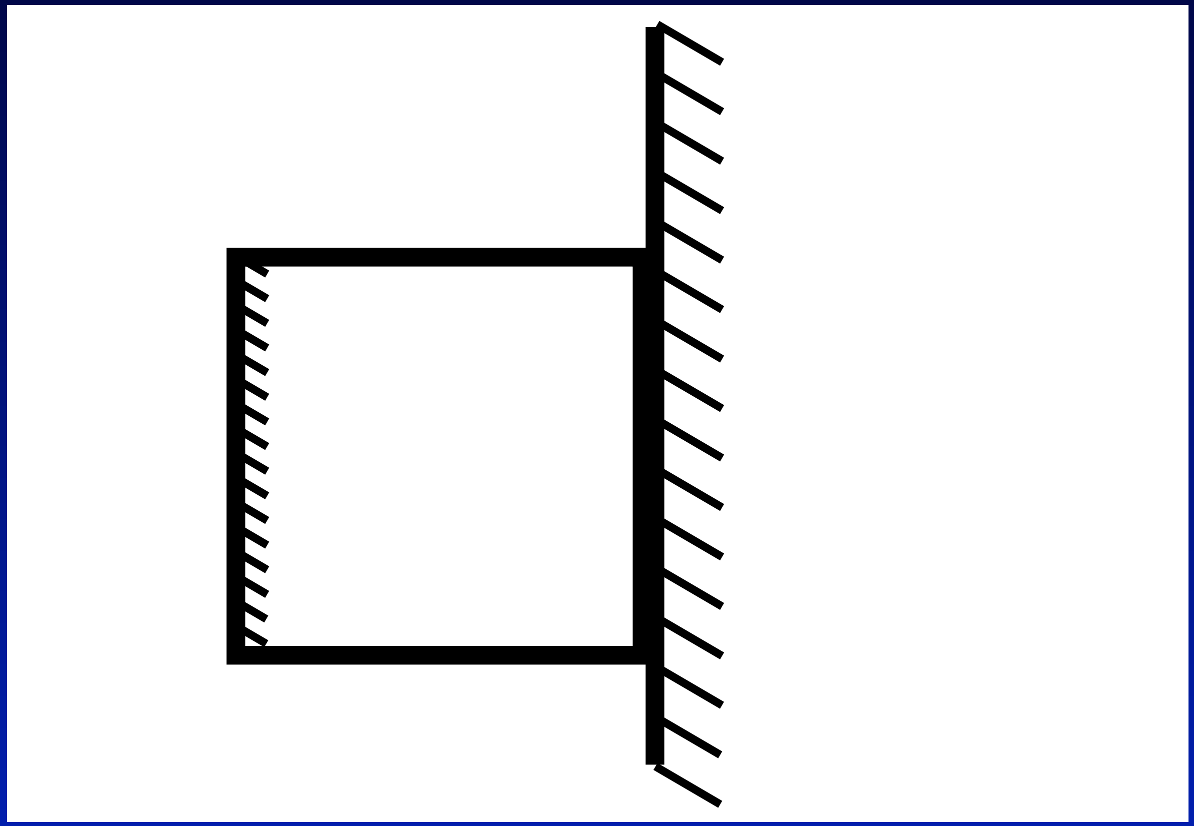
[Kalakrishnan, Righetti, Pastor, Schaal, IROS 11]

Constrained motion



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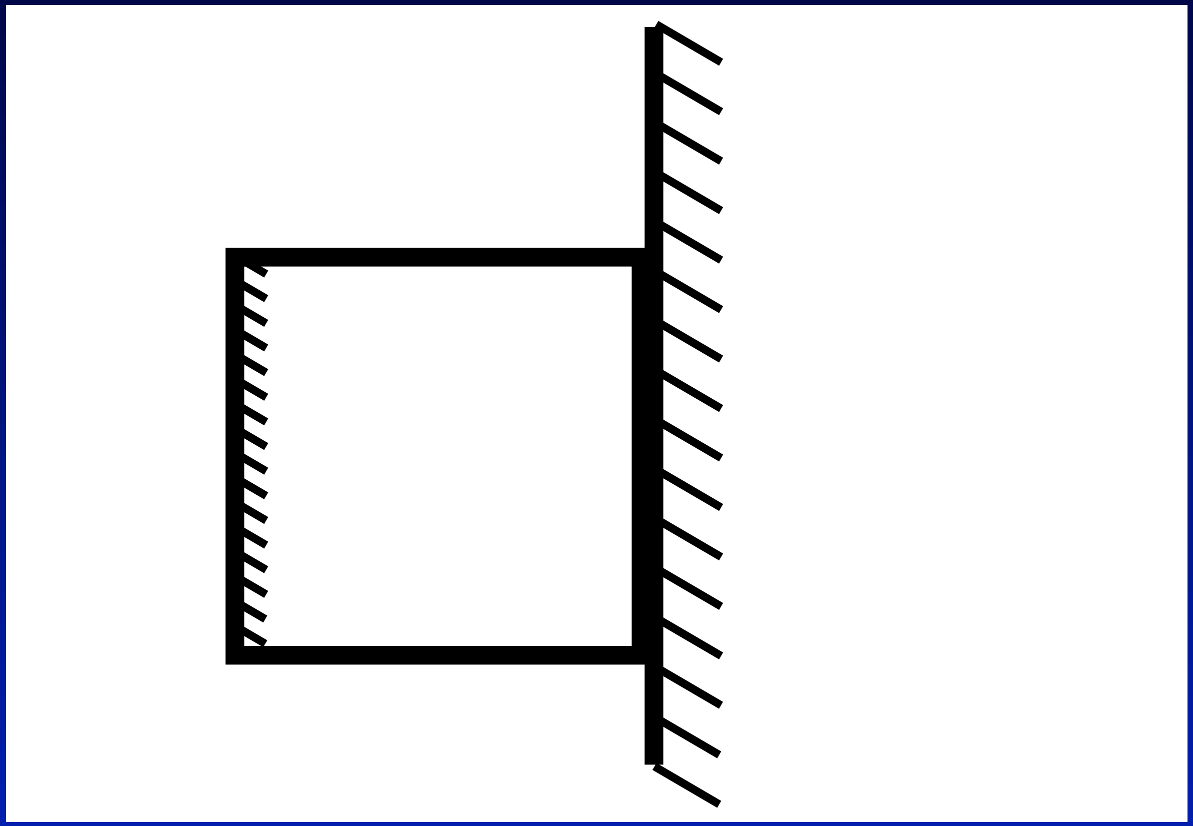
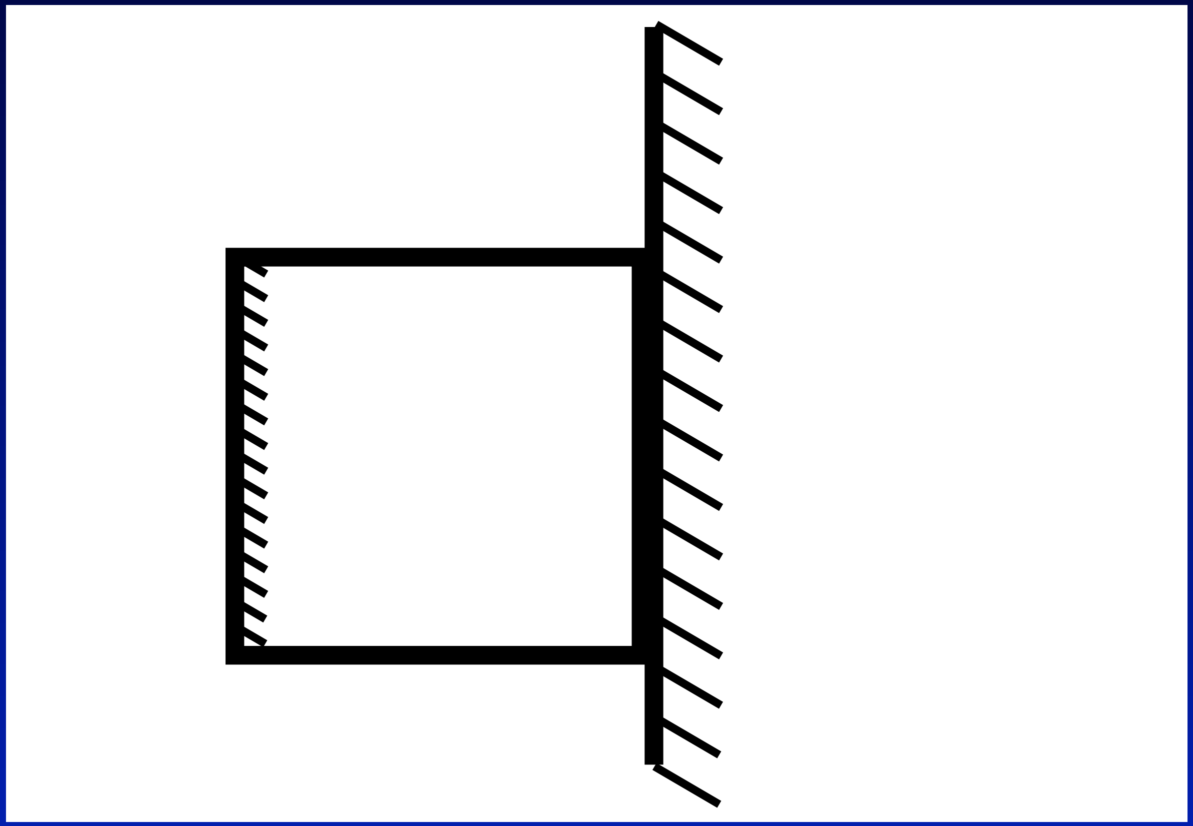


Two directions:

Constrained motion



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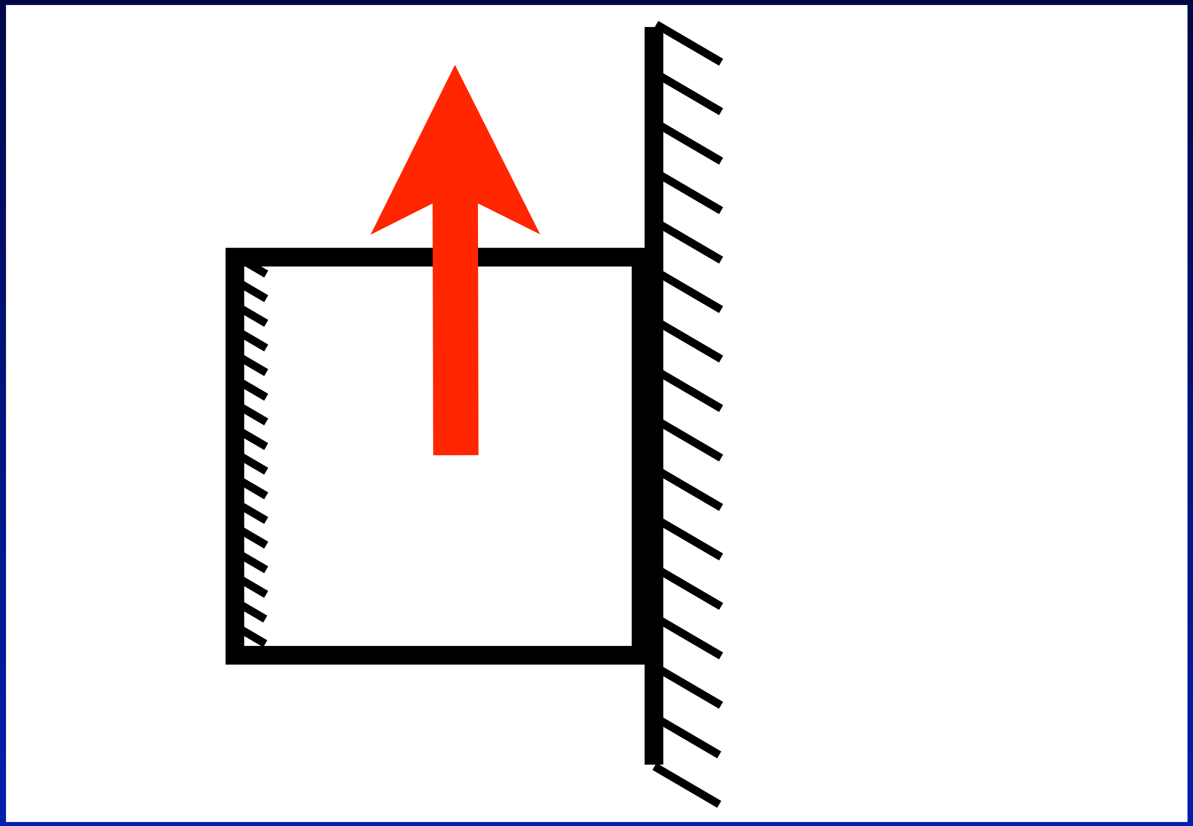

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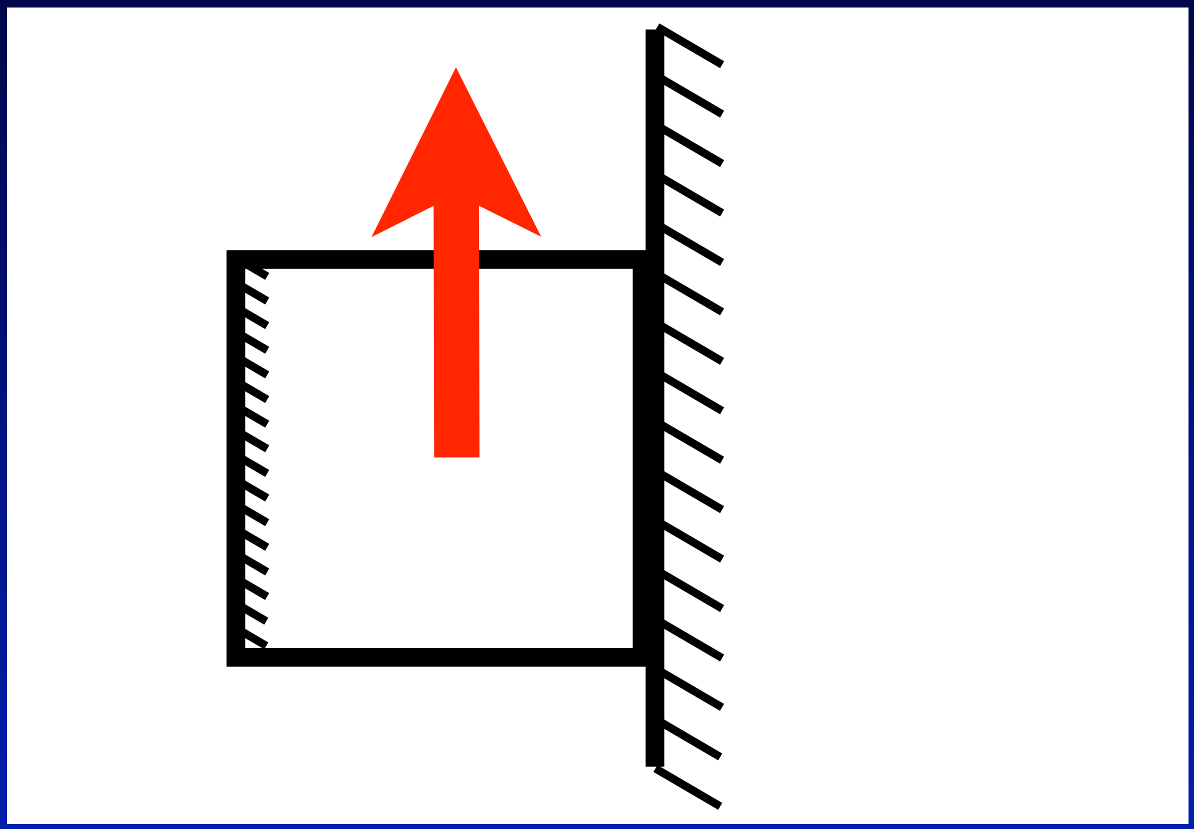

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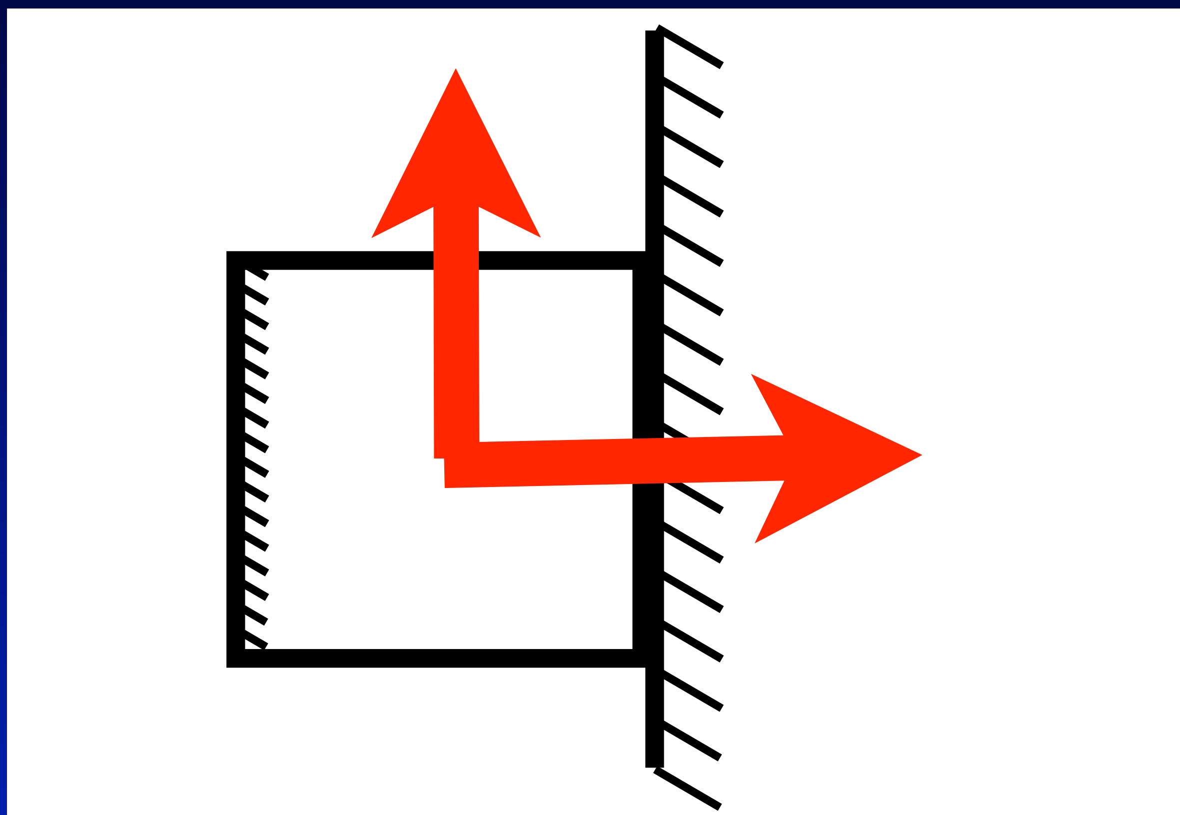

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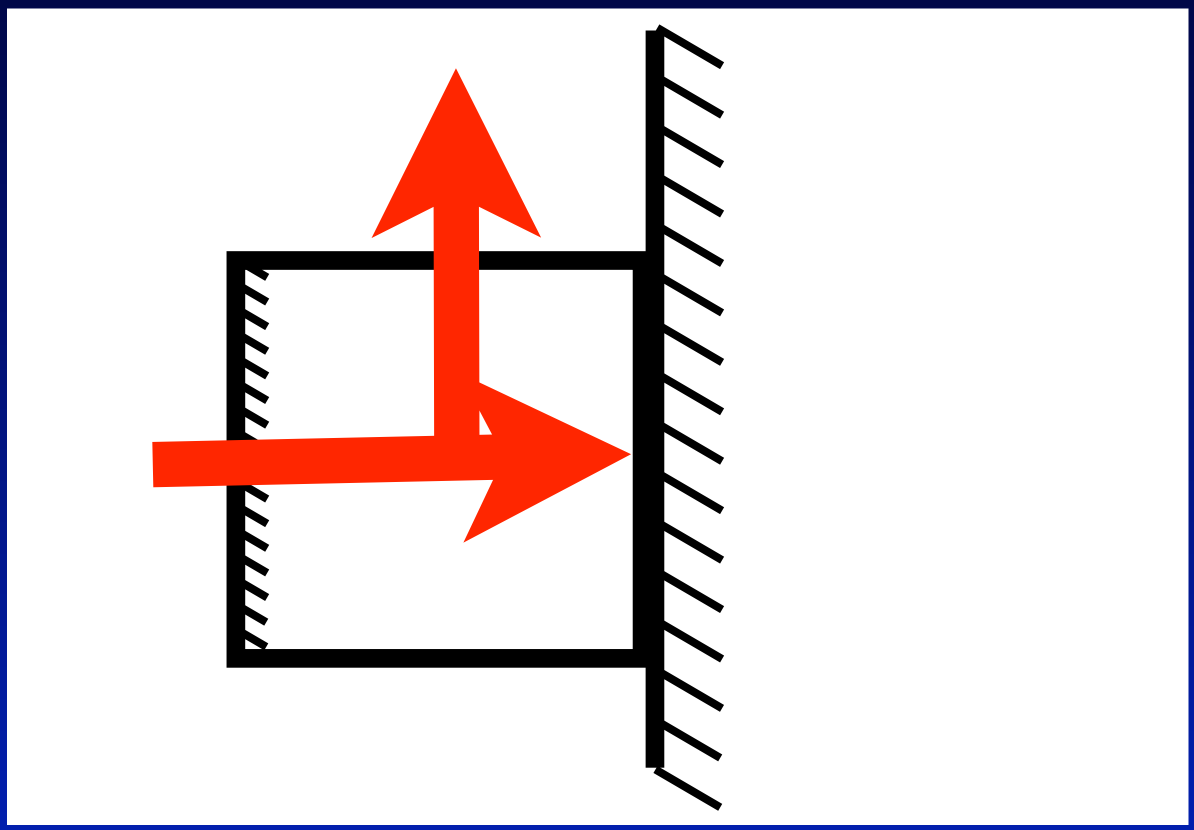

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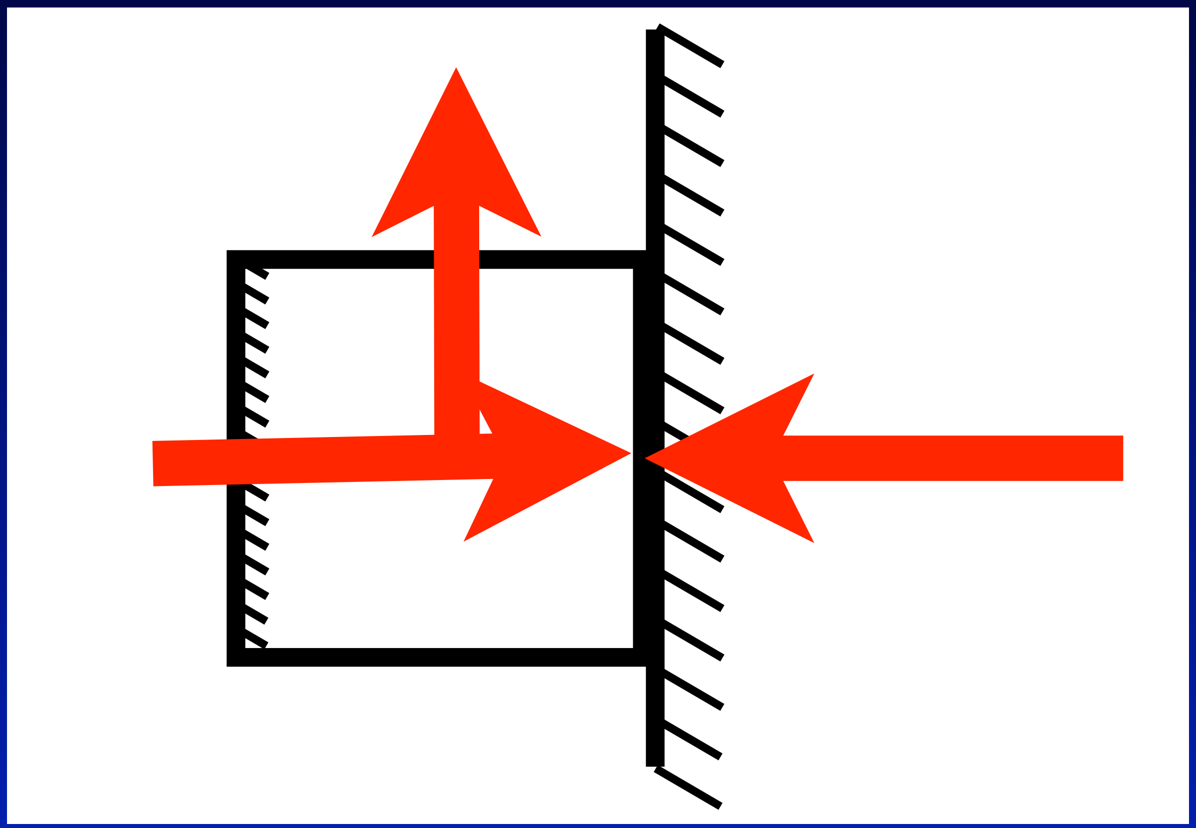

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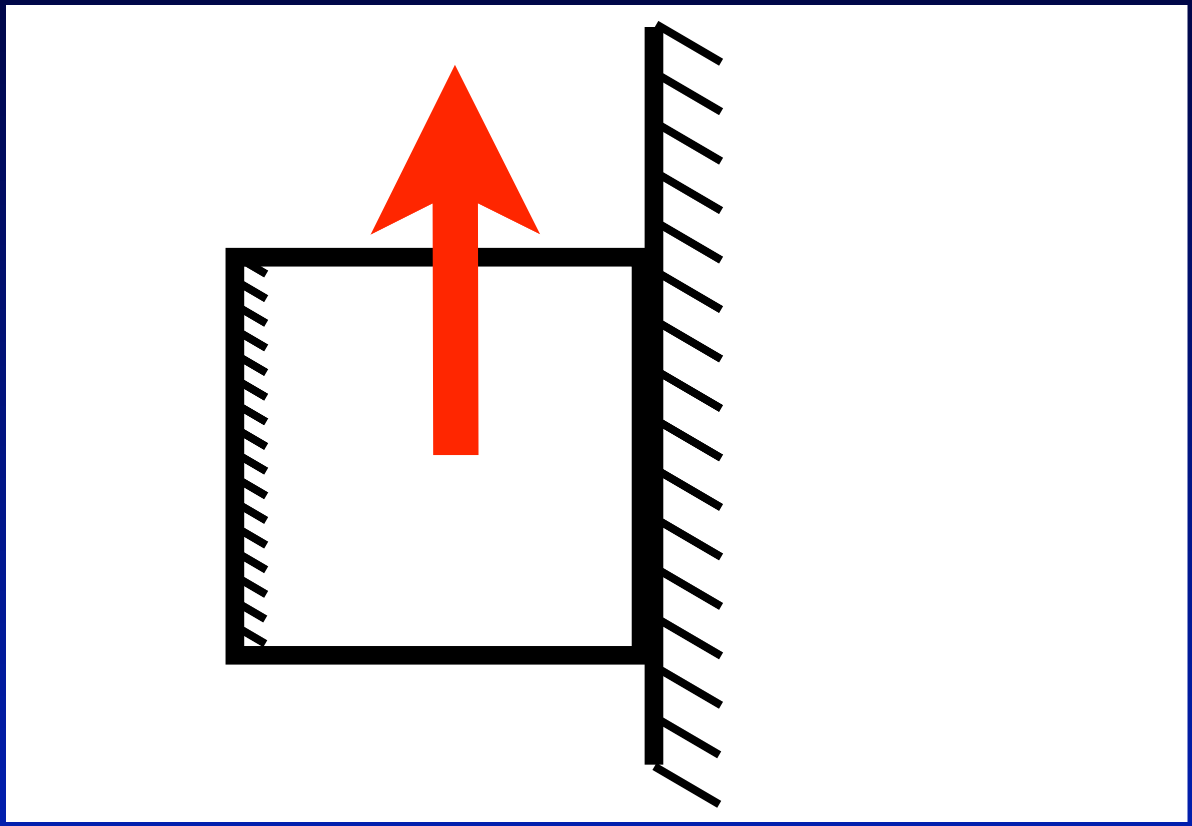

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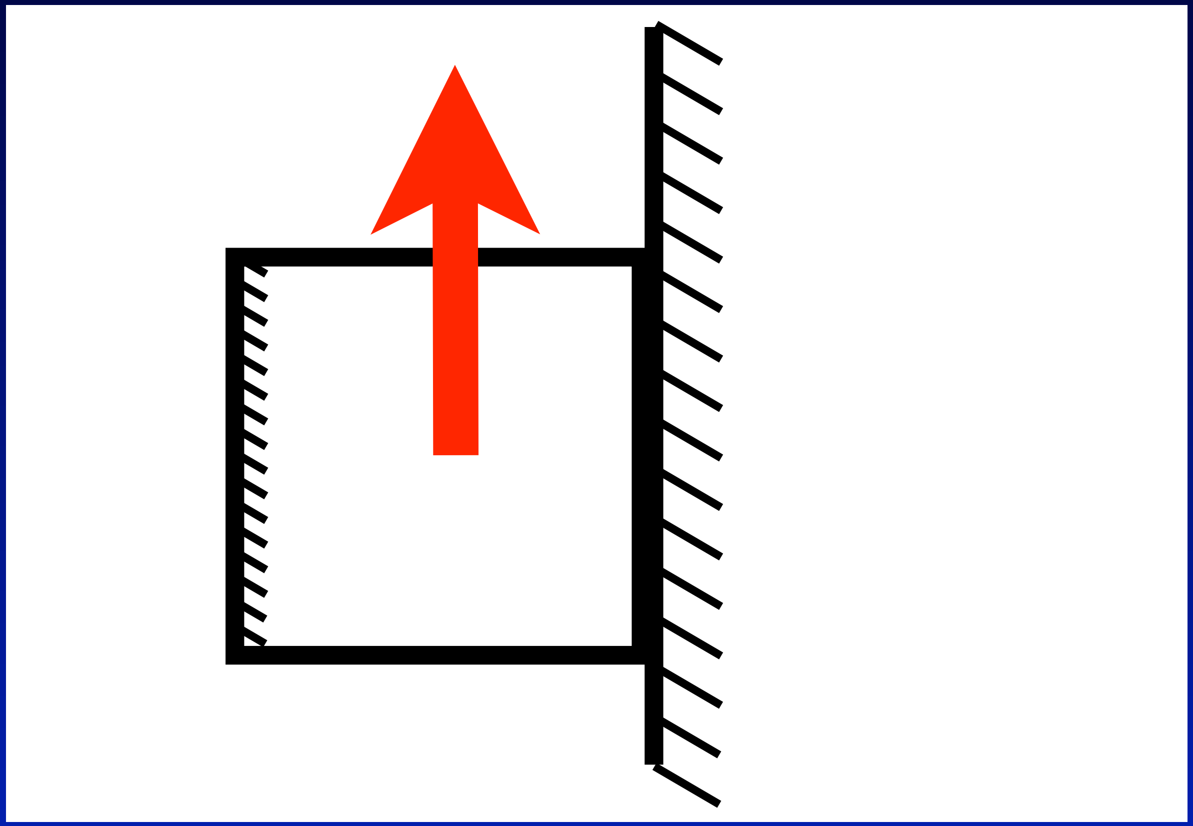

Two directions:

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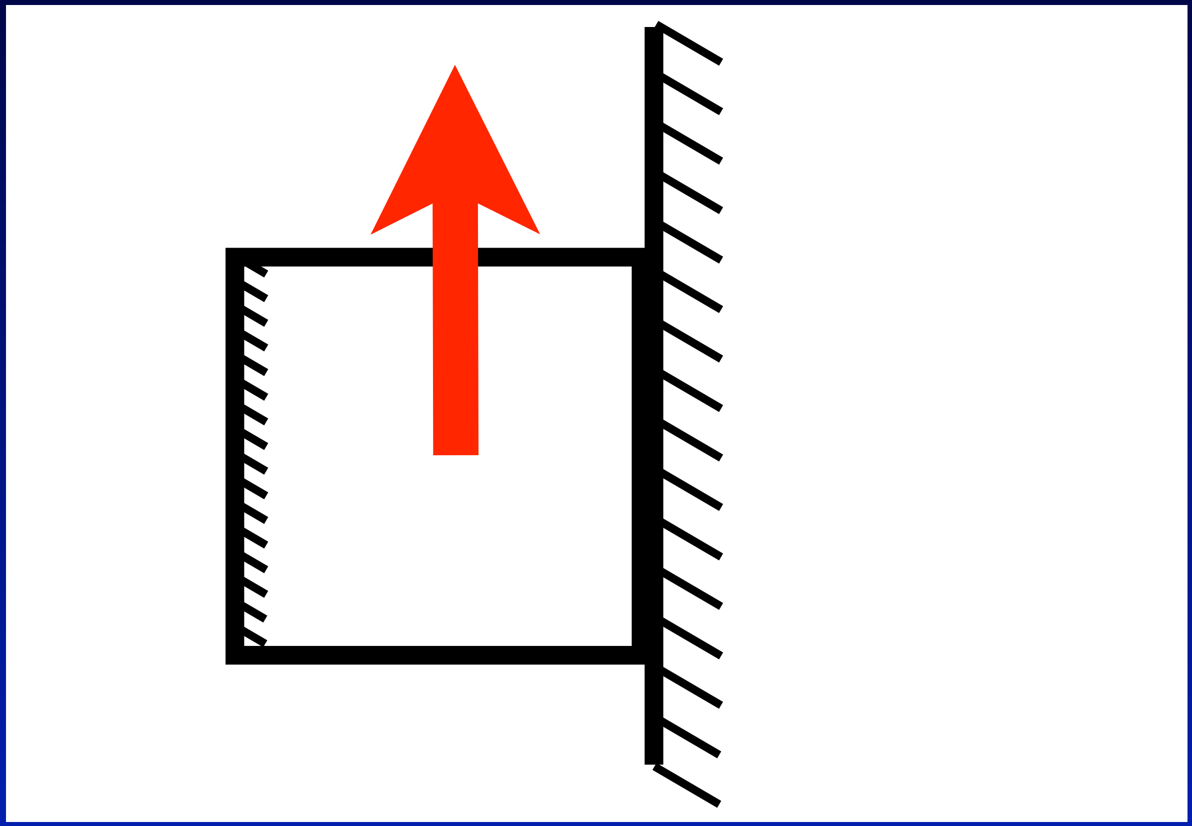
In constrained direction
sum of forces always zero

Constrained motion



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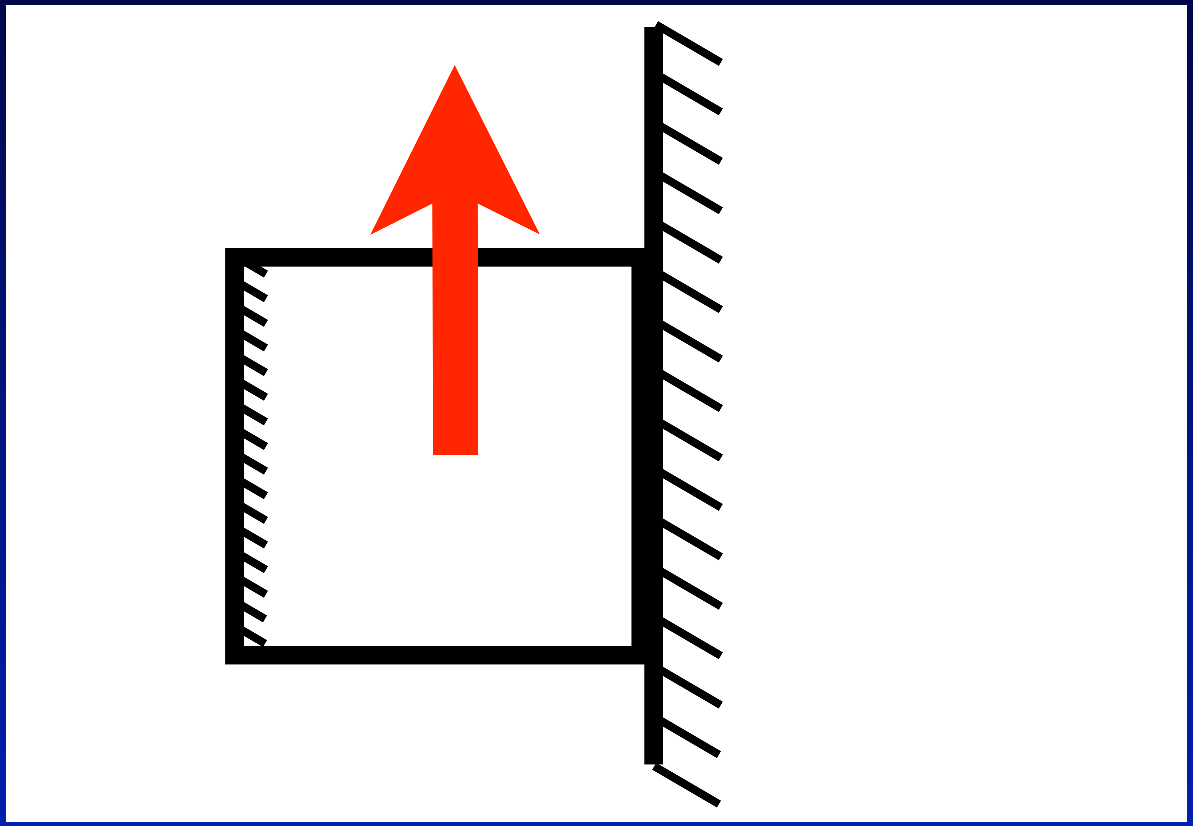
Give up control over position!

Constrained motion



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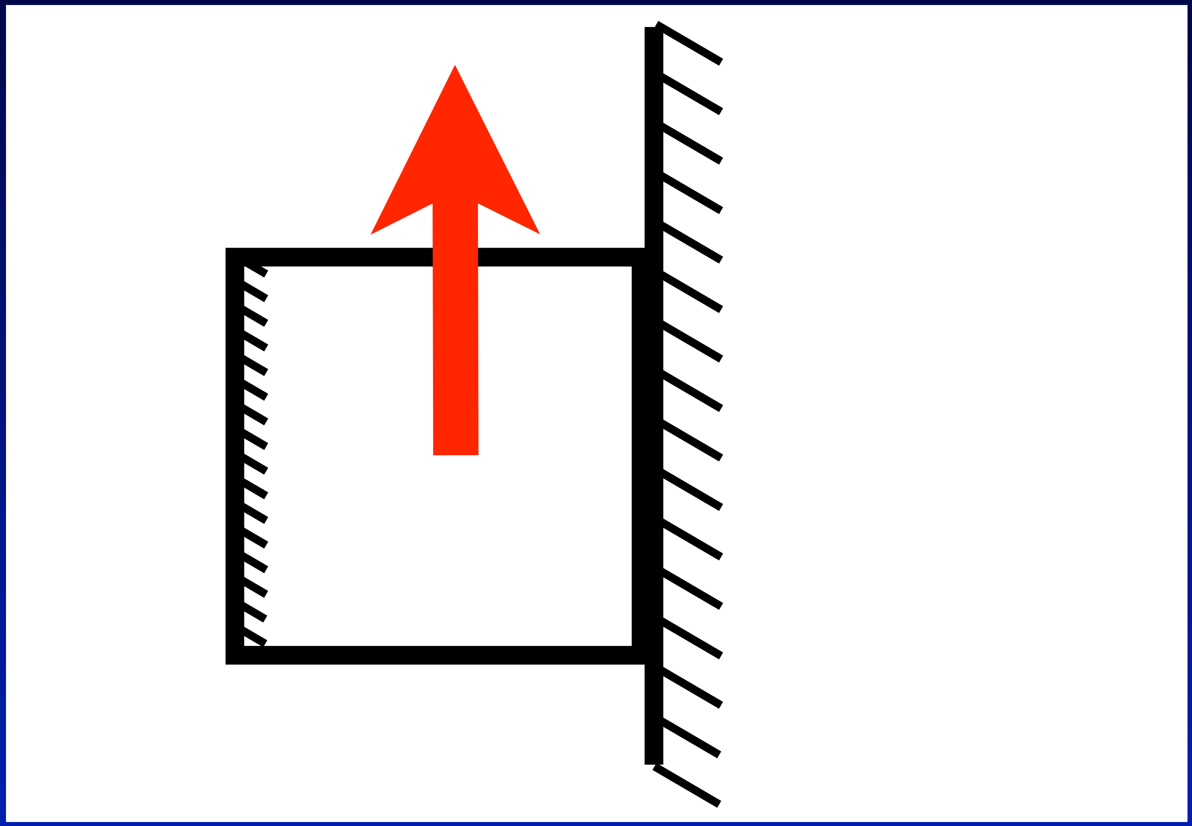
Give up control over position!
What remains?

Constrained motion



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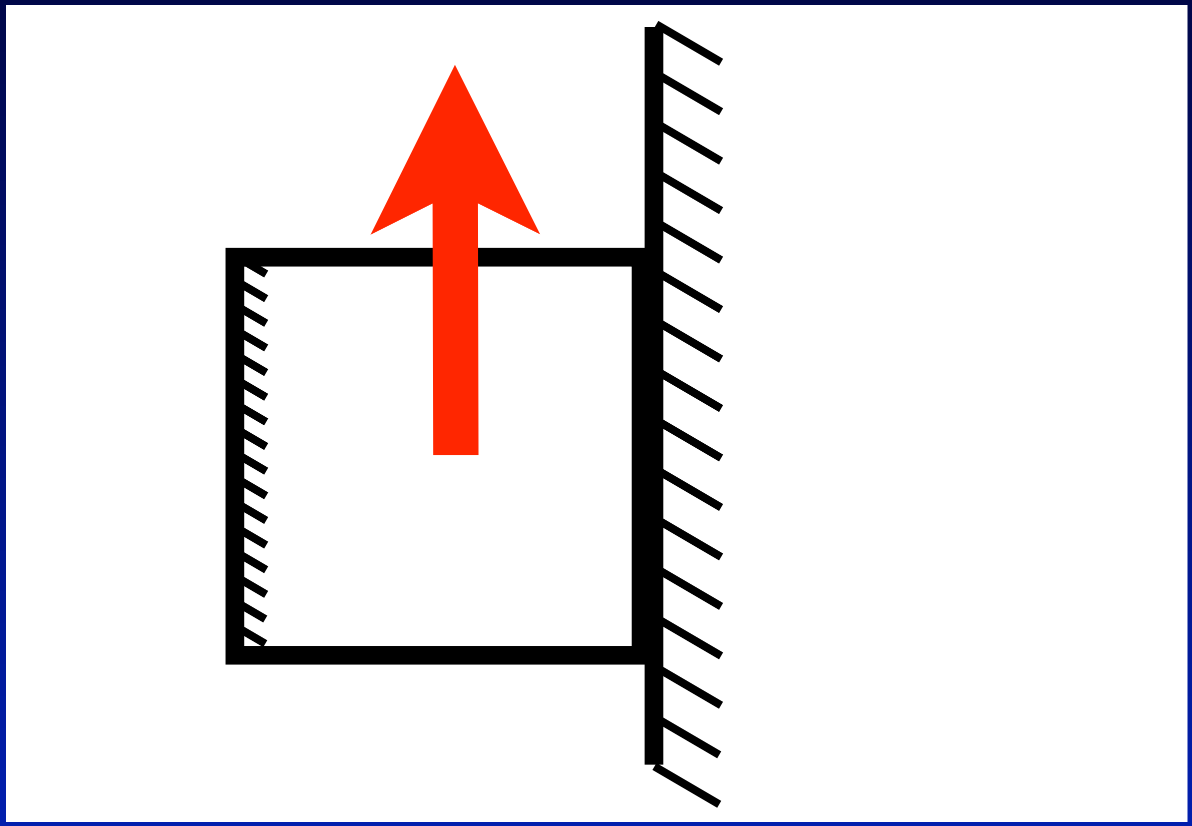

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Interaction control!

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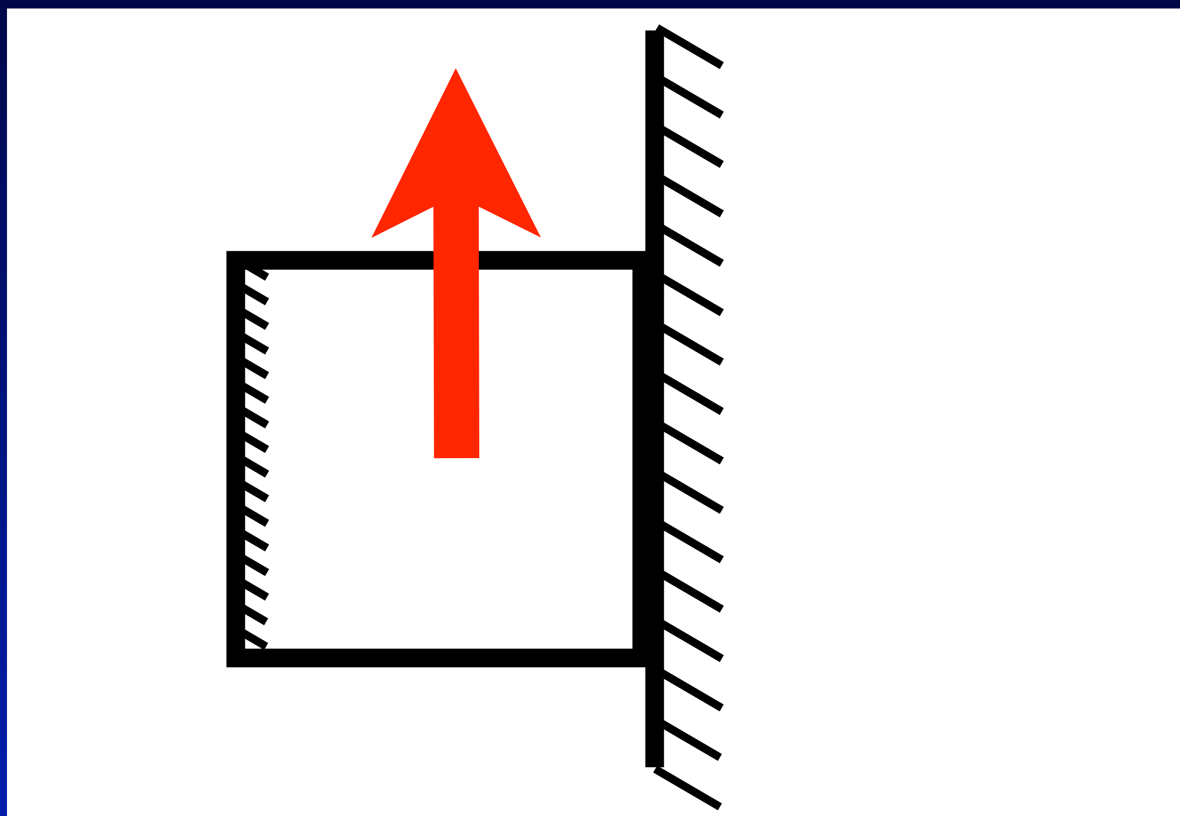

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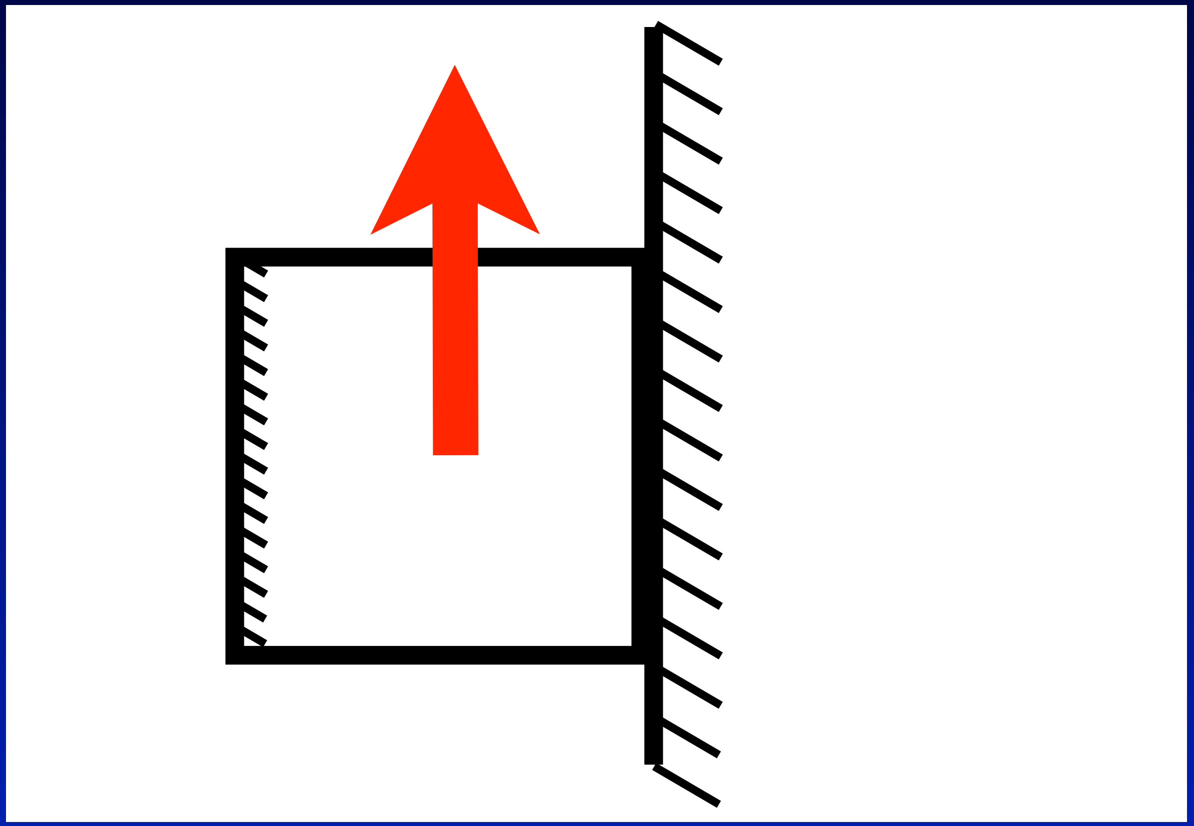

Two directions:
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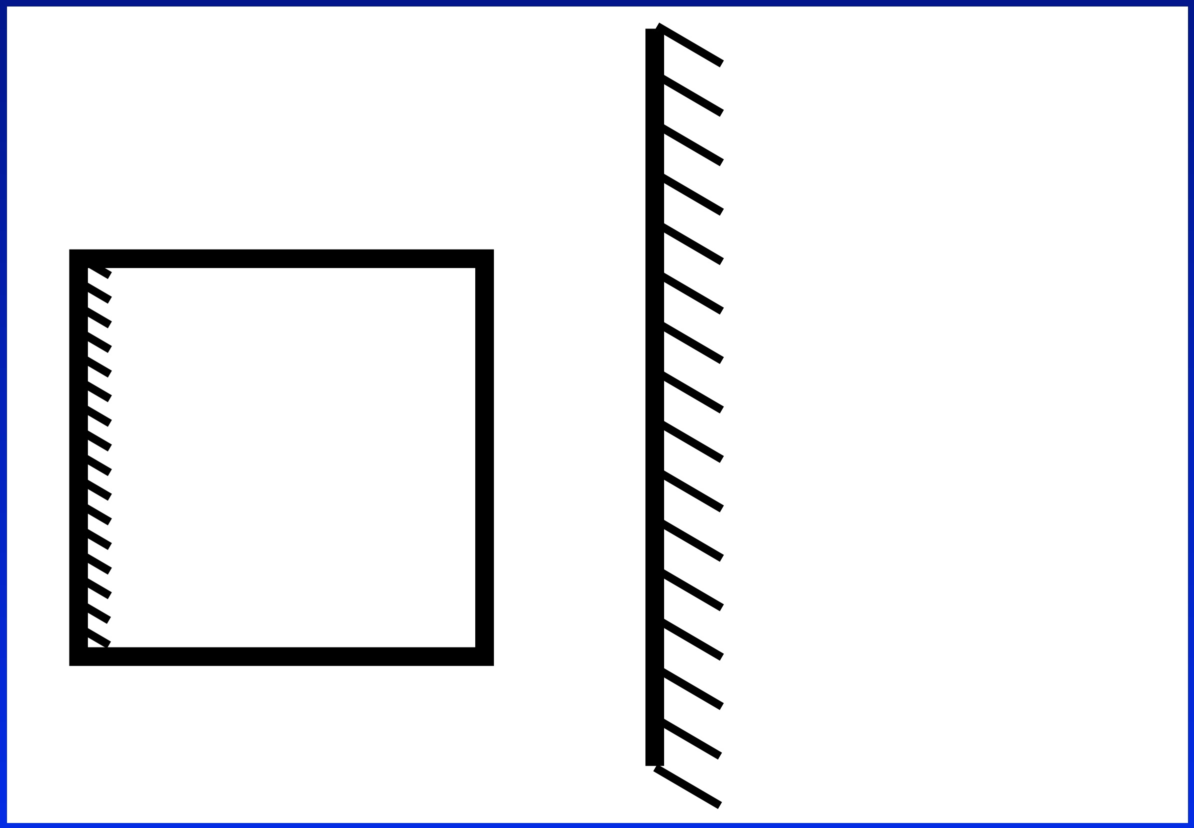
In constrained direction
sum of forces always zero

Many 'every day's' tasks involve,
contact with environment and
controlling force

Give up control over position!
What remains?
Force control!
Interaction control!
Impedance control...

Interaction! Dynamics!

We are interested in what happens when contact conditions change $\Rightarrow$ Contact dynamics!



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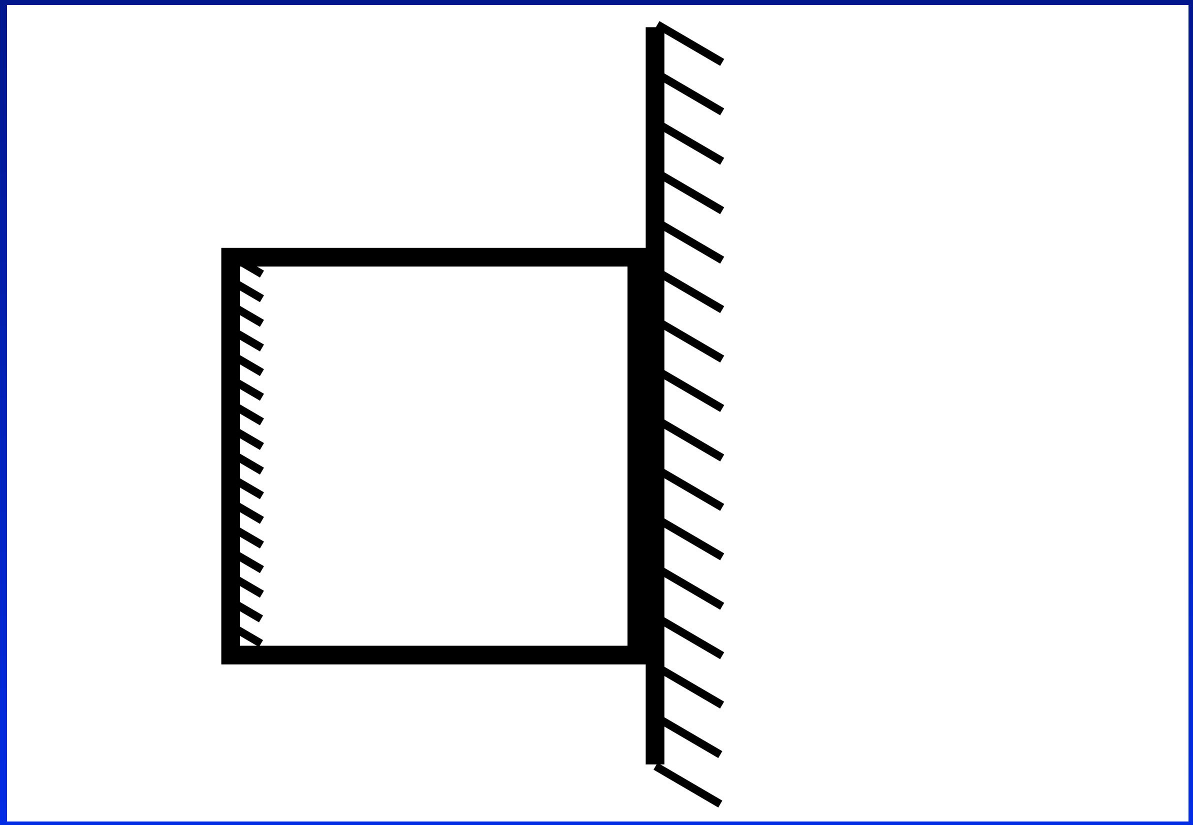

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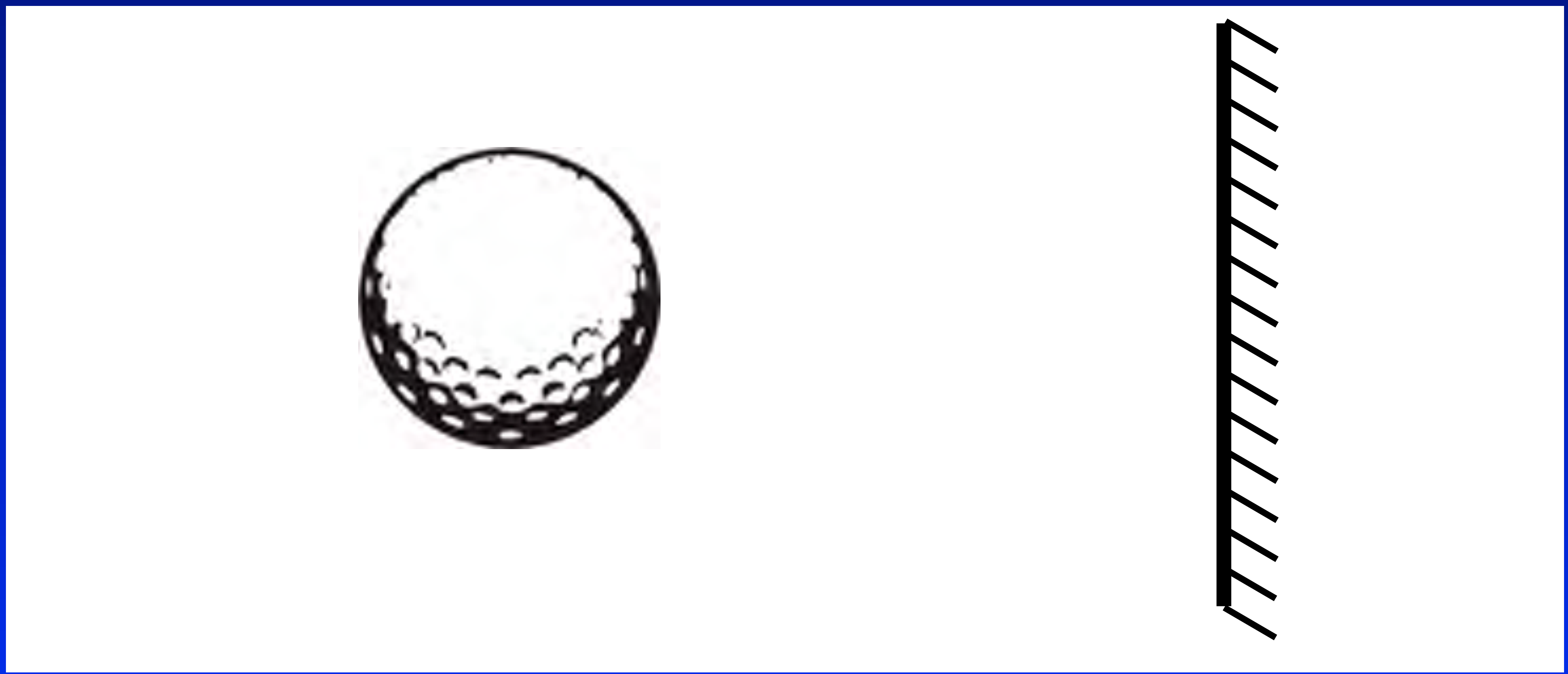

Collisions...

What happens if two masses come into contact?

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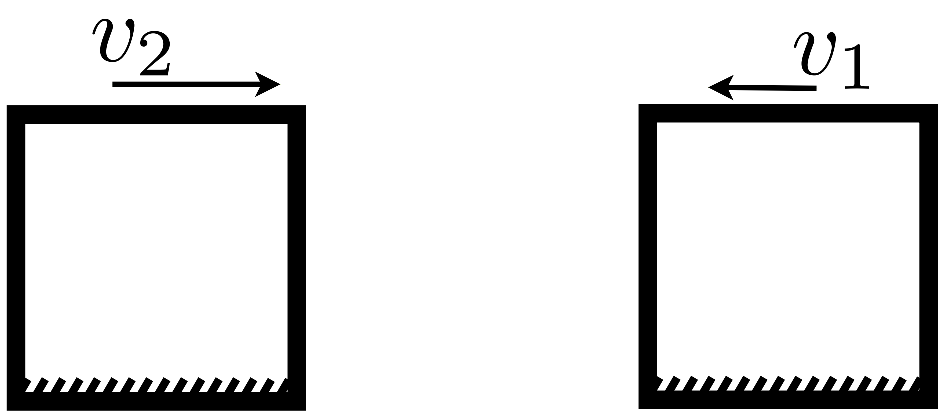

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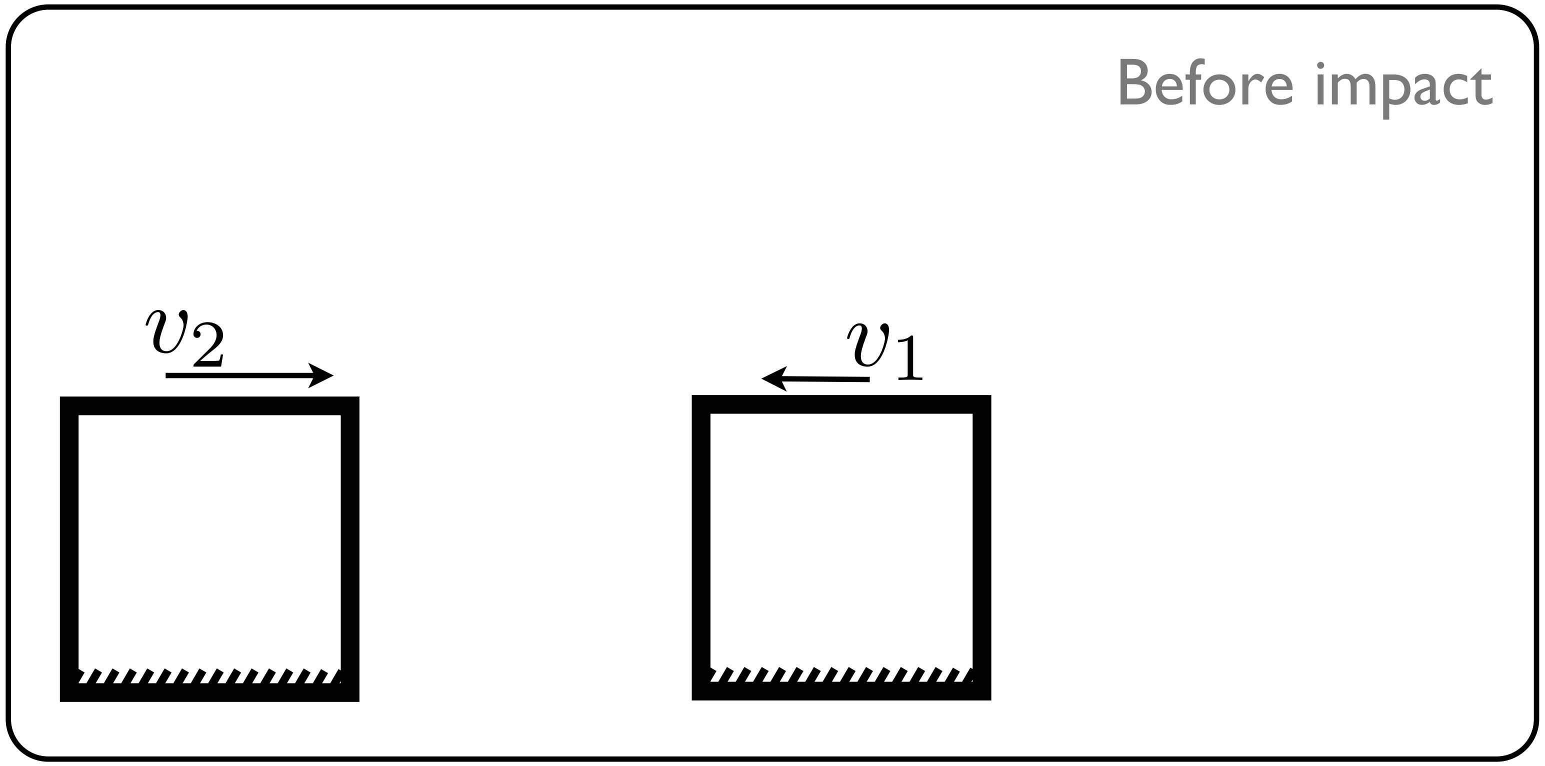

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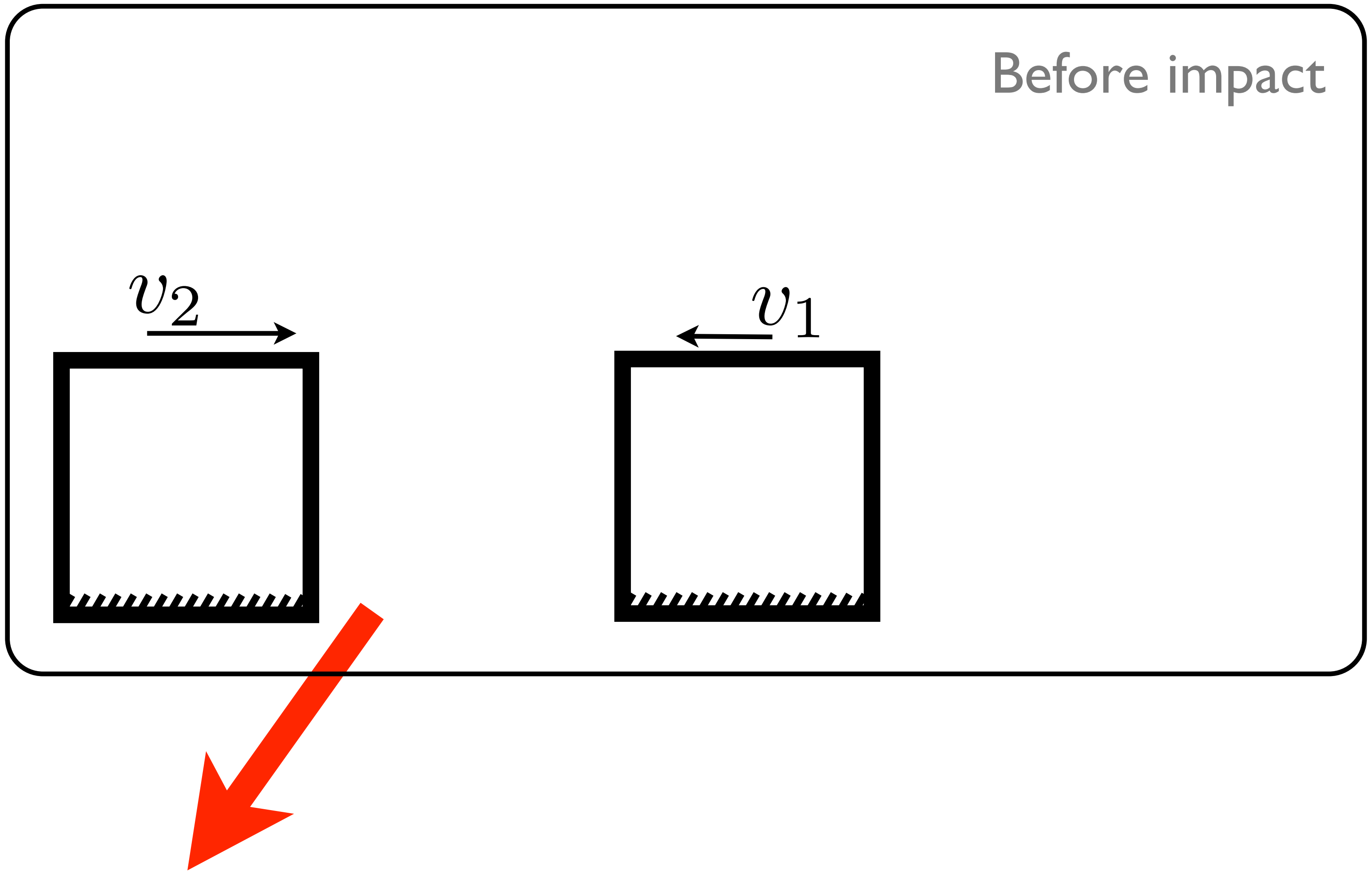

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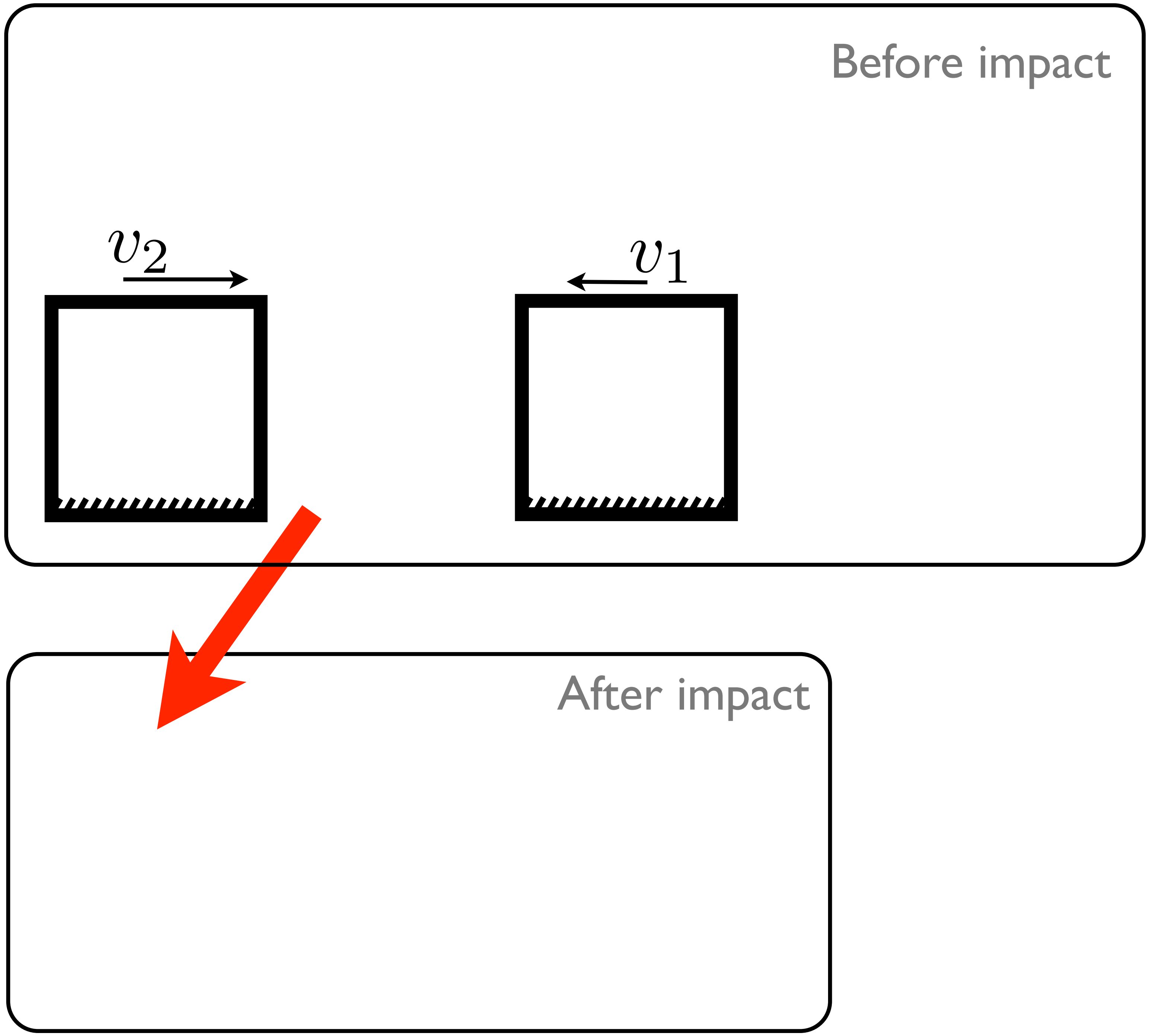

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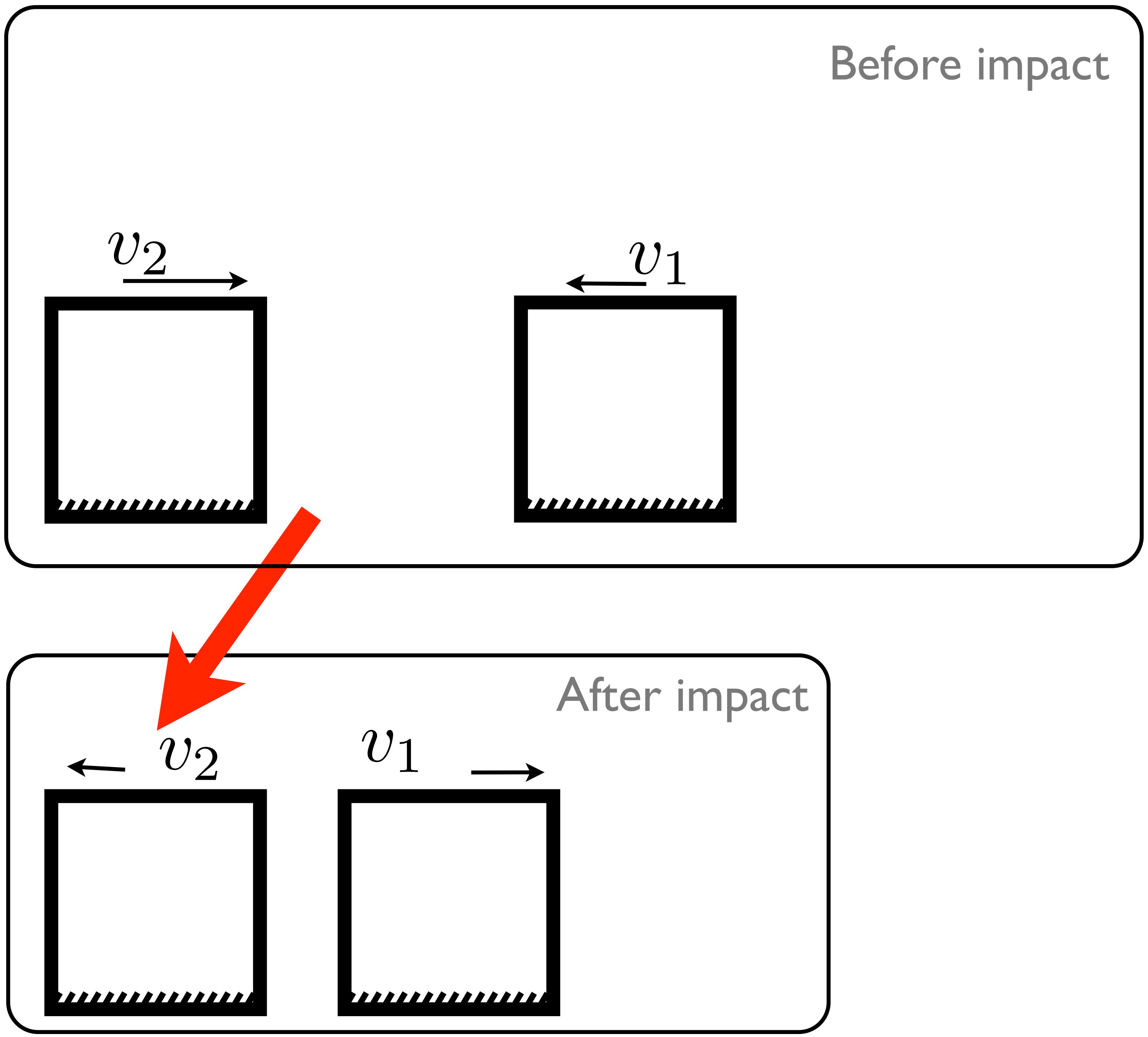

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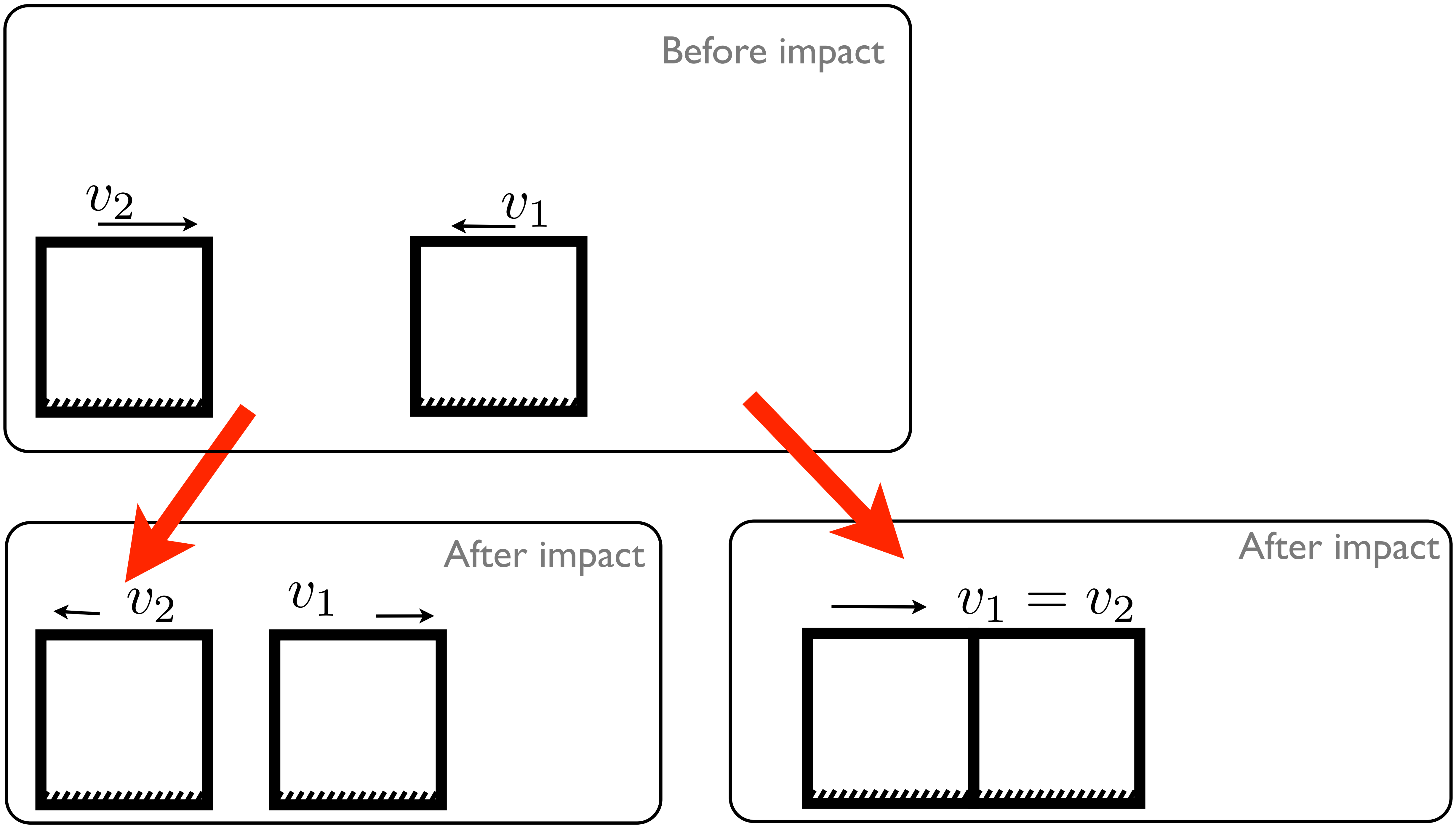

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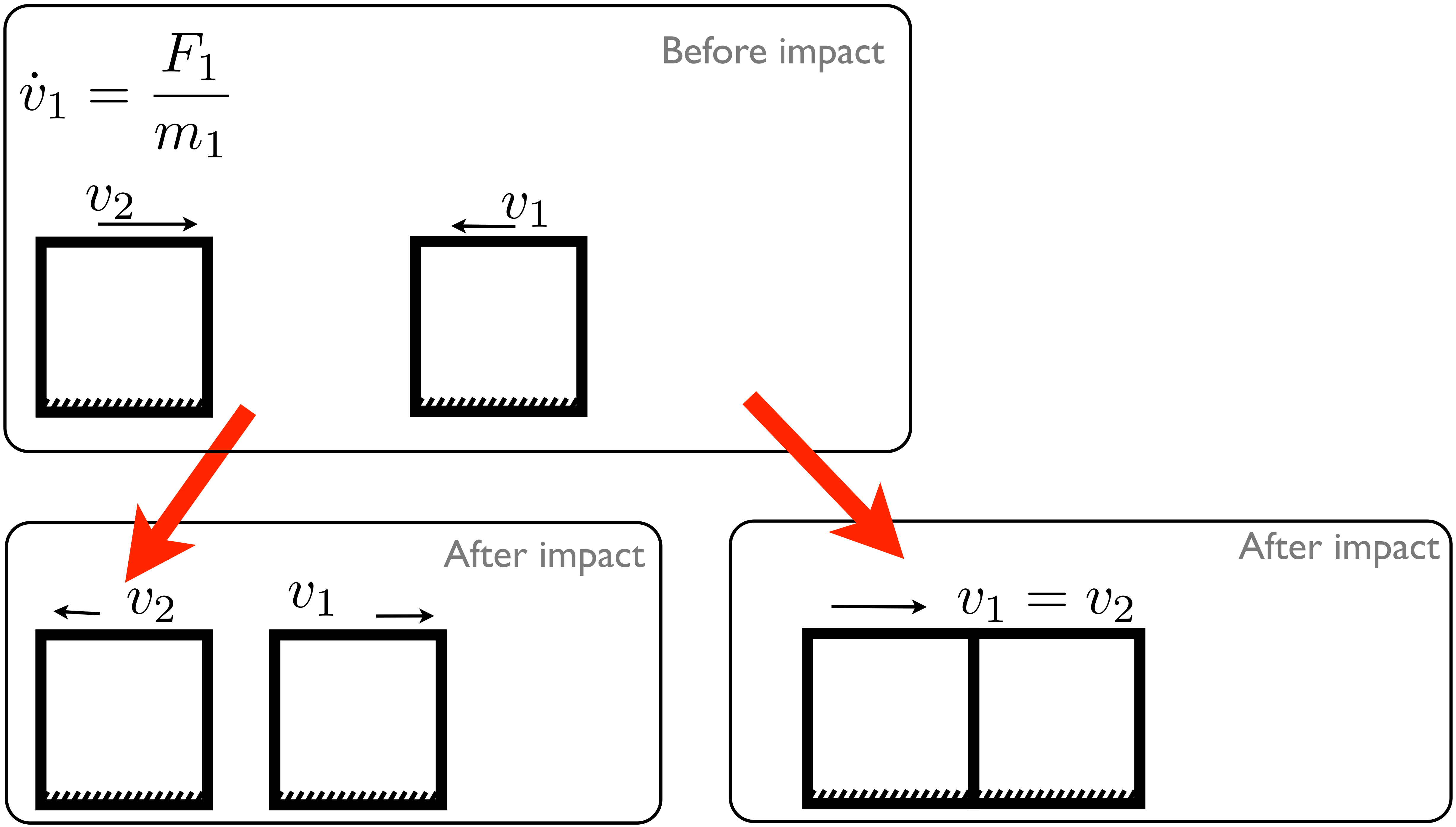

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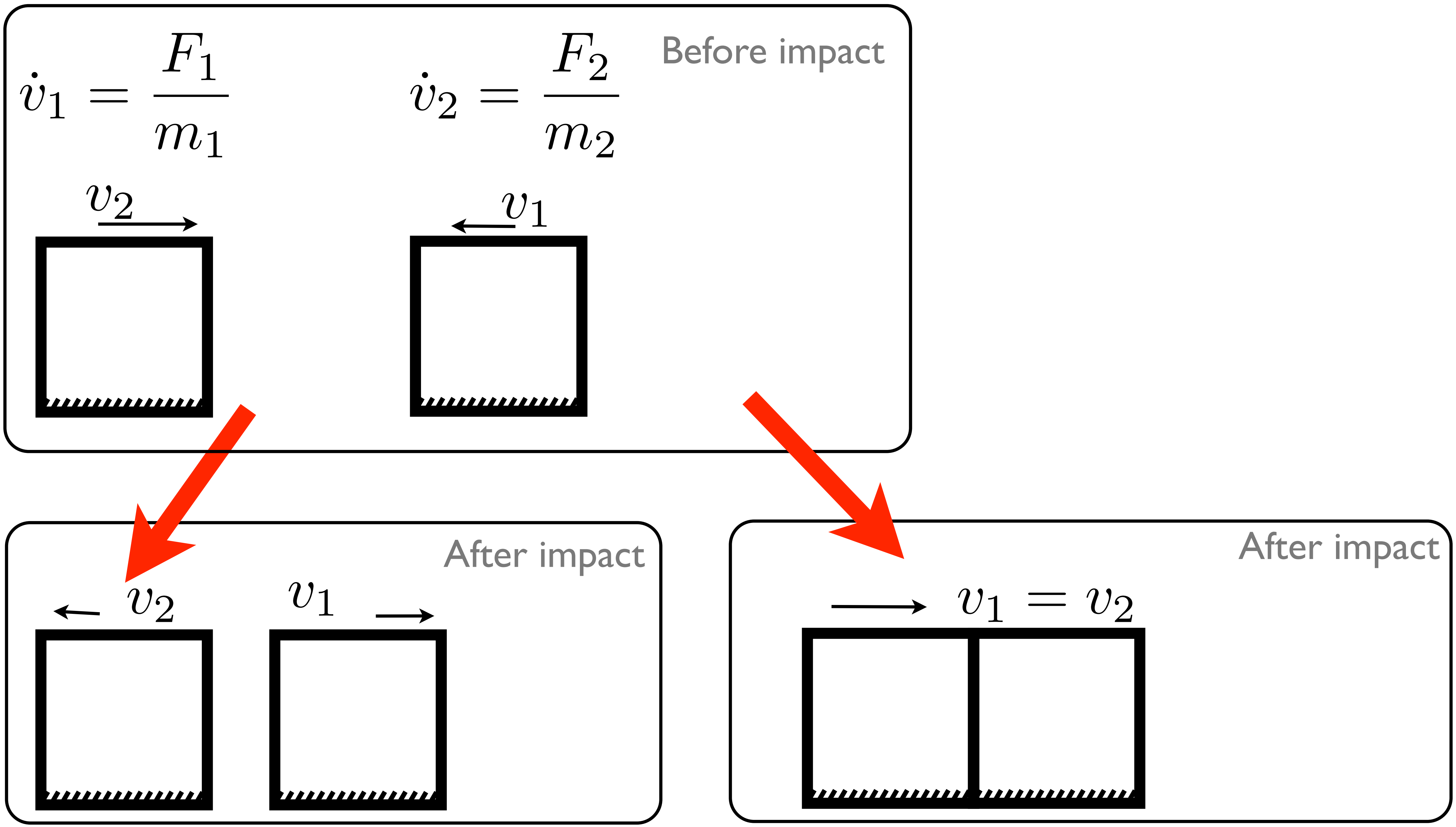

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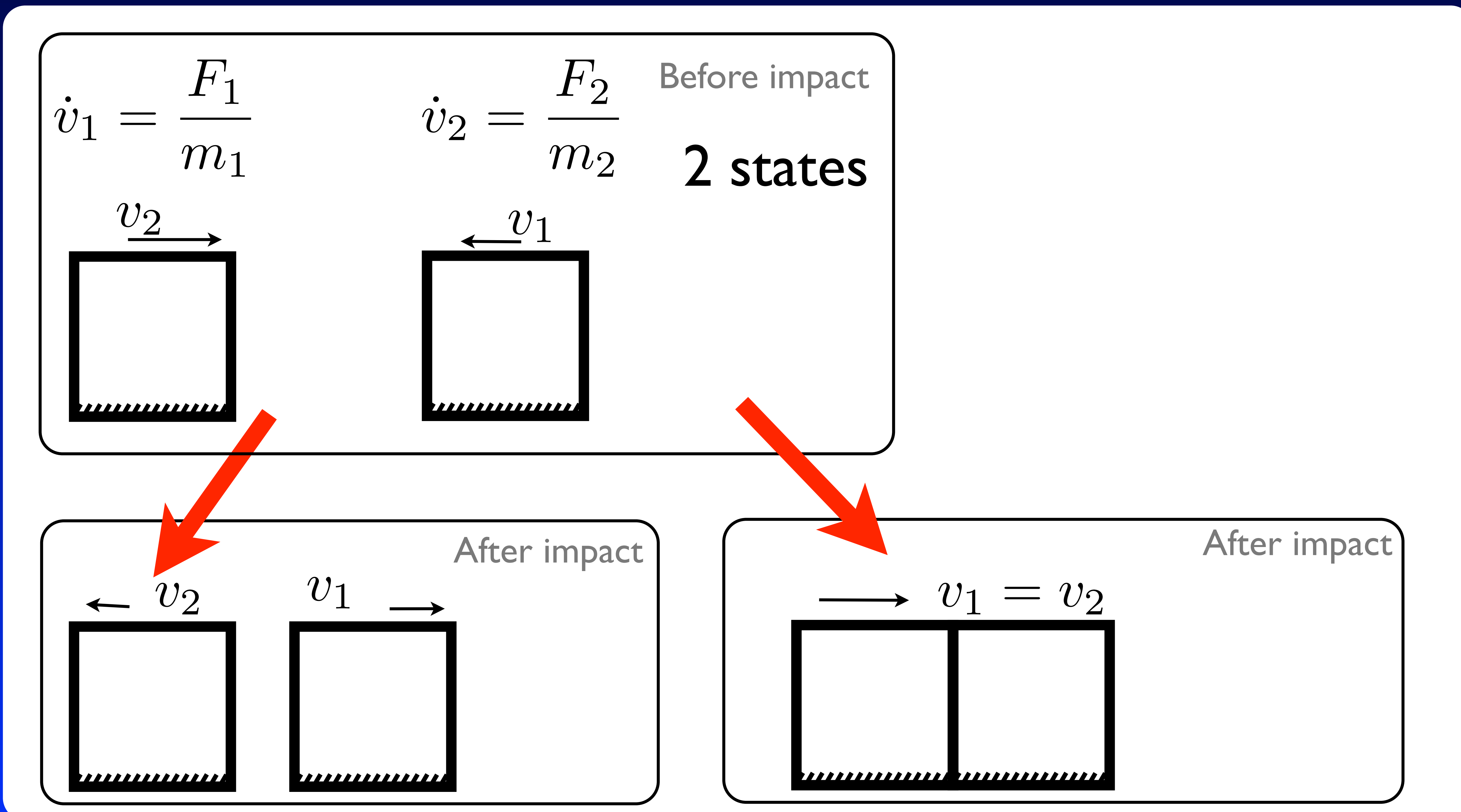

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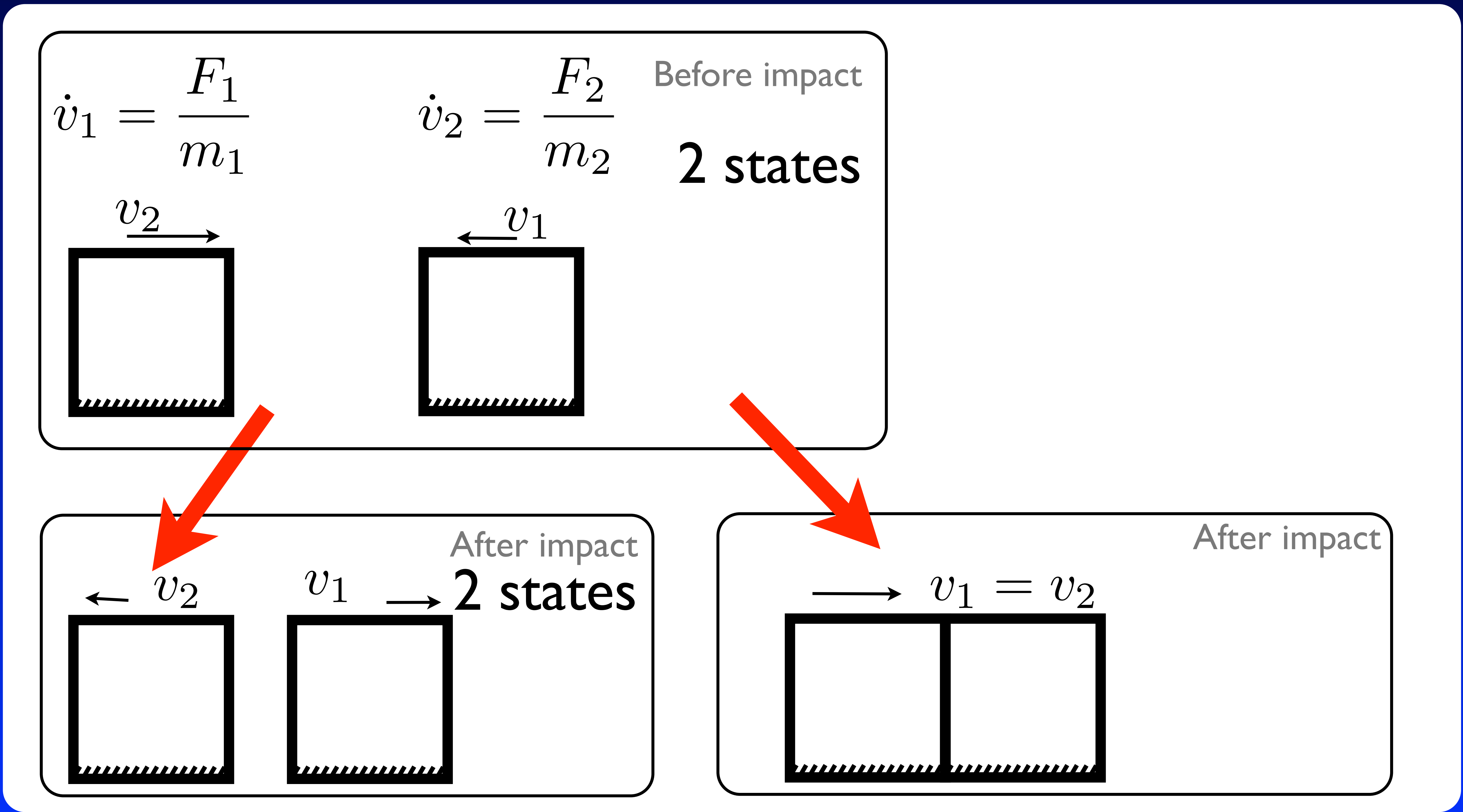

