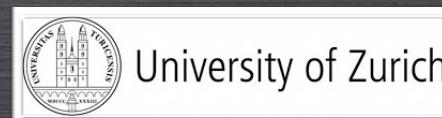


MORPHOLOGICAL COMPUTATION AND SOFT ROBOTICS

SHANGHAI LECTURES, OCTOBER 31, 2013

HELMUT HAUSER
ARTIFICIAL INTELLIGENCE LABORATORY

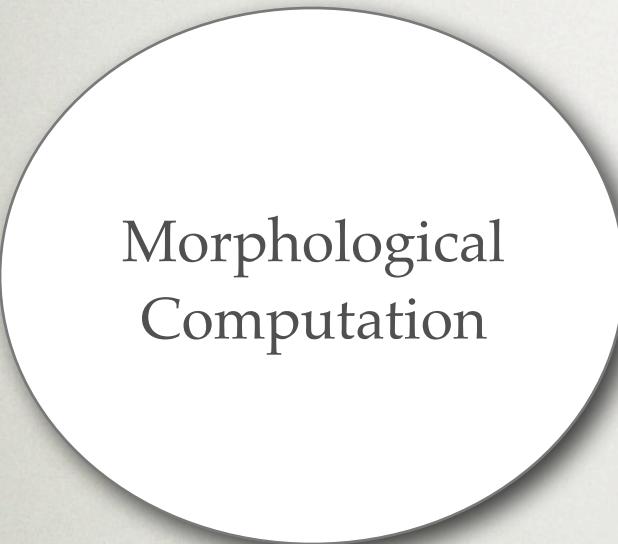


WHAT IS MORPHOLOGICAL COMPUTATION?



Morphological
Computation

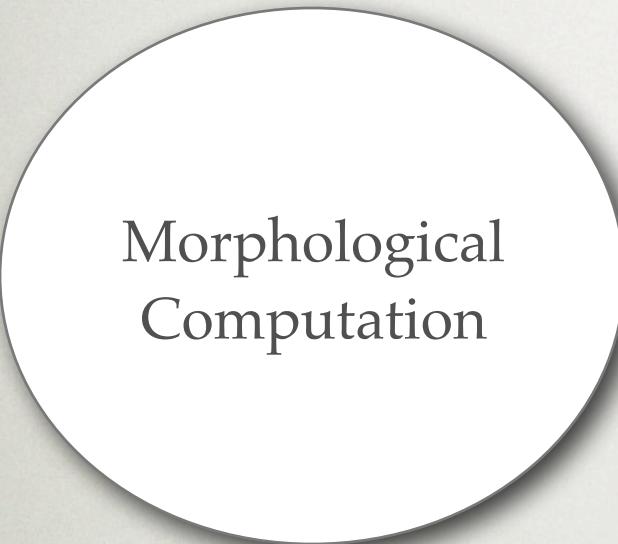
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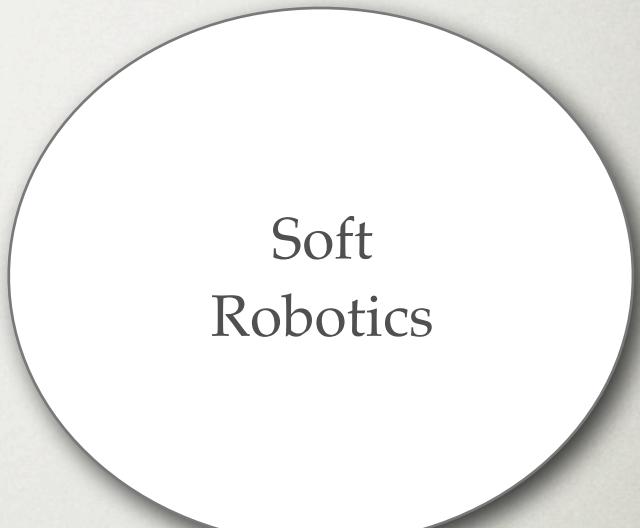
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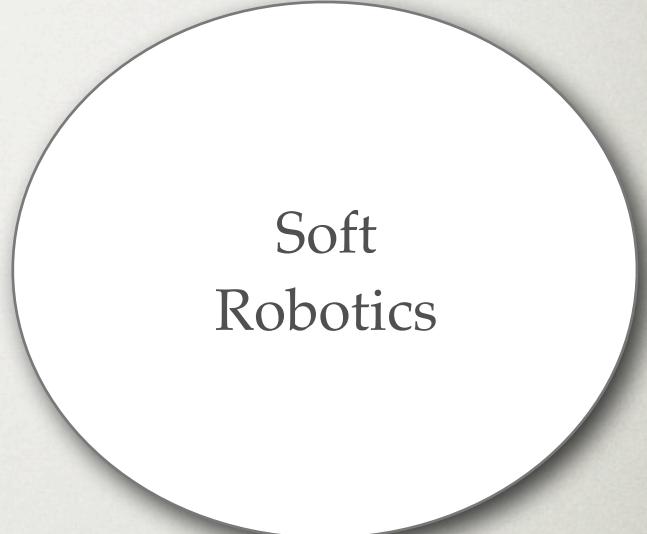
WHAT IS SOFT ROBOTICS?



Soft
Robotics

WHAT IS SOFT ROBOTICS?

- use of soft material

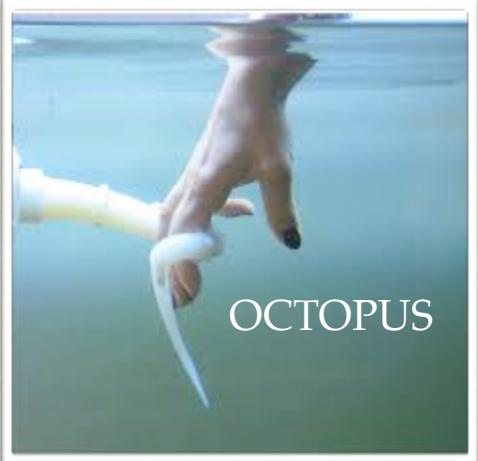


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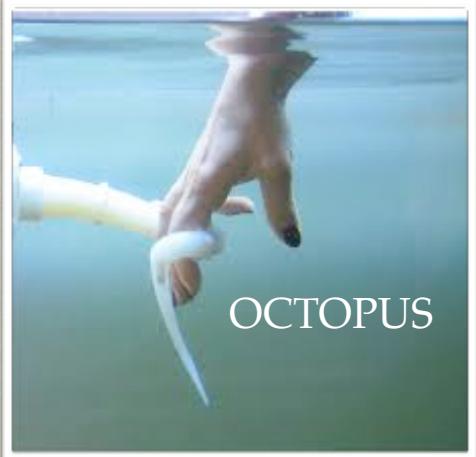
Soft
Robotics



WHAT IS SOFT ROBOTICS?

- use of soft material
- soft actuators

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Robotics



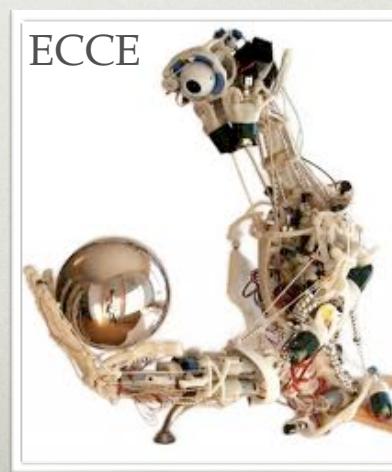
OCTOPUS



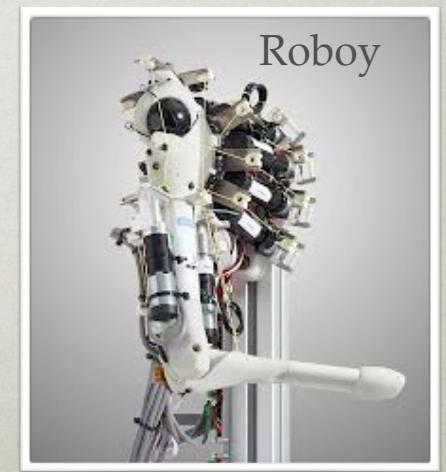
Havard



Tufts



ECCE

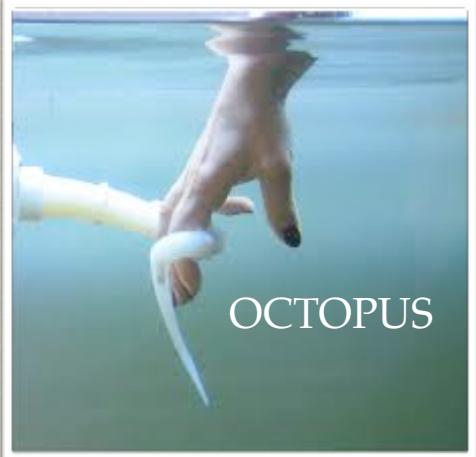


Roboy

WHAT IS SOFT ROBOTICS?

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- soft actuators
- often bio-inspired or biomimetic approaches

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Robotics



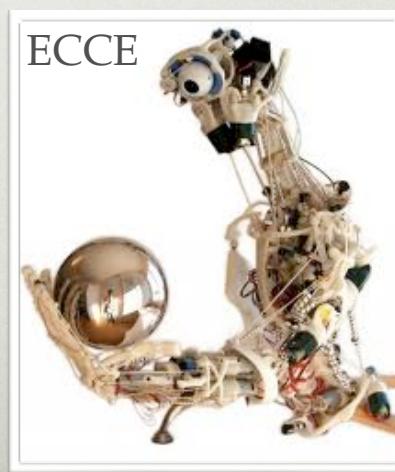
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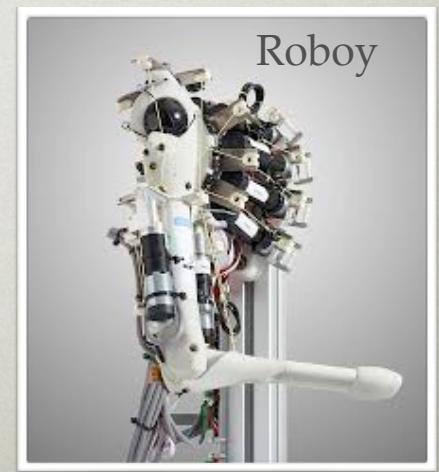
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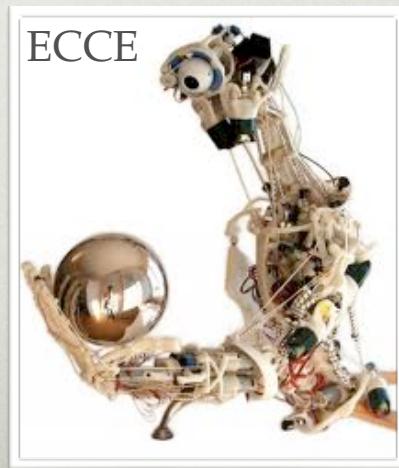
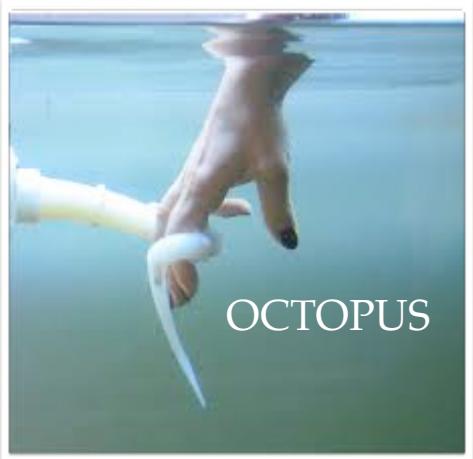


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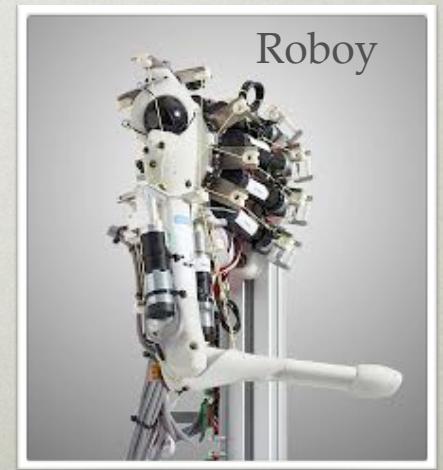
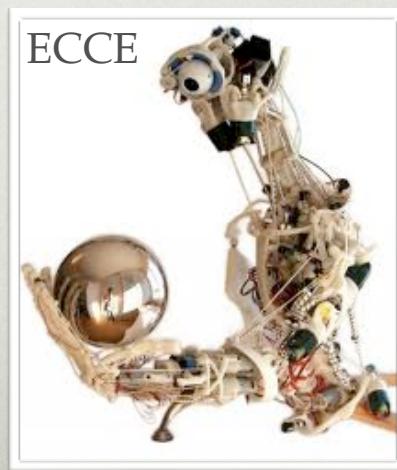
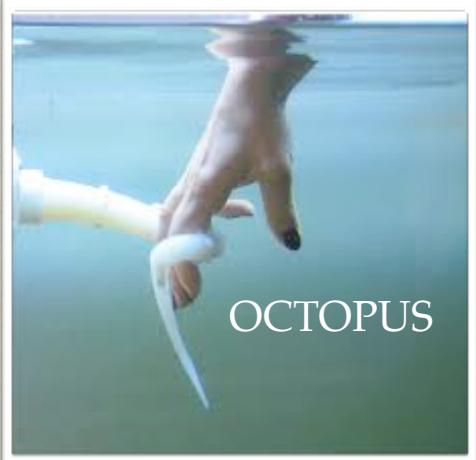
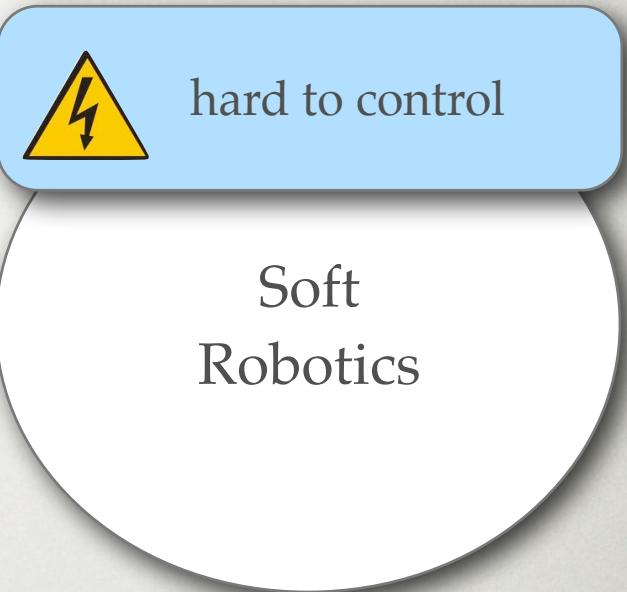
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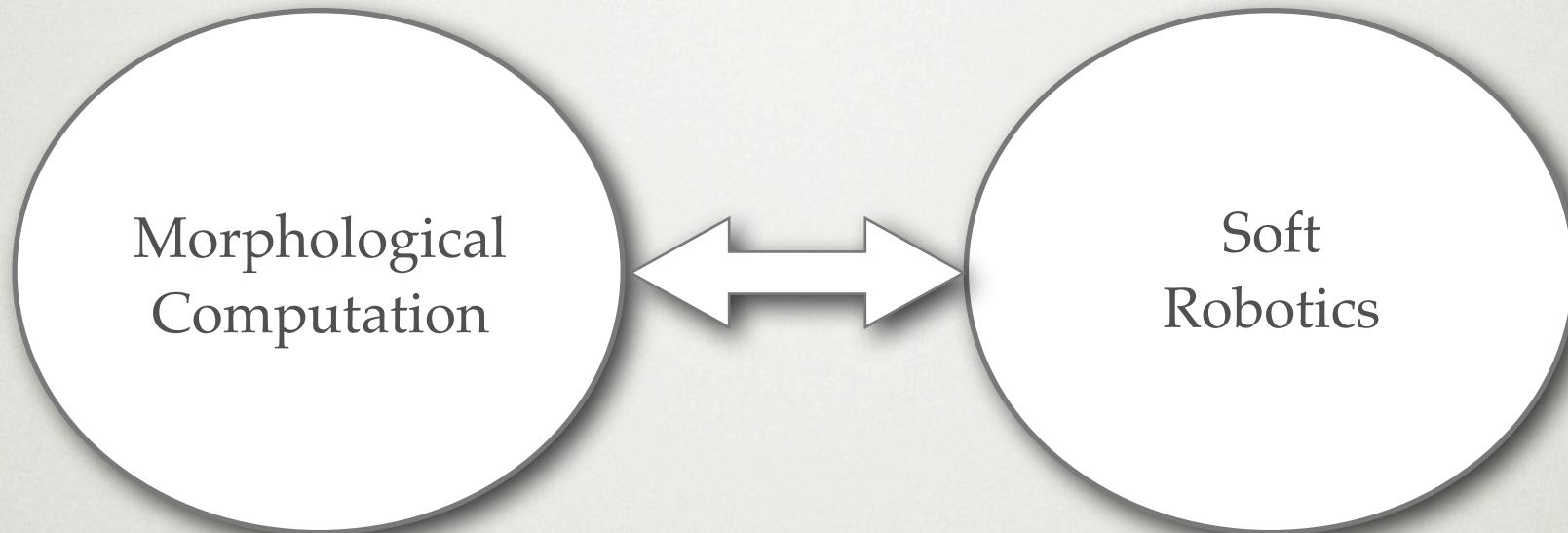


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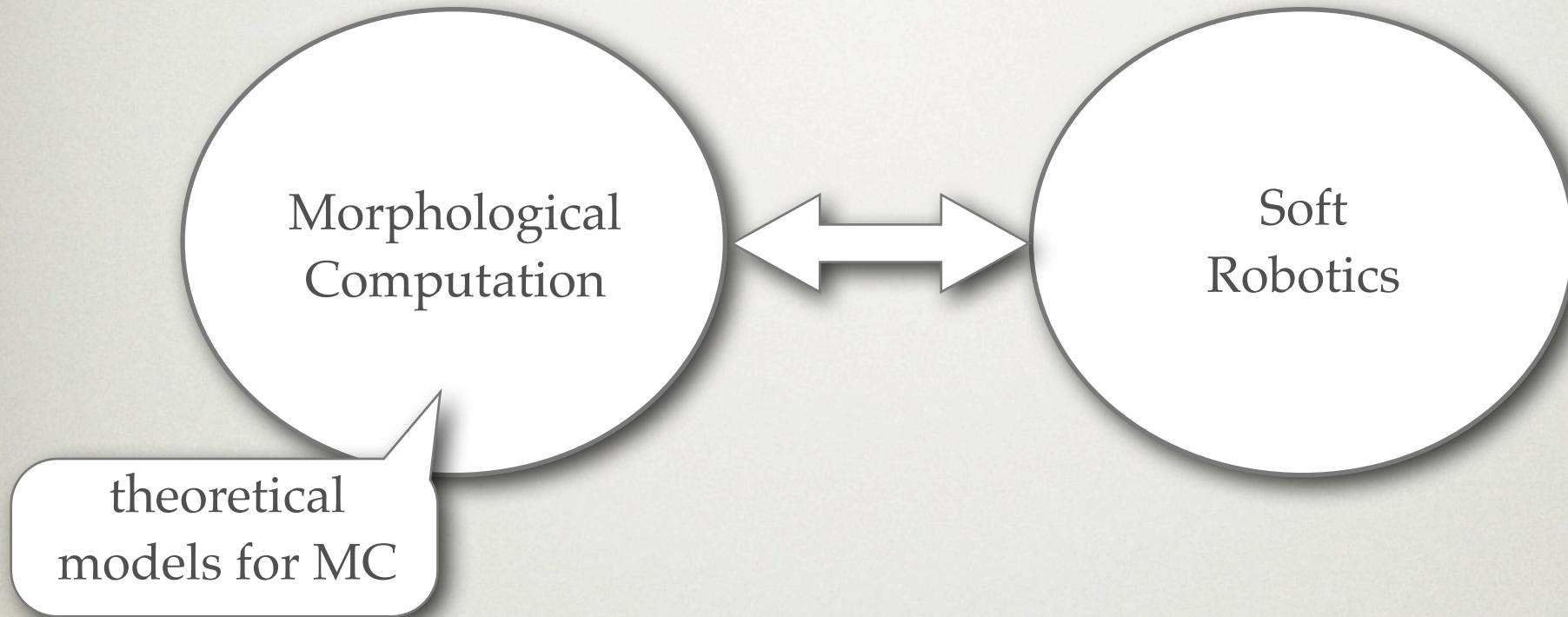
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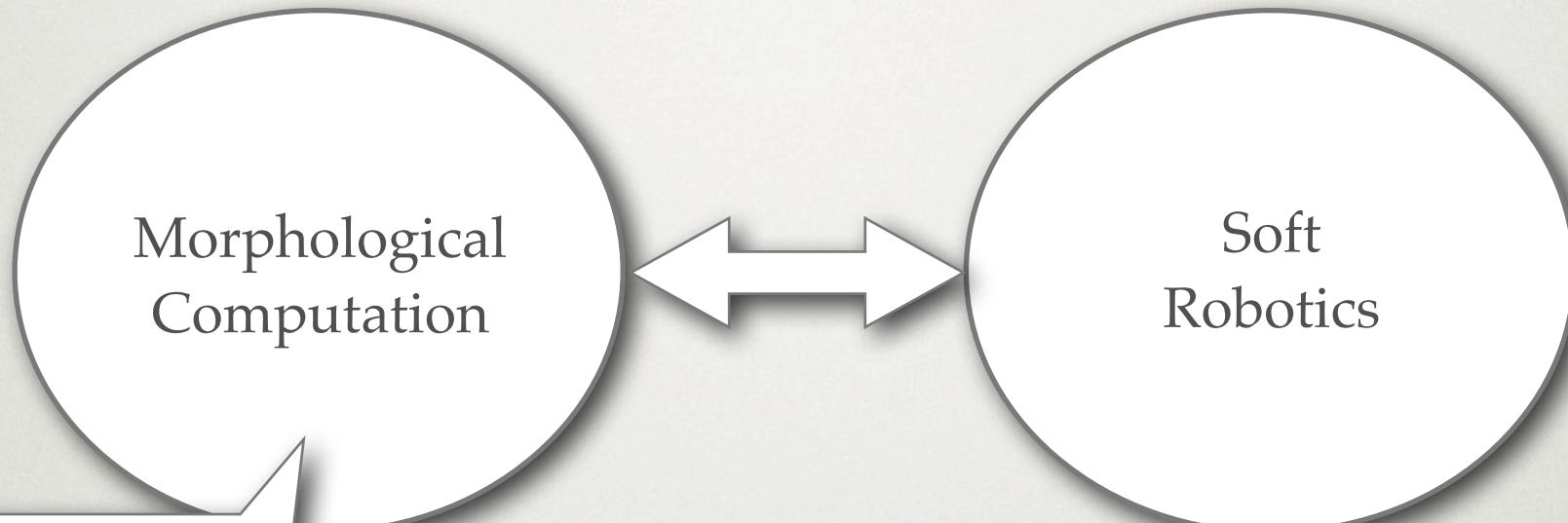
HOW ARE THEY CONNECTED?