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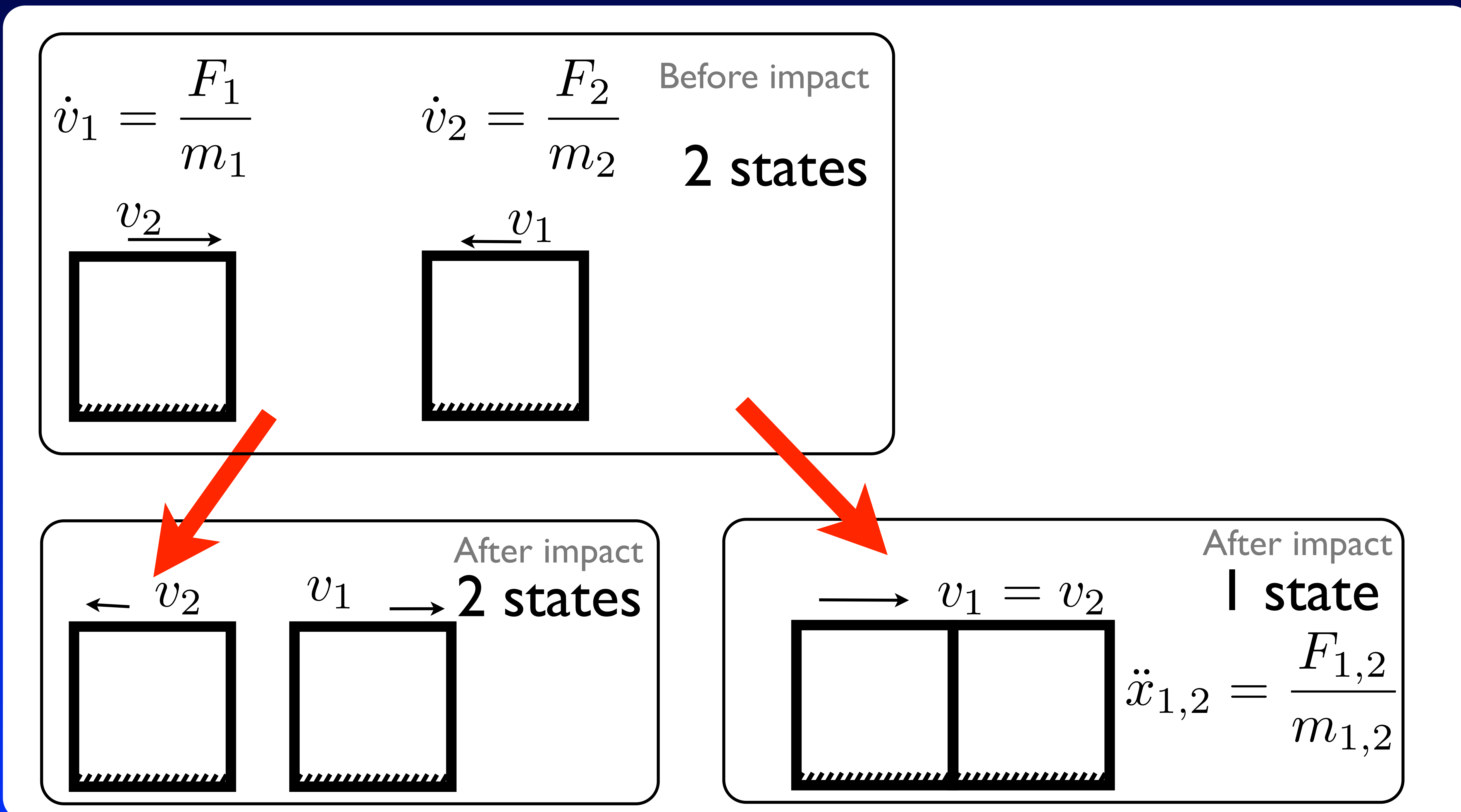

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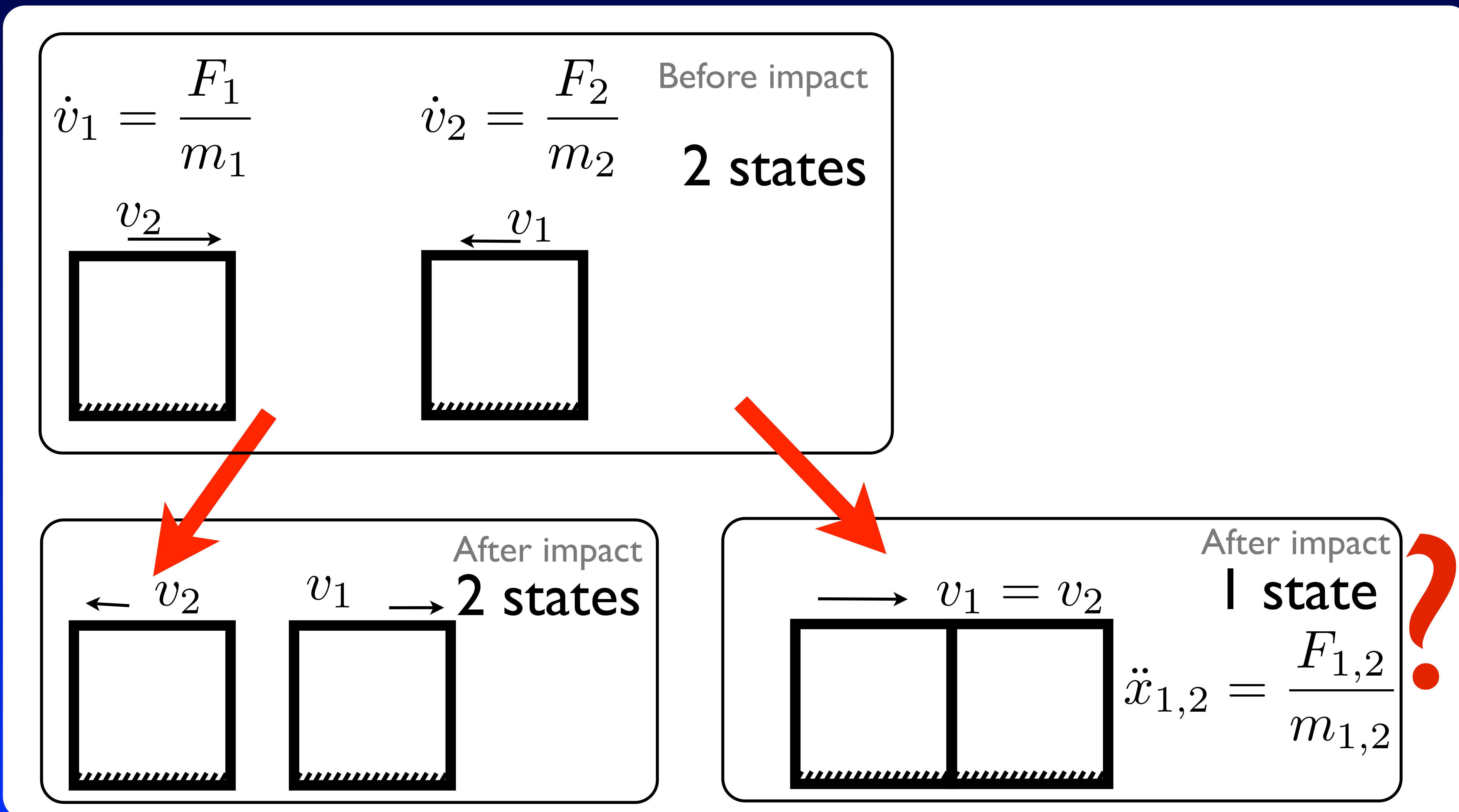

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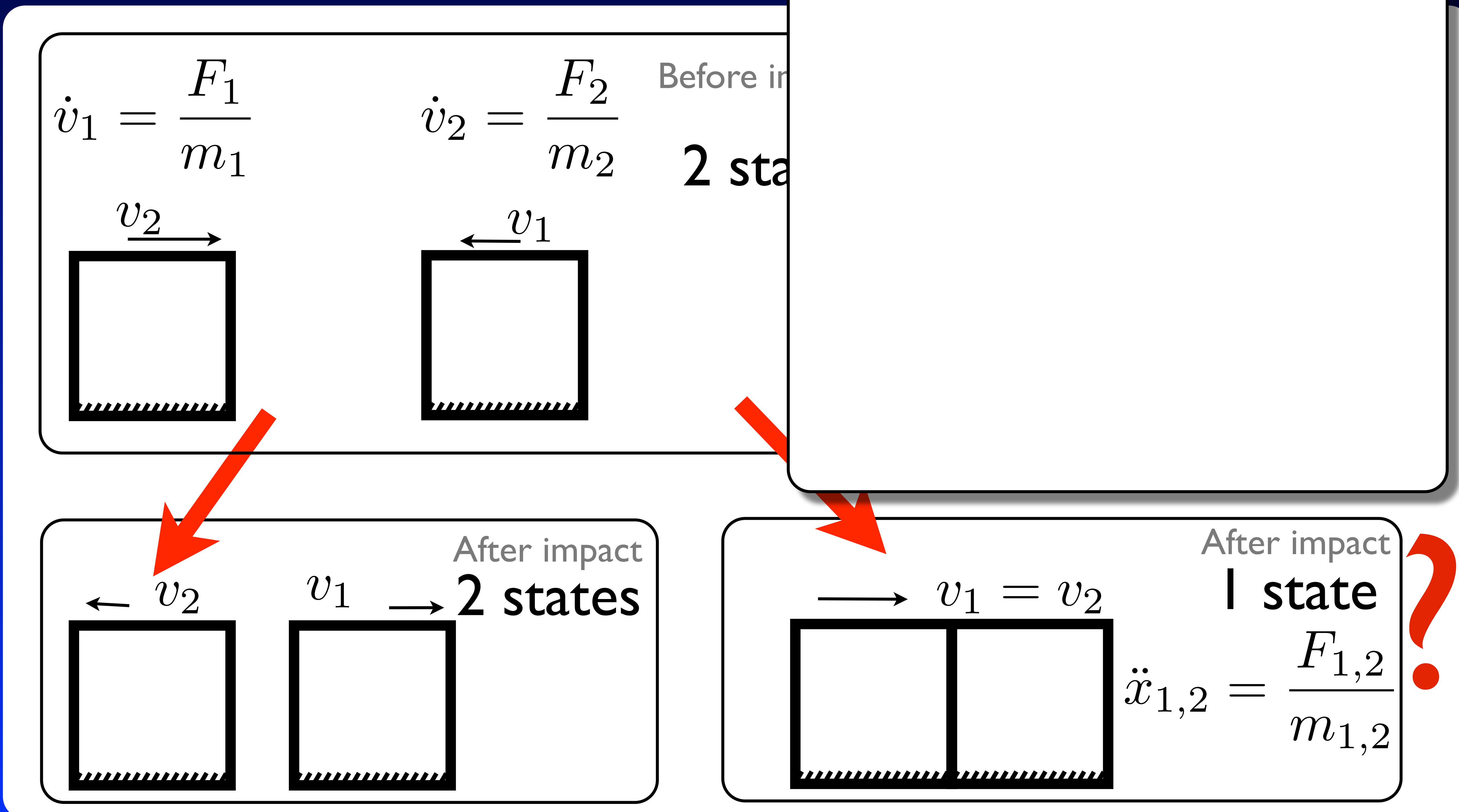

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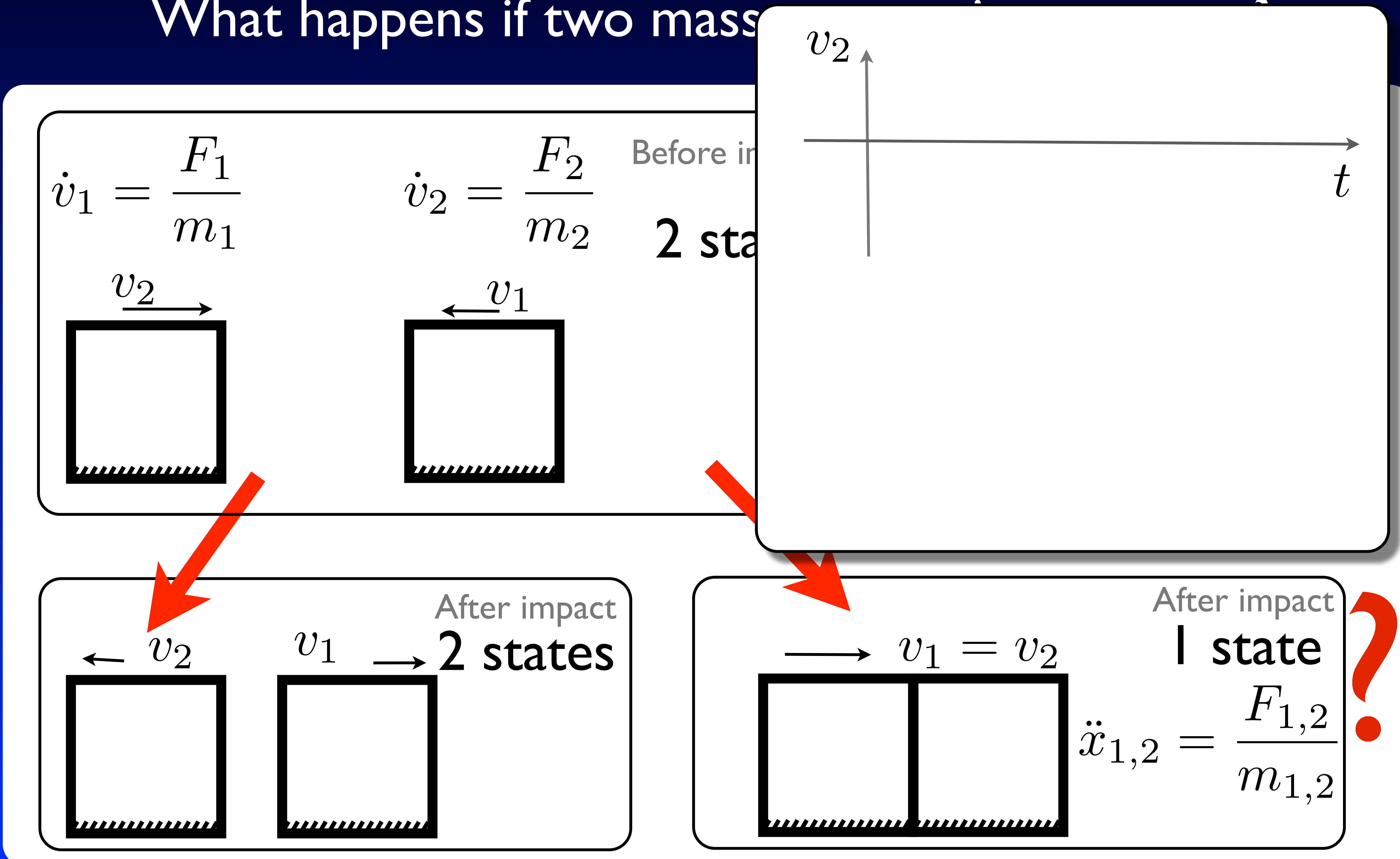


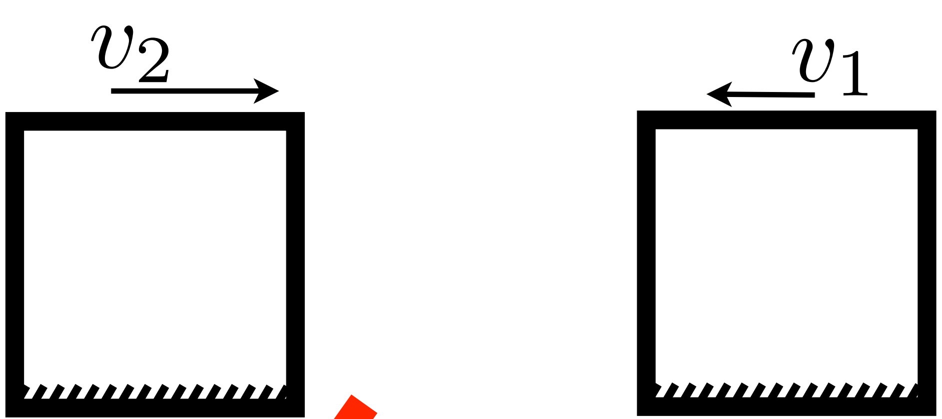
Collisions...

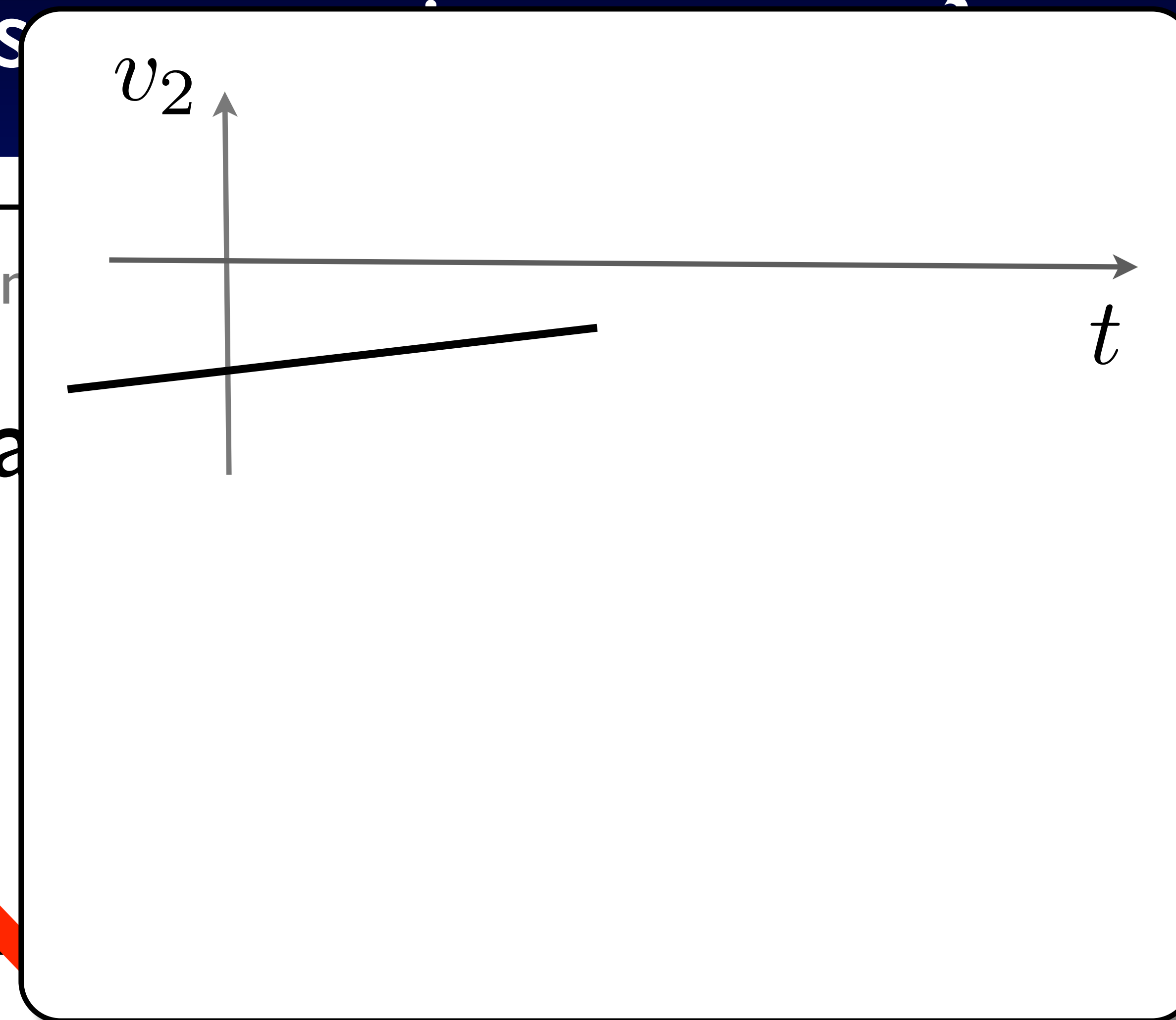
What happens if two mass

$$\dot{v}_1 = \frac{F_1}{m_1} \qquad \dot{v}_2 = \frac{F_2}{m_2}$$

Before i

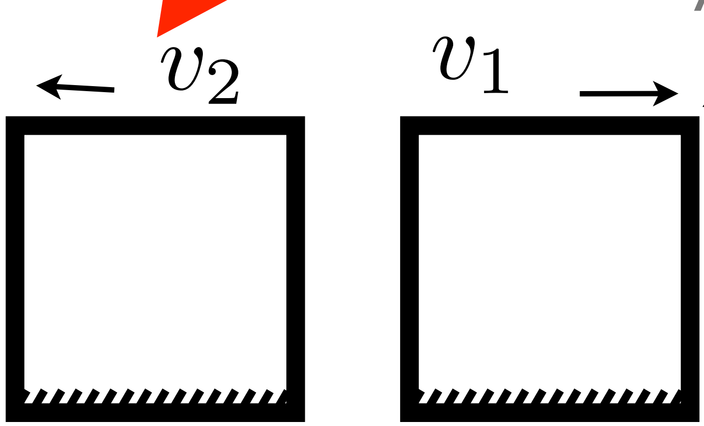
2 sta





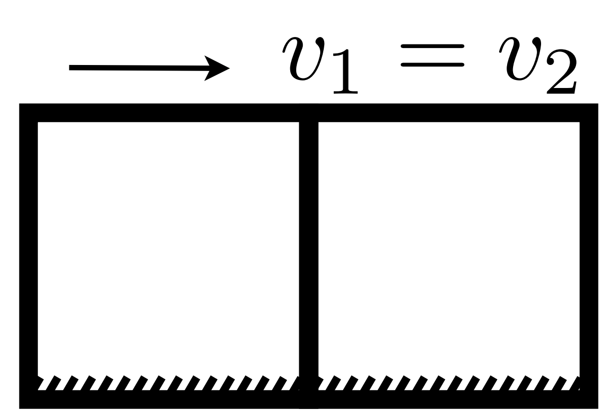
After impact

2 states



After impact

1 state

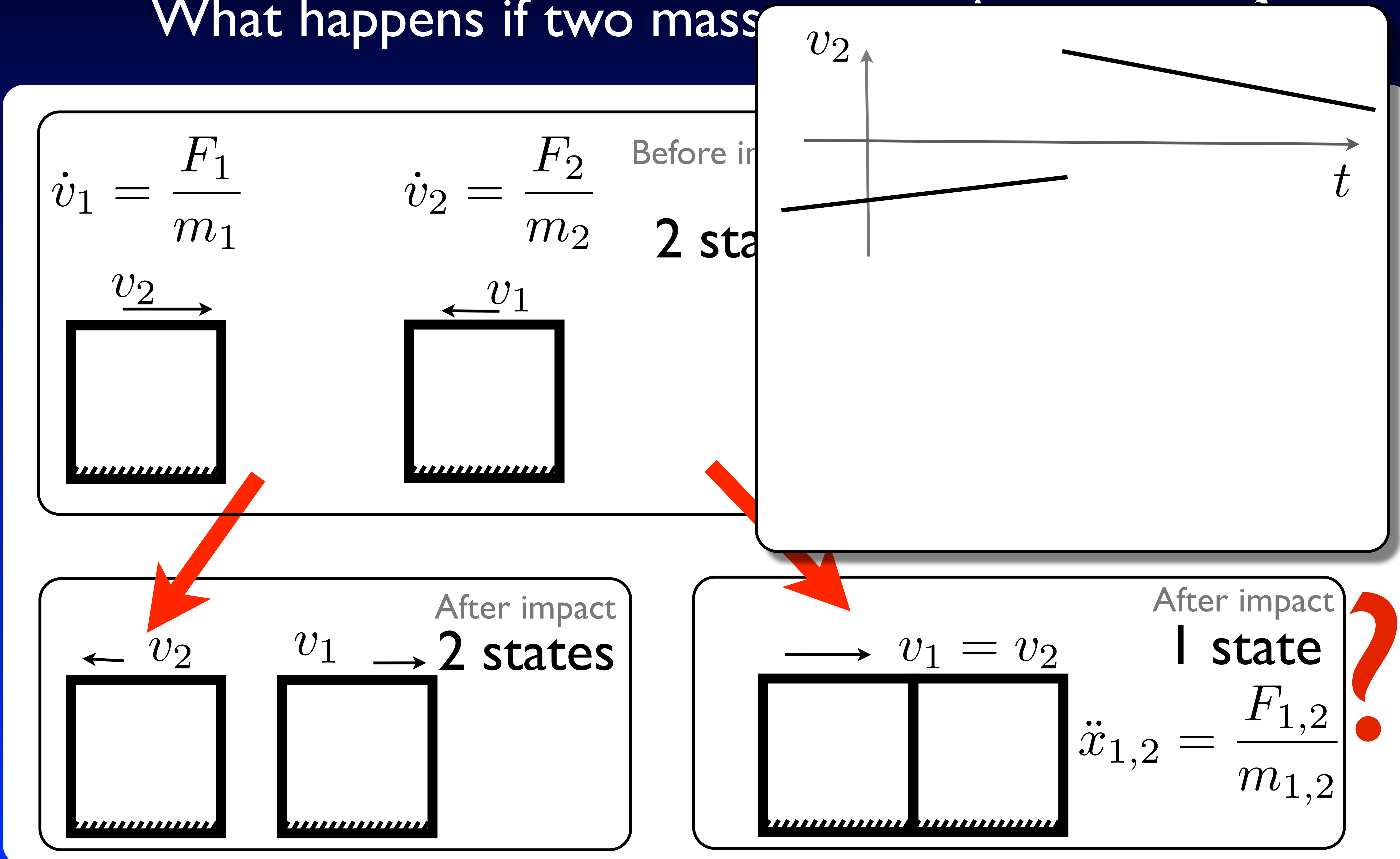


$$\ddot{x}_{1,2} = \frac{F_{1,2}}{m_{1,2}}$$

?

Collisions...

What happens if two mass



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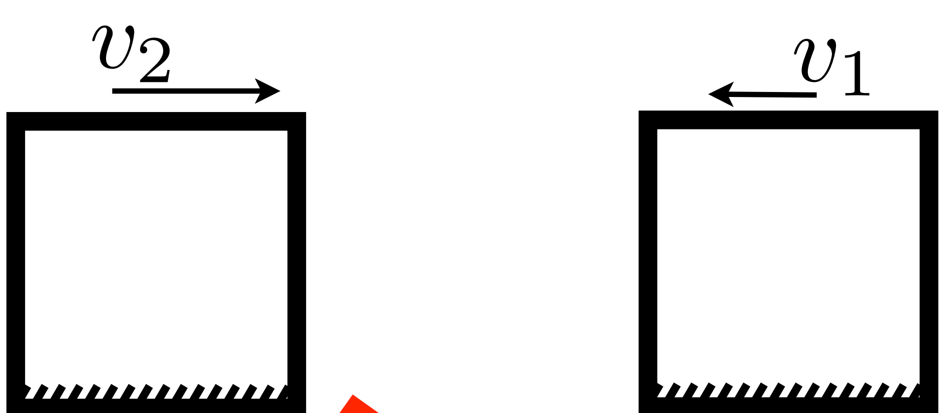

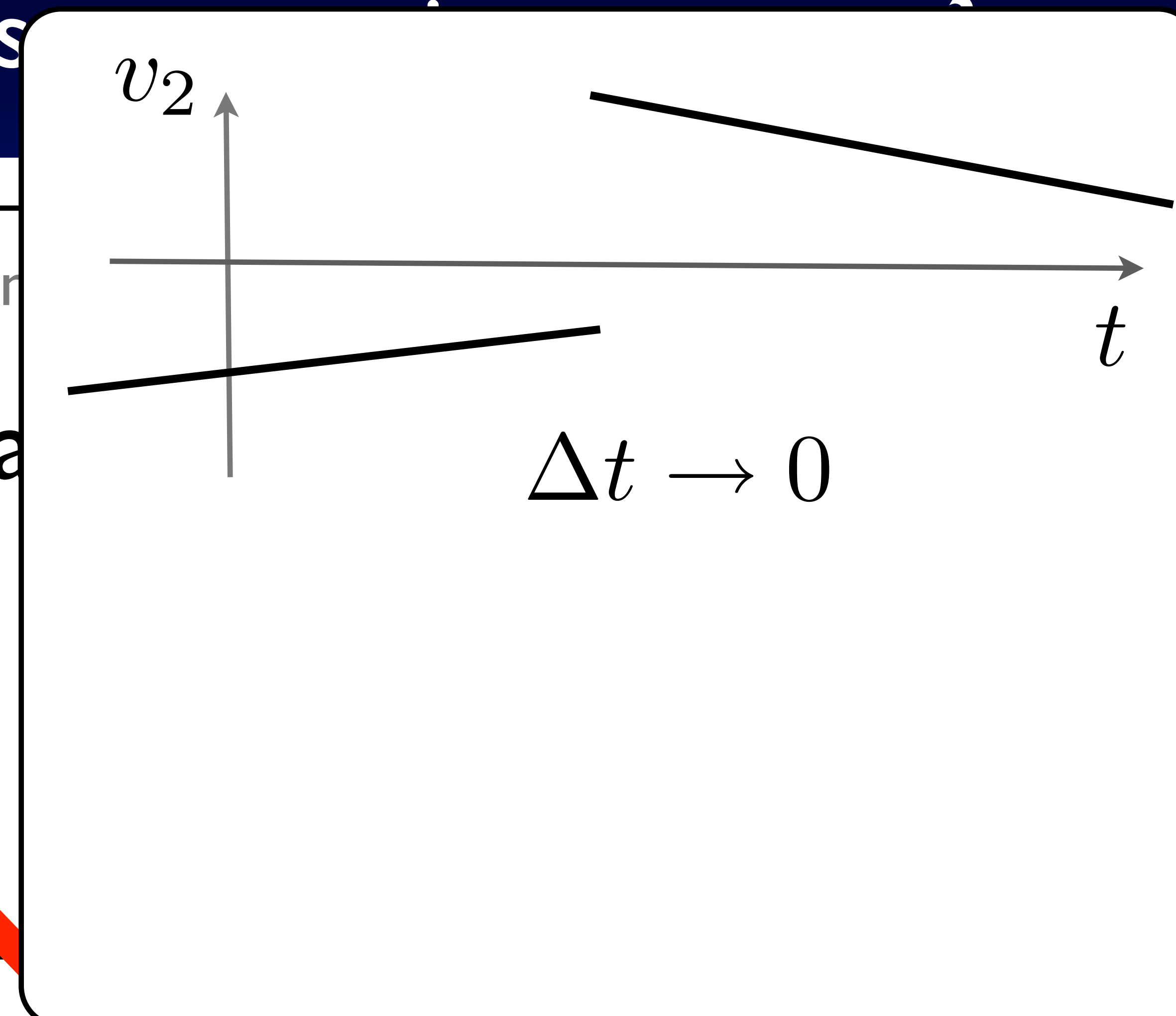

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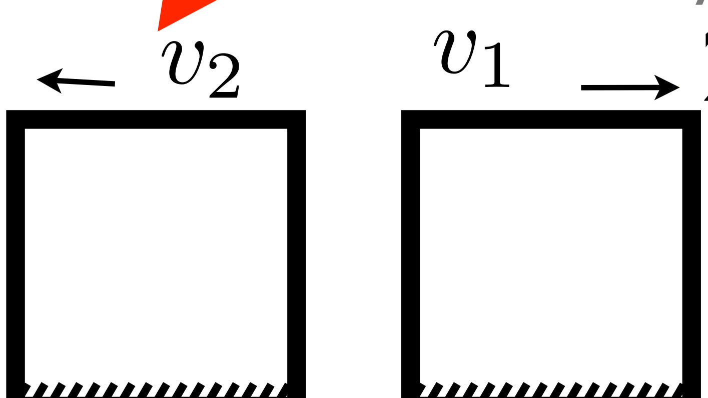

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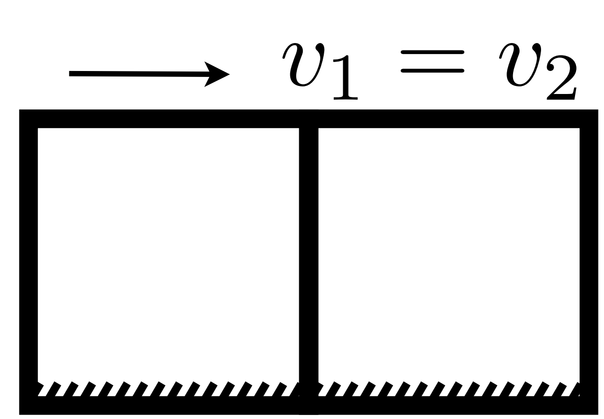

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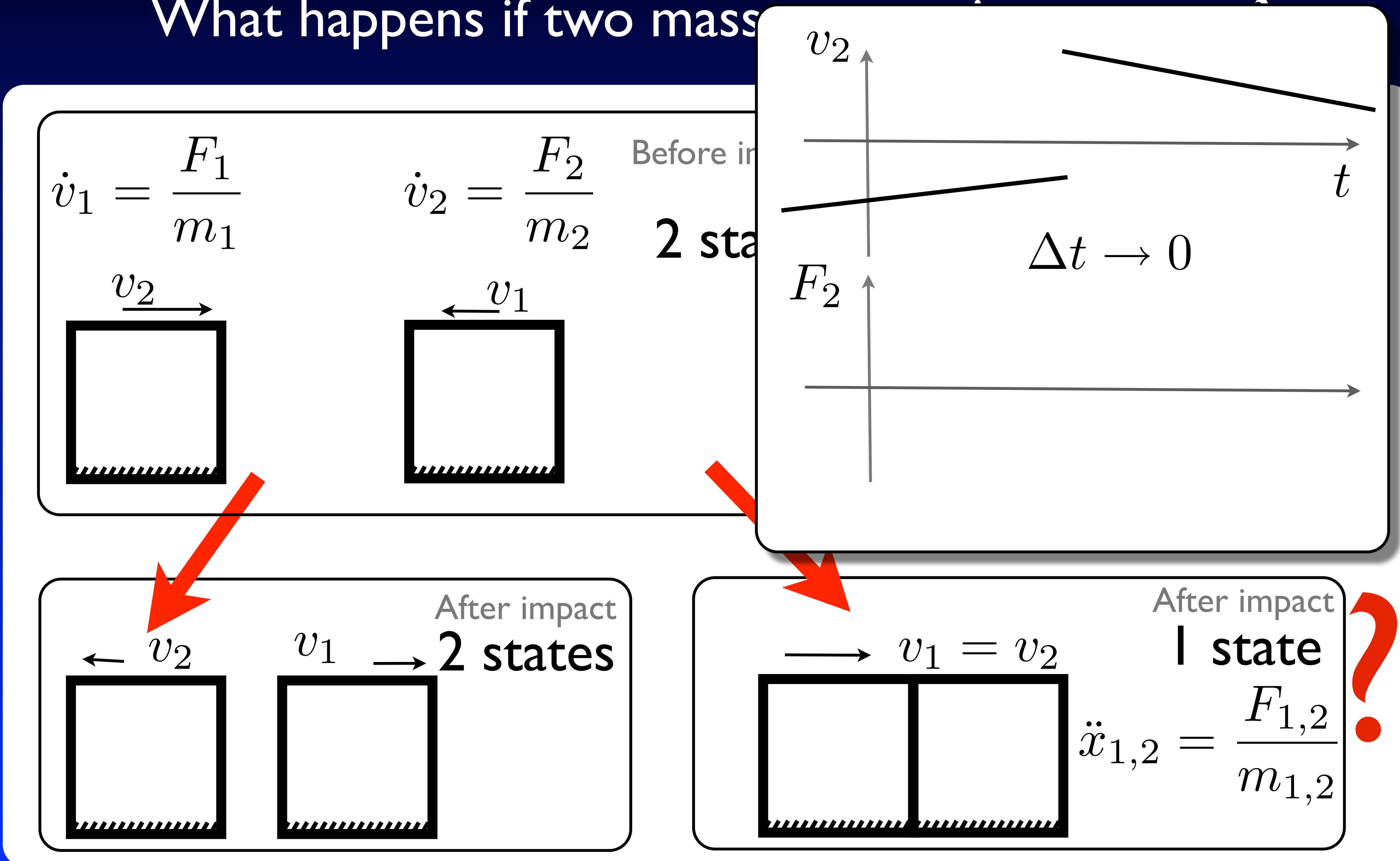

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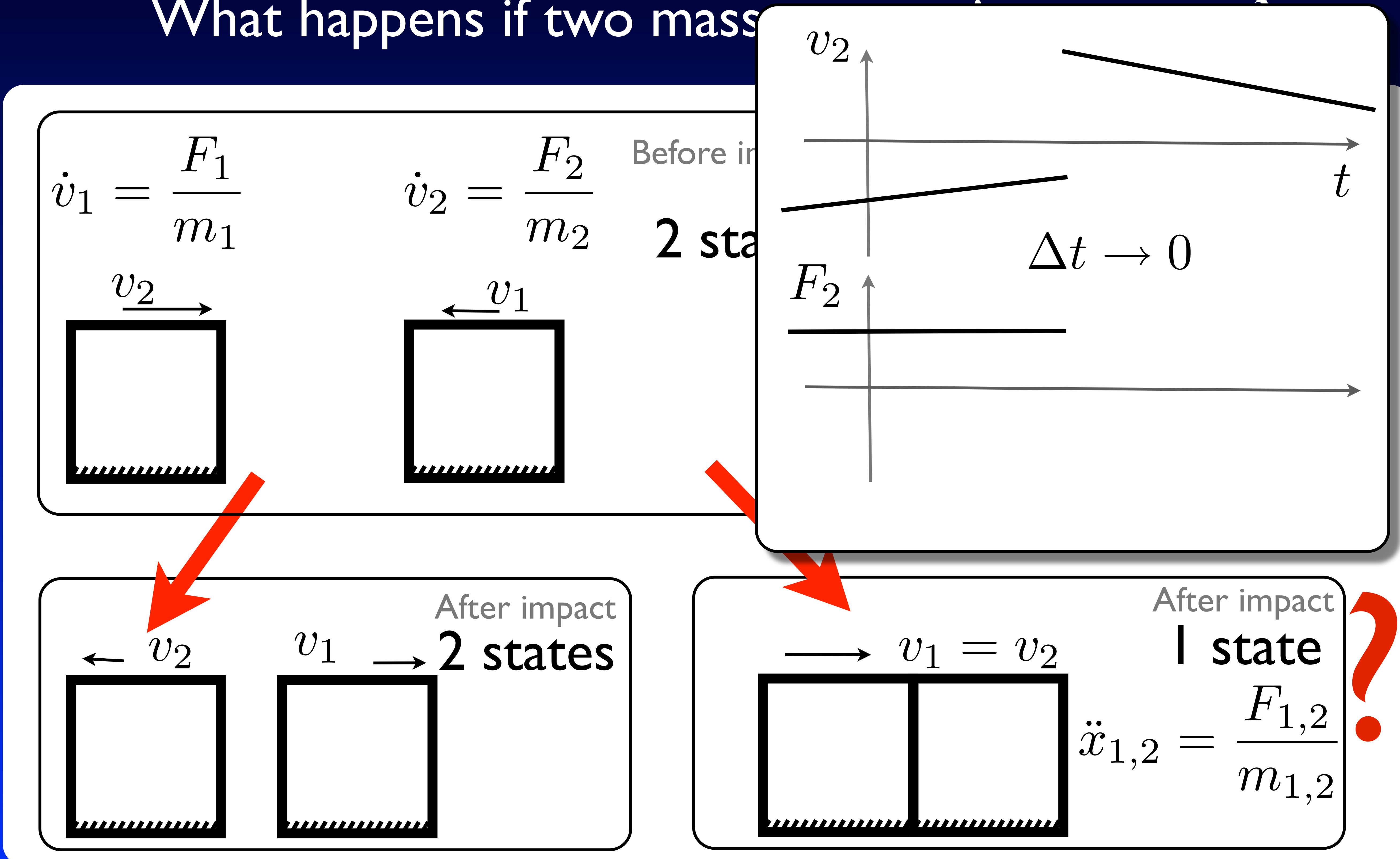

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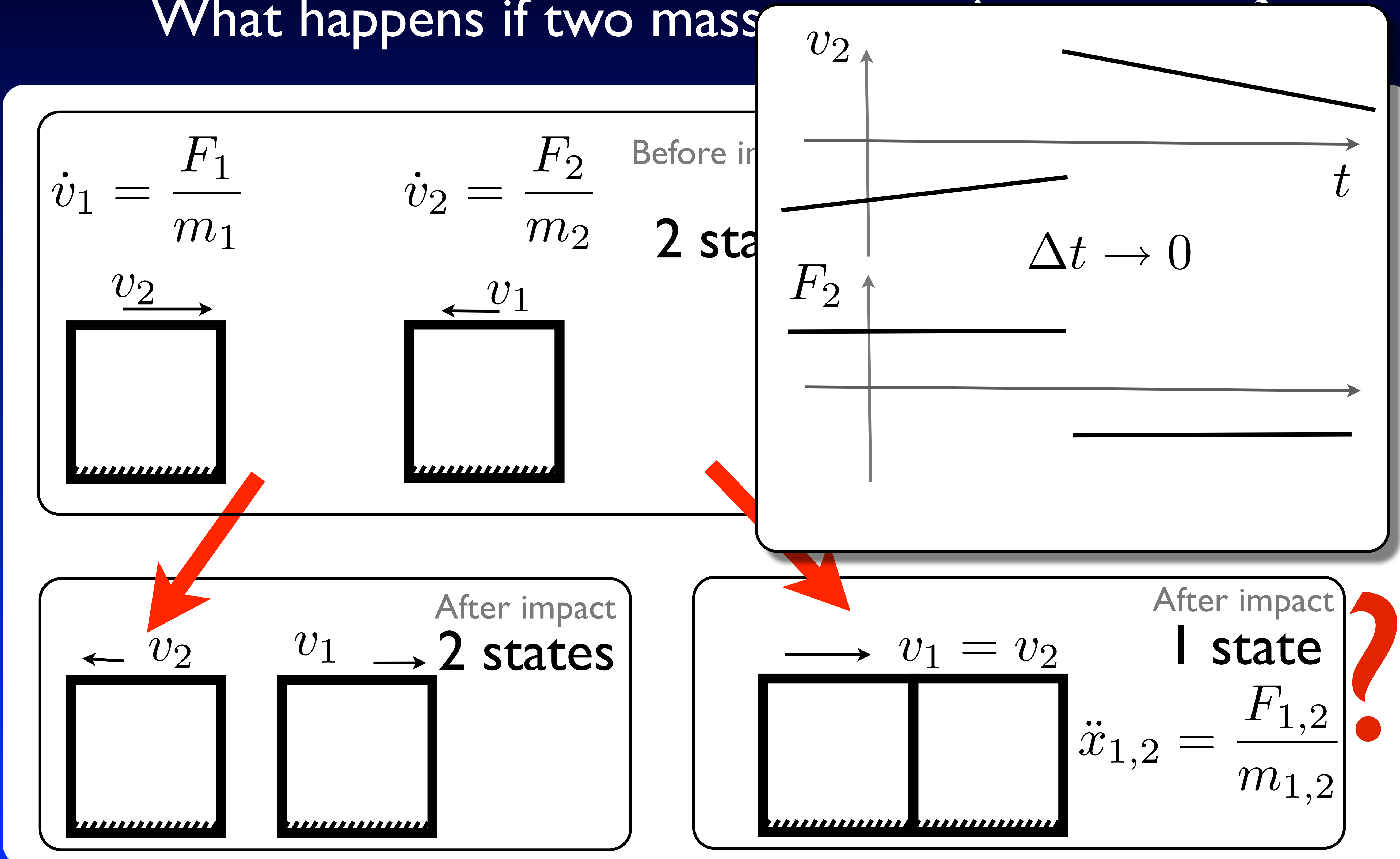

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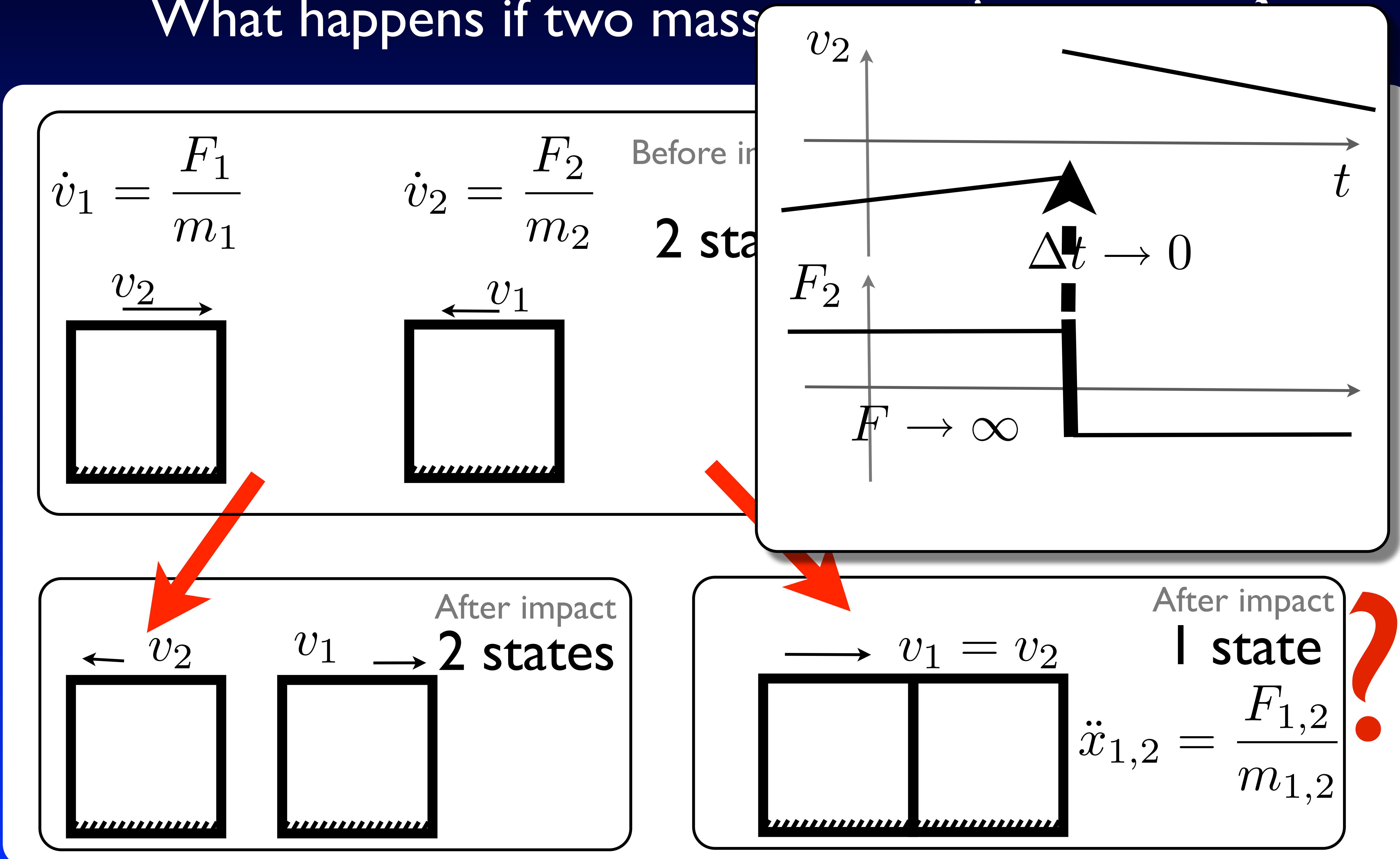

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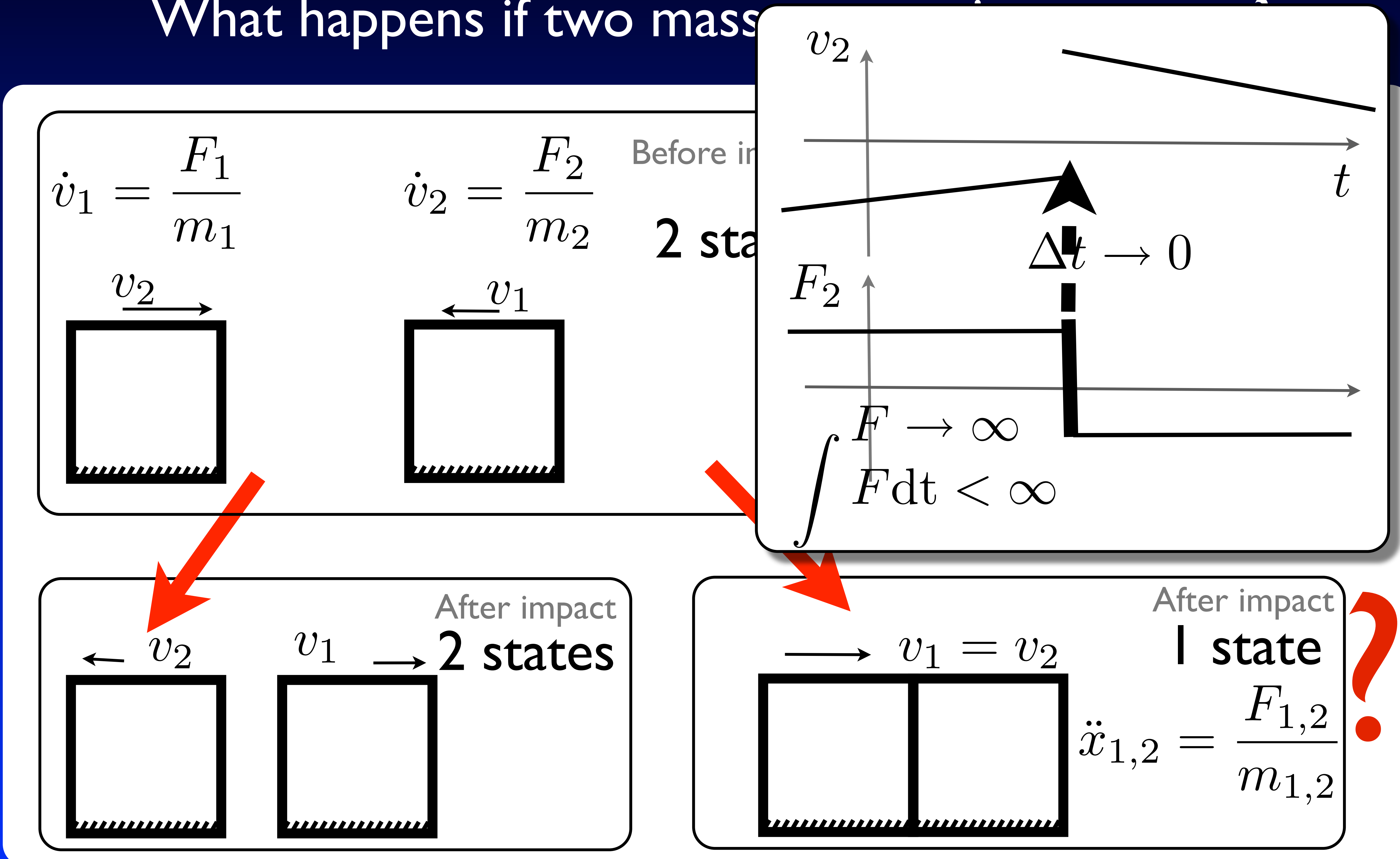

Collisions...

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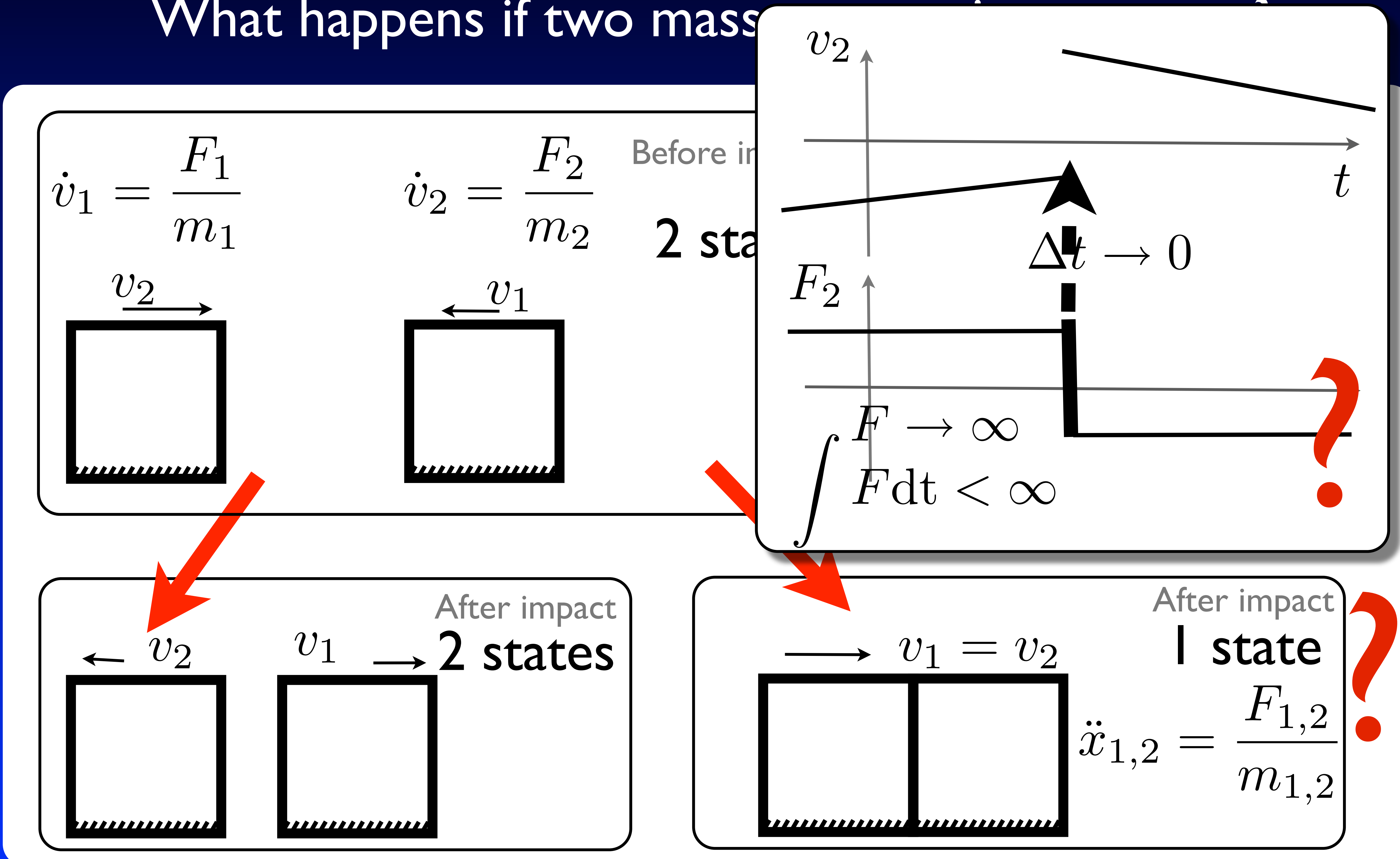

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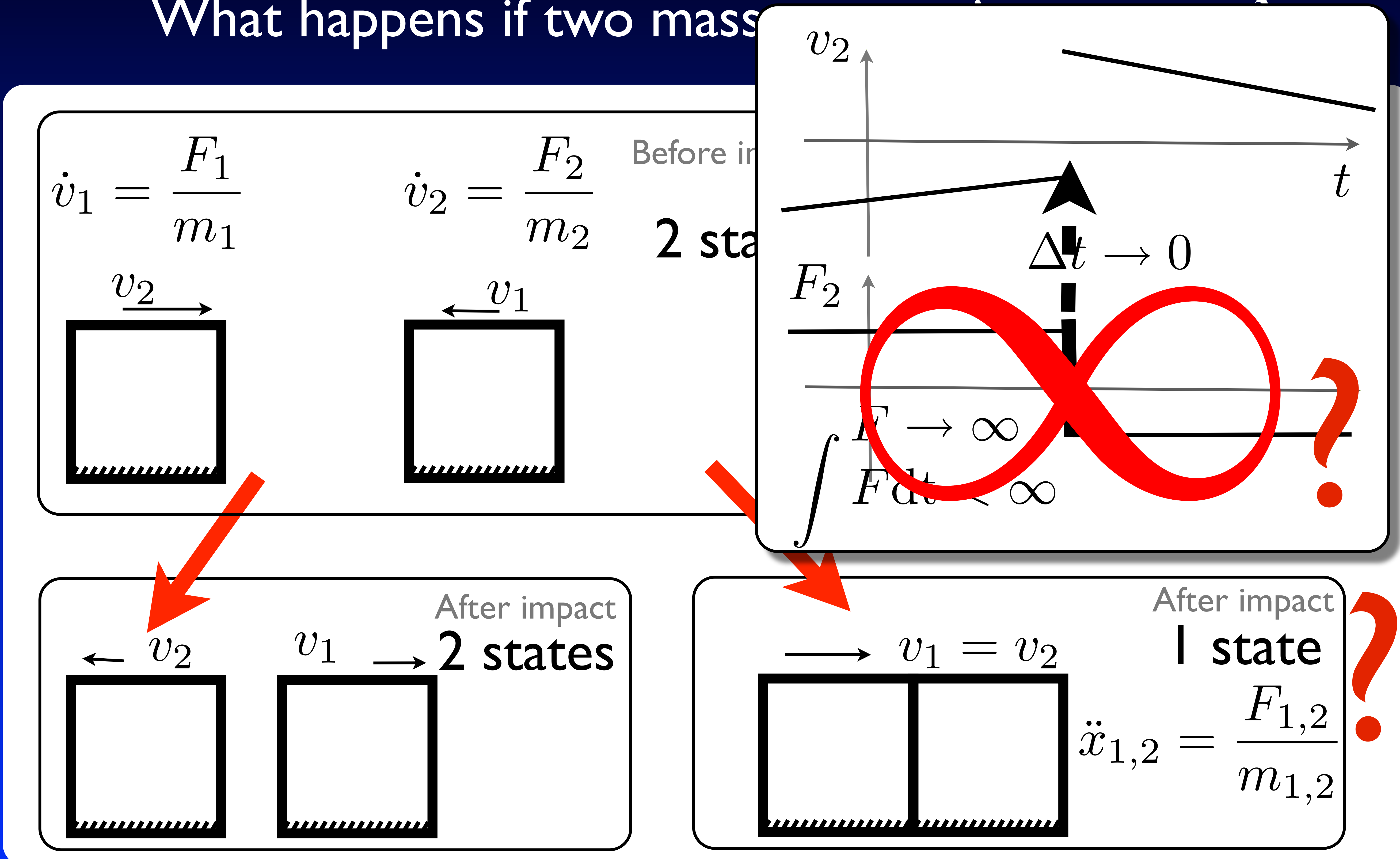

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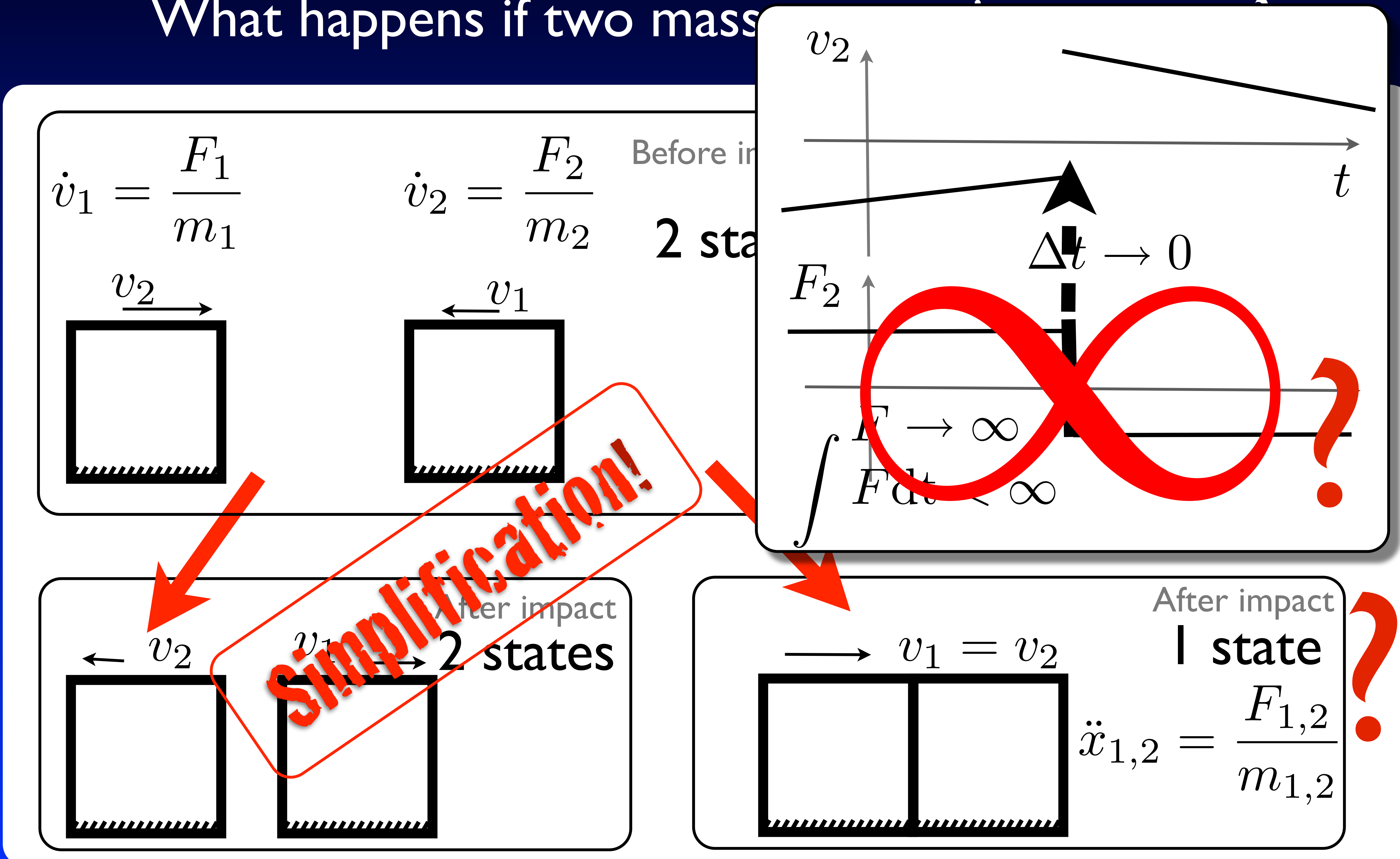

70’000 frames/sec

70’000 frames/sec

70’000 f

No instantaneous change of physical quantities!

To infinity, and beyond...

∞

Is useful as a shortcut in modeling, description.

To infinity, and beyond...

∞

Is useful as a shortcut in modeling, description.

Infinities occurring when analyzing a system with the goal to design controllers means incomplete problem description!

Collisions...

What about this situation?

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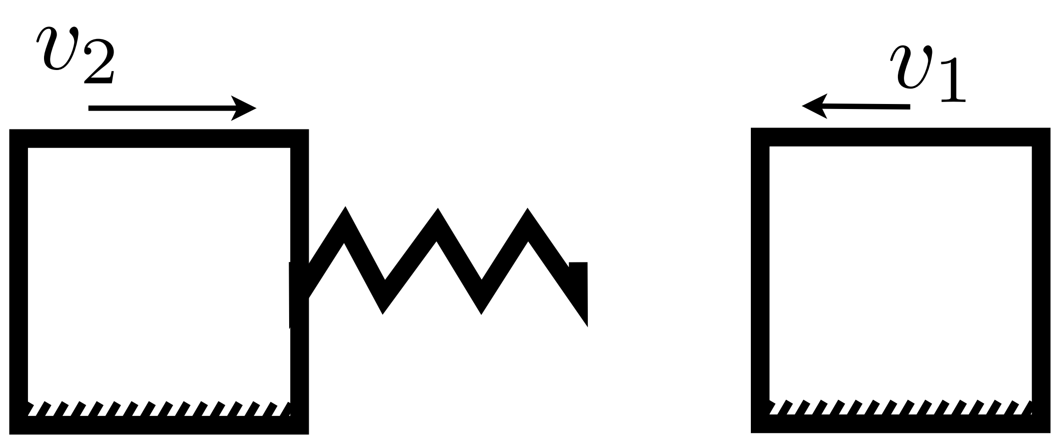

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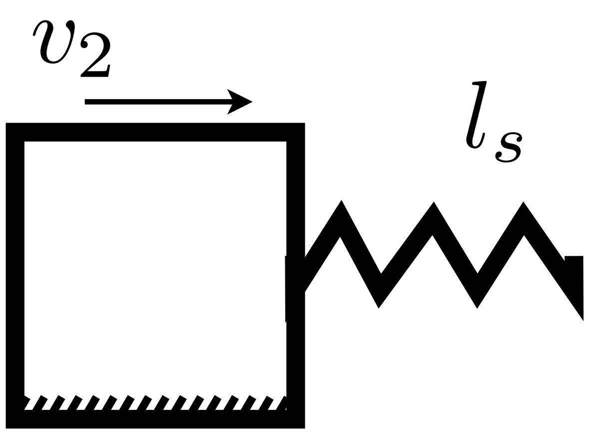

$$F_s = K l_s$$

Collisions...

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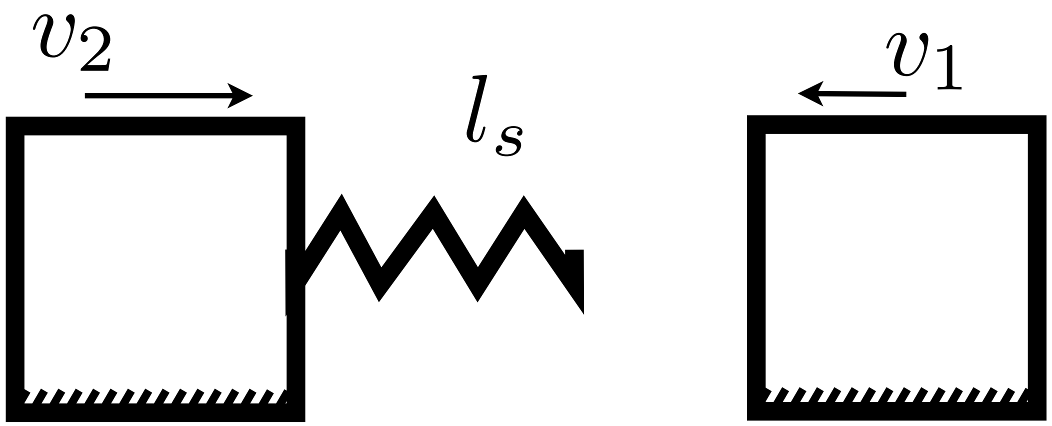

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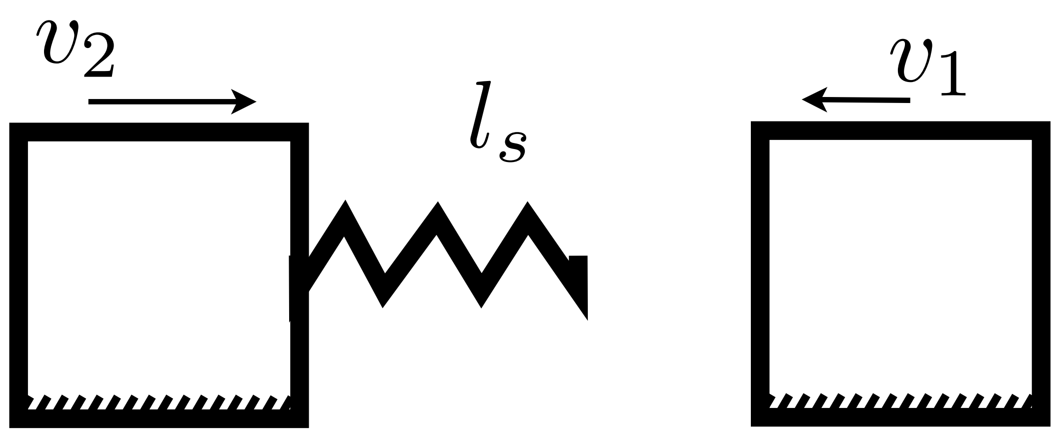

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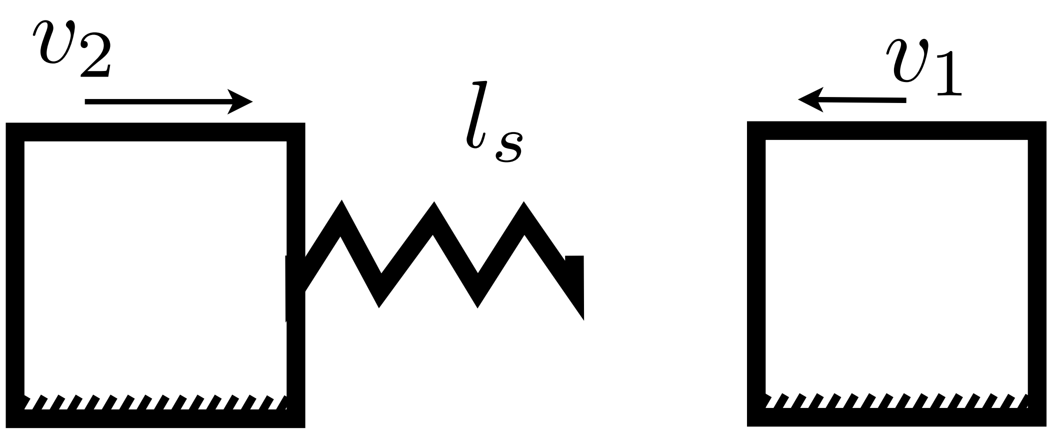

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2+'1' = 3 states

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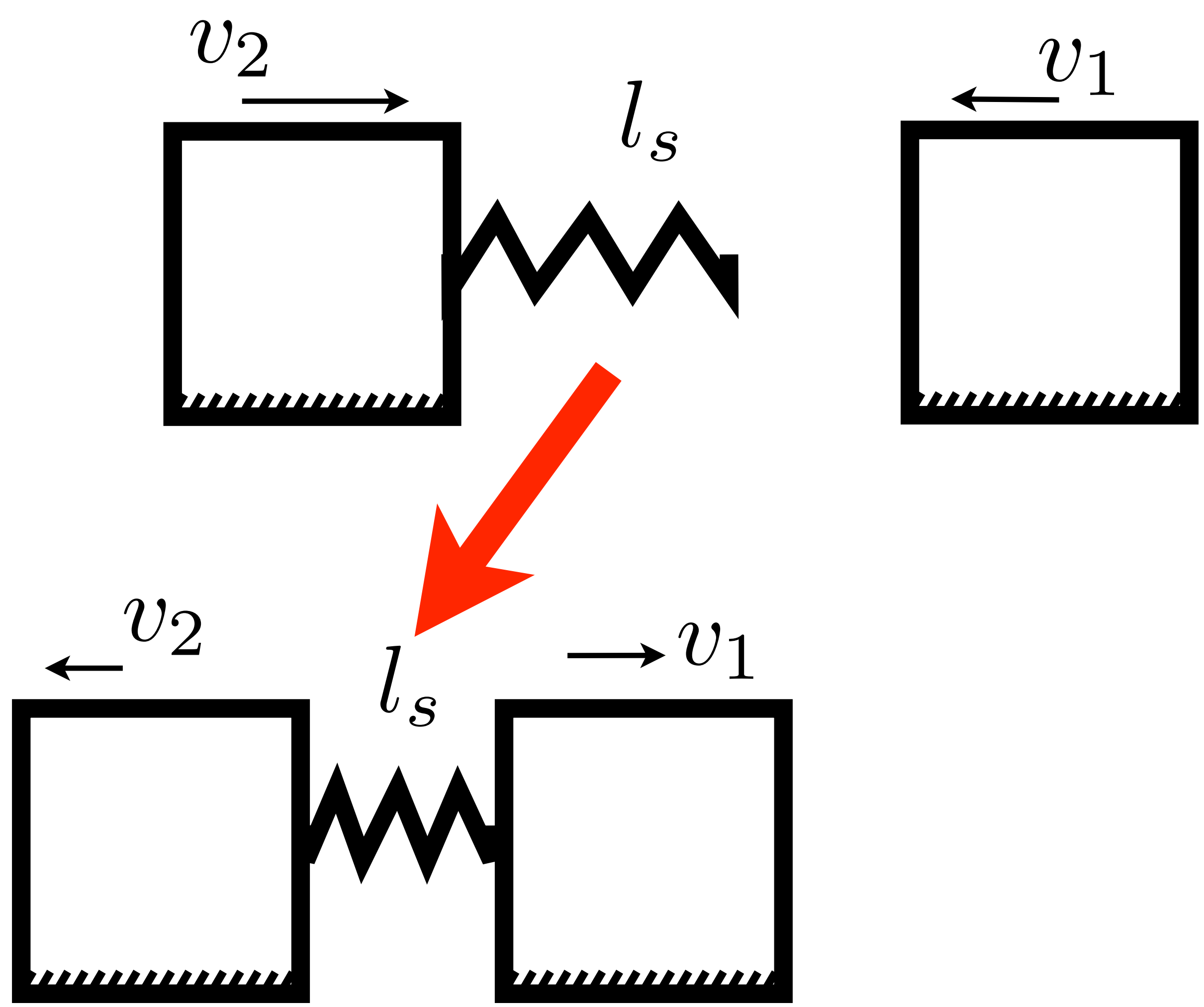

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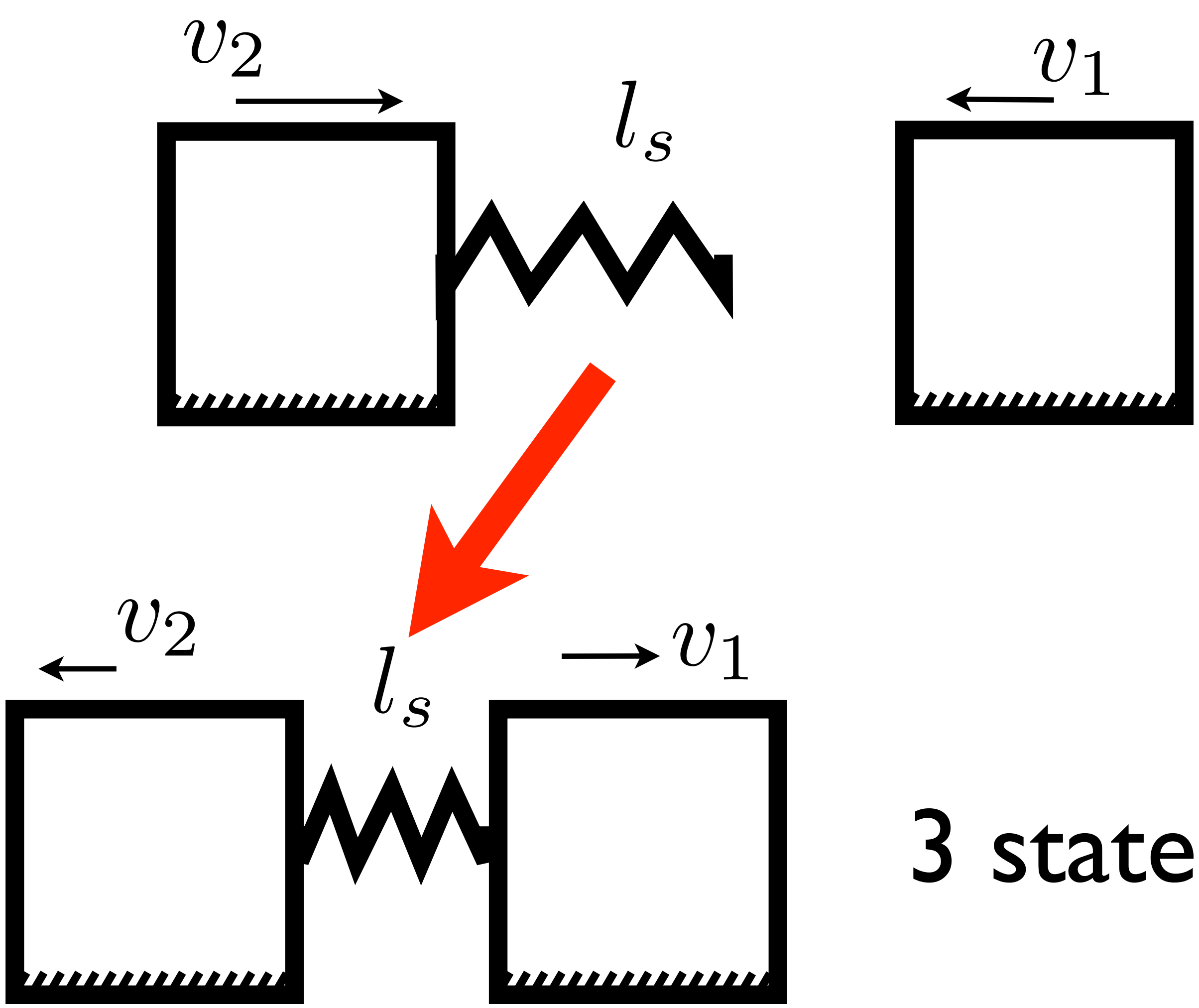

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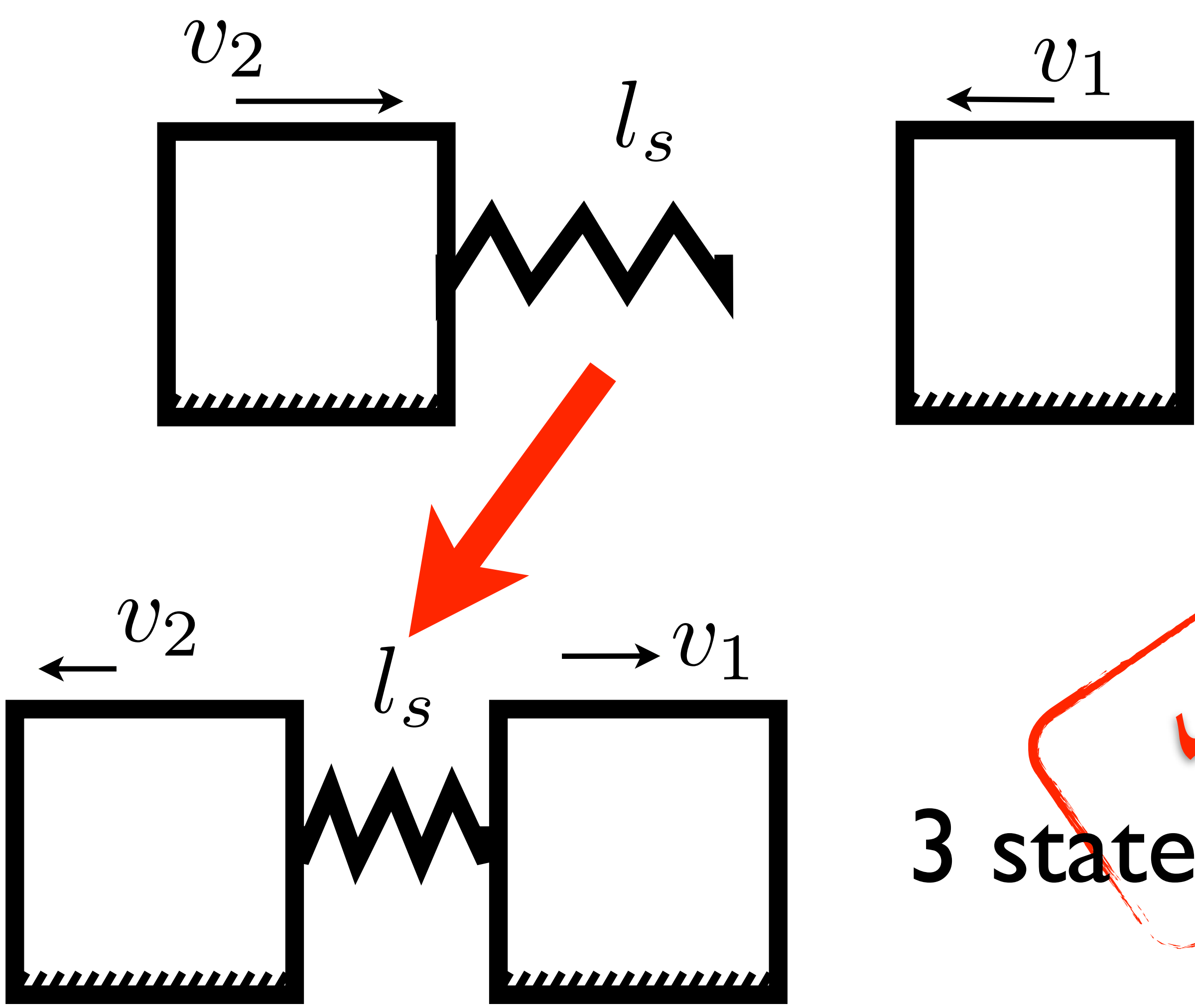

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3 states

‘Complete’

Collisio

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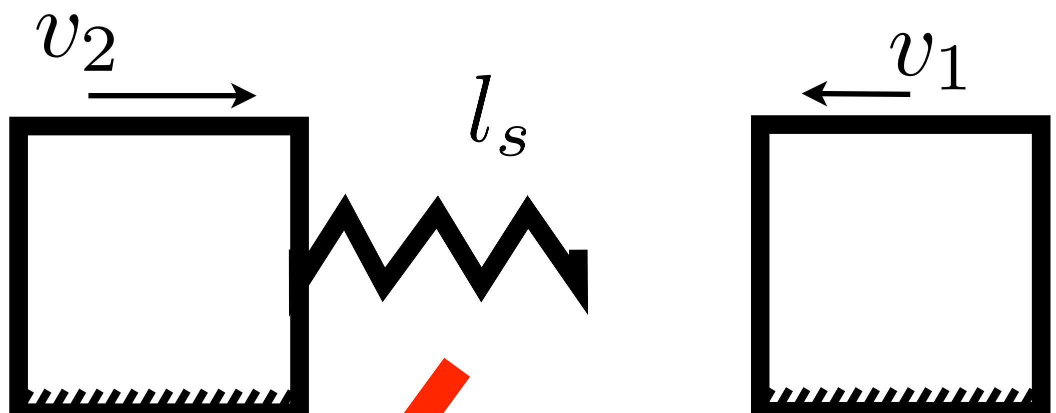

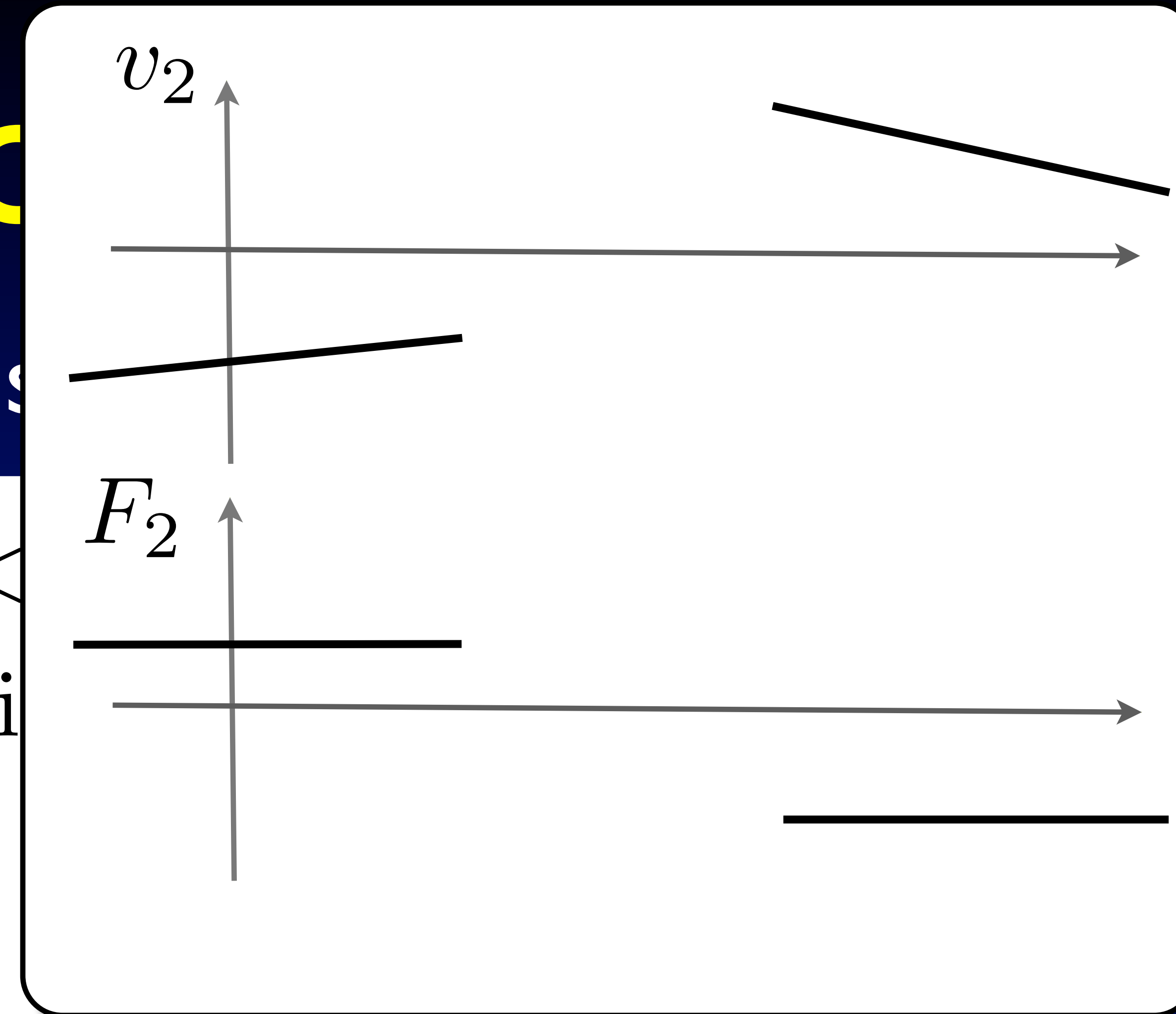

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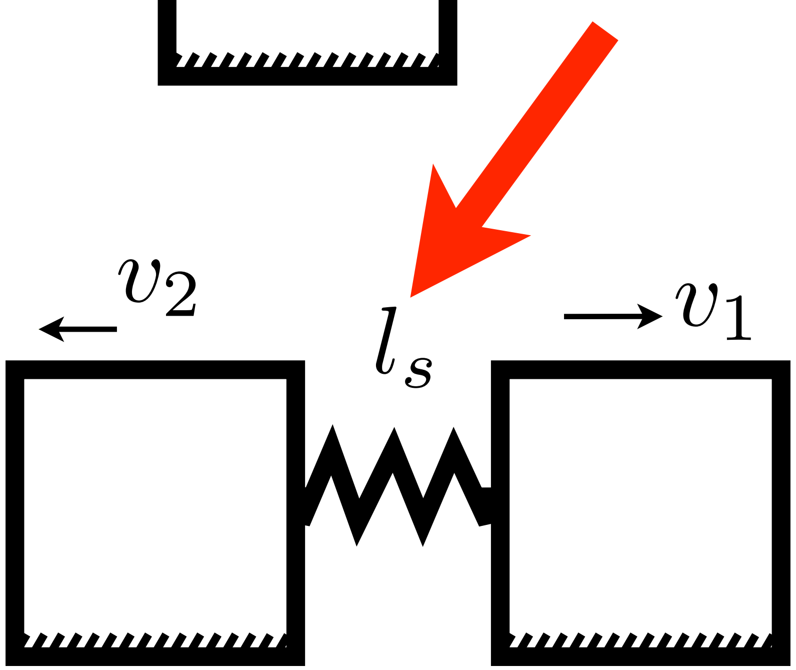

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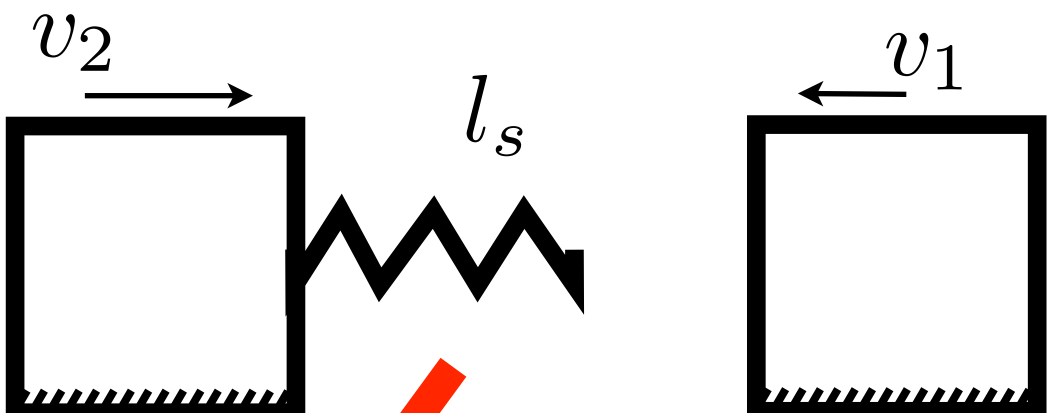

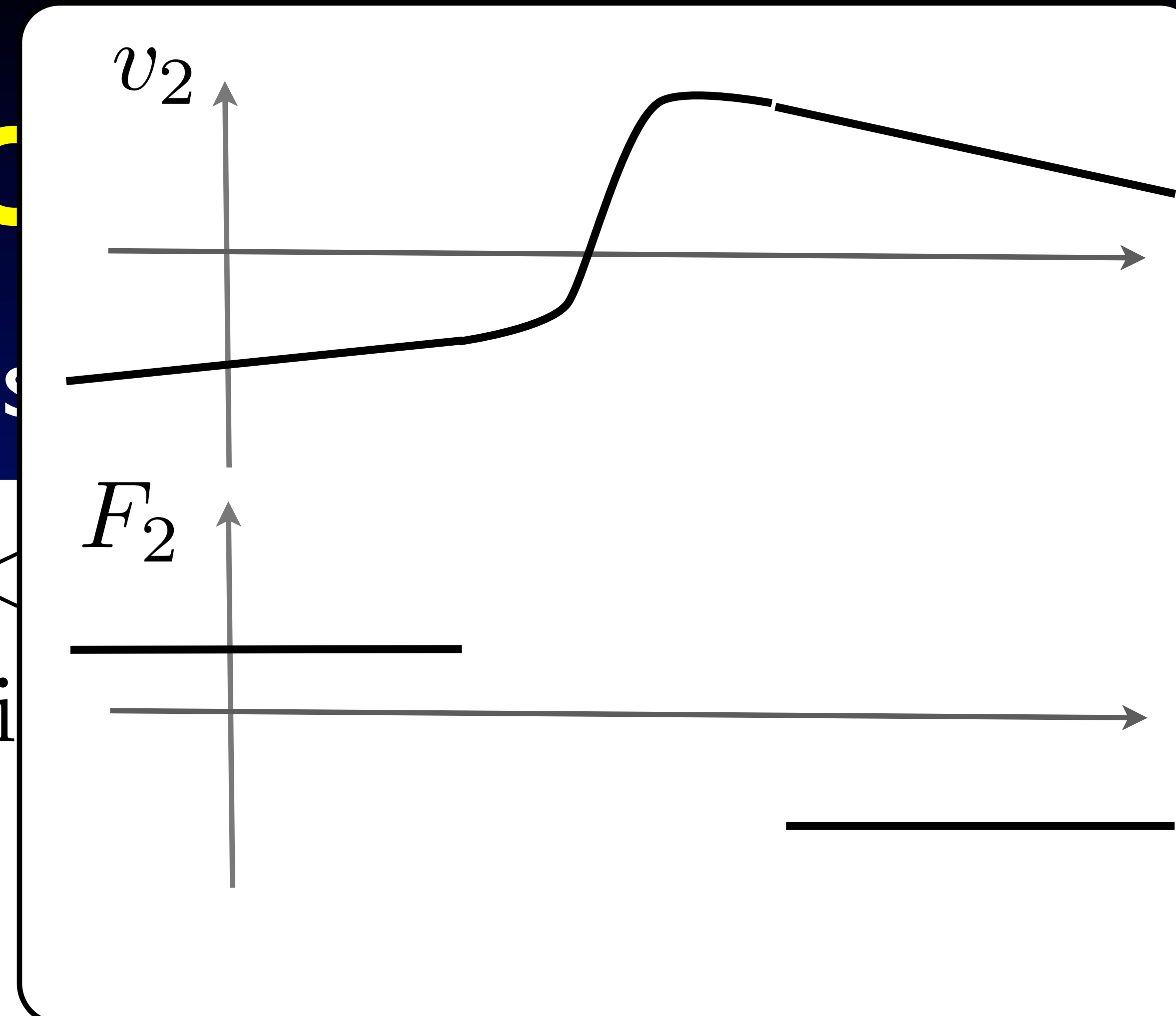

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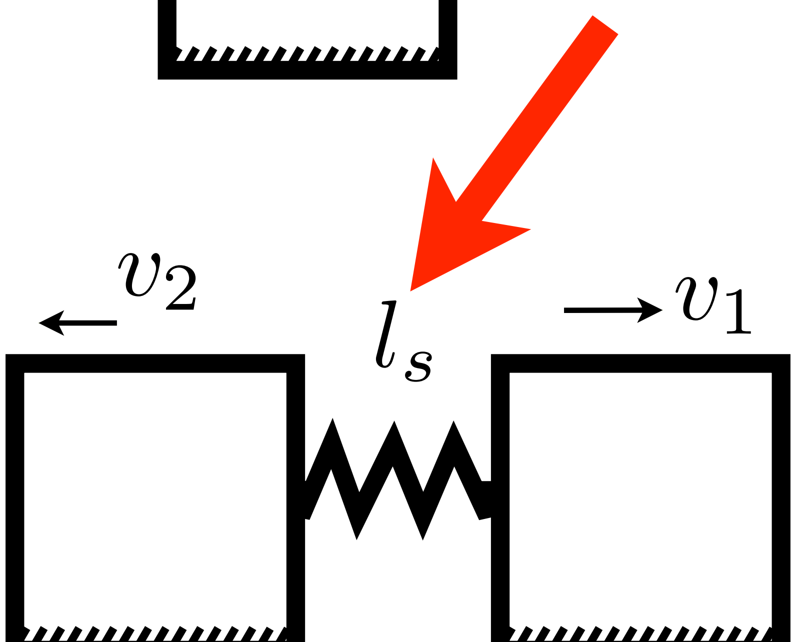

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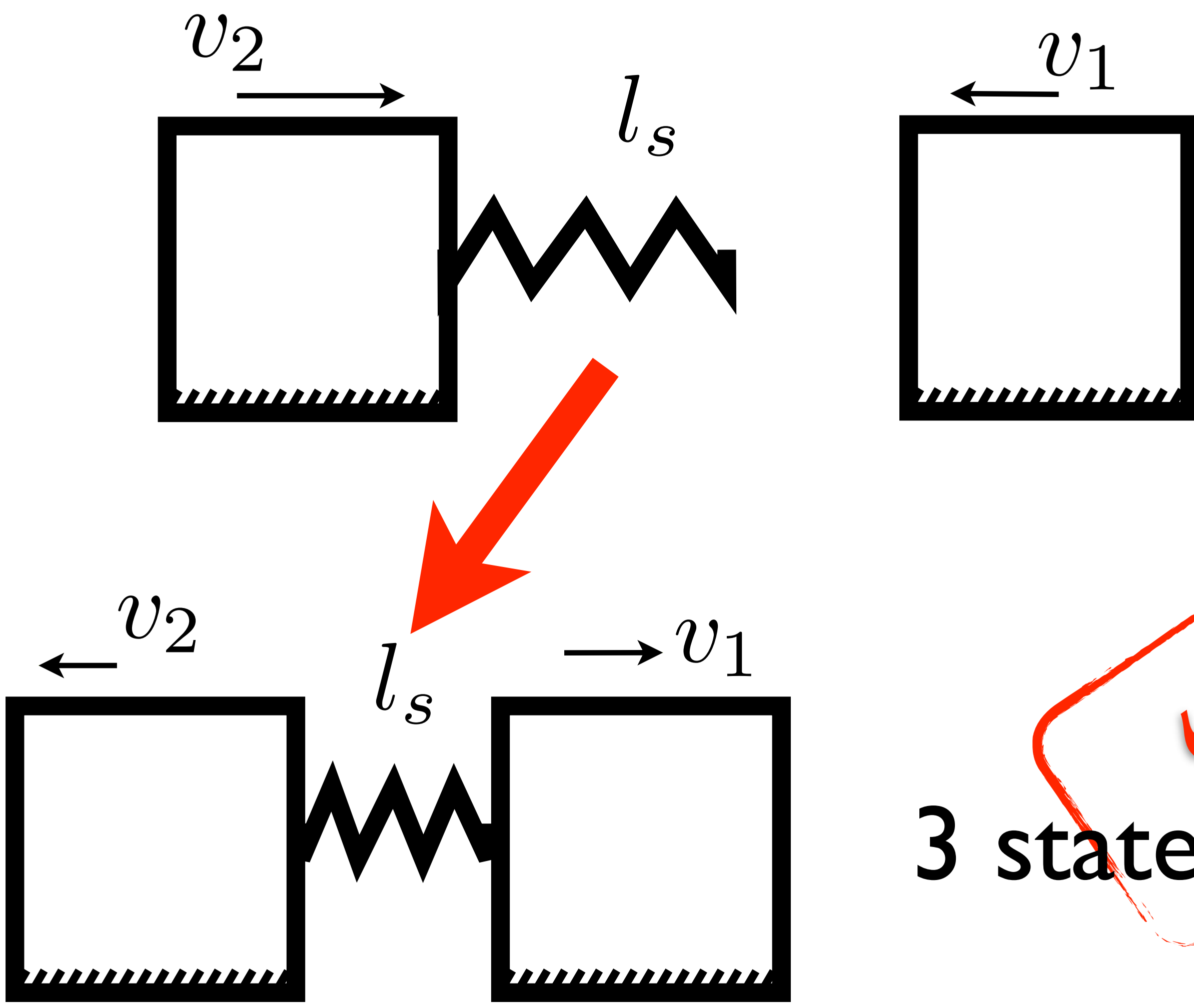