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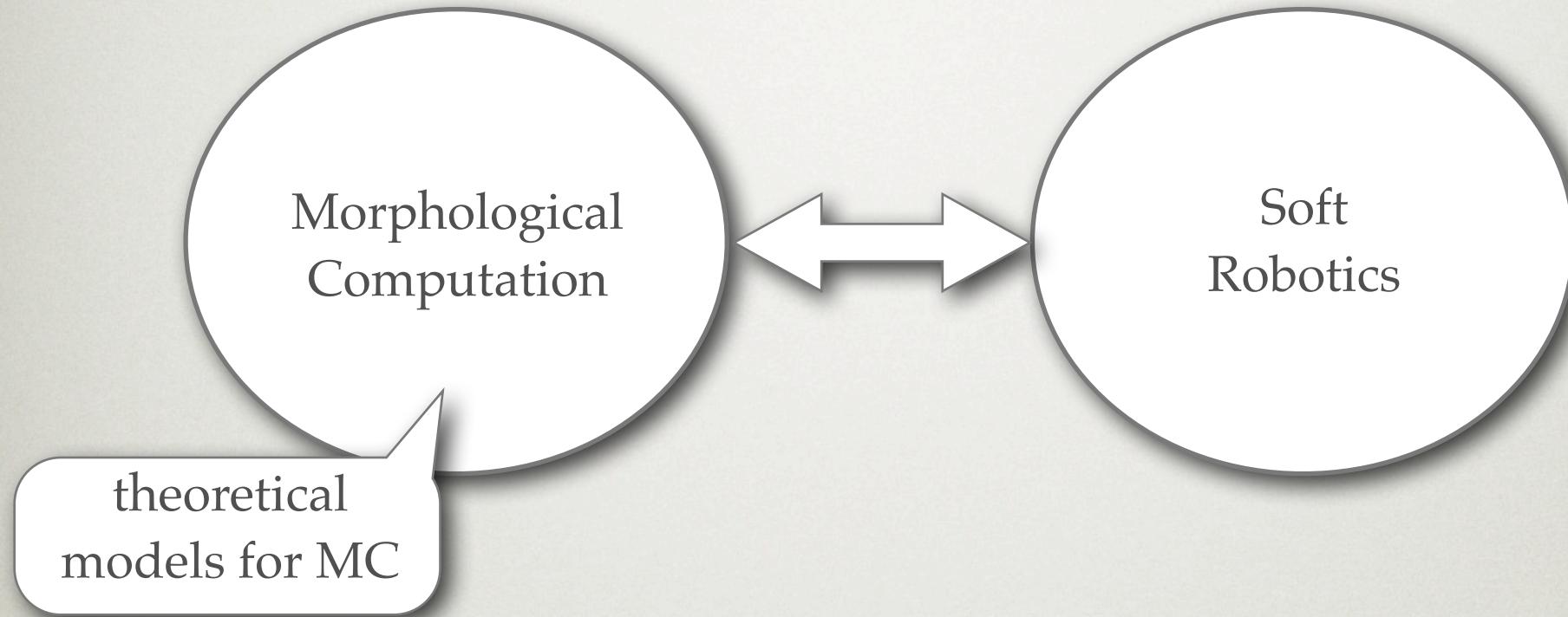


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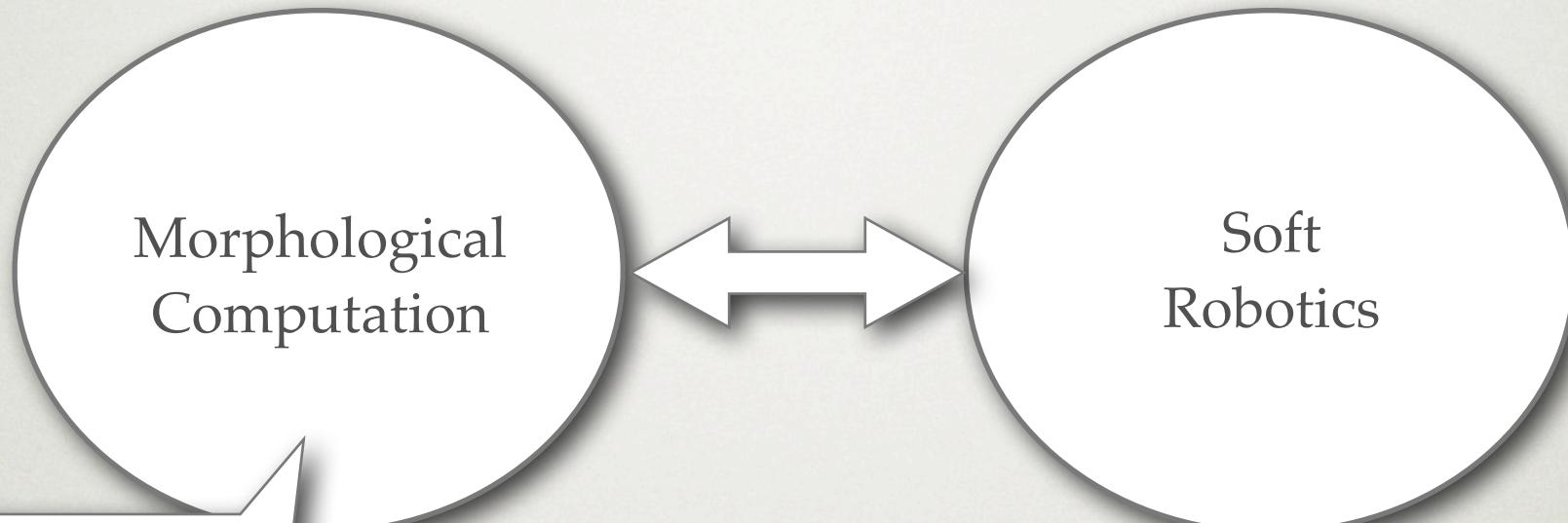
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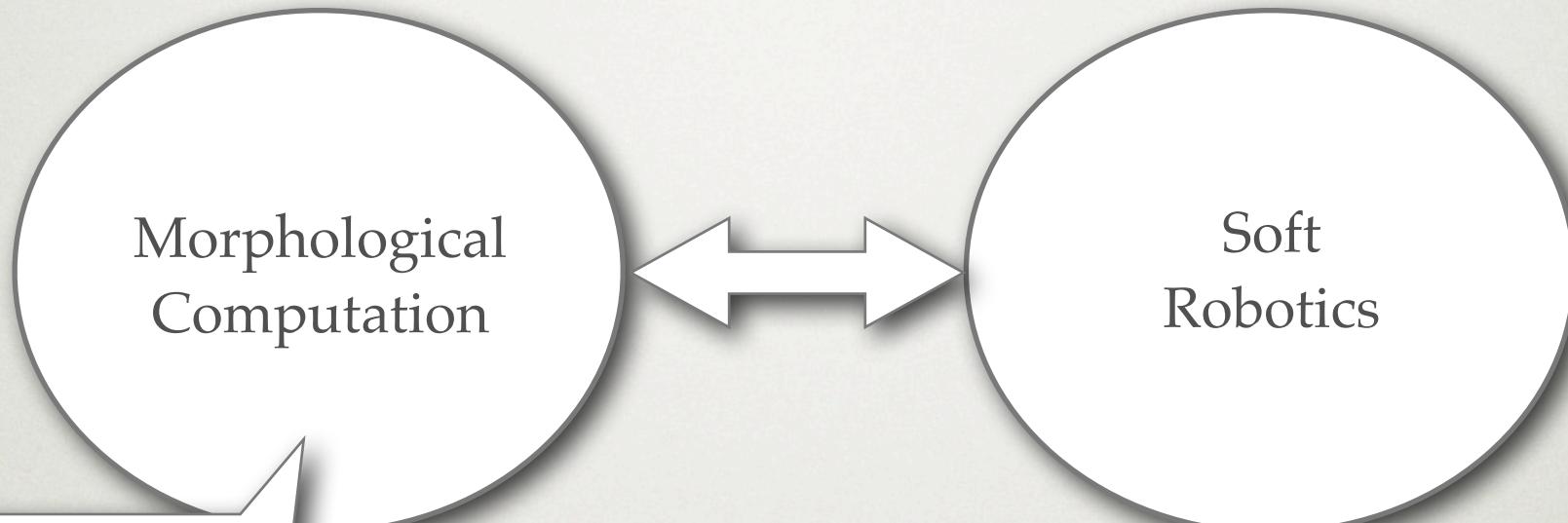
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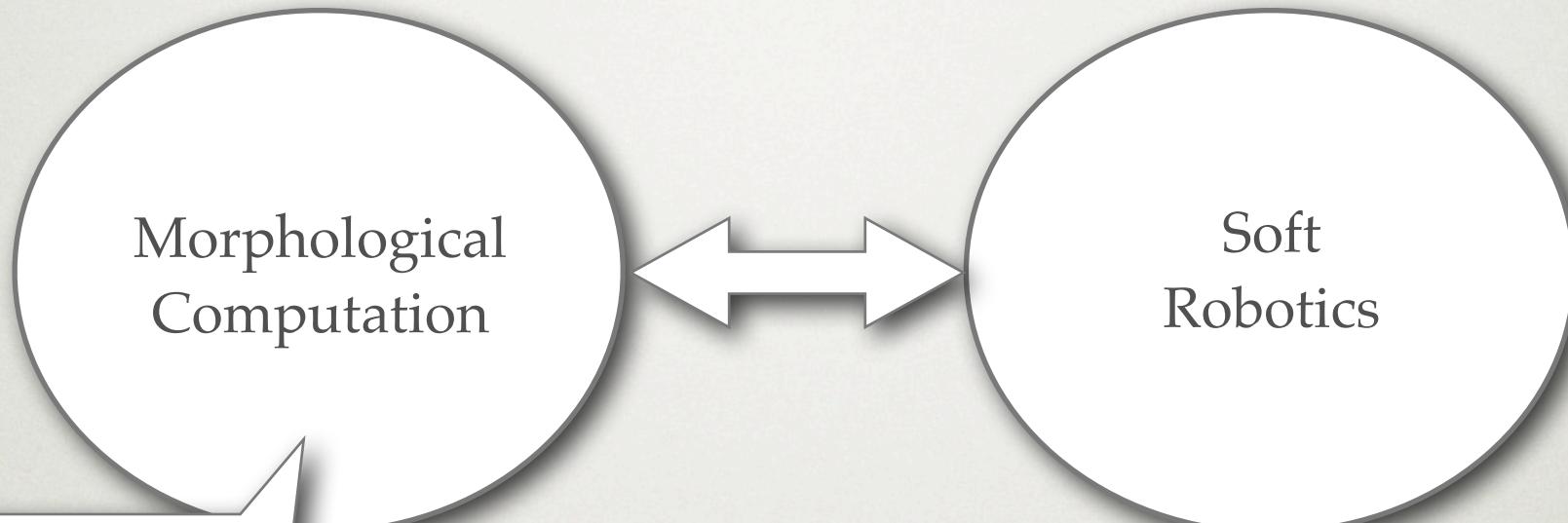
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HOW ARE THEY CONNECTED?



- High dimensionality
- Nonlinearity
- Compliance
- Noise

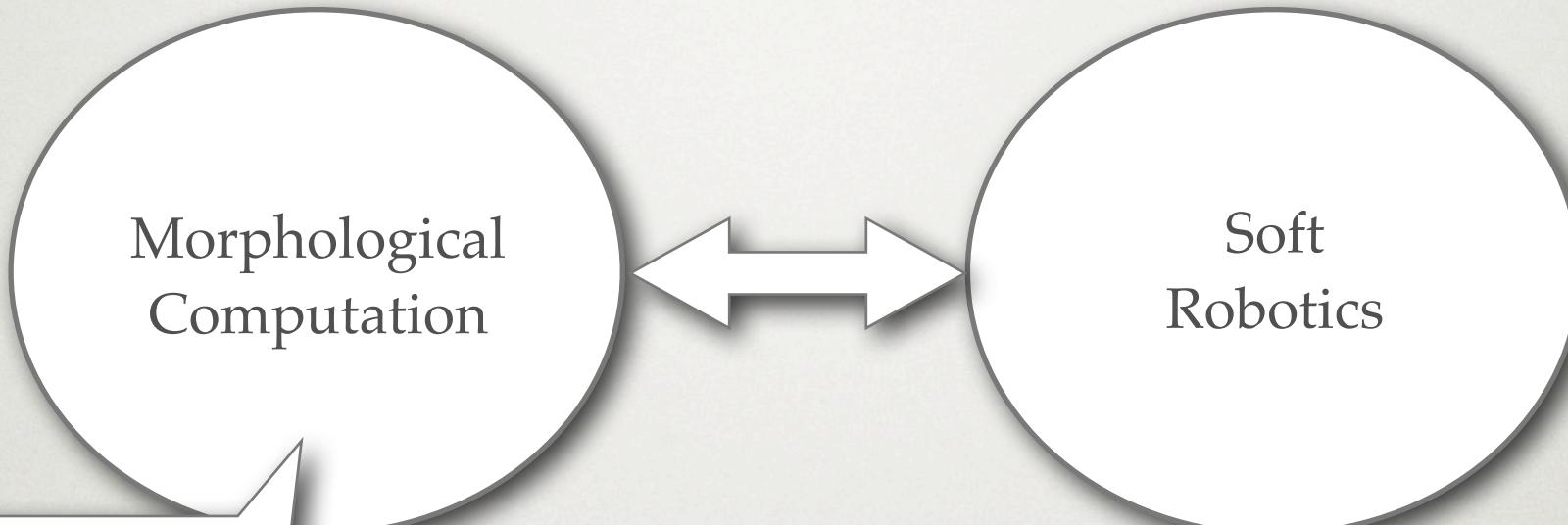
HOW ARE THEY CONNECTED?



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HOW ARE THEY CONNECTED?



theoretical
models for MC

- High dimensionality
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CLASSICAL ROBOT DESIGN



- rigid body parts
- high torque servos
- keep DoFs as low as possible
- fully actuated (at all time)

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- high torque servos
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to facilitate control

“NATURE’S APPROACH”



- soft body parts
- compliant muscle-tendon system
- large number of DoFs
- underactuation (passive DoFs)

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nightmare !

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WHAT KIND OF MORPHOLOGICAL COMPUTATION?

Morphology ?

Computation ?

WHAT KIND OF MORPHOLOGY?

Morphology ?

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- Form, shape

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- Physical parameters like spring constants, damping, friction, etc.
- Location of sensors and actuators
- Morphology of the environment

WHAT KIND OF MORPHOLOGICAL COMPUTATION?

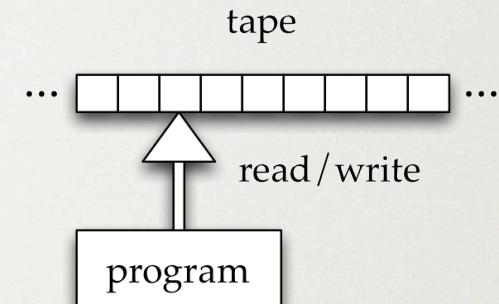
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WHAT KIND OF COMPUTATION?

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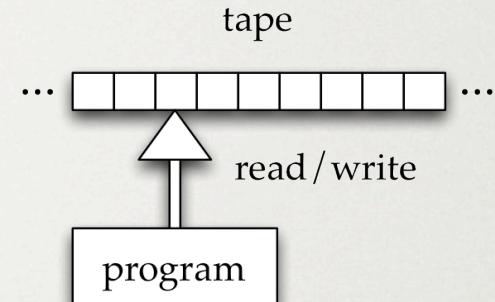
Turing



WHAT KIND OF COMPUTATION?

Computation ?

Turing

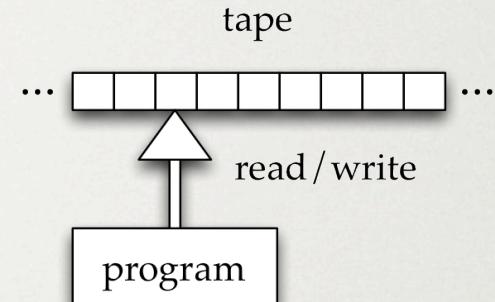


- Well defined, powerful concept

WHAT KIND OF COMPUTATION?

Computation ?

Turing

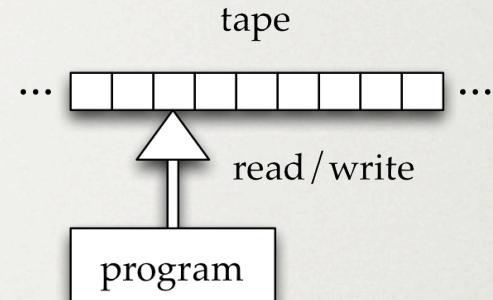


- Well defined, powerful concept
- However, not very biological

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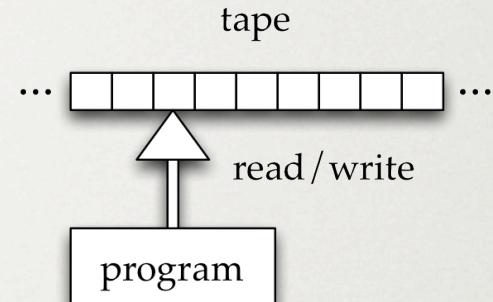


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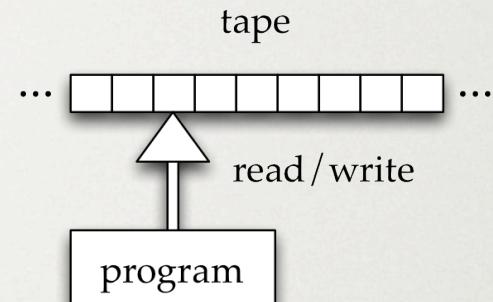


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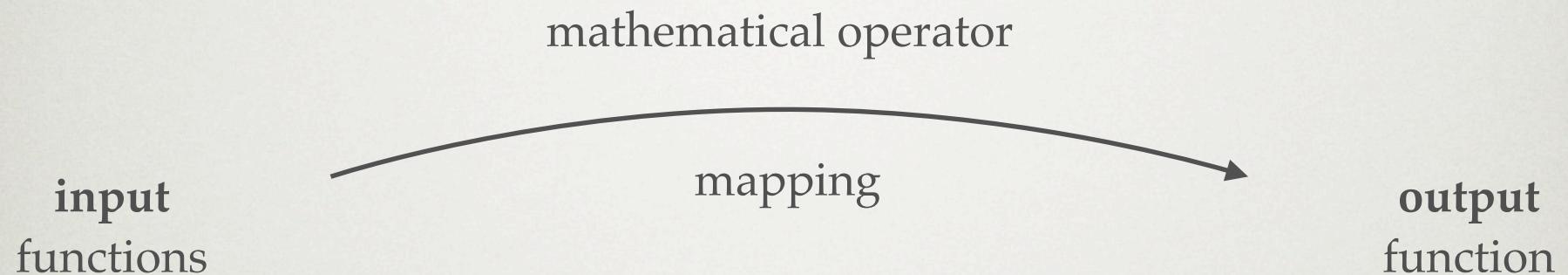
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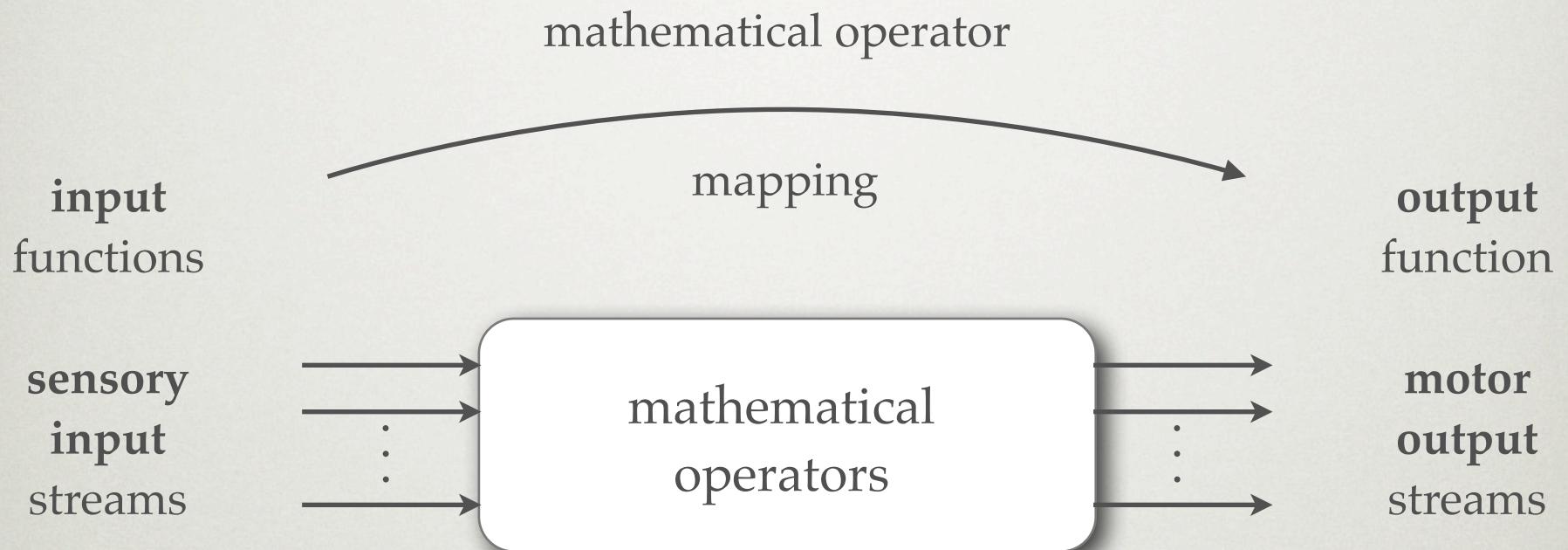


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- Mathematically speaking, we need **operators**