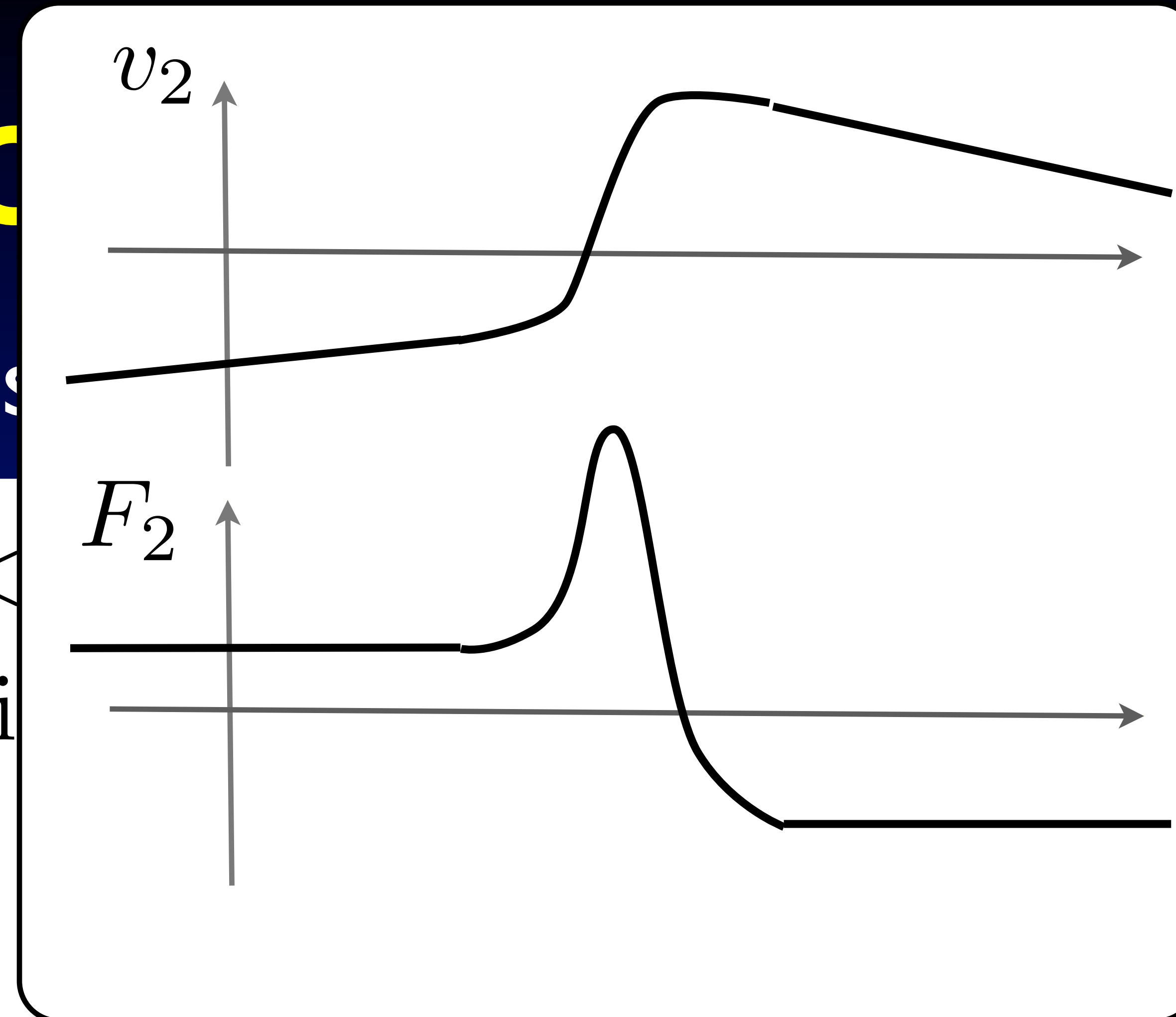

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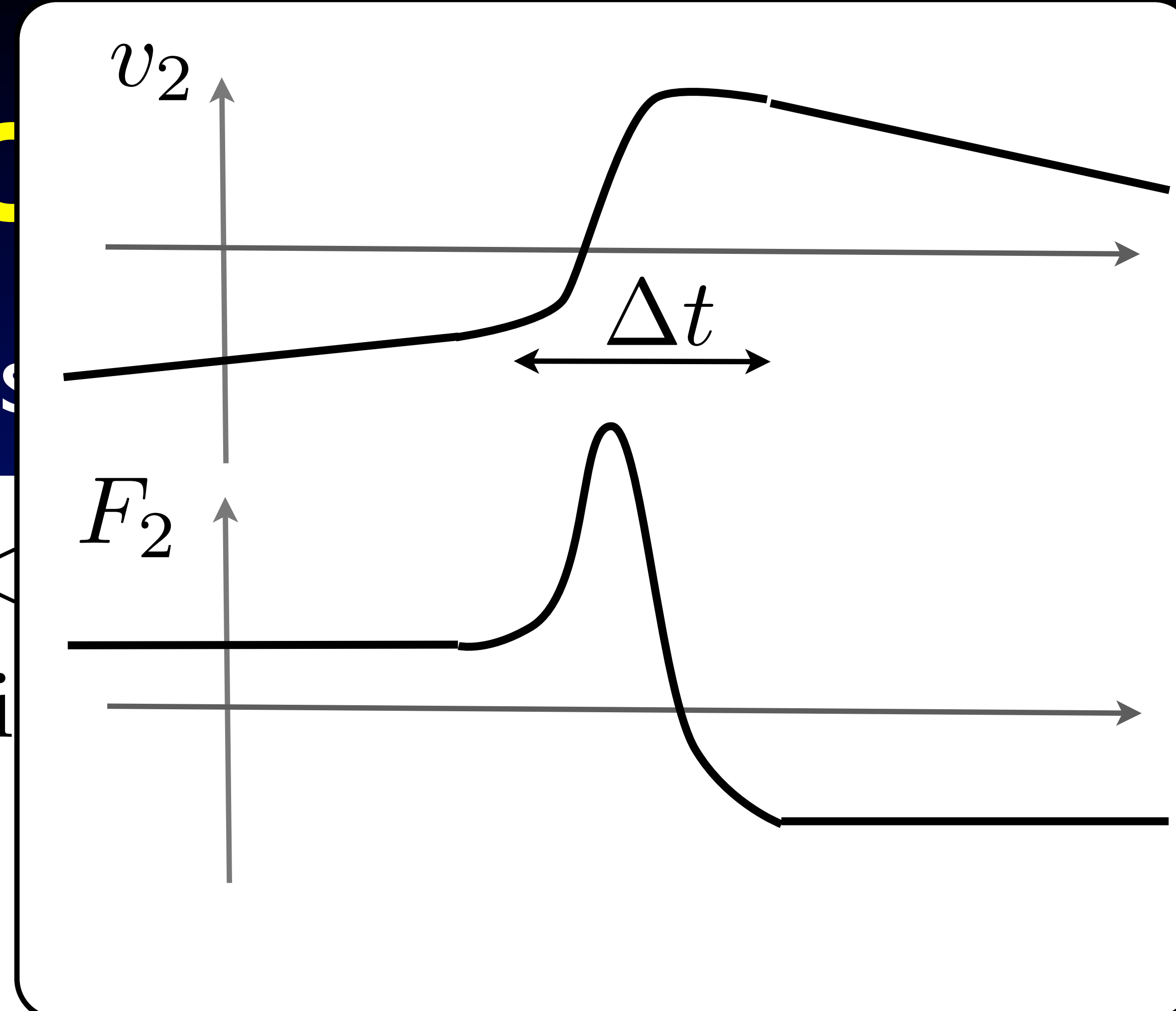

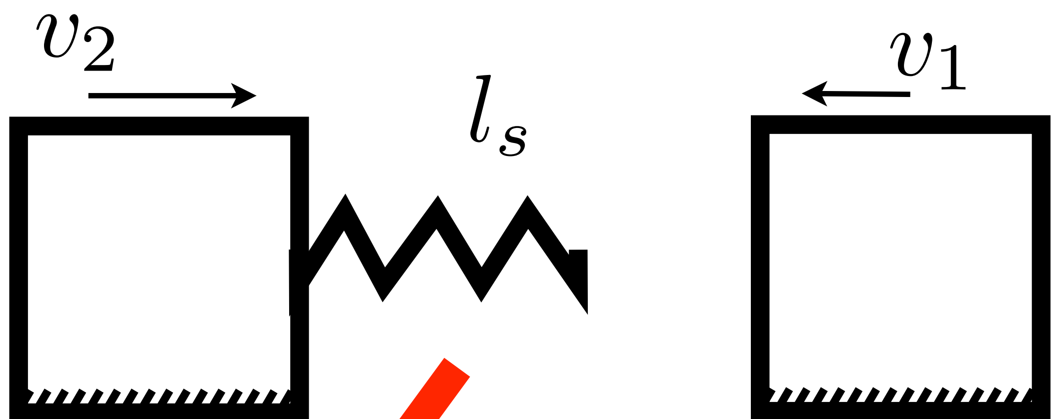

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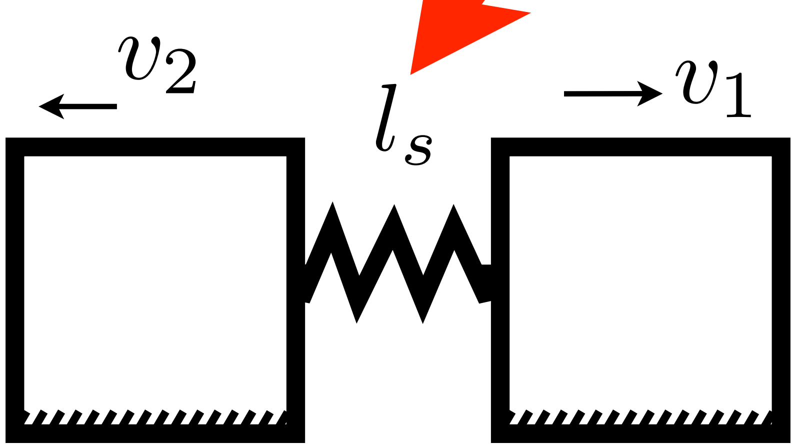

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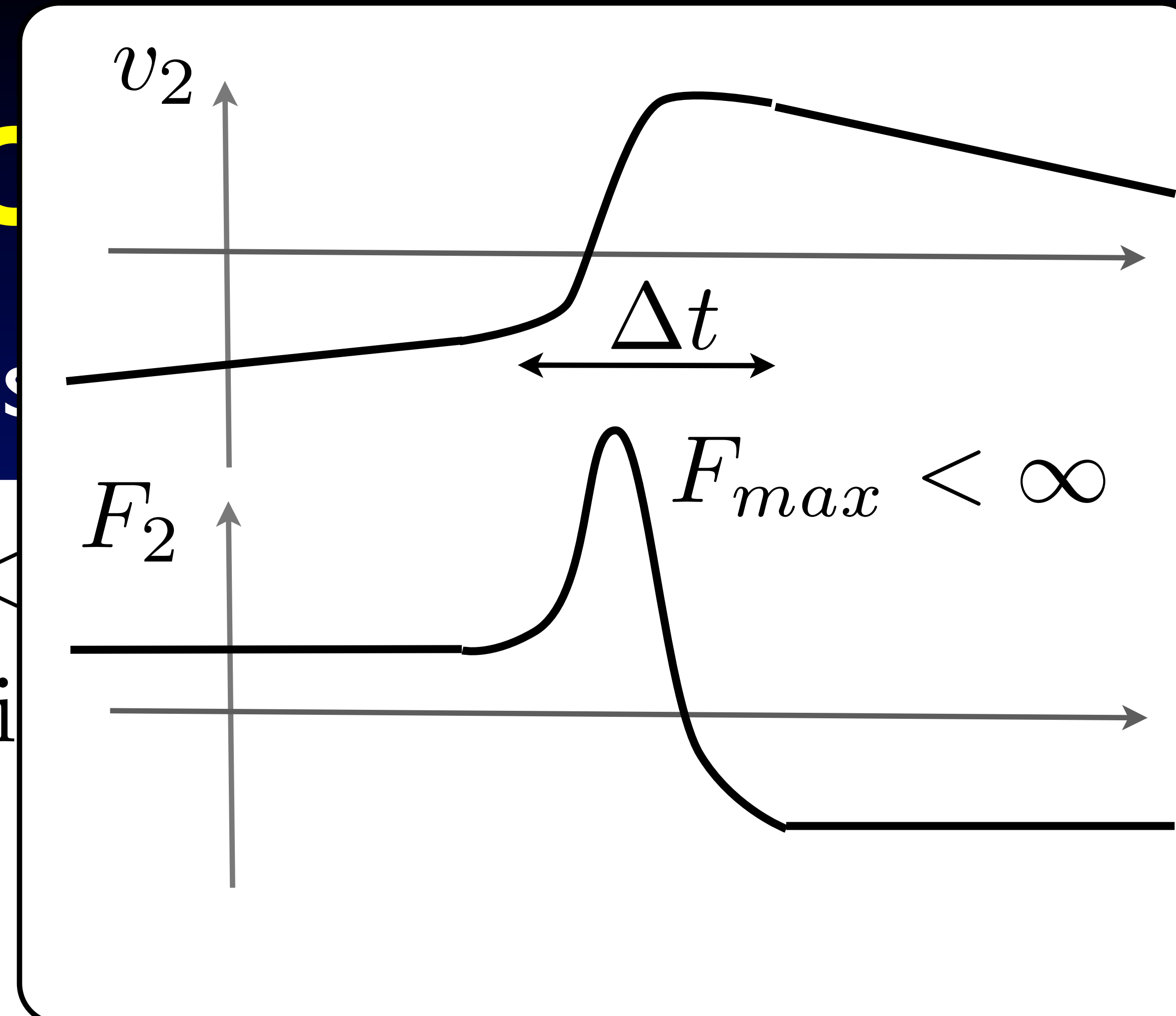

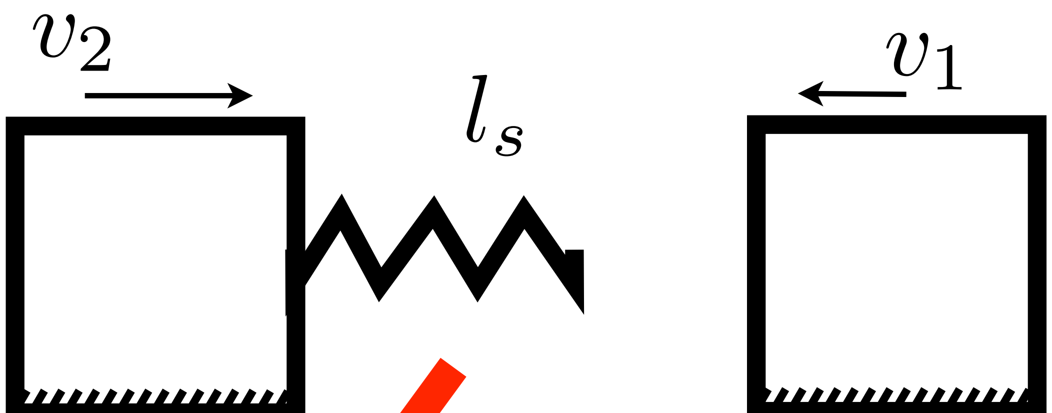

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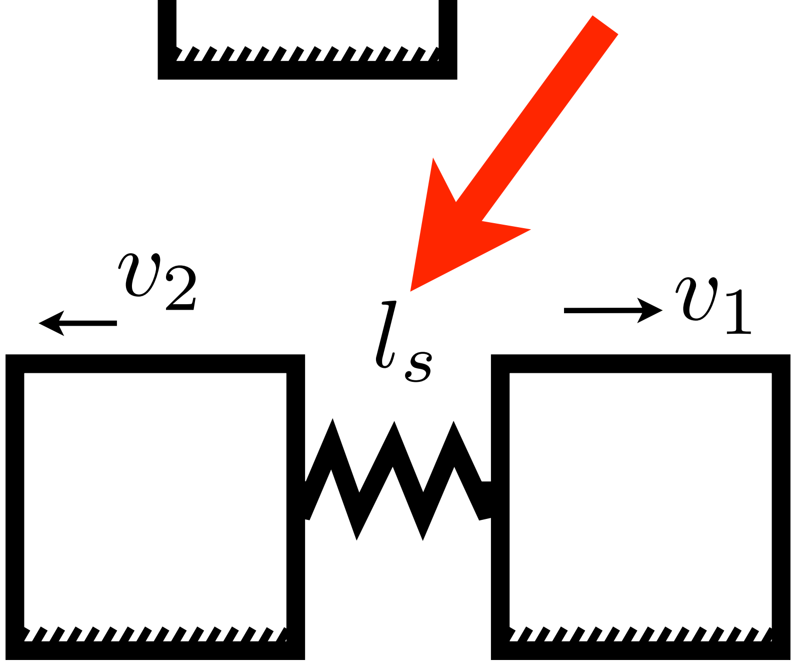

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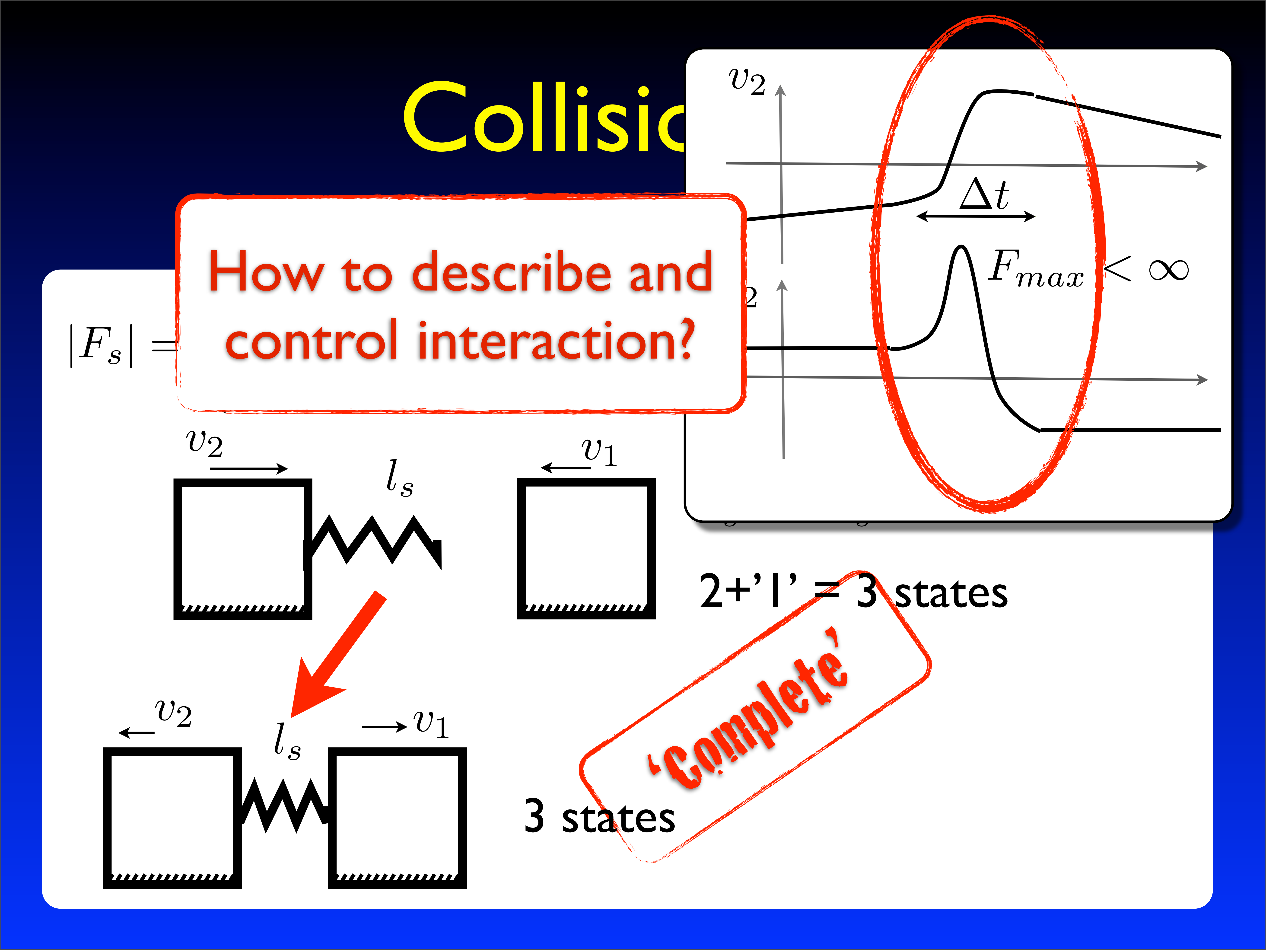
Collisio
How to describe and control interaction?
|F_s| =
v_2
Δt
F_max < ∞
v_2
v_1
l_s
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v_2
l_s
v_1
3 states
'Complete'

Two questions:

- How to characterize & control dynamics of interaction
- How to control forces?

Force control

Force control?

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Control 101:

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- In order to control a state, need to have influence on its (time) derivative

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Energy storages!

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Energy storages!

What are mechanical energy storages?

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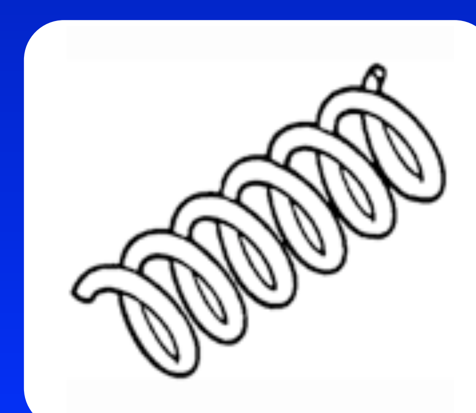

How/where can force be controlled?

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Input output-relations of ideal mechanical elements:

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Input

$$F = \int kv\,dt$$

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Input output-relations of ideal mechanical elements:

$$\dot{v} = \frac{1}{m}F$$

Output

$$v = \int \frac{1}{m} F dt$$

Input

$$\dot{F} = kv$$

$$F = \int kv dt$$

How/where can force be controlled?

Input output-relations of ideal mechanical elements:

Energy storage ⇔ states in eqs.

Input/Output ⇔ Causality

Input can be non-differentiable (e.g. steps) output can't

$$\dot{v} = \frac{1}{m} F$$

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Output

$$v = \int \frac{1}{m} F dt$$

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$$F = \int kv dt$$

Answer:

$$\dot{F} = kv$$

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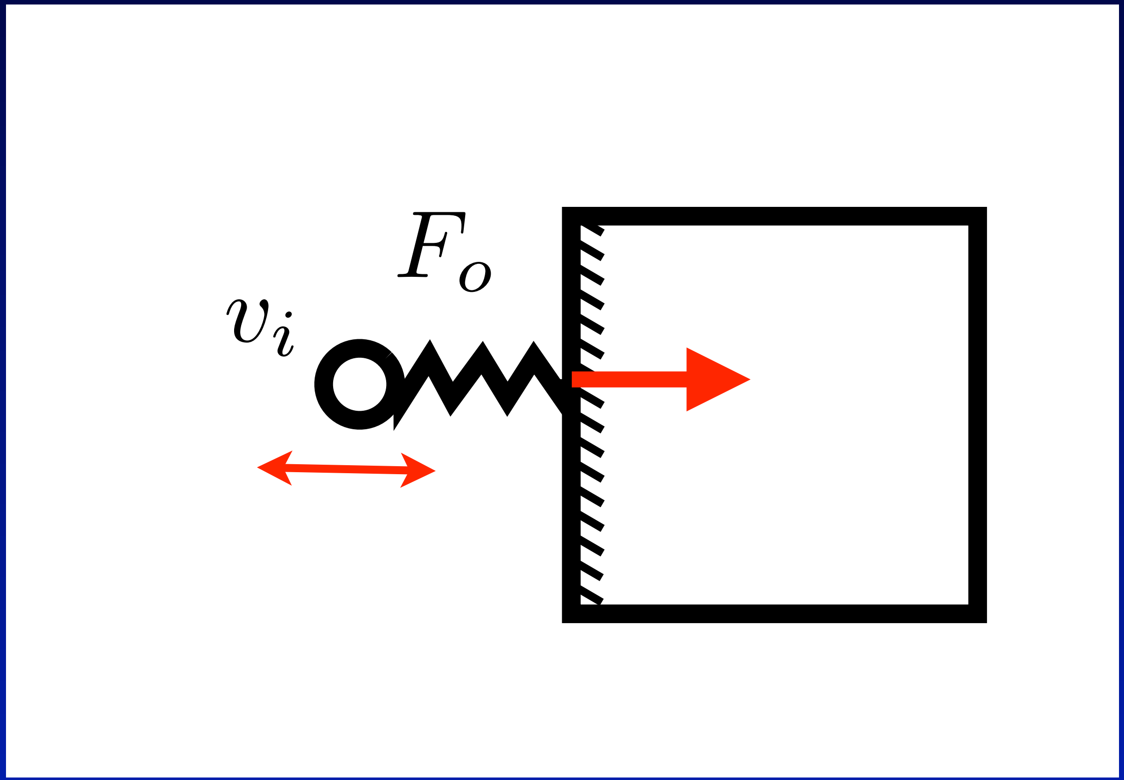

Force can be controlled by controlling expansion of a 'spring-like-element', i.e. imposing velocity on a 'spring'

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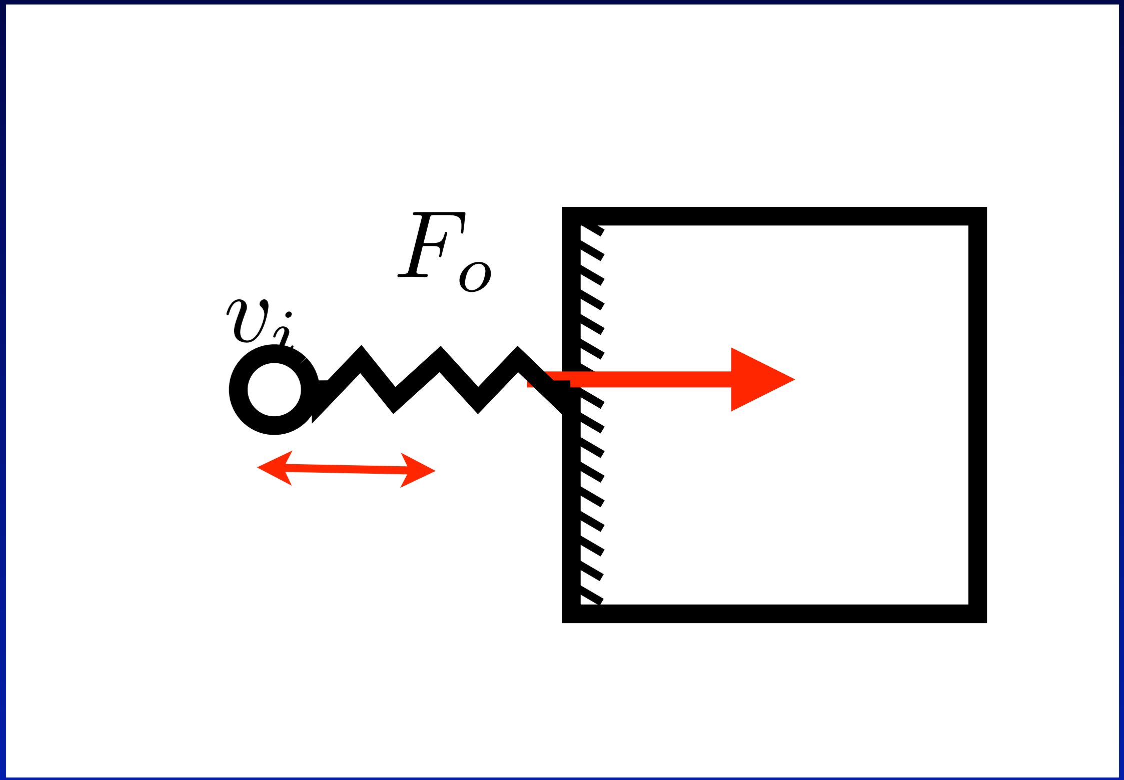

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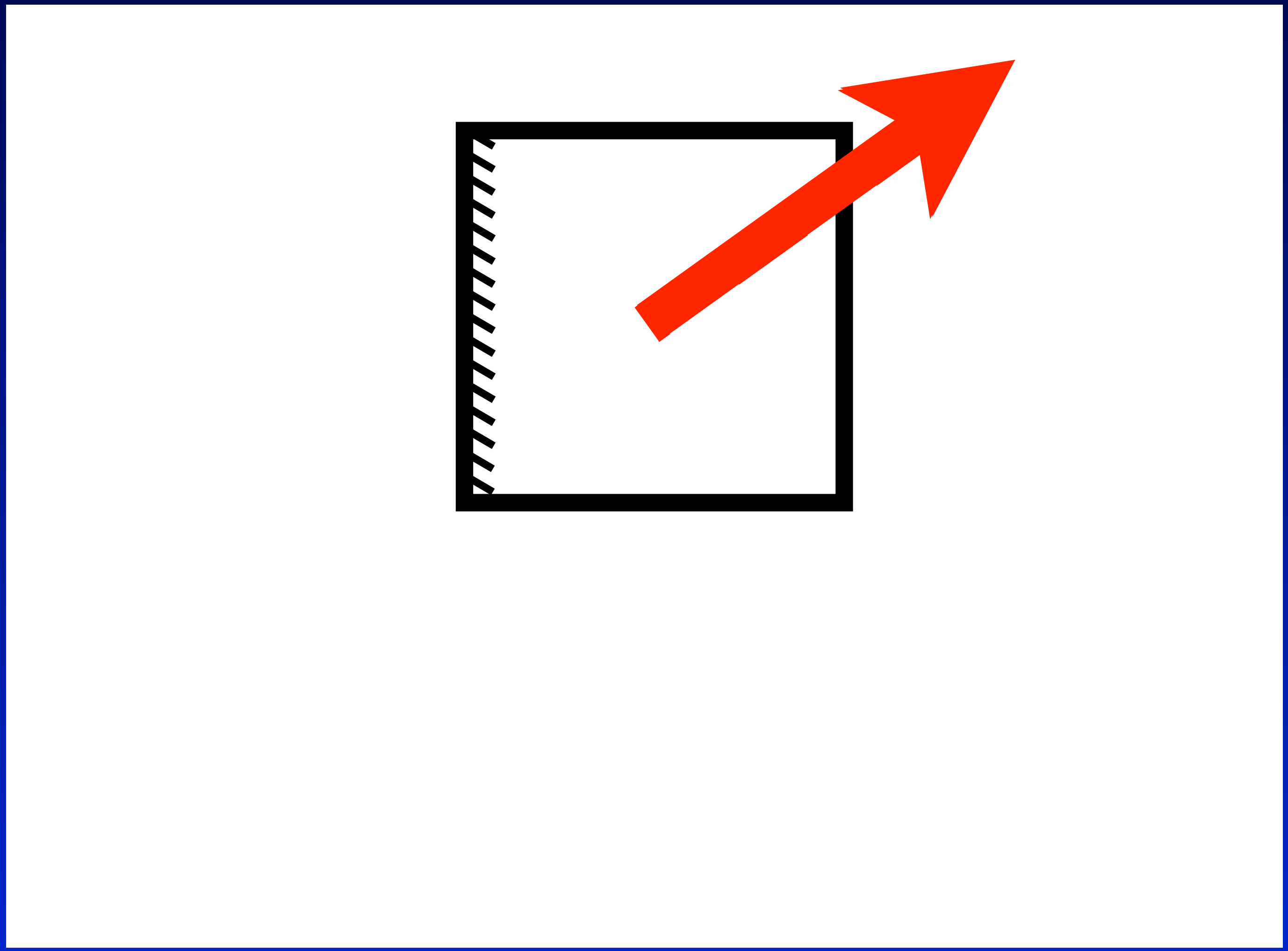

This is the dual to the force control problem!

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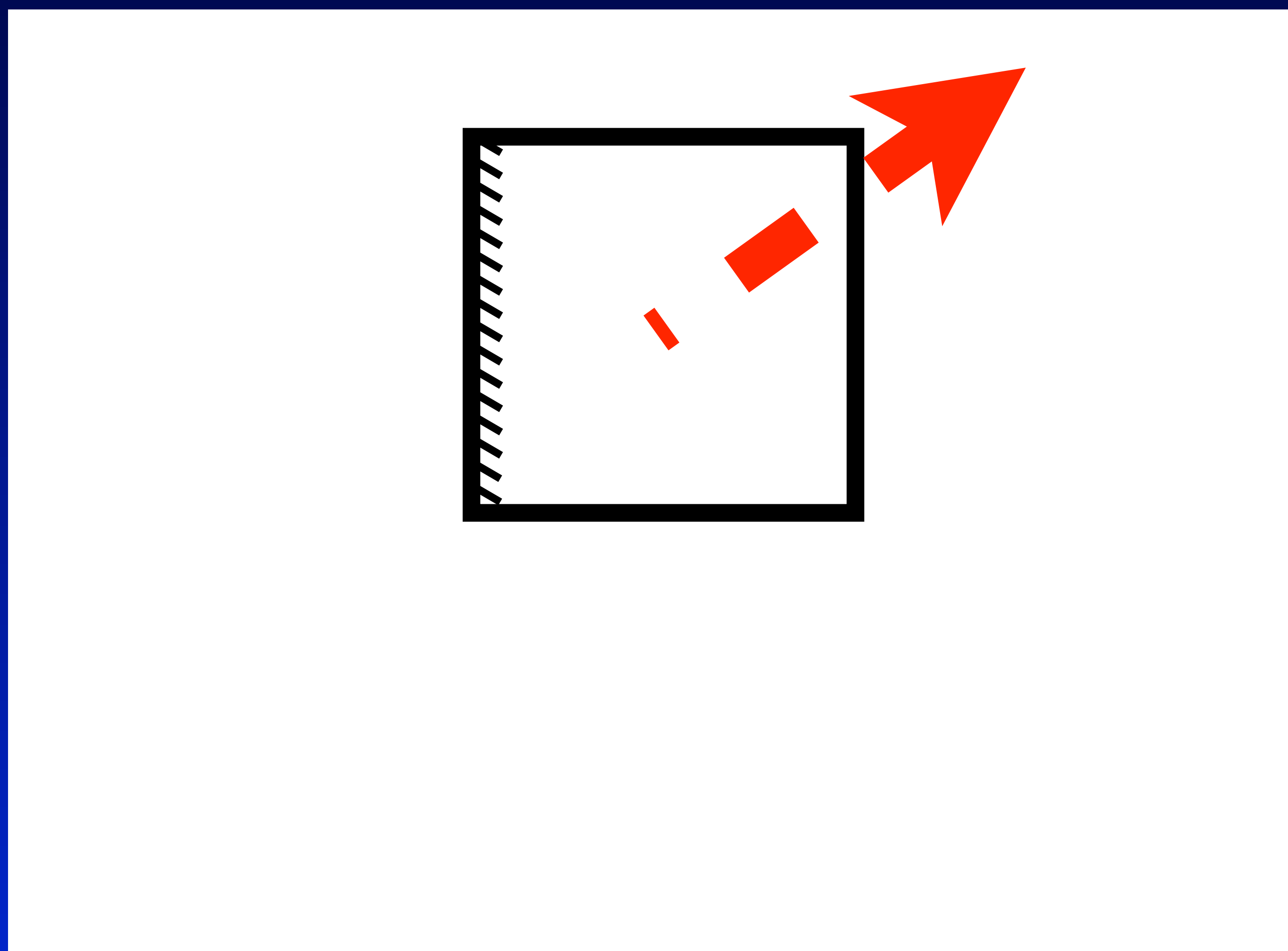

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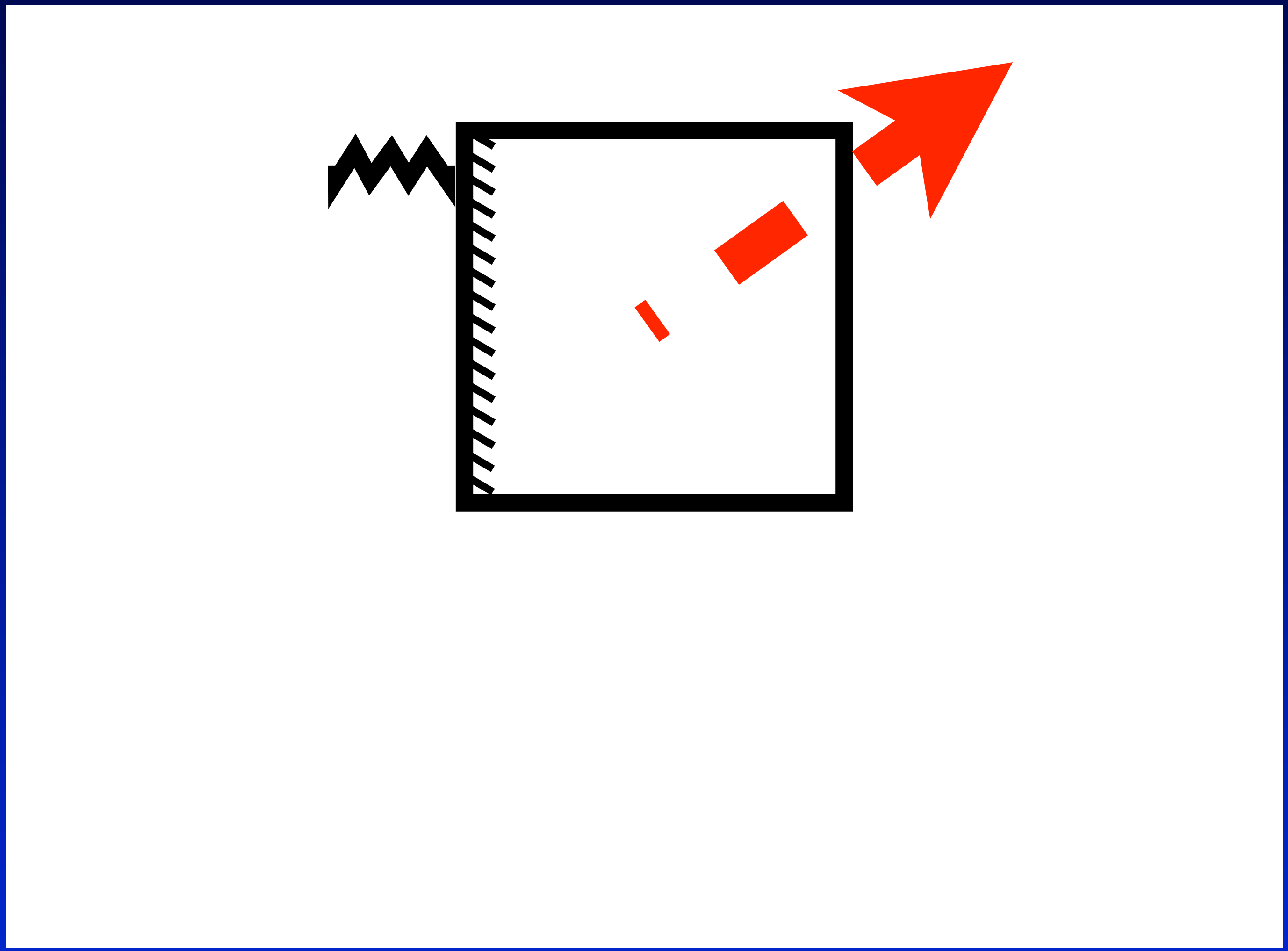

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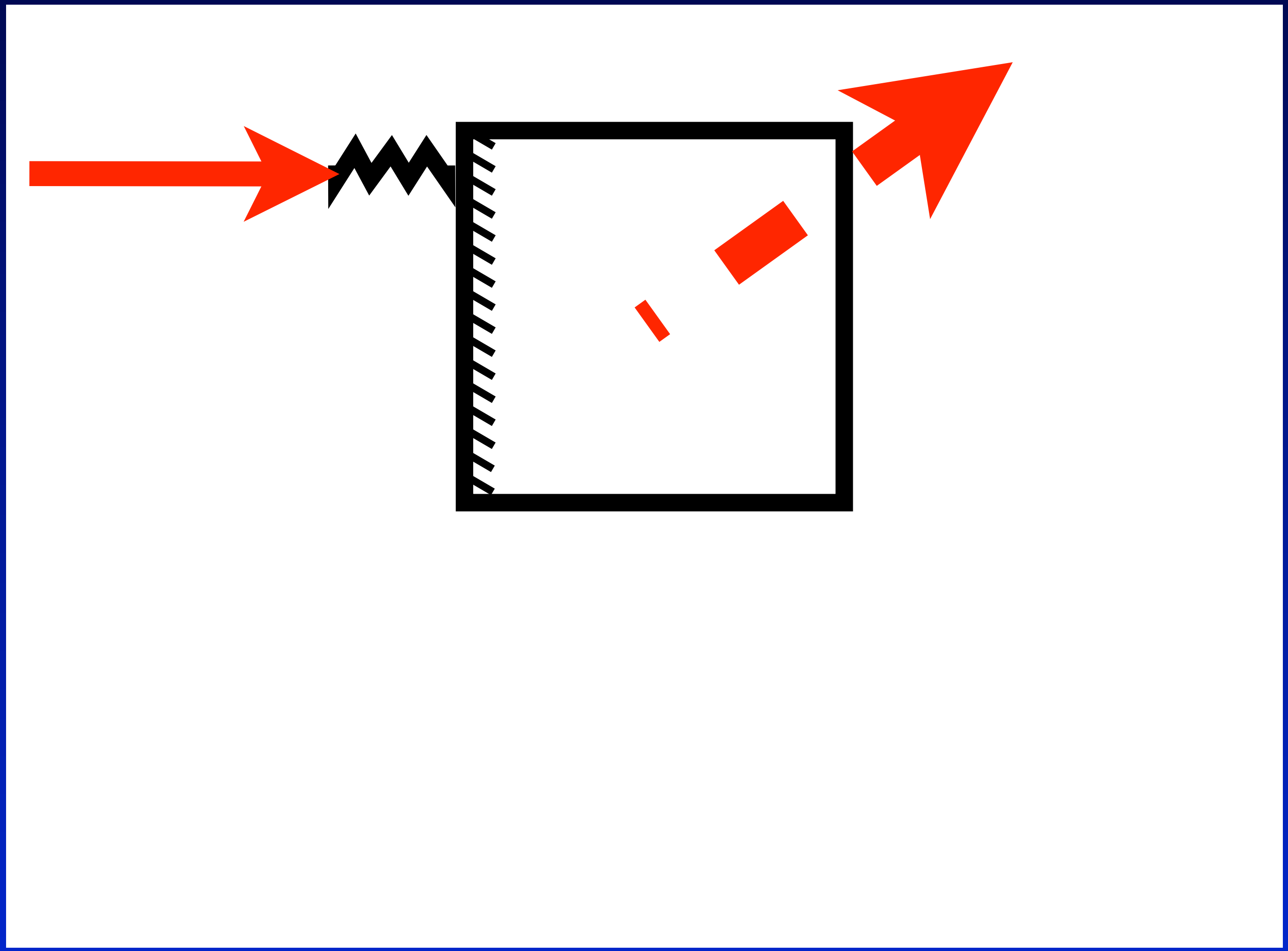

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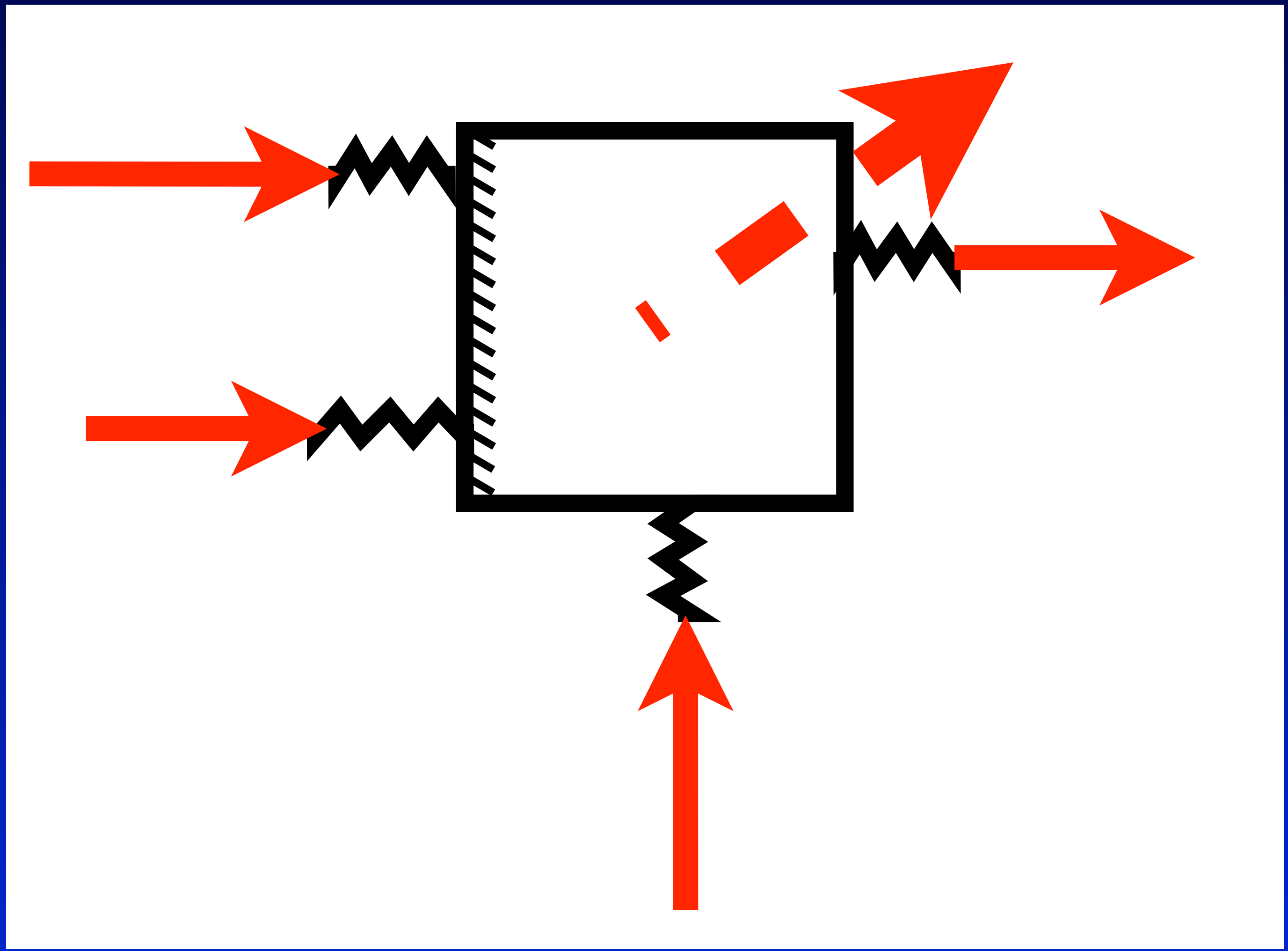

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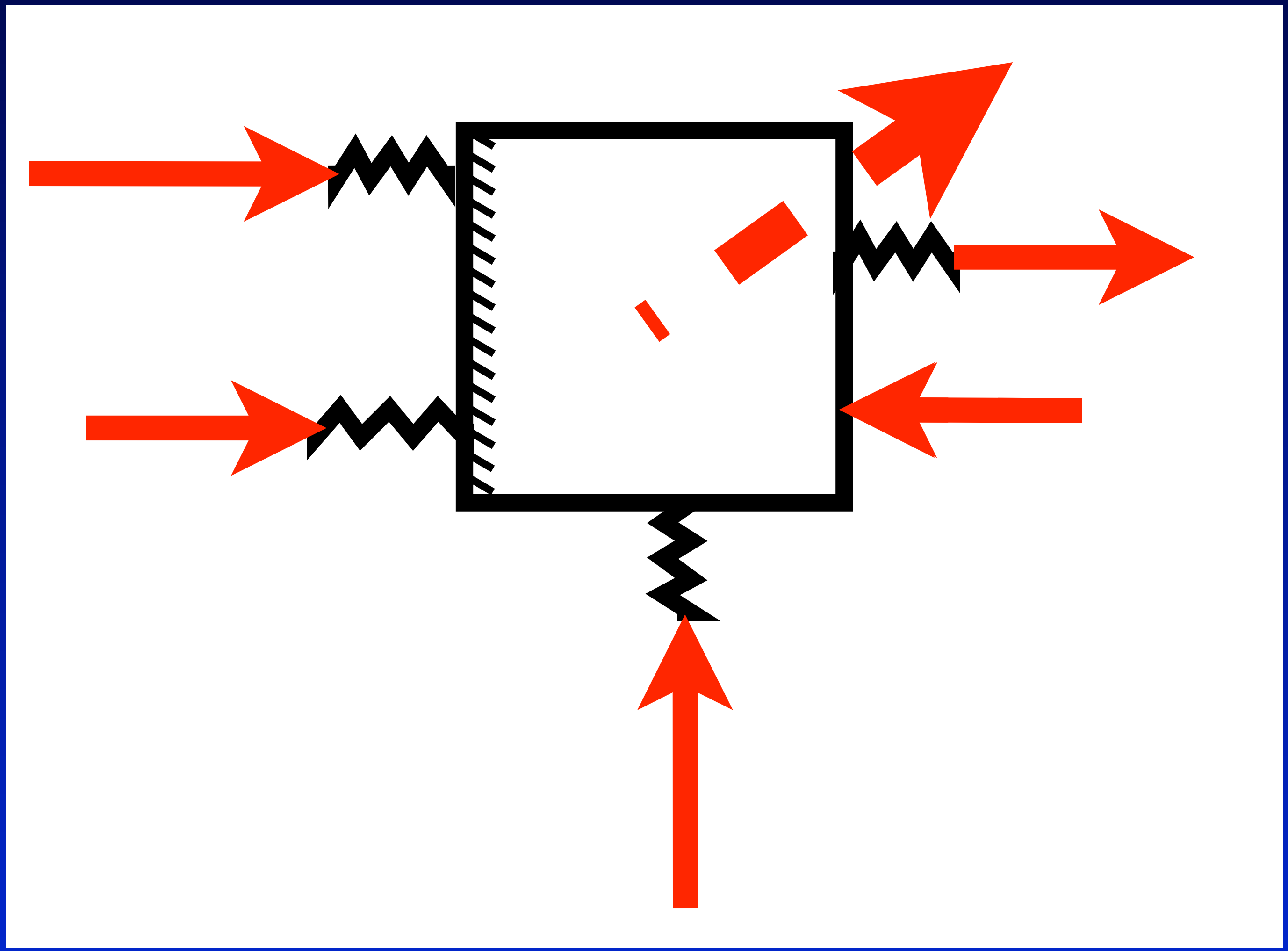

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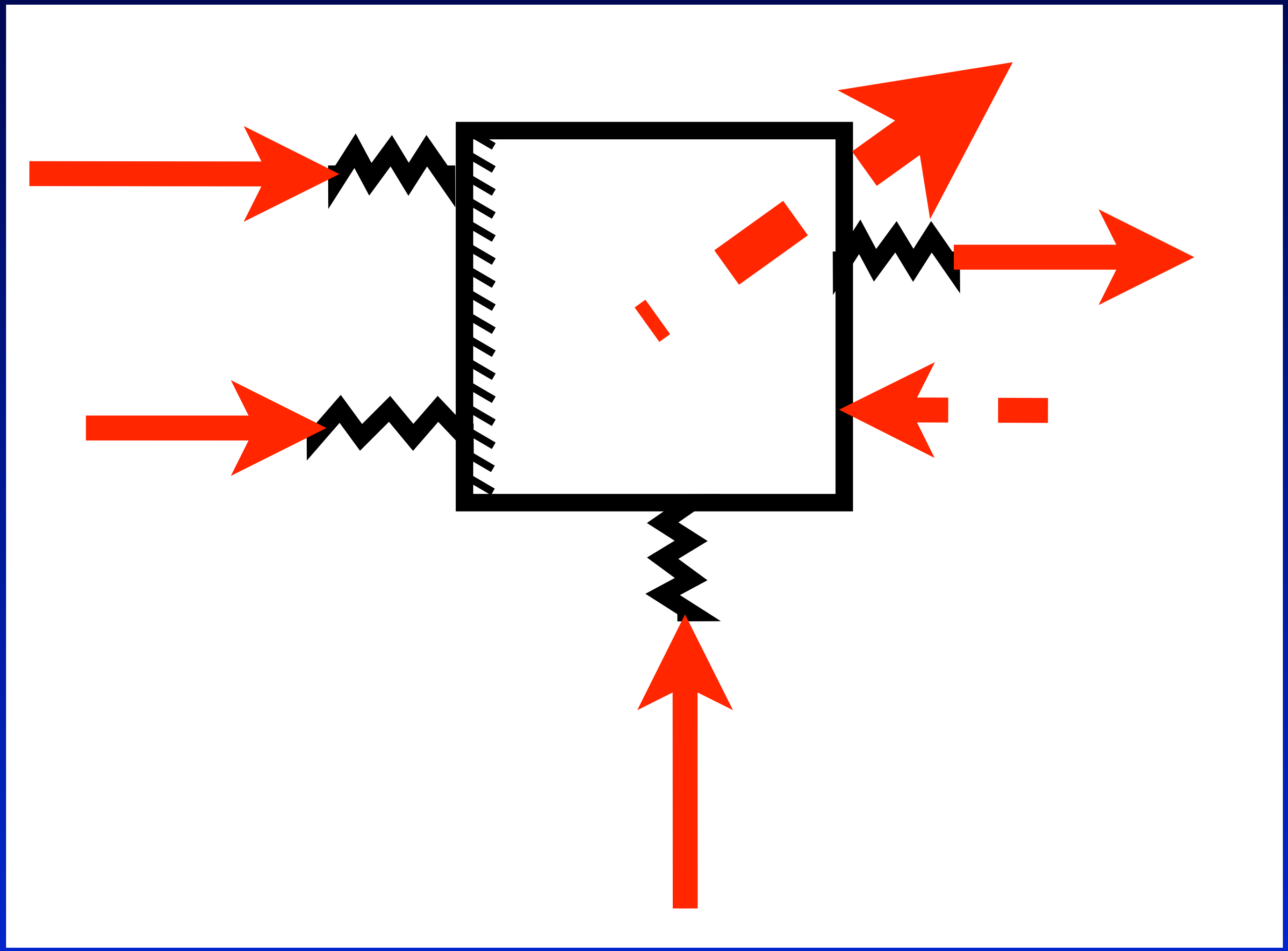

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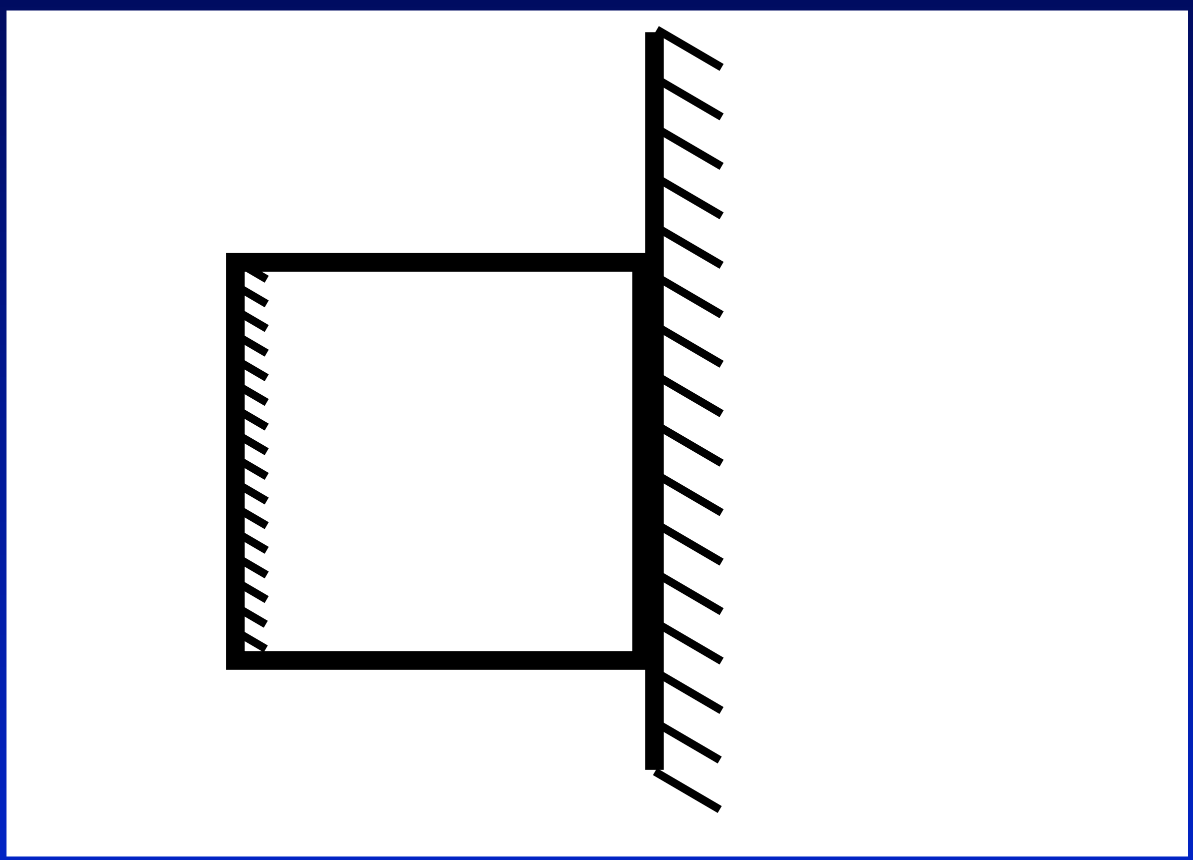
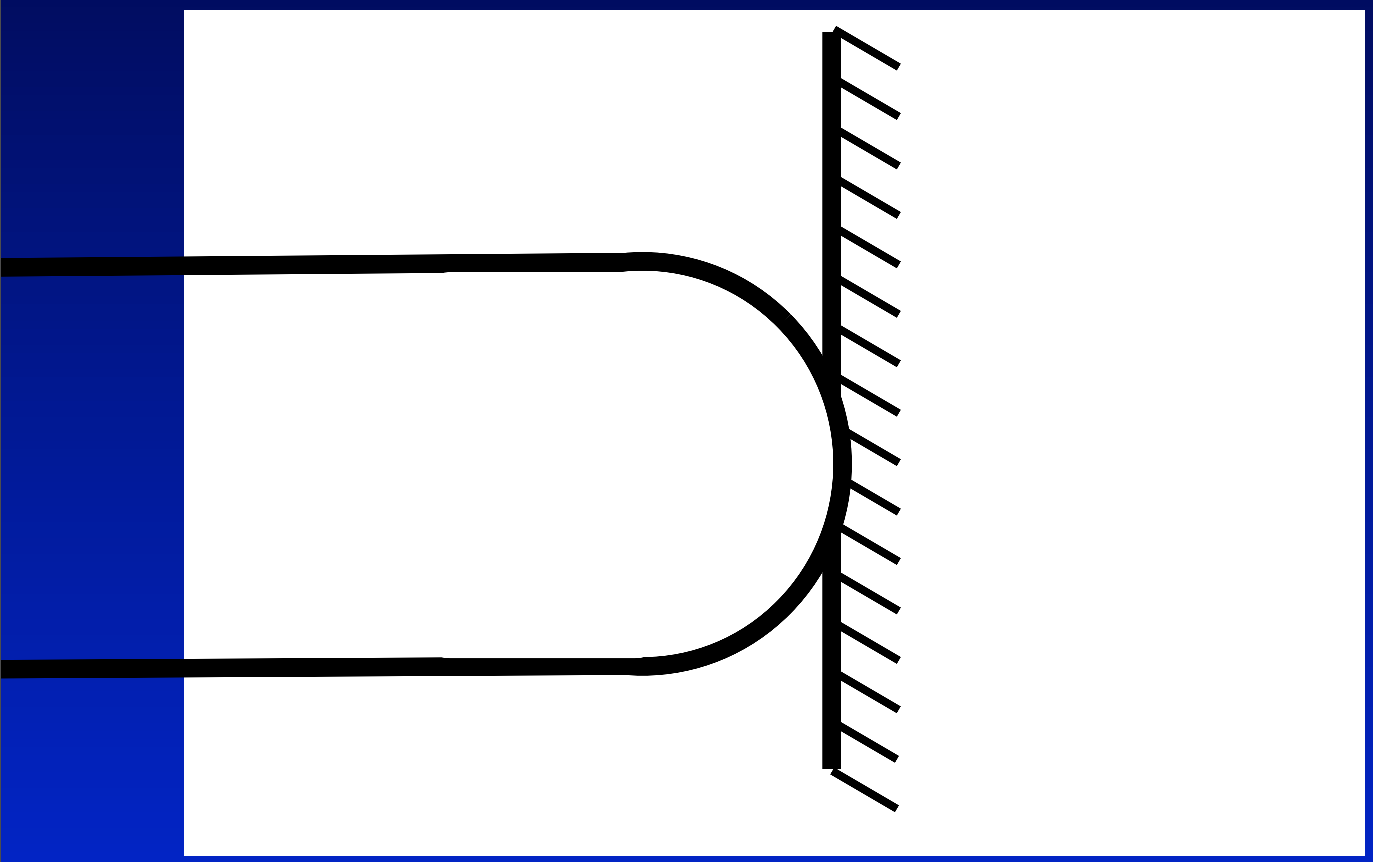
Interaction dynamics

Constrained motion



Two directions:
- constrained
- unconstrained

Constrained motion



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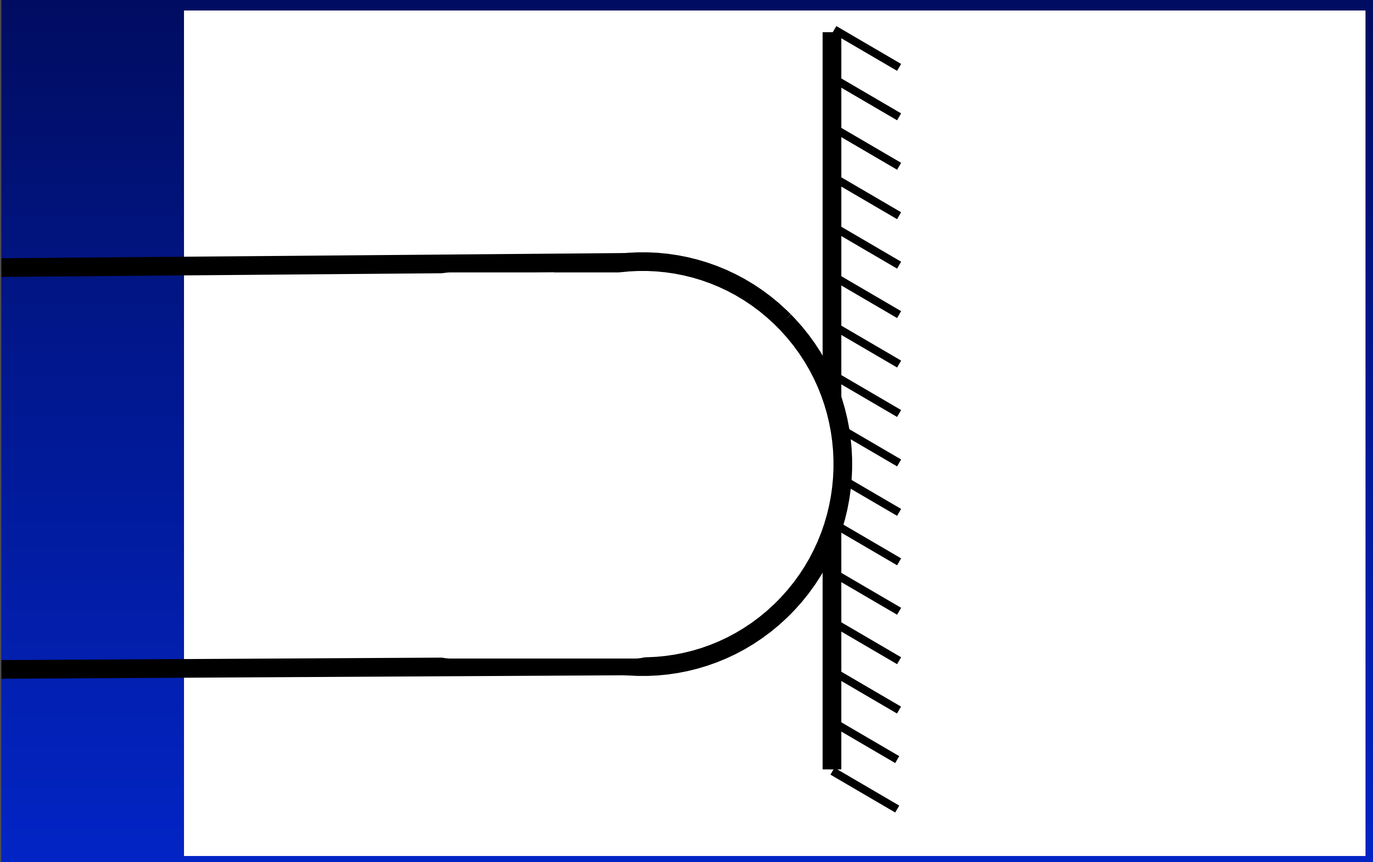

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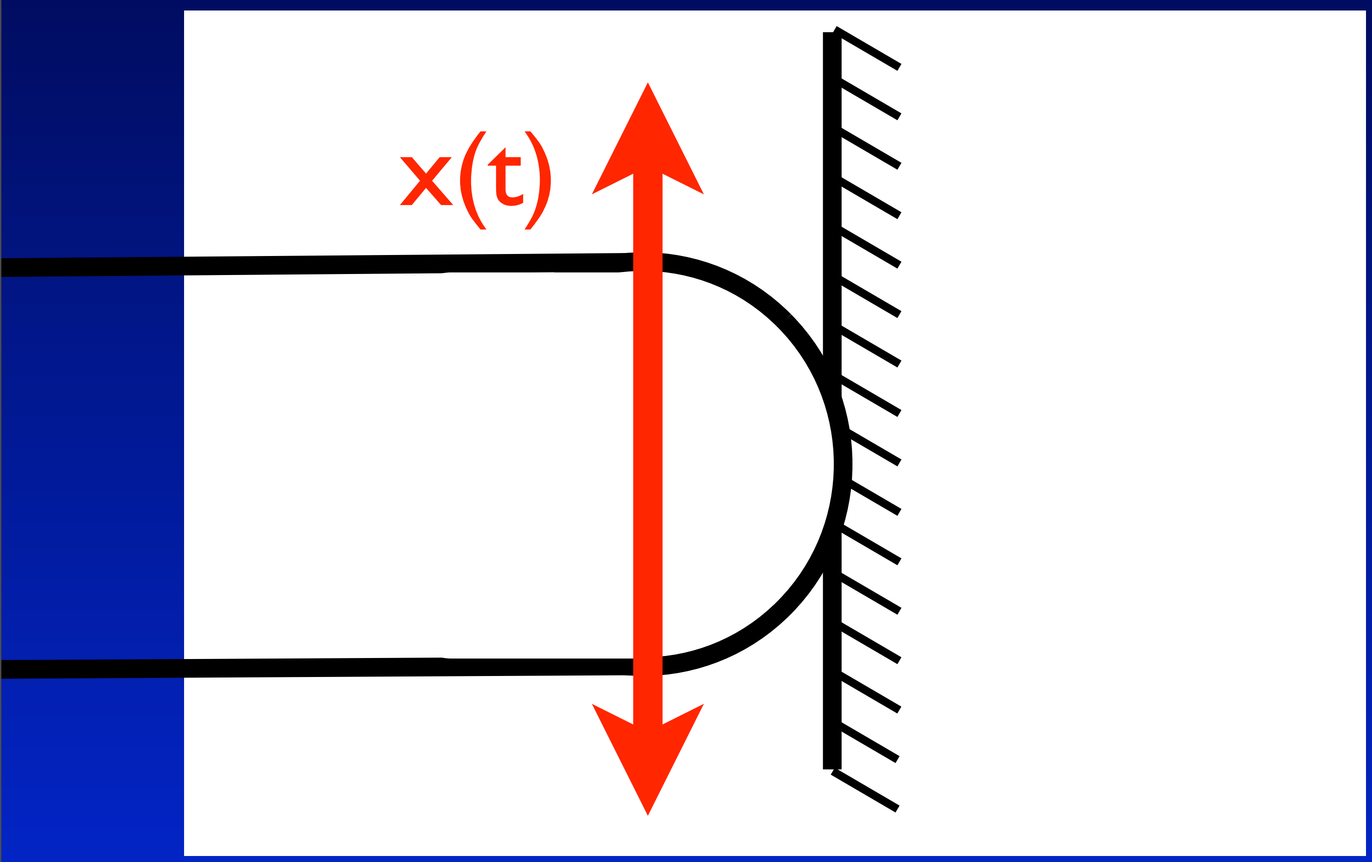
Frictionless positioning task

Constrained motion



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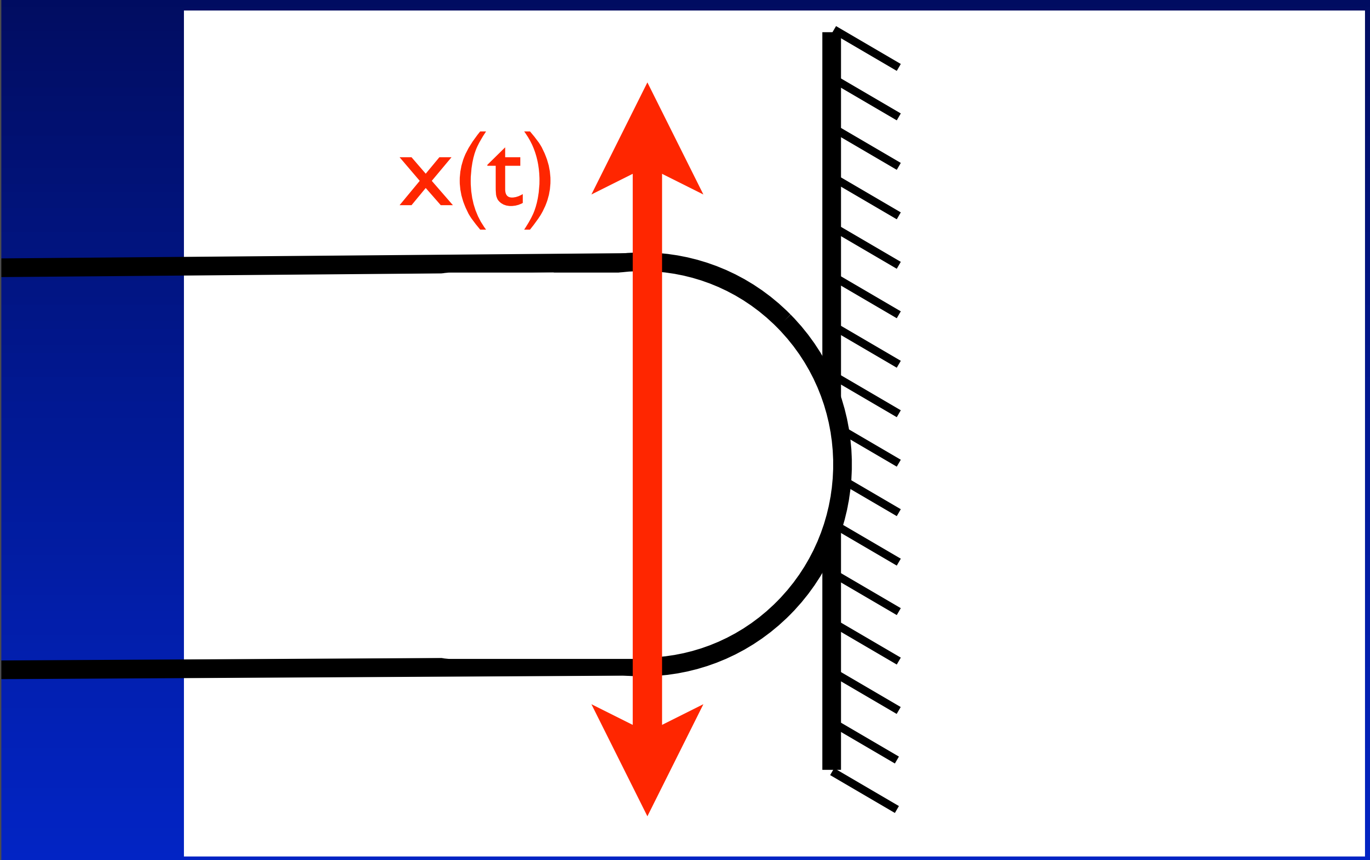

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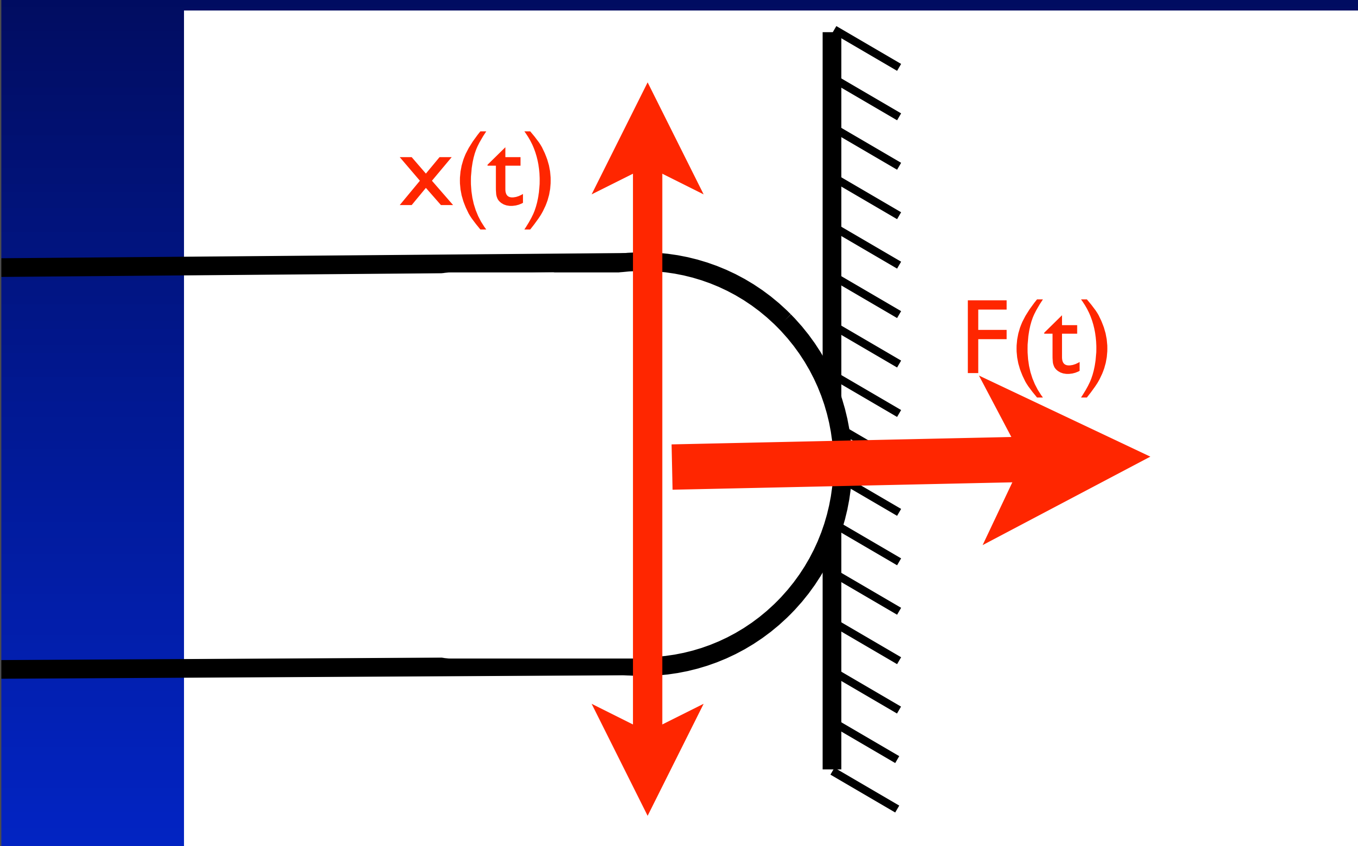
Frictionless positioning task

Force control task against stiff surface

Constrained motion



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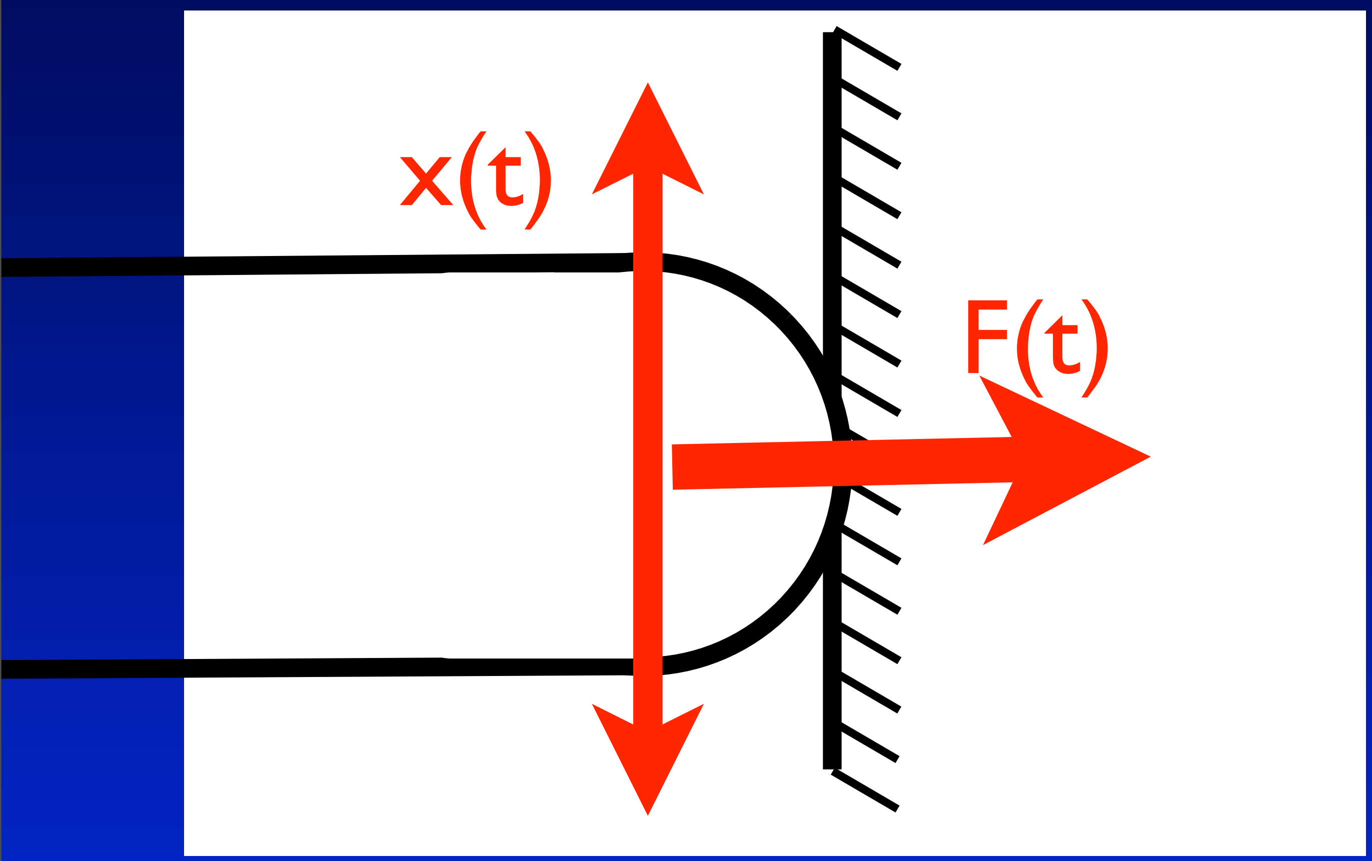

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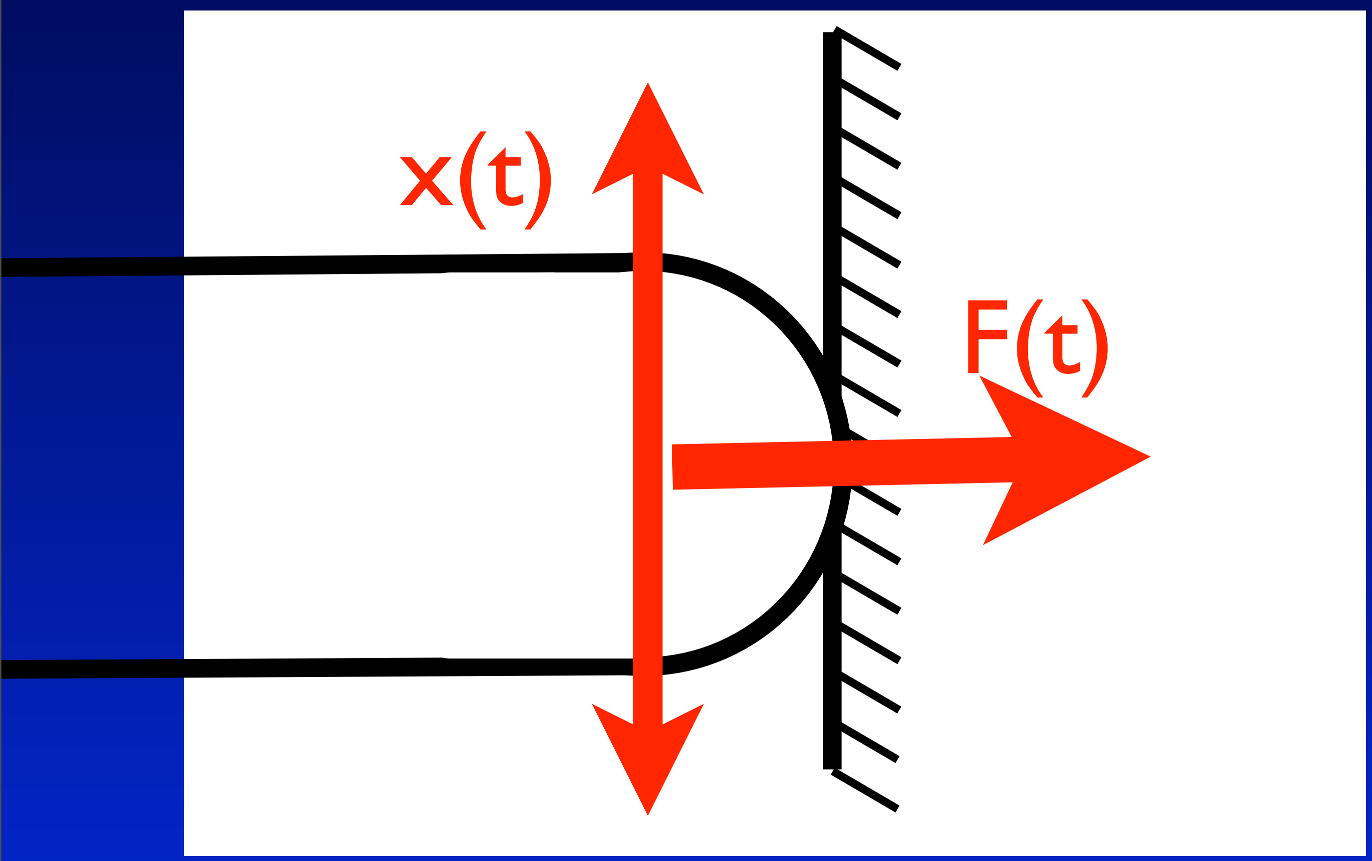

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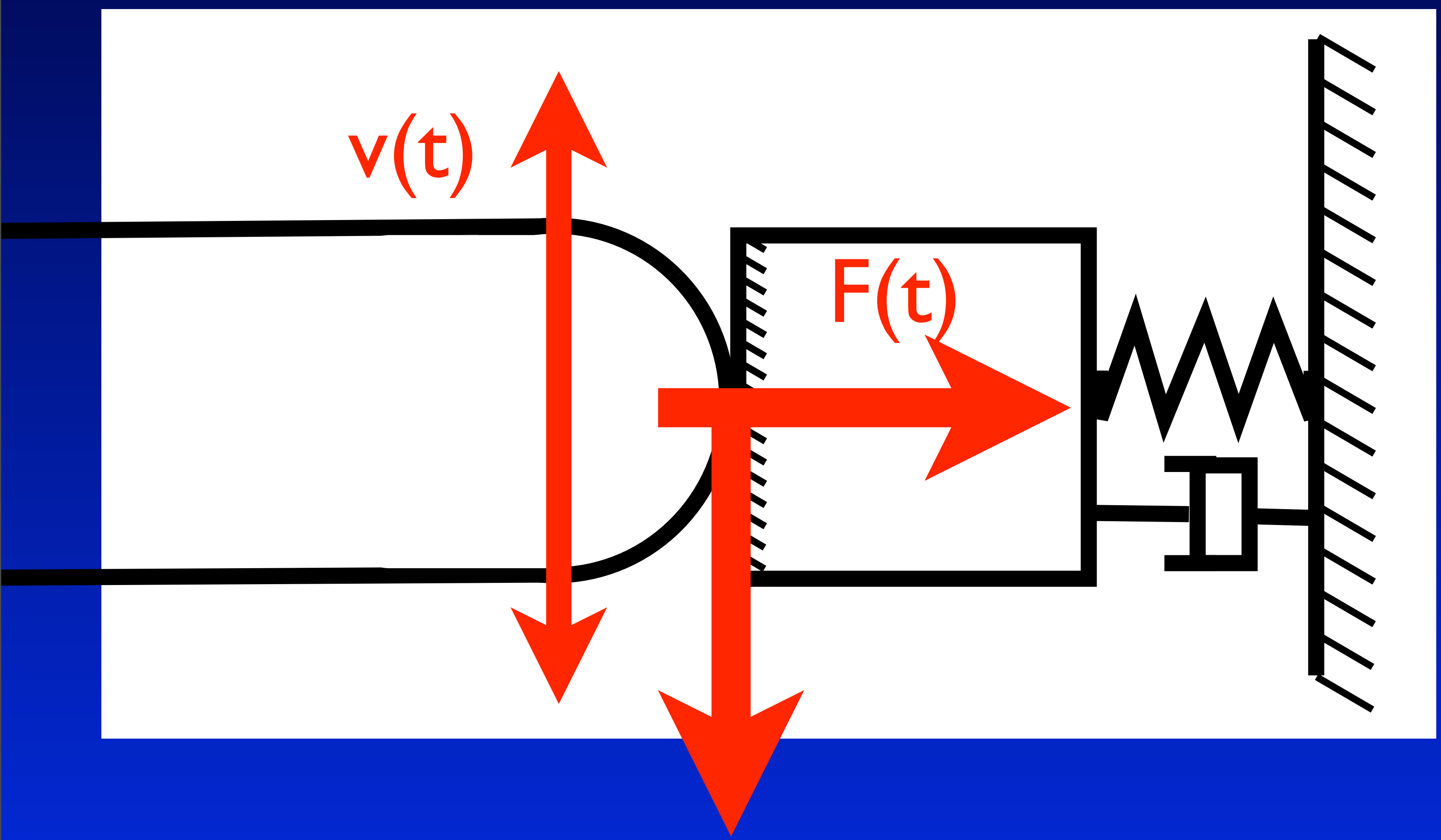
Force control task against stiff surface

What is the mechanical work done by robot on environment?

No work done in either direction!

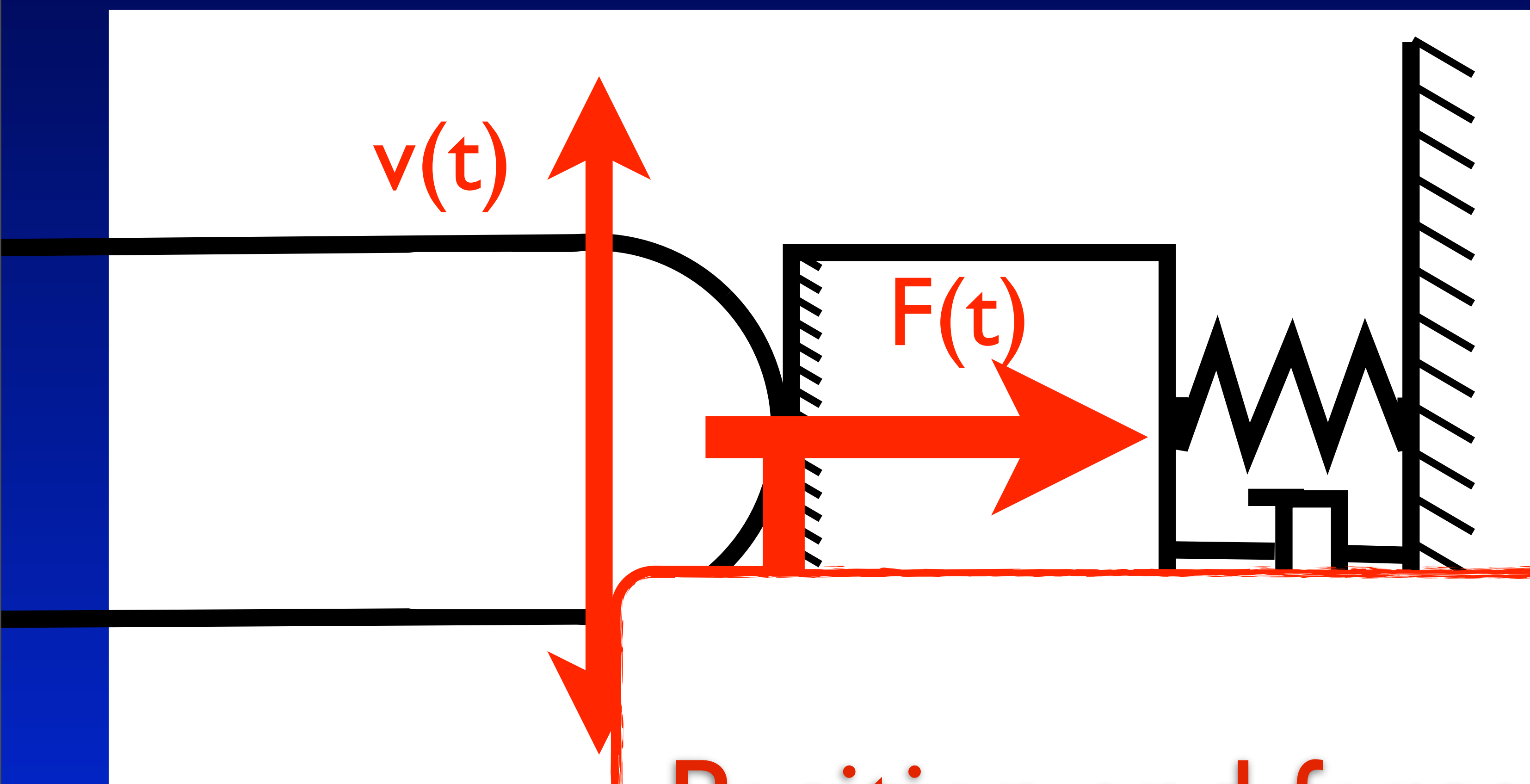
Constrained motion



And now?

- Friction
- Not completely stiff environment

Constrained motion



And now?

- Friction
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Position and force control if dW=0 are two boundary cases

Work...

Is there a systematic way to look at interaction of subsystems:

- What connections are possible?
- What quantities can imposed?
- How to describe 'interaction'?