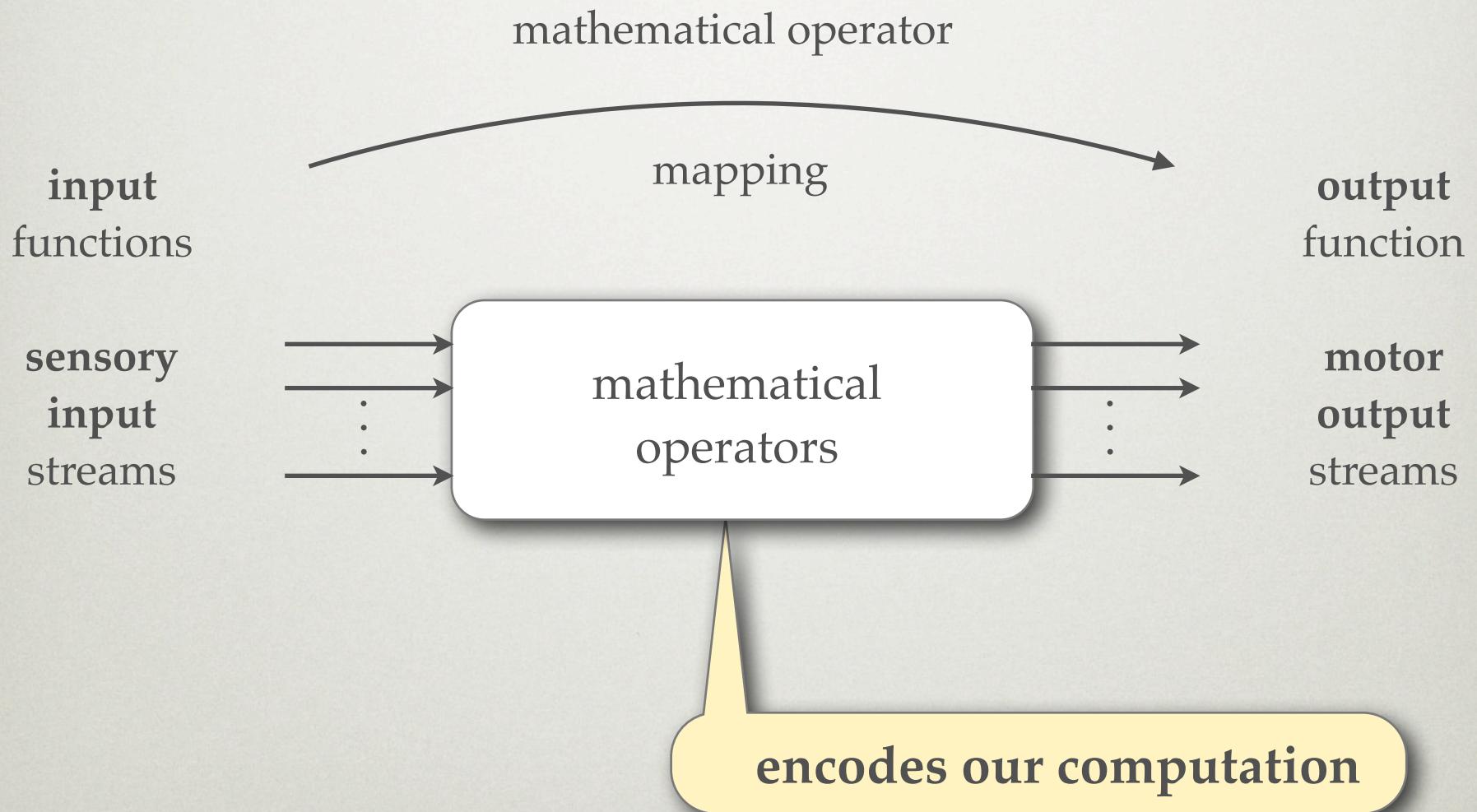
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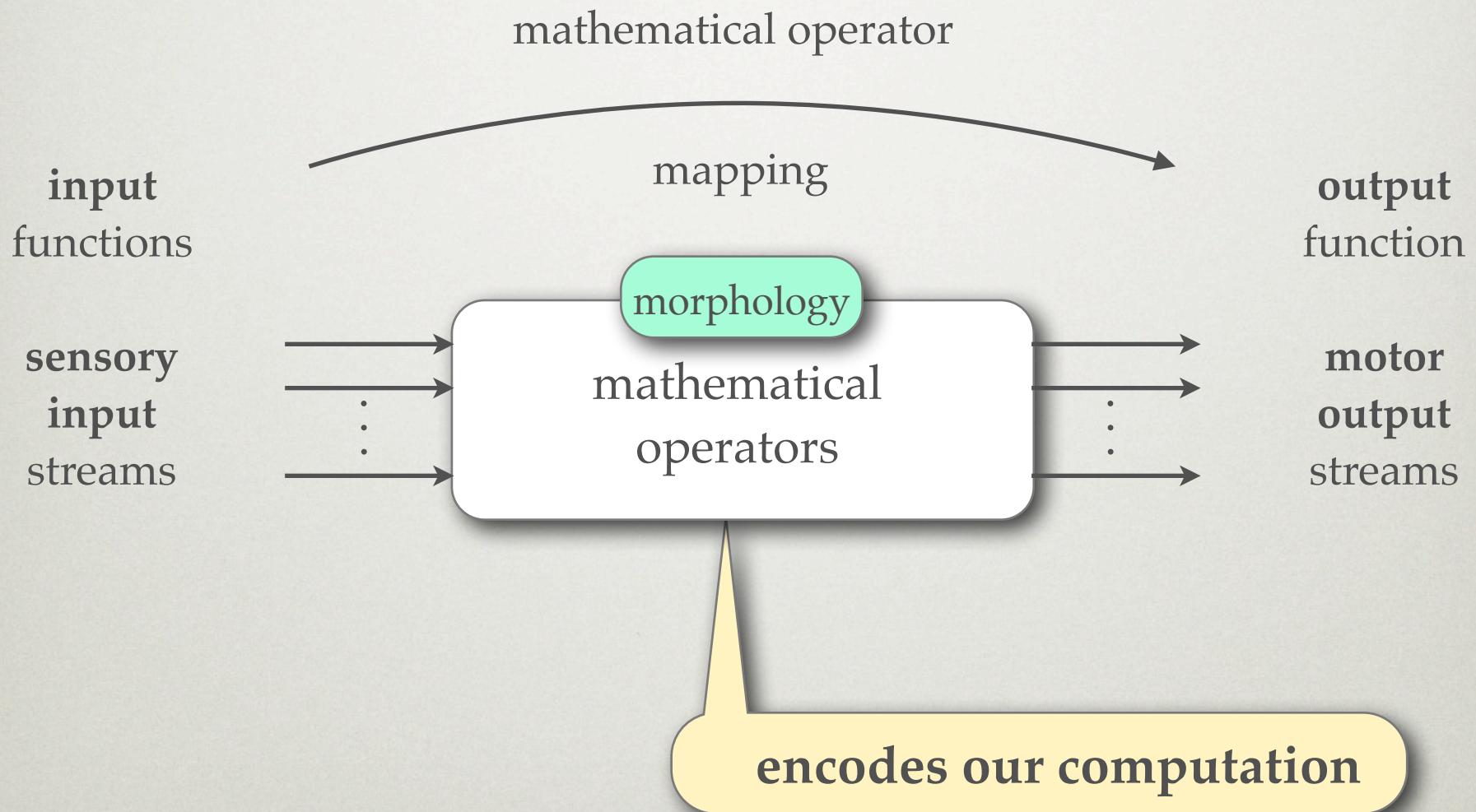
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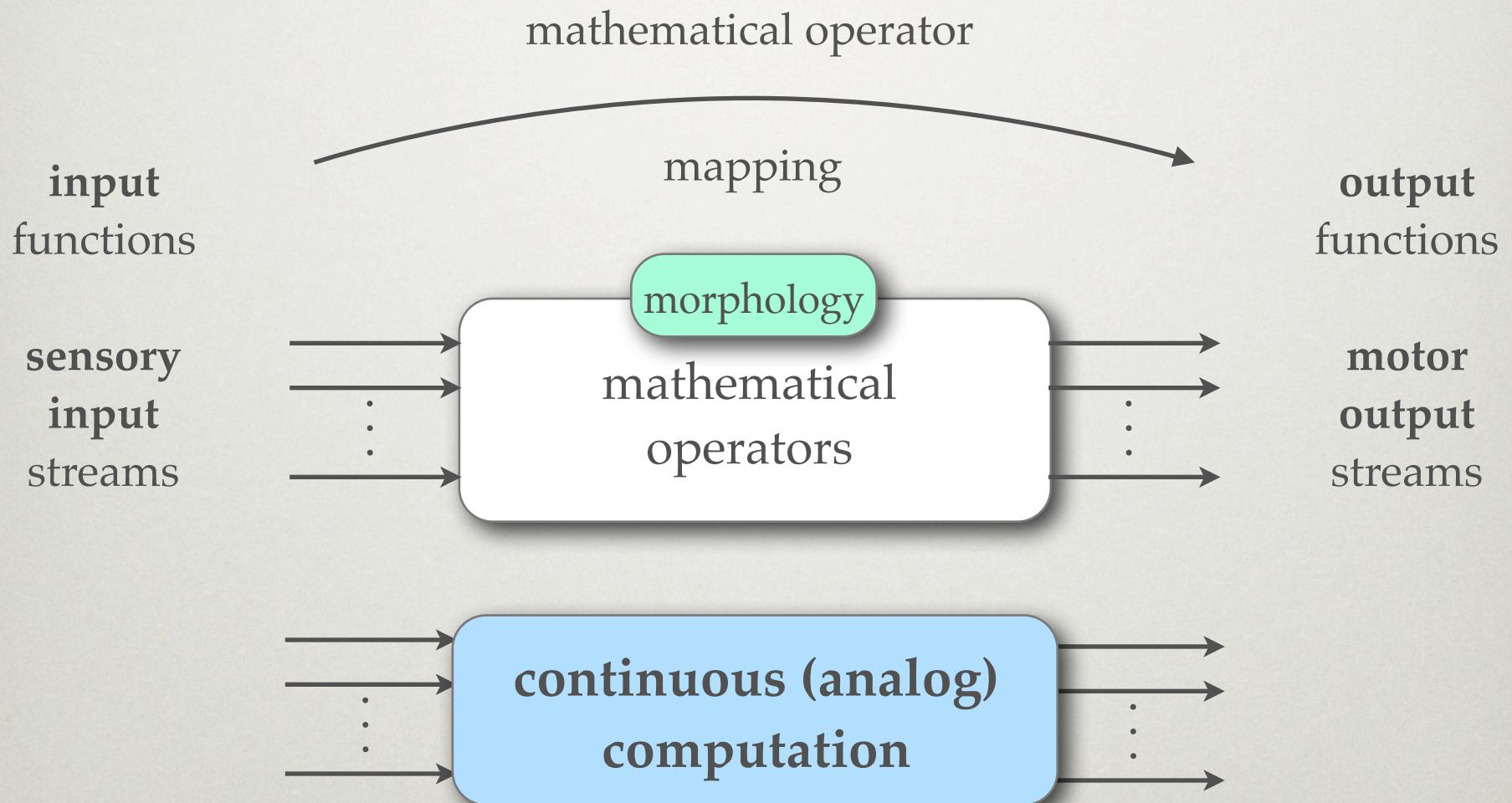
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FIRST THEORETICAL MODEL

- Based on a result by [Boyd and Chua 1985]

Hauser, Helmut, Auke J. Ijspeert, Rudolf M. Füchslin, Rolf Pfeifer, and Wolfgang Maass. "**Towards a theoretical foundation for morphological computation with compliant bodies**" Biological Cybernetics 105, no. 5-6 (2011): 355-370.

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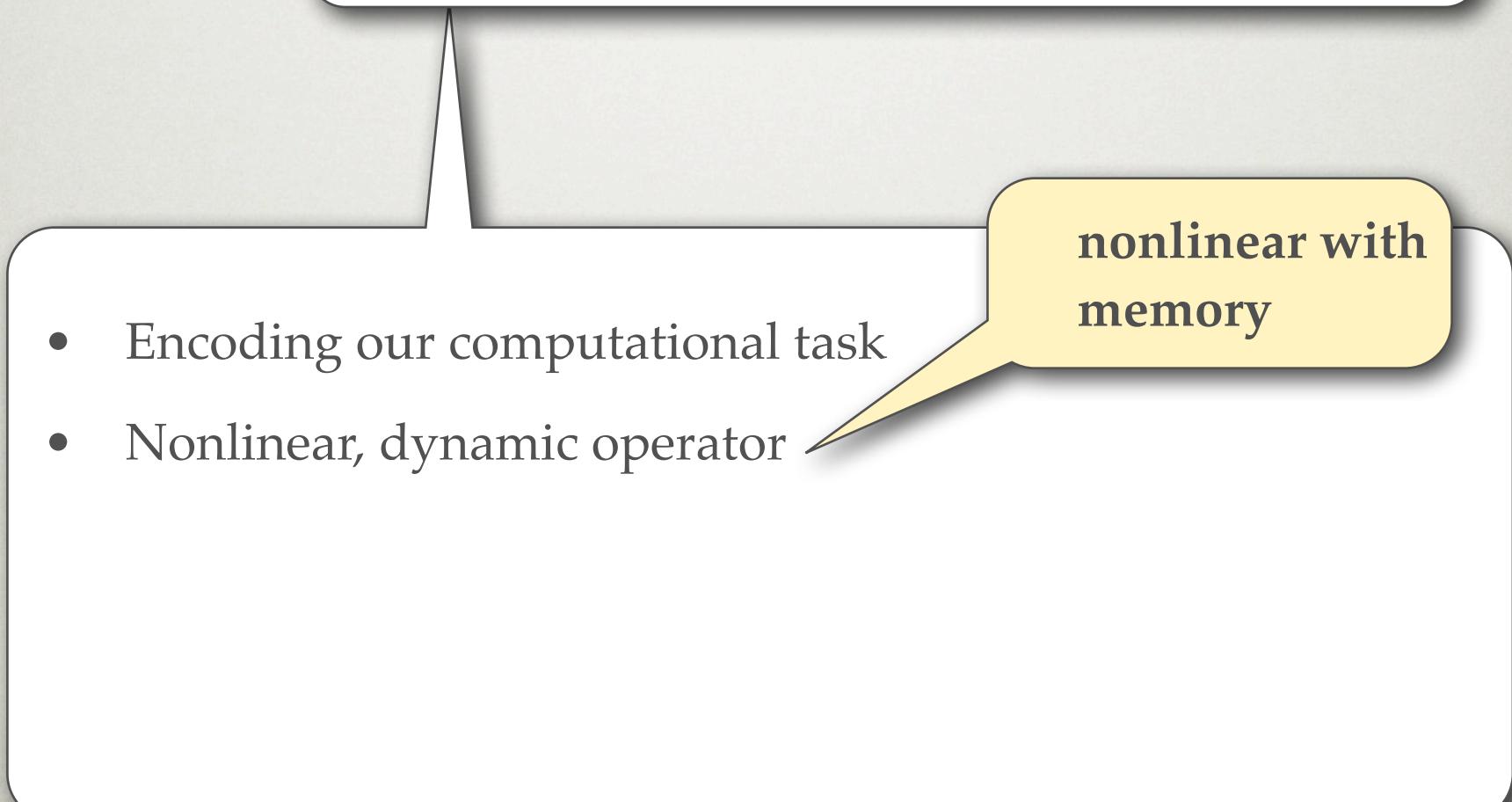
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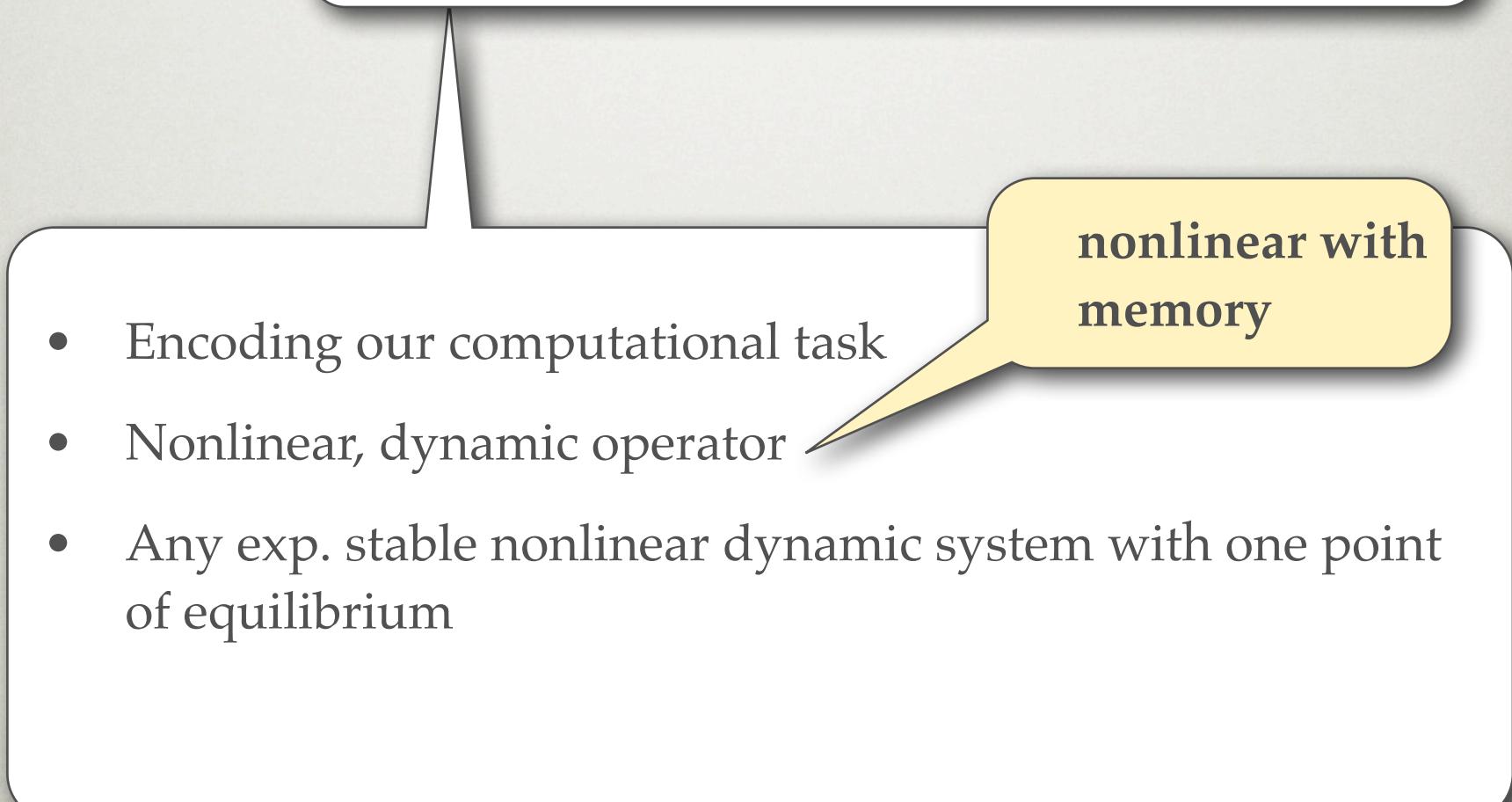


nonlinear with
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nonlinear controller

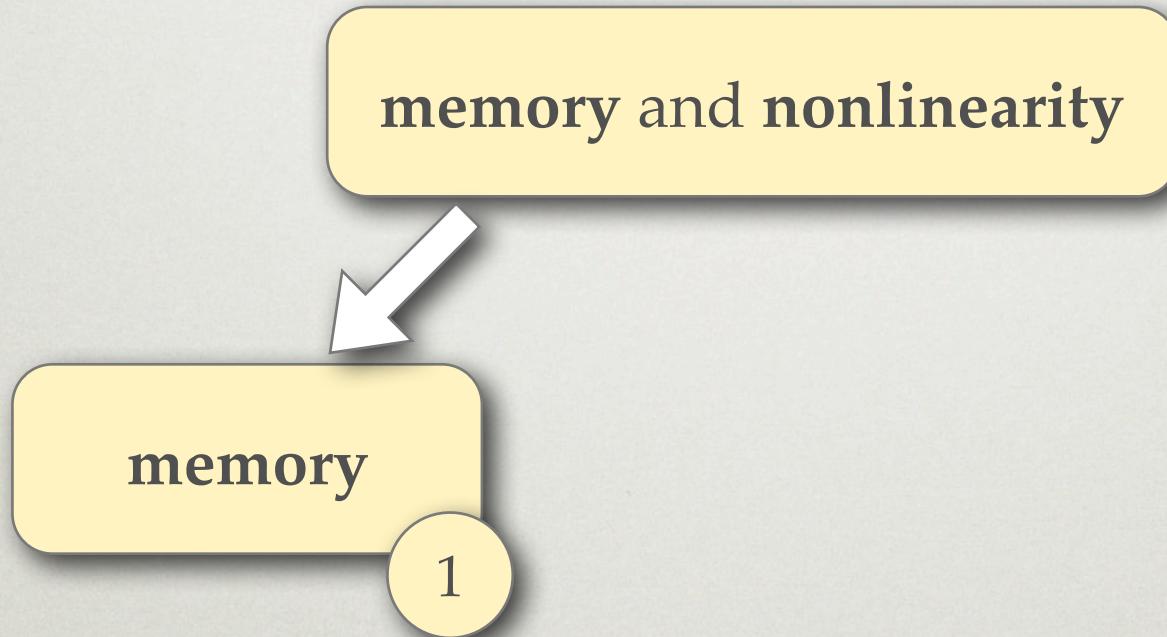
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memory and nonlinearity

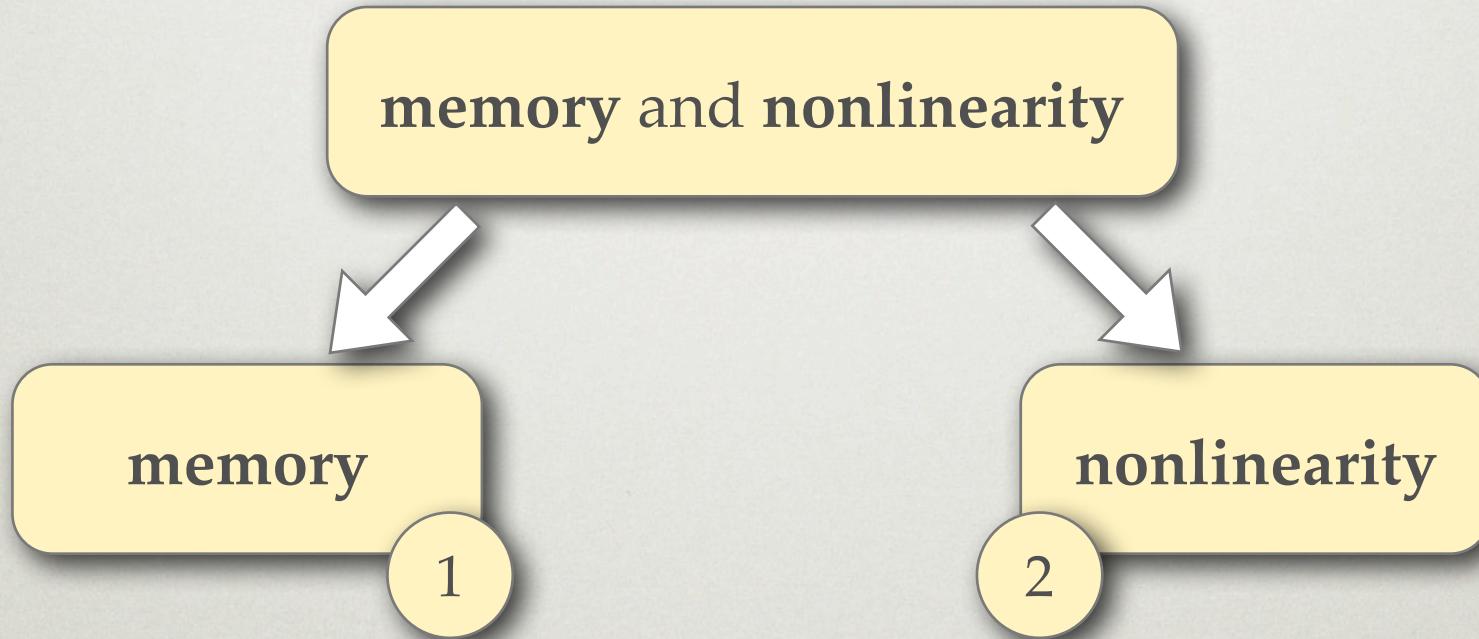
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temporal
integration



linear, dynamic

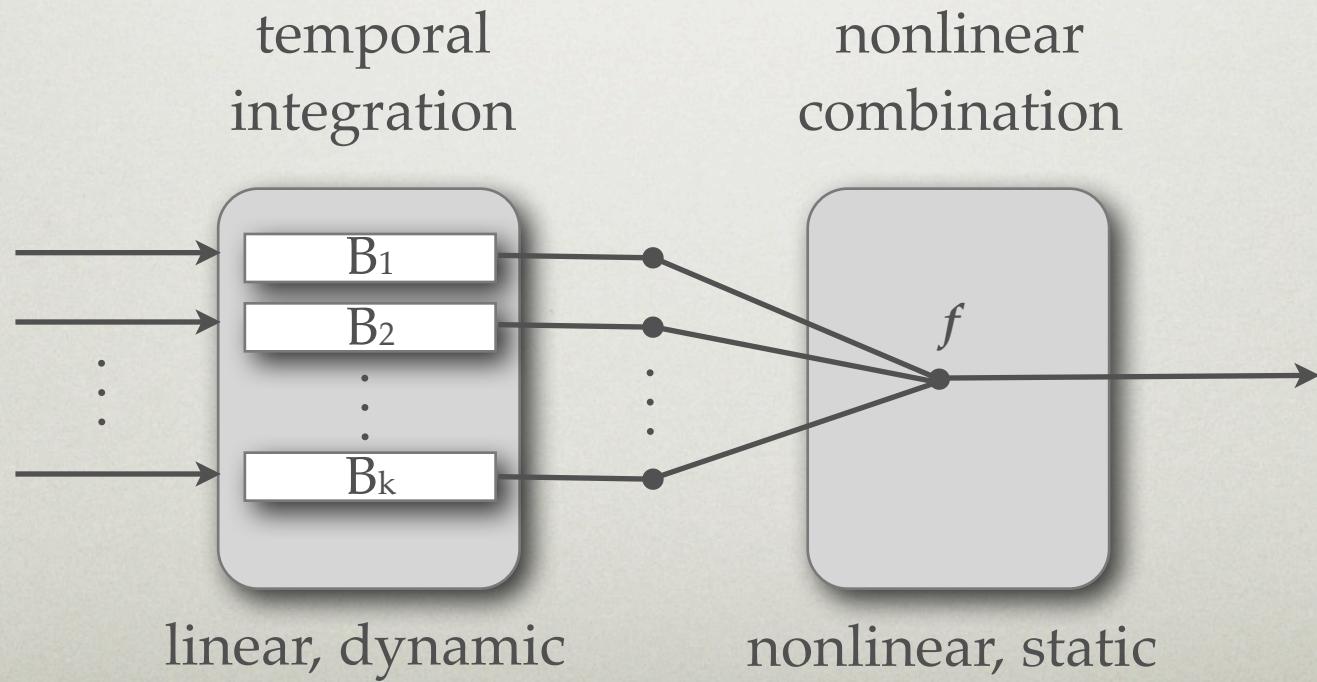
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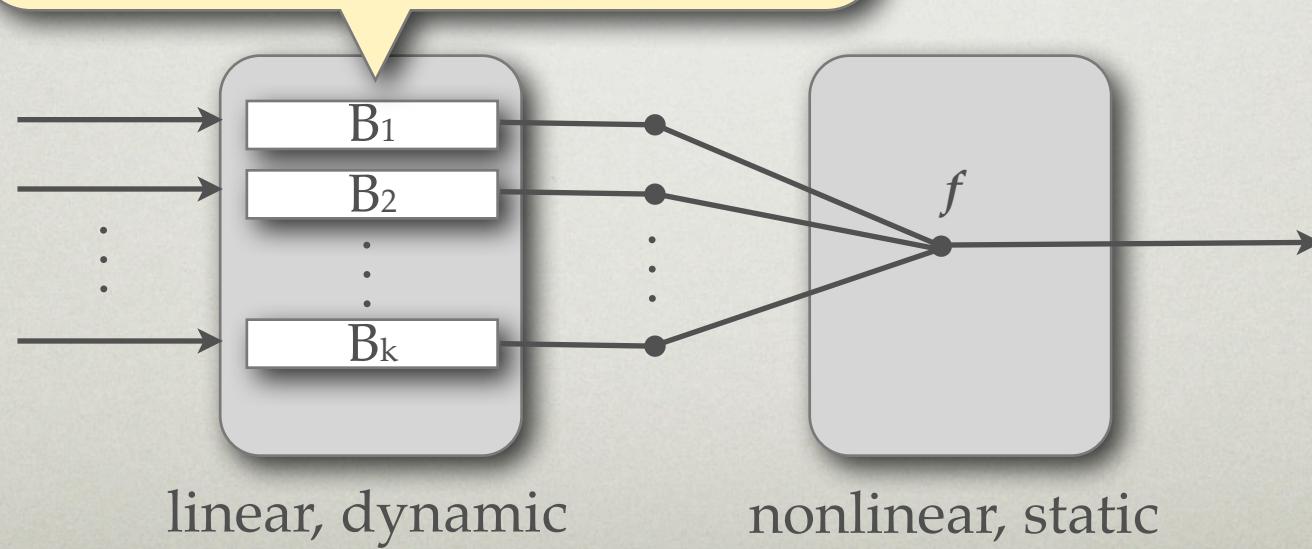
FIRST THEORETICAL MODEL