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Energy flow - instantaneous Work

Examples: Flow/effort variables

In any system two conjugate variables describe energy flow

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In any system two conjugate variables describe energy flow

	Effort	Flow

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Flow x Effort =
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Electricity	Voltage (diff. el. potential)	Electrical Current

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Flow x Effort = inst. work

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Mechanics	Force	Velocity
Fluids	Fluid Pressure	Fluid flow

Examples: Flow/effort variables

In any system two conjugate variables describe energy flow

Flow x Effort = inst. work

	Effort	Flow
Electricity	Voltage (diff. el. potential)	Electrical Current
Mechanics	Force	Velocity
Fluids	Fluid Pressure	Fluid flow
Gases	Air Pressure	Air flow

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input	Output

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input	Output	

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input	Output	
Effort		

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input	Output
Effort	Flow

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

Input	Output	
Effort	Flow	Admittance

Impedance & Admittance

Dynamic relationship between F/E

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Effort	Flow	Admittance
Flow		

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

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Effort	Flow	Admittance
Flow	Effort	

Impedance & Admittance

Dynamic relationship between F/E

Input-output relations:

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Effort	Flow	Admittance
Flow	Effort	Impedance

Impedance & Admittance

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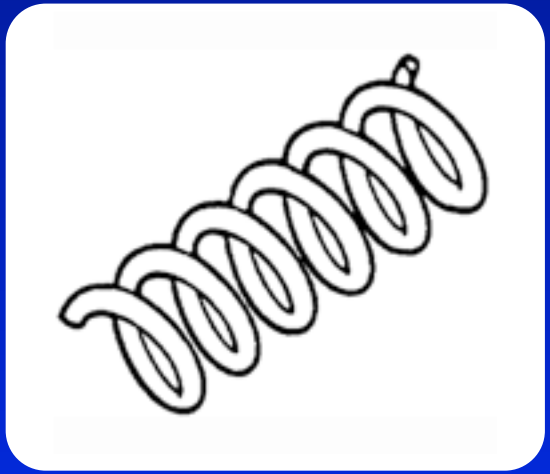

Impedance & Admittance

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Input-output relations:

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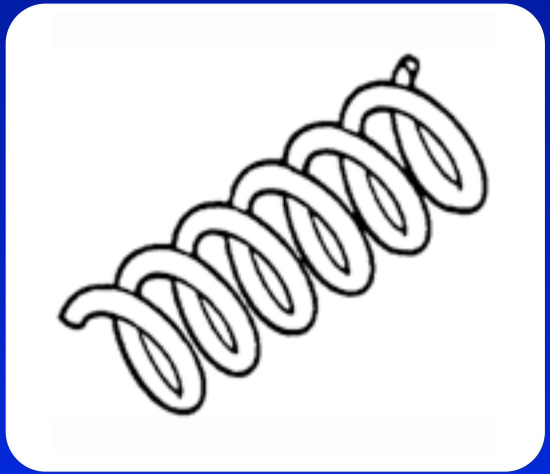
$$\dot{v} = \frac{1}{m}F$$

$$v = \int \frac{1}{m}F dt$$



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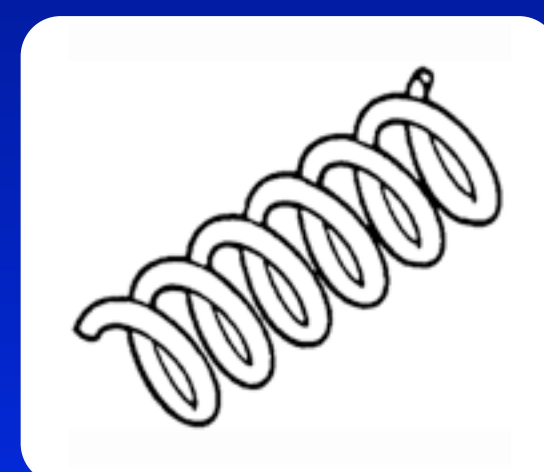

$$\dot{F} = kv$$

$$F = \int kv dt$$

Impedance & Admittance

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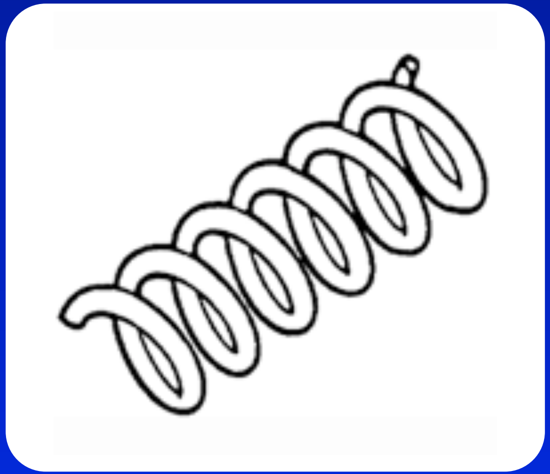

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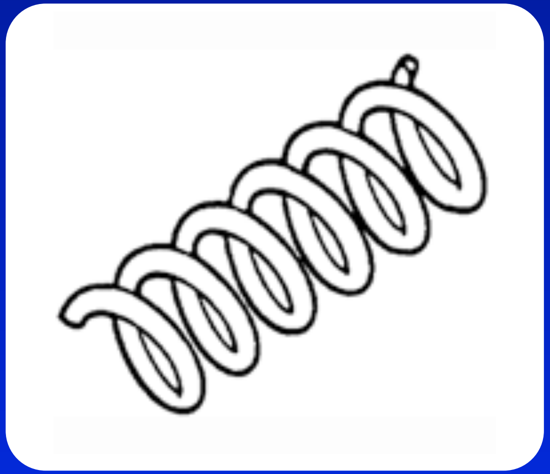

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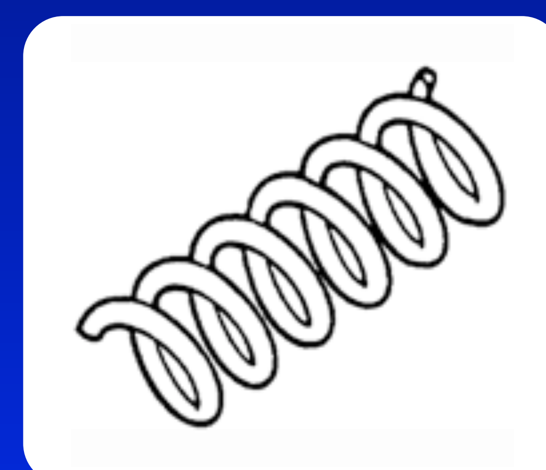

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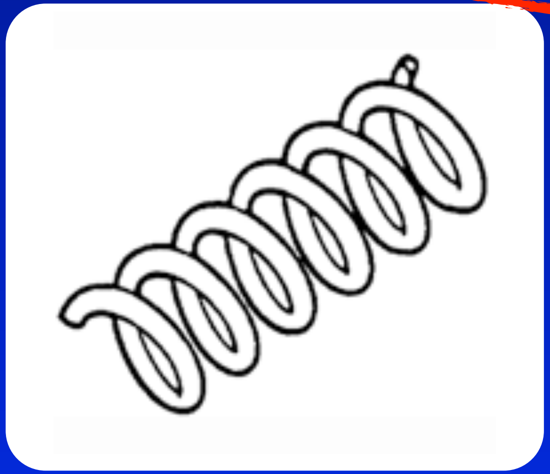

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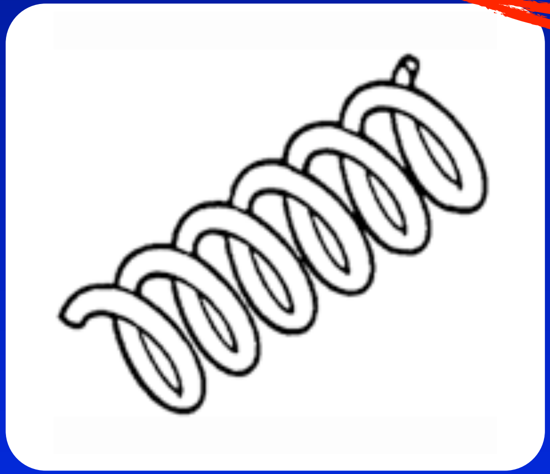

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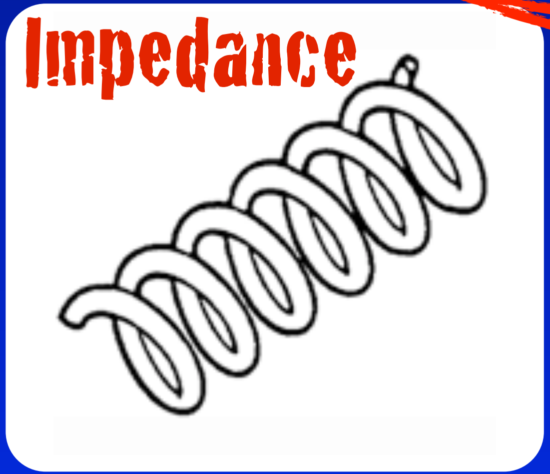

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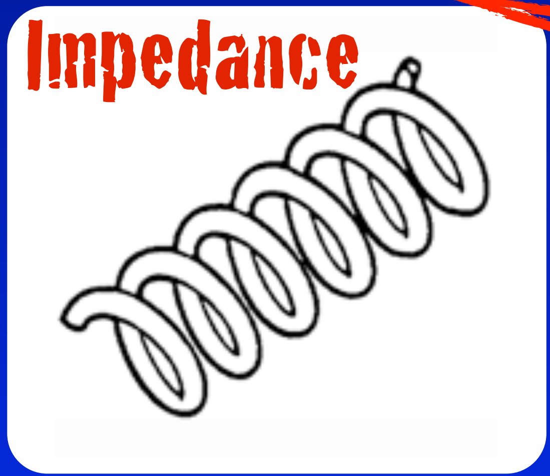

$$\dot{F} = kv$$

$$F = \int kv dt$$

Admittance: Flow storage

Impedance: Effort storage

Linear Impedance/Admittance

Linear Impedance/Admittance

Linear Impedance:

Linear Impedance/Admittance

Linear Impedance: $$Z(s) = \frac{F(s)}{v(s)}$$

Linear Impedance/Admittance

Linear Impedance: $$Z(s) = \frac{F(s)}{v(s)}$$

Spring:

Linear Impedance/Admittance

Linear Impedance: $$Z(s) = \frac{F(s)}{v(s)}$$

Spring: $$K\frac{1}{s}$$

Linear Impedance/Admittance

Linear Impedance: $Z(s) = \dfrac{F(s)}{v(s)}$

Spring: $K\dfrac{1}{s}$

Mass:

Linear Impedance/Admittance

Linear Impedance: $$Z(s) = \frac{F(s)}{v(s)}$$

Spring: $$K\frac{1}{s}$$

Mass: $$Ms$$

Linear Impedance/Admittance

Linear Impedance: $Z(s) = \frac{F(s)}{v(s)}$

Spring: $K\frac{1}{s}$

Mass: Ms

Spring-mass-damper:

Linear Impedance/Admittance

Linear Impedance: $Z(s) = \dfrac{F(s)}{v(s)}$

Spring: $K\dfrac{1}{s}$

Mass: Ms

Spring-mass-damper: $Ms + D + \dfrac{1}{s}K$

Linear Impedance/Admittance

Linear Impedance: $$Z(s) = \frac{F(s)}{v(s)}$$

Spring: $$K\frac{1}{s}$$

Mass: $$Ms$$

Spring-mass-damper: $$Ms + D + \frac{1}{s}K$$

Linear Admittance:

Linear Impedance/Admittance

Linear Impedance: $Z(s) = \frac{F(s)}{v(s)}$

Spring: $K\frac{1}{s}$

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Spring-mass-damper: $Ms + D + \frac{1}{s}K$

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Linear Impedance/Admittance

Linear Impedance: $Z(s) = \frac{F(s)}{v(s)}$

Spring: $K\frac{1}{s}$

Mass: $M s$

Spring-mass-damper: $M s + D + \frac{1}{s} K$

Linear Admittance: $A(s) = \frac{v(s)}{F(s)}$ $\frac{1}{Z(s)}$

Linear Impedance/Admittance

Linear Impedance: $Z(s) = \dfrac{F(s)}{v(s)}$

Spring: $K\dfrac{1}{s}$

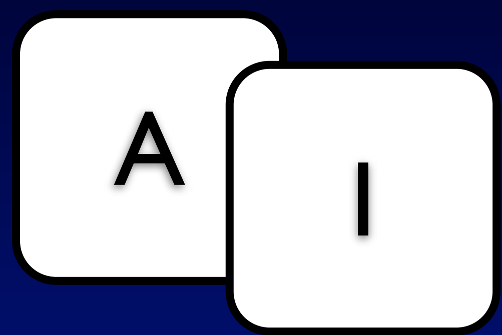
Mass: Ms

Spring-mass-damper:

Linear Admittance:

In a nonlinear system Admittance is NOT inverse of Impedance

Physically possible connections



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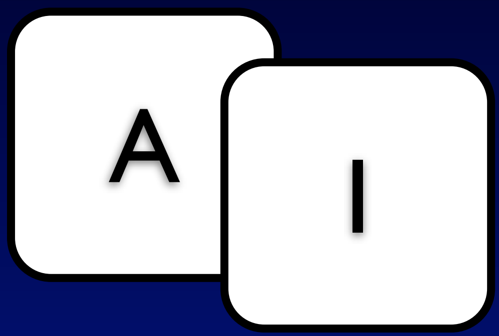

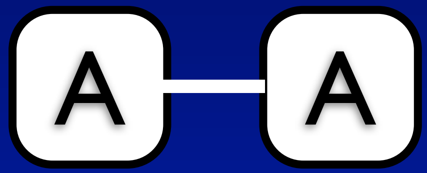

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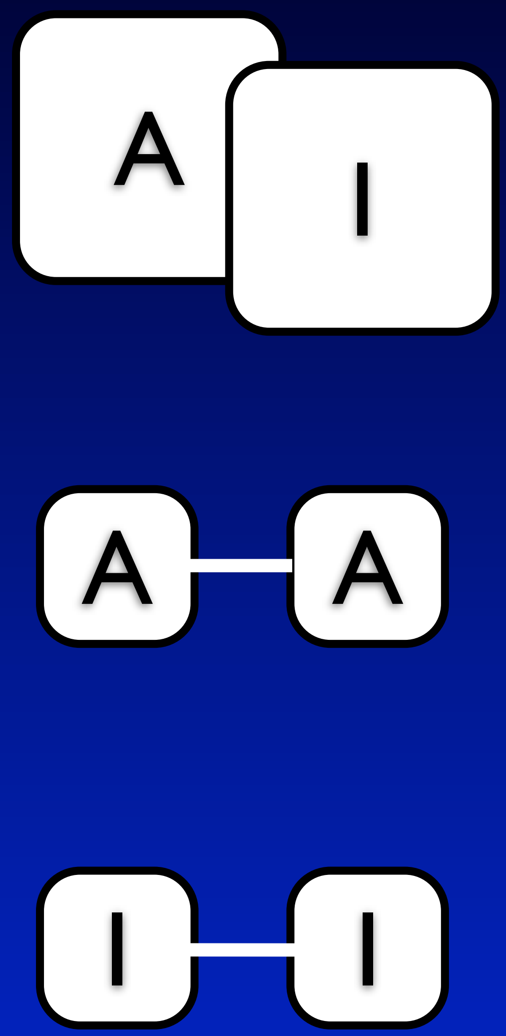

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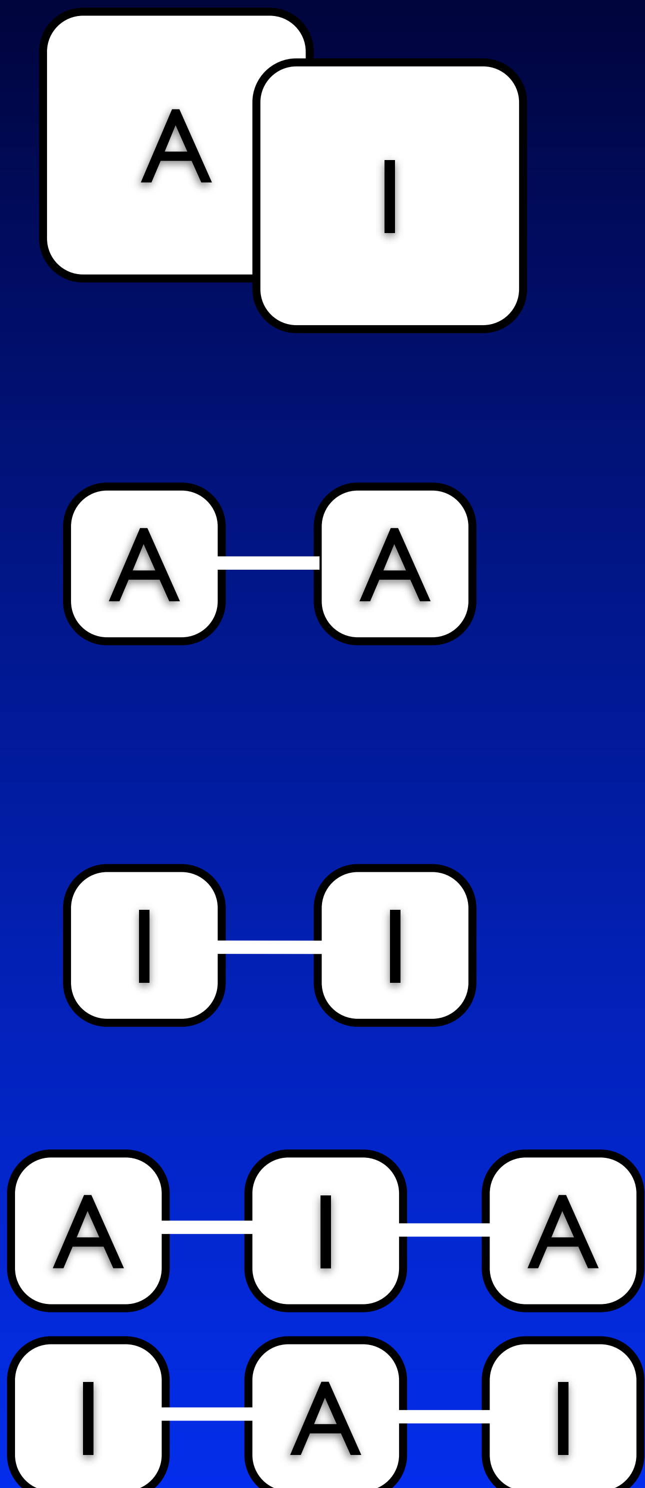

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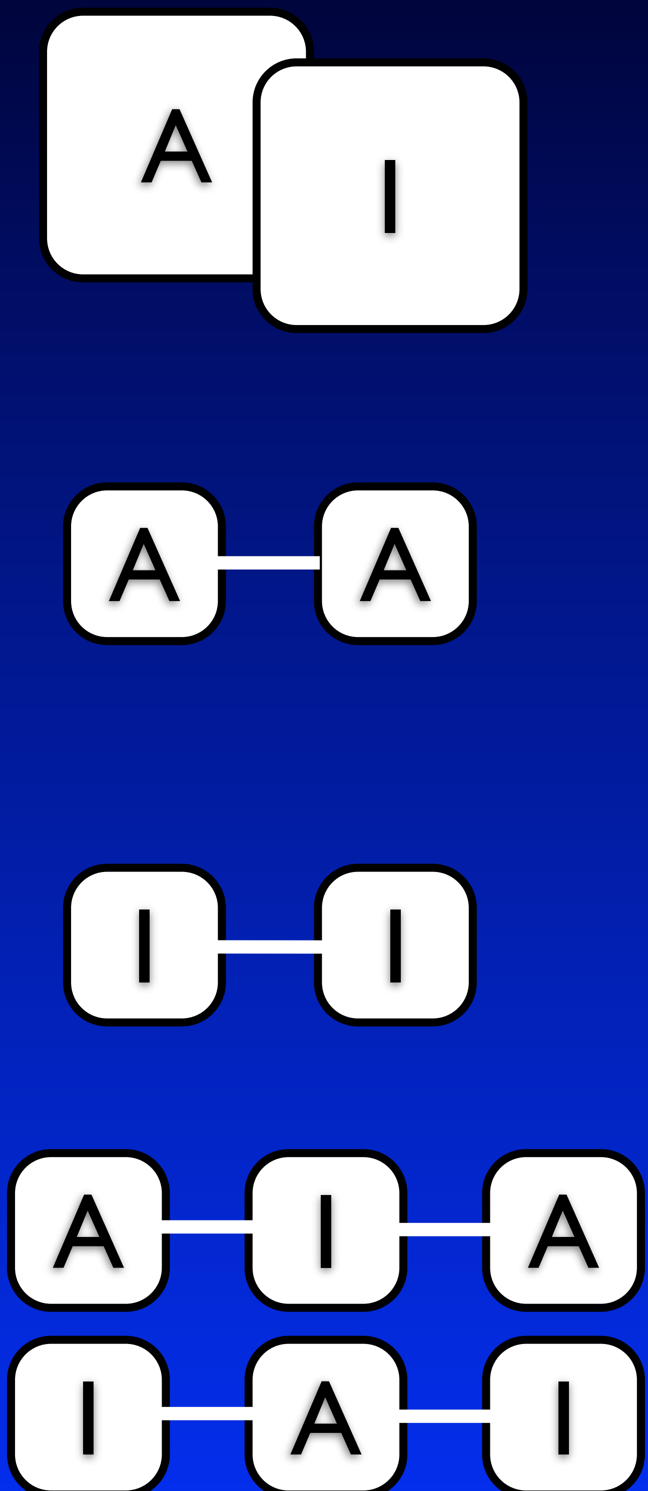
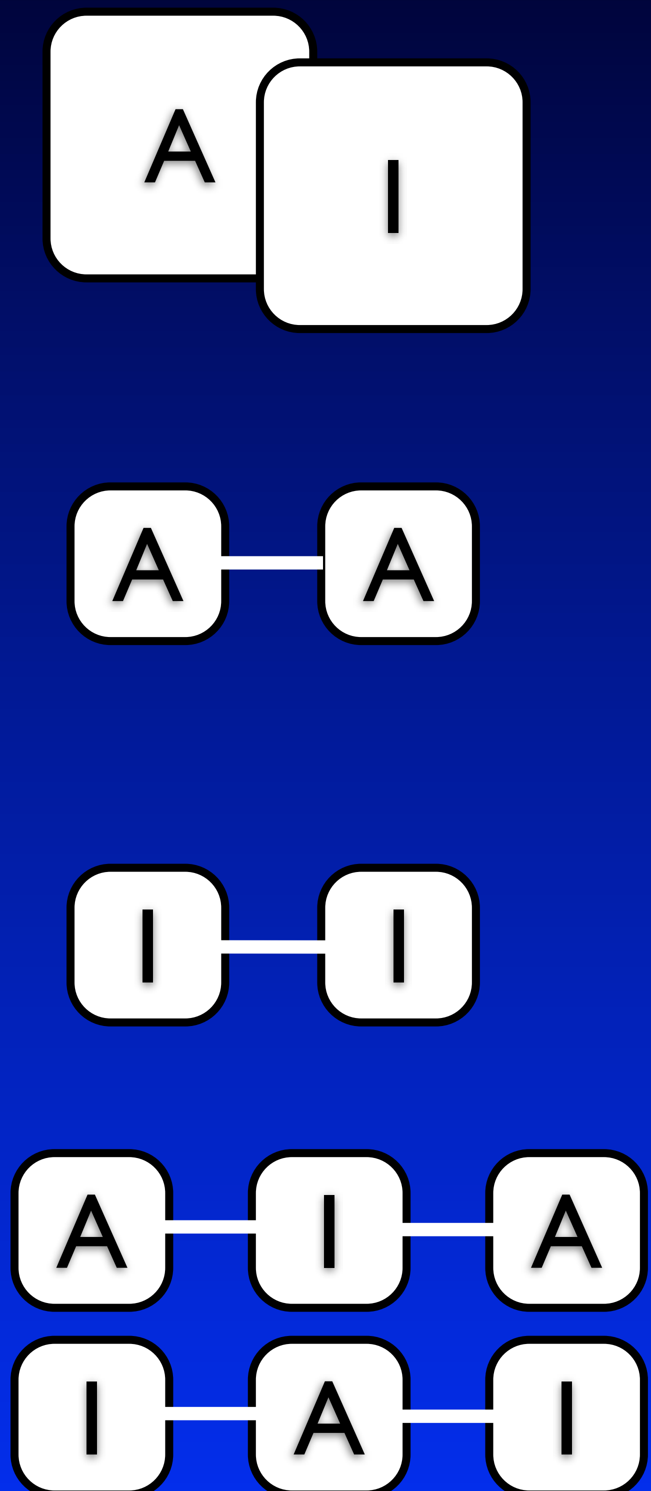


Input/Output ⇔ Causality

Physically possible connections



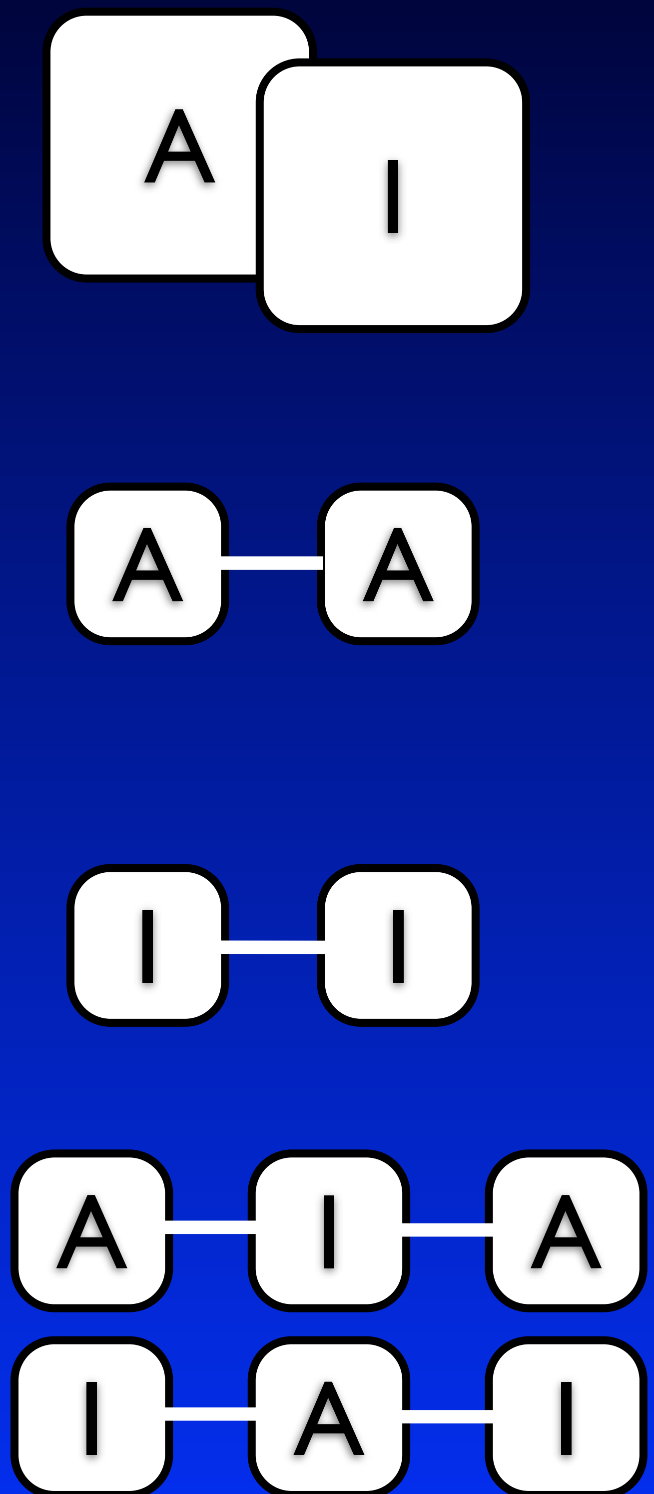
Input/Output ⇔ Causality

Causality

Several important constraints on the behavior of physical systems can be identified. Along each degree of freedom, instantaneous power flow between two or more physical systems (e.g., a physical system and its environment) is always definable as the product of two conjugate variables, an effort (e.g., a force, a voltage) and a flow (e.g., a velocity, a current) [20]. An obvious but important physical constraint is that no one system may determine both variables. Along any degree of freedom a manipulator may impress a force on its environment or impose a displacement or velocity on it, but not both.

[Hogan 85]

Physically possible connections



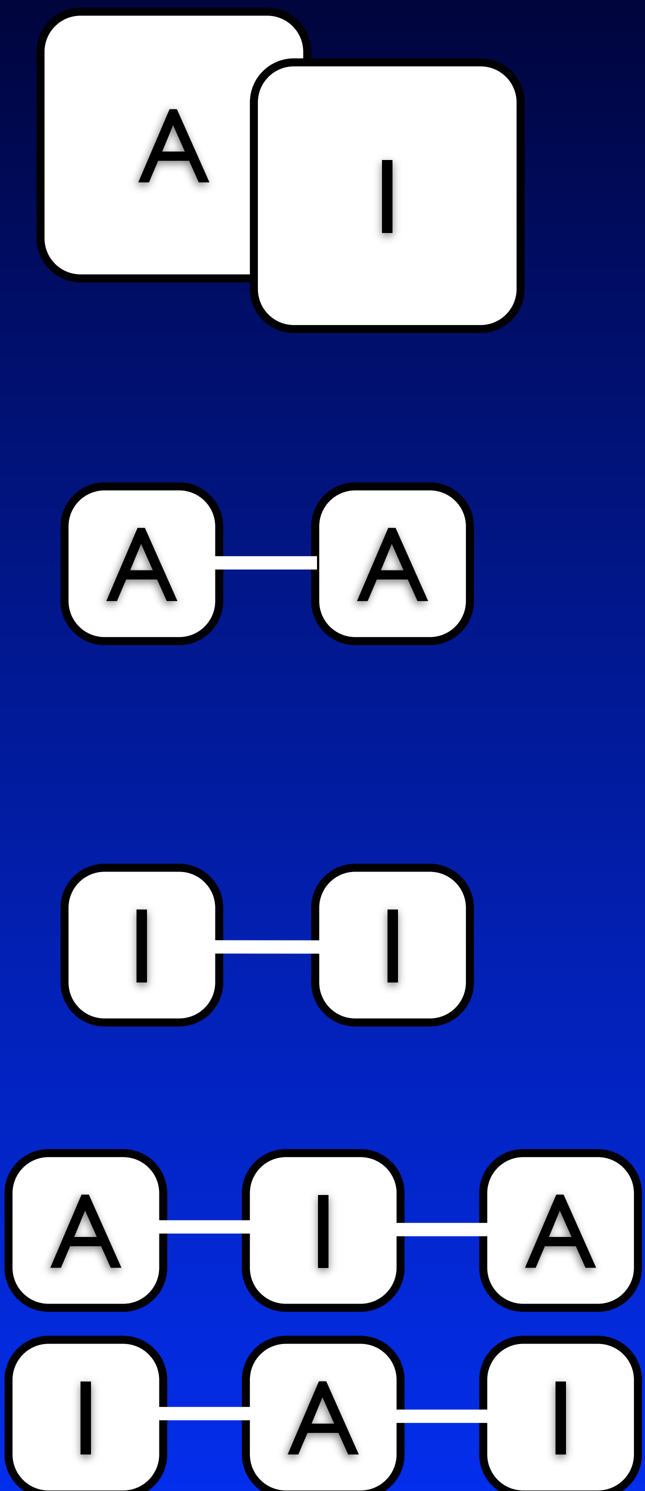
Input/Output ⇔ Causality

The most important consequence of dynamic interaction between two physical systems is that one must physically complement the other: Along any degree of freedom, if one is an impedance, the other must be an admittance and vice versa. Now, for almost all manipulatory tasks the environment at least contains inertias and/or kinematic constraints, physical systems which accept force inputs and which determine their own motion in response. However, as described above, while a constrained inertial object can always be pushed on, it cannot always be moved; These systems are properly described as admittances. Seen from the manipulator, the world is an admittance.

When a manipulator is mechanically coupled to its environment, to ensure physical compatibility with the environmental admittance, the manipulator should assume the behavior of an impedance. Because the mechanical interaction with the environment will change with different tasks, or even in the course of a single task—the manipulator may be coupled to the environment in one phase and decoupled from it in another—the behavior of the manipulator should be adaptable. Thus the controller should be capable of modulating the impedance of the manipulator as appropriate for a particular phase of a task.

[Hogan 85]

Physically possible connections



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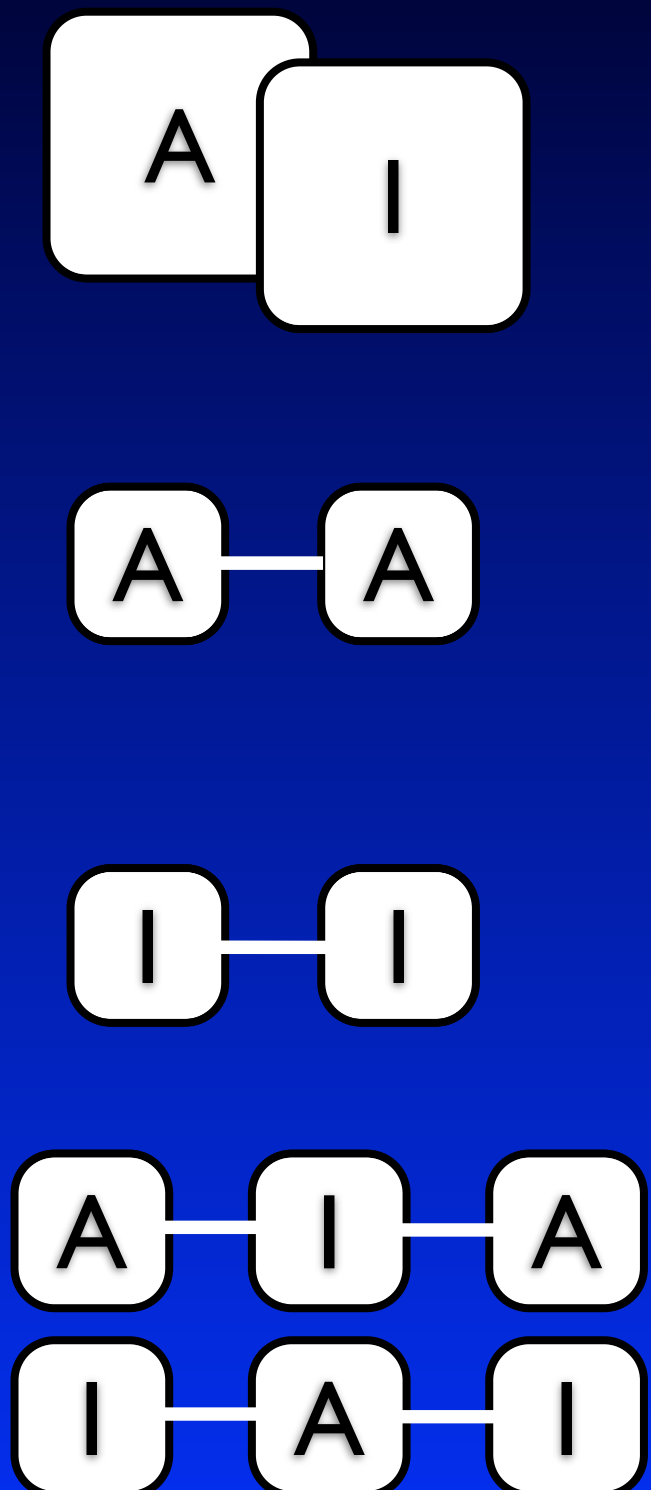

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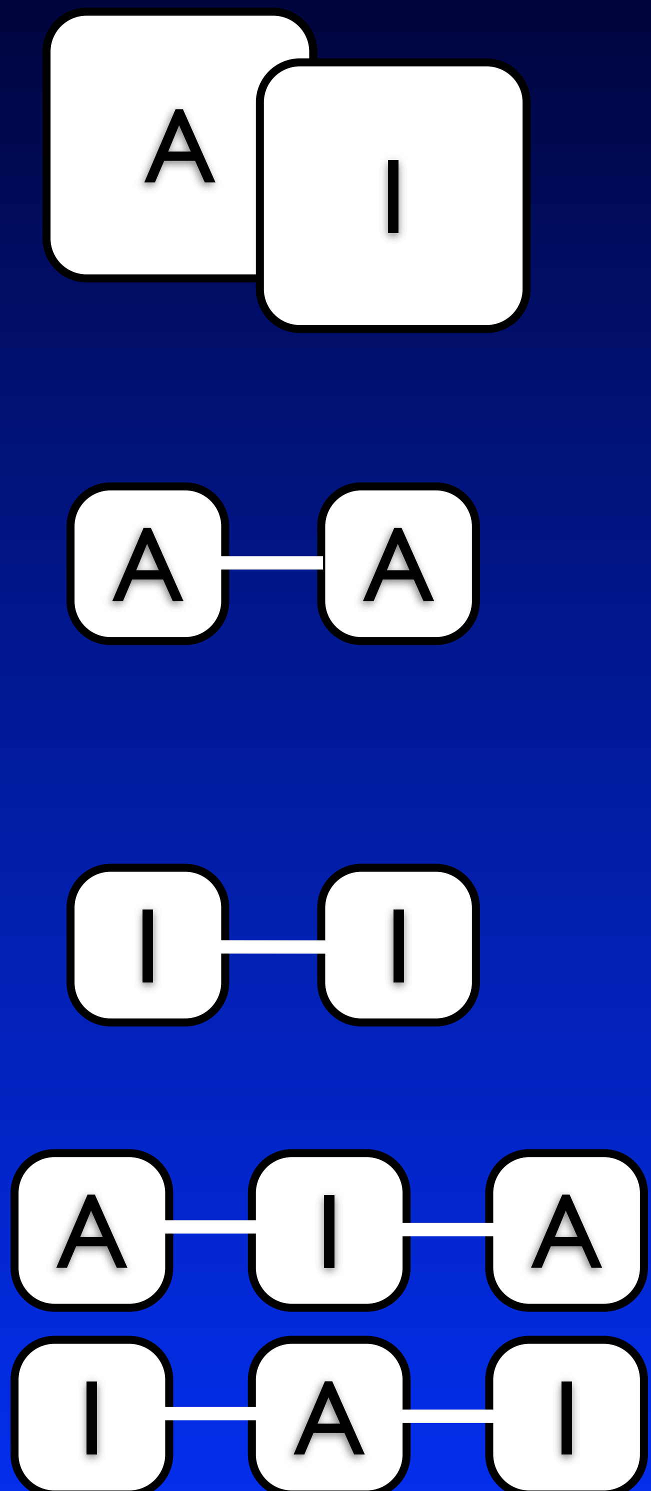

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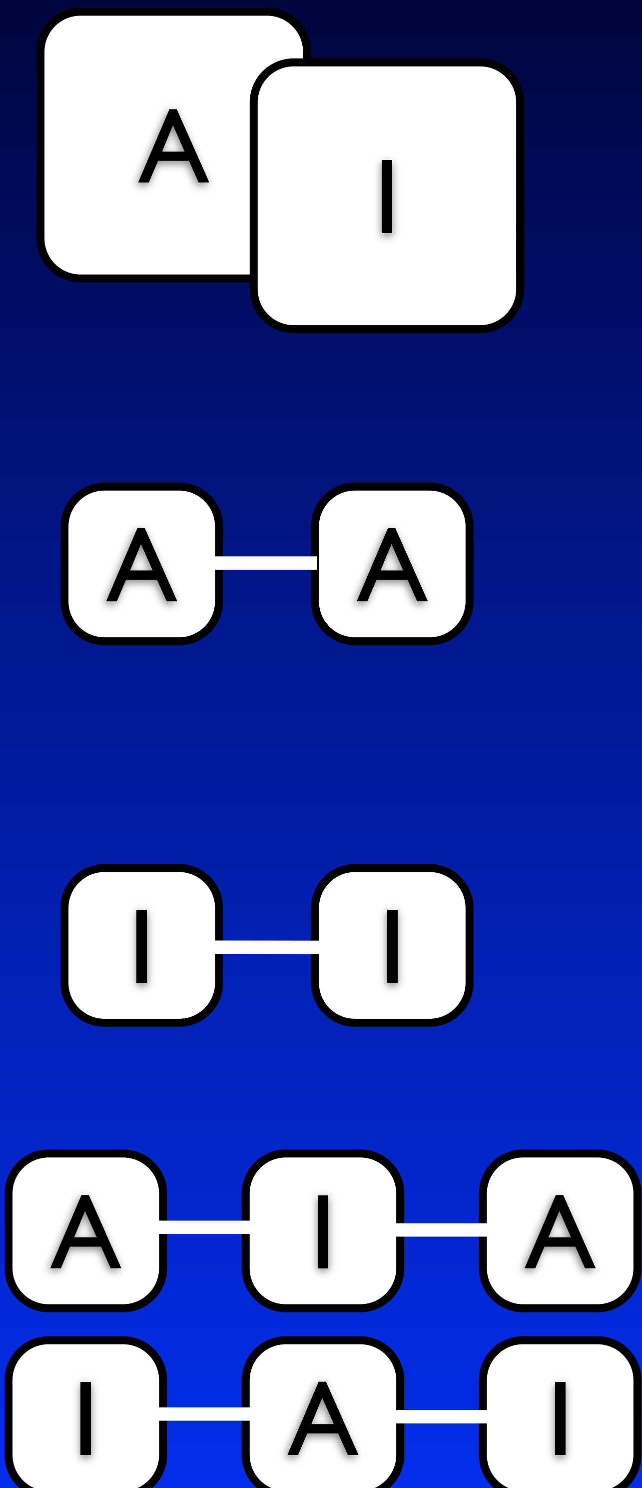

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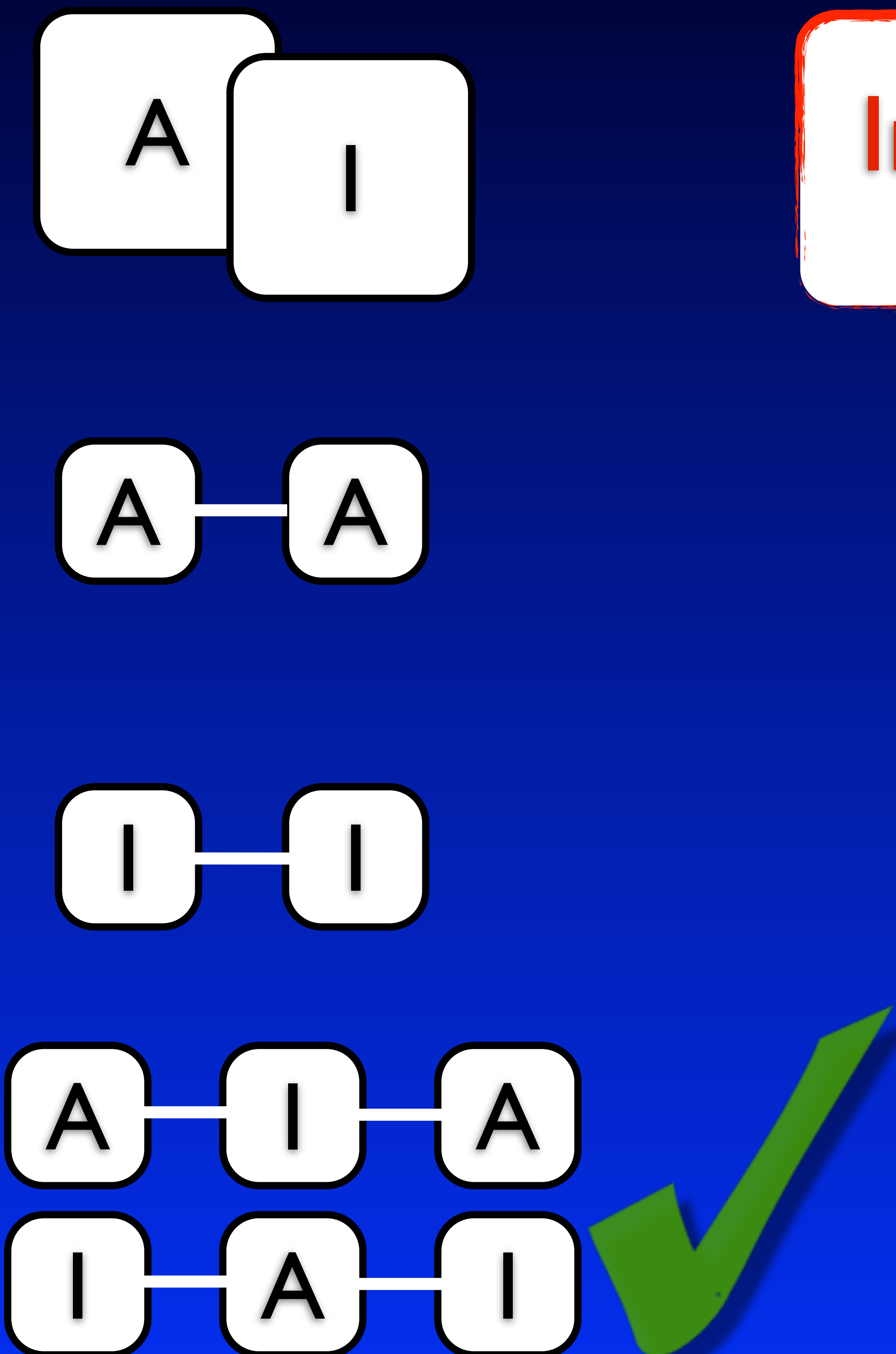

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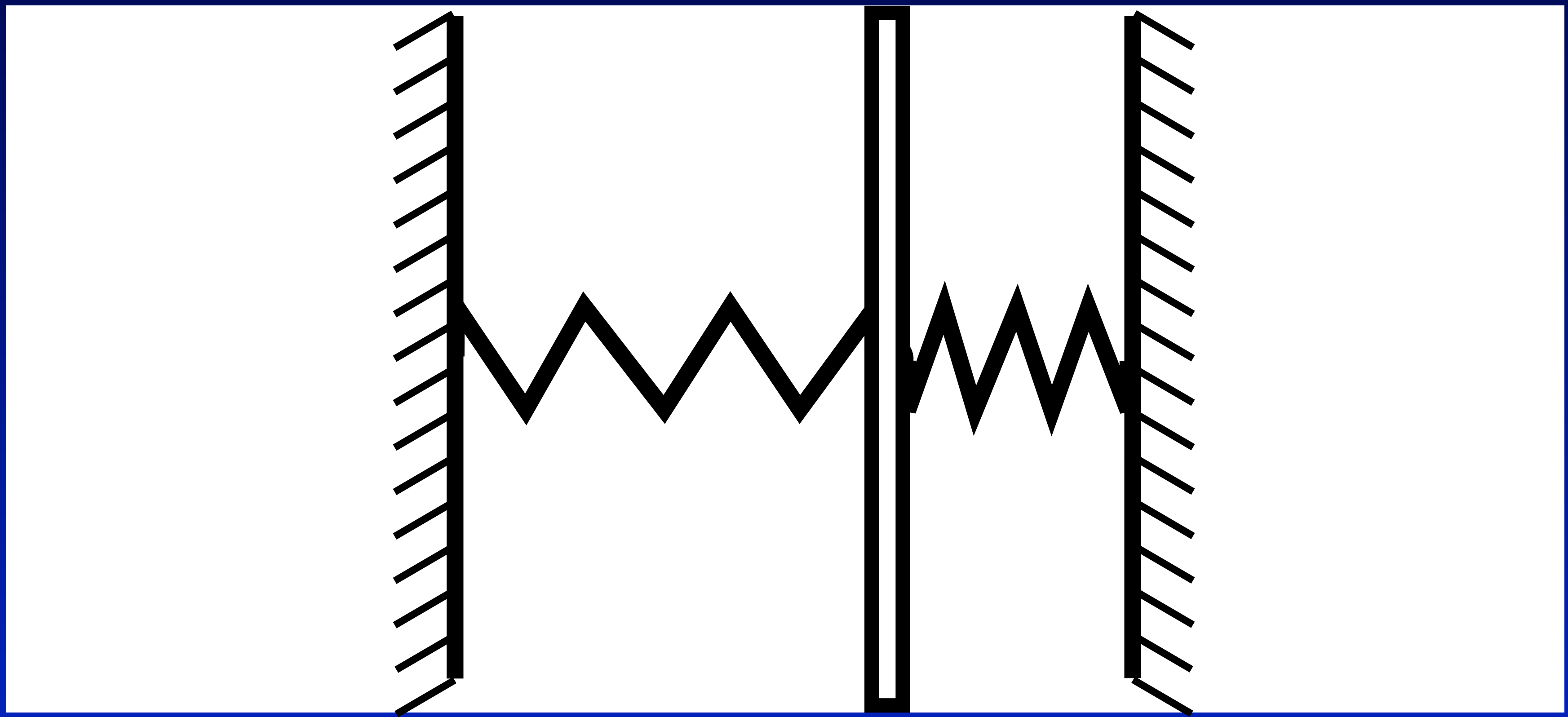
[Hogan 85]

Example: series springs



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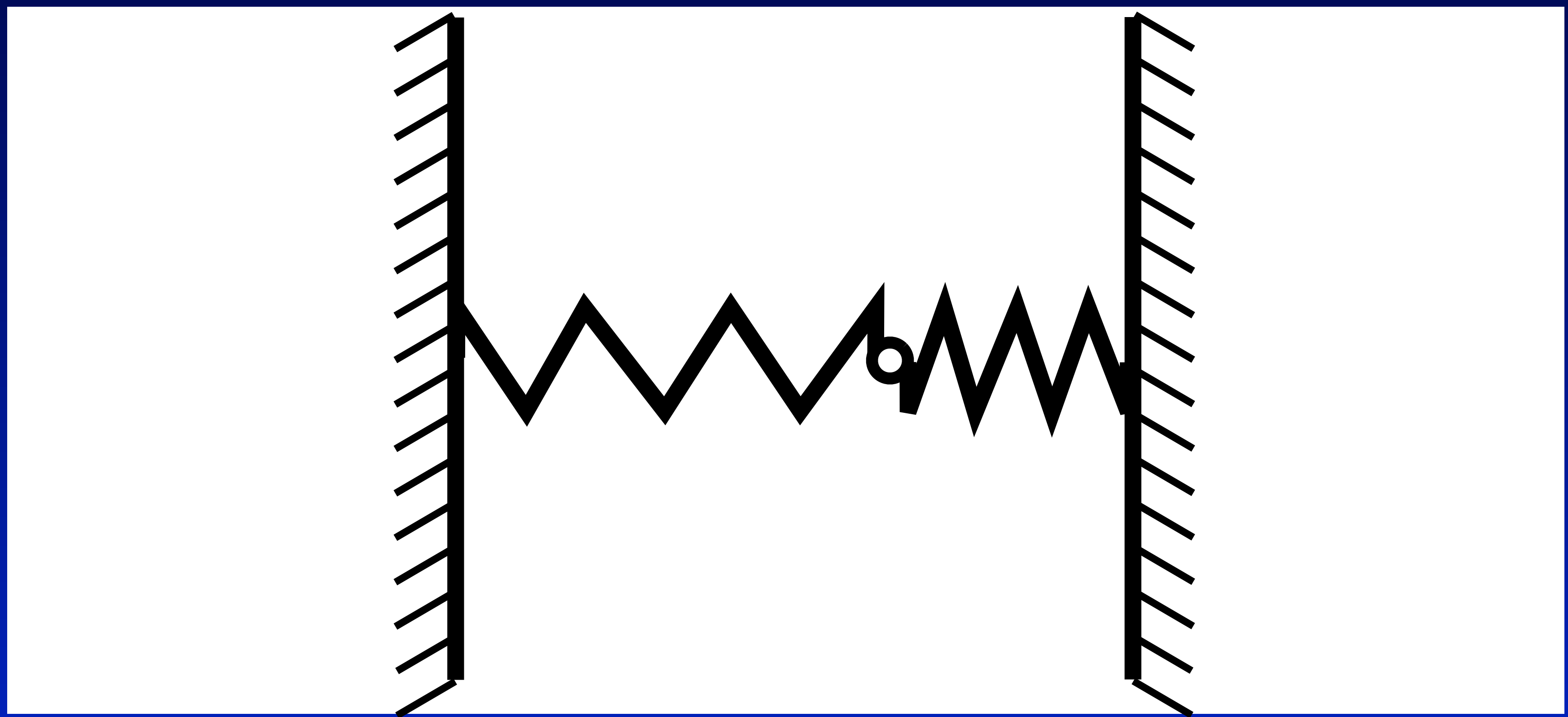

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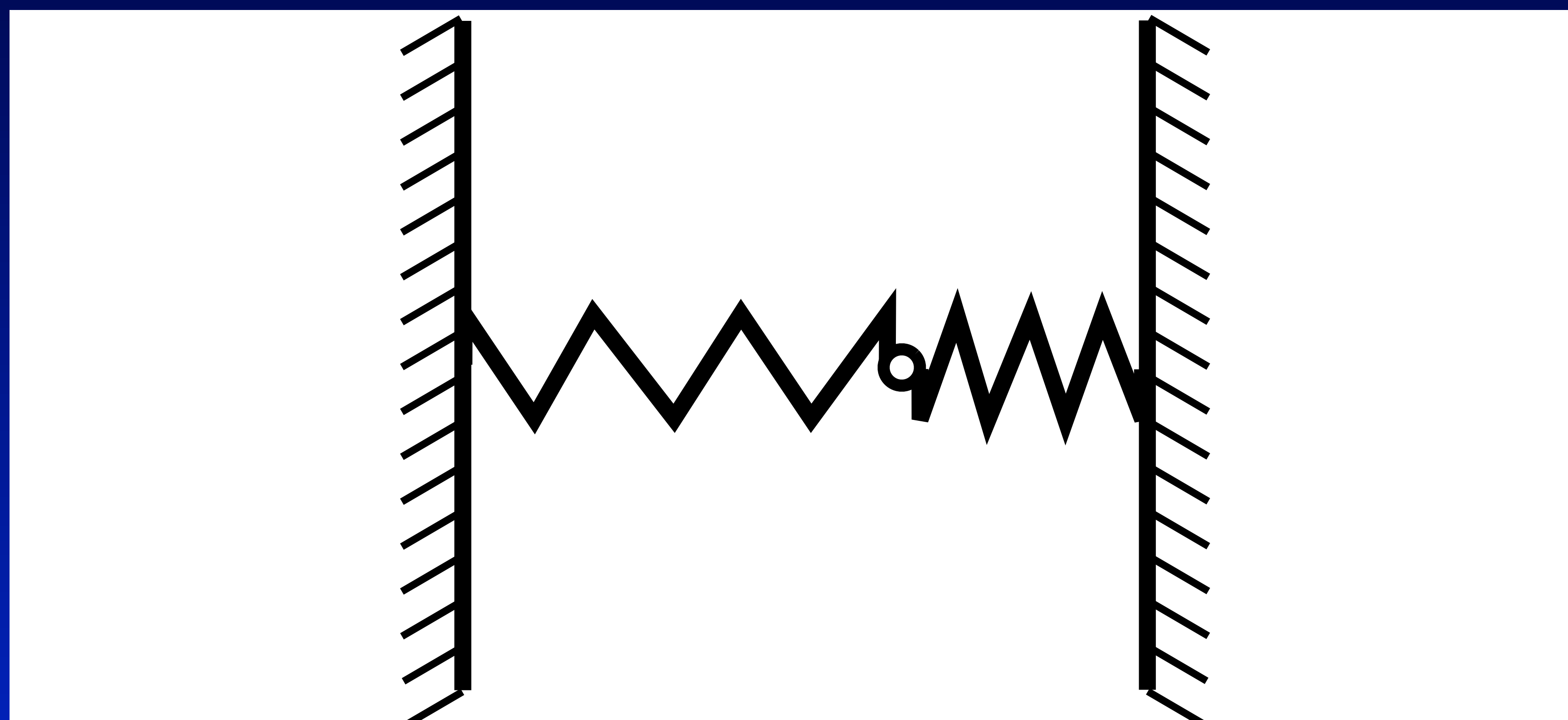
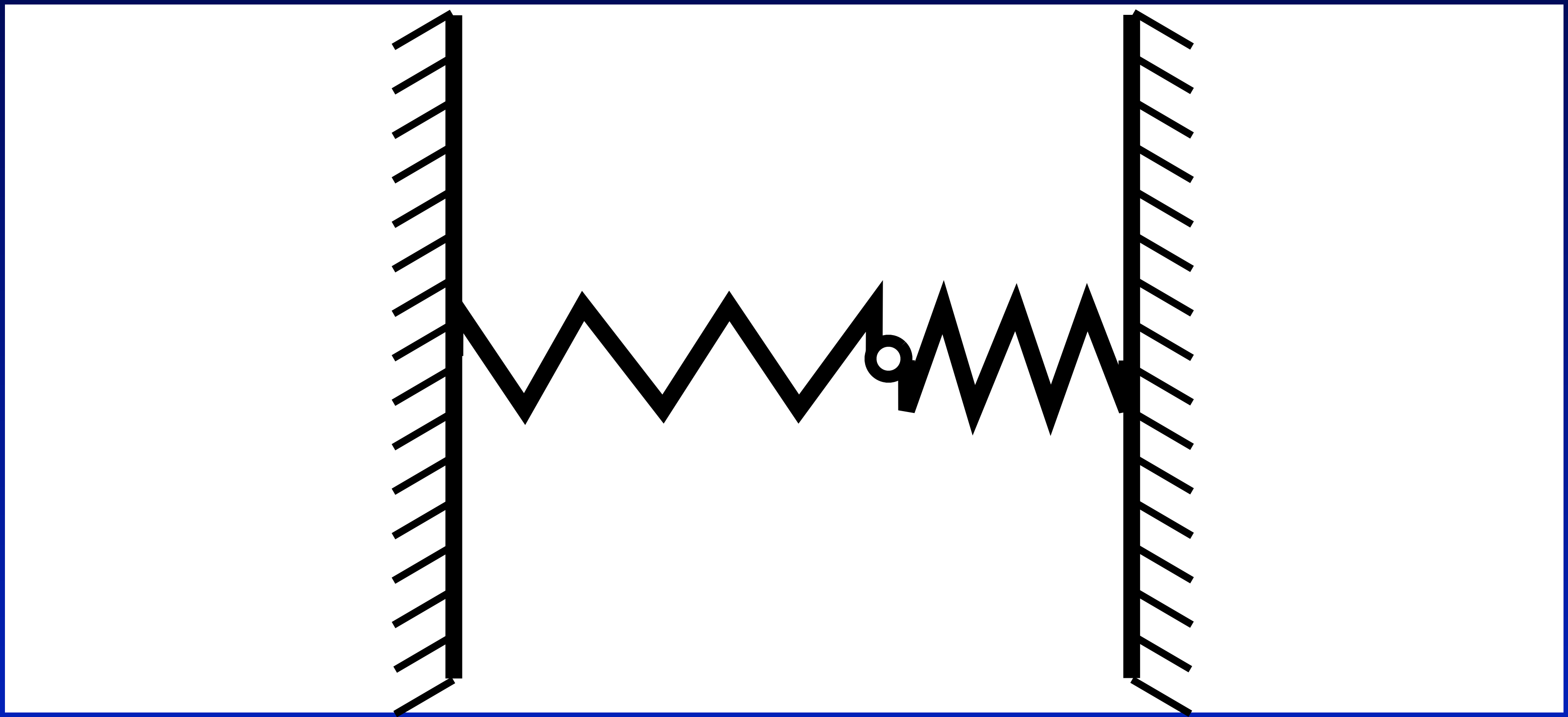


Force balance: $F_{\Sigma} = F_1 + F_2$

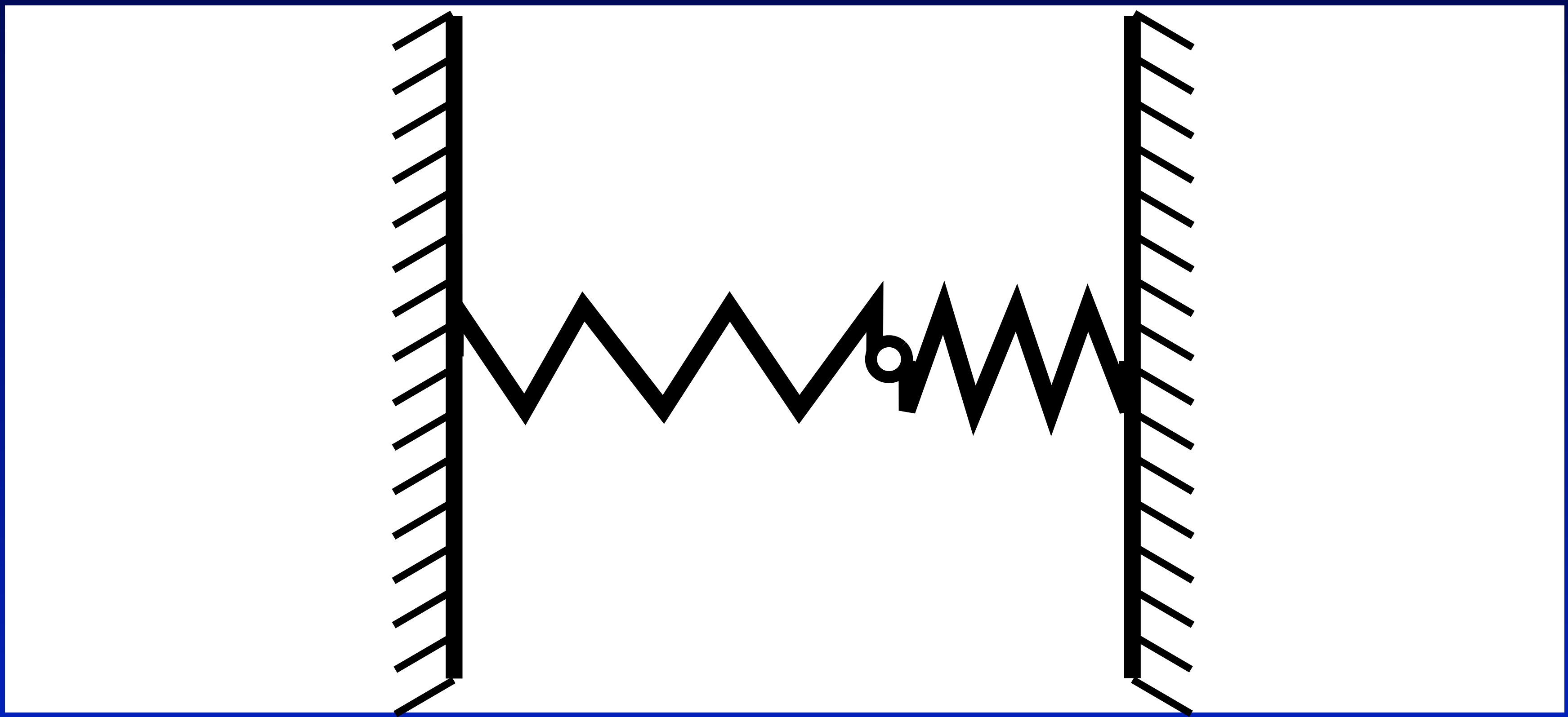
Example: series springs



Force balance: $F_\Sigma = F_1 + F_2$

Acceleration: $\ddot{x} = \dfrac{F_\Sigma}{m}$

Example: series springs

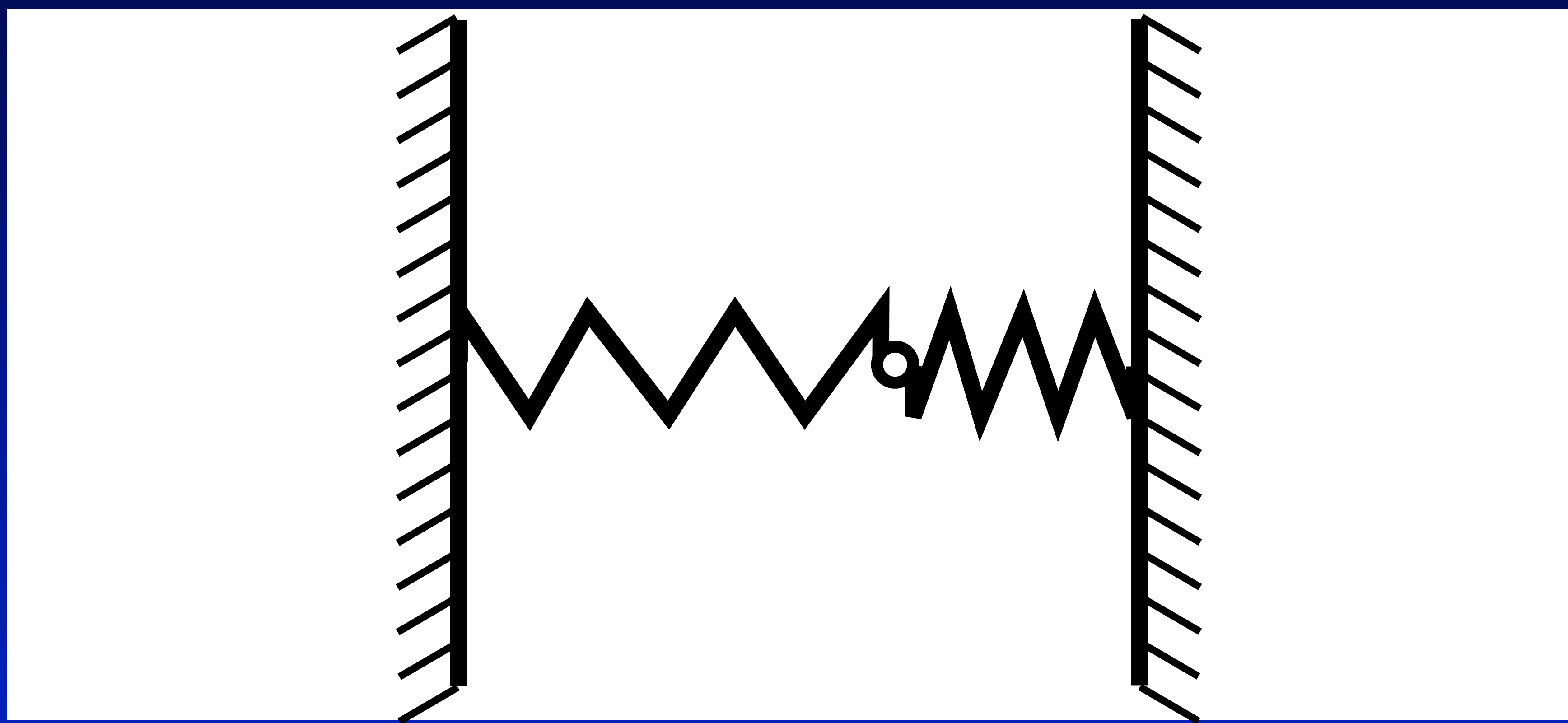


Force balance: $F_\Sigma = F_1 + F_2$

Acceleration: $\ddot{x} = \dfrac{F_\Sigma}{m}$ $\quad m \to 0$

[Ideal spring]

Example: series springs

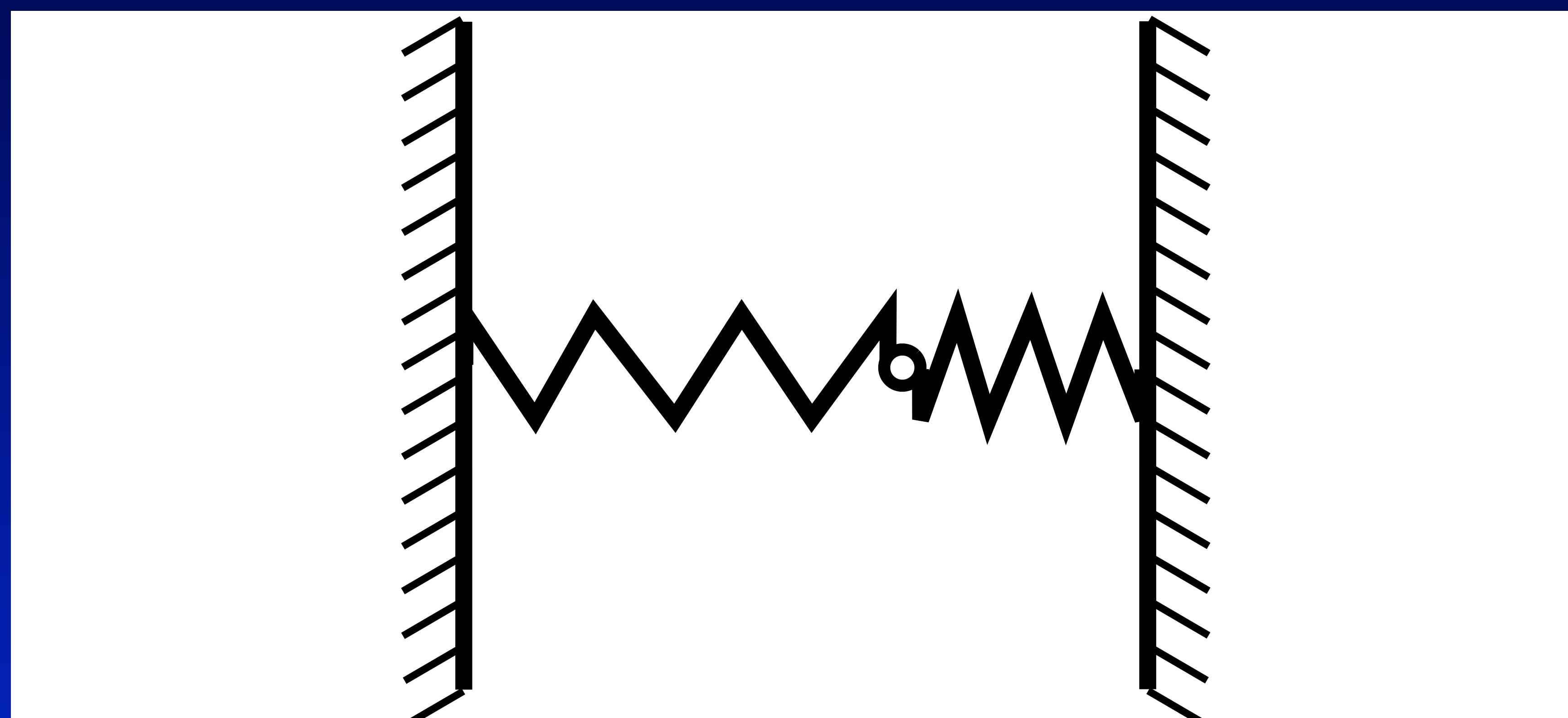


Force balance: $F_\Sigma = F_1 + F_2$

Acceleration: $\ddot{x} = \frac{F_\Sigma}{m}$ $m \rightarrow 0$!!!!

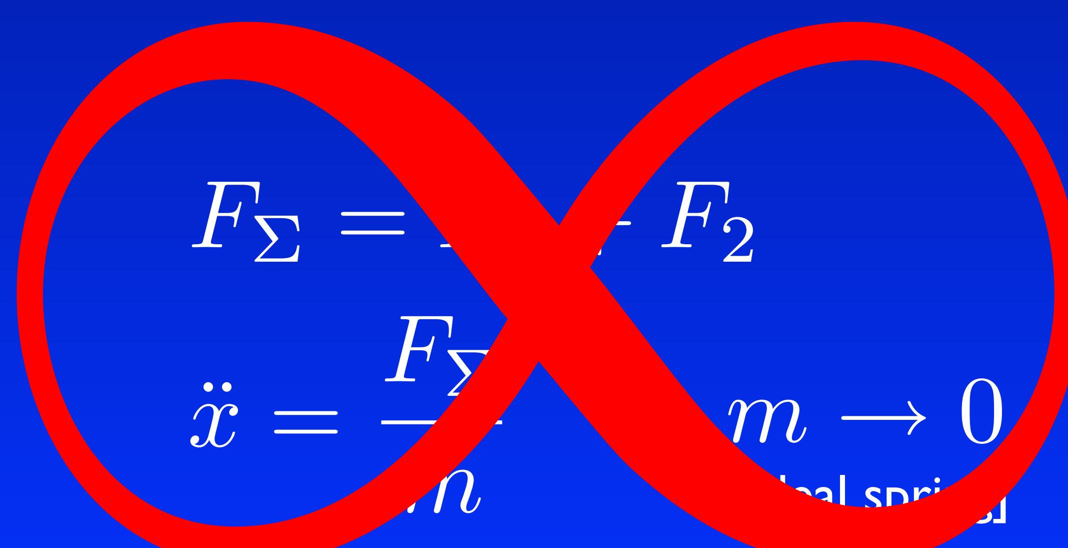
[Ideal spring]

Example: series springs



Force balance: $F_\Sigma = F_1 + F_2$

Acceleration: $\ddot{x} = \frac{F_\Sigma}{m}$ $\quad m \to 0$ [ideal springs] !!!!



"Hogan's rule"

In the most common case in which the environment is an admittance (e.g., a mass, possibly kinematically constrained) that relation should be an impedance, a function, possibly nonlinear, dynamic, or even discontinuous, specifying the force produced in response to a motion imposed by the environment.

N. Hogan: "Impedance Control: An Approach to Manipulation: Part I —Theory", Journal of Dynamic Systems, Measurement, and Control 1985

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"Hogan's rule"

Imposes position!

In the most common case in which the environment is an admittance (e.g., a mass, possibly kinematically constrained) that relation should be an impedance, a function, possibly nonlinear, dynamic, or even discontinuous, specifying the force produced in response to a motion imposed by the environment.

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How can this be achieved? Let’s see...

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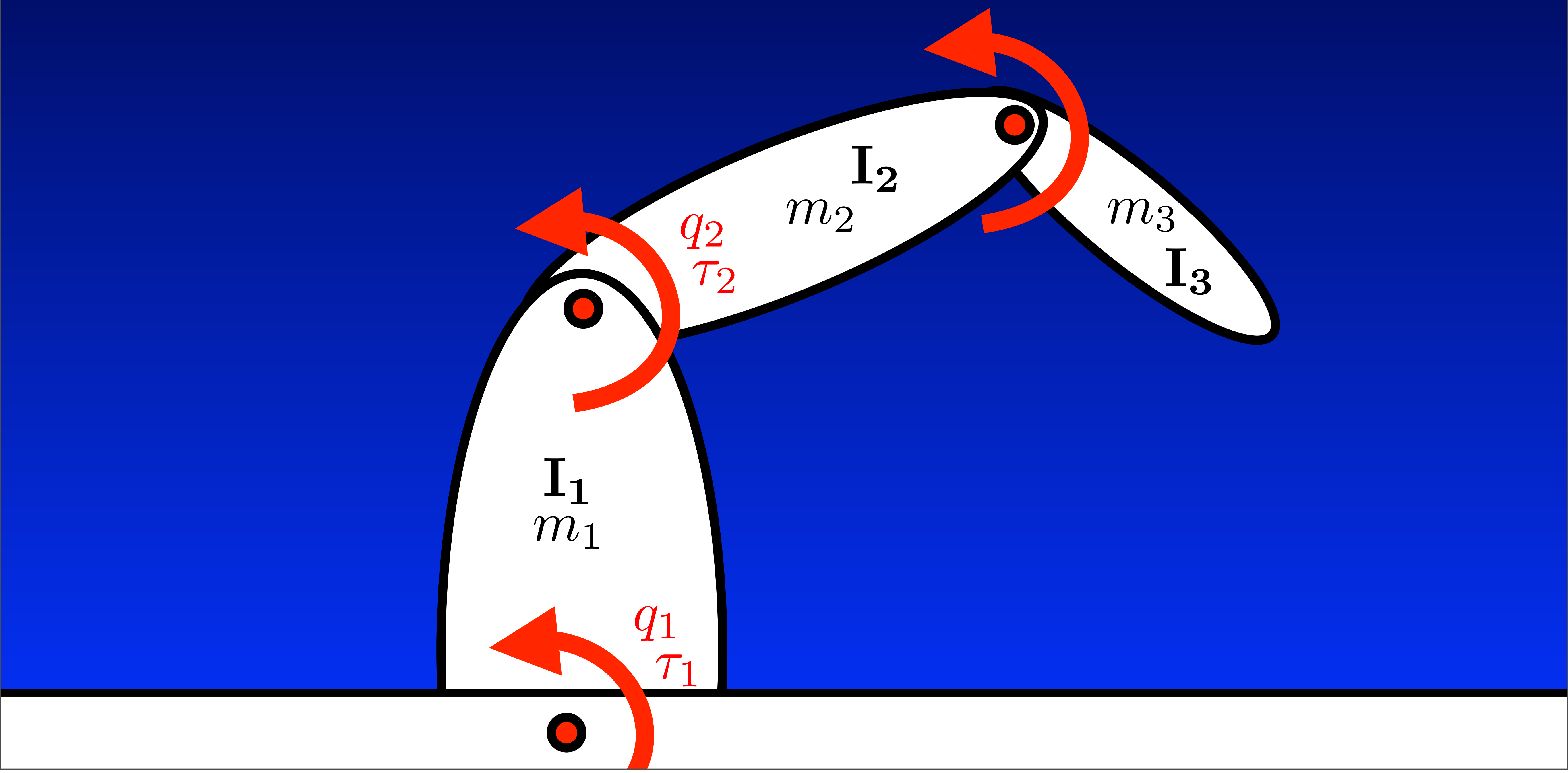
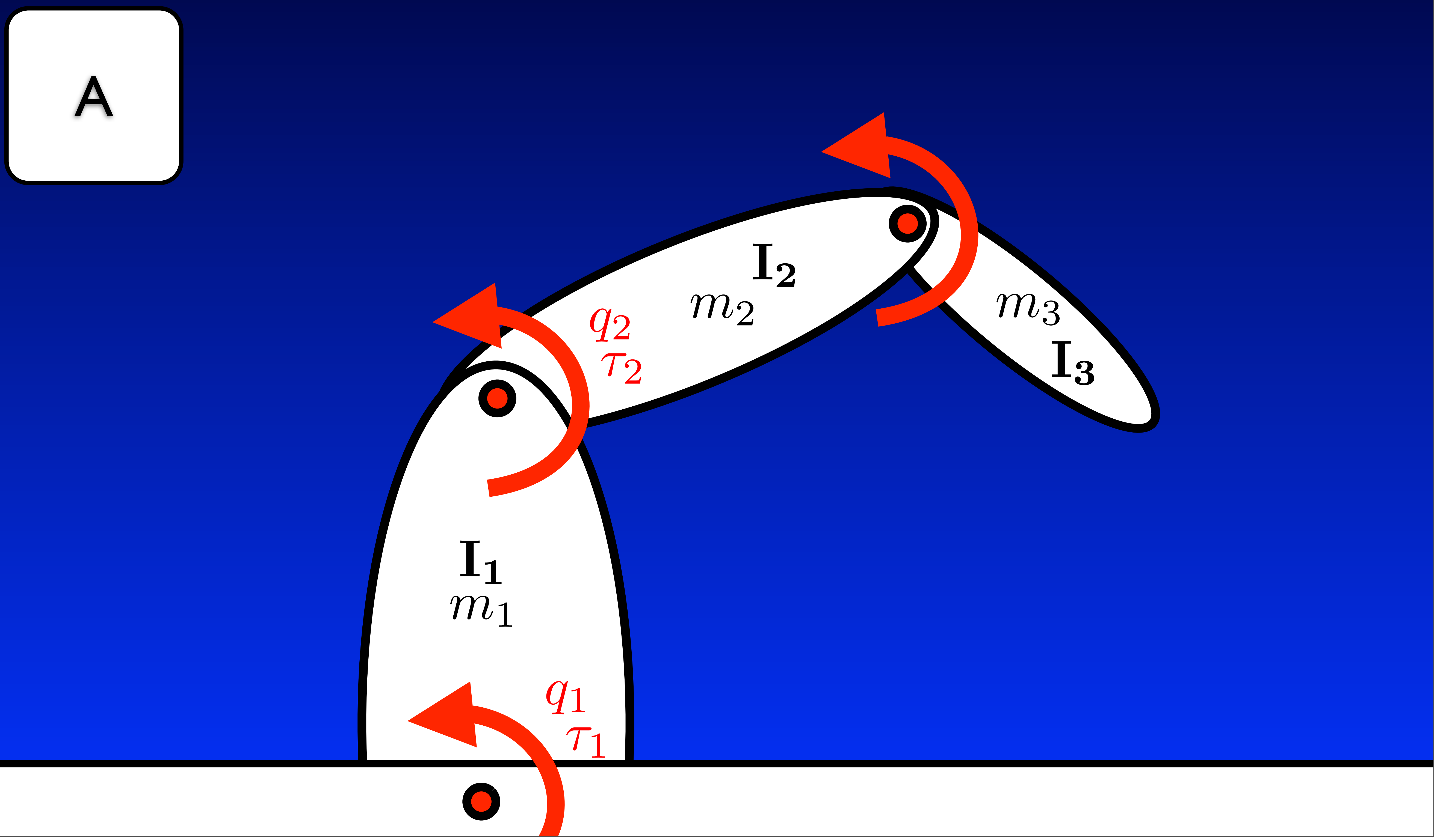
Need torque source!



Need torque source!



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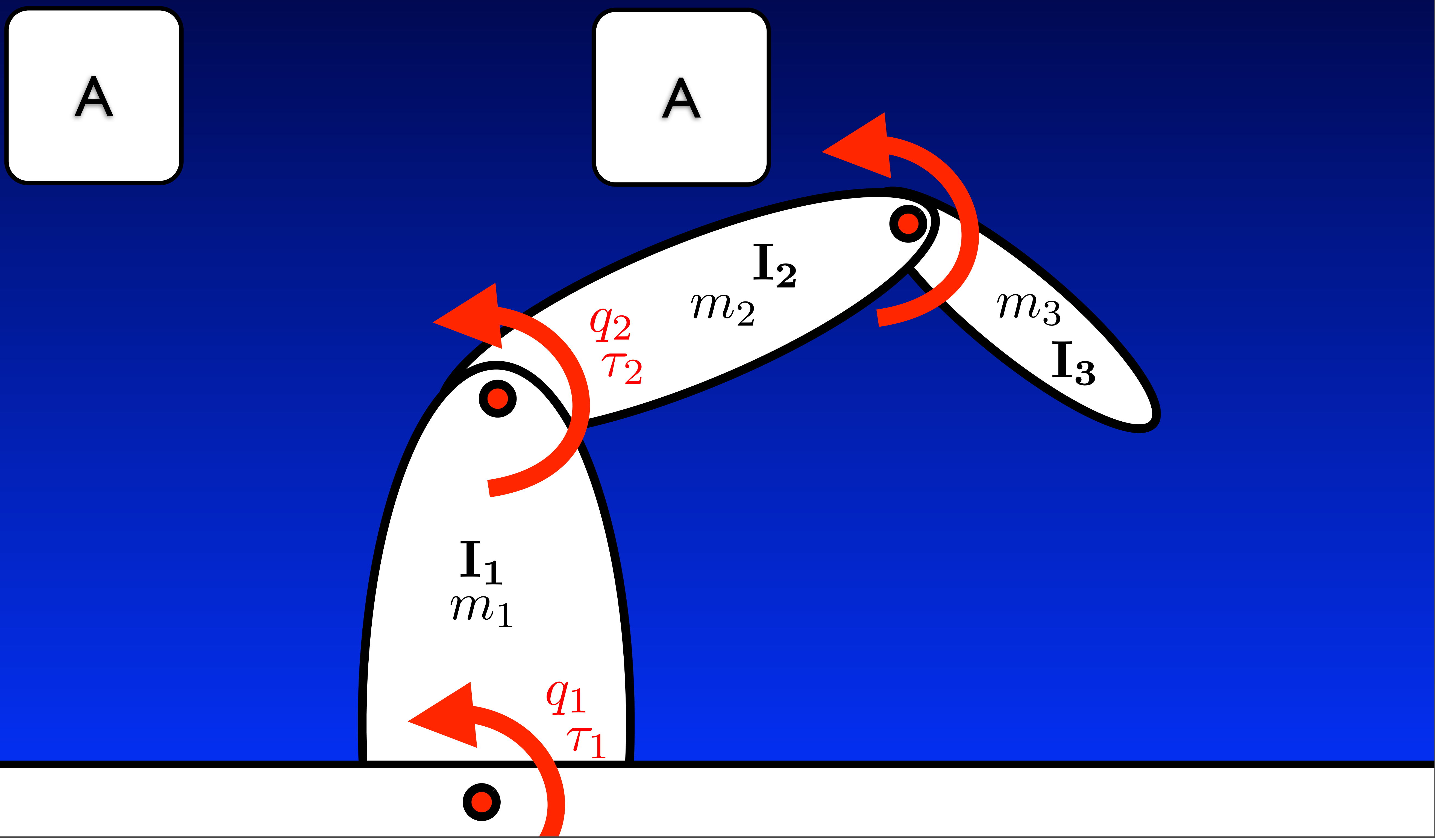

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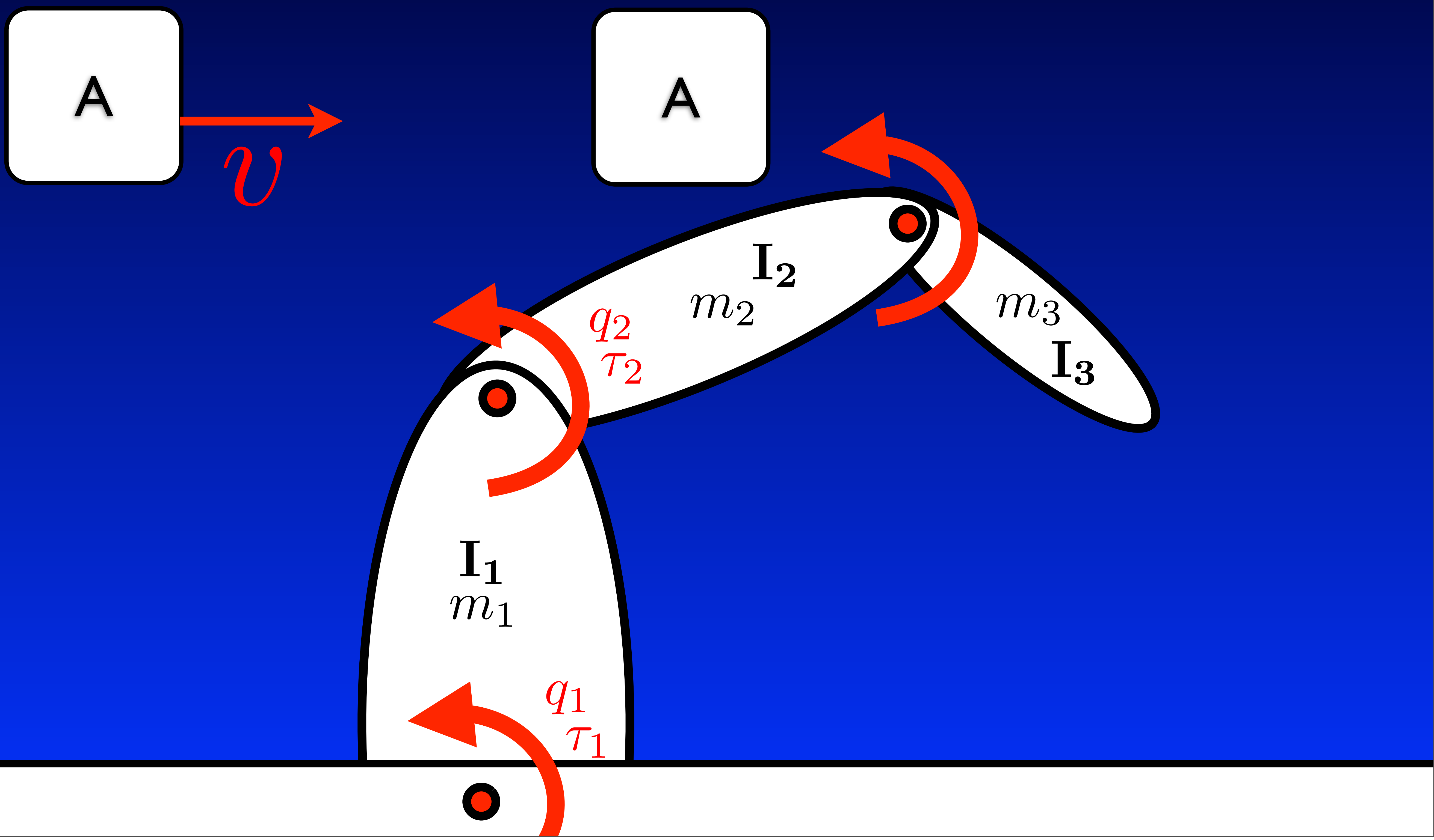

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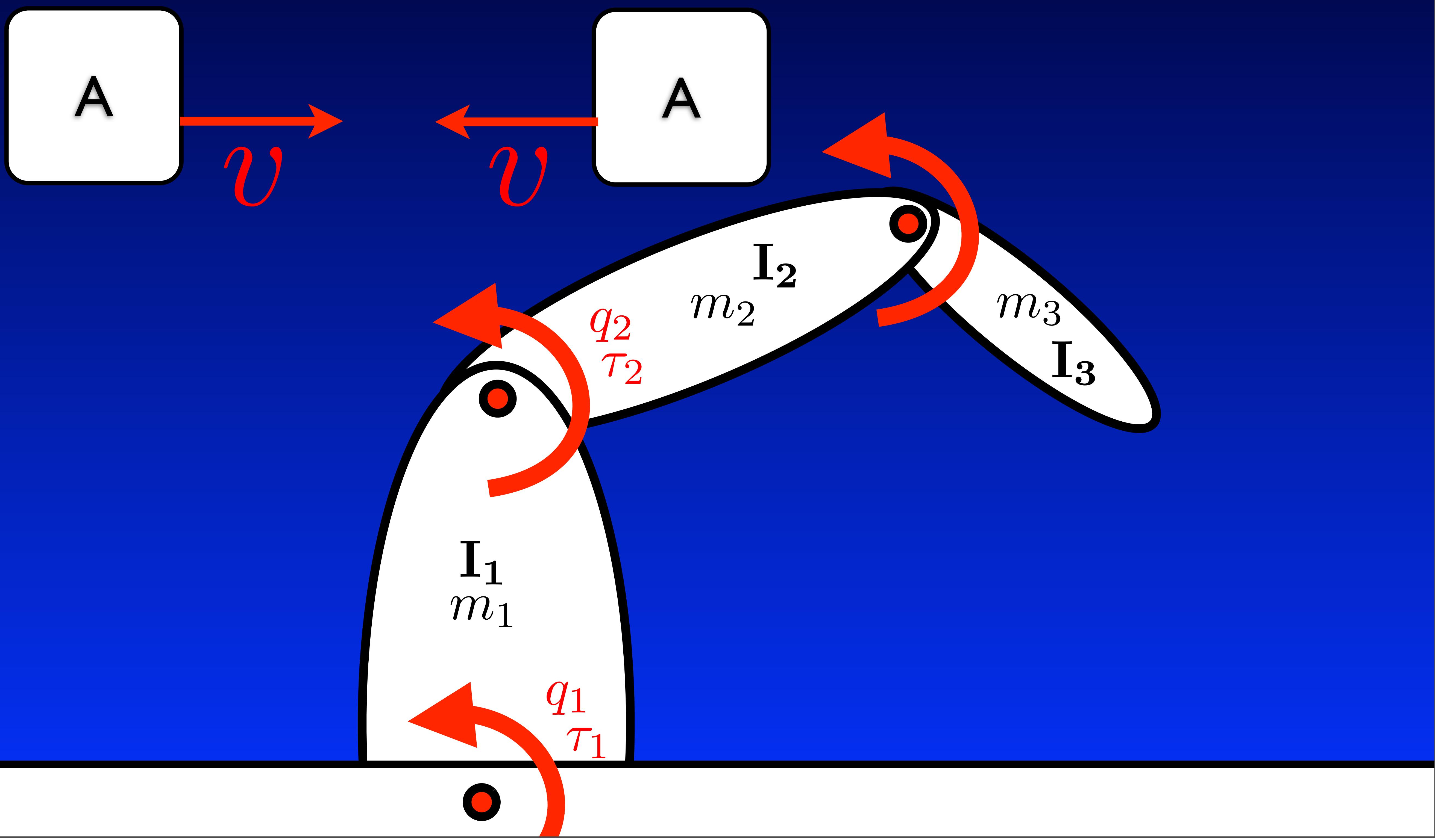

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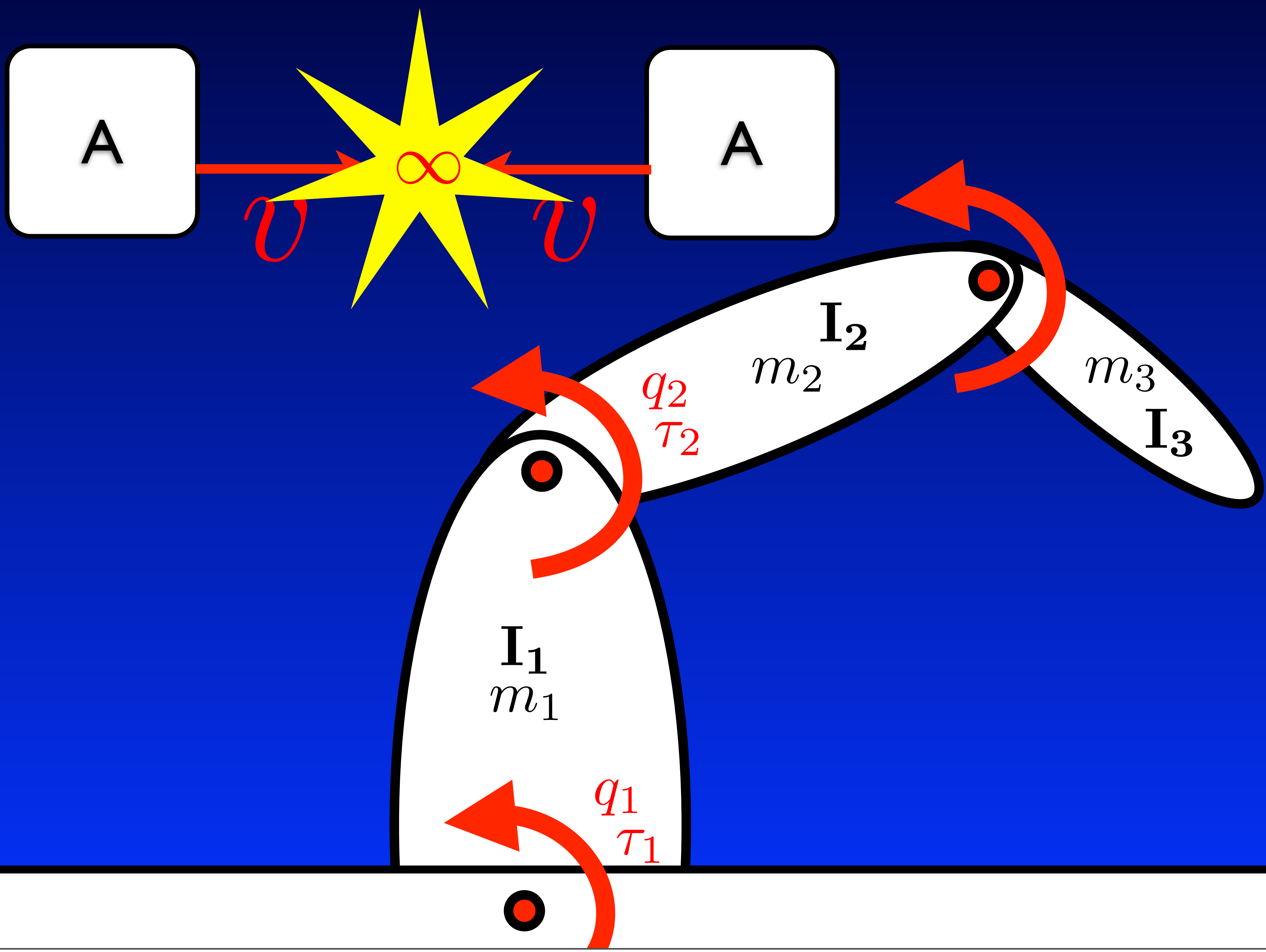

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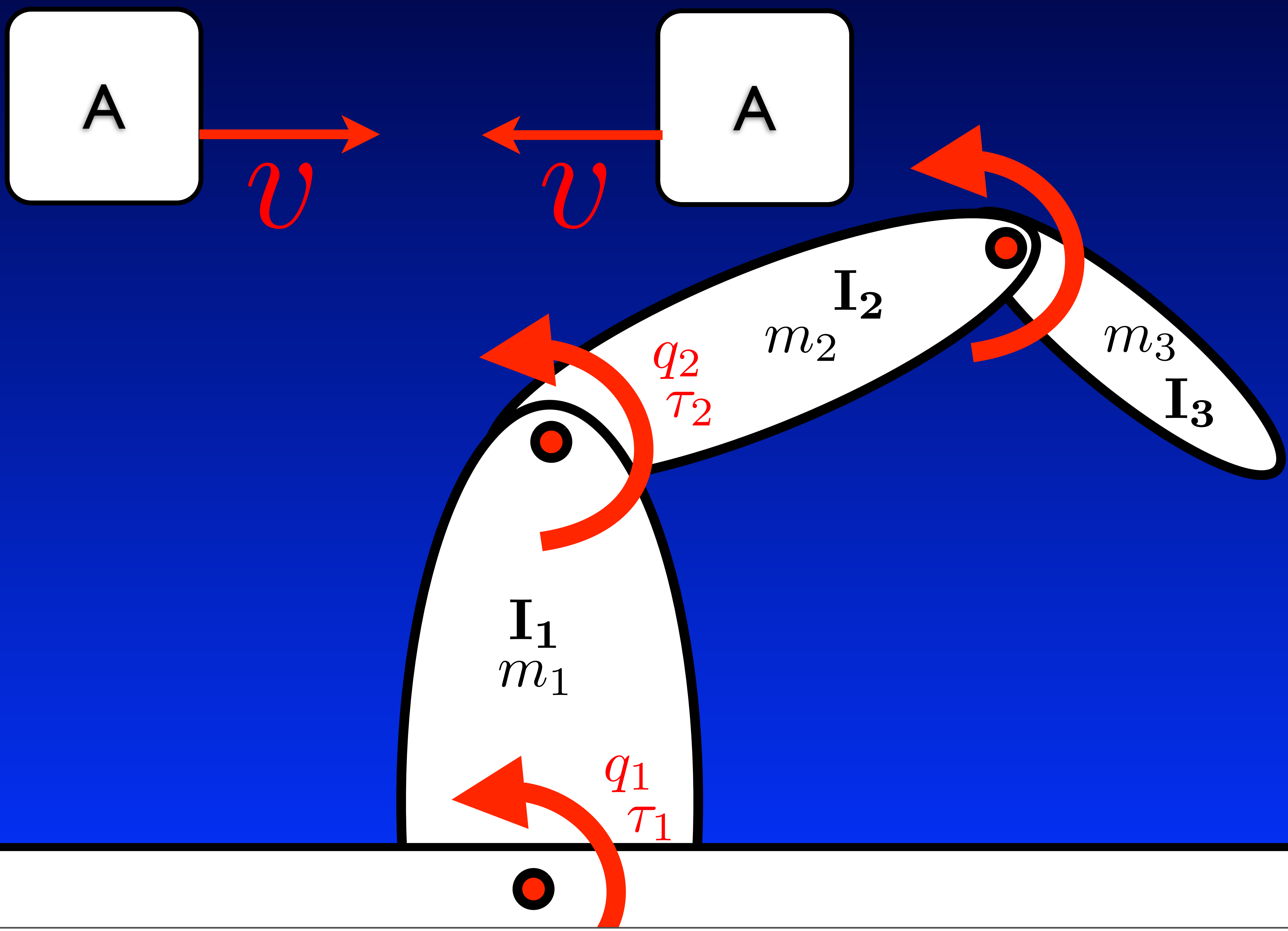

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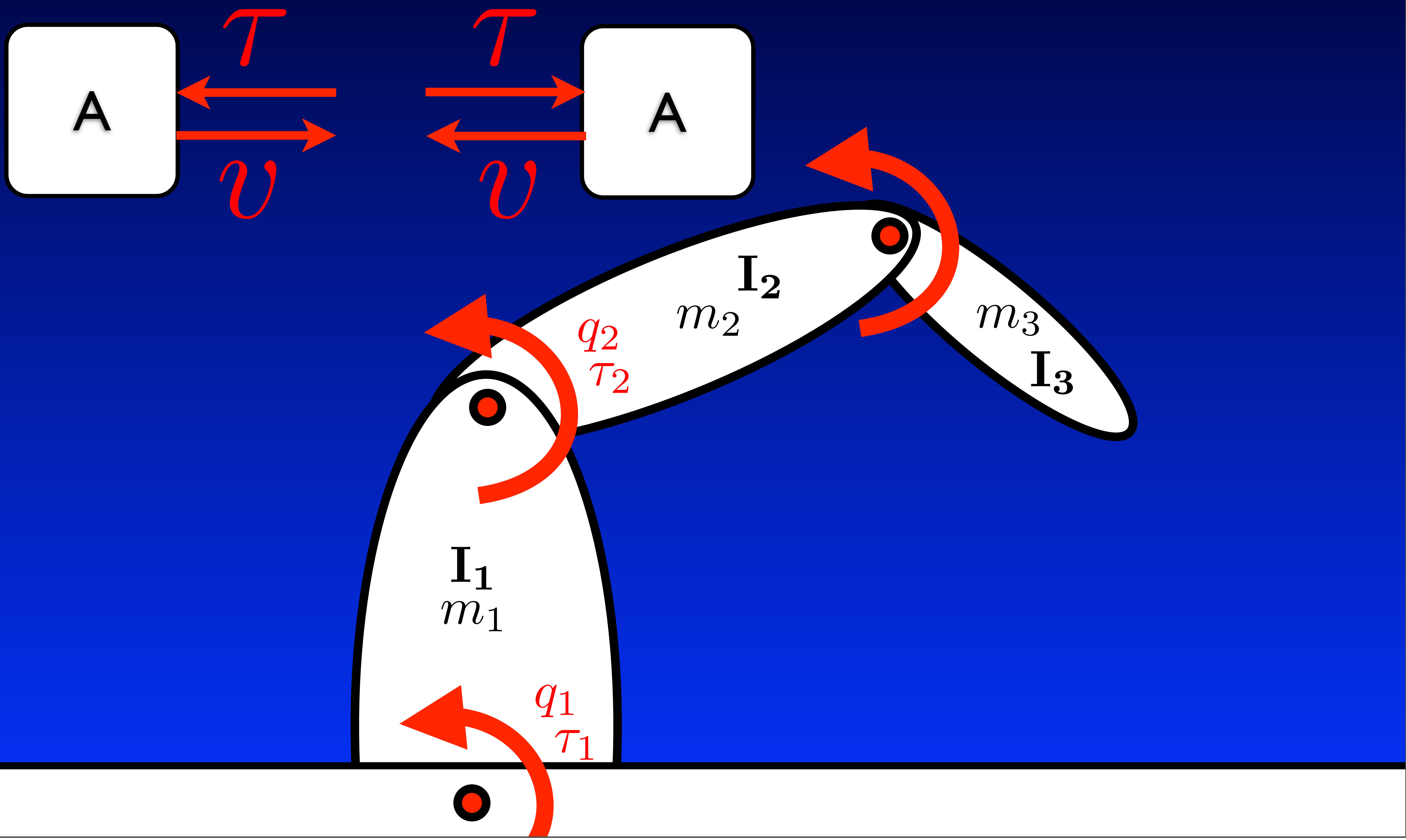

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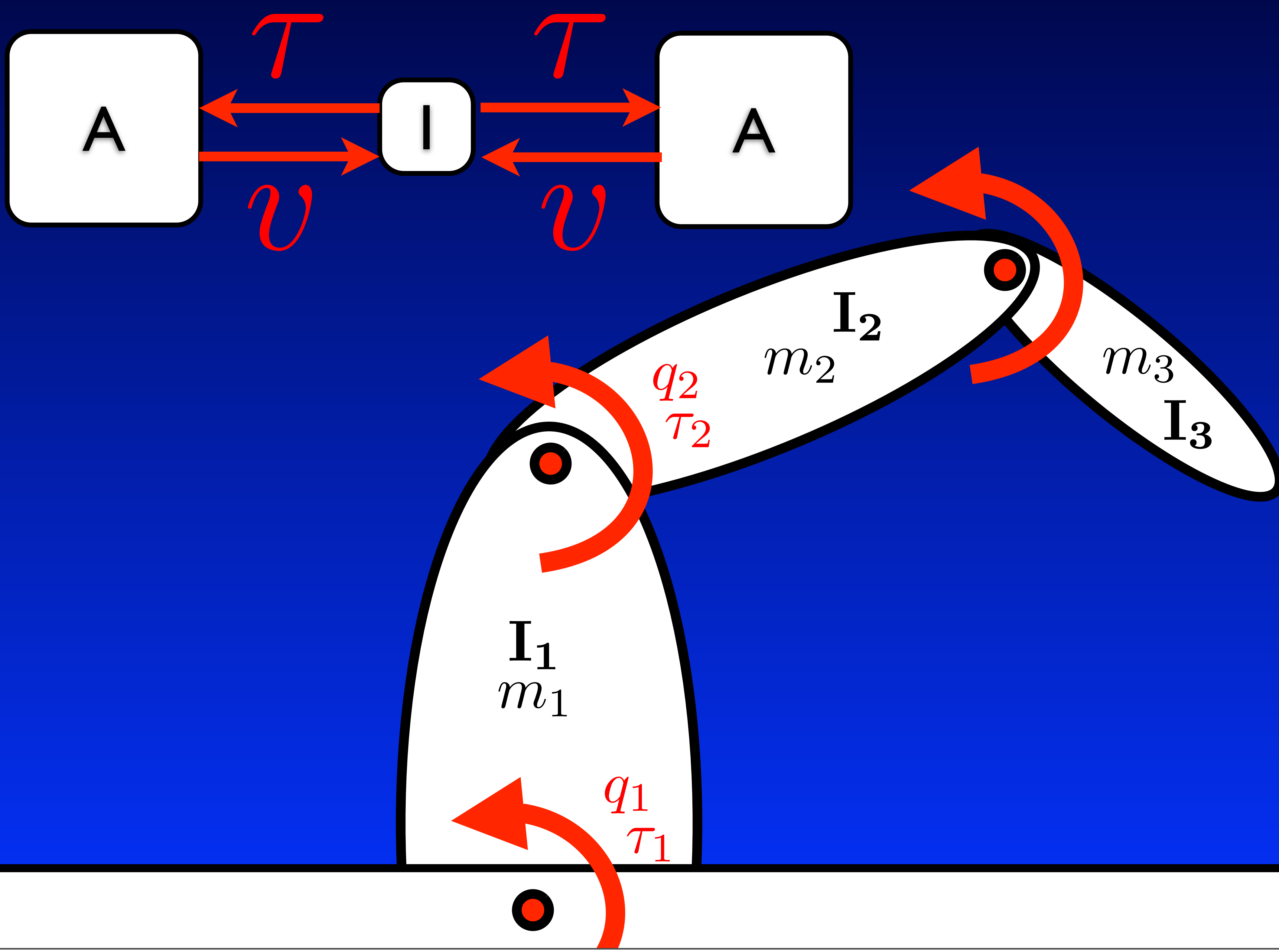
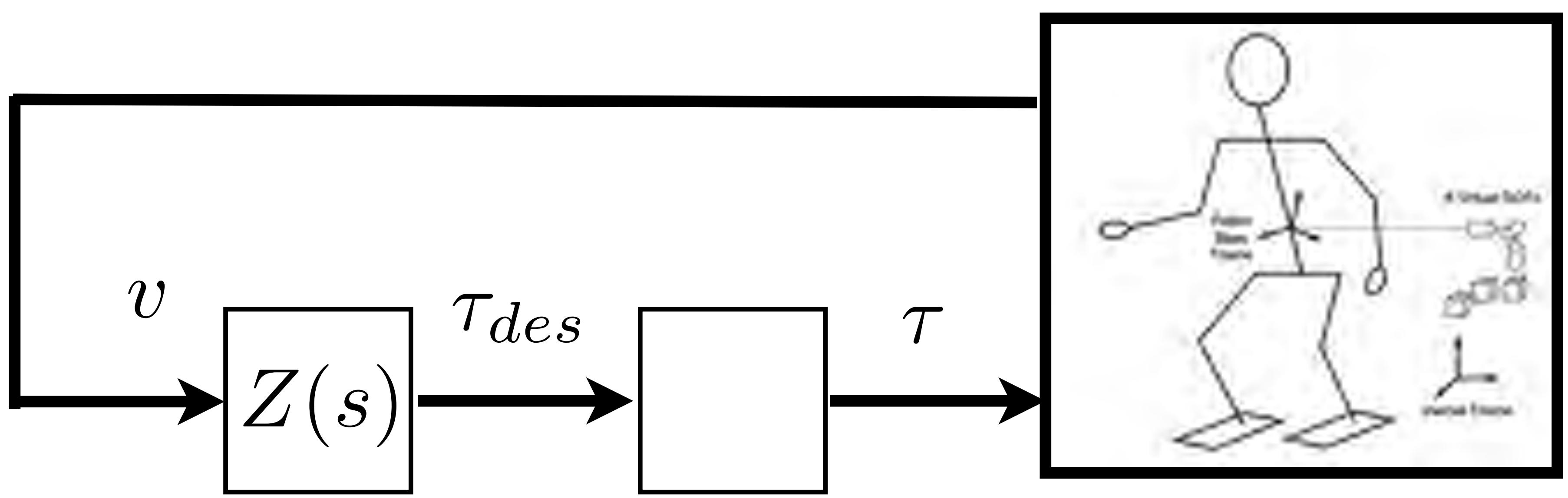


Torque/force source!!!

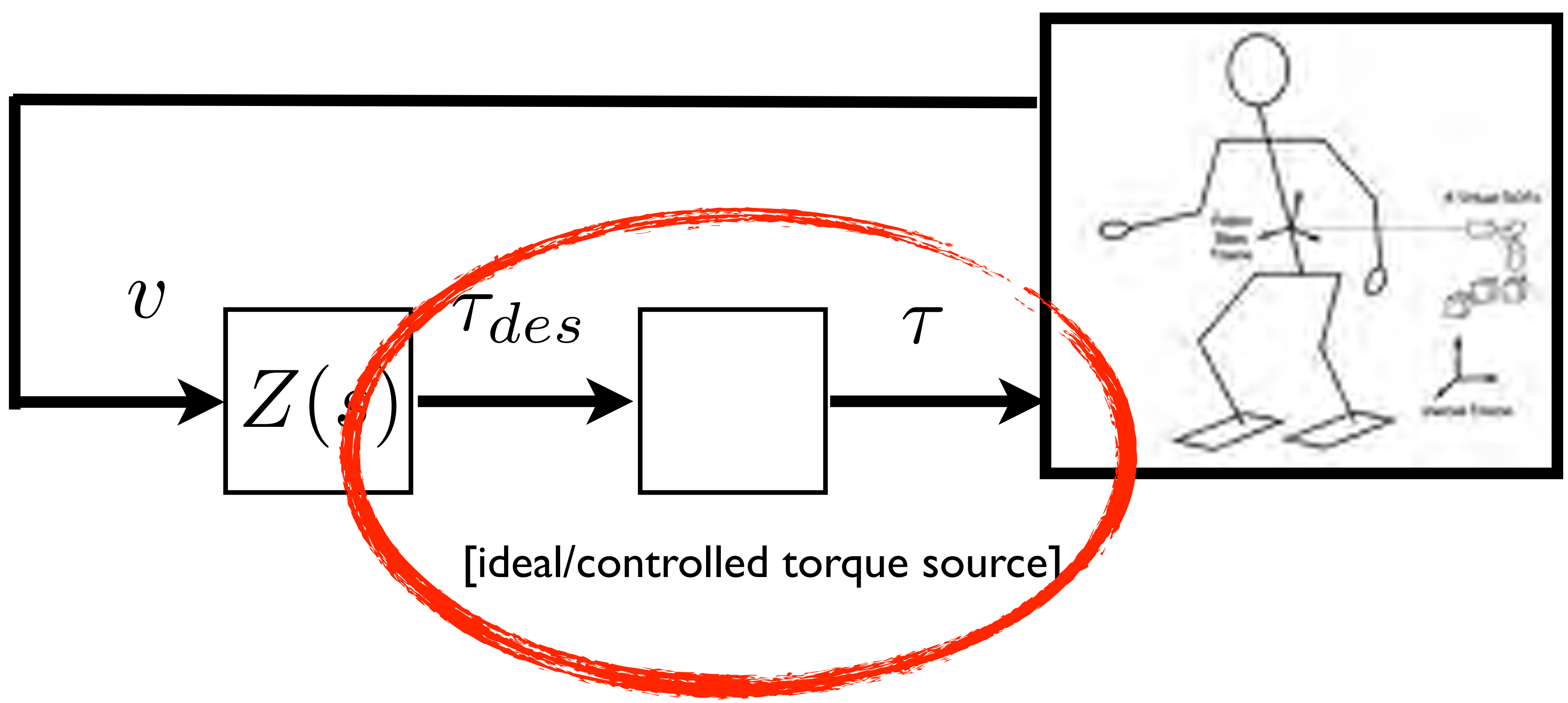
Fundamental need for torque source



[ideal/controlled torque source]

Torque/force source!!!

Fundamental need for torque source



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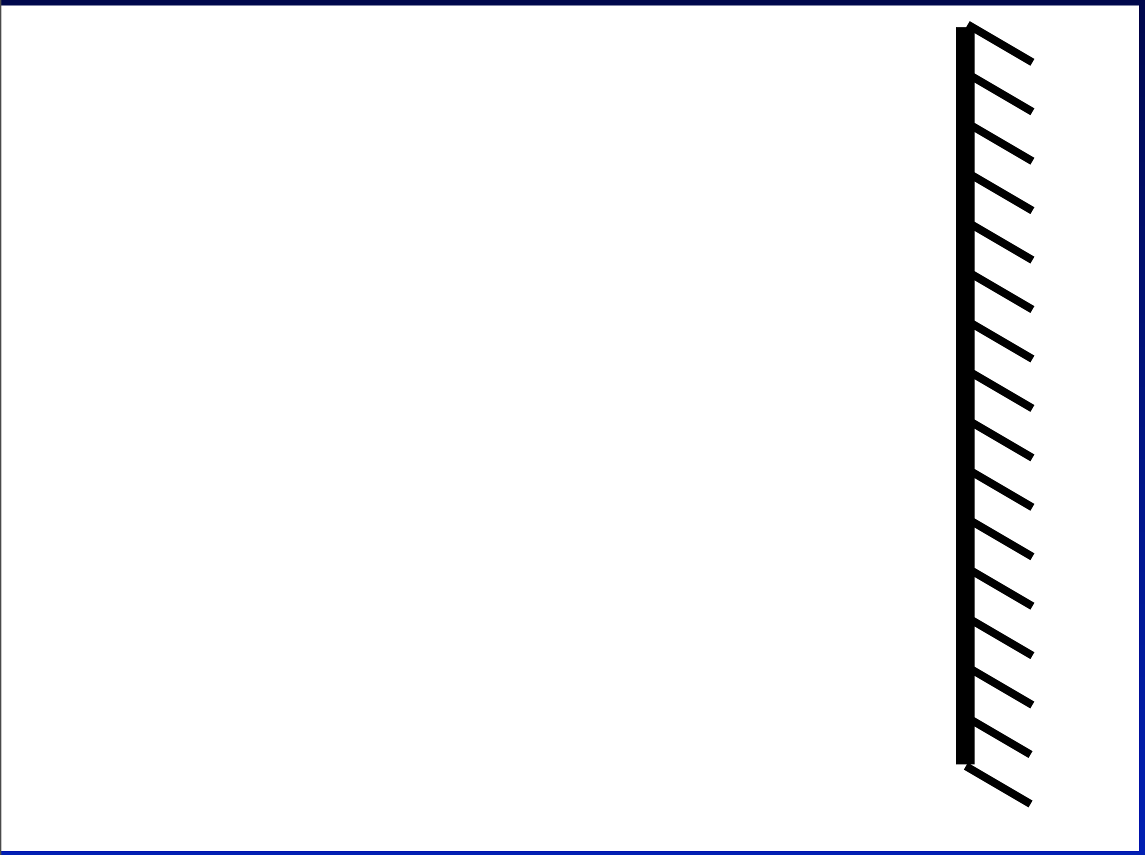

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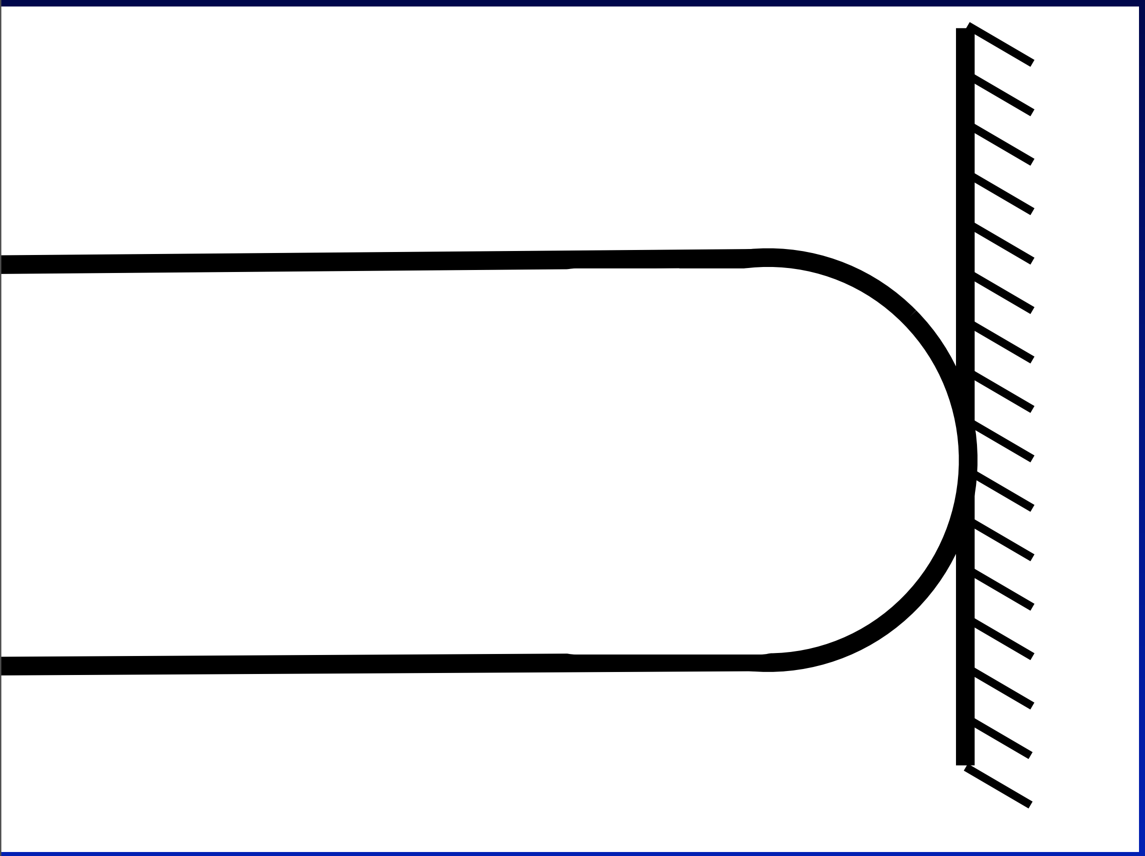

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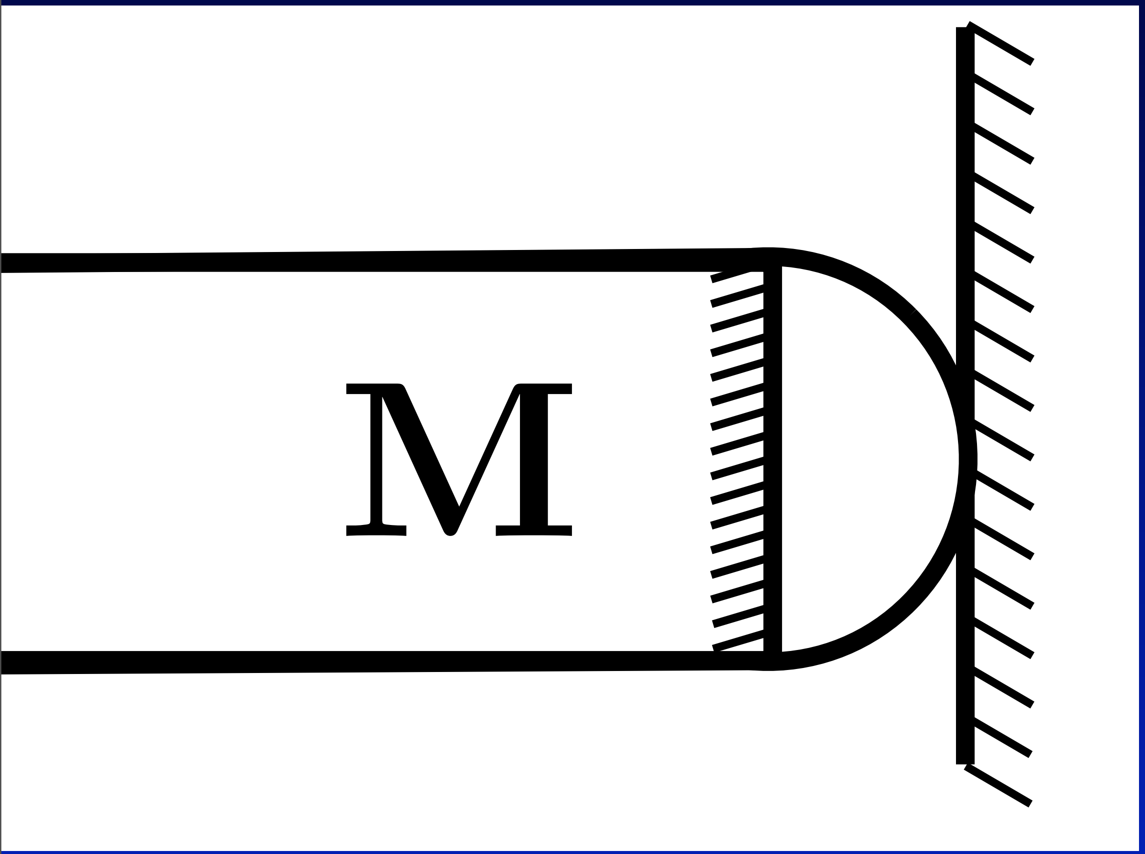

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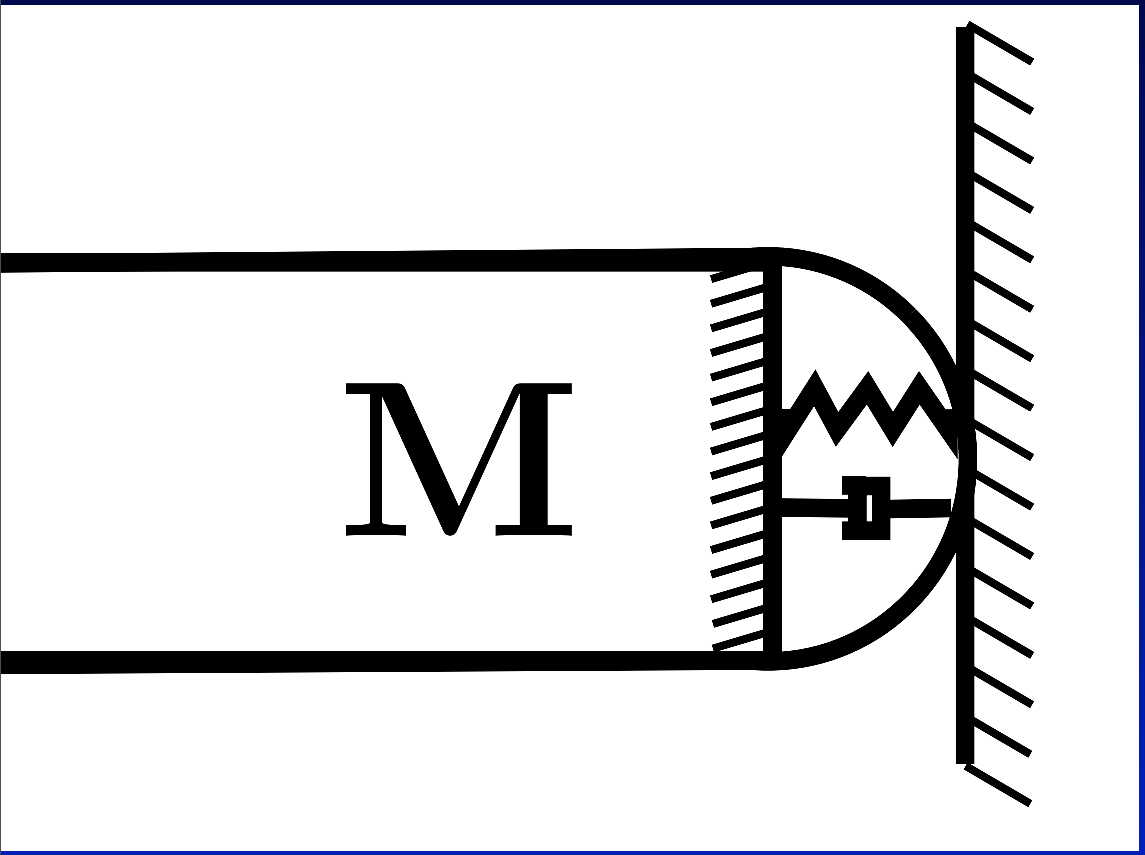

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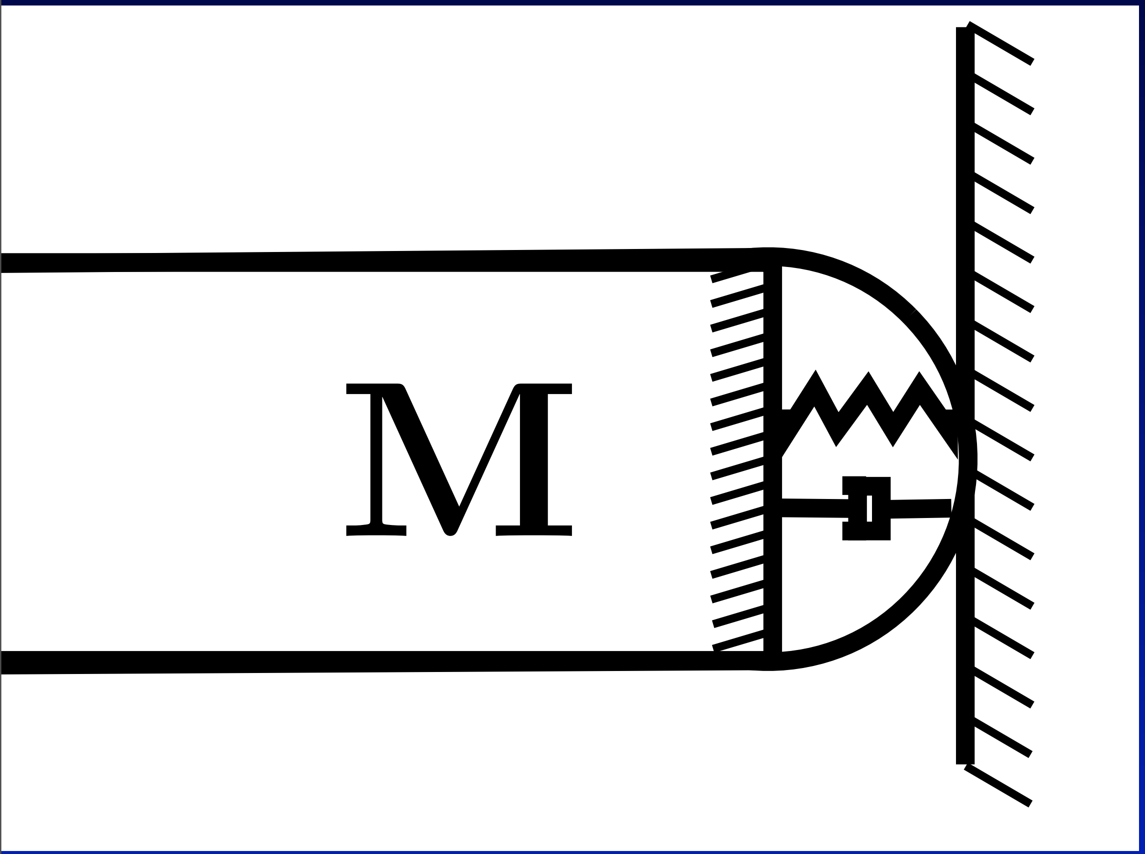
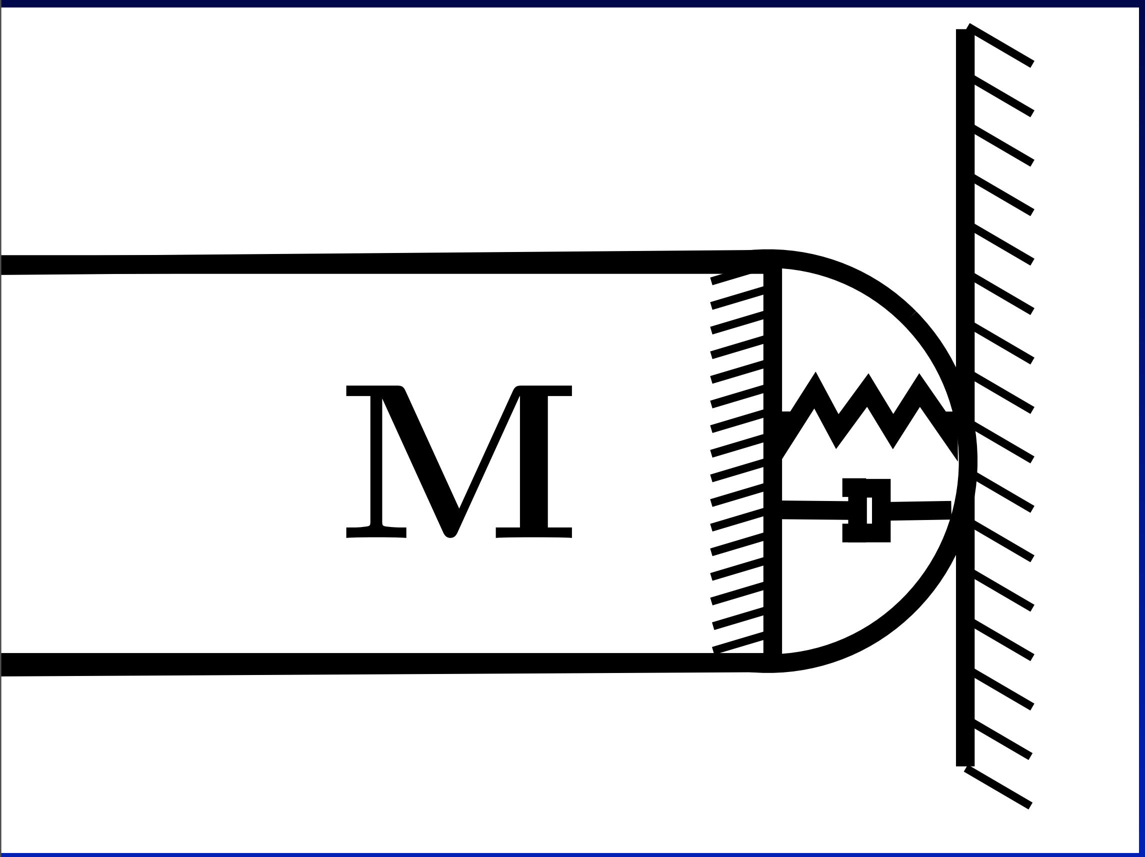


A

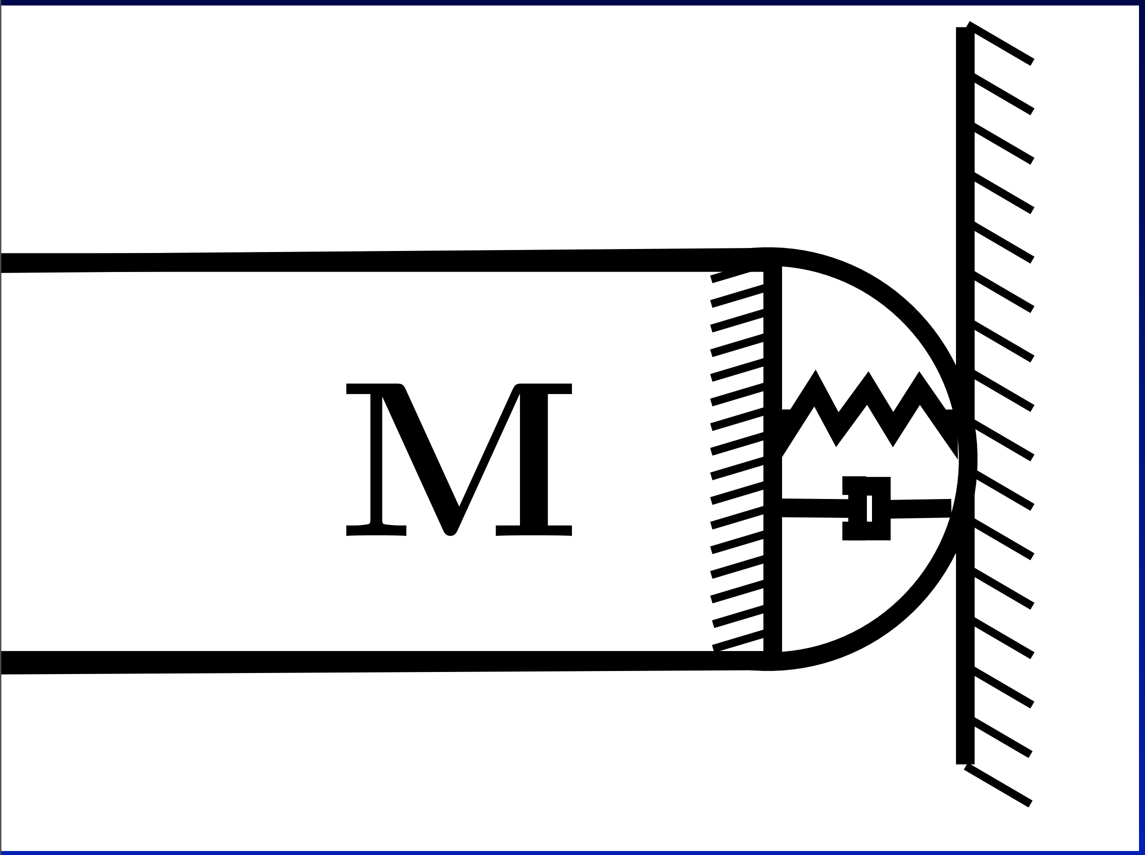
Endeffector

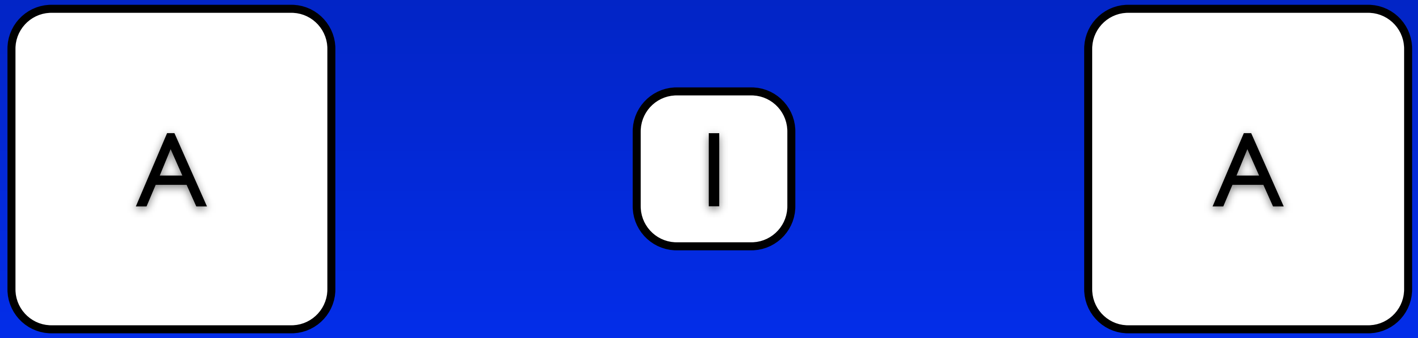


A

A

Endeffector





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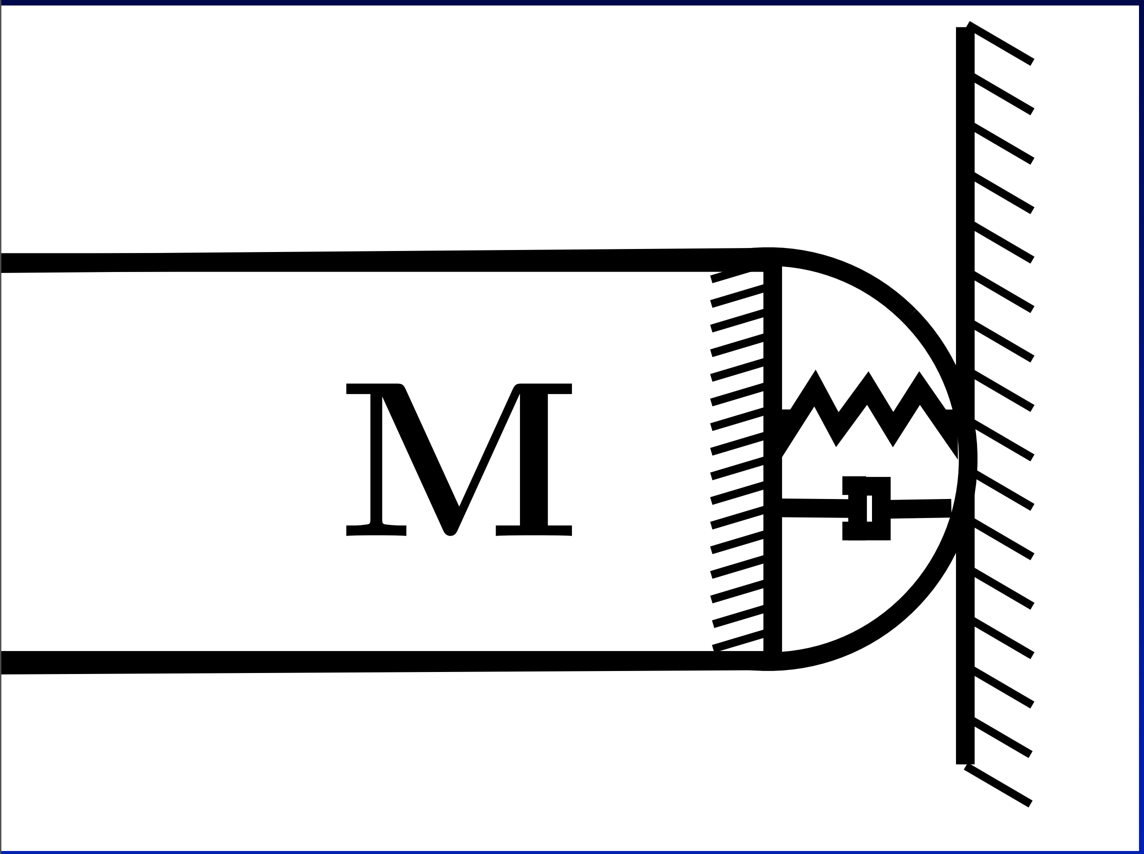

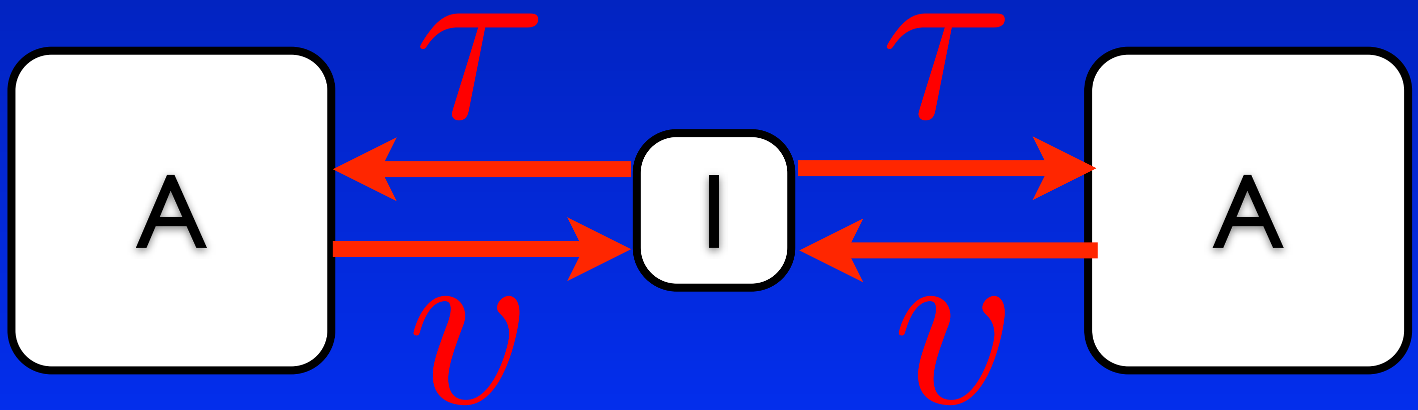

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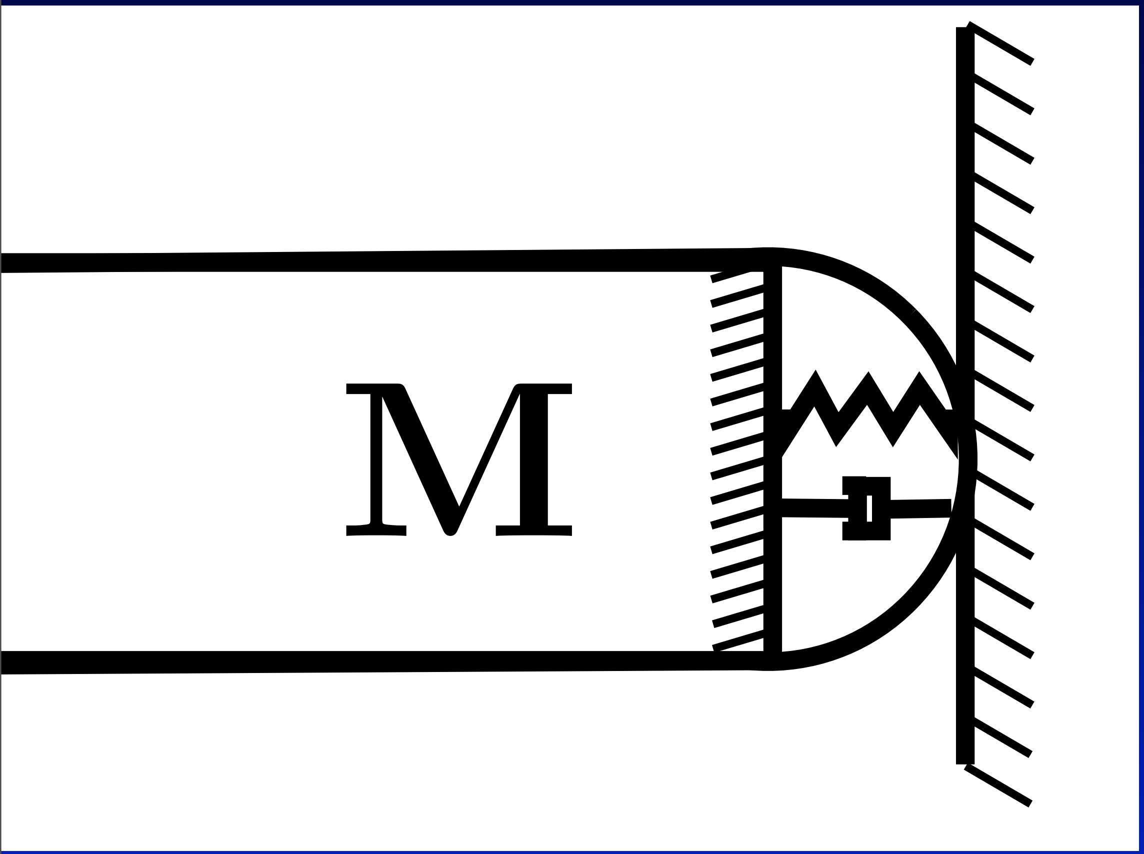
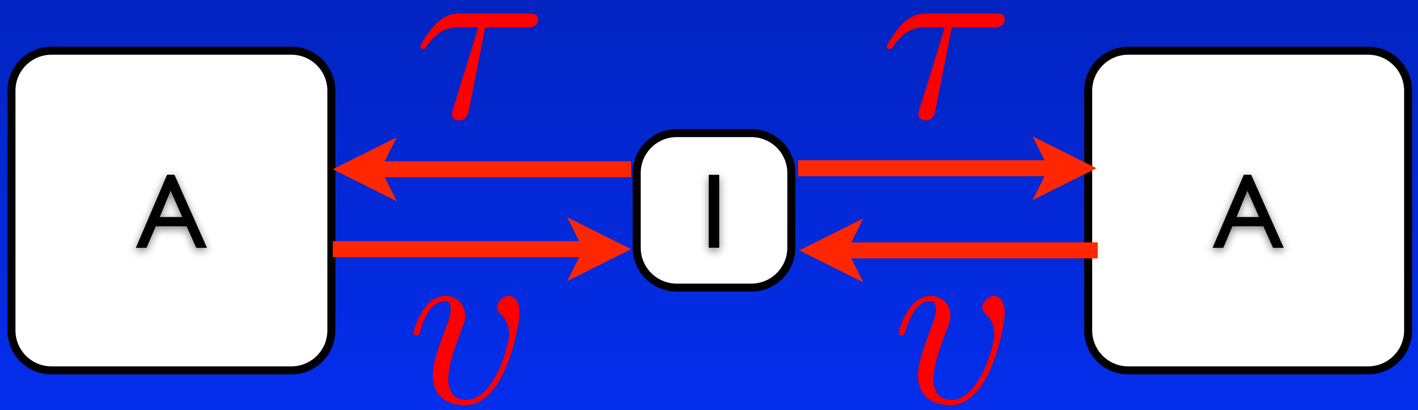


If the world has inertial behavior and robot has inertial behavior, need a compliant element to ensure stable contact/controllability of contacts



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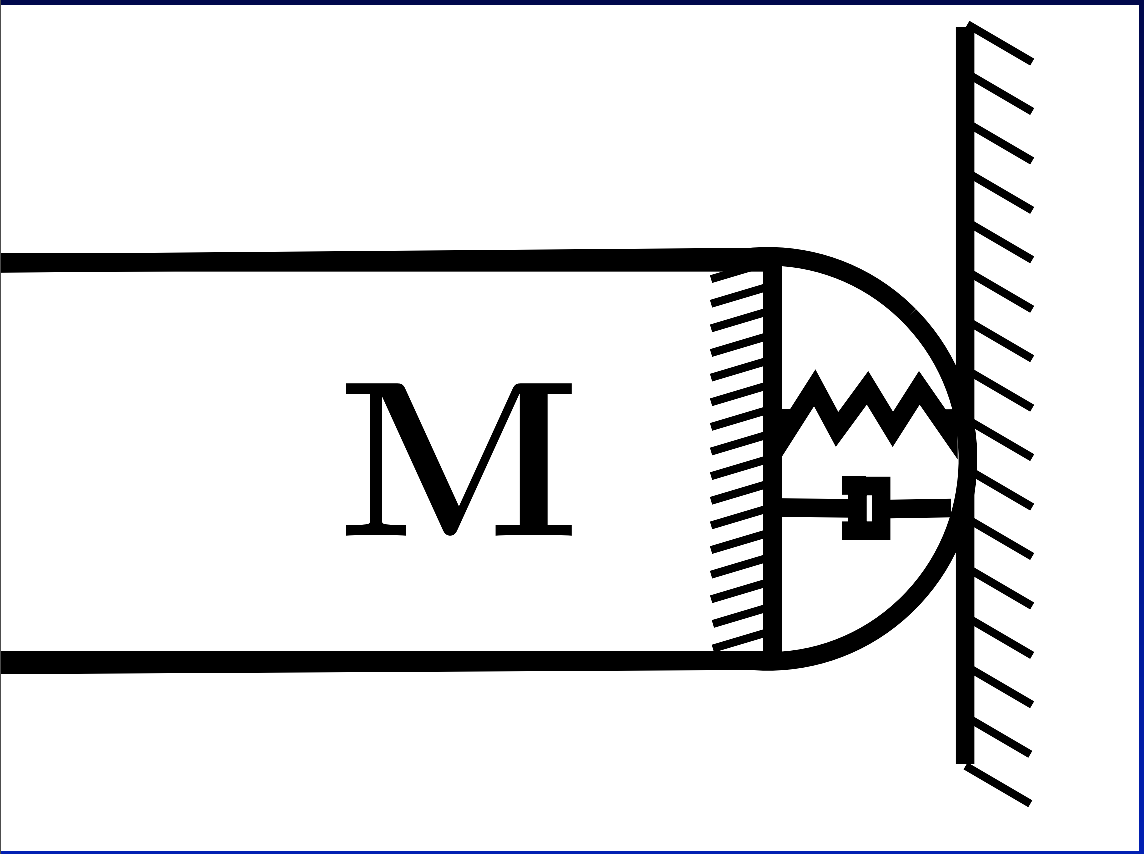

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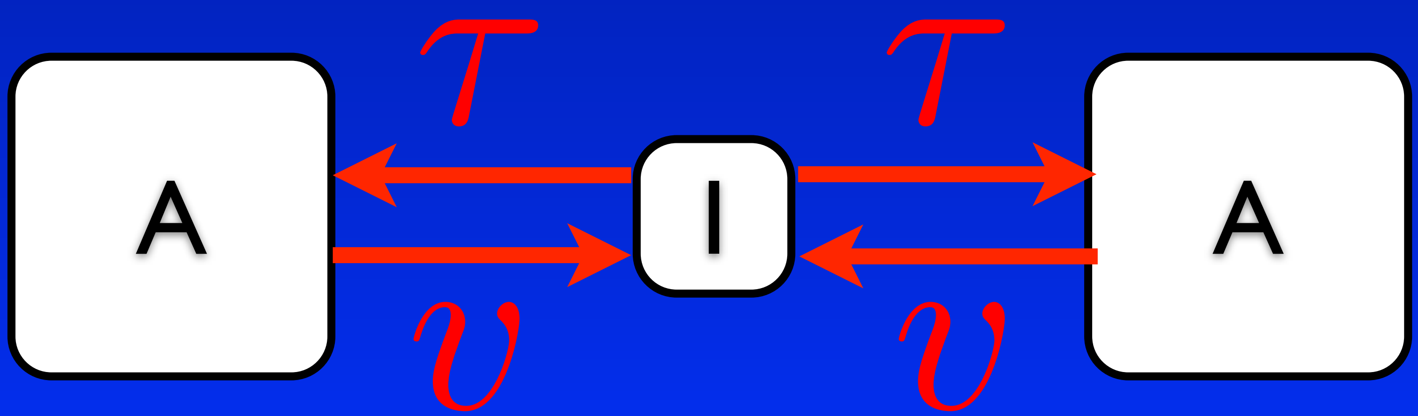
Soft: low inertia, high compliance



A versatile robot

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Two important consequences:

A versatile robot

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- Robot needs (somewhat) soft interface

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The stiffer the actuation system
the higher the bandwidth:
Soft outside, stiff inside

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Soft outside, stiff inside

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Interaction Control

Interaction *control*

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If we can control impedance, can control energy exchange during interaction / Work being done...

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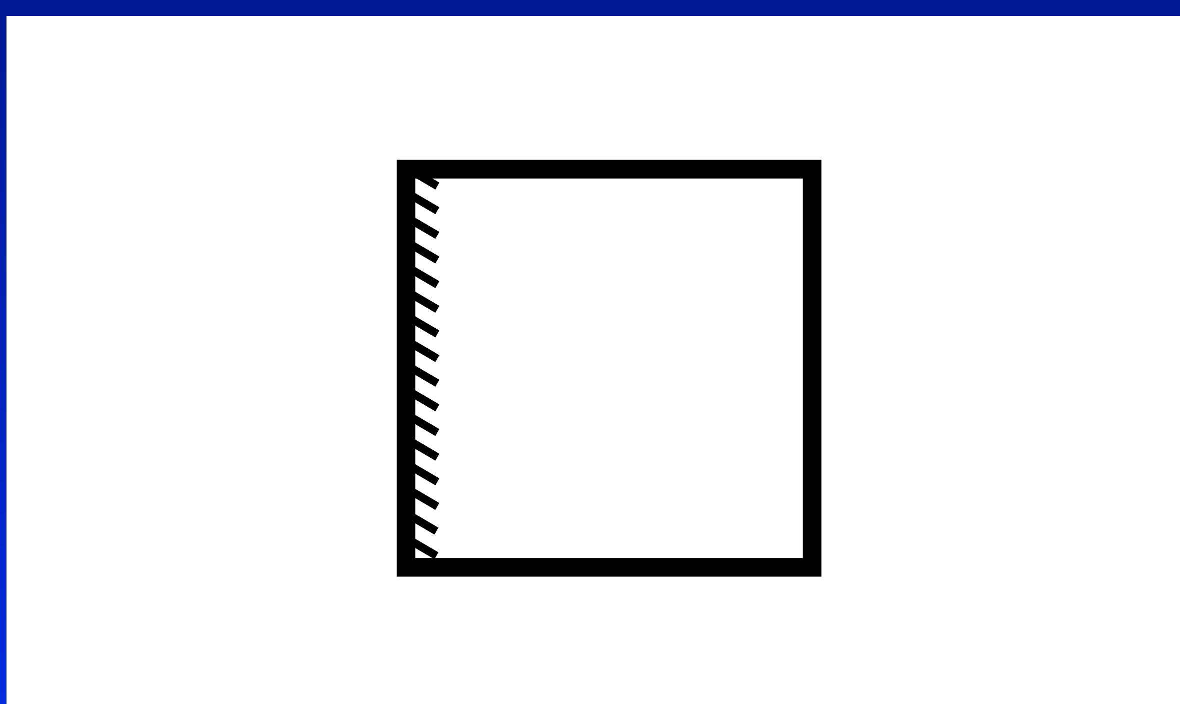
⇒ Impedance control!!! Interaction control!!!

Interaction *Control*

Impedance *feedback* control



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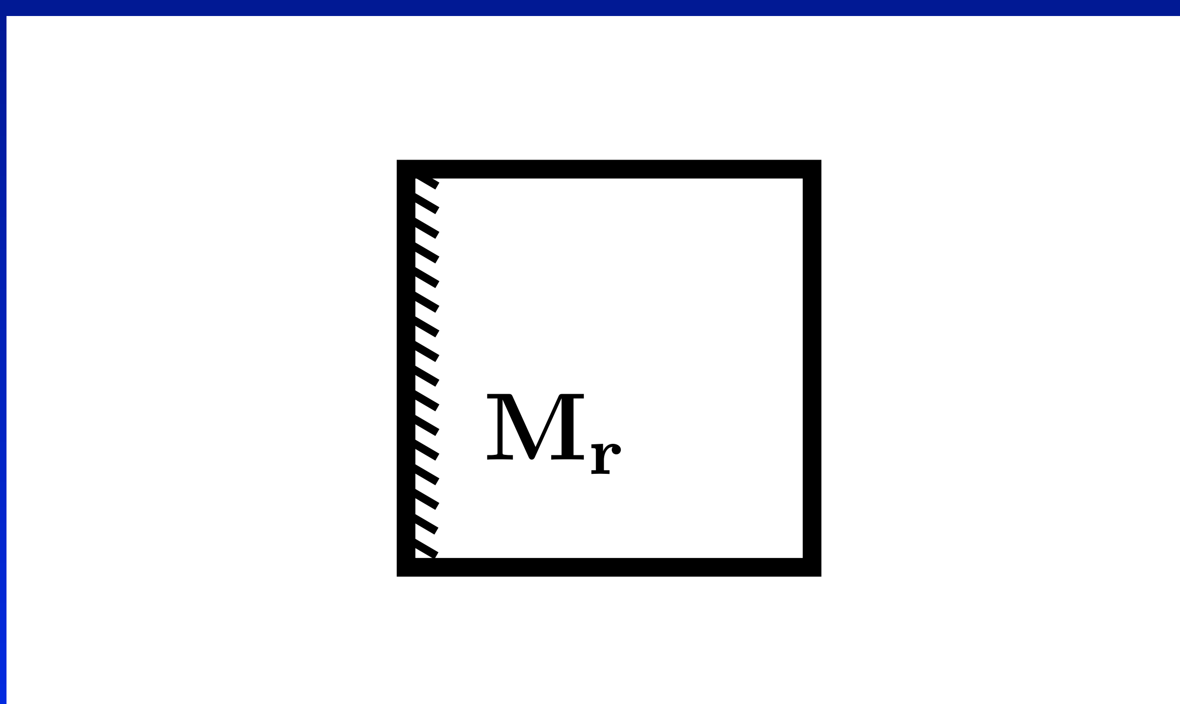
Impedance *feedback* control



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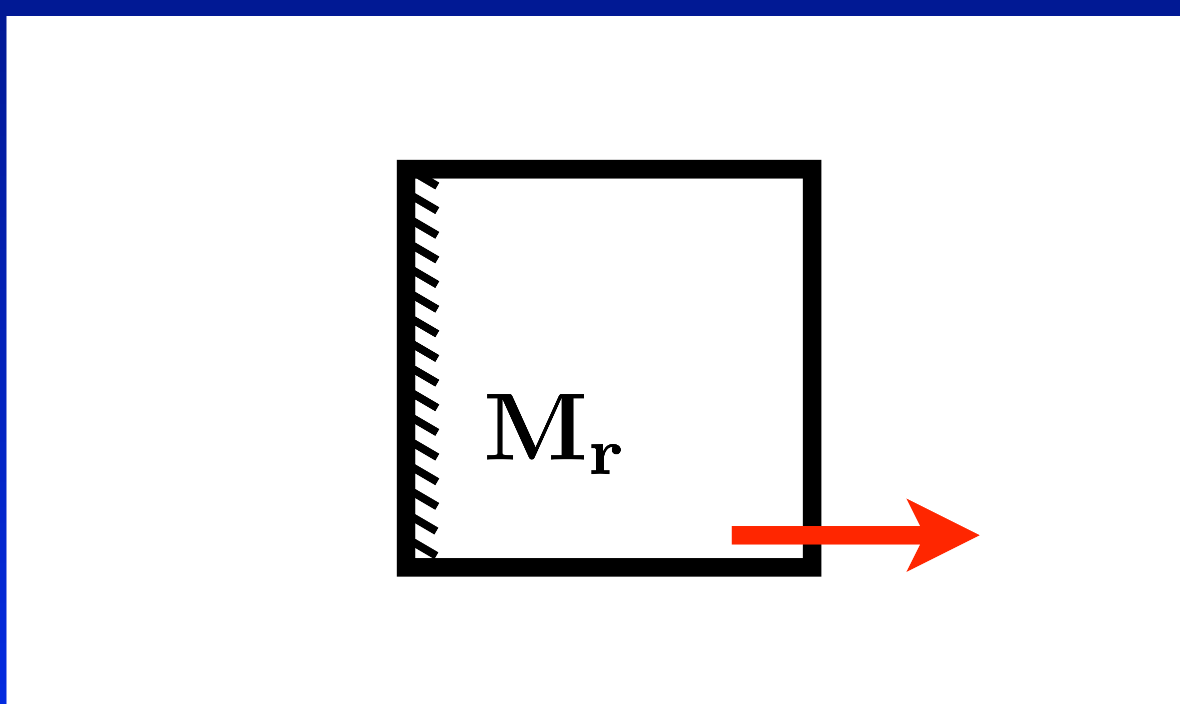

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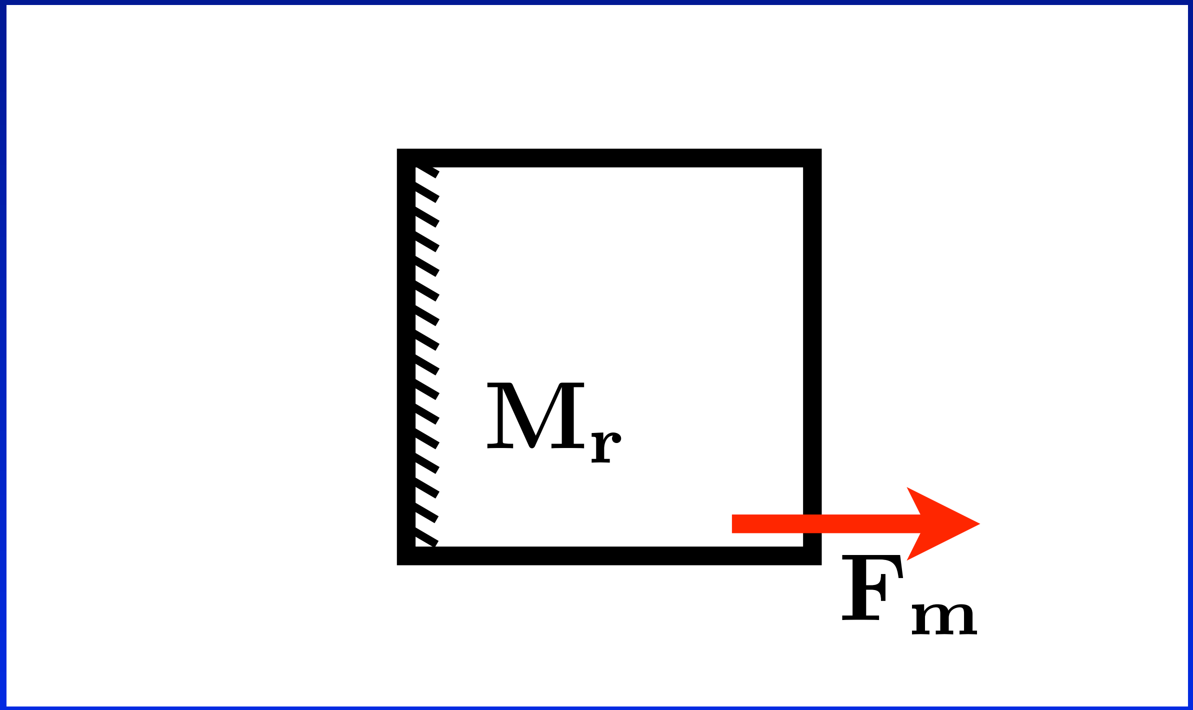

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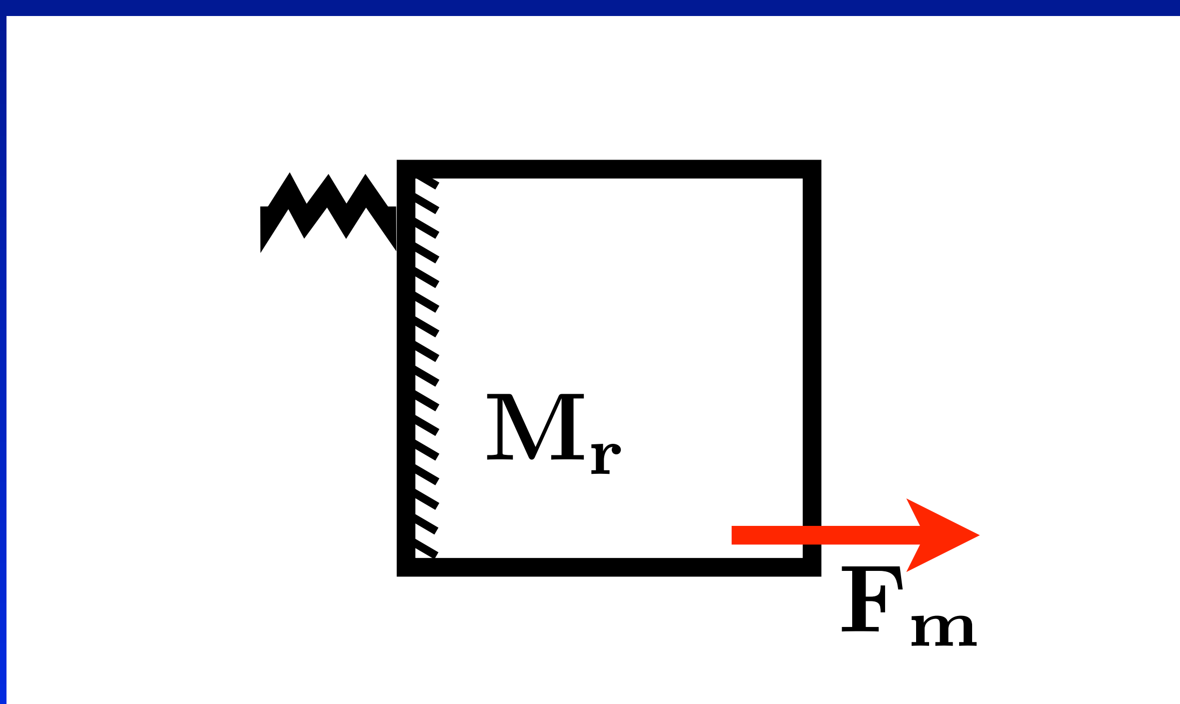

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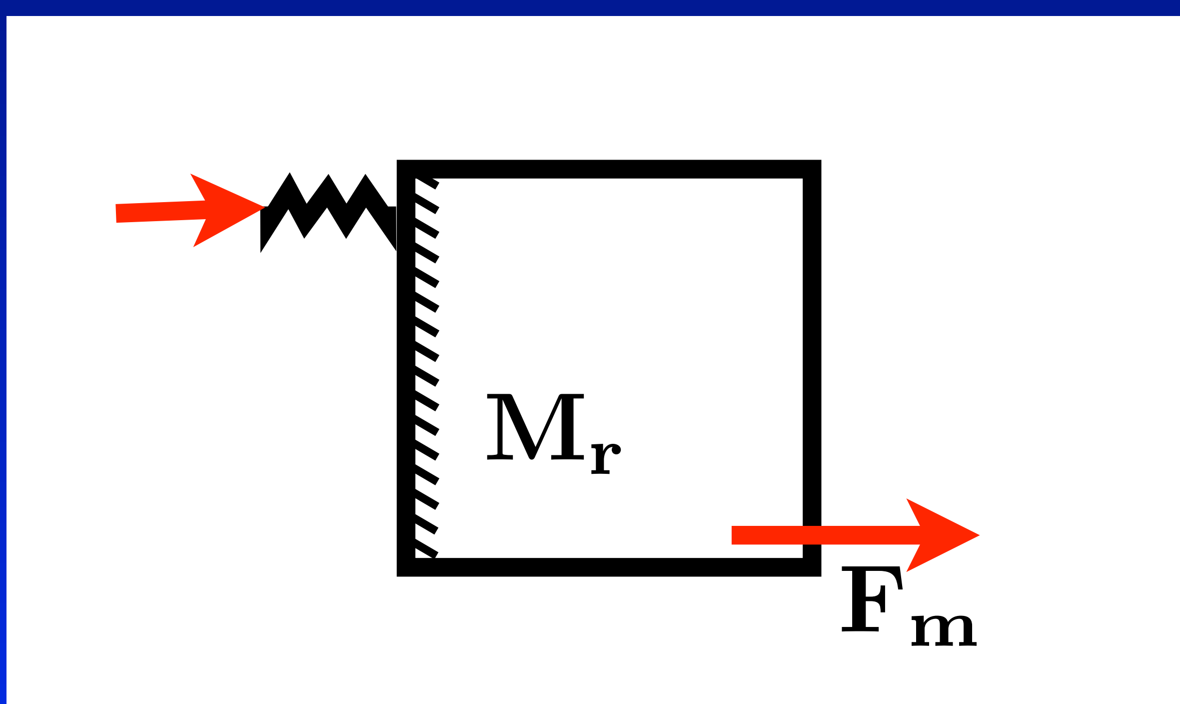

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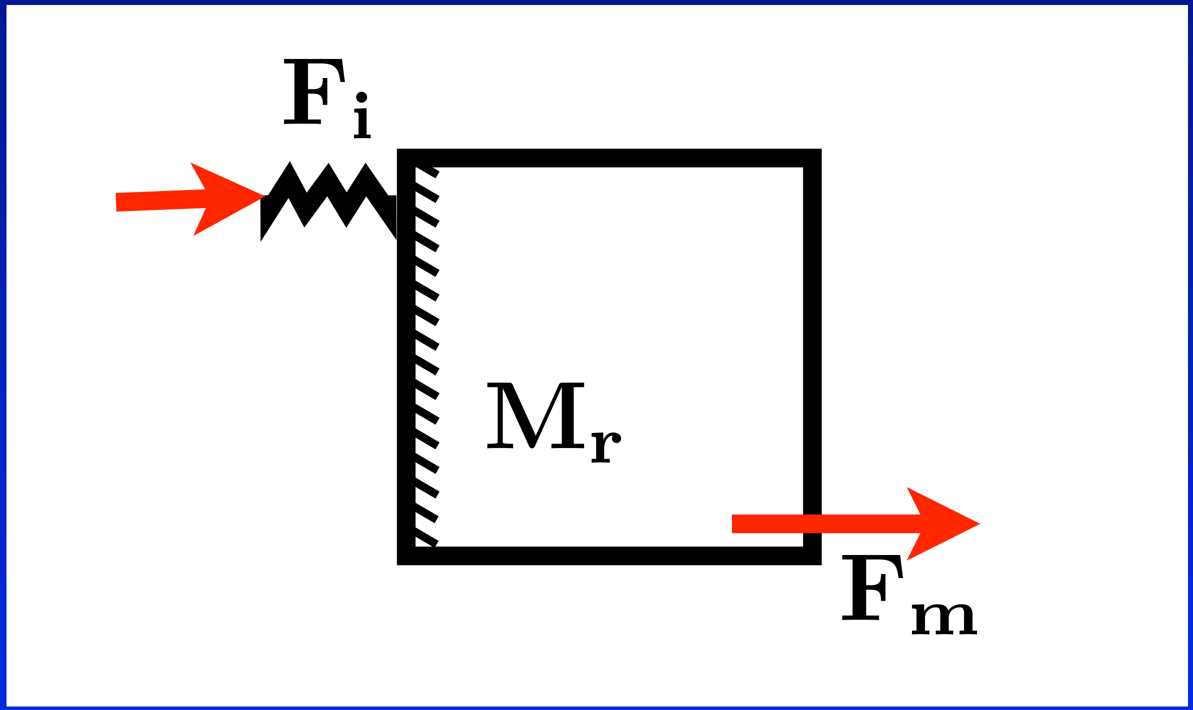
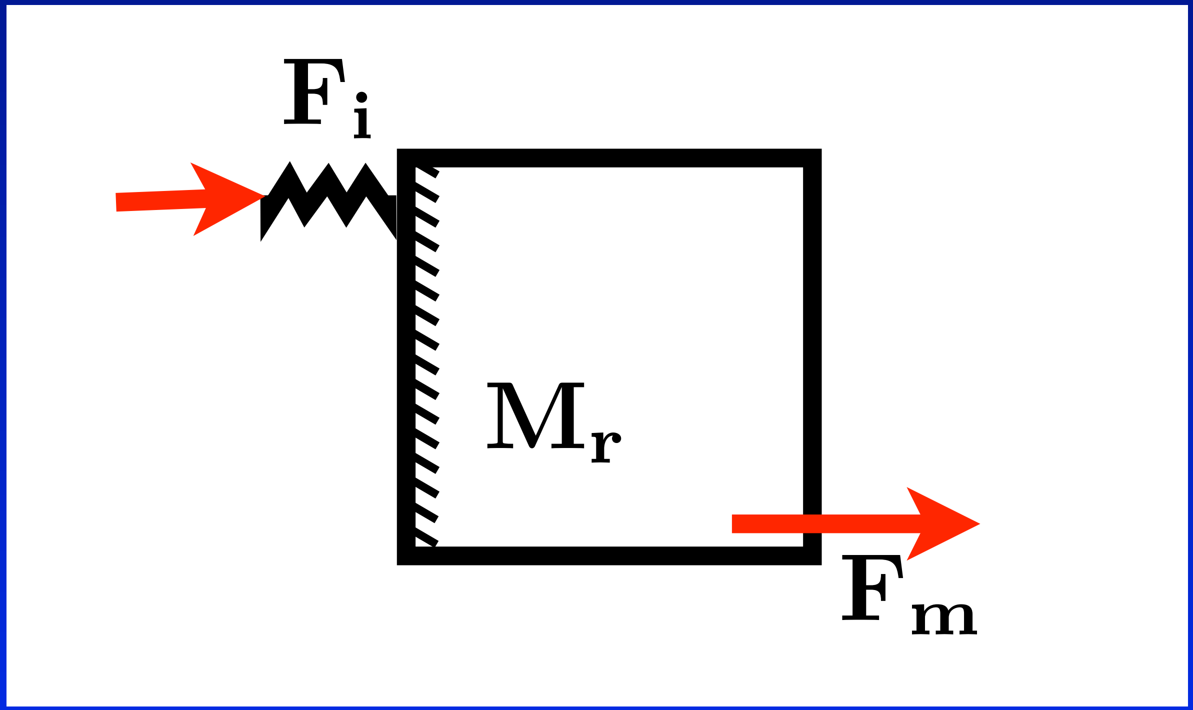


Interaction *Control*

Impedance *feedback* control

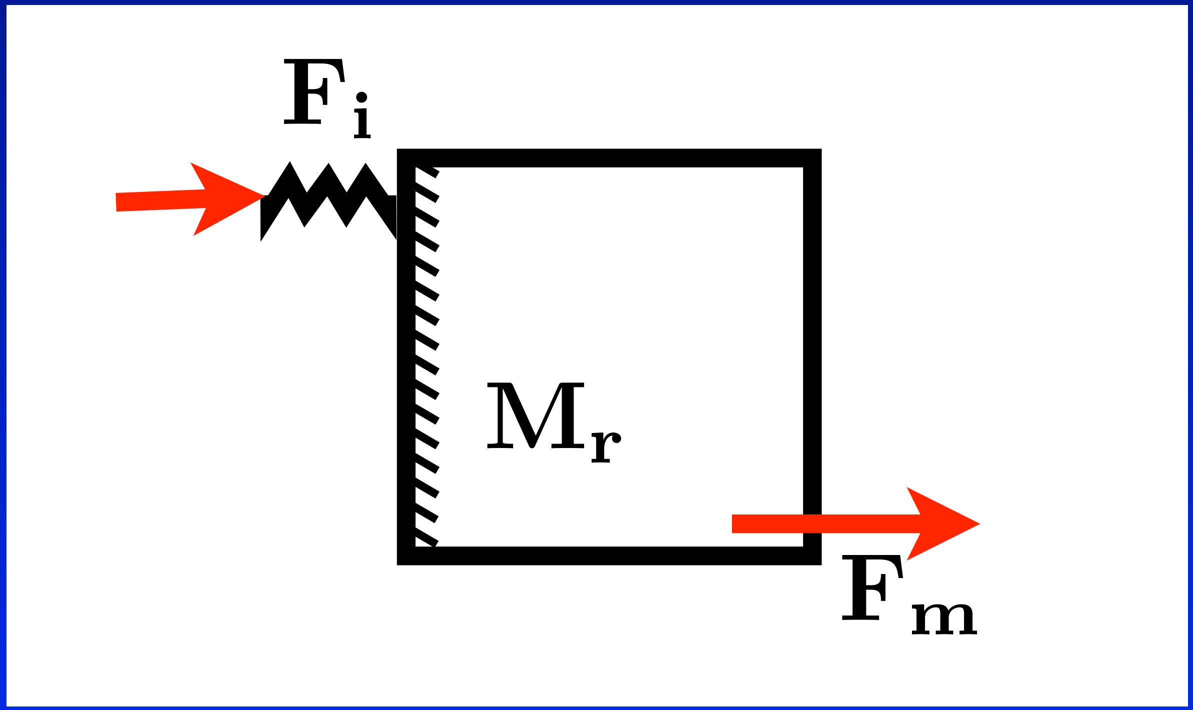
Desired: $\mathrm{M_d}$



Interaction *Control*

Impedance *feedback* control

Desired: $\mathrm{M_d}$ Newton's law:



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Impedance *feedback* control

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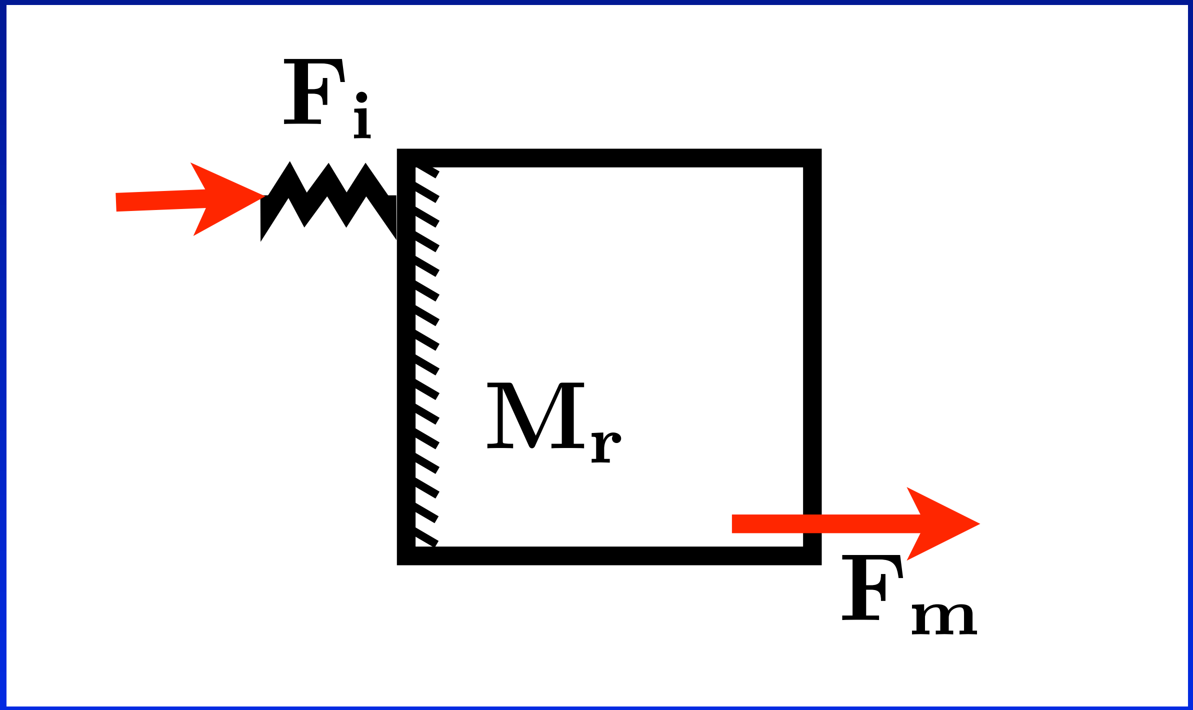

Interaction *Control*

Impedance *feedback* control

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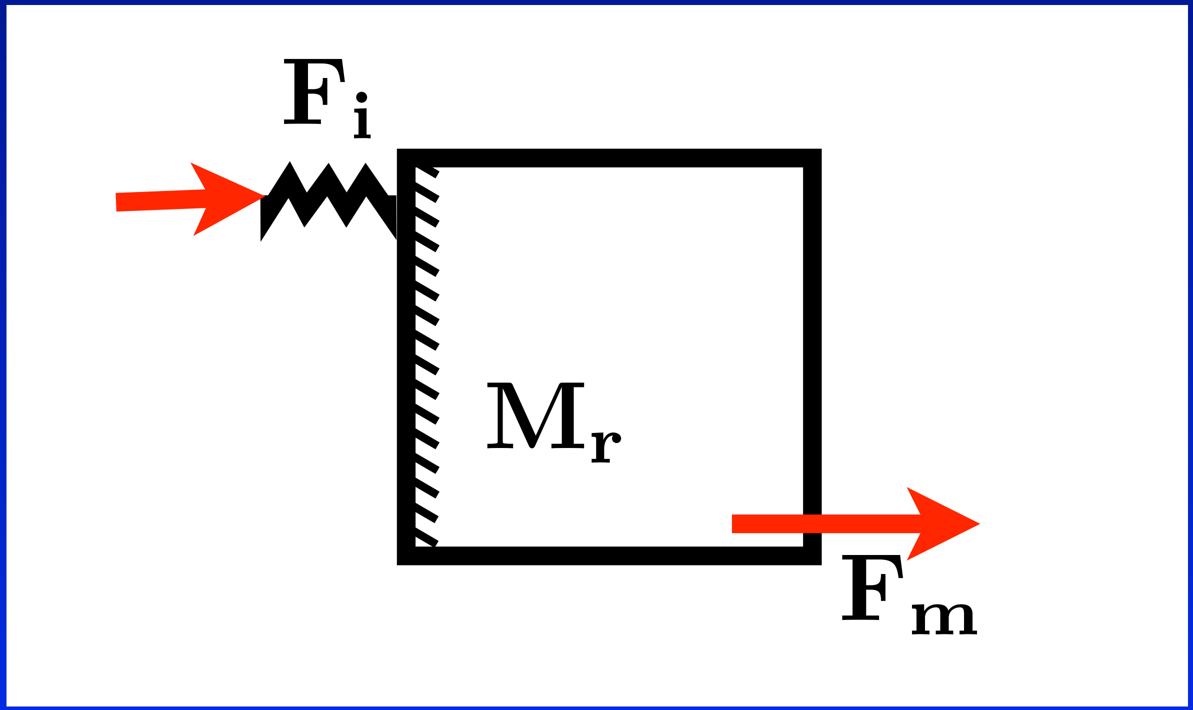
Expected acceleration:



Interaction *Control*

Impedance *feedback* control

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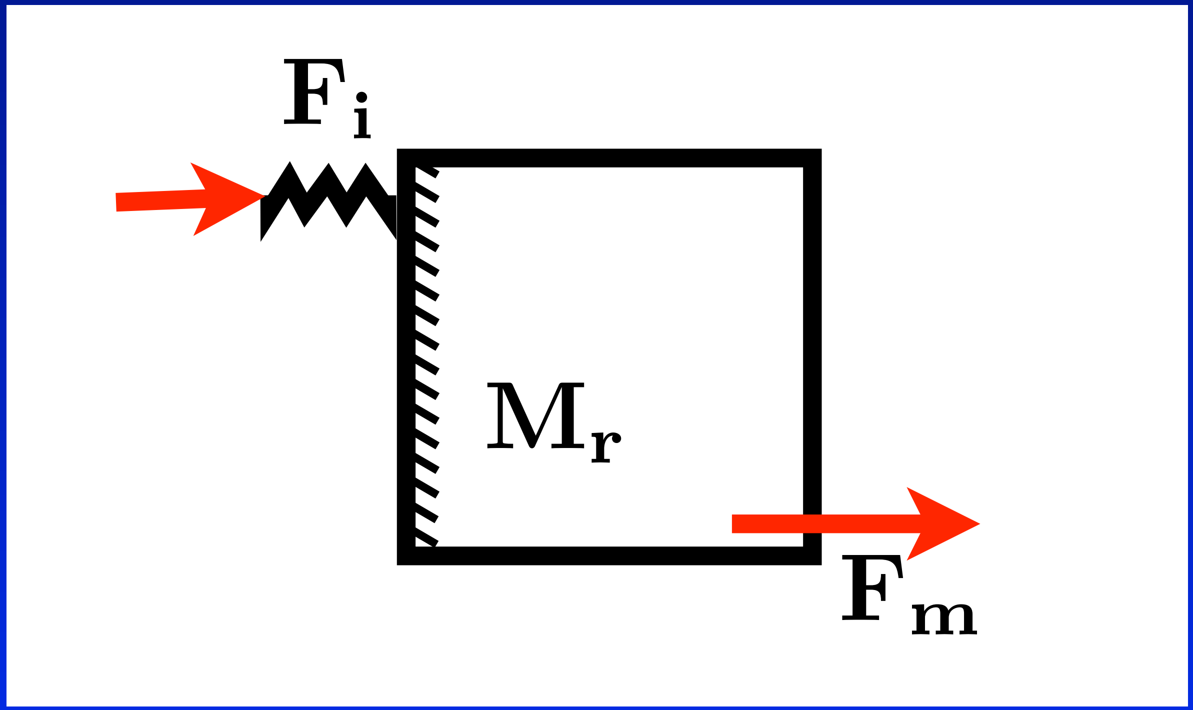

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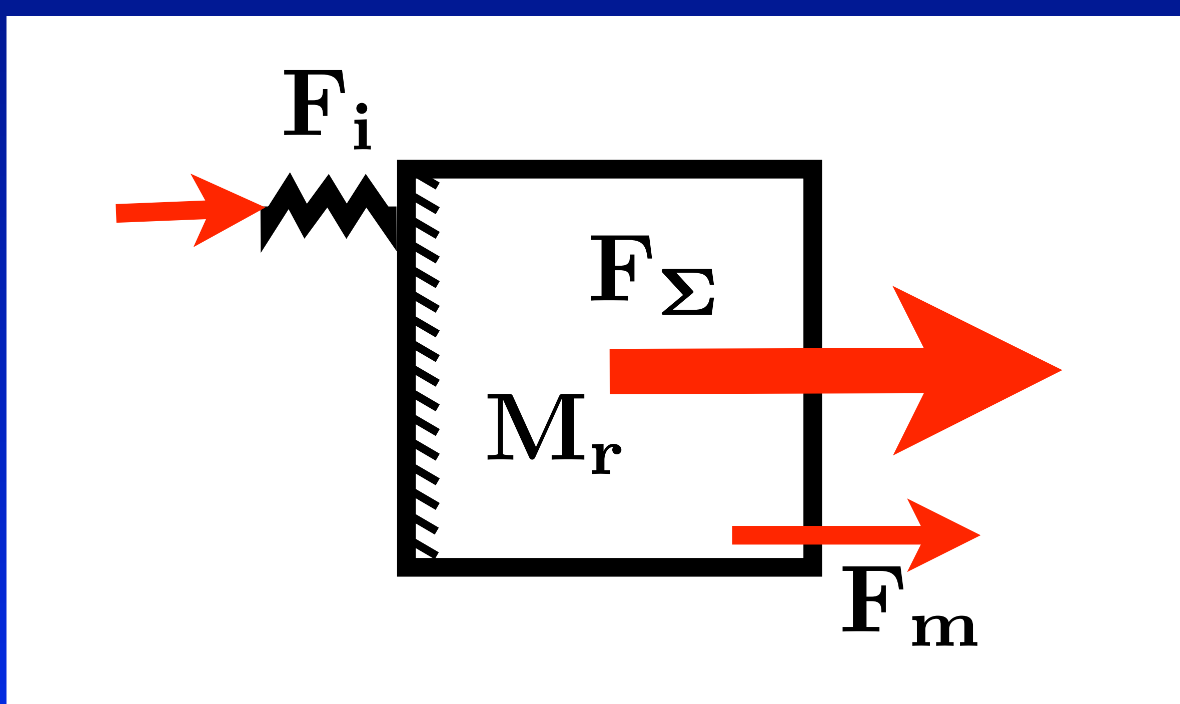

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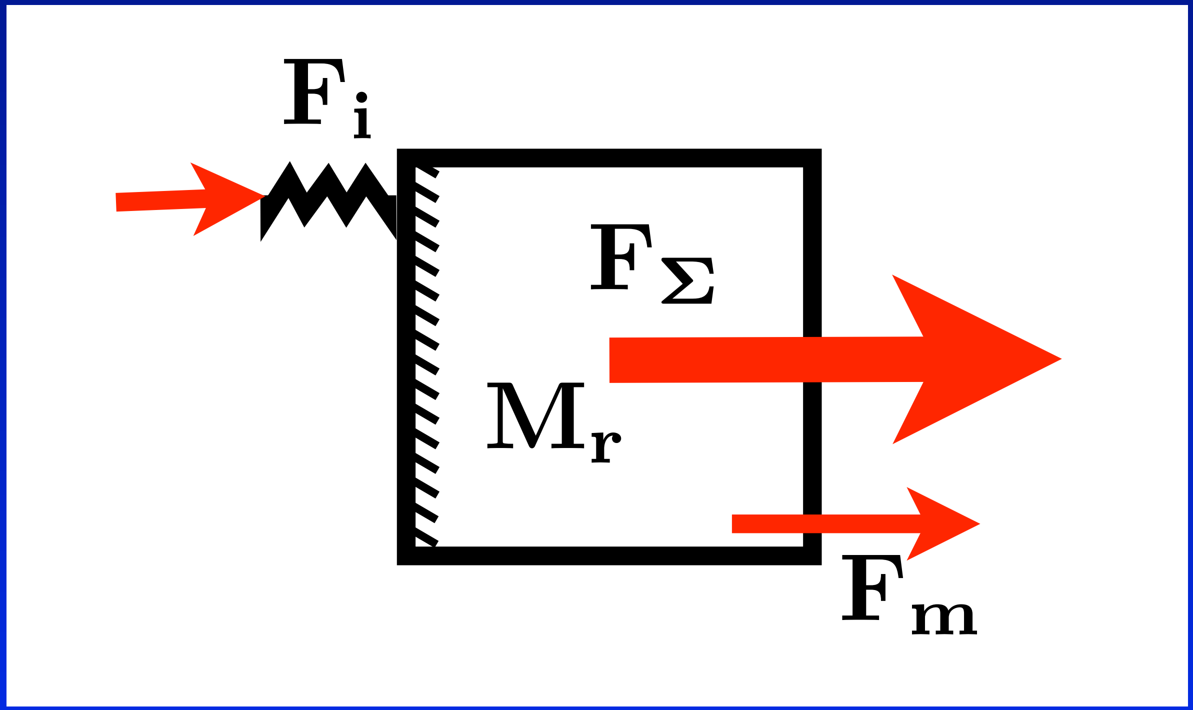

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$$\mathbf{F_\Sigma} = \mathbf{F_m} + \mathbf{F_i}$$

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Impedance *feedback* control

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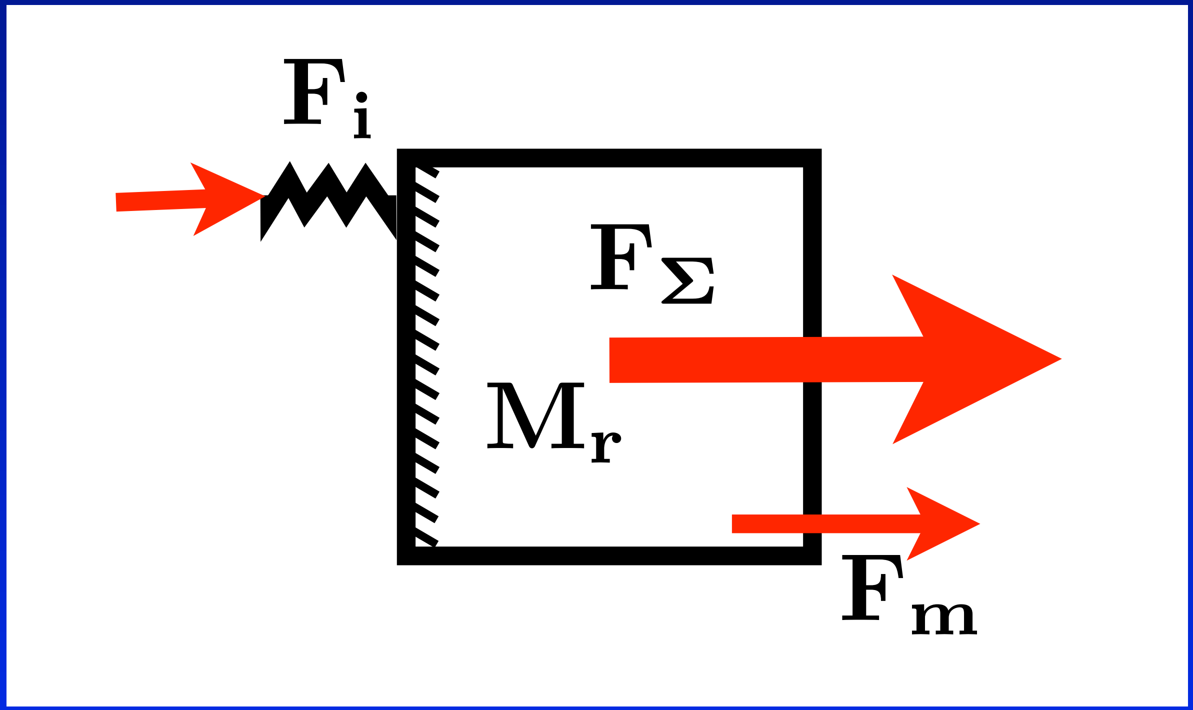

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Impedance *feedback* control

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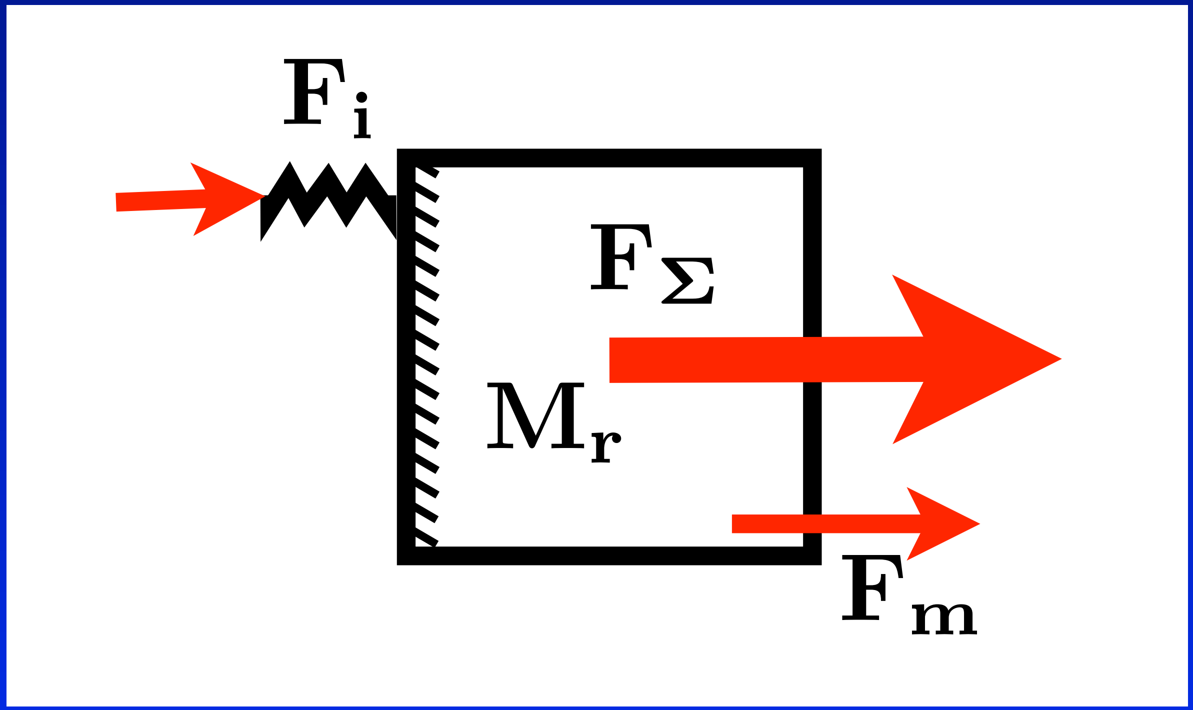