- Basic idea [Ishai et al., 1985]
- A neural network can be seen as a computation

Stage 1

Has to **integrate** information over time (fading memory)

Has to **separate** signals

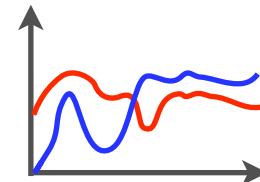


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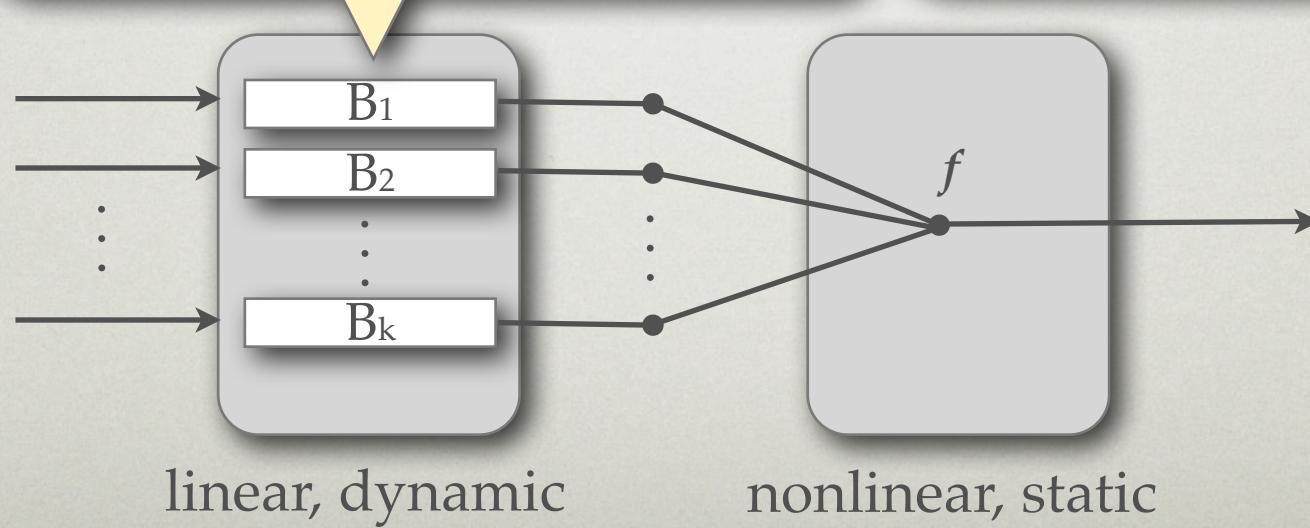
- Basic idea
- All information is contained between the components

Stage 1

Has to **integrate** information over time (fading memory)



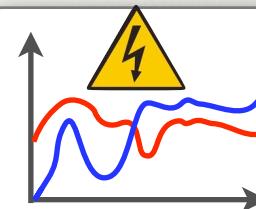
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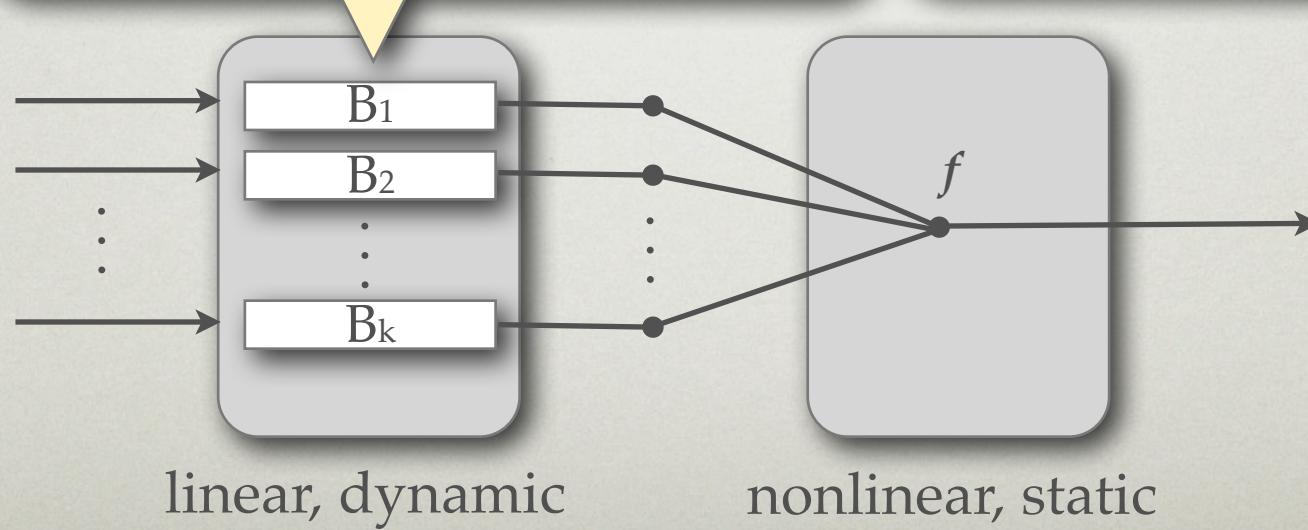
FIRST THEORETICAL MODEL

- Basic idea
 - A signal can be seen as a combination of different components
- Has to **integrate** information over time (fading memory)

Stage 1



Has to **separate** signals



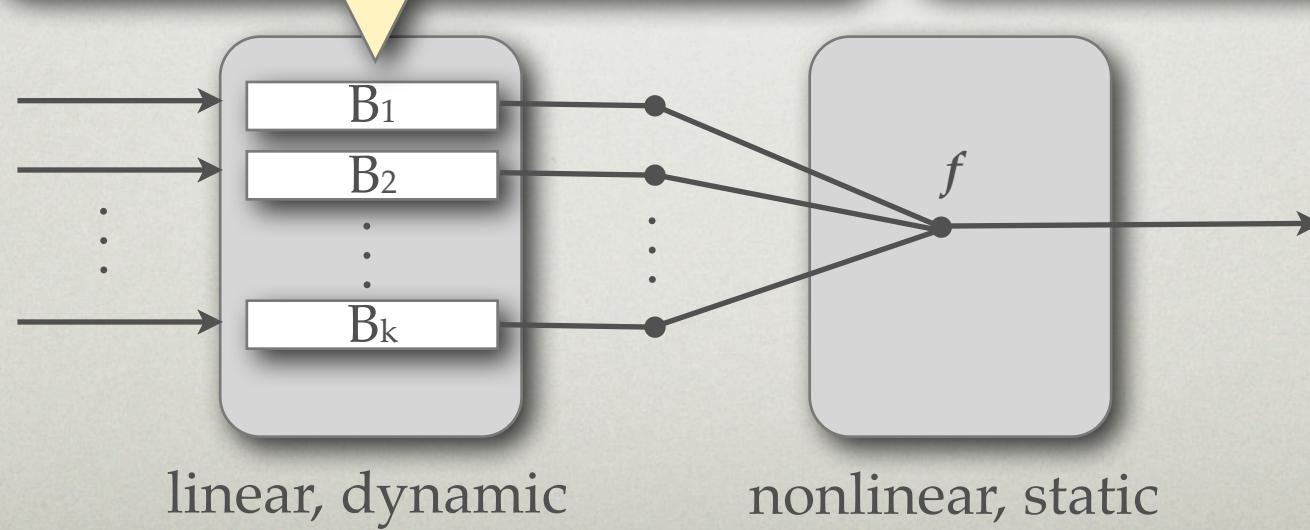
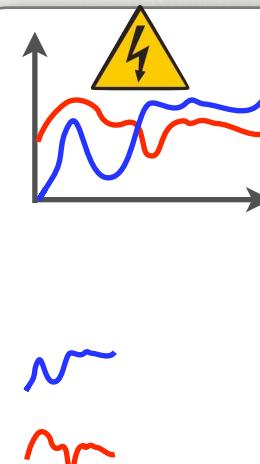
FIRST THEORETICAL MODEL

- Basic idea
- A signal can be composed of several components

Stage 1

Has to **integrate** information over time (fading memory)

Has to **separate** signals



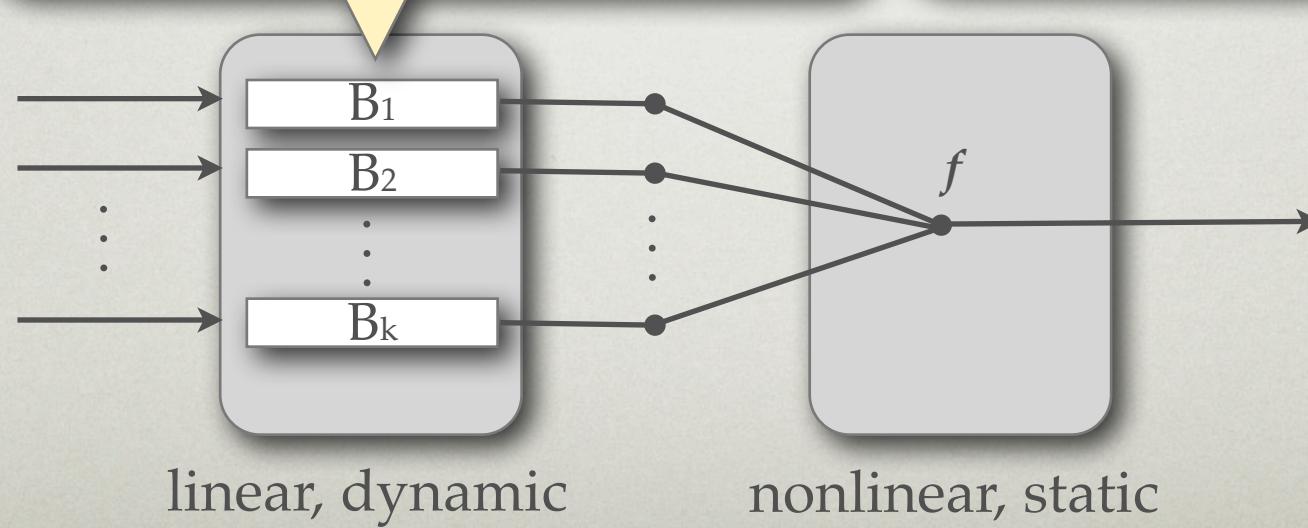
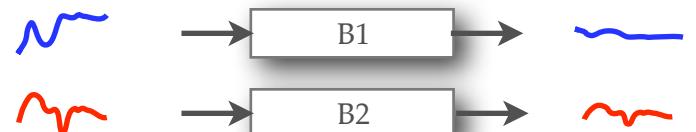
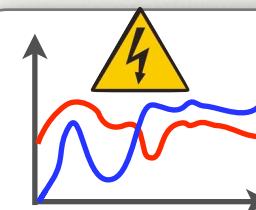
FIRST THEORETICAL MODEL