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Interaction *Control*

Impedance *feedback* control

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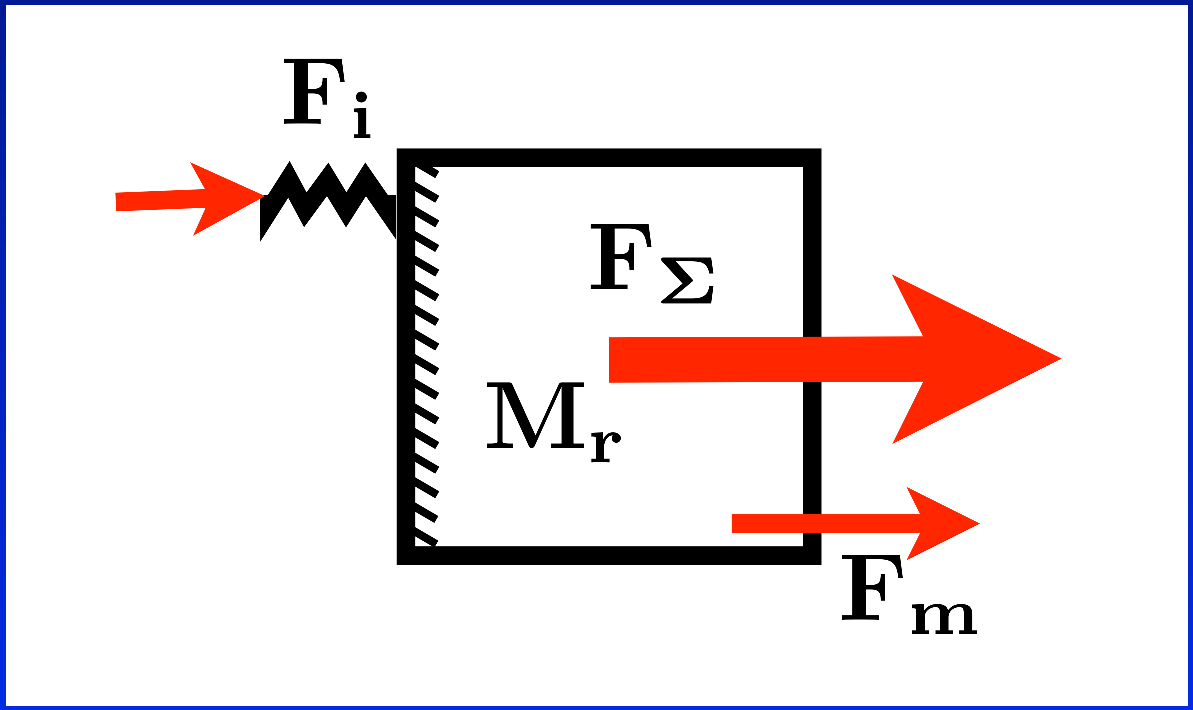

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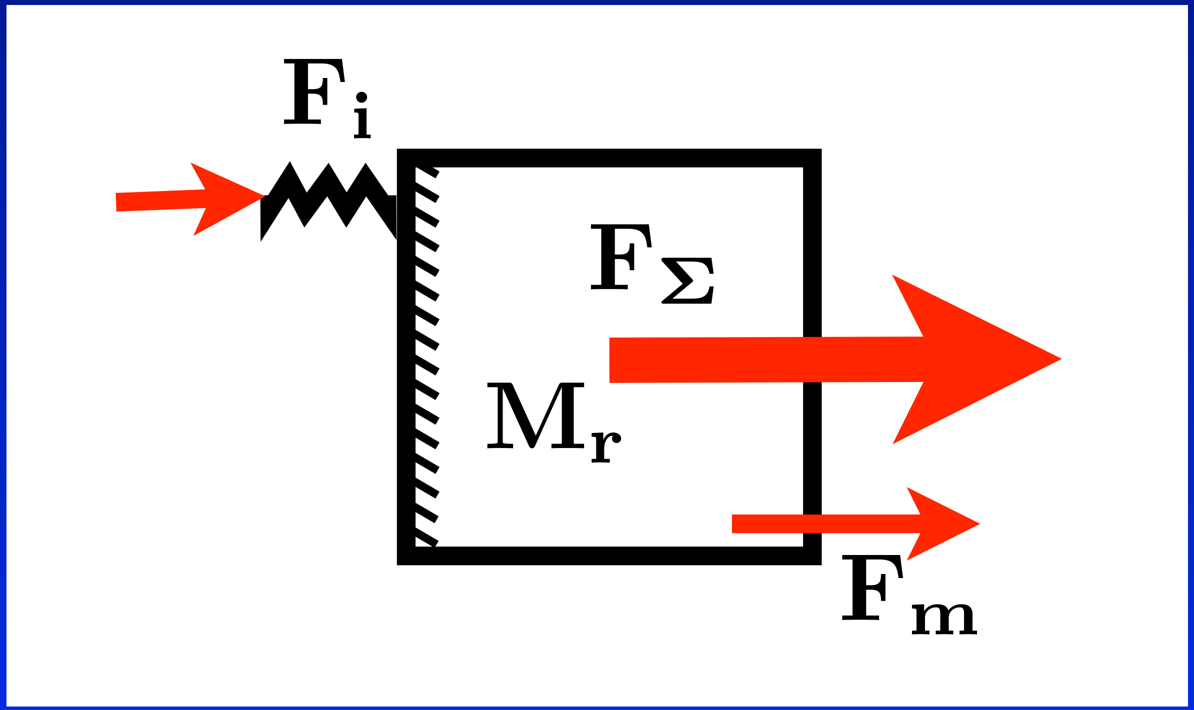
solve for Motor force

Interaction *Control*

Impedance *feedback* control

Desired: $\mathbf{M_d}$ Newton's law: $\mathbf{F_i} = \mathbf{M_d}\ddot{\mathbf{x}}$

Expected acceleration: $\ddot{x} = \frac{\mathbf{F_i}}{\mathbf{M_d}}$



'Real': $\mathbf{F_\Sigma} = \mathbf{M_r}\ddot{\mathbf{x}}$

$\mathbf{F_\Sigma} = \mathbf{F_m} + \mathbf{F_i}$

solve for Motor force

$\Rightarrow$

Interaction *Control*

Impedance *feedback* control

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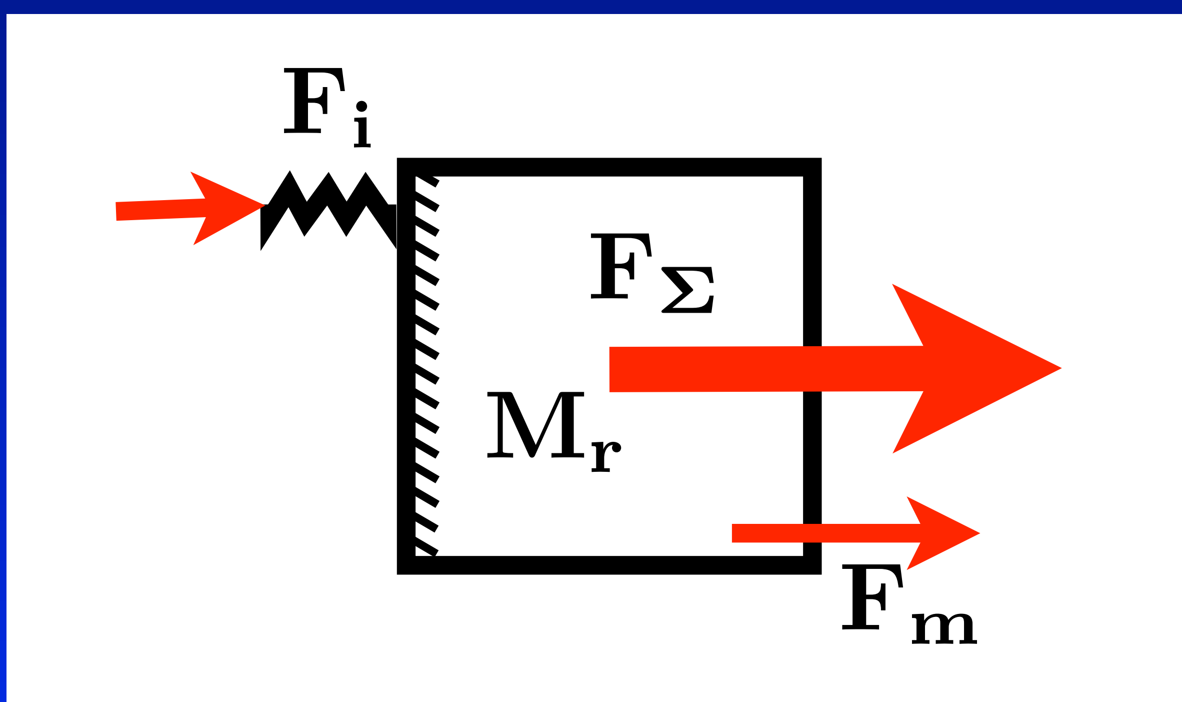
Expected acceleration: $\ddot{x} = \dfrac{\mathbf{F_i}}{\mathbf{M_d}}$



'Real': $\mathbf{F_\Sigma} = \mathbf{M_r}\ddot{\mathbf{x}}$

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solve for Motor force

$$\Rightarrow \quad \mathbf{F_m} = \mathbf{F_i}\frac{\mathbf{M_r}}{\mathbf{M_d}} - \mathbf{F_i}$$

Interaction *Control*

Impedance *feedback* control

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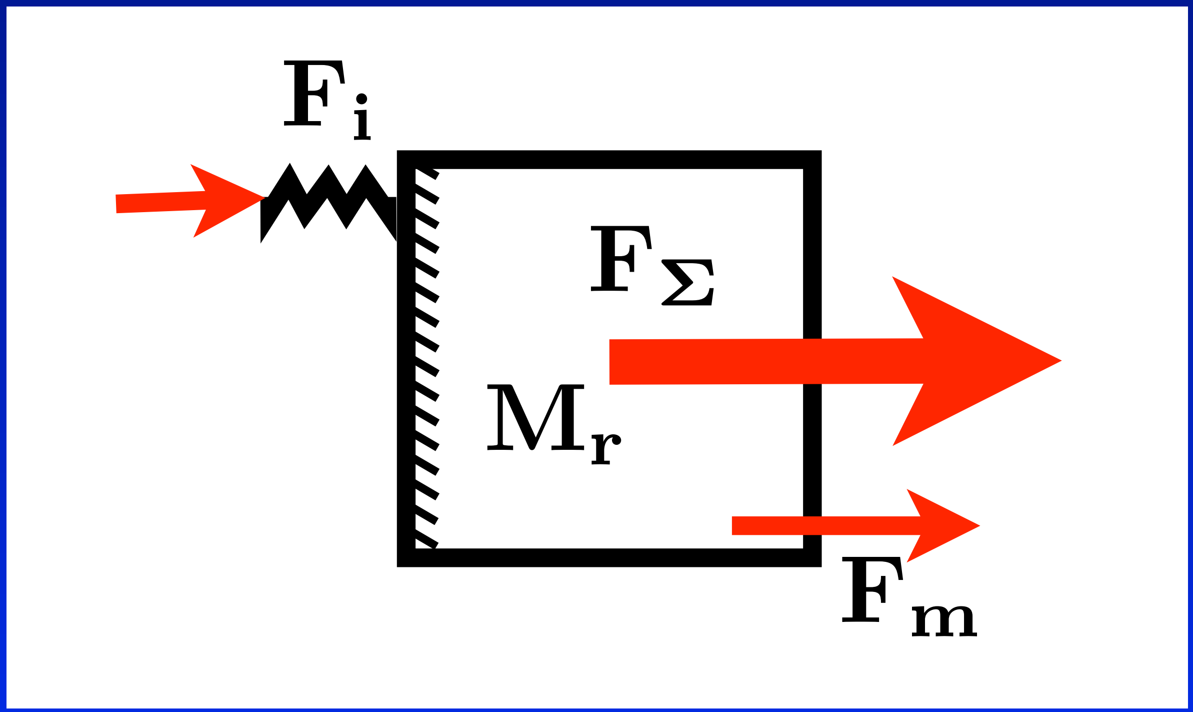

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solve for Motor force

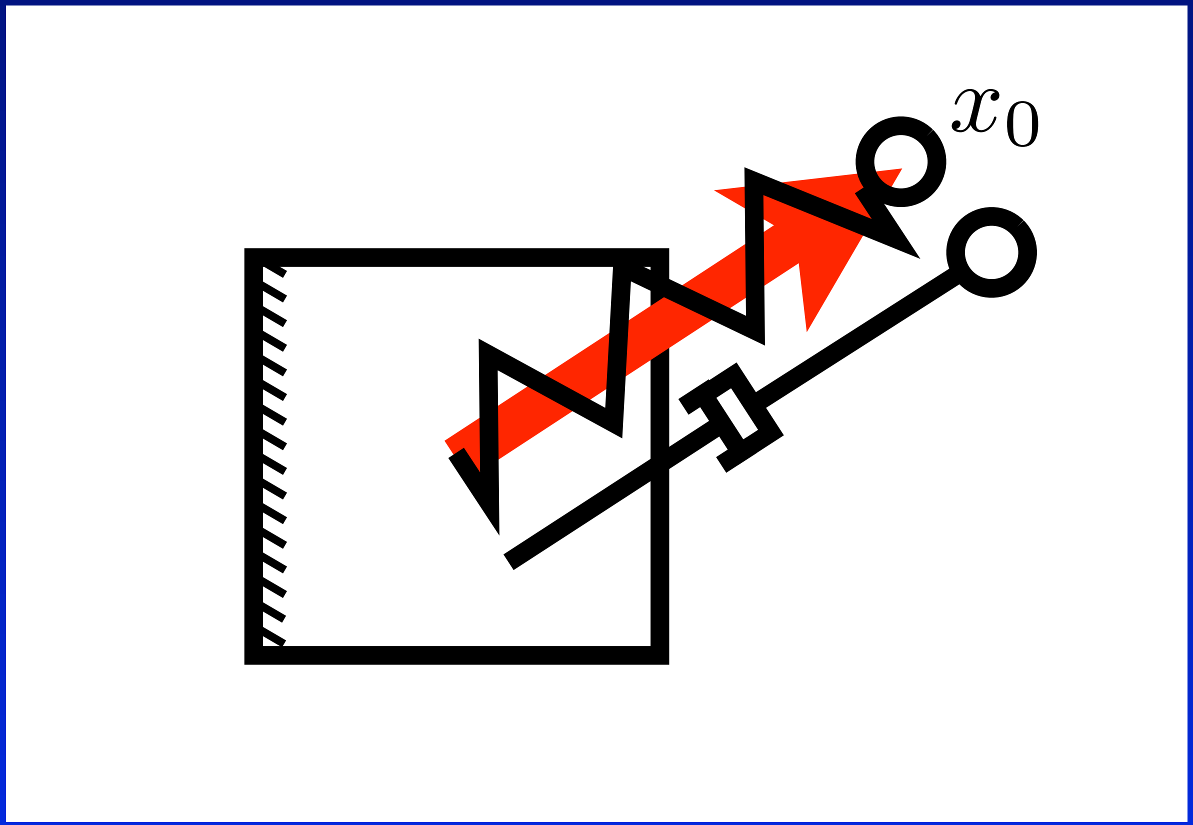
$$\Rightarrow \quad \mathbf{F_m} = \mathbf{F_i}\frac{\mathbf{M_r}}{\mathbf{M_d}} - \mathbf{F_i}$$

Idea: a force should lead to certain acceleration, control acceleration to be the one expected by monitoring interaction force and adding whatever force is needed to accelerate in accordance with desired impedance

Interaction Control

Impedance *feedback* control

Desired mass plus desired spring damper



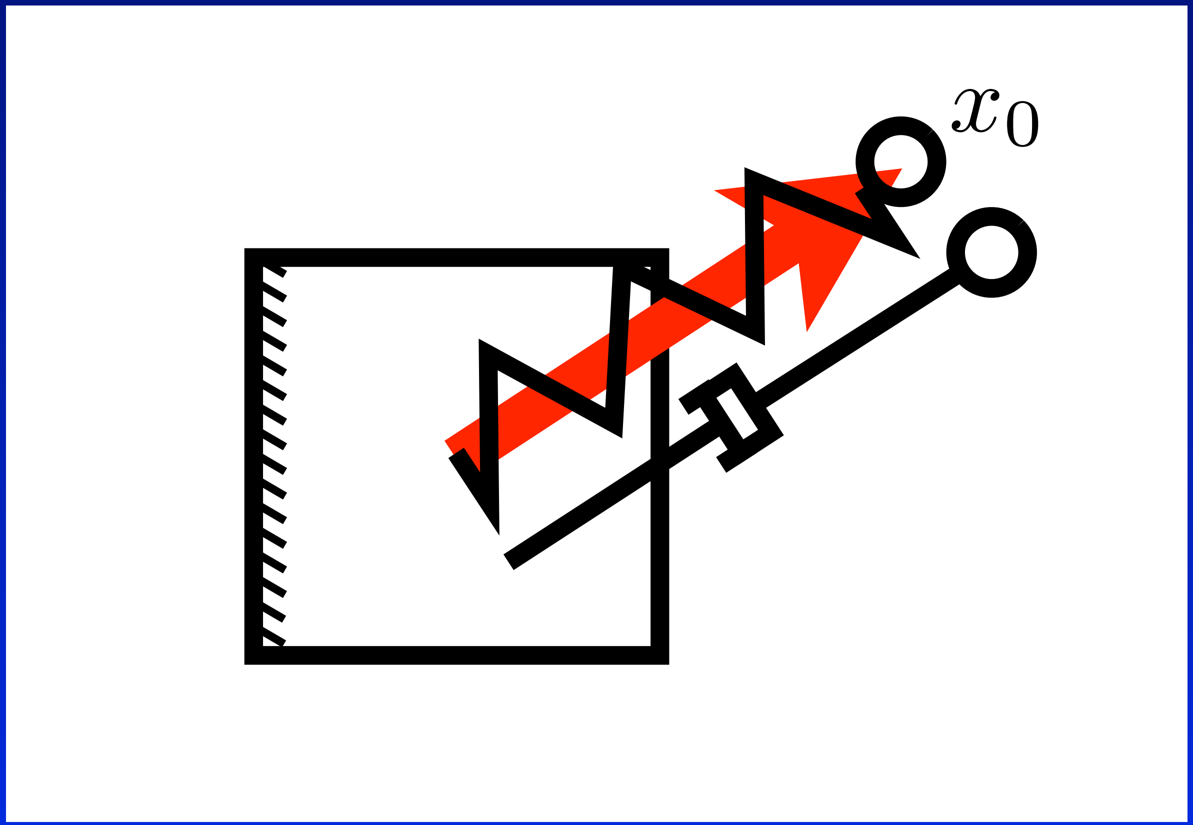
$$F = K_s(x_0 - x)$$

$$F = K_d(v_0 - v)$$

Interaction Control

Impedance *feedback* control

Desired mass plus desired spring damper



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Expected acceleration:

Interaction Control

Impedance *feedback* control

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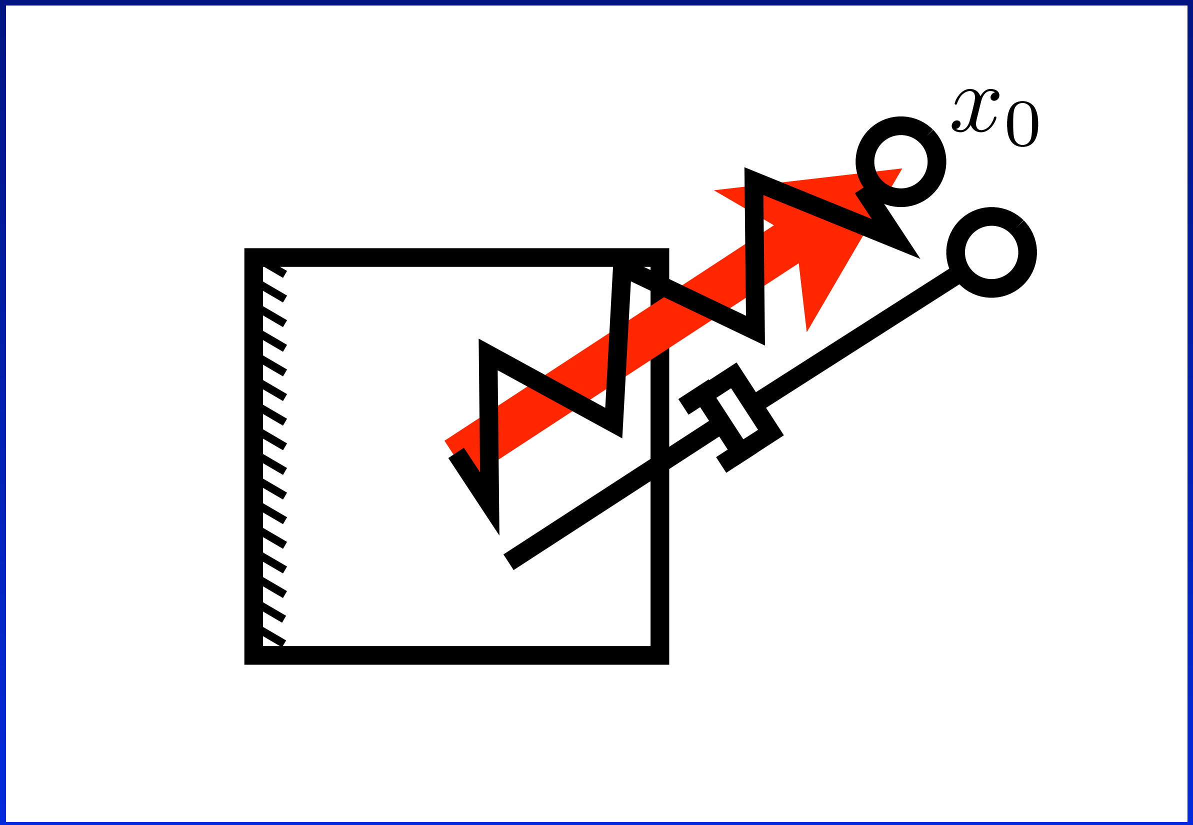

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Interaction Control

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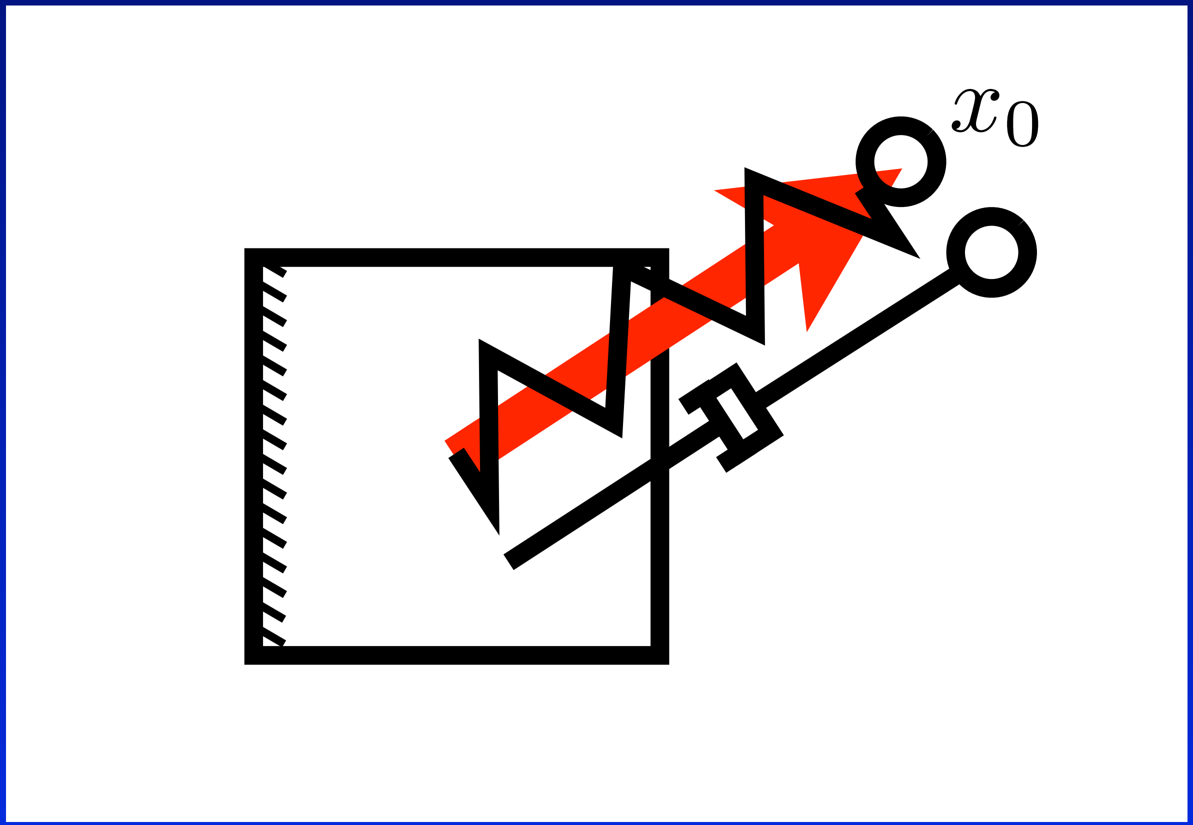

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Interaction Control

Impedance *feedback* control

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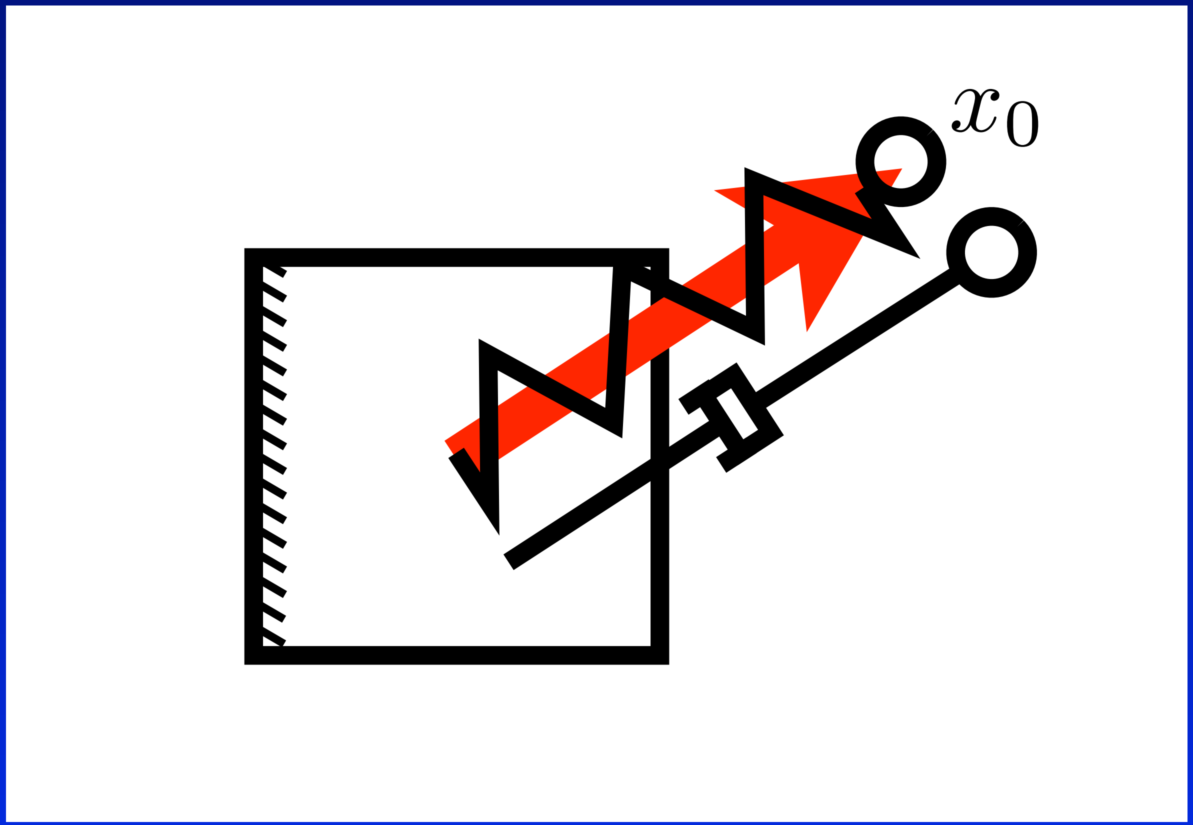

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Interaction Control

Impedance *feedback* control

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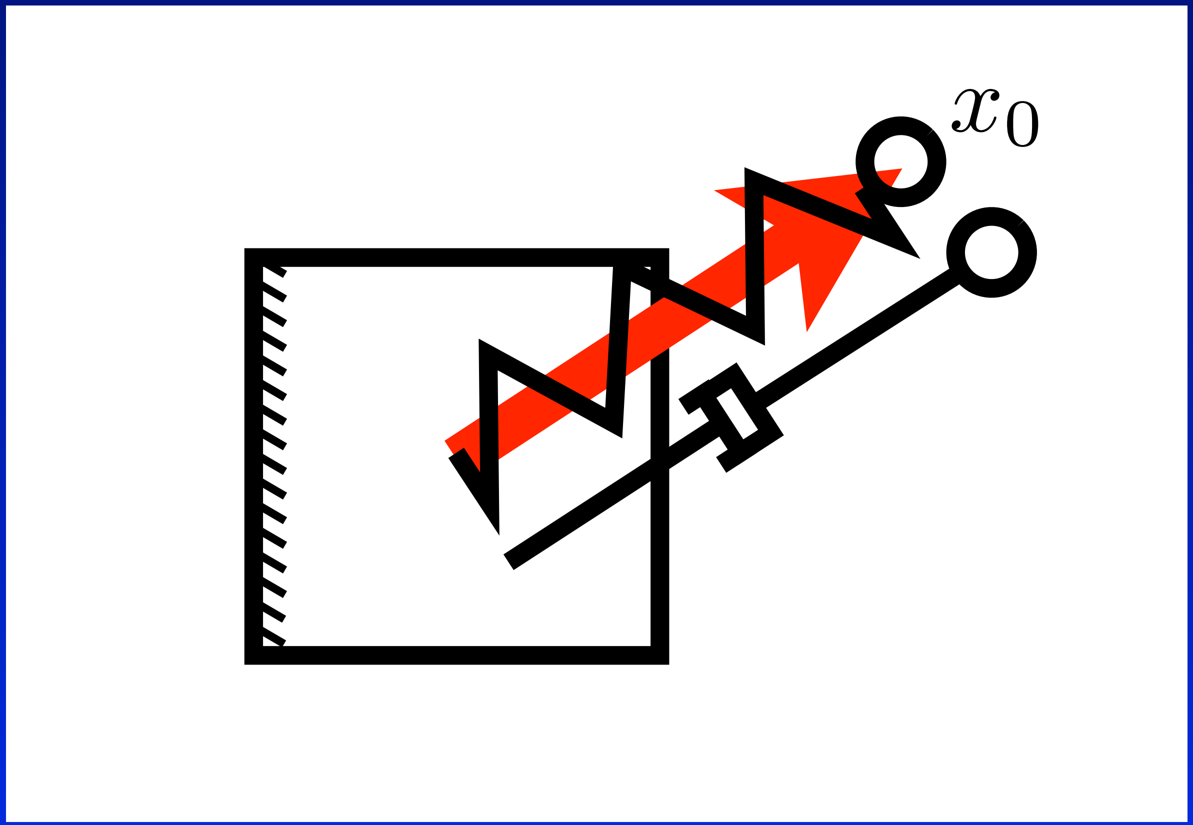

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Expected acceleration: $\ddot{x} = \frac{\mathbf{F_i}}{\mathbf{M_d}}$

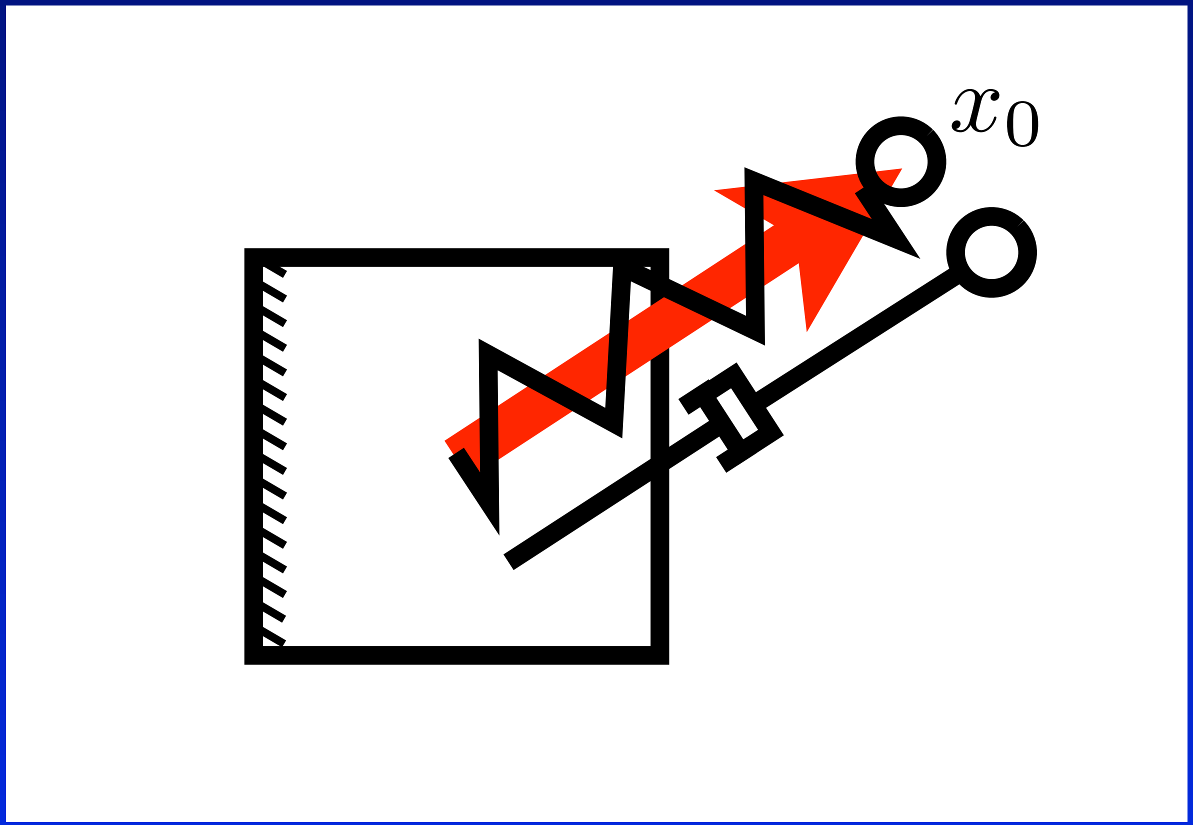
'Real': $\mathbf{F_\Sigma} = \mathbf{M_r}\ddot{\mathbf{x}}$

$$\mathbf{F_\Sigma} = \mathbf{F_m} + \mathbf{F_i}$$

Interaction Control

Impedance *feedback* control

Desired mass plus desired spring damper



$$F = K_s(x_0 - x)$$

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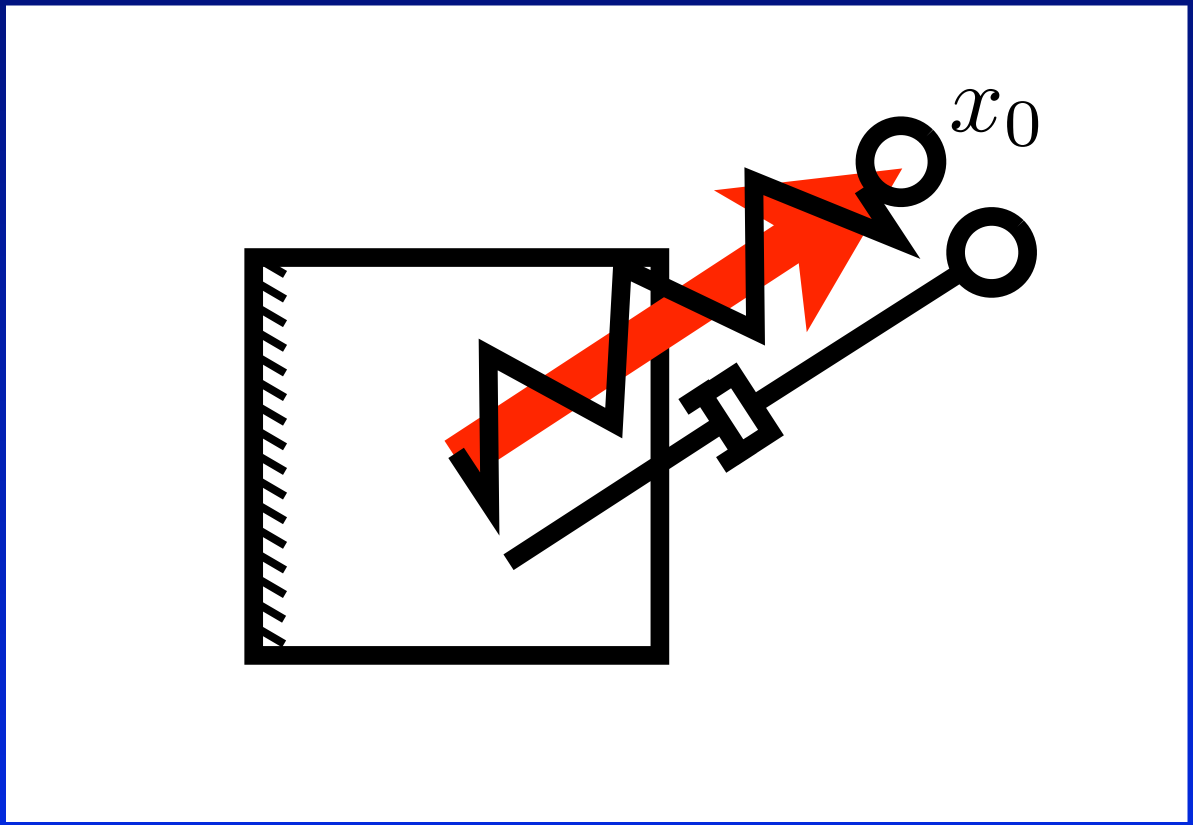

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solve for Motor force

Interaction Control

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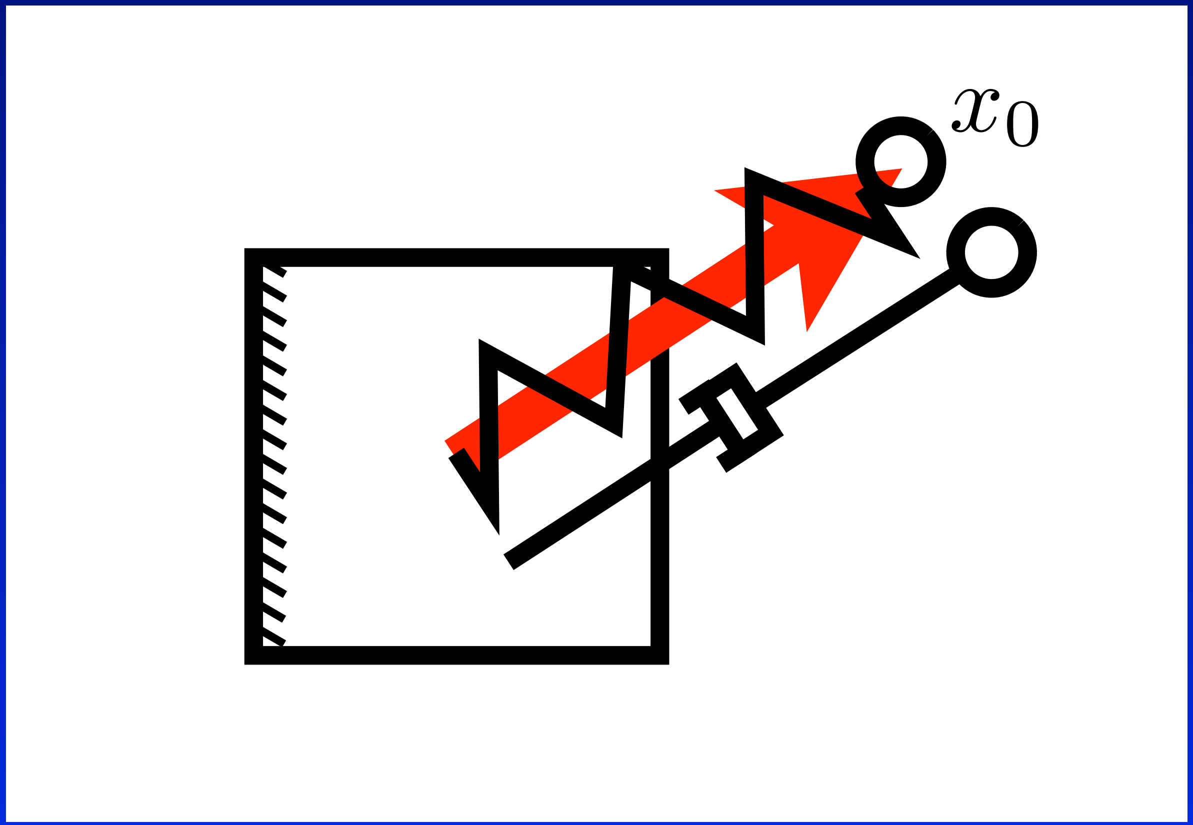

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$$\mathbf{F_\Sigma = F_m + F_i}$$

solve for Motor force

$$\mathbf{F_m = F_i \frac{M_r K}{M_d}(x_o - x) - F_i}$$

Impedance control

Spring-mass-damper, articulated system

map endeffector accelerations in joint accelerations

$$\ddot{\mathbf{q}} = \mathbf{J}^{-1}\ddot{\mathbf{x}}$$

$$\begin{aligned}
\mathbf{Tact} &= I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}K[\mathbf{X}_0 - L(\theta)] + S(\theta) \\
&+ I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}B[\mathbf{V}_0 - \mathbf{J}(\theta)\omega] + V(\omega) \\
&+ I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{Fint} - \mathbf{J}^{t}(\theta)\mathbf{Fint} \\
&- I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega) + C(\theta,\omega)
\end{aligned}$$

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+ \; & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}B[\mathbf{V}_0 - \mathbf{J}(\theta)\omega] + V(\omega) \\
+ \; & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{Fint} - \mathbf{J}^{t}(\theta)\mathbf{Fint} \\
- \; & I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega) + C(\theta,\omega)
\end{aligned}
$$

Spring

Impedance control

Spring-mass-damper, articulated system

map endeffector accelerations in joint accelerations

$$\ddot{\mathbf{q}} = \mathbf{J}^{-1}\ddot{\mathbf{x}}$$

$$\begin{aligned}\mathrm{Tact} = {} & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}K[\mathbf{X}_0 - L(\theta)] \\ & + I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}B[\mathbf{V}_0 - \mathbf{J}(\theta)\omega] \\ & + I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{F}\mathrm{int} - \mathbf{J}^{t}(\theta)\mathbf{F}\mathrm{int} \\ & - I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega) + C(\theta,\omega)\end{aligned}$$

Spring

Damper

Impedance control

Spring-mass-damper, articulated system

map endeffector accelerations in joint accelerations

$$\ddot{\mathbf{q}} = \mathbf{J}^{-1}\ddot{\mathbf{x}}$$

$$
\begin{aligned}
\mathrm{Tact} = \; & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}K[\mathbf{X}_0 - L(\theta)] \quad \text{Spring} \\
+ \; & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}B[\mathbf{V}_0 - \mathbf{J}(\theta)\omega] \quad \text{Damper} \\
\text{Mass} \quad & I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{F}\mathrm{int} - \mathbf{J}^{\mathrm{t}}(\theta)\mathbf{F}\mathrm{int} \\
- \; & I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega) + C(\theta,\omega)
\end{aligned}
$$

Impedance control

Spring-mass-damper, articulated system

map endeffector accelerations in joint accelerations

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\end{aligned}$$

Spring

Damper

Mass

applied ex

Impedance control

Spring-mass-damper, articulated system

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Impedance control

Spring-mass-damper, articulated system

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& - I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega)
\end{aligned}$$

Spring

Damper

Mass

applied ex

gravity and Coriolis

Impedance control

Spring-mass-damper, articulated system

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$\ddot{\mathbf{q}} = \mathbf{J}^{-1}\ddot{\mathbf{x}}$

$$
\begin{aligned}
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& \quad I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{Fint} - \mathbf{J}^{t}(\theta)\mathbf{Fint} \\
&- I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega)
\end{aligned}
$$

Spring

Damper

Mass

applied ex

gravity and Coriolis

Des. Force ⇒ acceleration ⇒ joint space ⇒ torques

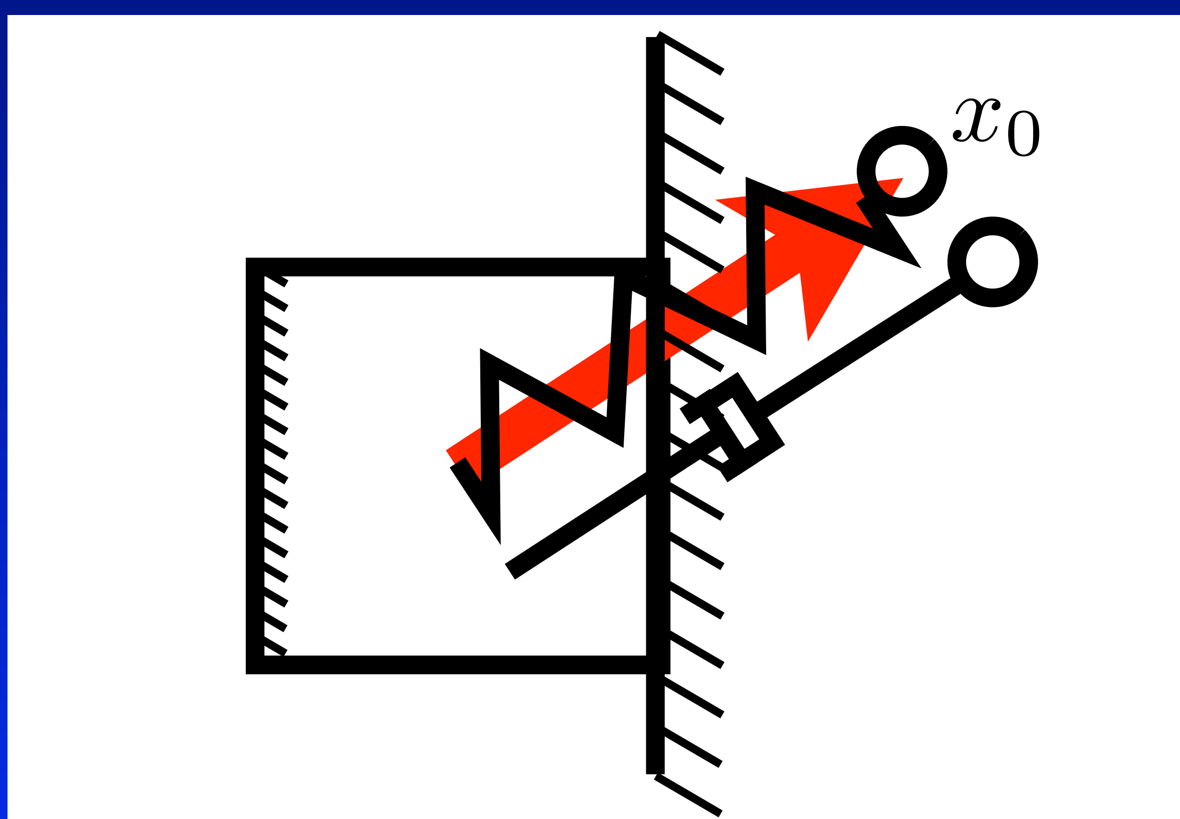
Indirect force control

Control of interation force by ...

PD control law:

$$F = K_s(x_0 - x)$$

$$F = K_d(v_0 - v)$$



Virtual trajectory

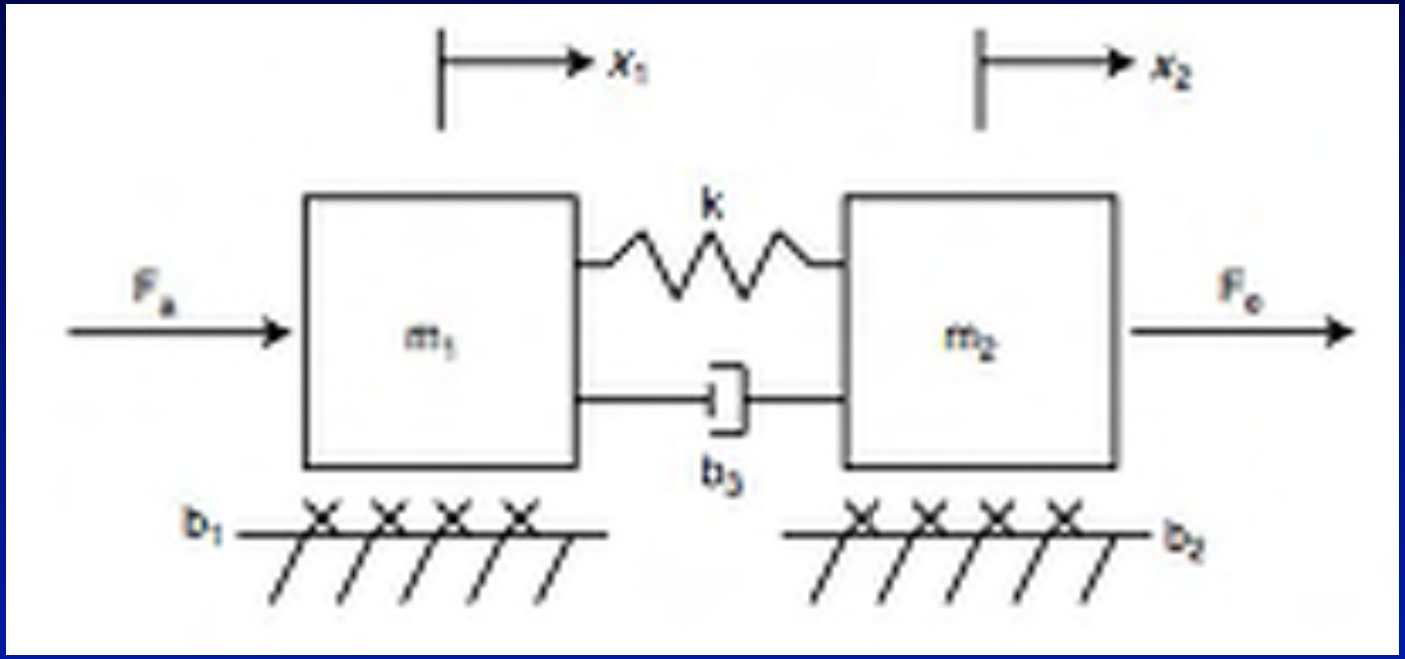
What about environment stiffness???

[Colgate 88, Hogan 05]

Stability issues

[Colgate 88, Hogan 05]

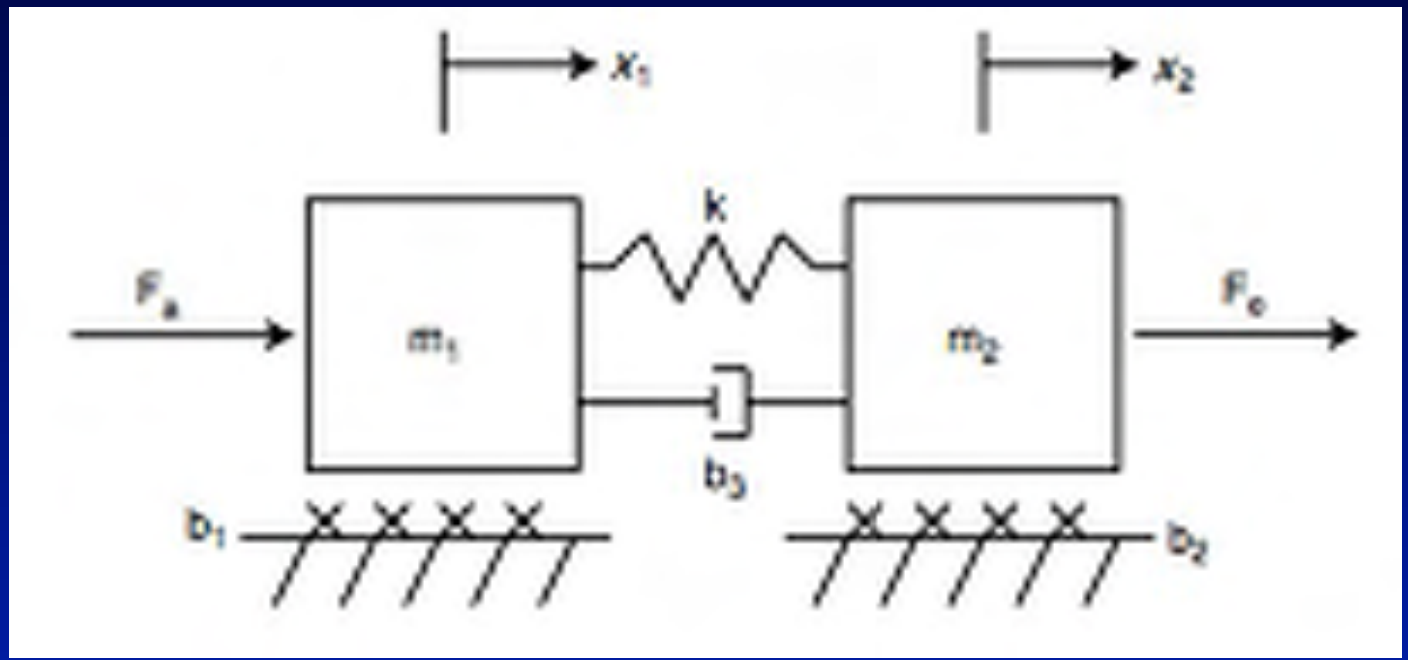
Stability issues



[Colgate 88, Hogan 05]

Stability issues

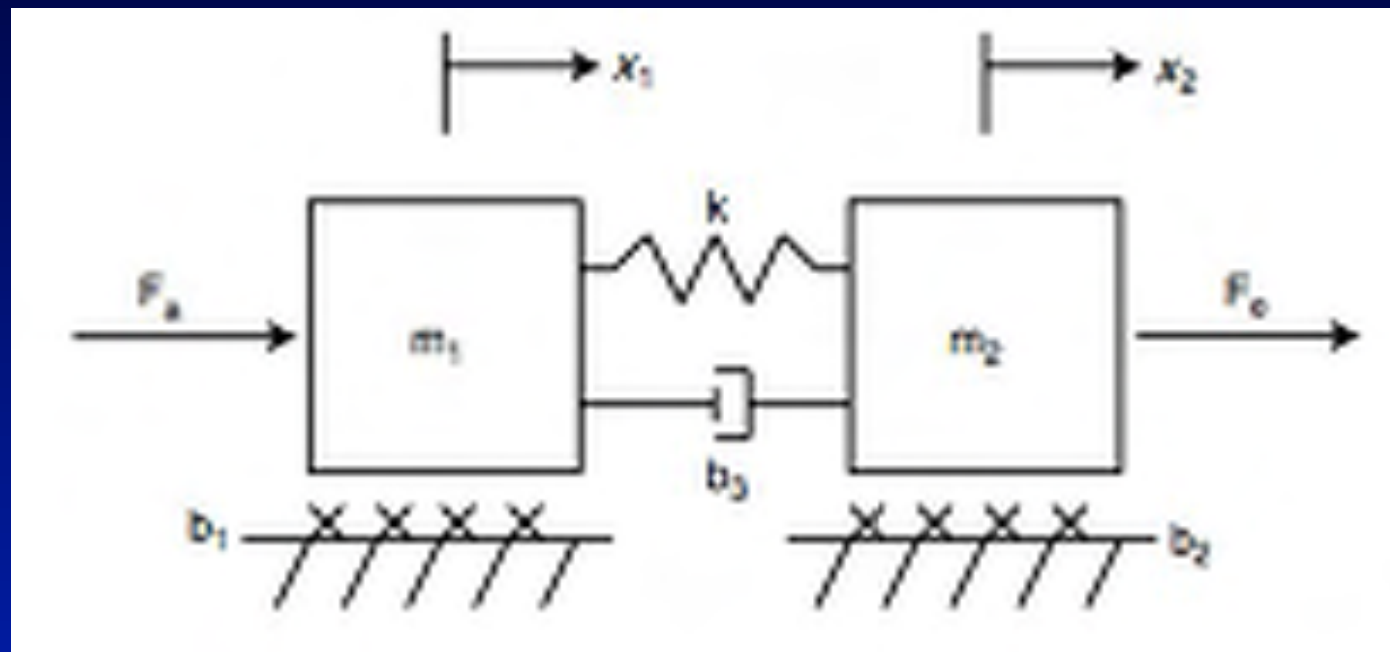
Regulate F_e through F_a



[Colgate 88, Hogan 05]

Stability issues

Regulate F_e through F_a

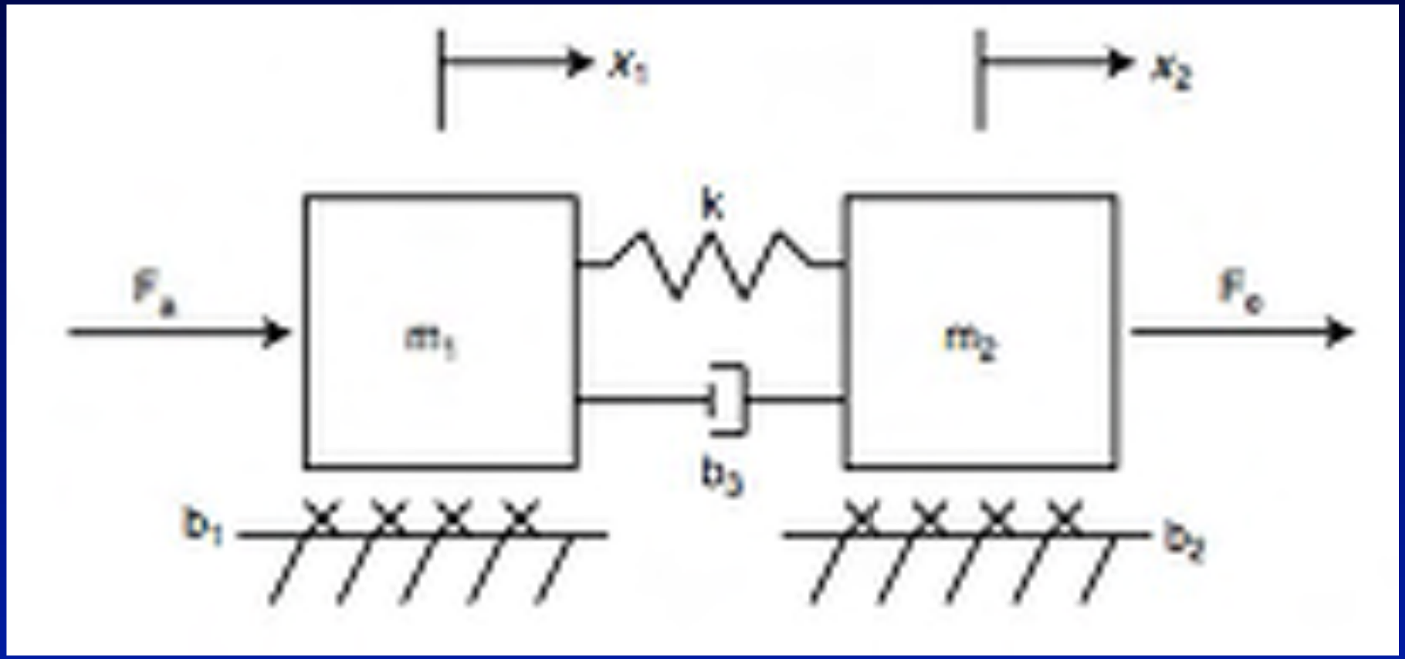


Close force feedback loop with gain K_f

[Colgate 88, Hogan 05]

Stability issues

Regulate F_e through F_a



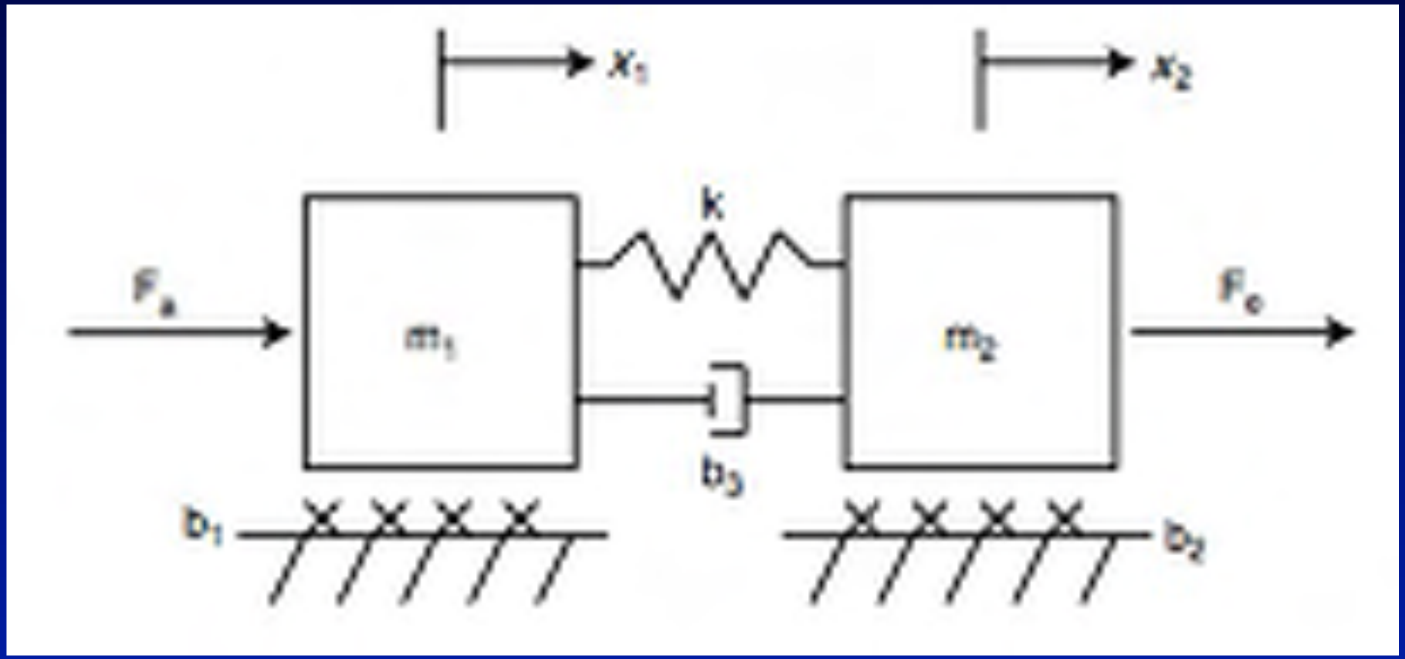
Close force feedback loop with gain K_f

Physical equivalence of closed loop system

[Colgate 88, Hogan 05]

Stability issues

Regulate F_e through F_a



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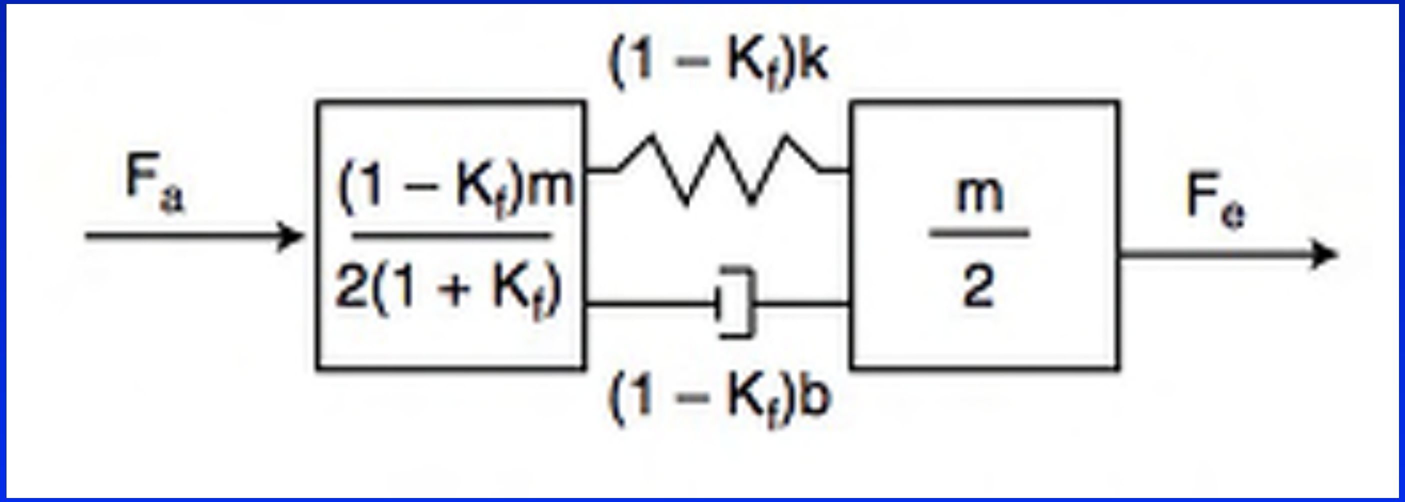
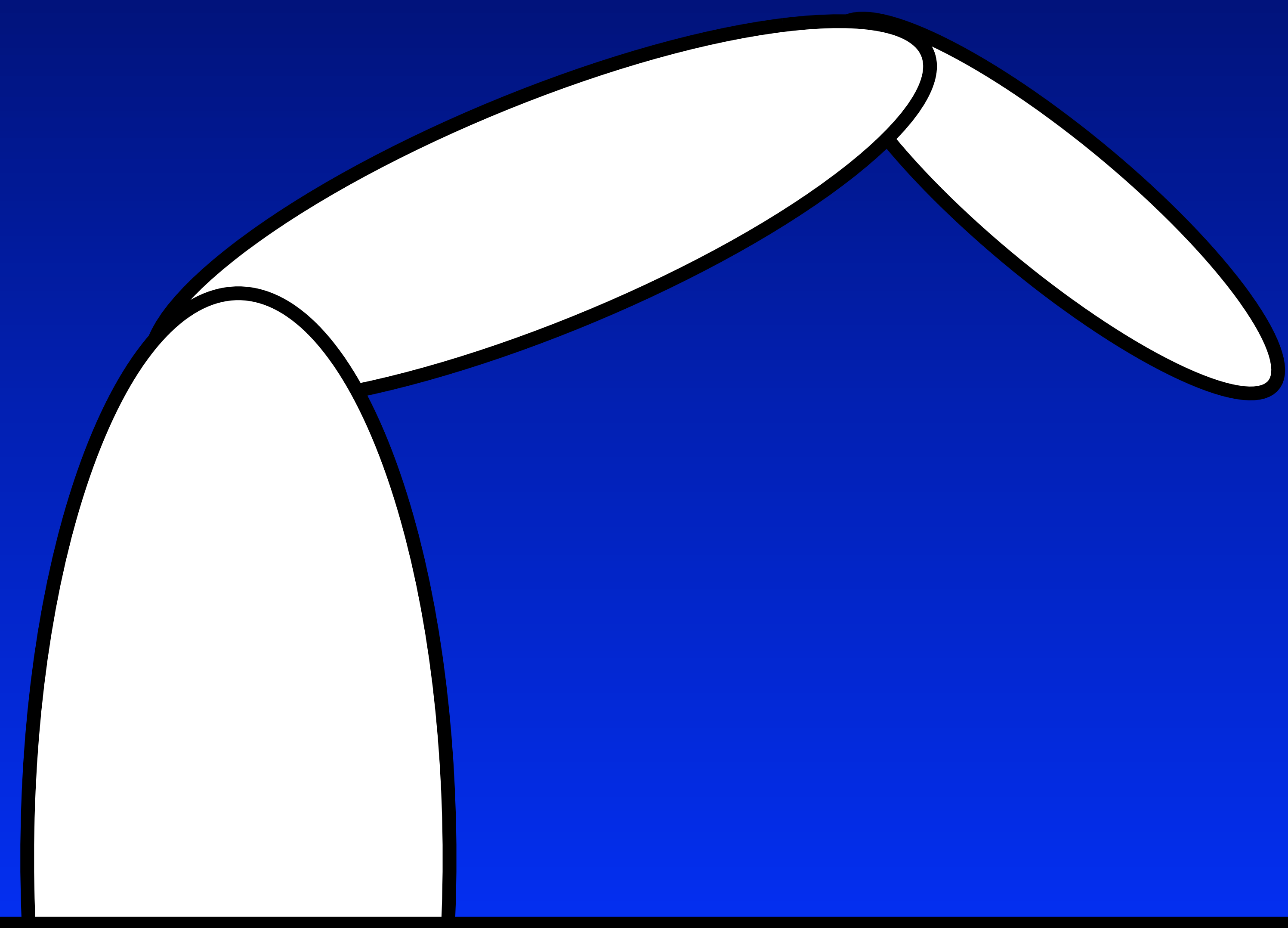


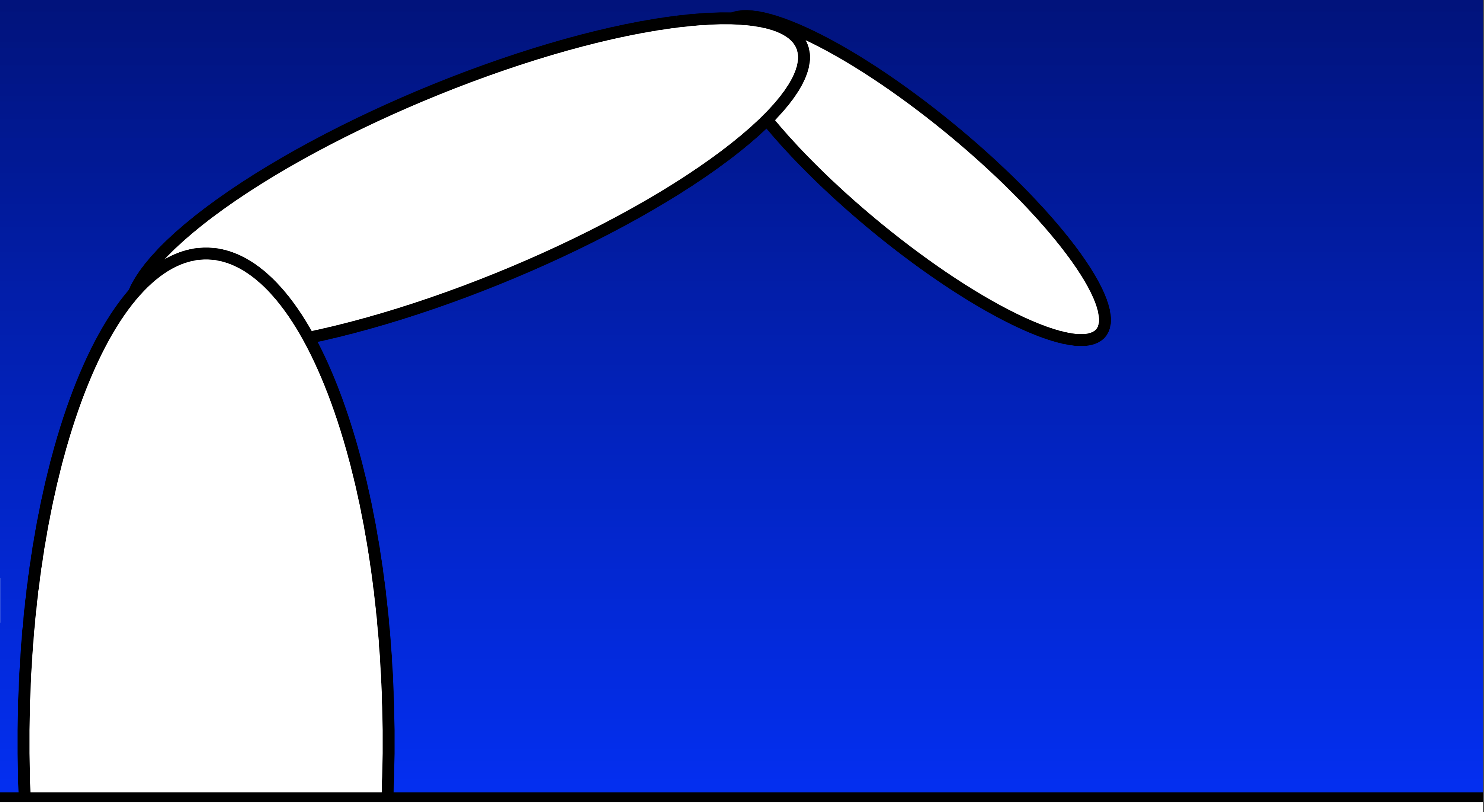
Physical equivalence of closed loop system

Force control of multibody/ articulated systems

Rigid body dynamics

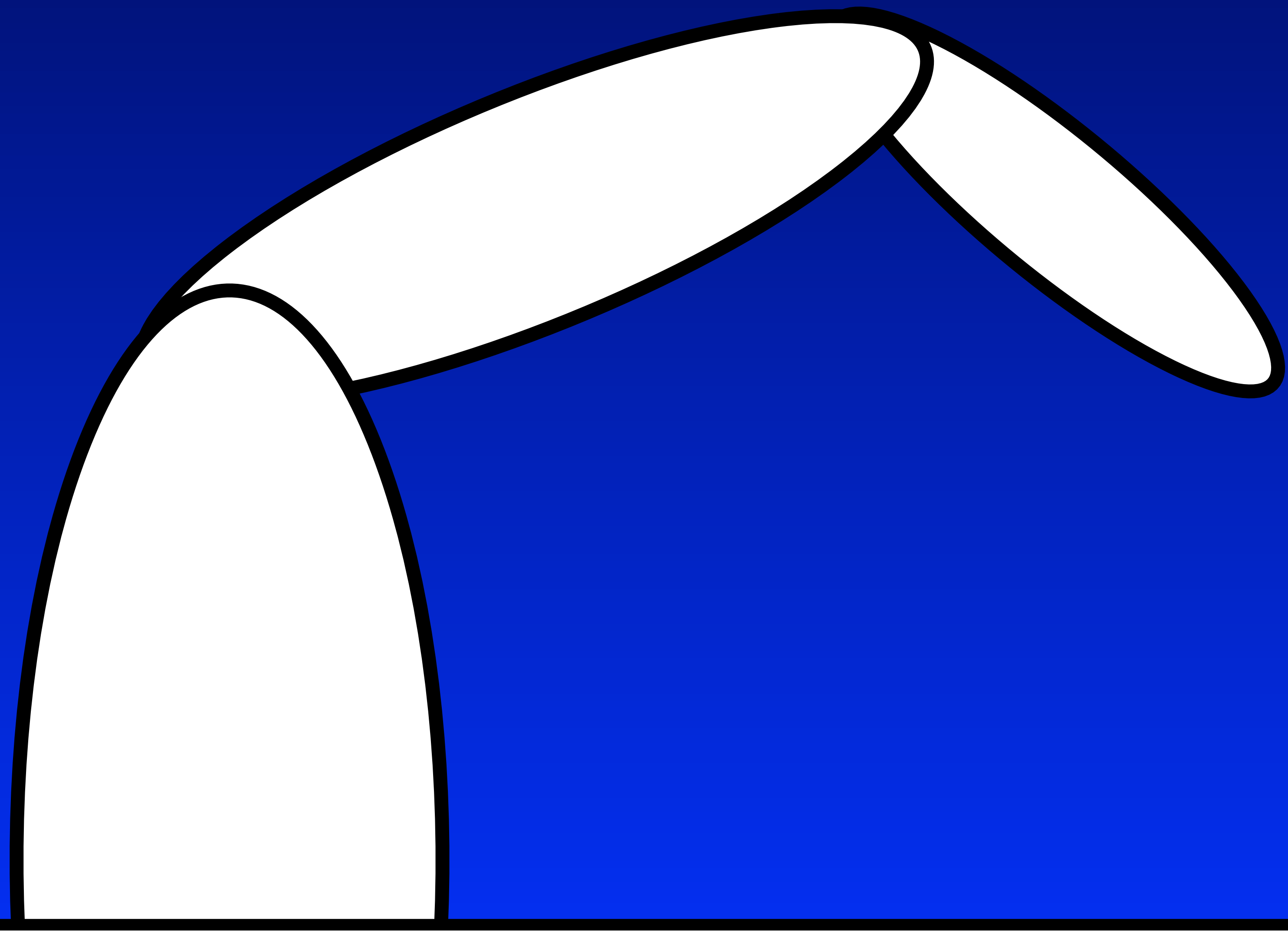


Rigid body dynamics

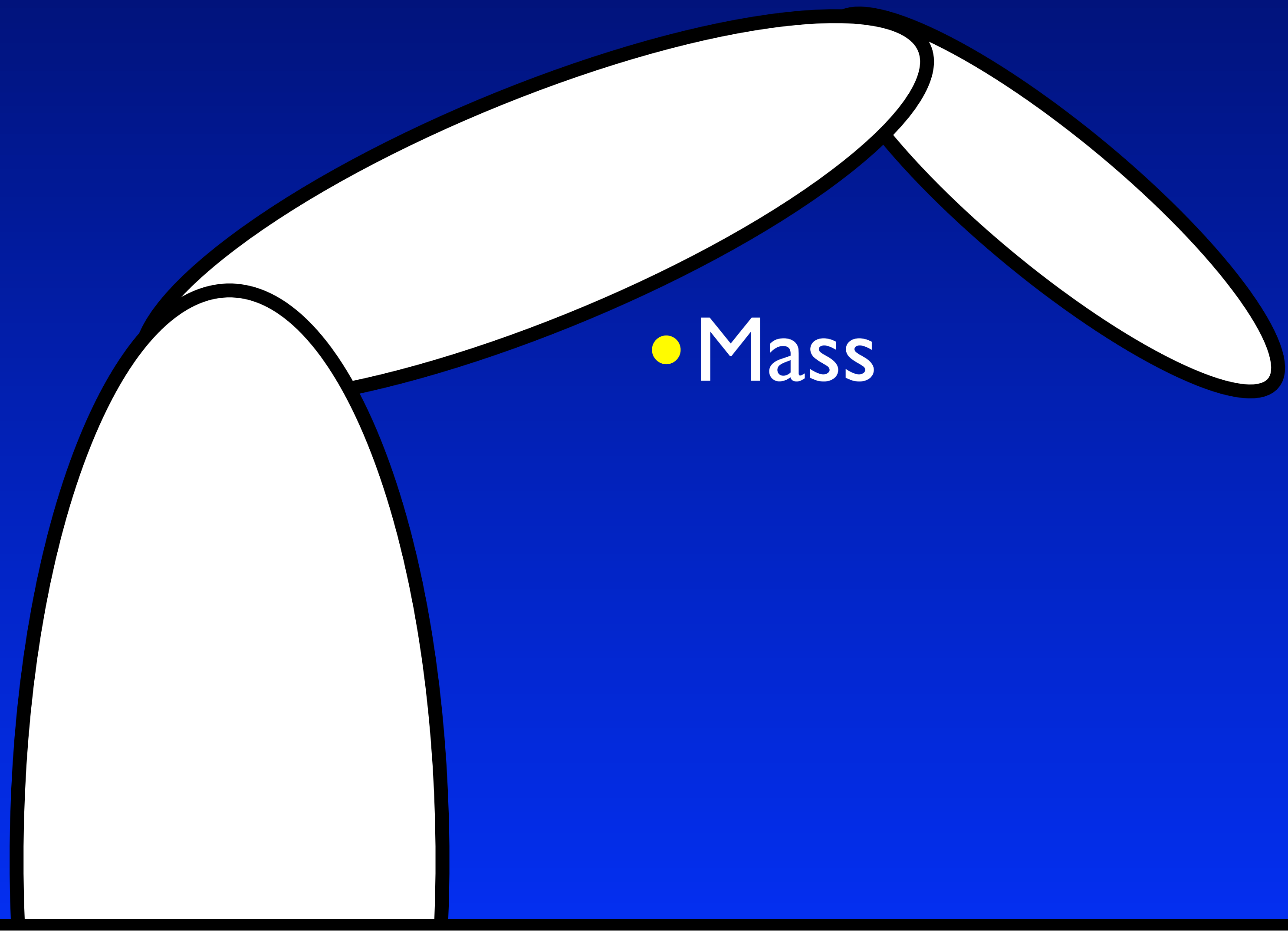


[from Kljuno 2010]

Rigid body dynamics

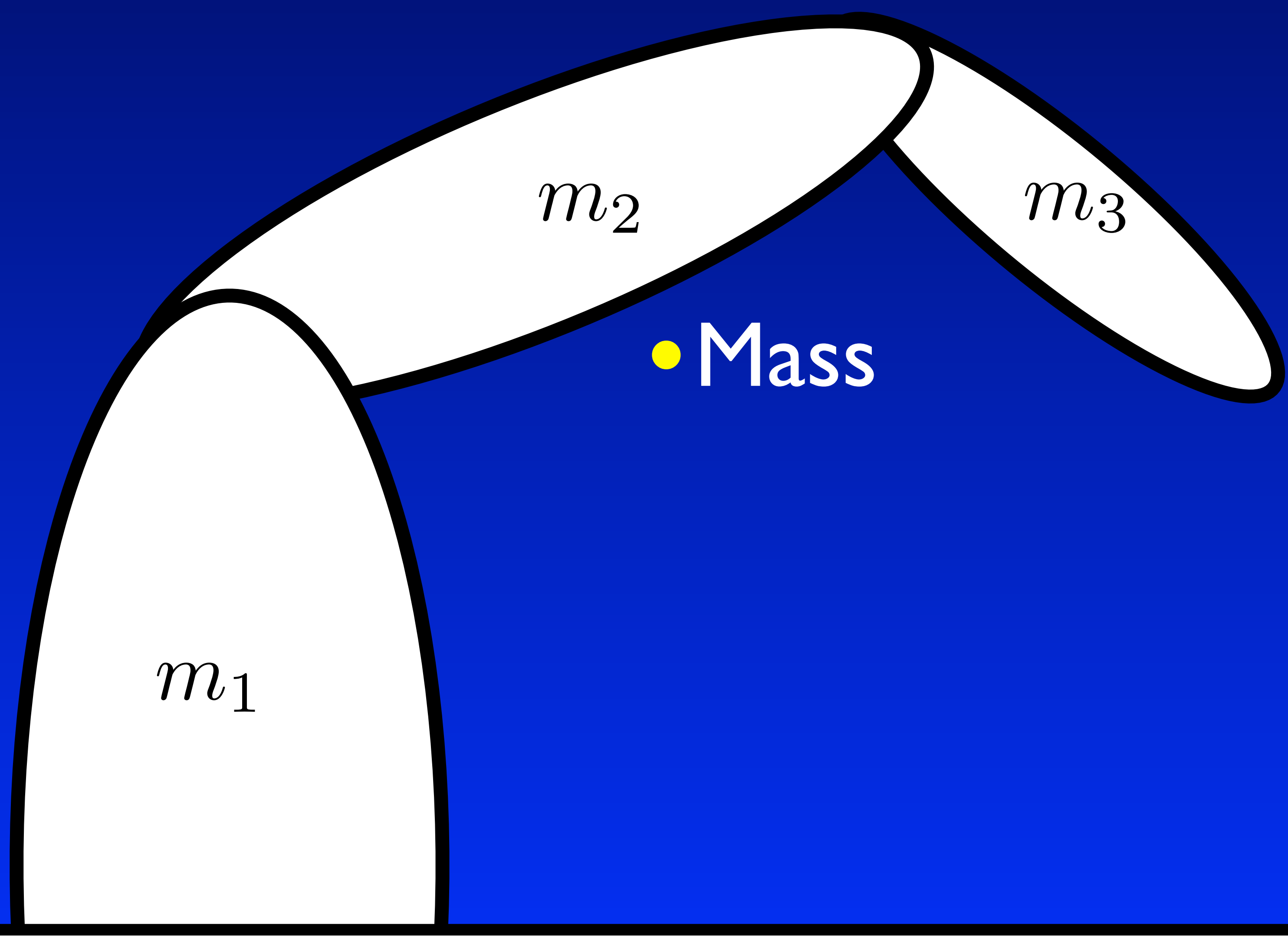


Rigid body dynamics



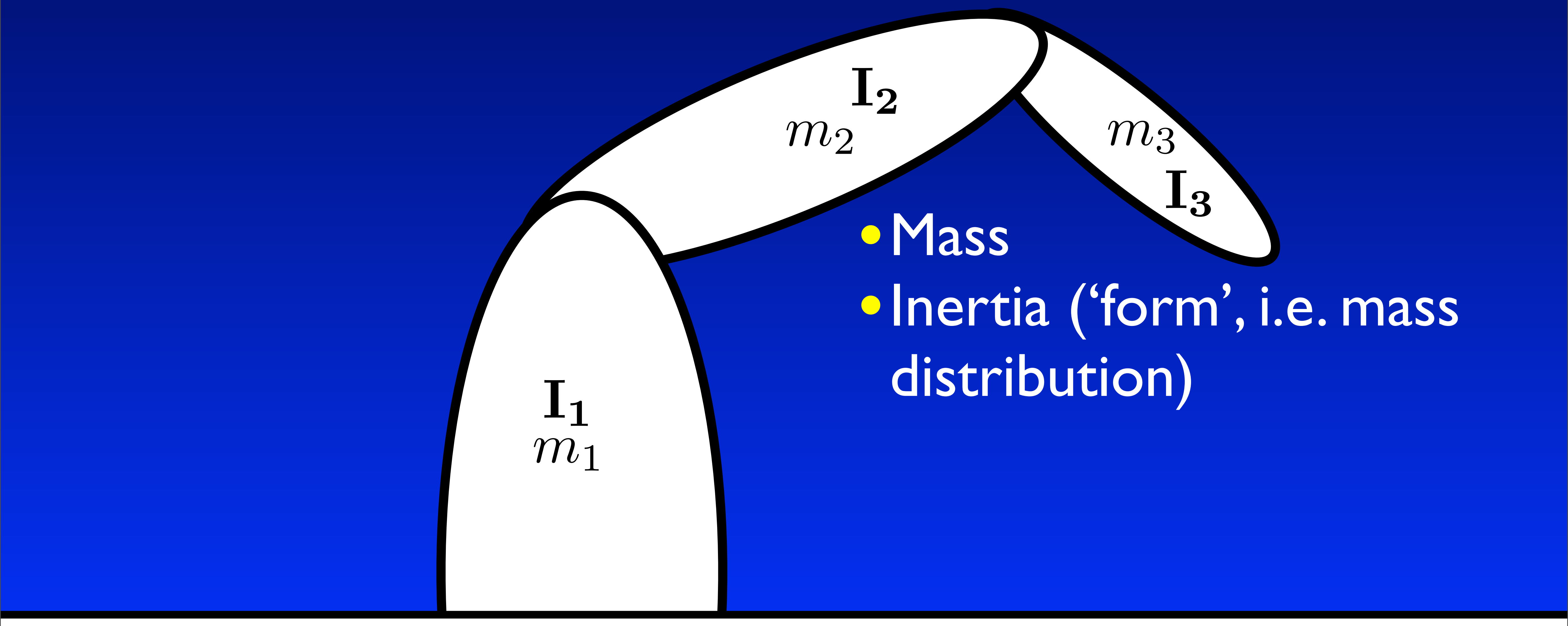
- Mass

Rigid body dynamics



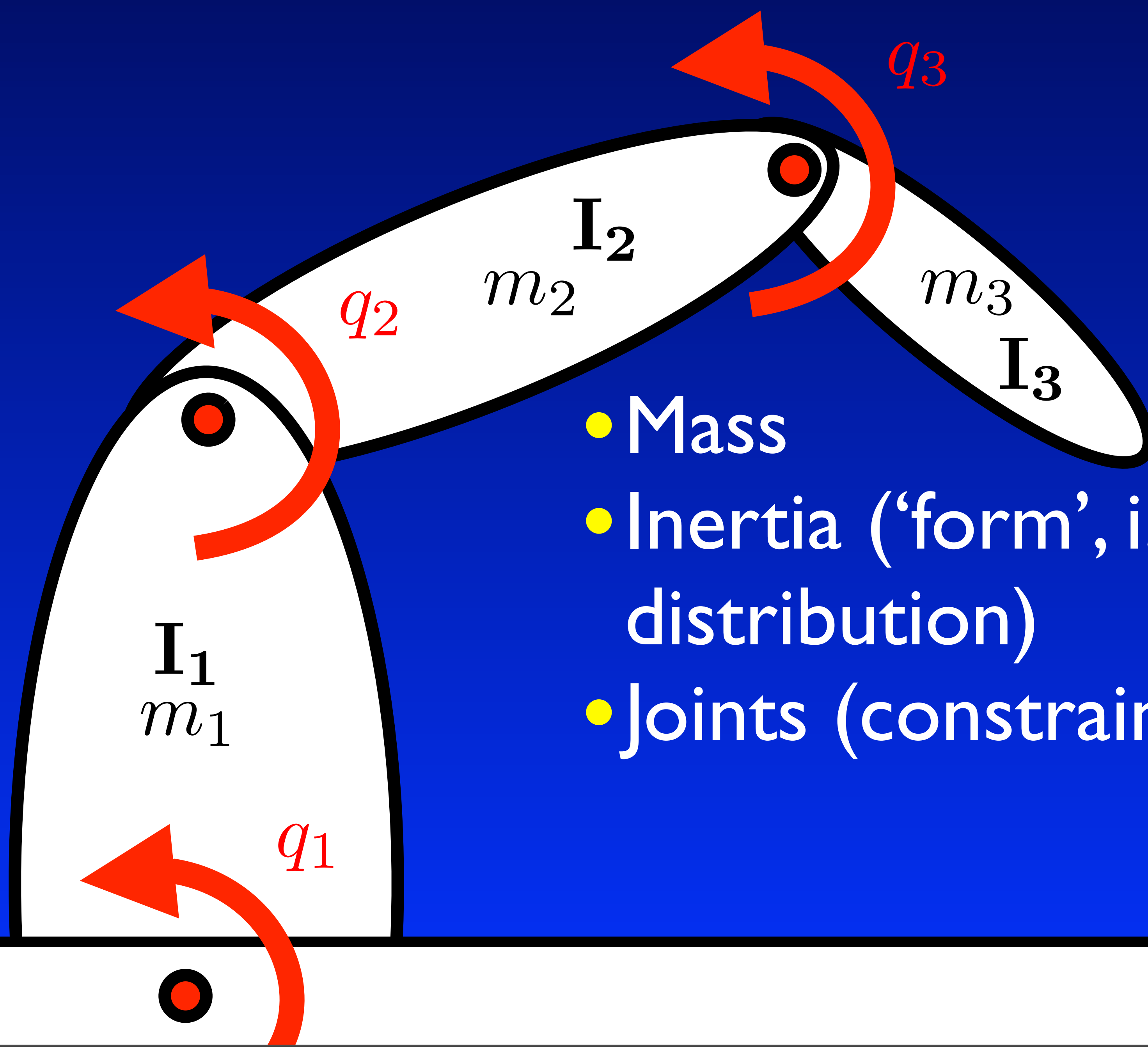
- Mass

Rigid body dynamics



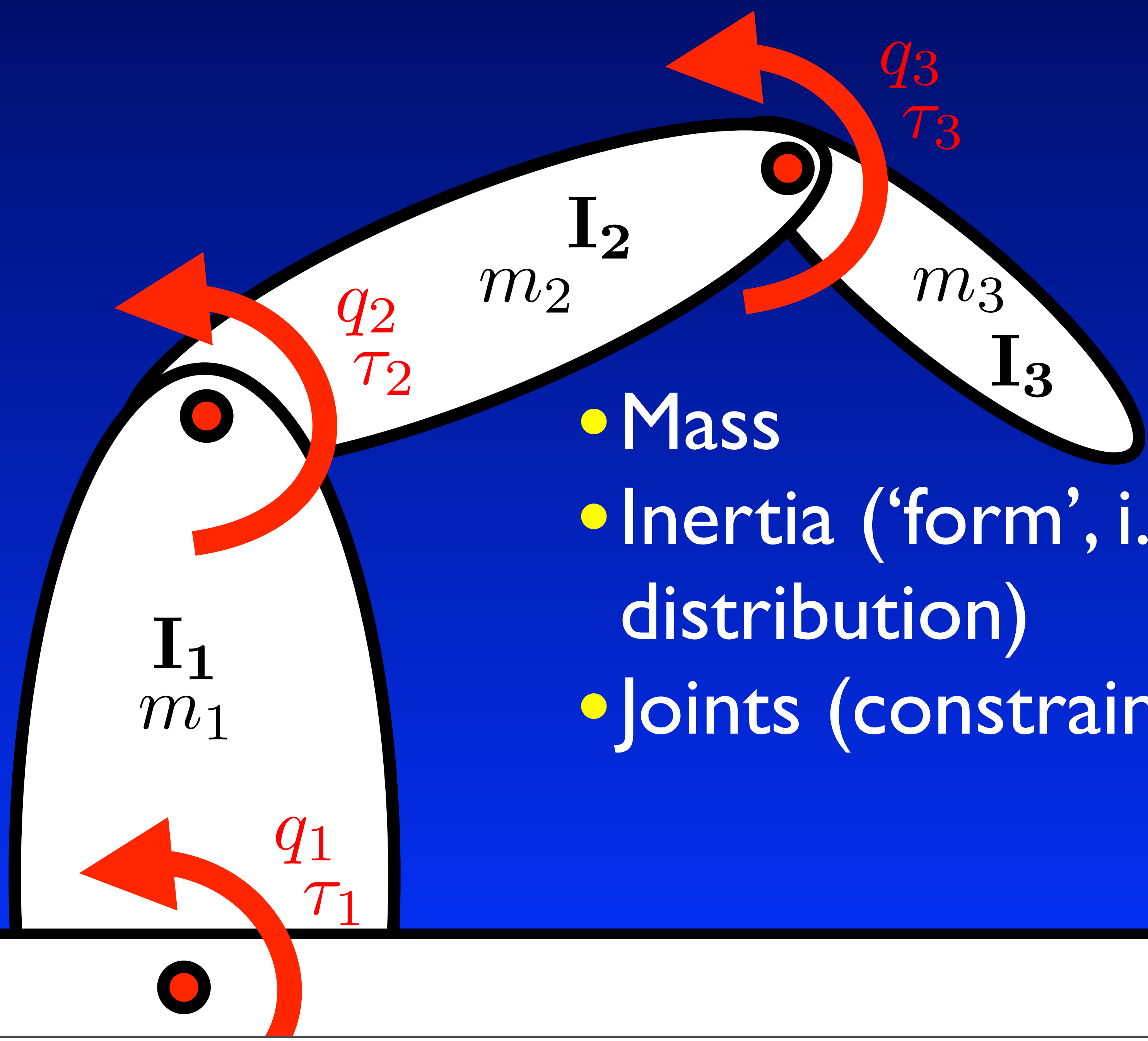
- Mass
- Inertia ('form', i.e. mass distribution)

Rigid body dynamics



- Mass
- Inertia ('form', i.e. mass distribution)
- Joints (constraints)

Rigid body dynamics



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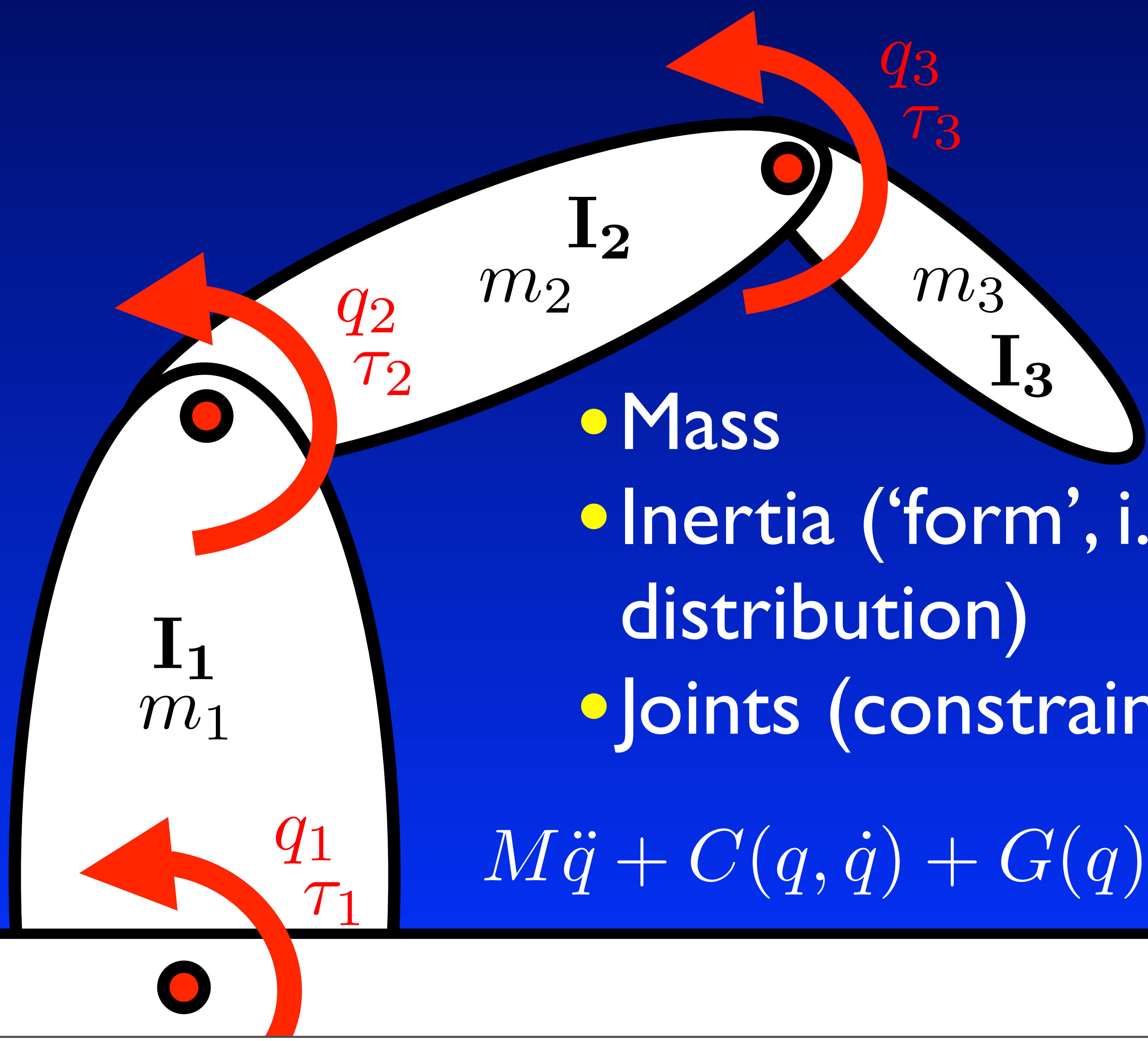
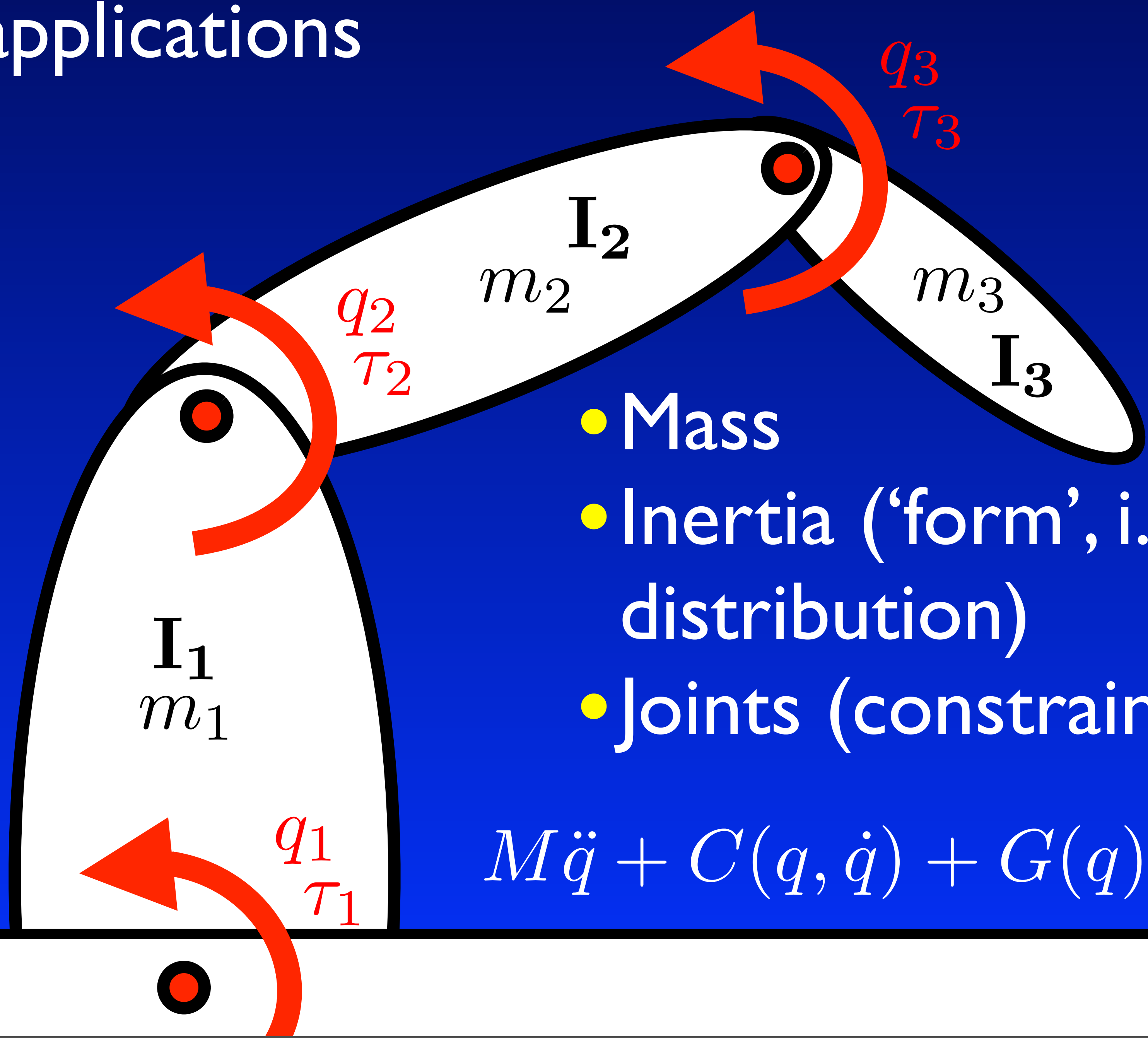


- Mass
- Inertia ('form', i.e. mass distribution)
- Joints (constraints)

$$M\ddot{q} + C(q,\dot{q}) + G(q) = \tau$$

Rigid body dynamics

Cf. Marco Hutter's lecture
Tomorrow: applications



- Mass
- Inertia ('form', i.e. mass distribution)
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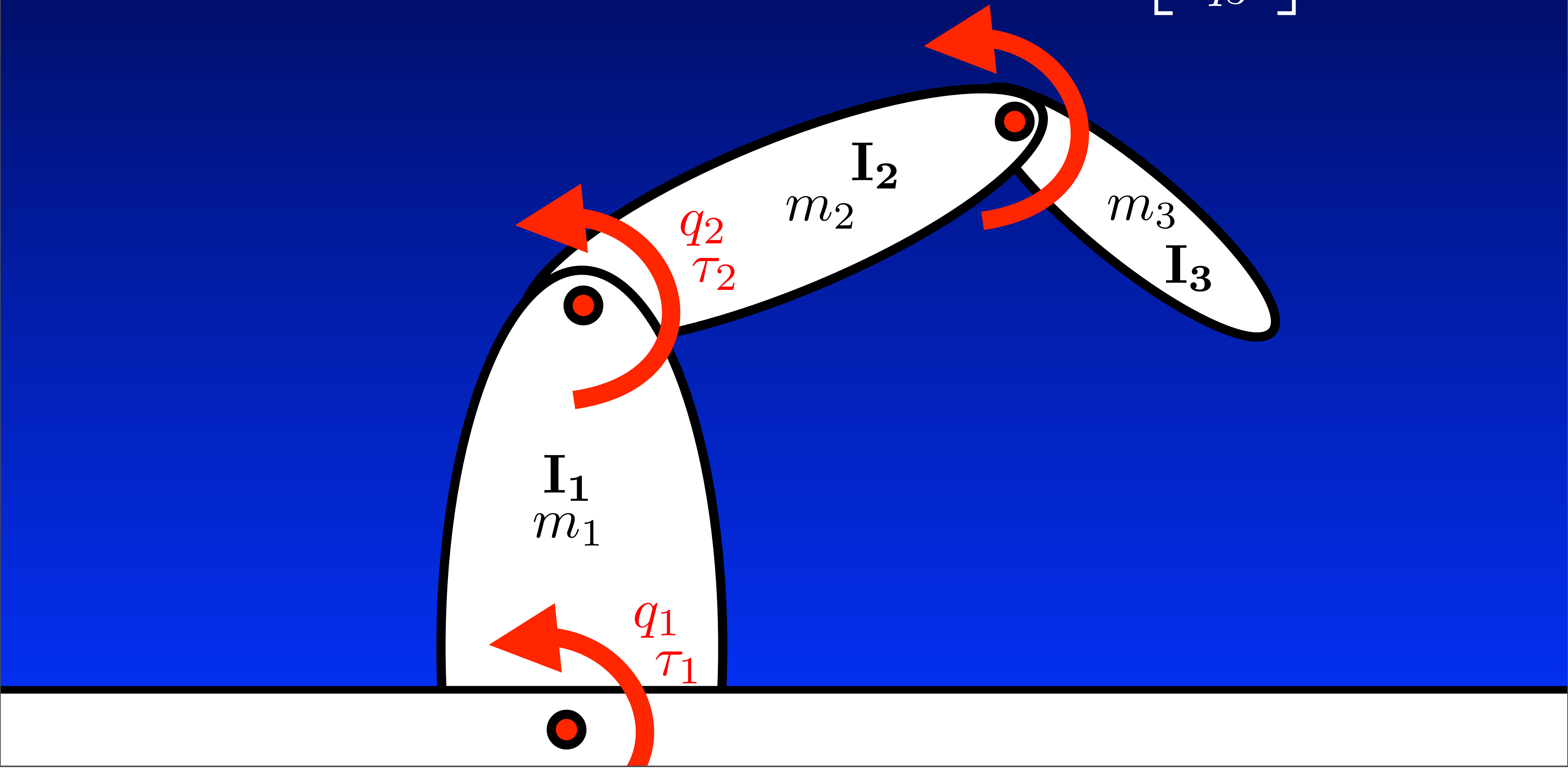
$$M\ddot{q} + C(q, \dot{q}) + G(q) = \tau$$

Kinematic chain

Joint coordinates: $q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$



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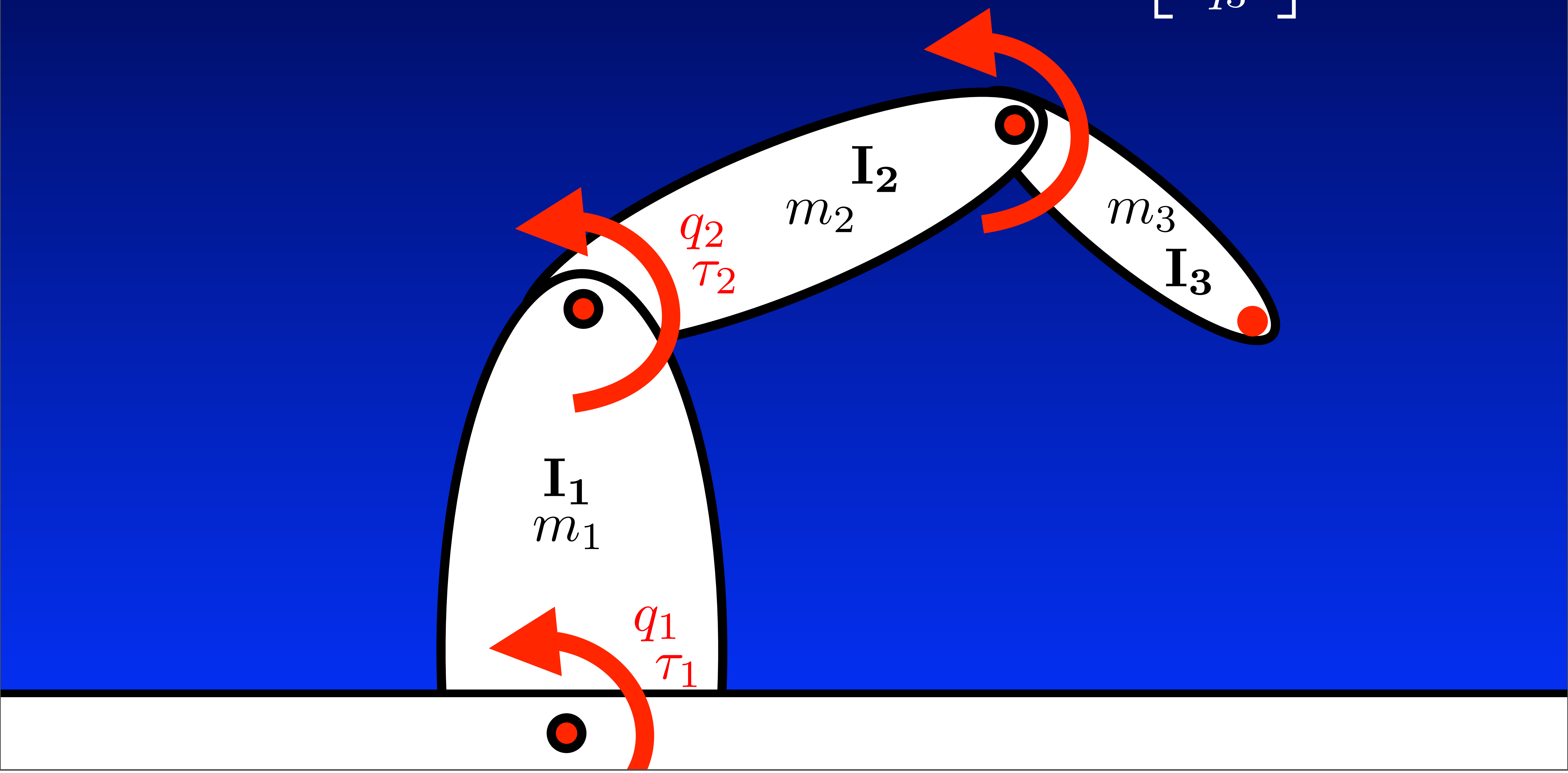

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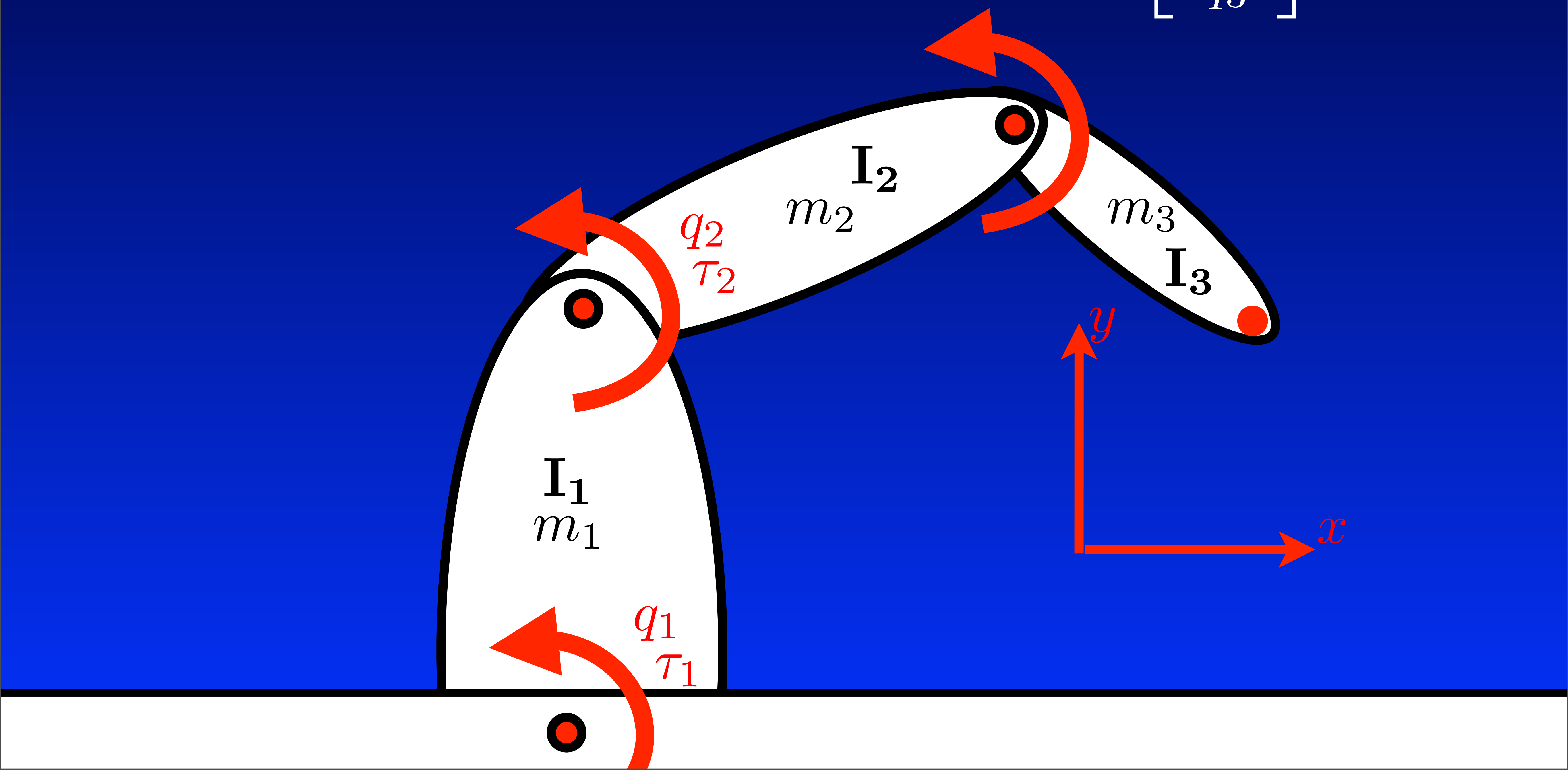

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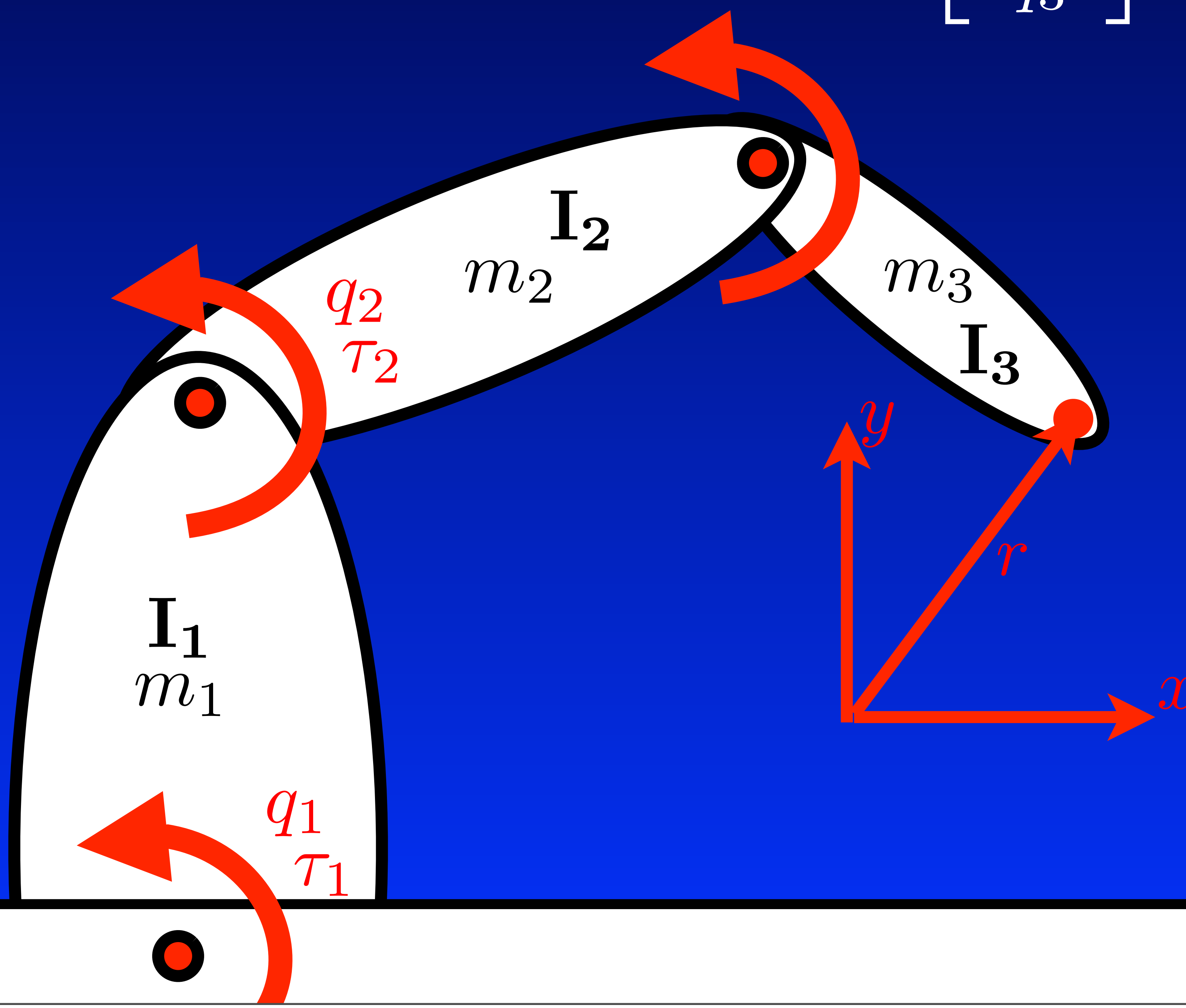
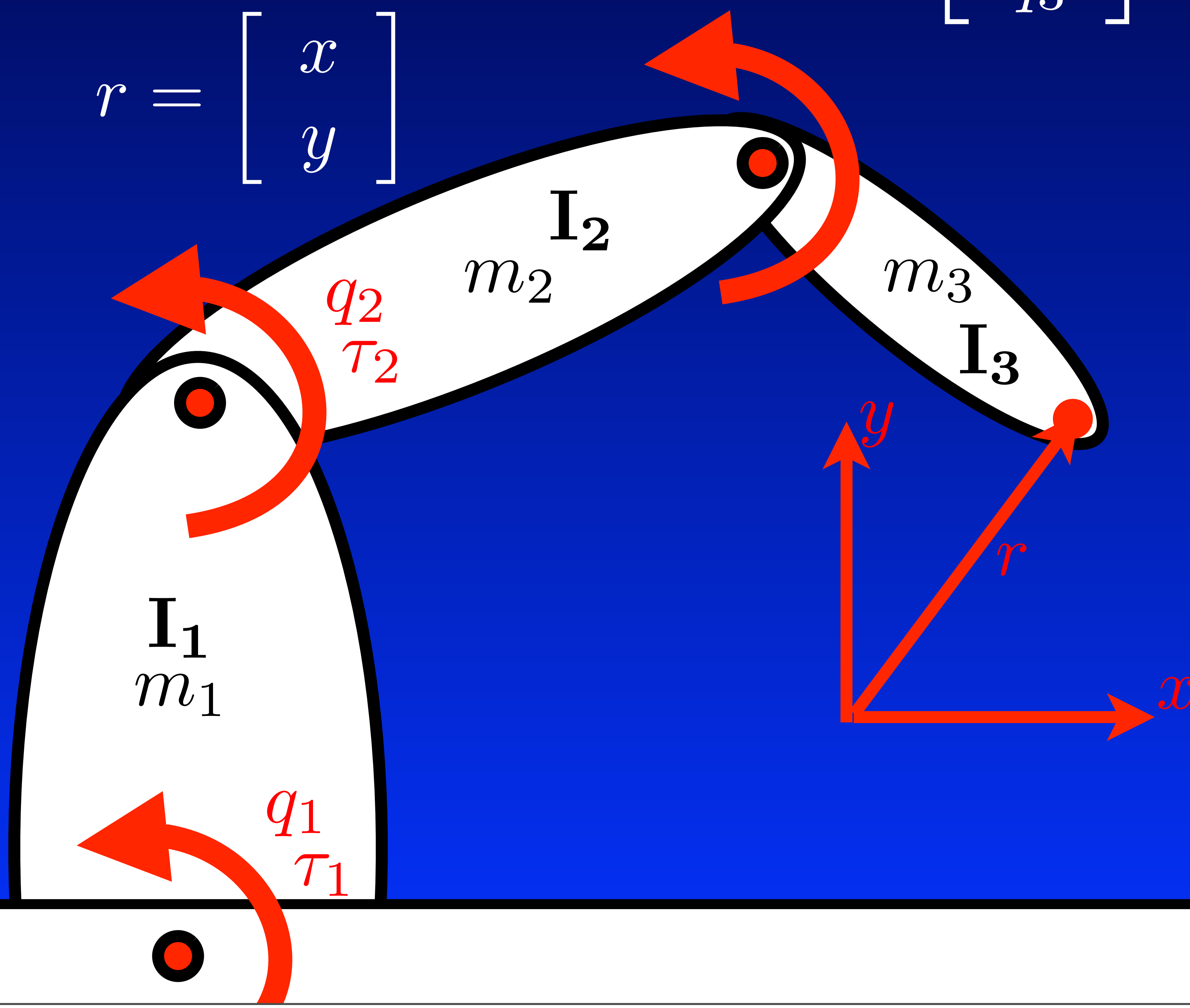


Kinematic chain

Joint coordinates: $q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$

Endeffector coordinates: $r = \begin{bmatrix} x \\ y \end{bmatrix}$



Kinematic chain

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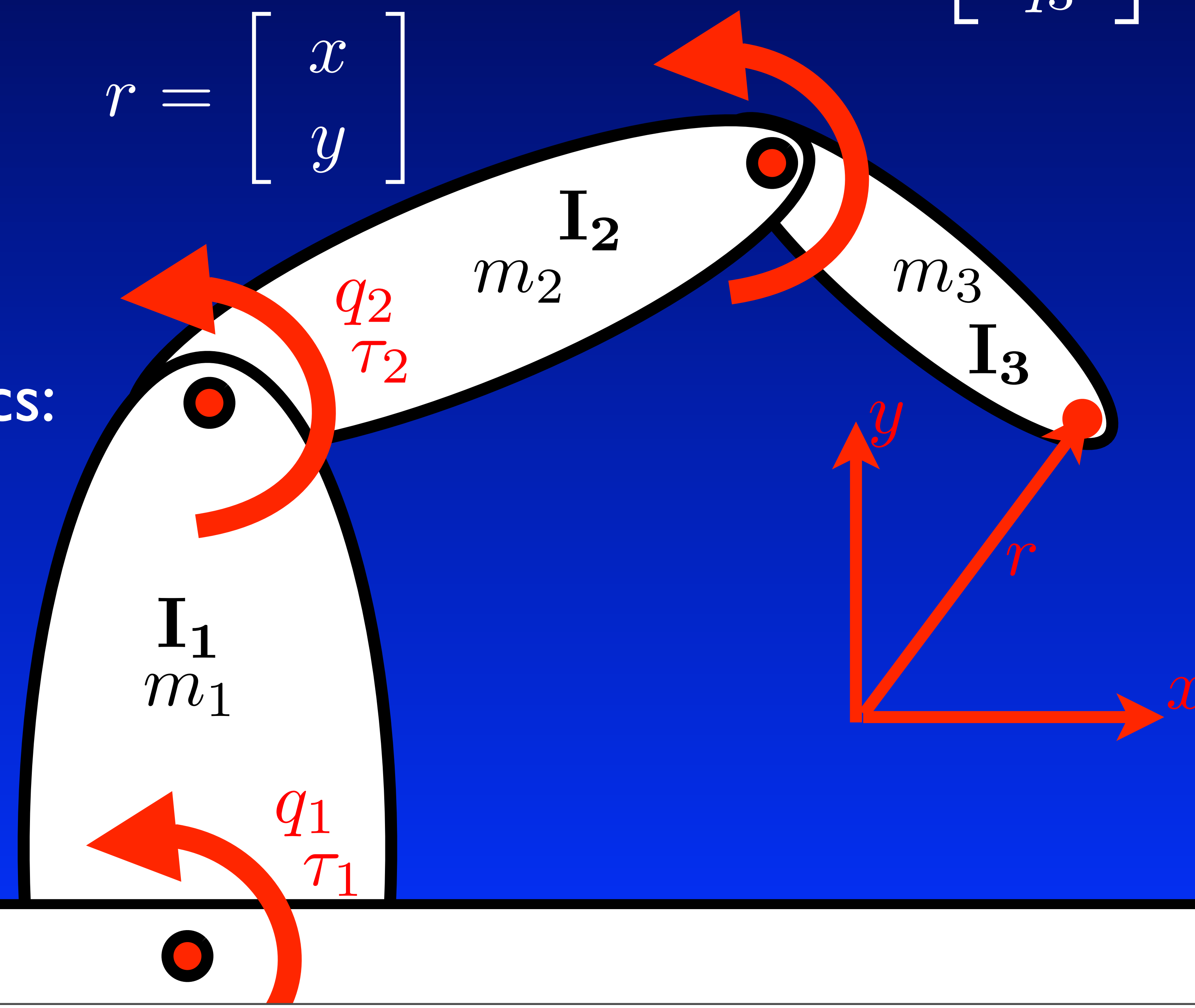
Endeffector coordinates: $r = \begin{bmatrix} x \\ y \end{bmatrix}$

Forward kinematics:

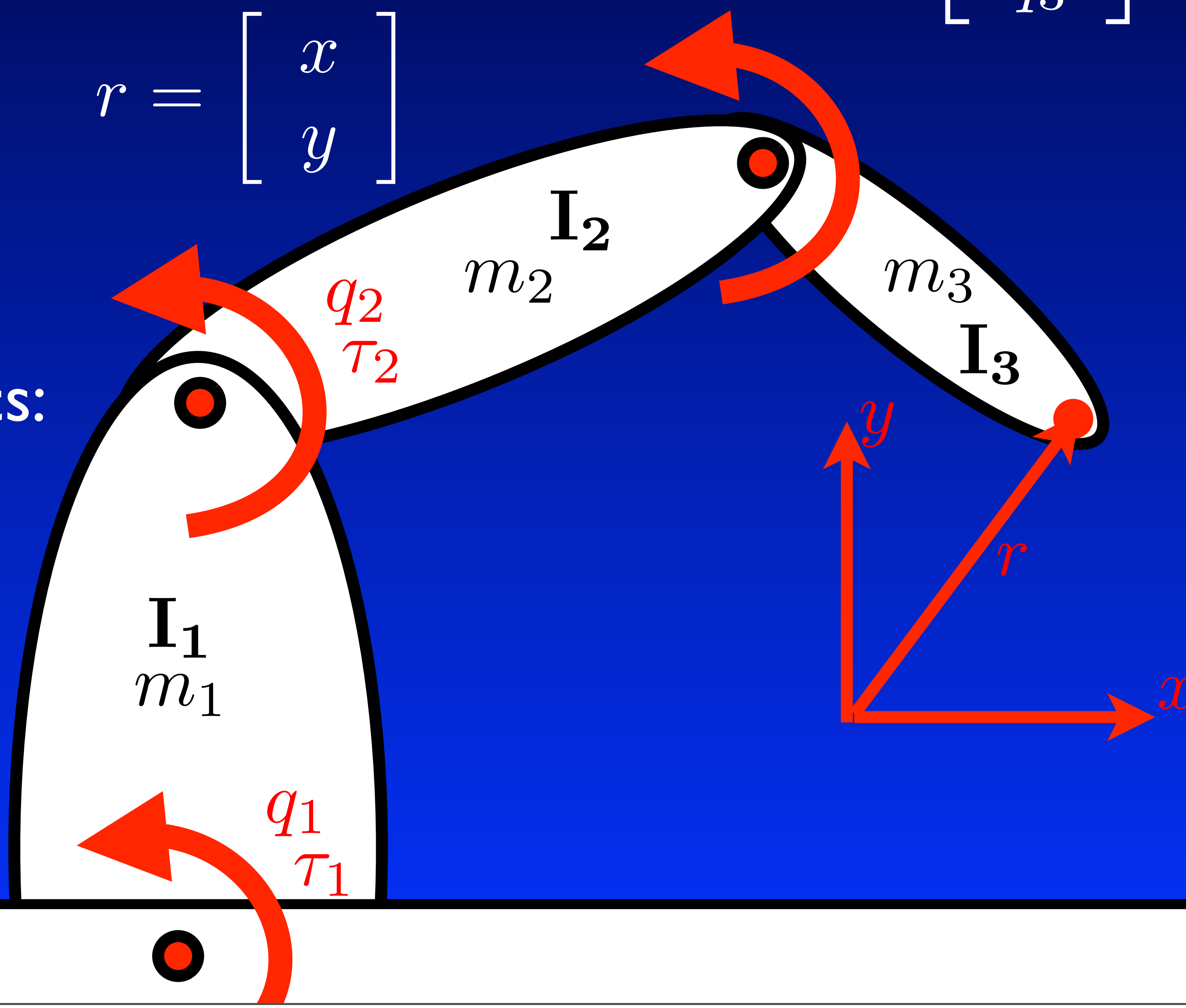


Kinematic chain

Joint coordinates: $q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$

Endeffector coordinates: $r = \begin{bmatrix} x \\ y \end{bmatrix}$

Forward kinematics:
$r = T(q)$



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Forward kinematics:
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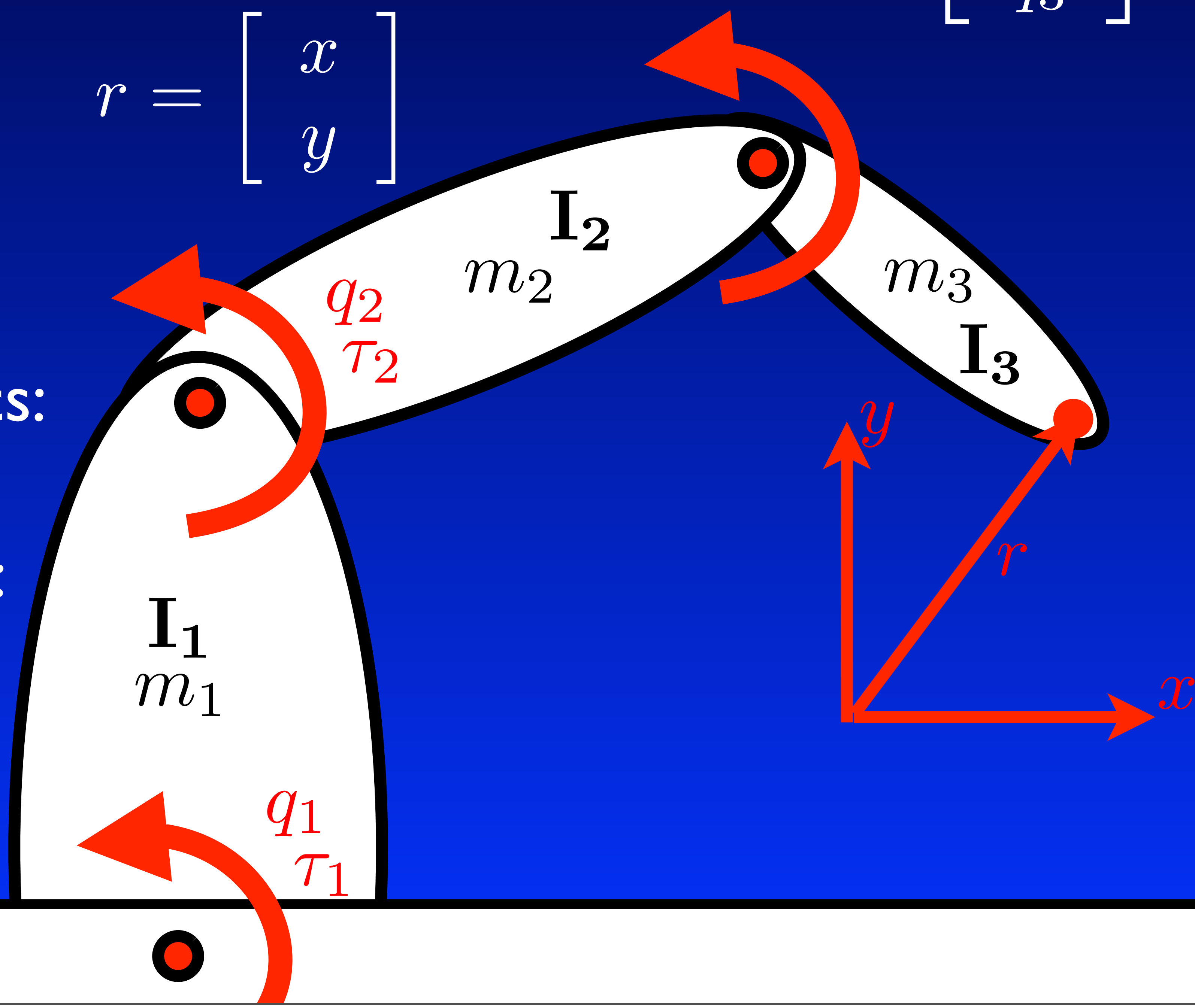
Inverse kinematics:



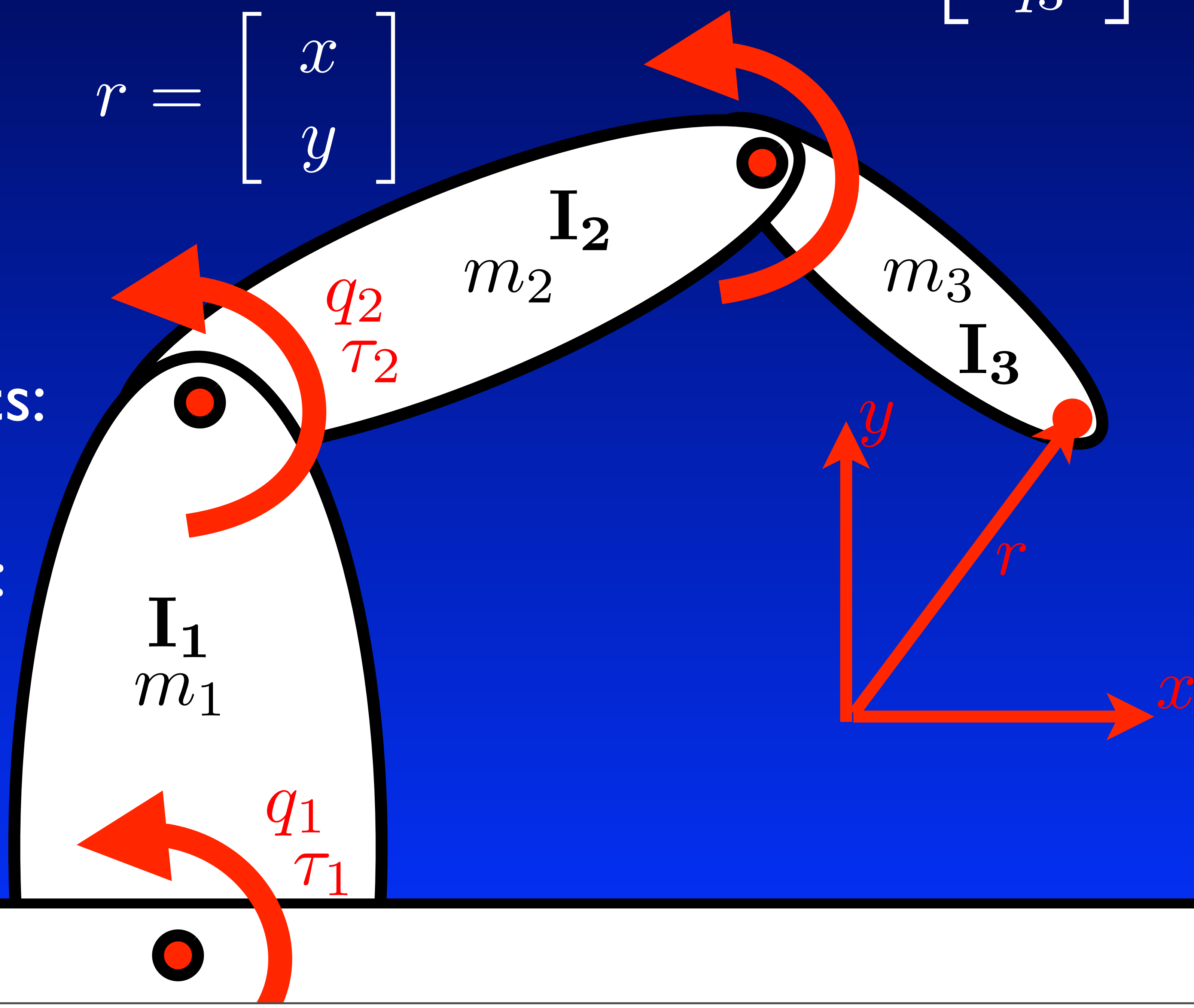
Kinematic chain

Joint coordinates: $q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$

Endeffector coordinates: $r = \begin{bmatrix} x \\ y \end{bmatrix}$

Forward kinematics:
$r = T(q)$

Inverse kinematics:
$q = T^{-1}(r)$



Derivation of task space differential

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$\mathbf{x} = \mathbf{T}(\mathbf{q}(\mathbf{t}))$ Forward kinematics

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$$\mathbf{x} = \mathbf{T}(\mathbf{q})$$

$$\dot{\mathbf{x}} = \frac{\mathbf{d}}{\mathbf{dt}}\mathbf{T}(\mathbf{q})$$

Derivation of task space differential

$$\mathbf{x} = \mathbf{T}(\mathbf{q}(\mathbf{t}))$$ Forward kinematics

$$\mathbf{x} = \mathbf{T}(\mathbf{q})$$

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Derivative chain rule

Derivation of task space differential

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$$\dot{\mathbf{x}} = \frac{\partial}{\partial \mathbf{q}}\mathbf{T}(\mathbf{q})\dot{\mathbf{q}}$$ Derivative chain rule

Derivation of task space differential

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Forward kinematics

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$$\dot{\mathbf{x}} = \frac{\partial}{\partial \mathbf{q}}\mathbf{T}(\mathbf{q})\dot{\mathbf{q}}$$

Derivative chain rule

$$\frac{\partial}{\partial \mathbf{q}}\mathbf{T}(\mathbf{q}) = \frac{\partial \mathbf{x}}{\partial \mathbf{q}}$$

Derivation of task space differential

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Derivation of task space differential

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$$\frac{\partial}{\partial \mathbf{q}}\mathbf{T}(\mathbf{q}) = \frac{\partial \mathbf{x}}{\partial \mathbf{q}} = \mathbf{J}(\mathbf{q})$$ Jacobian

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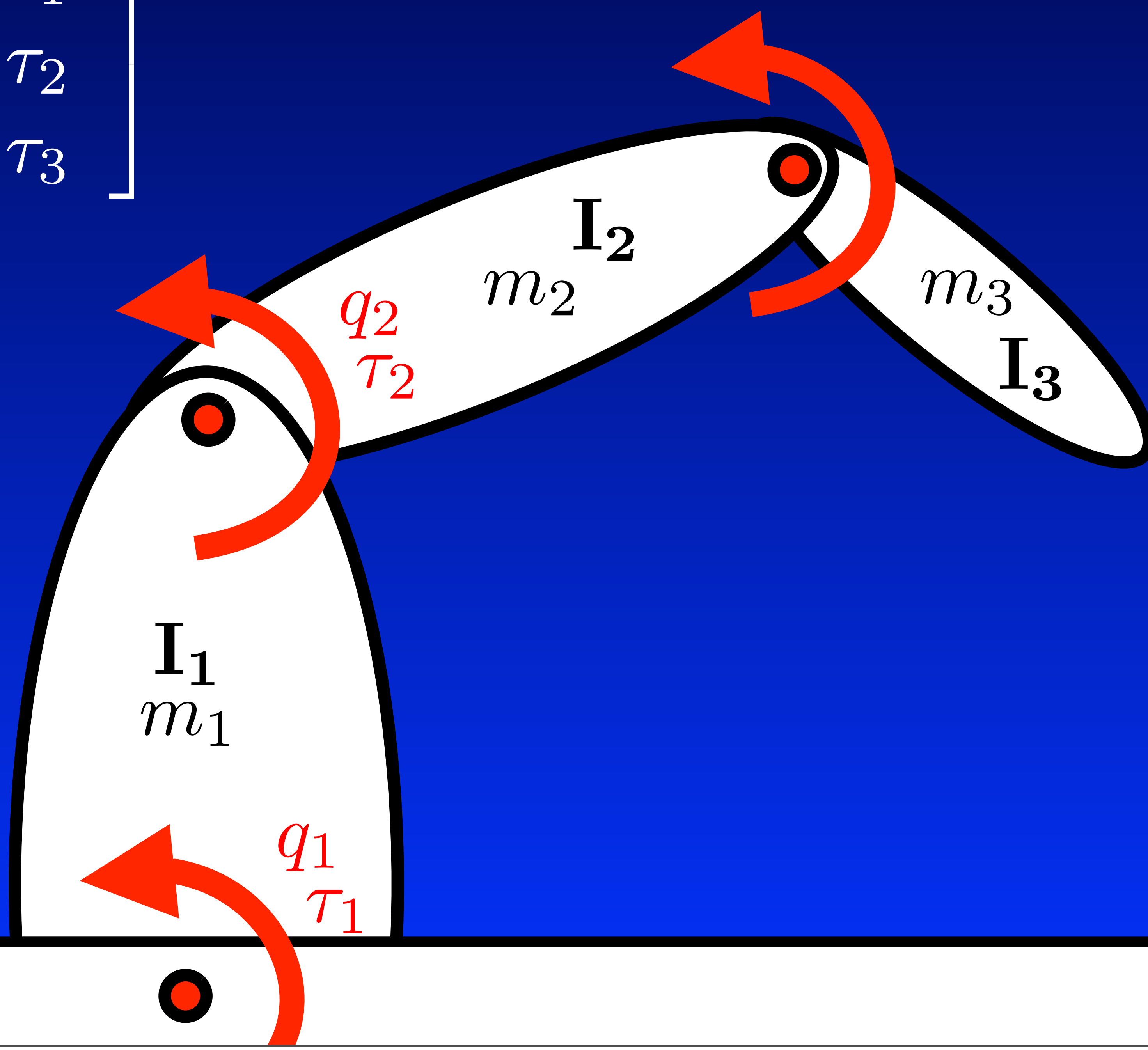
$$\frac{\partial}{\partial \mathbf{q}}\mathbf{T}(\mathbf{q}) = \frac{\partial \mathbf{x}}{\partial \mathbf{q}} = \mathbf{J}(\mathbf{q})$$ Jacobian

$$\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$$

Forces and torques

Relationship of force and torque in an articulated robot

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix}$$



Forces and torques

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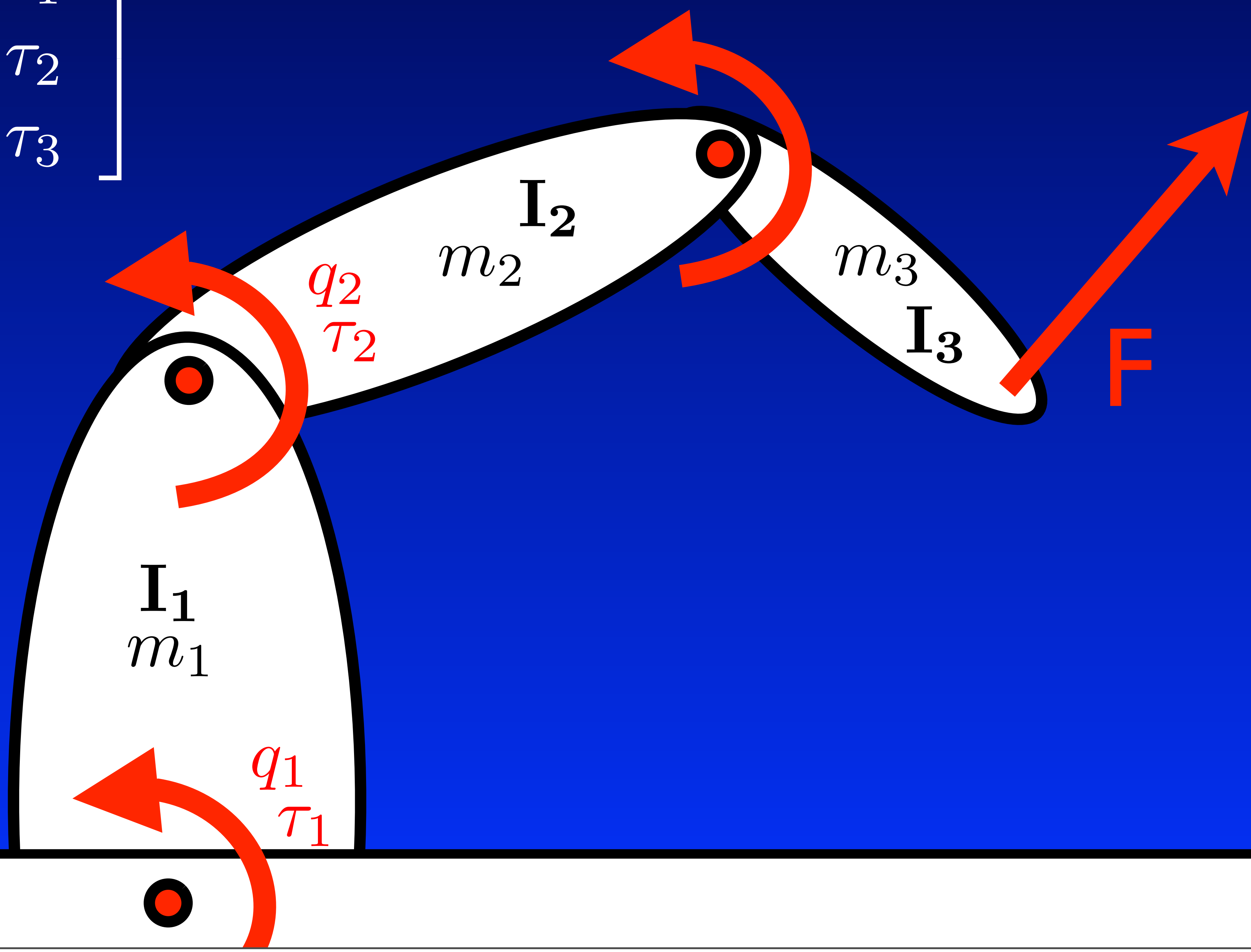
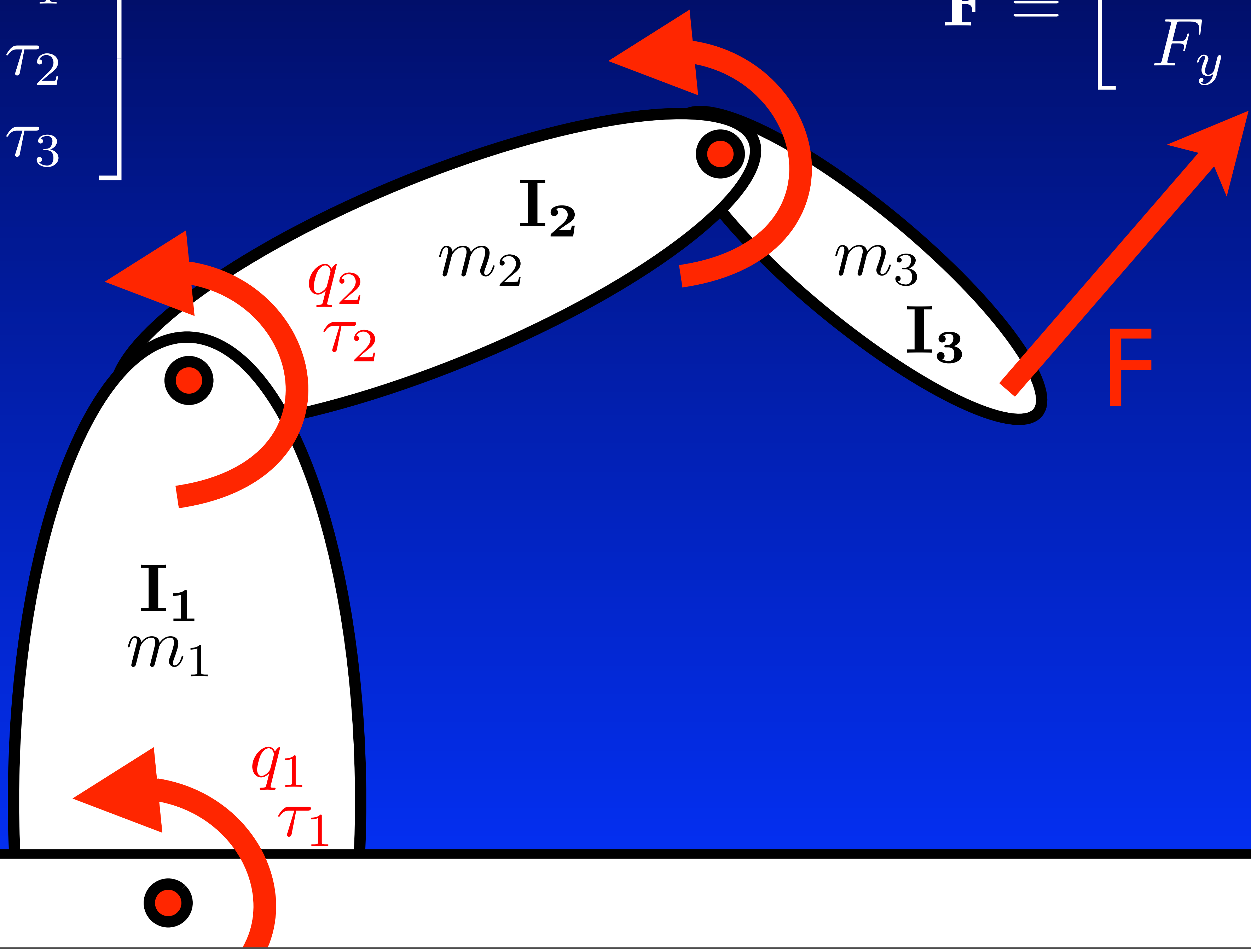


Forces and torques

Relationship of force and torque in an articulated robot

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \qquad \mathbf{F} = \begin{bmatrix} F_x \\ F_y \end{bmatrix}$$



Principle of Virtual Work

(Virtual) work - must be the same in both coordinate systems

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$$F \cdot \delta x = \tau \cdot \delta\theta$$

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rewrite scalar product:

Principle of Virtual Work

(Virtual) work - must be the same in both coordinate systems

$$F \cdot \delta x = \tau \cdot \delta \theta$$

rewrite scalar product:

$$F^T \delta x = \tau^T \delta \theta$$

Principle of Virtual Work

(Virtual) work - must be the same in both coordinate systems

$$F \cdot \delta x = \tau \cdot \delta\theta$$

rewrite scalar product:

$$F^T \delta x = \tau^T \delta\theta$$

Use definition of Jacobian

Principle of Virtual Work

(Virtual) work - must be the same in both coordinate systems

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$$\boxed{\tau = J^T F}$$

Forces and RBD

Chain of rigid bodies: are is still admittances...

The only thing that changes are added constraints on possible motions ⇒ reduction of DOF

Need for torque source!

Jacobian transpose force control

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$$\tau = J^T F$$

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We can use the Jacobian transpose law to:

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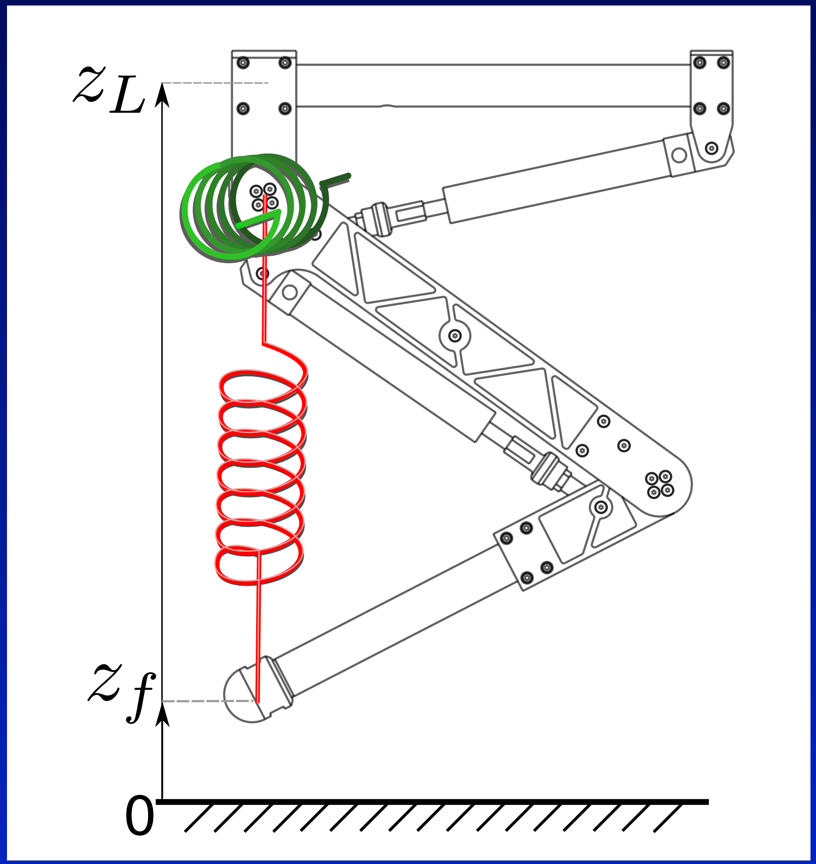
Example: Virtual model control (Pratt 2001)

Virtual model control



[Semini, 2010]
[Boaventura et al, 2011]

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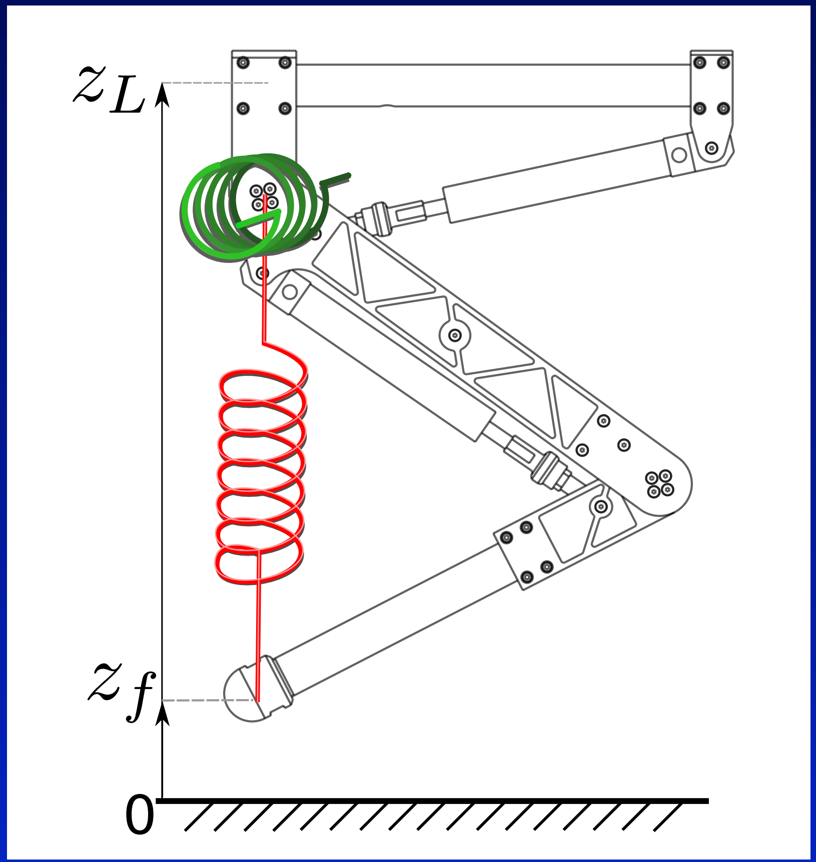

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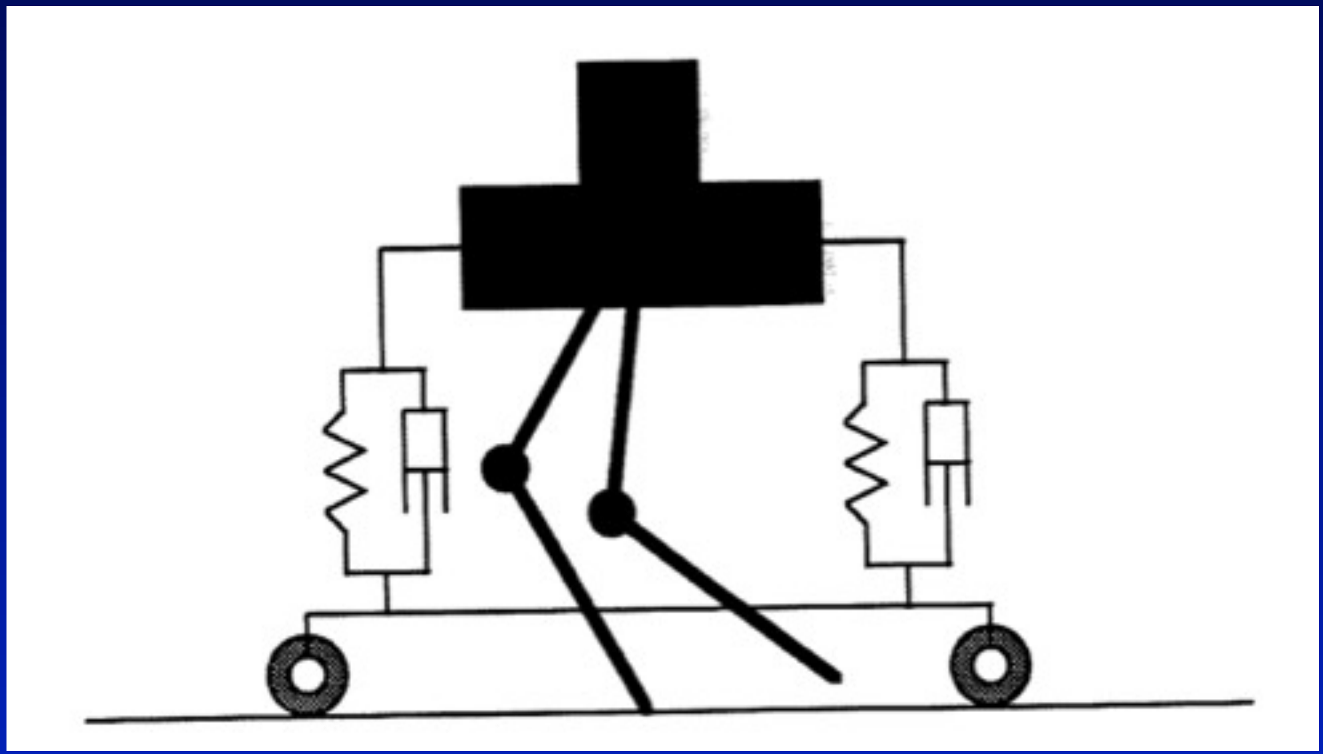

[Pratt et al, 2001]

Virtual model implementation

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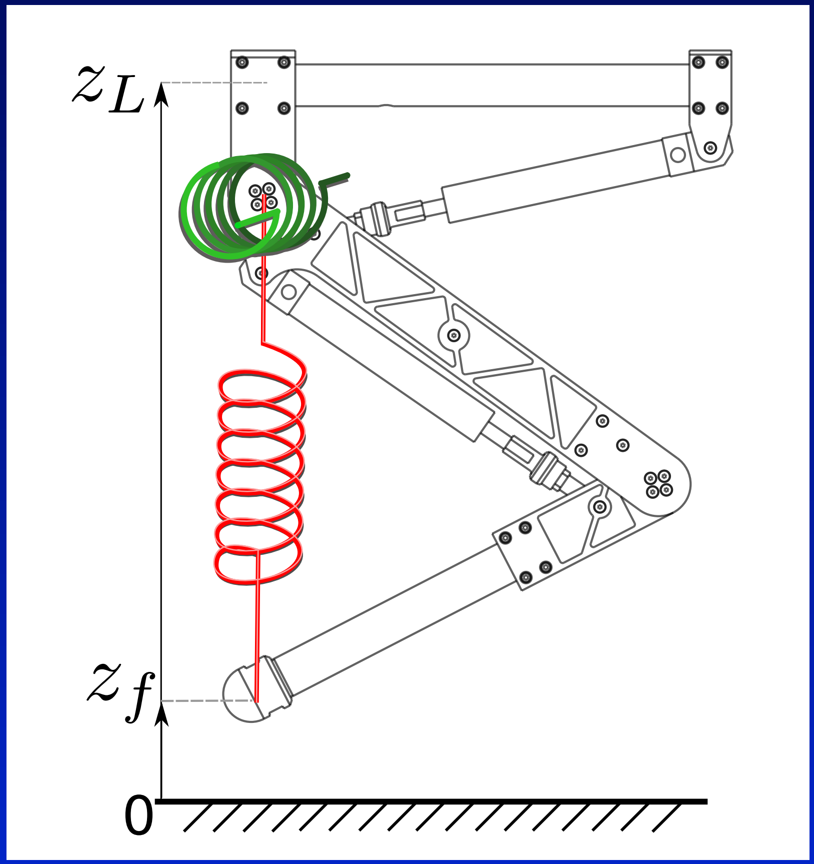
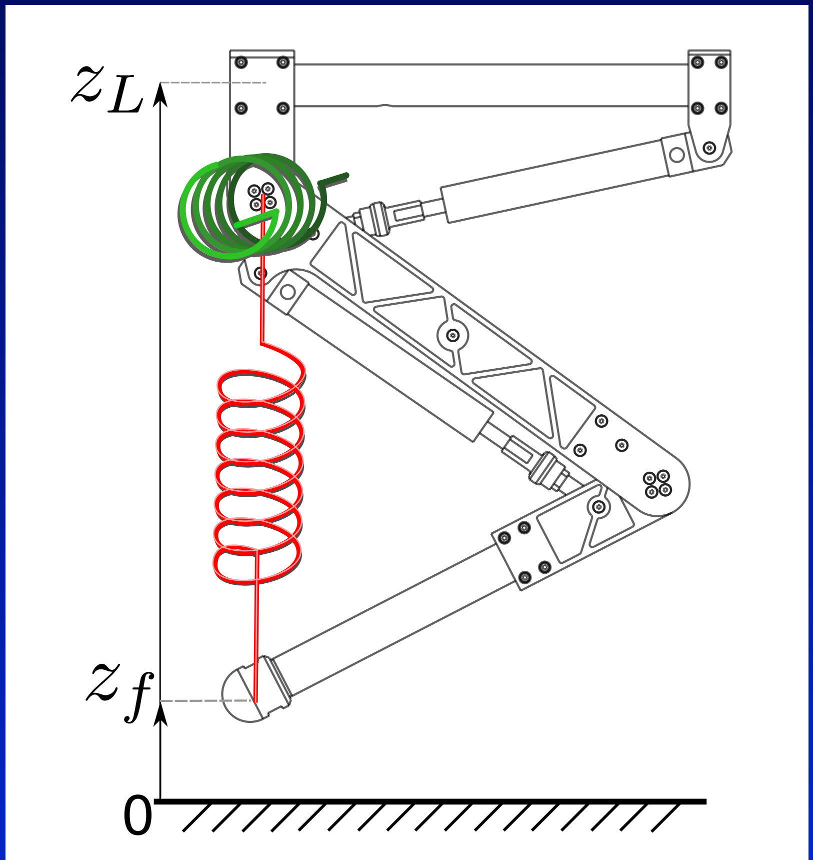


Virtual model implementation

1) Virtual spring law



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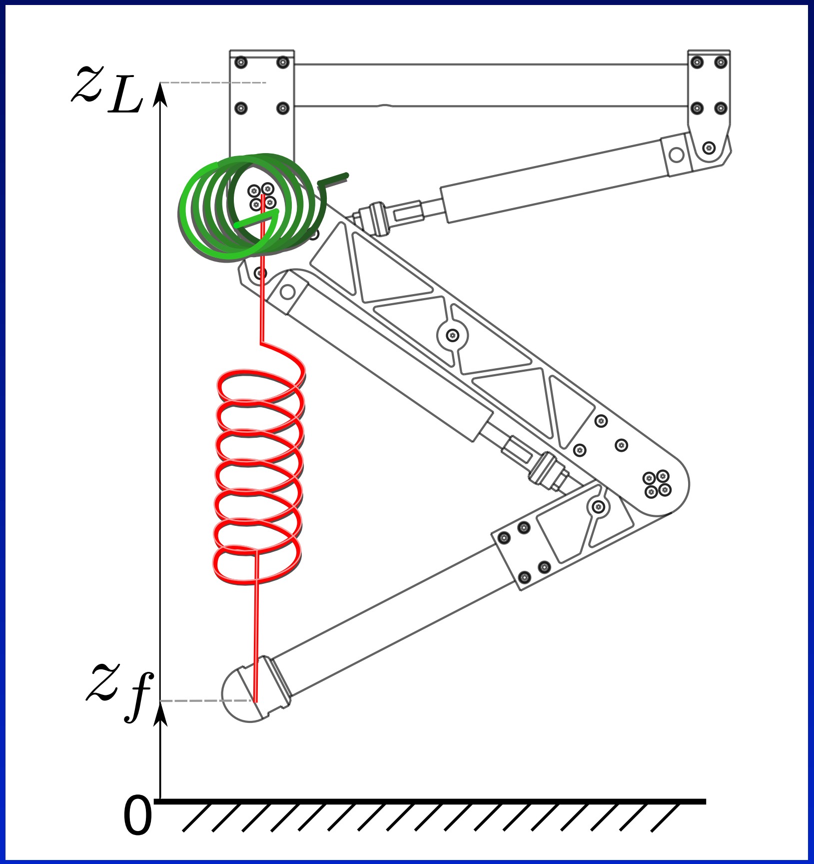
$$\mathbf{F} = \mathbf{K_s}(\mathbf{x_1} - \mathbf{x_2} - \mathbf{l_0})$$



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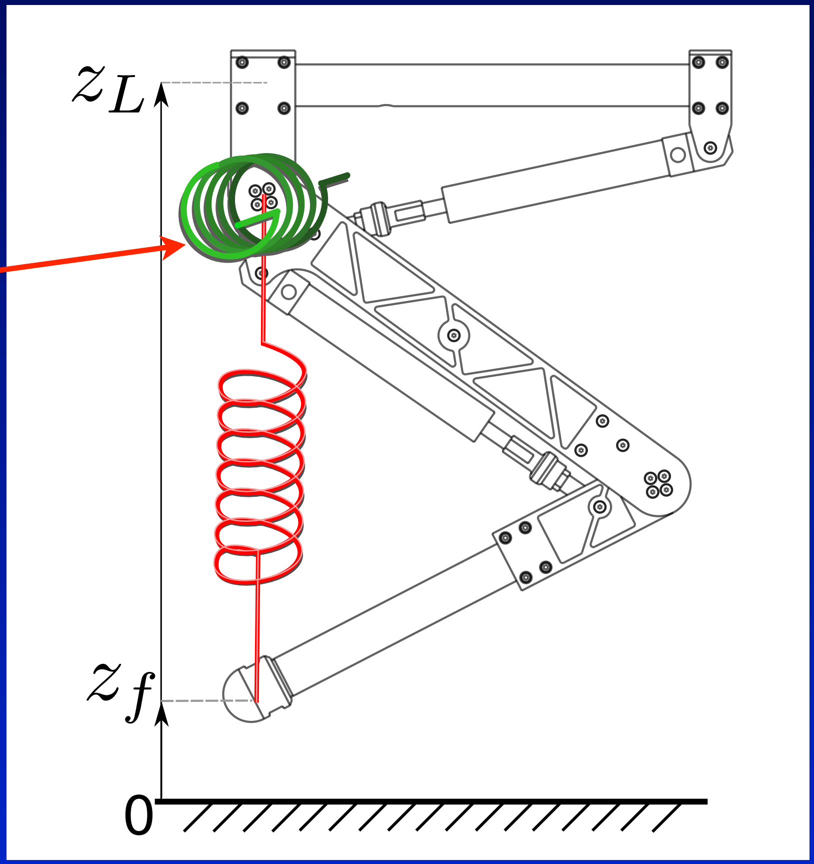

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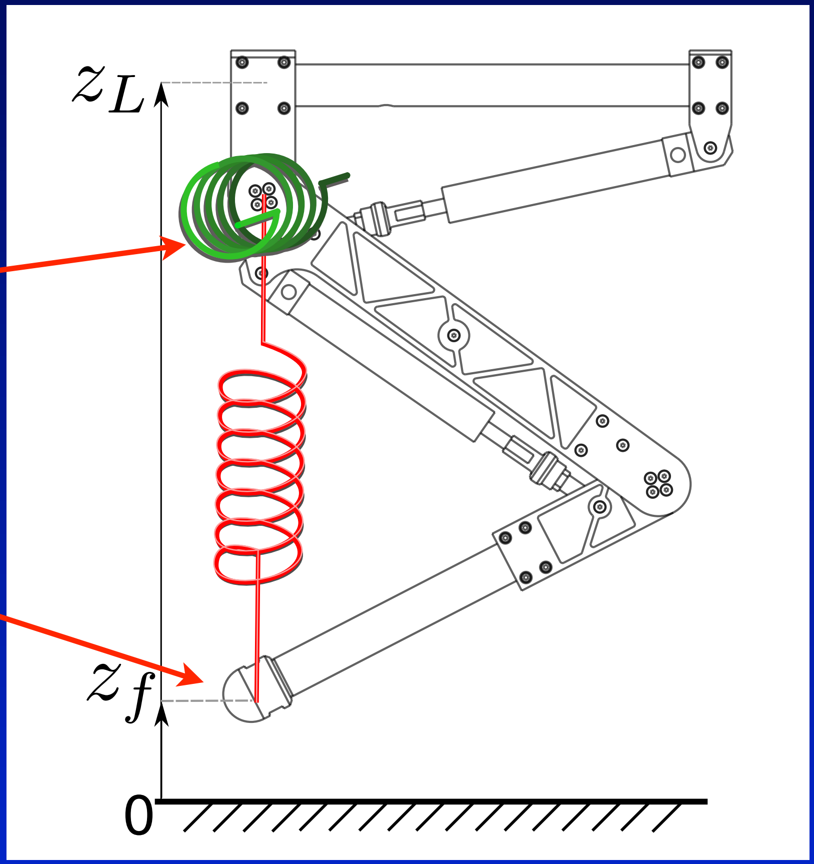

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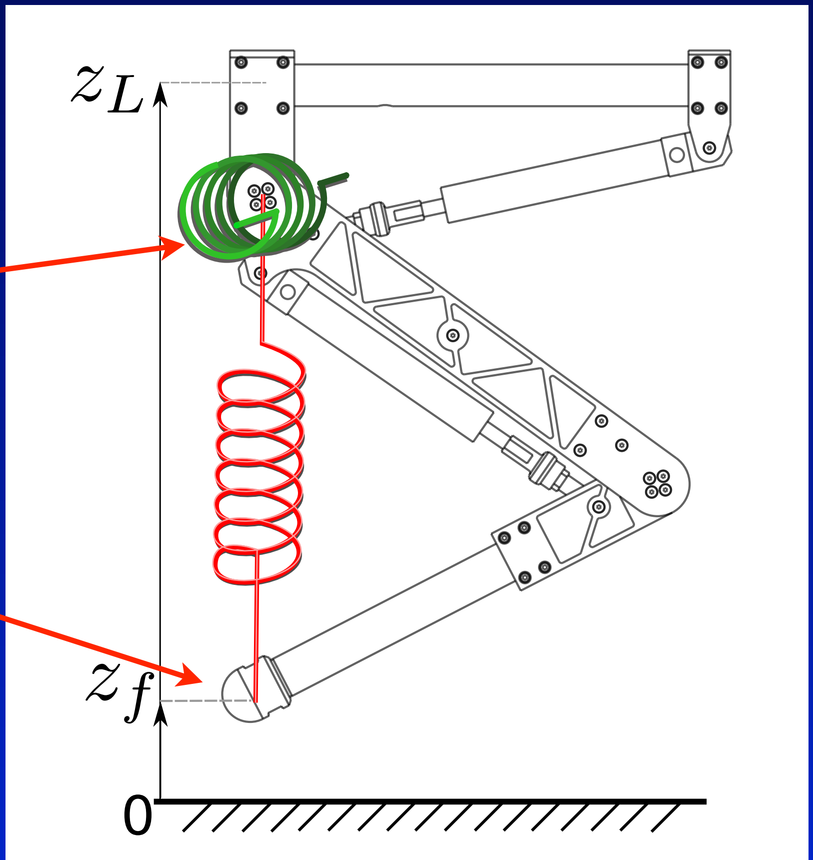

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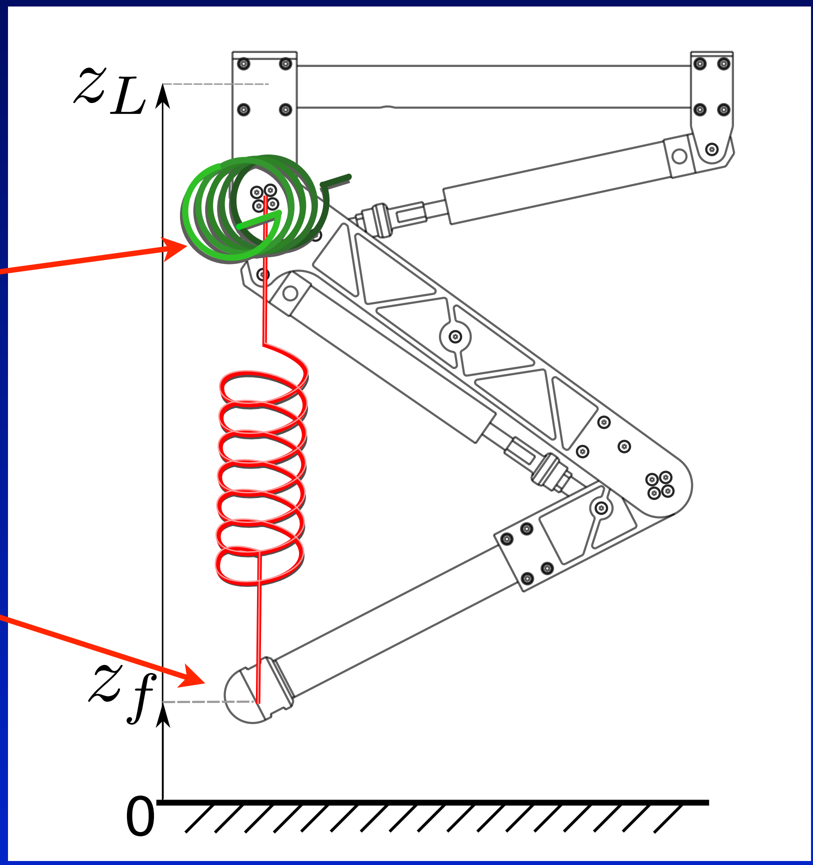
$$\mathbf{J}$$



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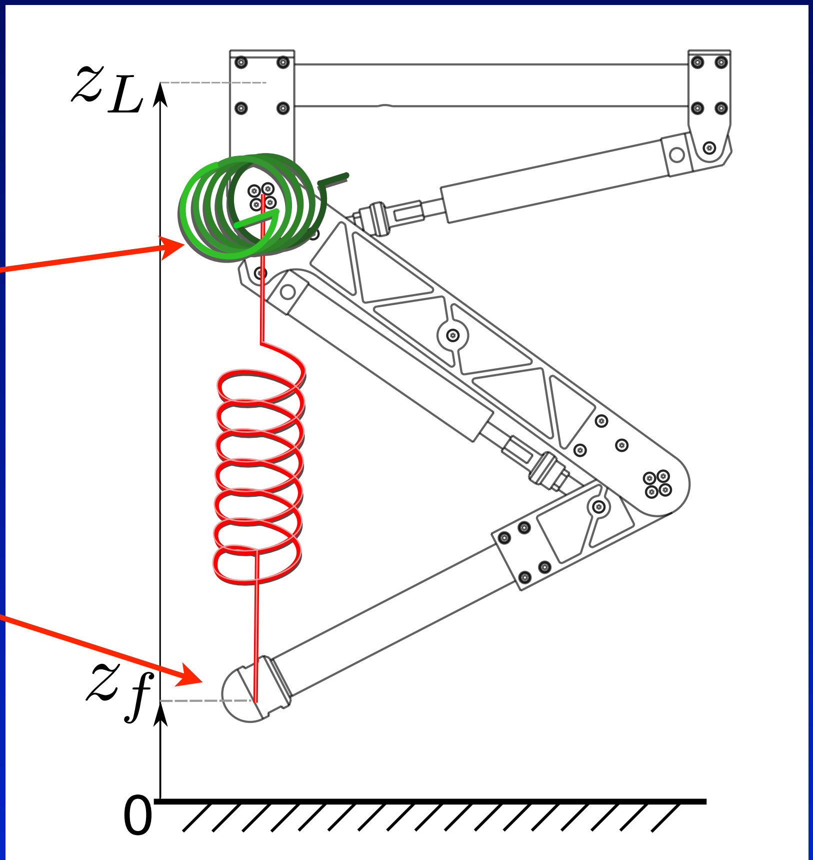

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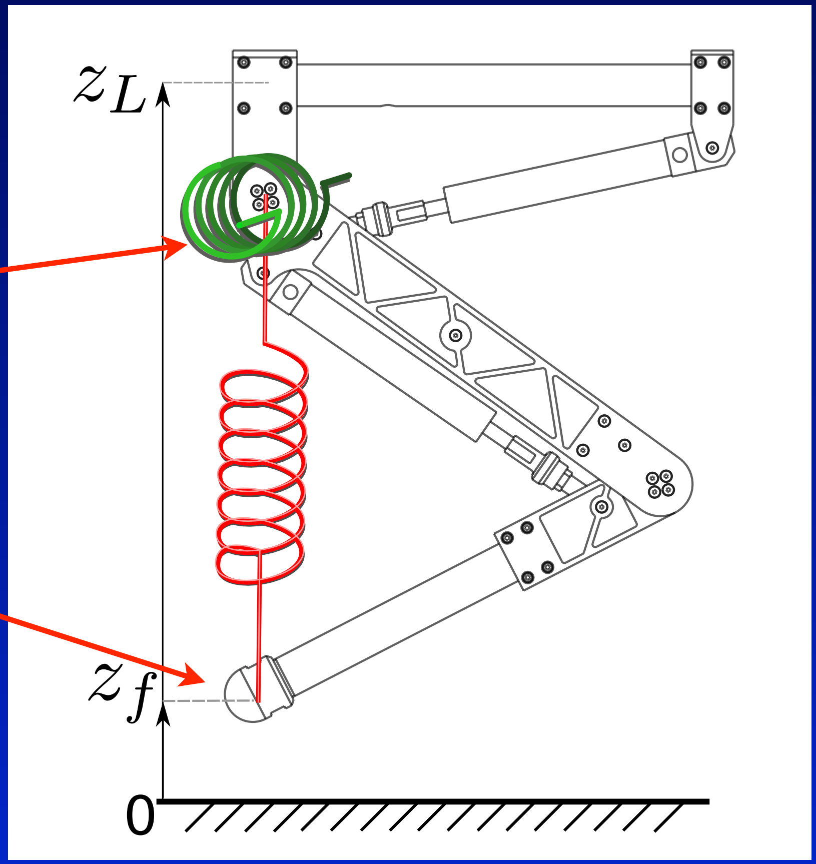

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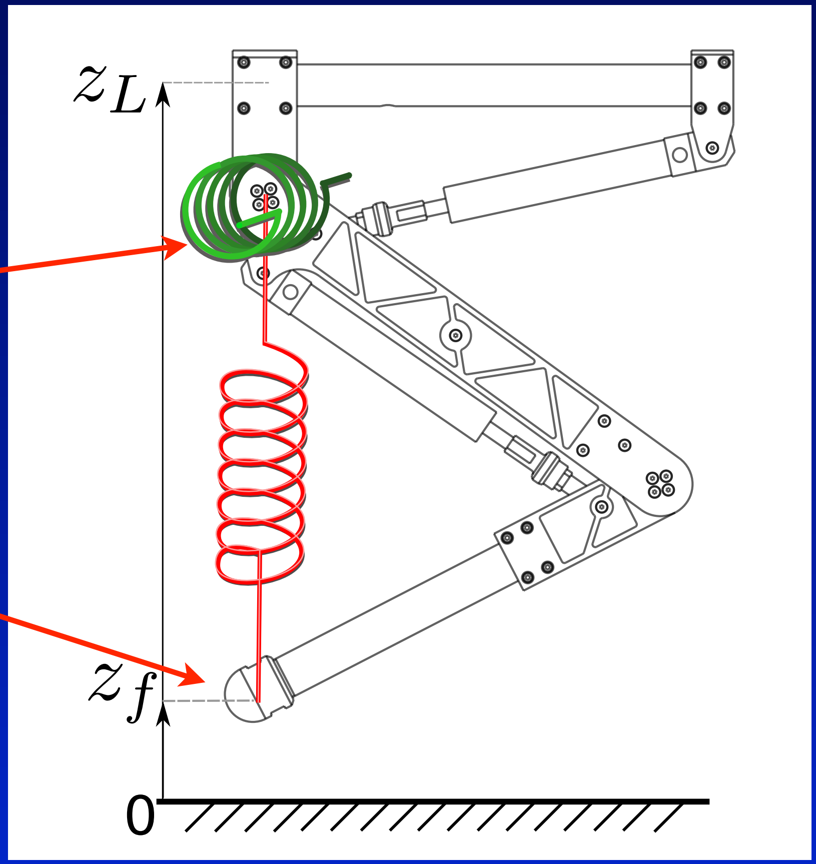

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[4) Use close loop force control]

Example: Virtual spring

[Boaventura, Buchli, Frigerio, Semini]

HyQ Leg - C. Semini

- Hydraulic actuation: flow control
- Closed loop torque control
- Virtual springs
- $\Rightarrow$ Jacobian transpose

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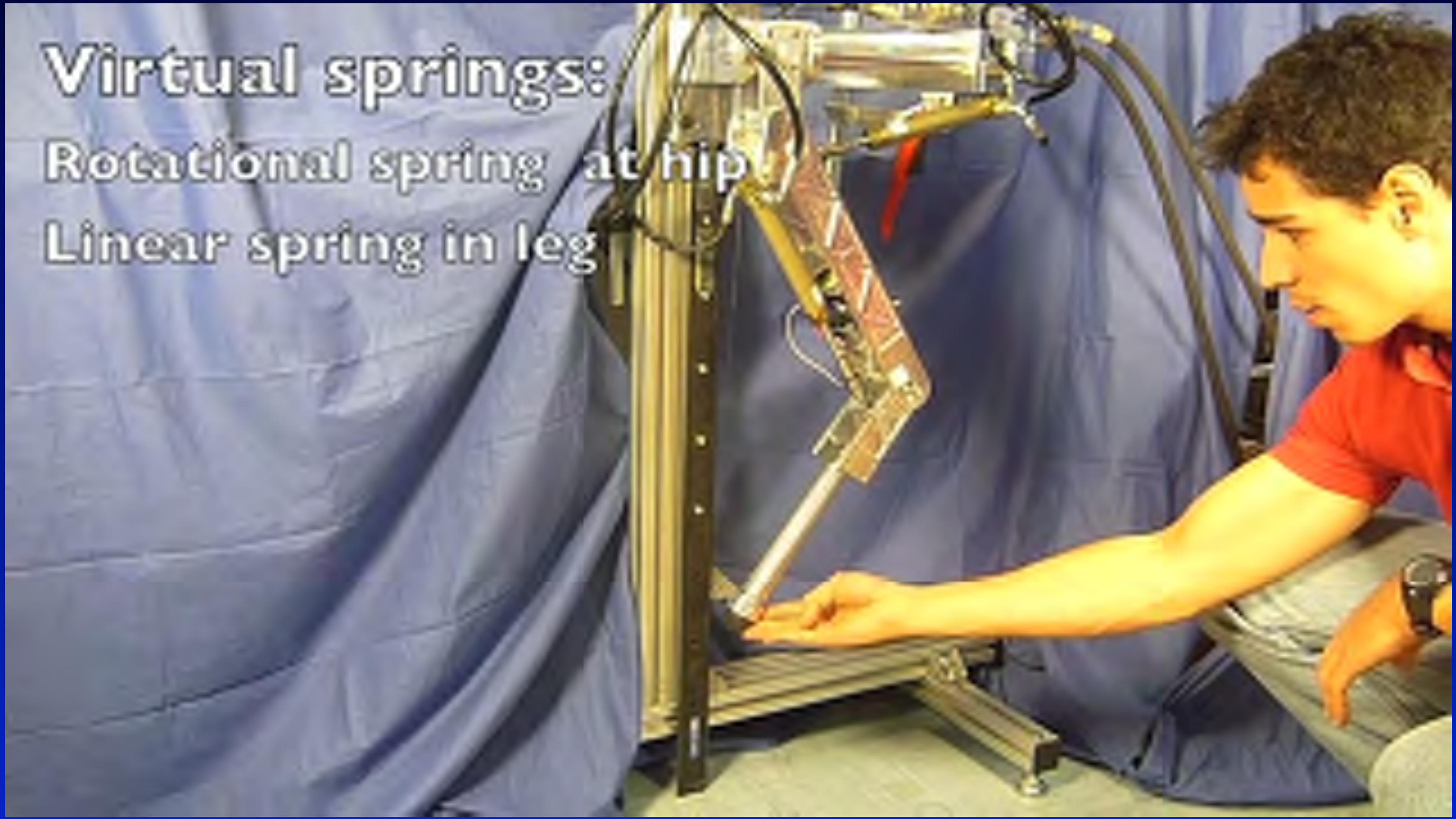

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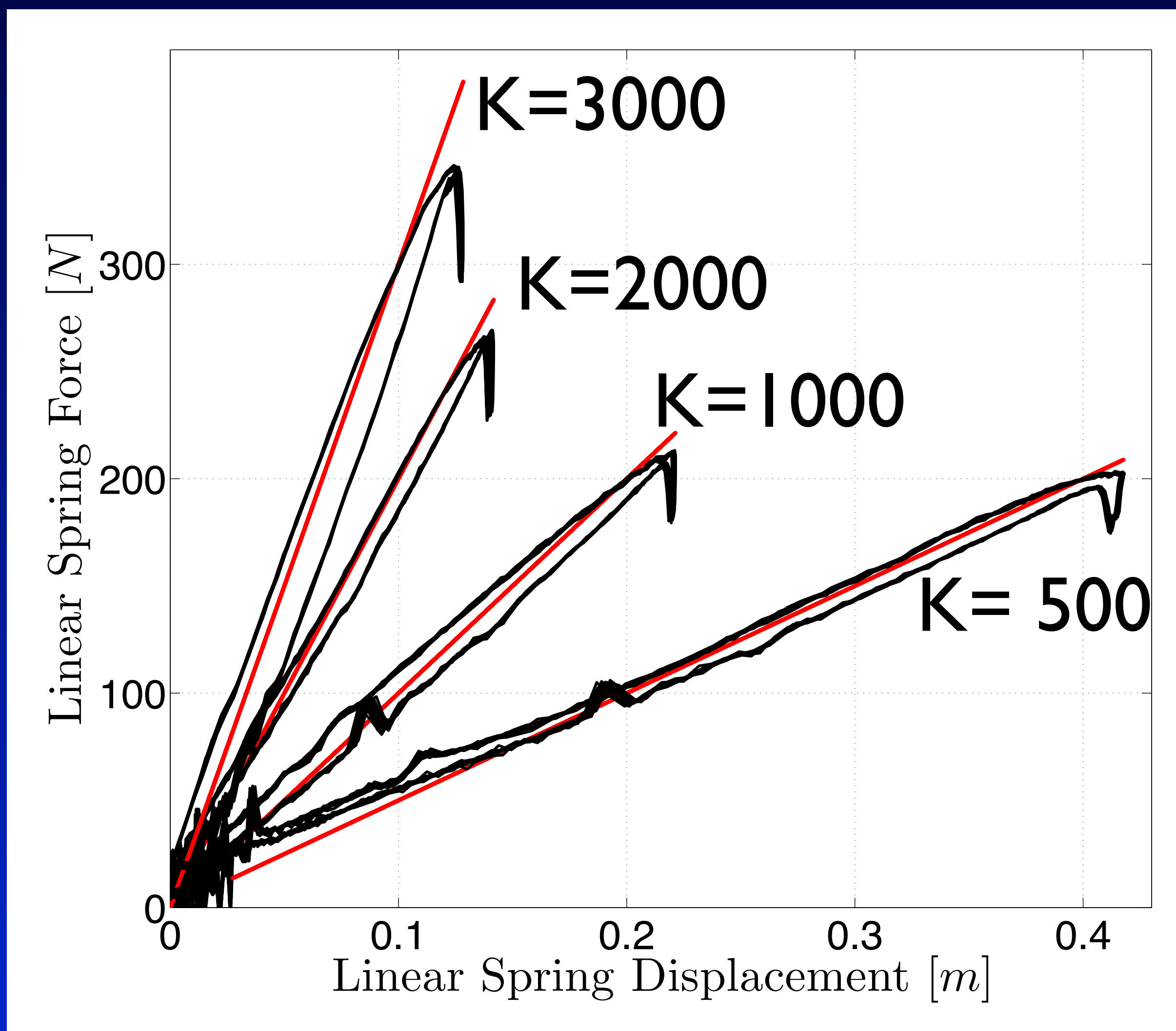
Results



Varying spring constants

[Boaventura, Buchli, Frigerio, Semini]

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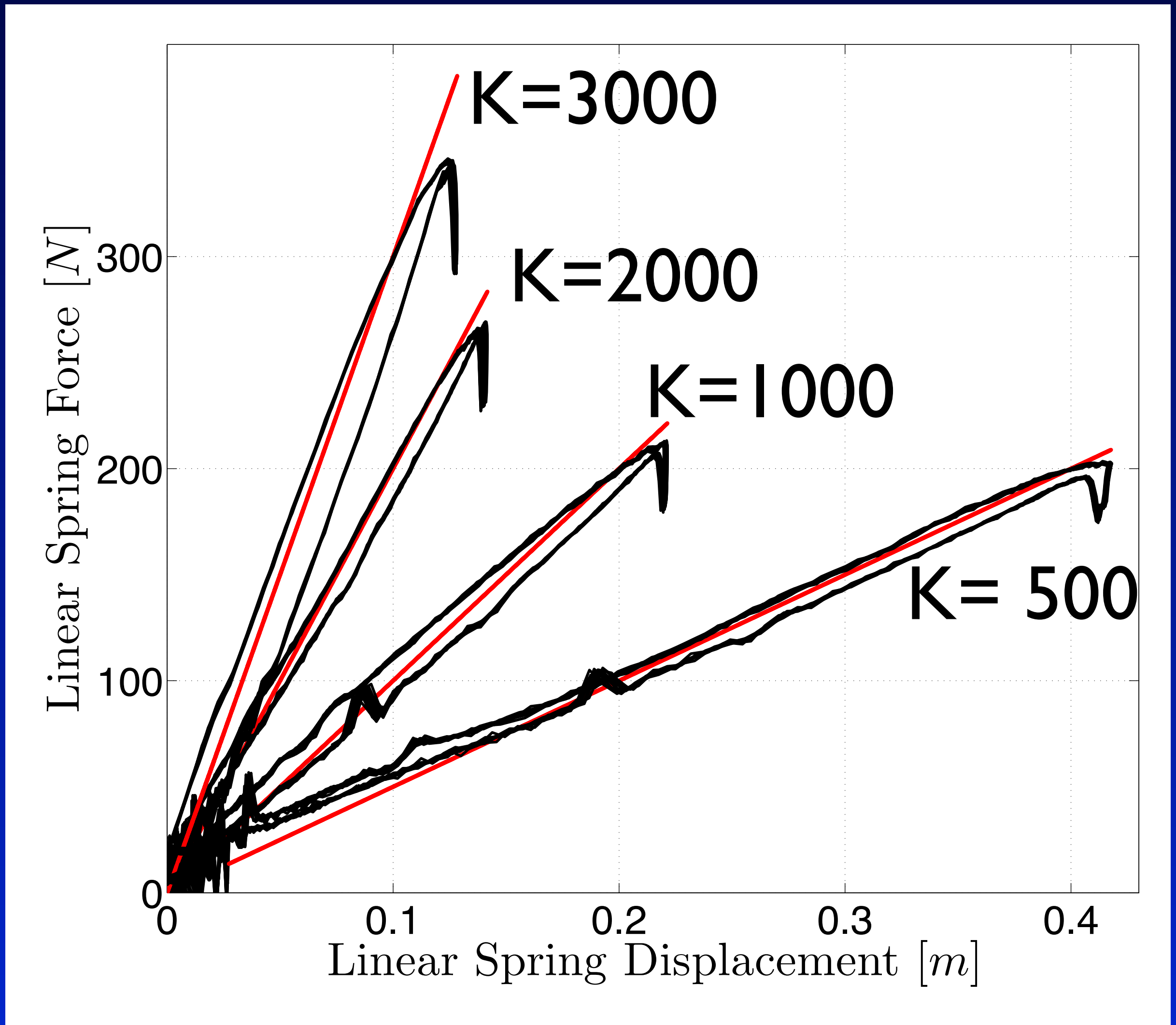

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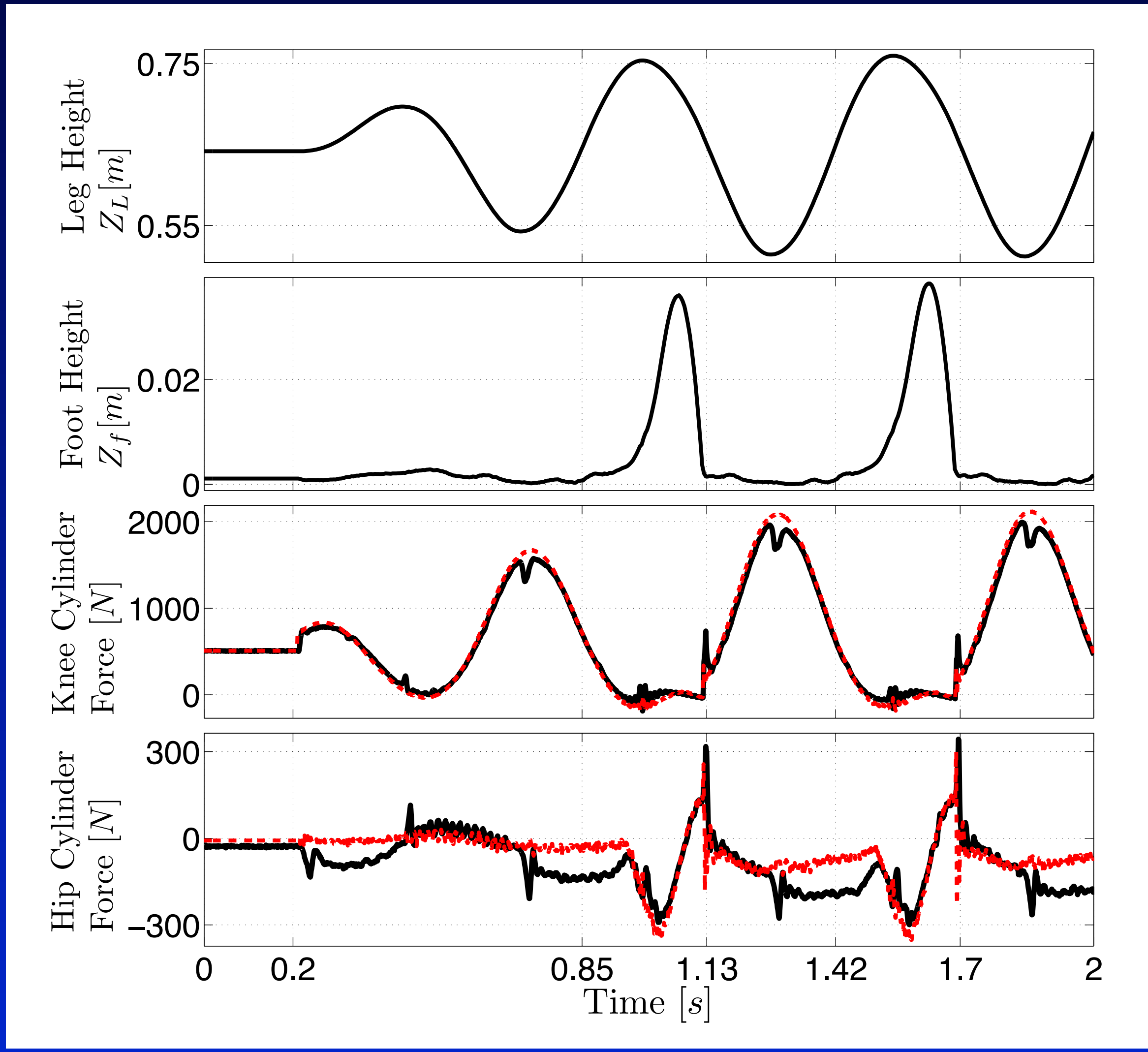

Virtual spring hopping

[Boaventura, Buchli, Frigerio, Semini]

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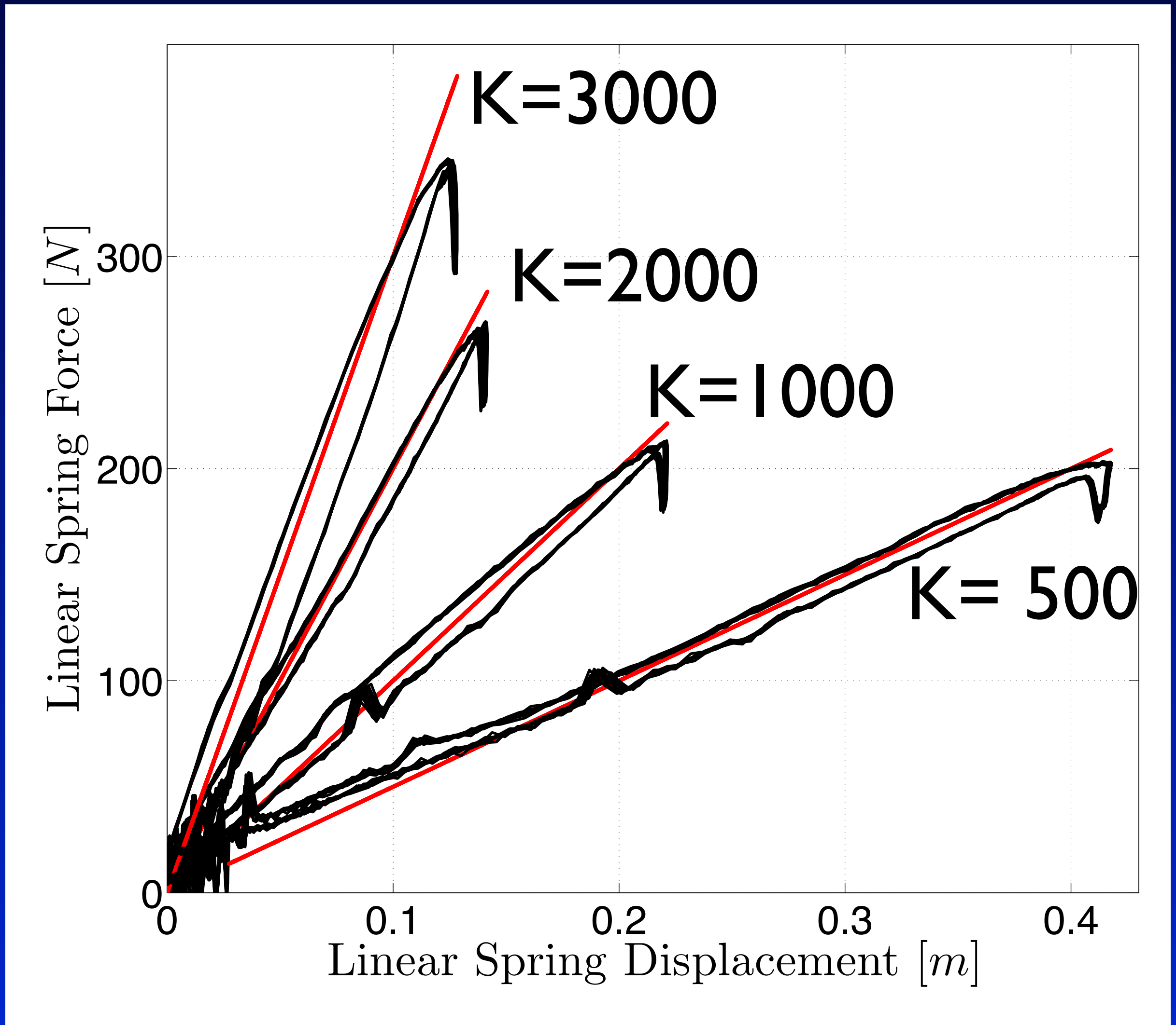
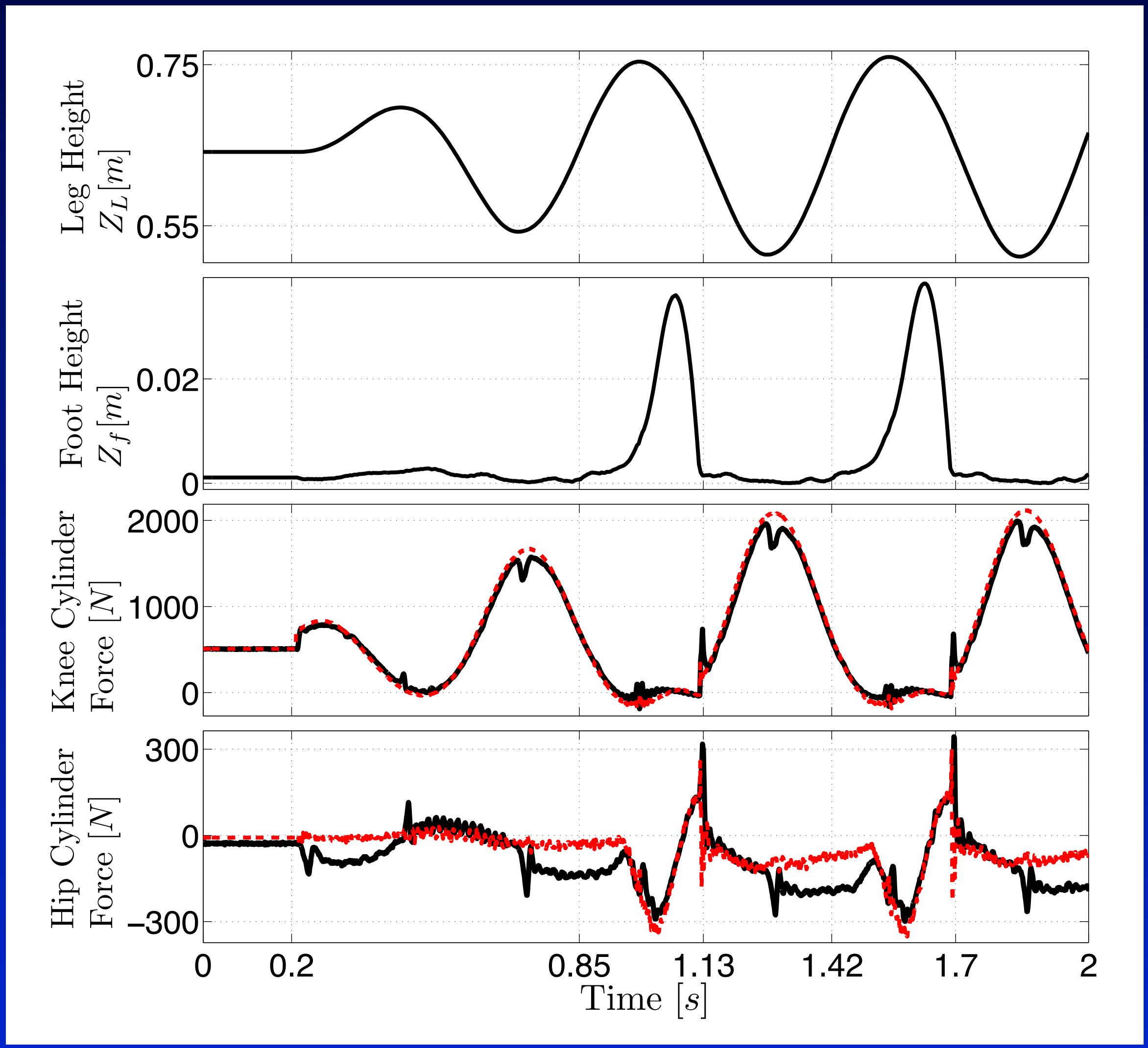




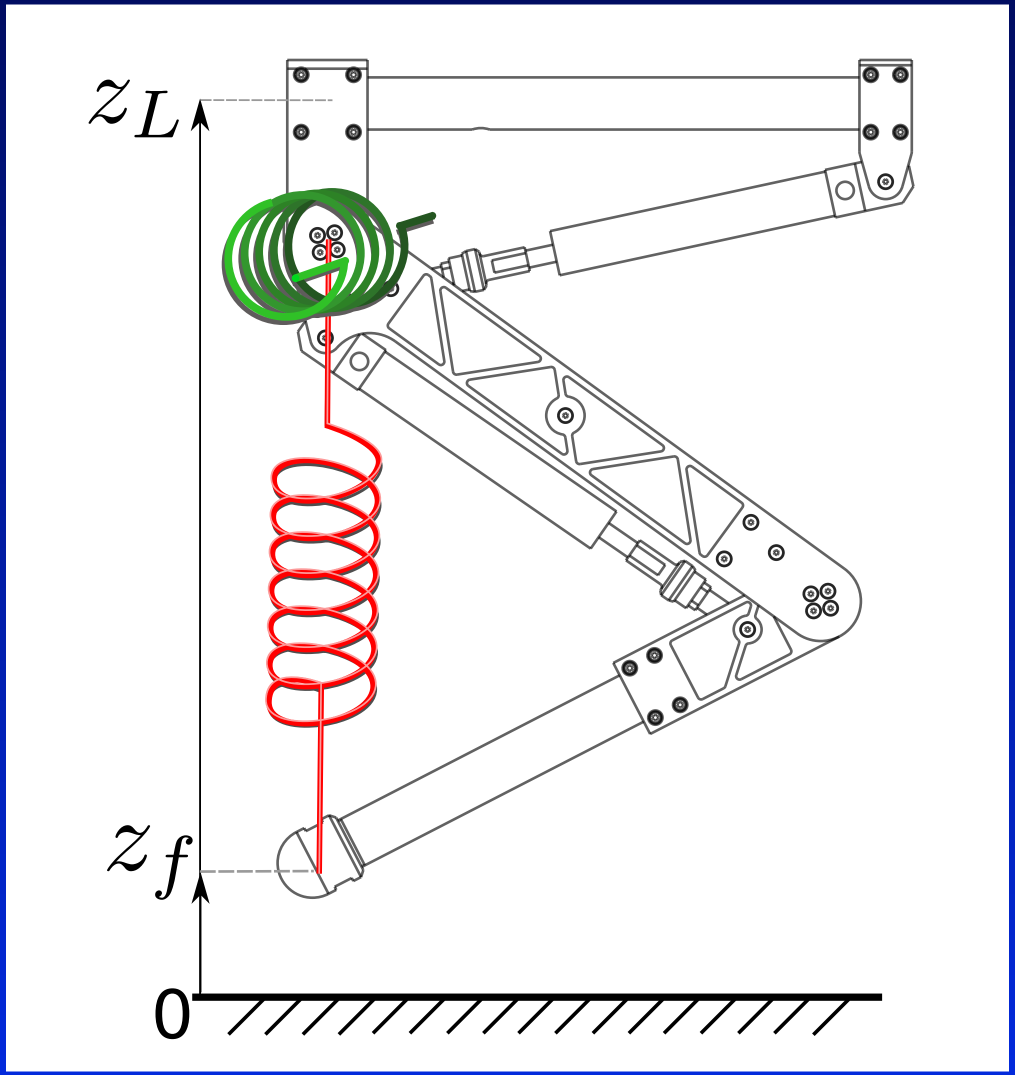
Varying spring constants

Virtual spring hopping

Can emulate non-linear springs, muscle models, etc etc!

[Boaventura, Buchli, Frigerio, Semini]

2-link leg: Jacobian



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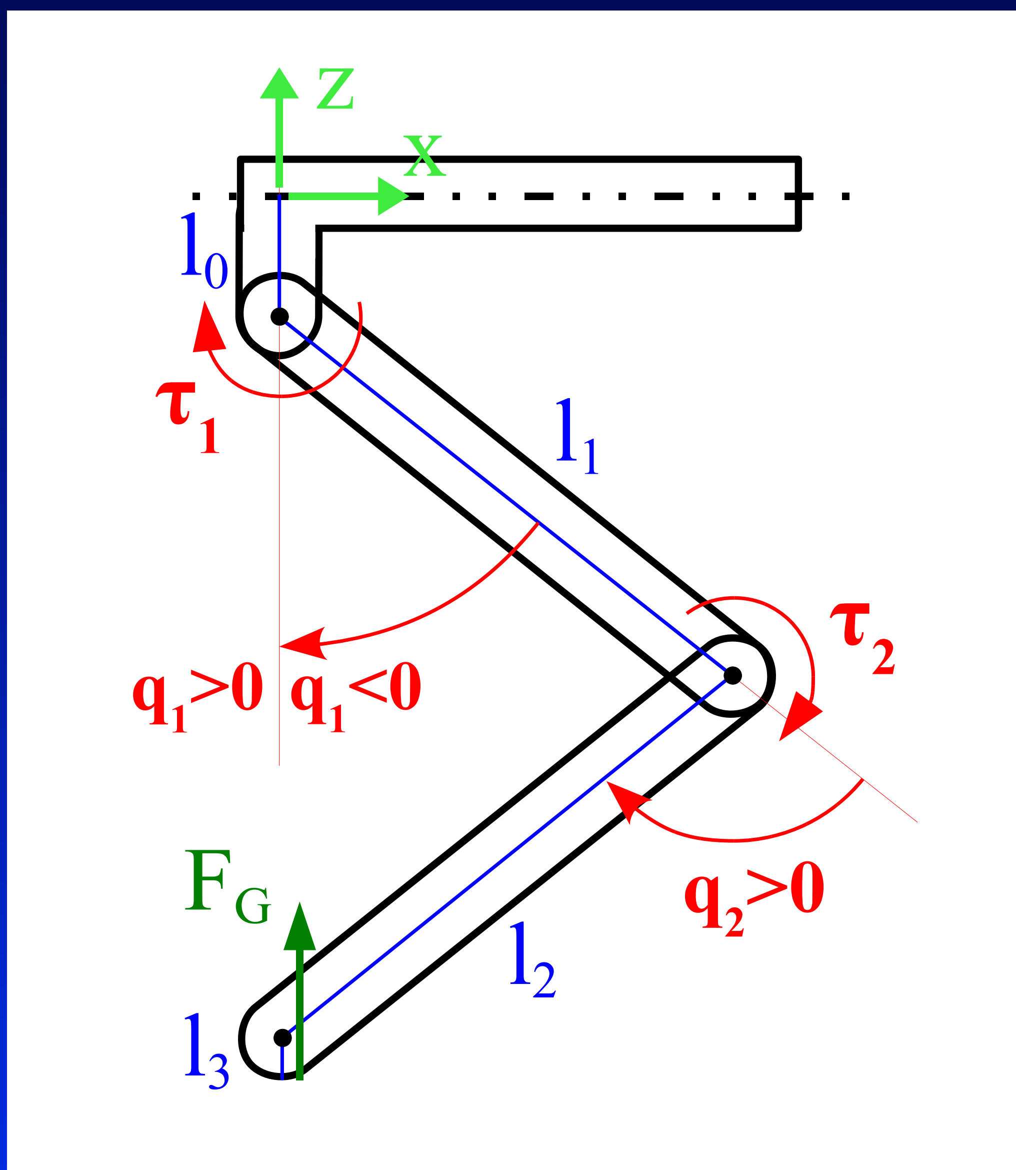

[Semini 2010 PhD Thesis]

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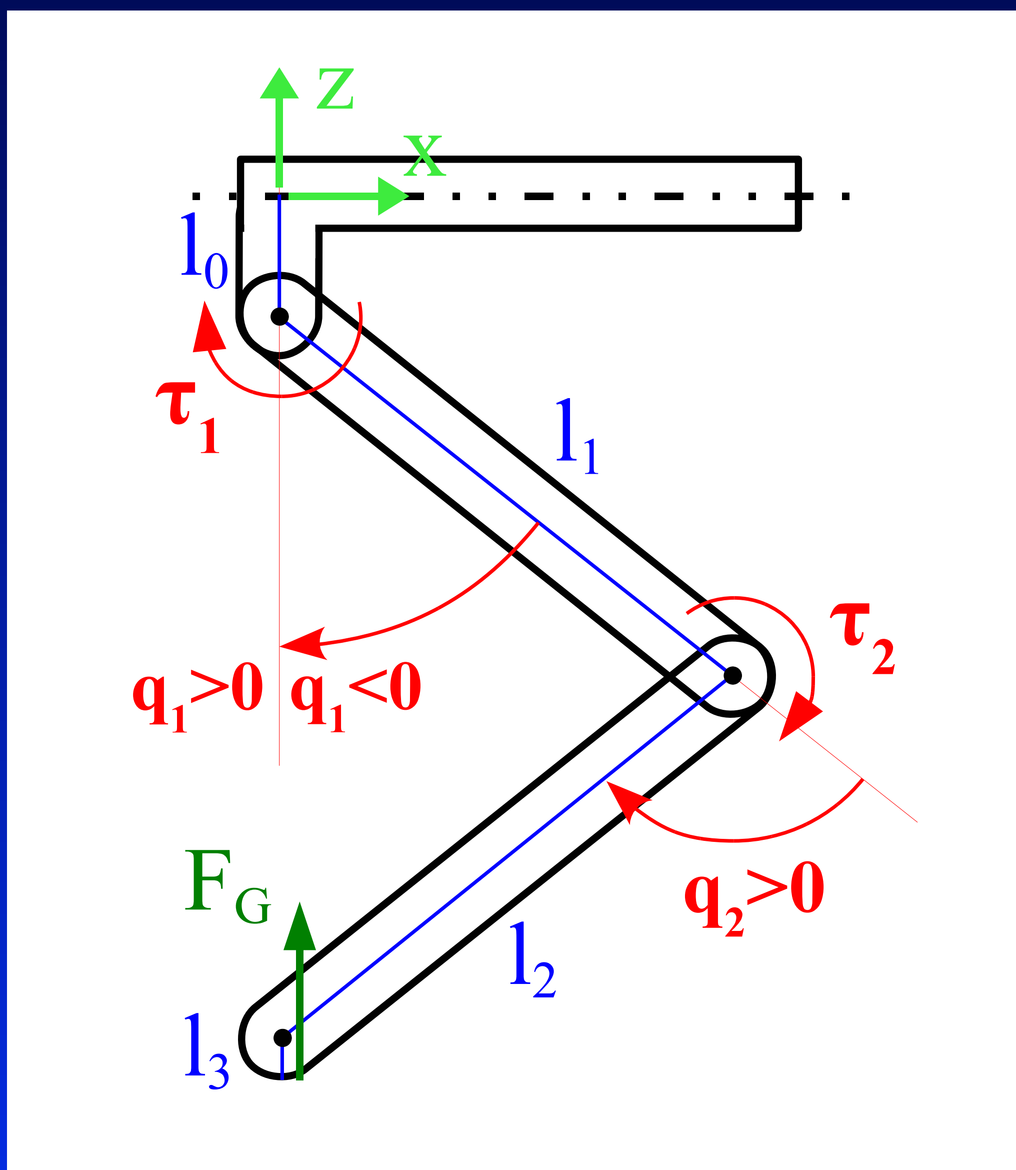

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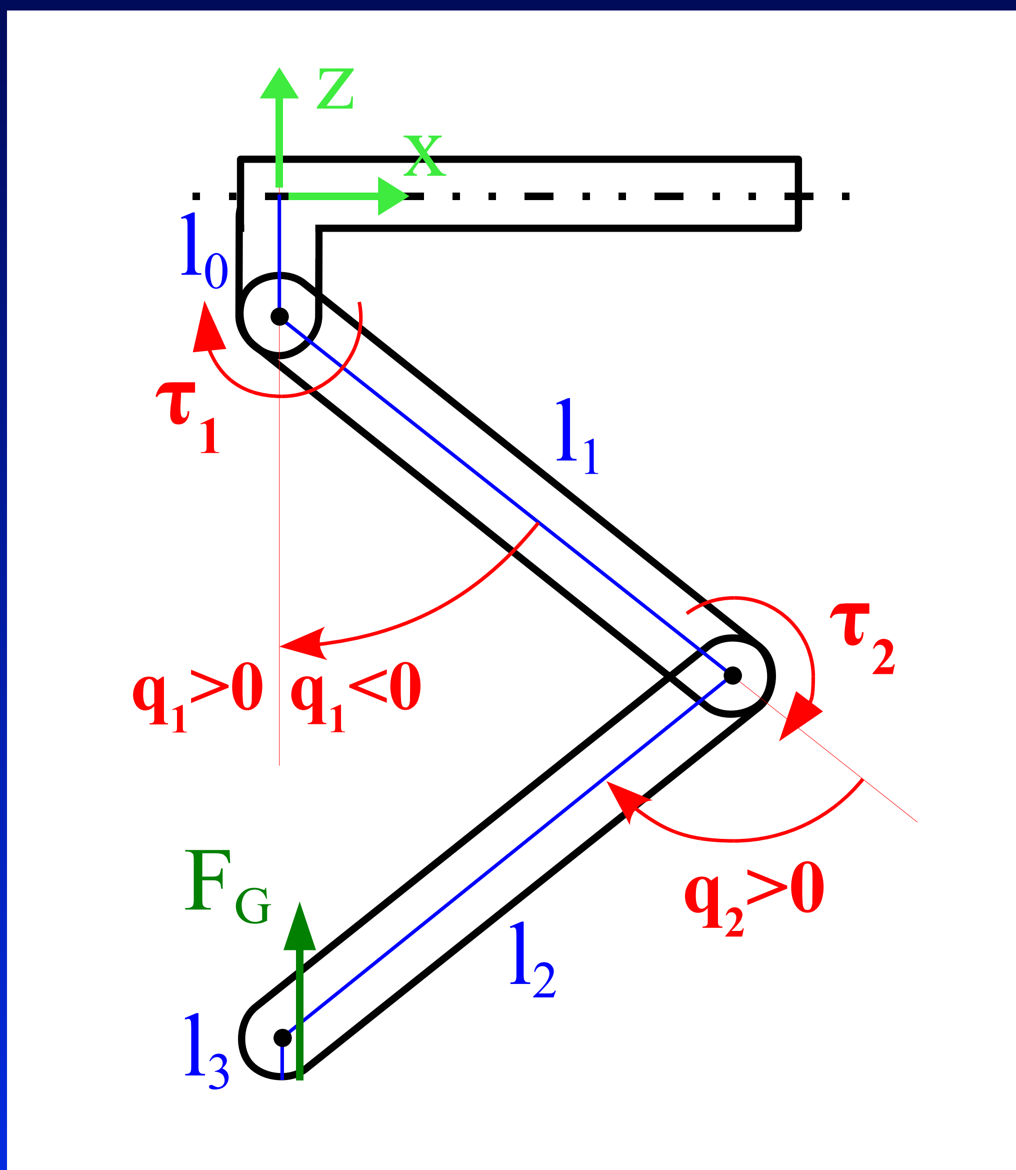

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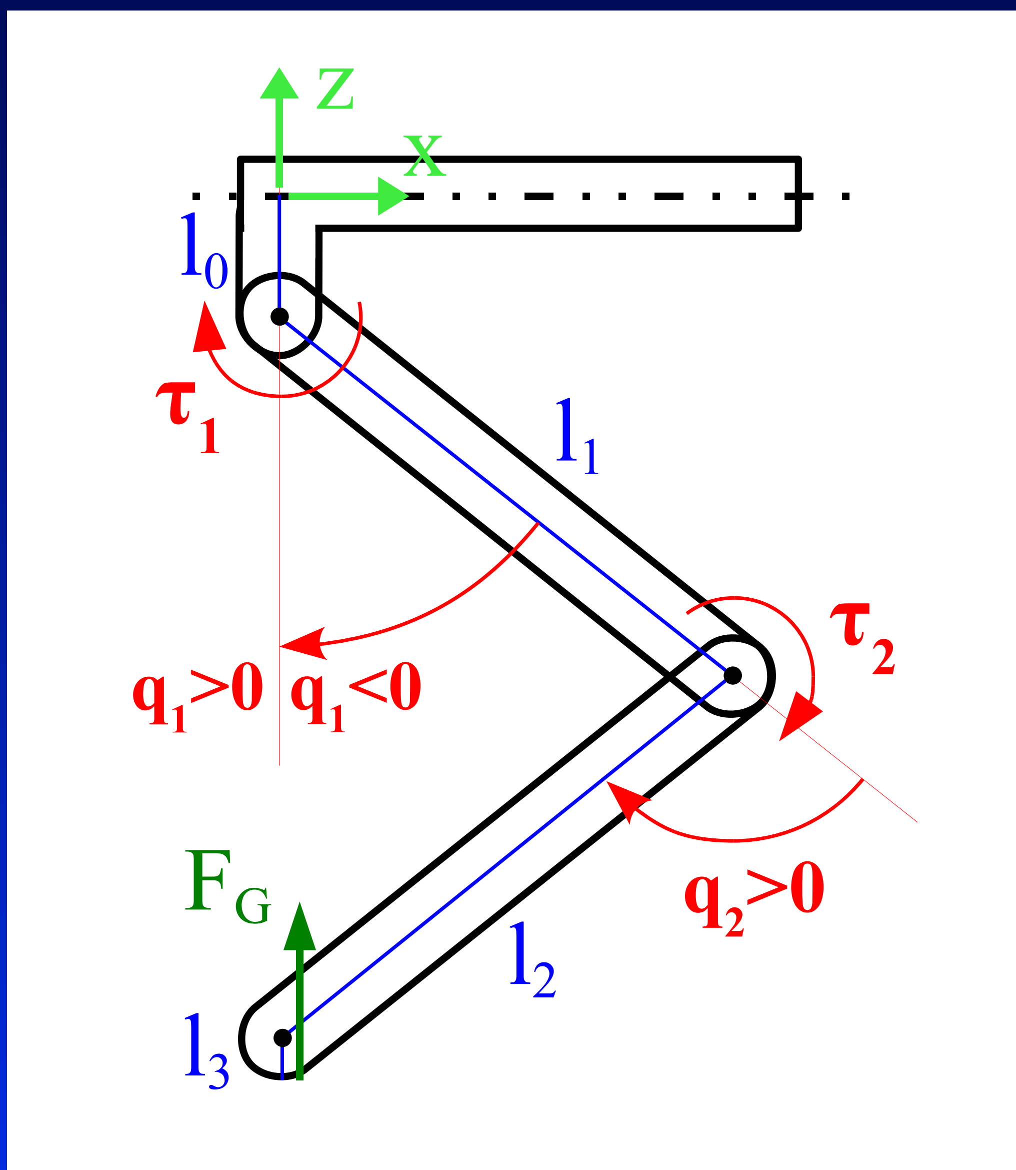

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[Semini 2010 PhD Thesis]

Hardware

What HW for force control

What hardware to implement a torque source?

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Electrical:

- Gear head (speed/ruggedness)
- Bandwidth
+ Commercial availability

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Hydraulic:

+ rugged
+ simple to control
+ simple mechanics
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+ high velocity / high force
- limited commercial availability of small elements
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Piezo, Polymers, Shape memory alloy, carbon nano tubes???

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Marco Hutter &
Claudio Semini

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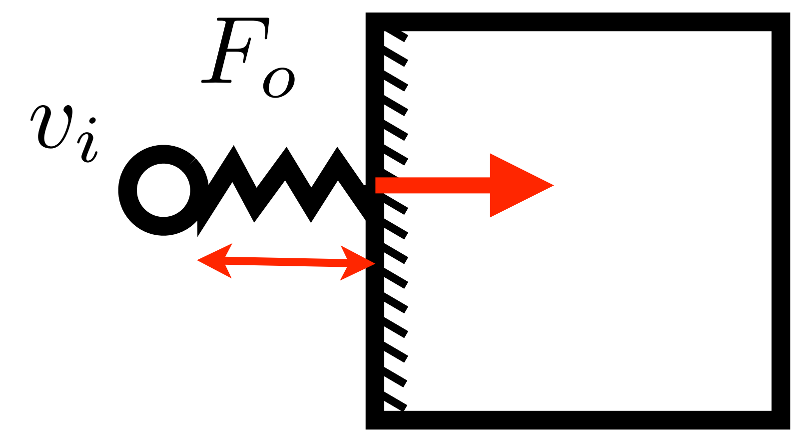

Force can be controlled by controlling expansion of a 'spring-like-element', i.e. imposing velocity on a 'spring'

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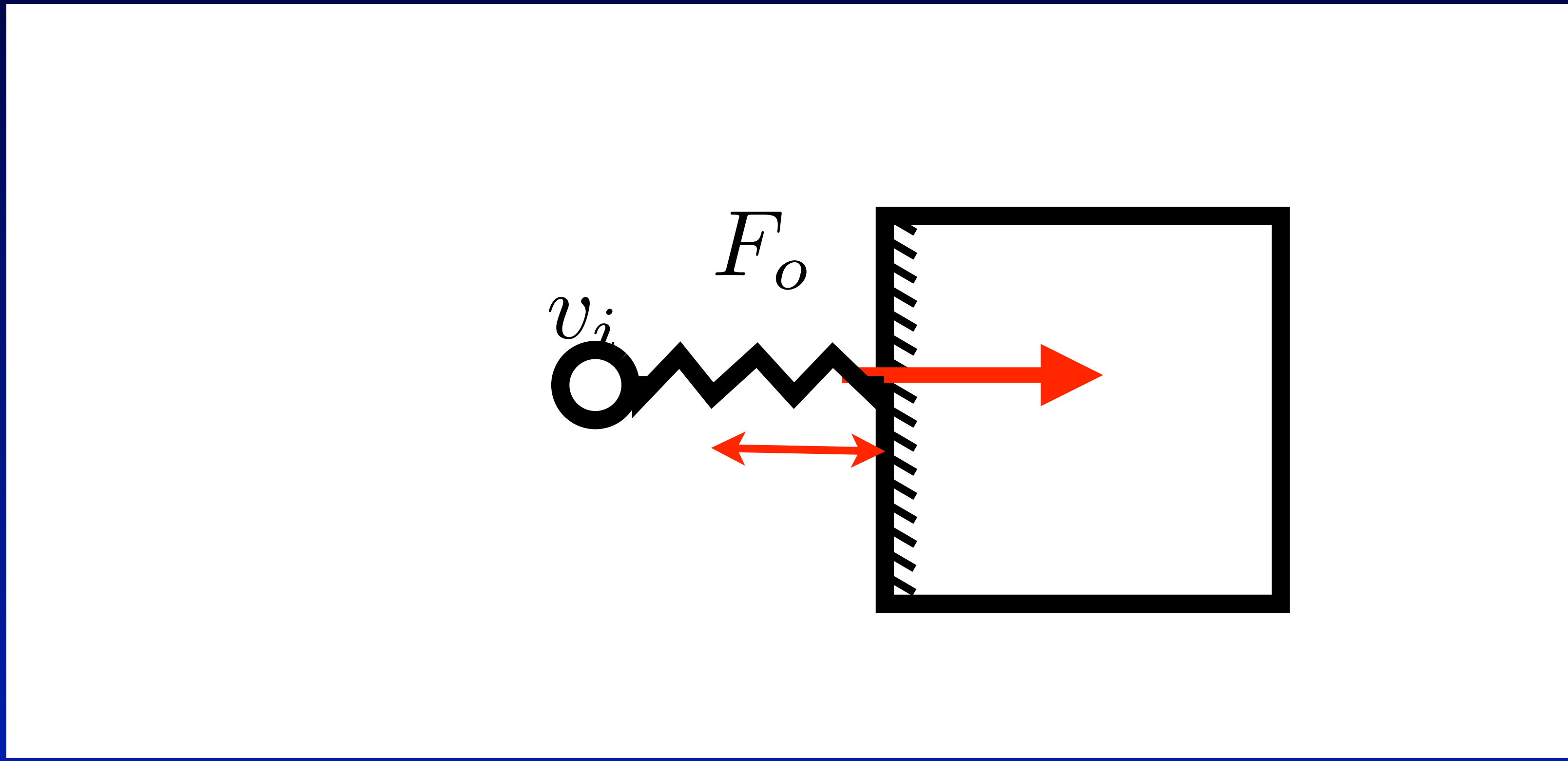

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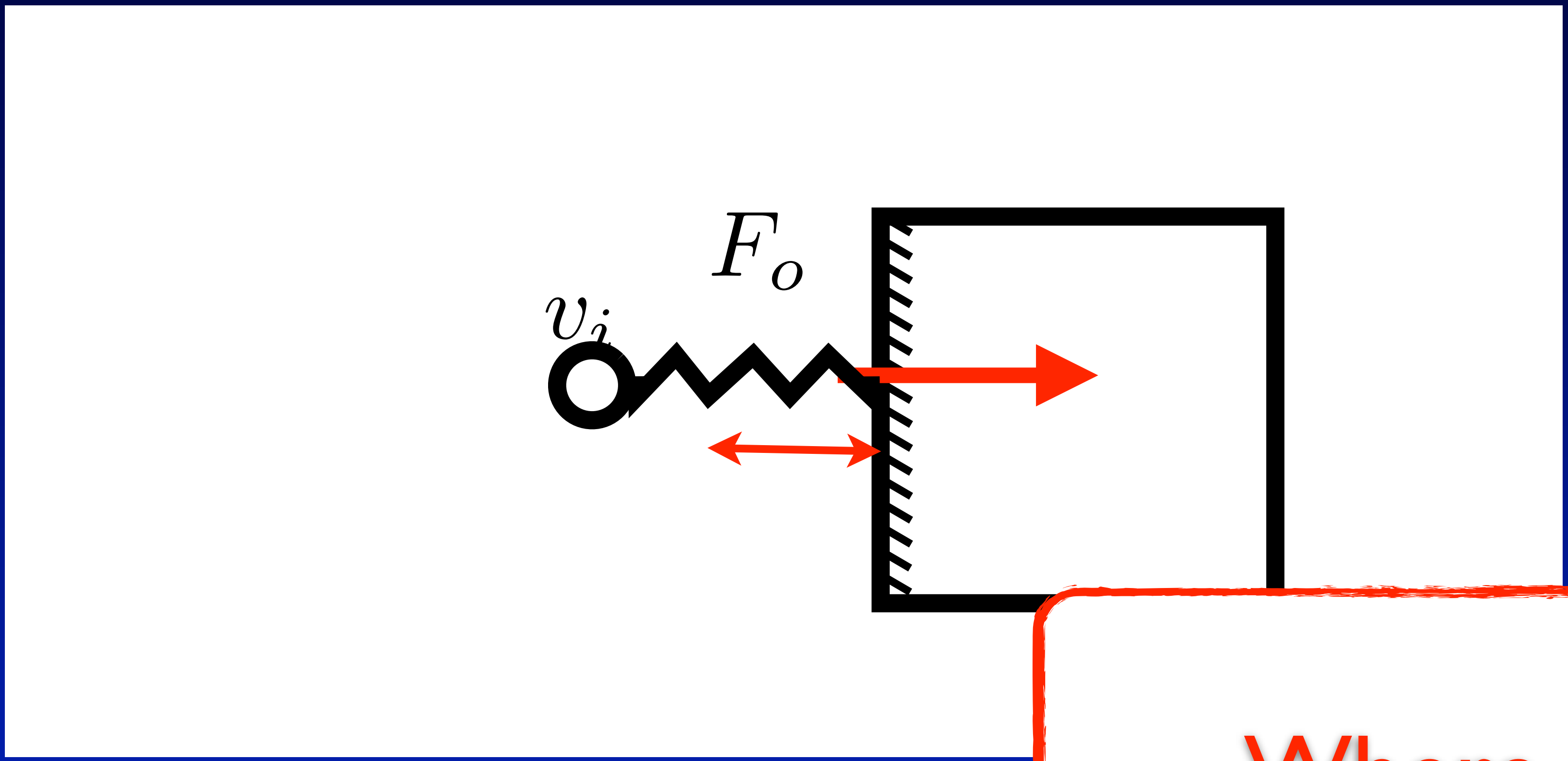

Where is the spring???

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[Harmonic drive]

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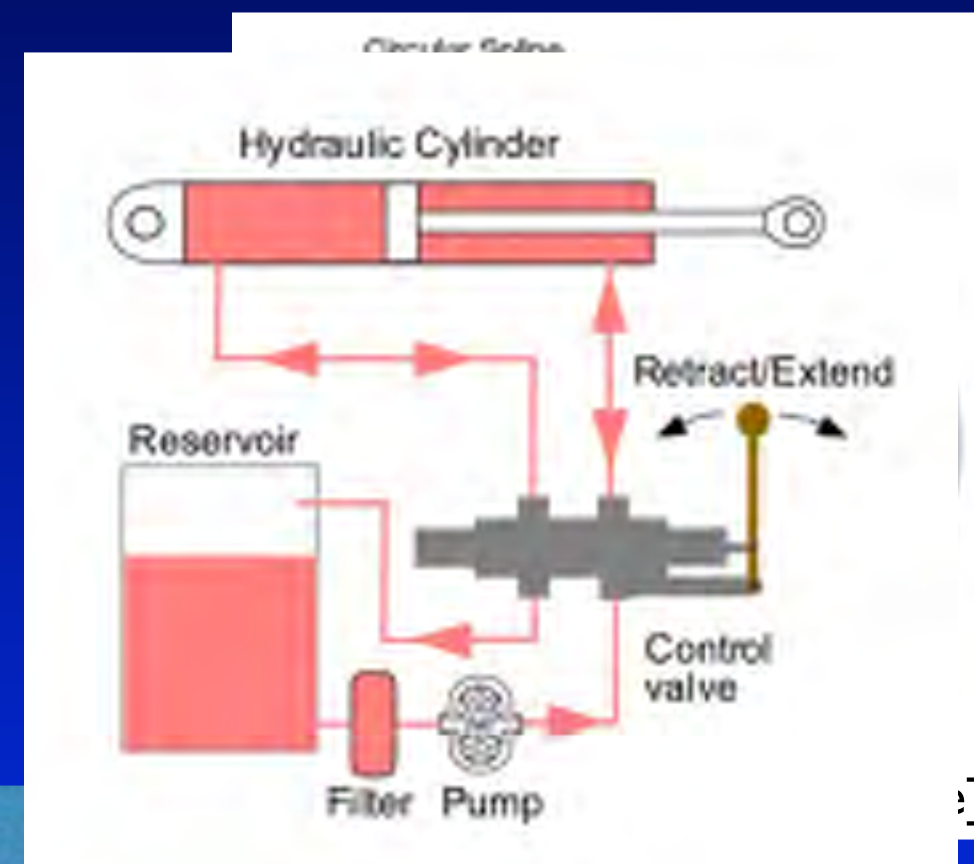

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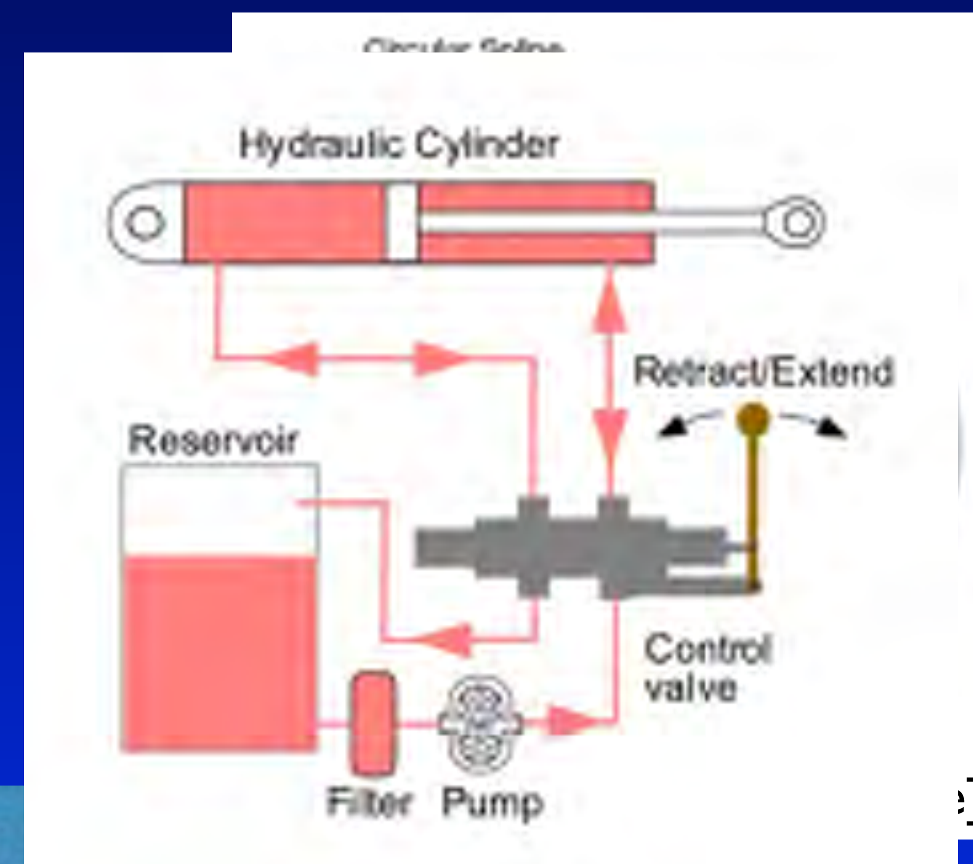

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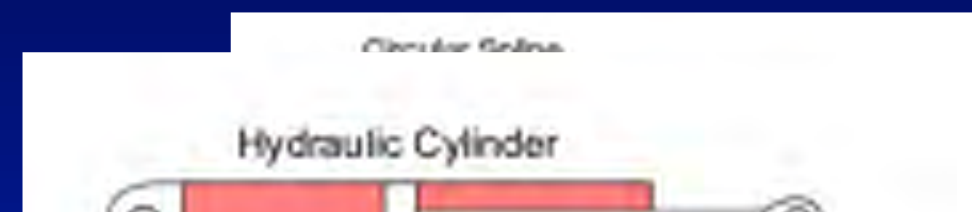
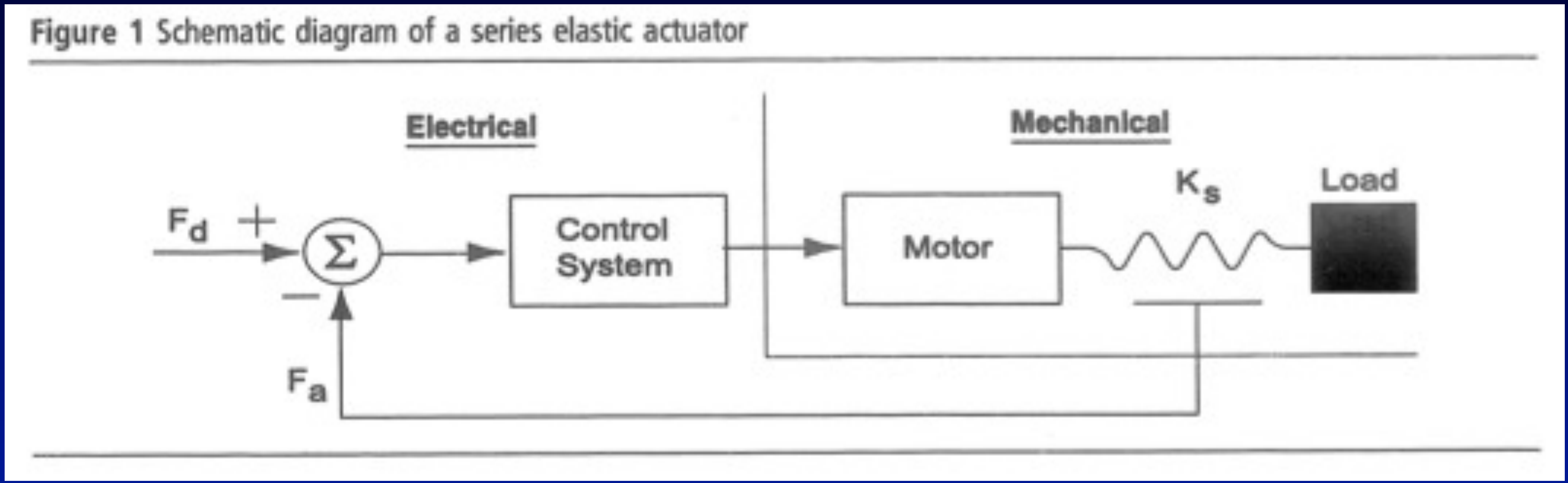



[Yobotics e-SEA]

Closed loop force control



[Pratt et al, 2002]

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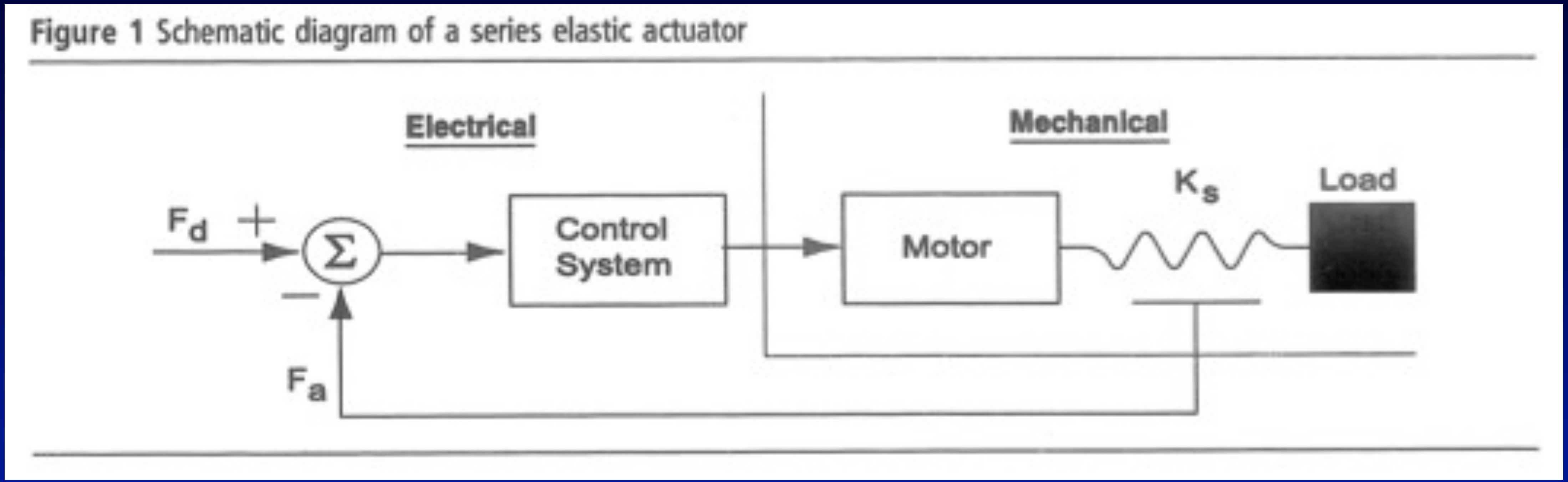

$\dot{F} \approx u$

[Pratt et al, 2002]

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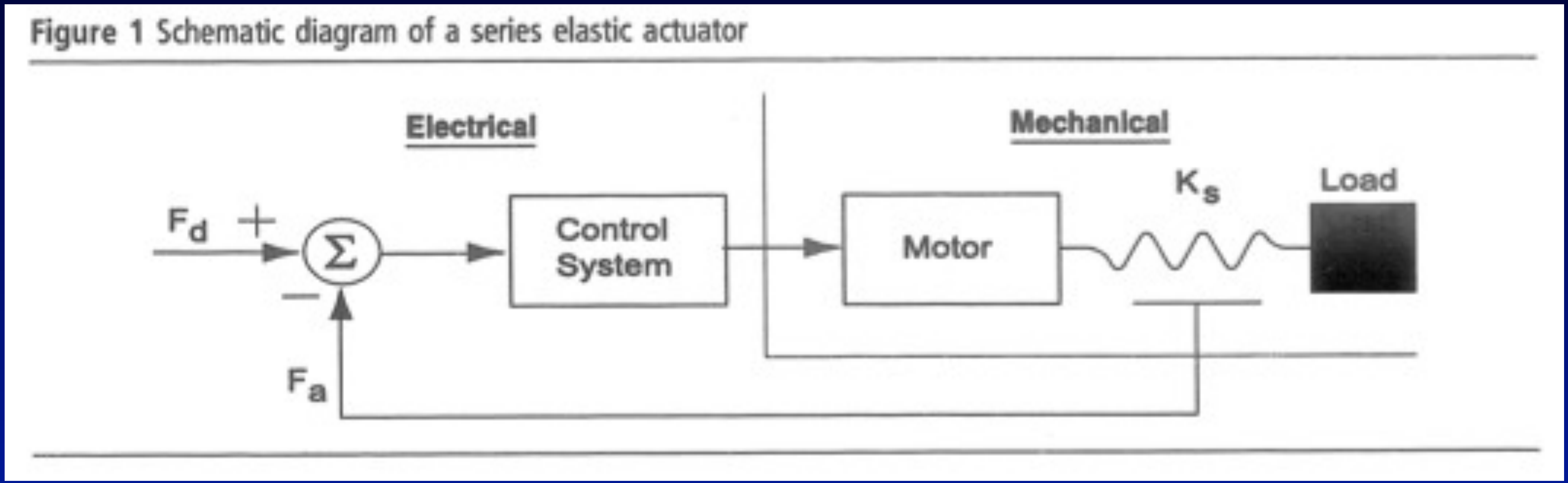

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$$\dot{F} \approx u$$

$$u = -K(F_a - F_d)$$

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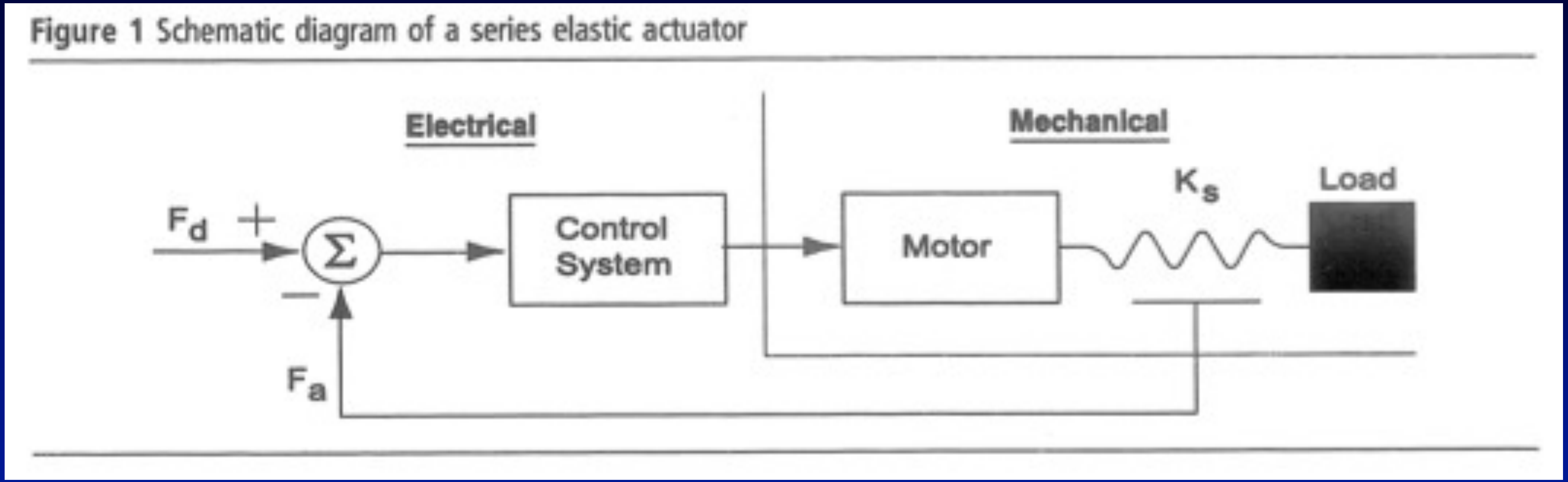
Closed loop force control



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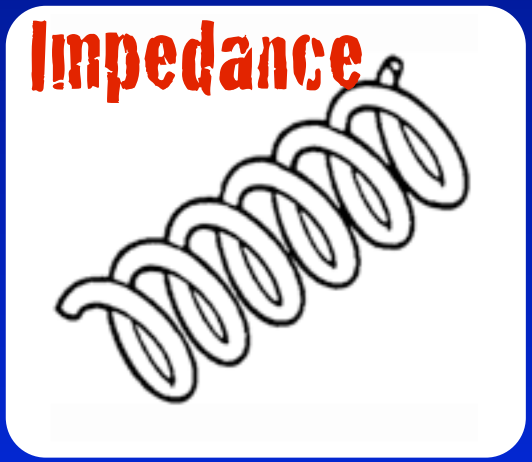

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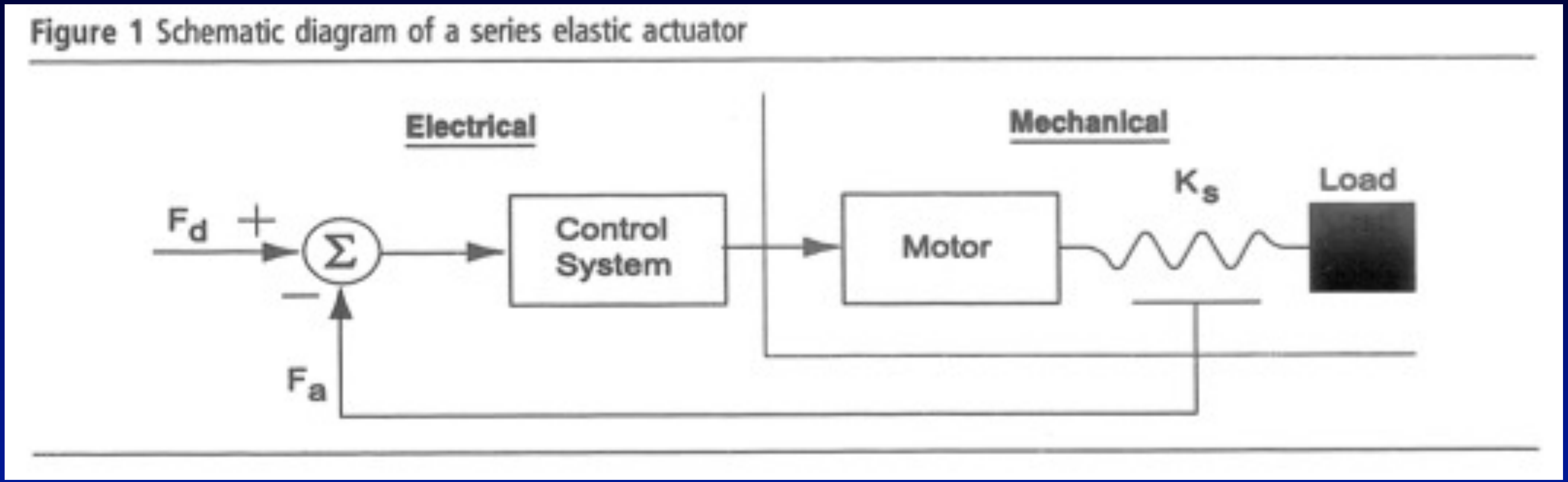

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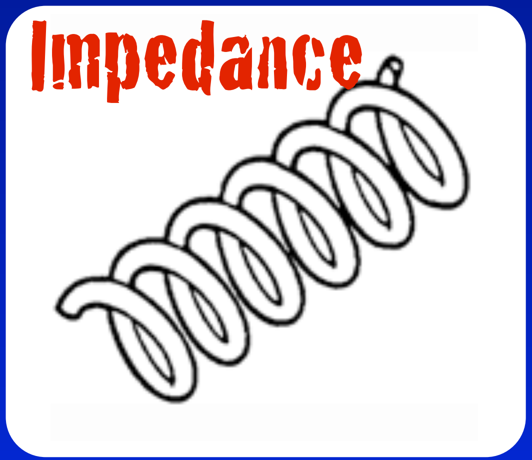
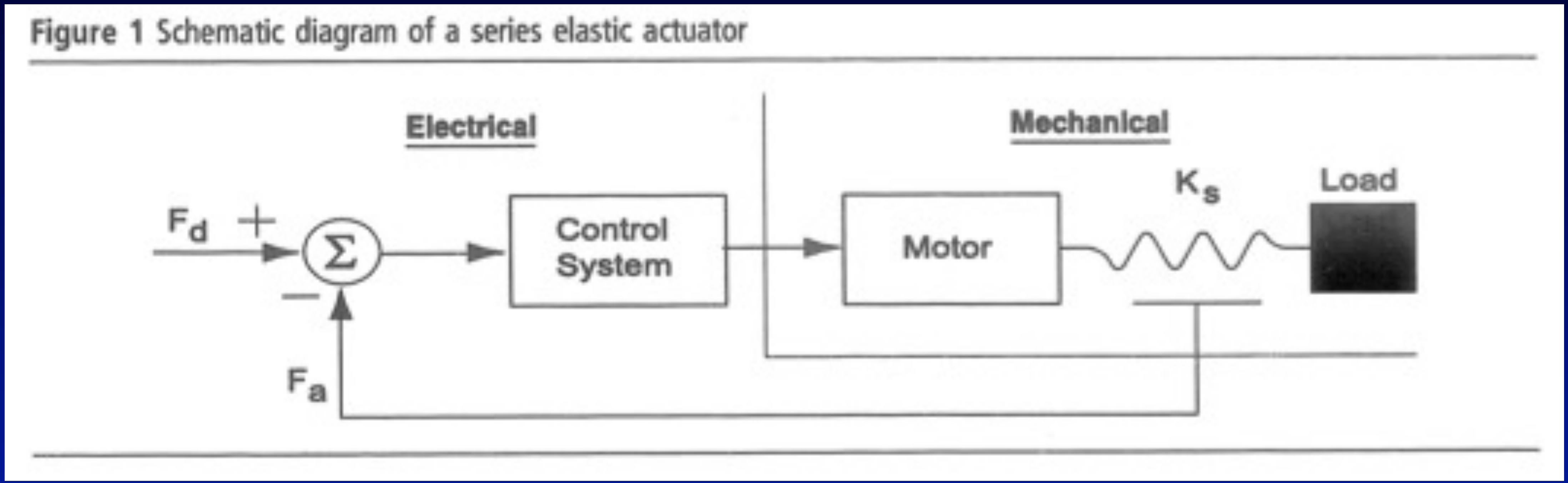


$$\dot{F} = kv$$

$$\dot{F} \approx v$$

Closed loop force control



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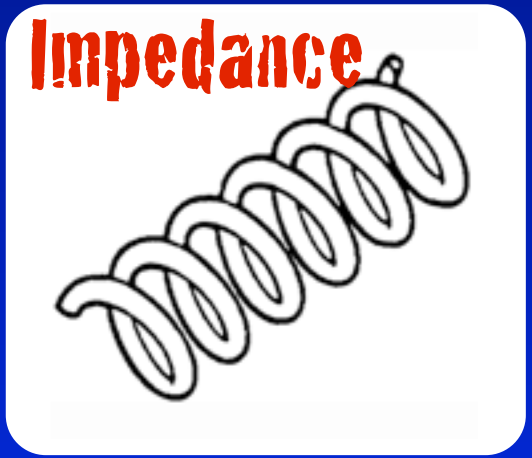

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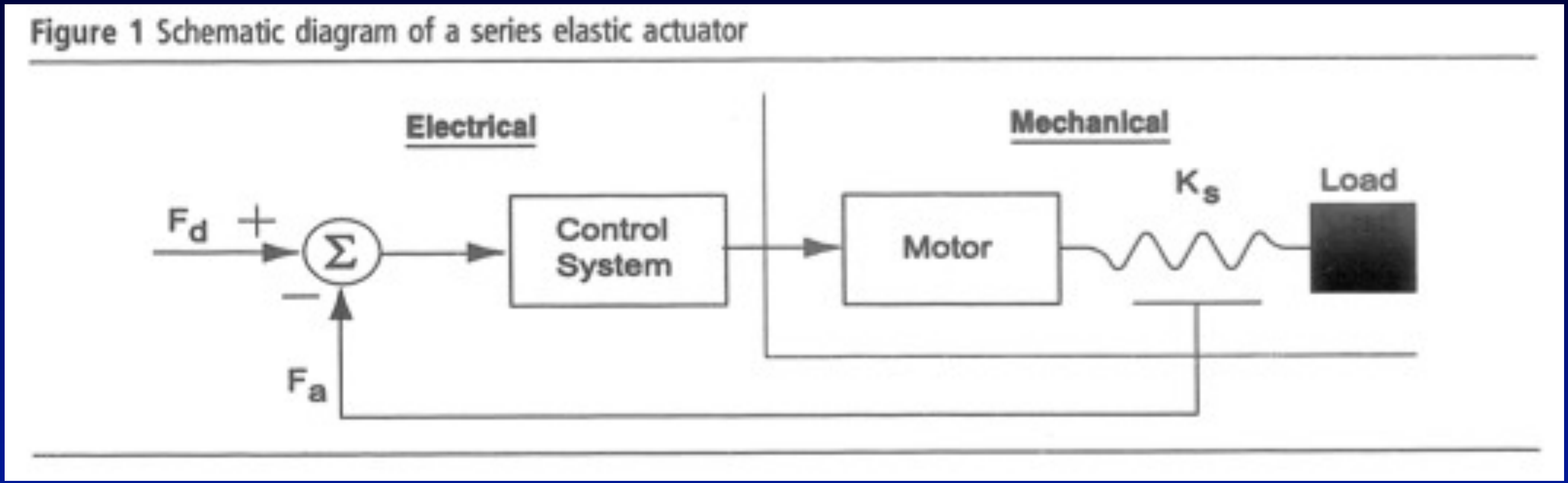
⇒ velocity setpoint for the motor

Closed loop force control



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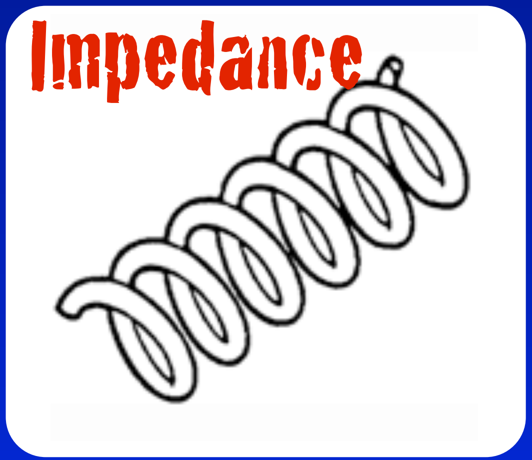
$$\dot{F} \approx u$$
$$u = -K(F_a - F_d)$$
$$u = -KF_e$$



$$\dot{F} = kv$$
$$\dot{F} \approx v$$

⇒ velocity setpoint for the motor

This control law is independent of the technology of the 'motor' and 'spring'!

SEA: Force control over *soft* spring

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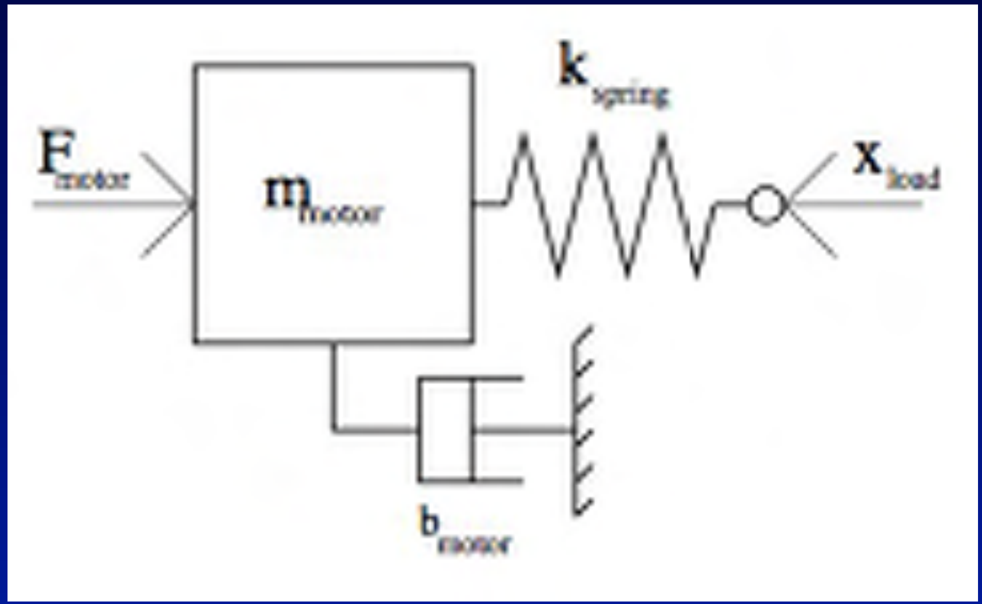

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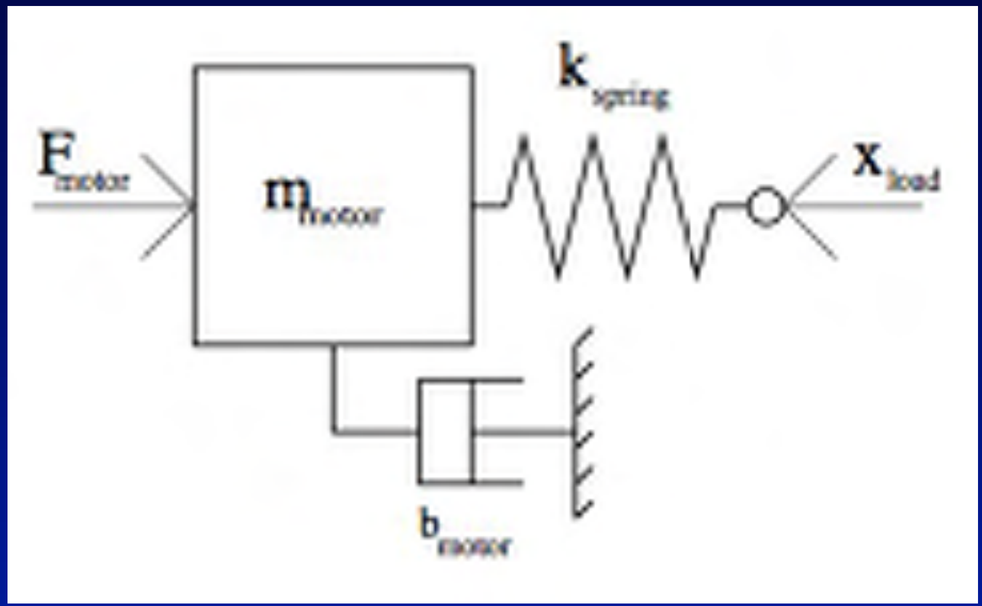

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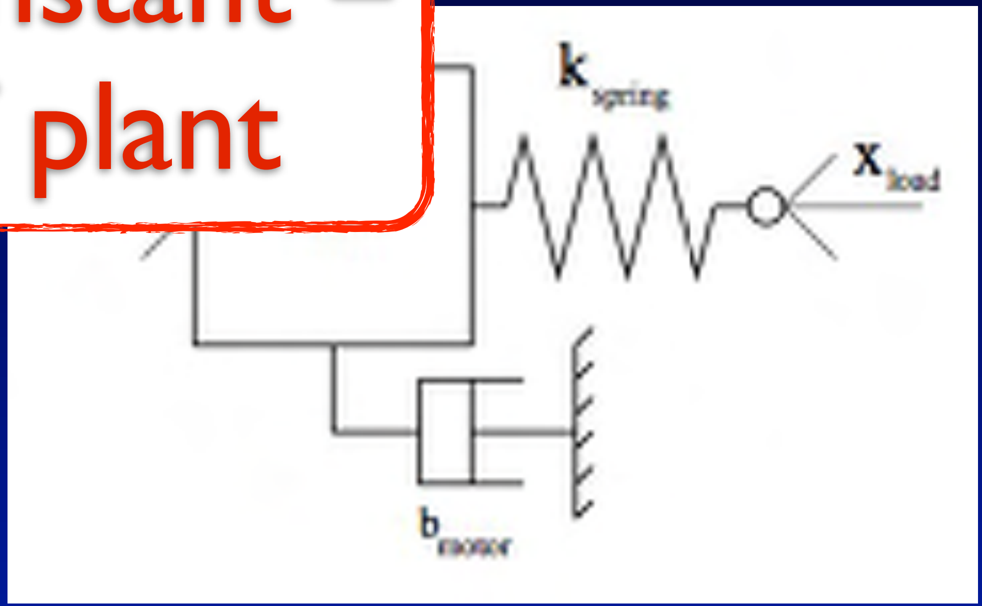

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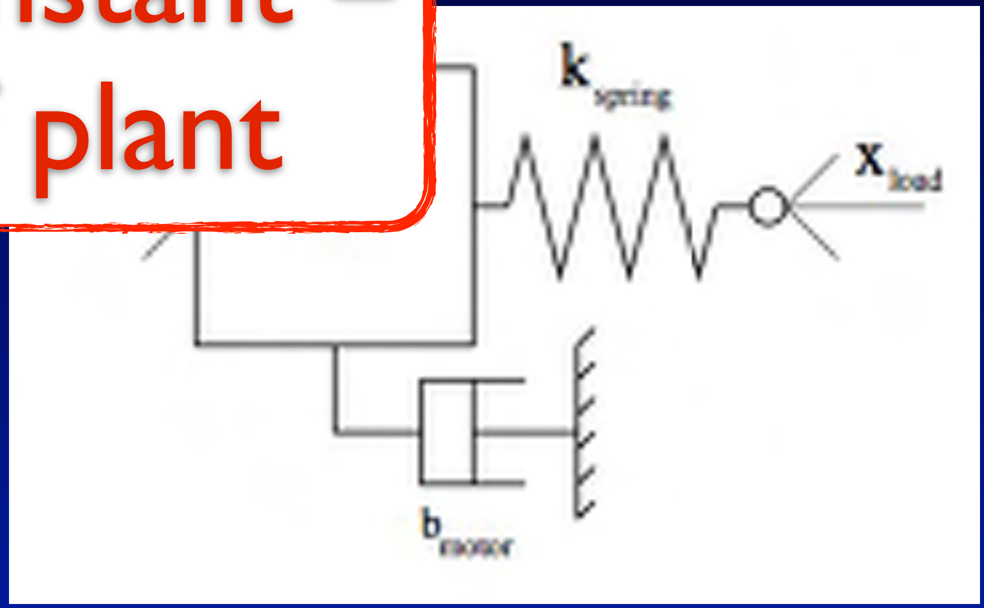

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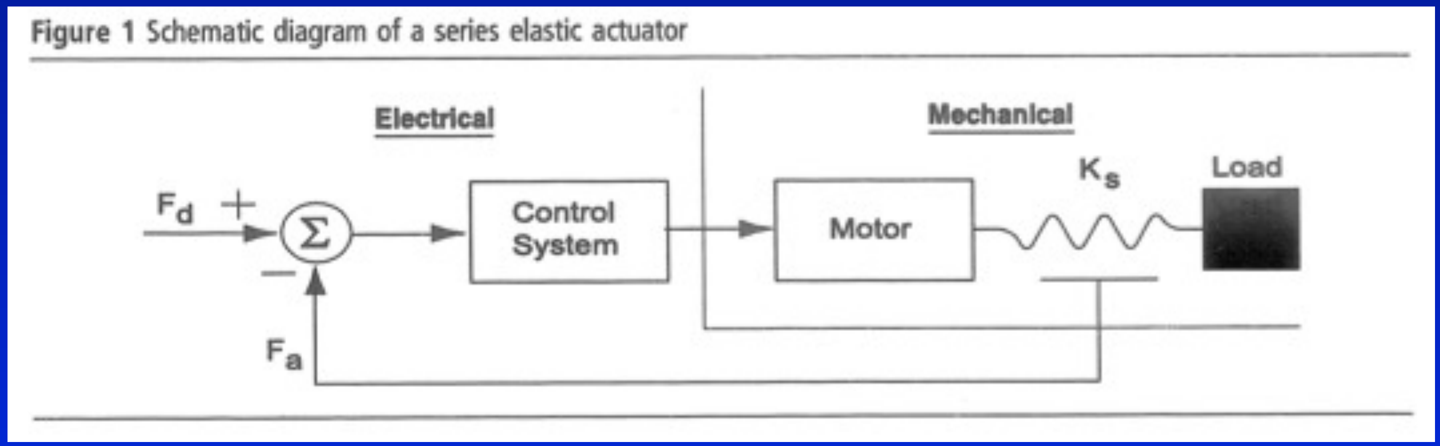

Figure 1 Schematic diagram of a series elastic actuator

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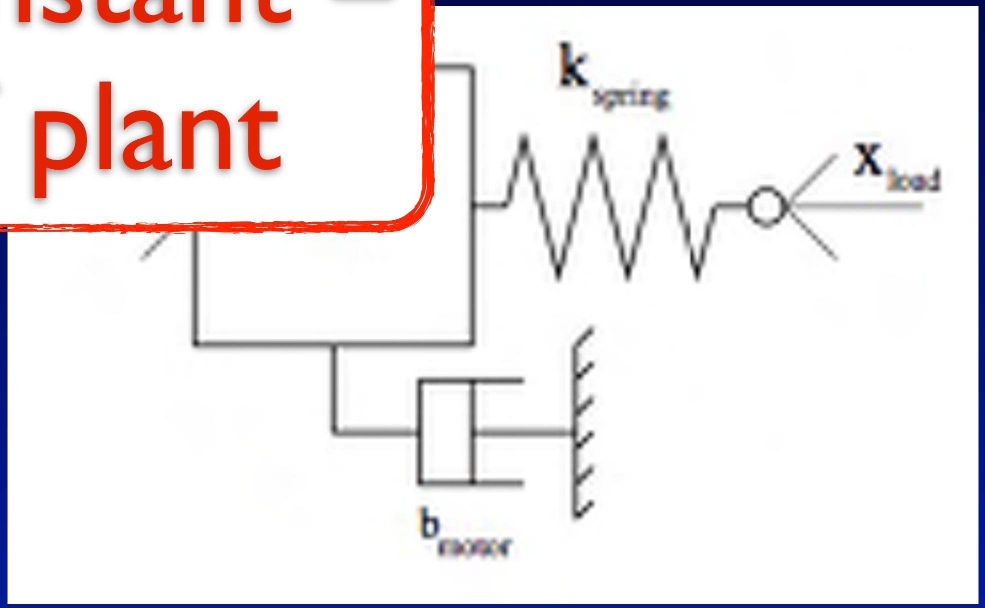

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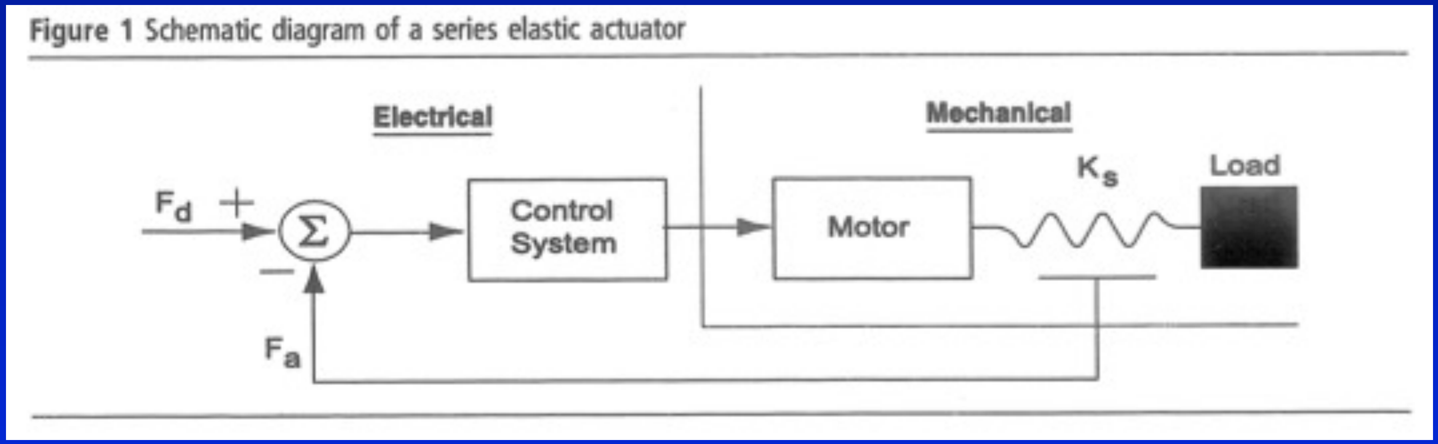

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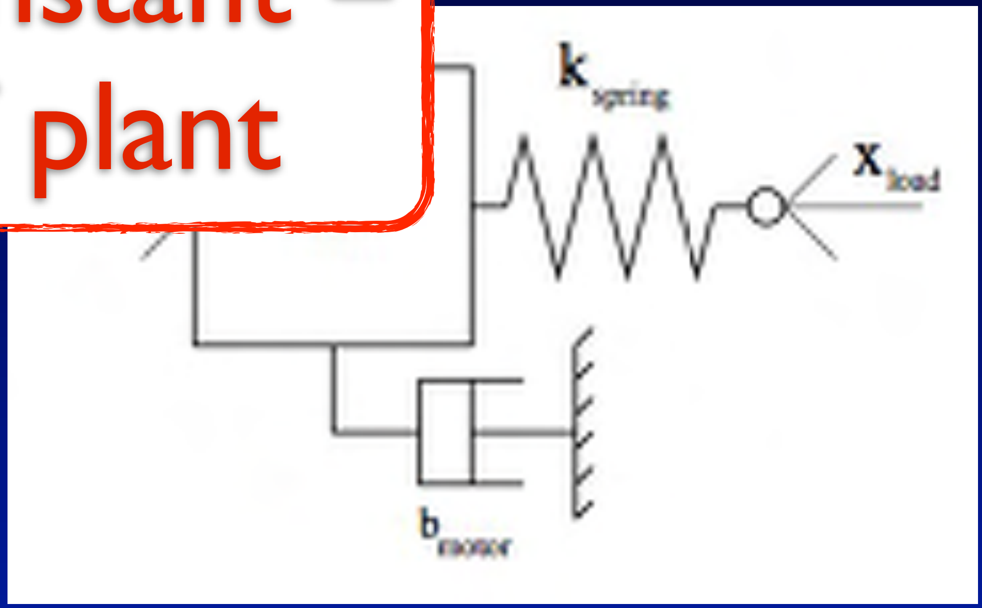

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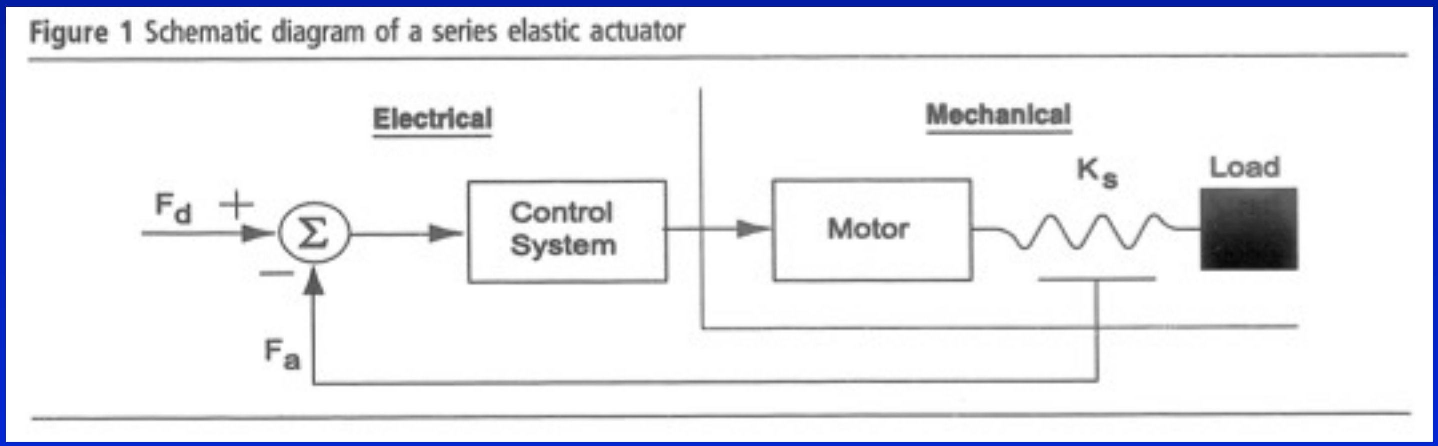

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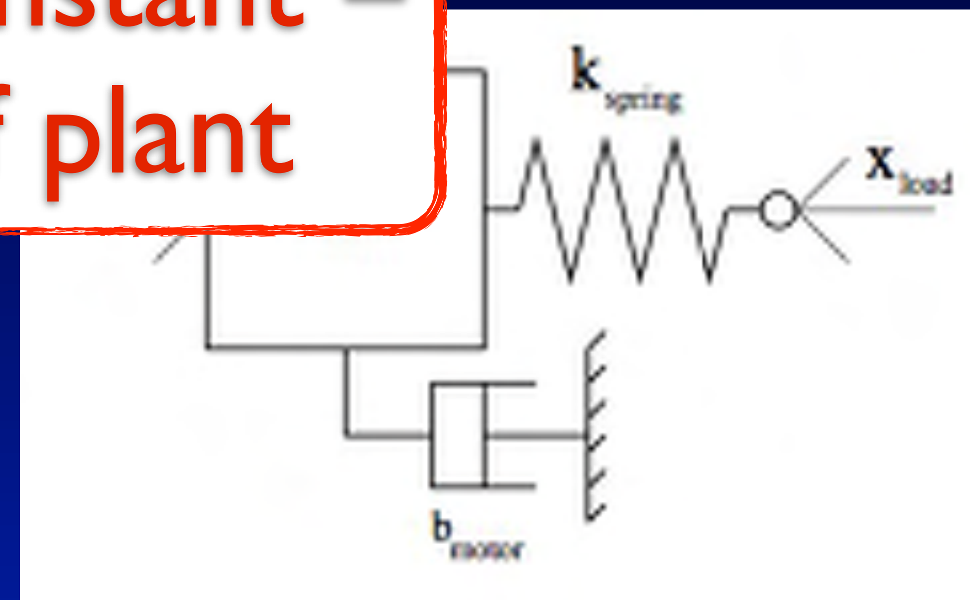

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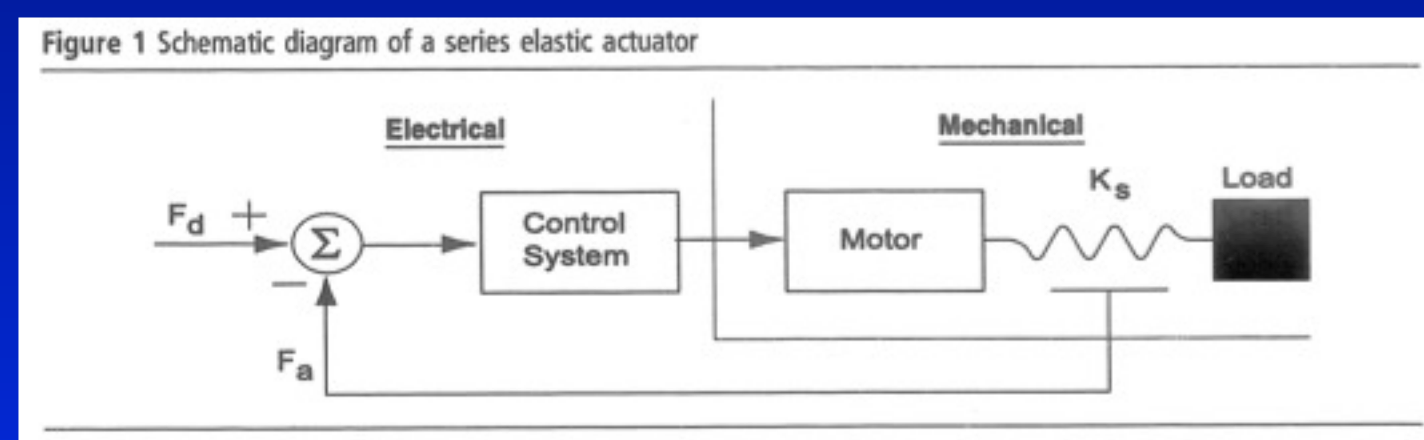

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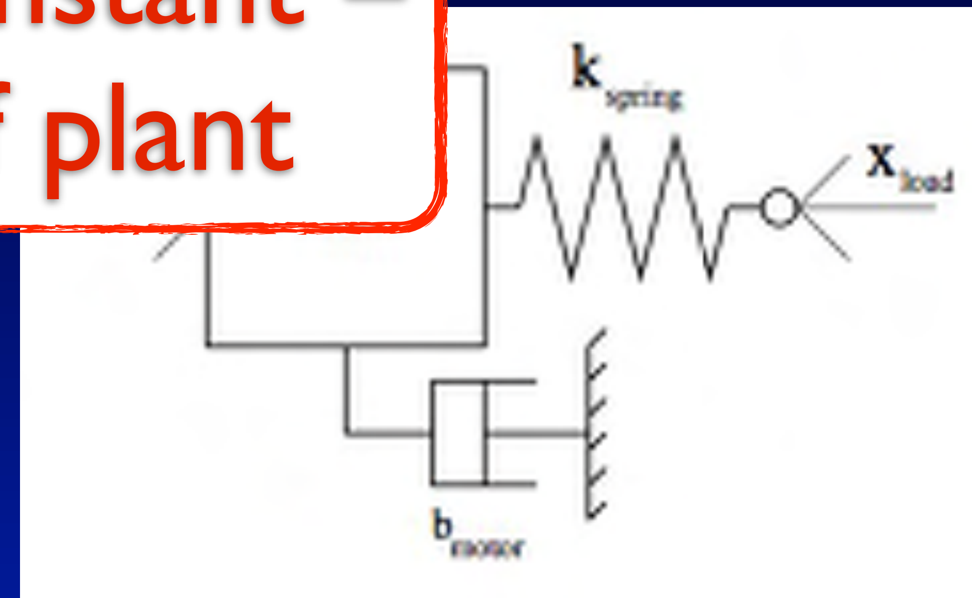

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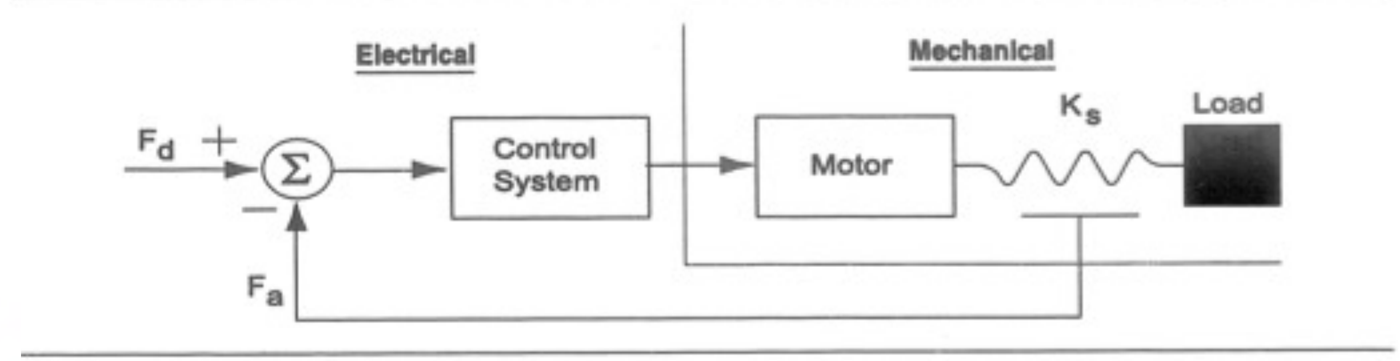

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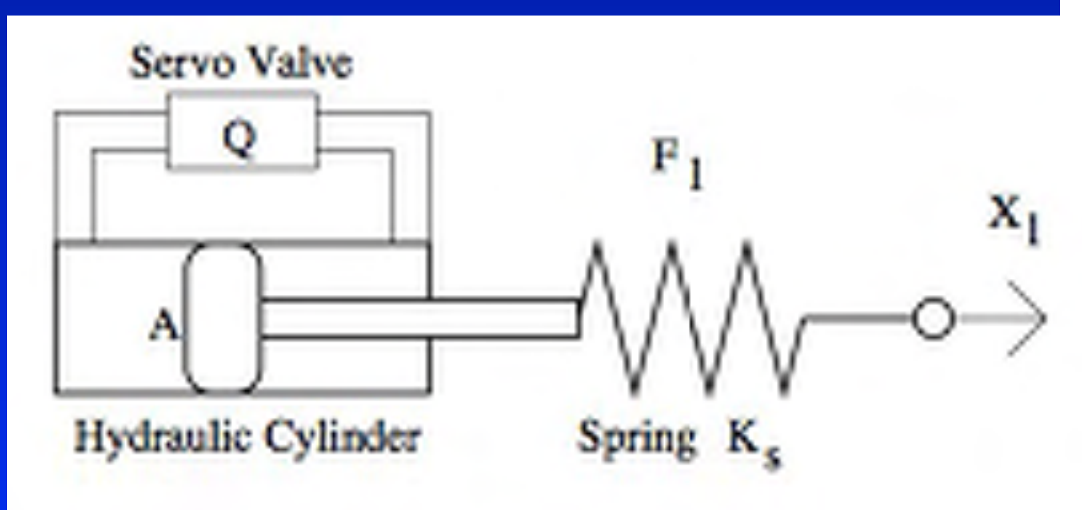

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Pros/Cons of active/passive compliance

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Important: The discussion of impedance and control is applicable entirely to passive or active elements: SYSTEMS THEORY!

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[DLR]

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- Kinematic models are very easy to obtain and can already be very helpful (VM control etc)
- Full dynamic models are a bit more tricky, but often we don't need a very accurate model to gain advantage

Wrap up

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- Force is always controlled and measured over an impedance

END LECTURE 1