- Basic idea
- A signal is composed of two parts

Stage 1

Has to **integrate** information over time (fading memory)

Has to **separate** signals



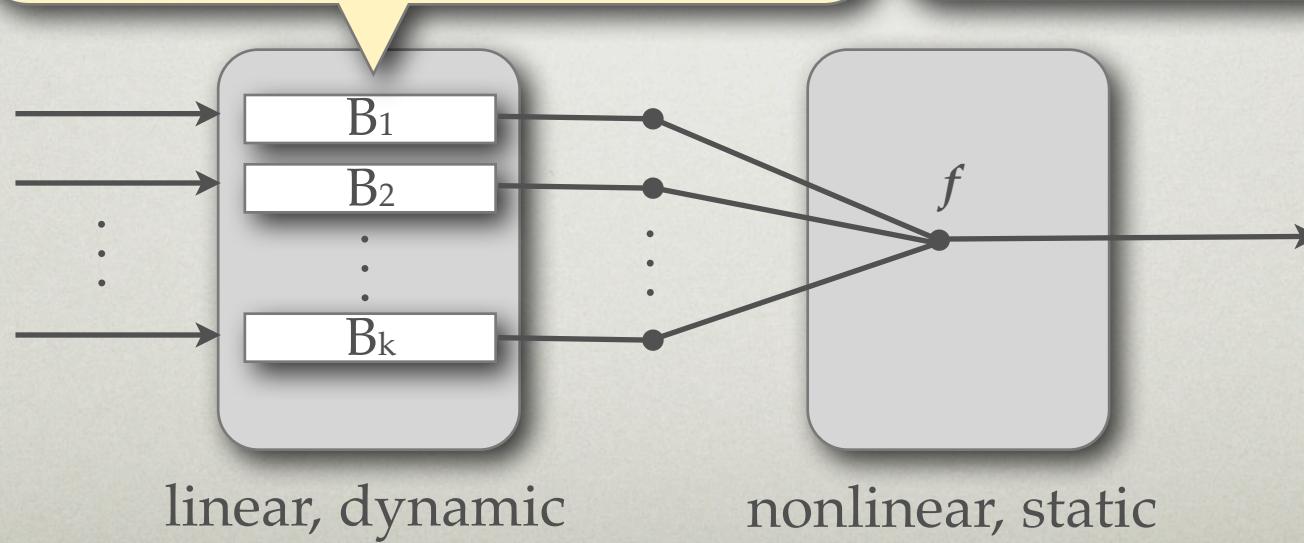
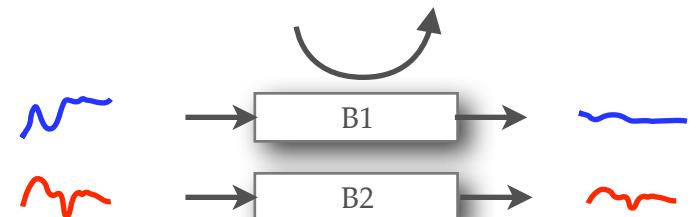
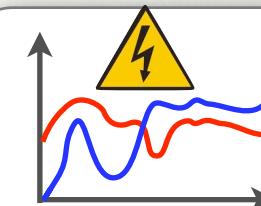
FIRST THEORETICAL MODEL

- Basic idea
- A signal is a sum of two components

Stage 1

Has to **integrate** information over time (fading memory)

Has to **separate** signals



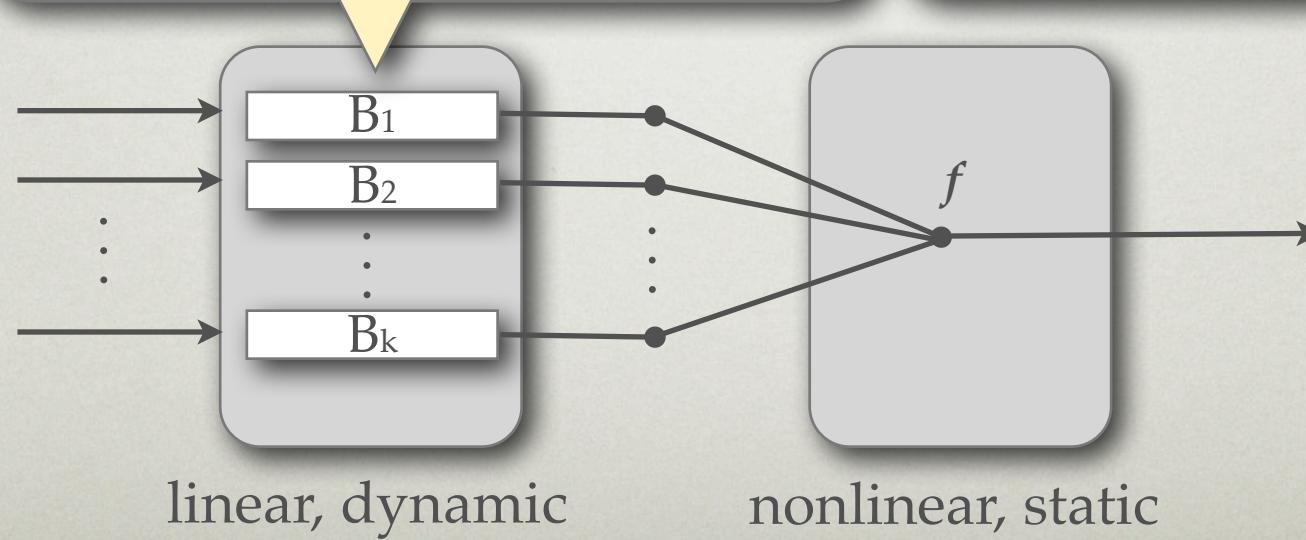
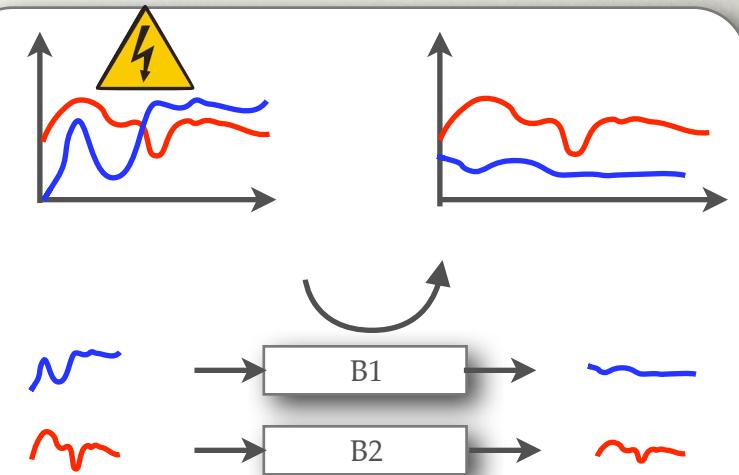
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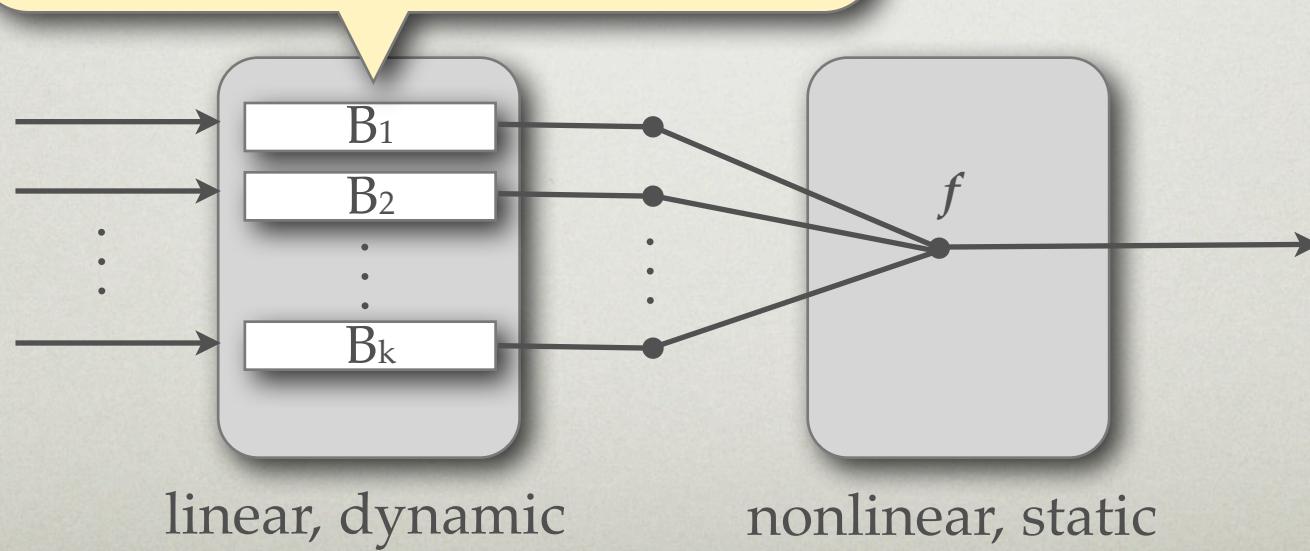
FIRST THEORETICAL MODEL

- Bar
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Stage 1

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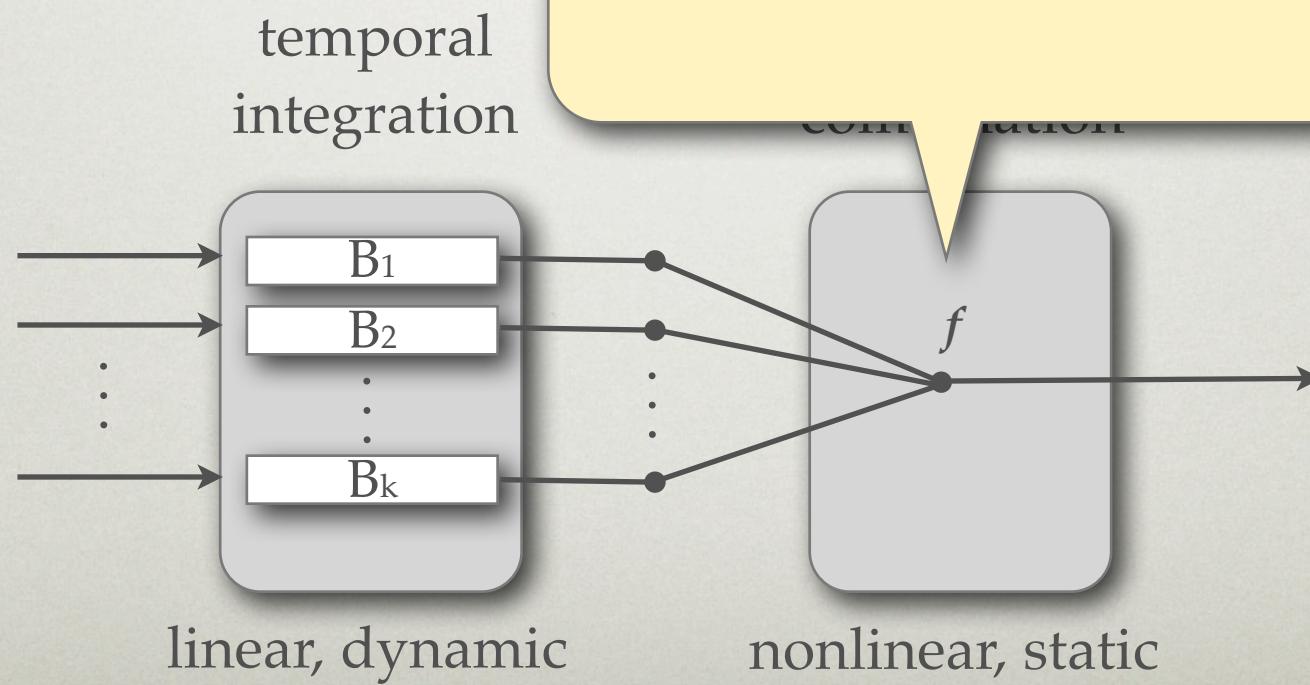
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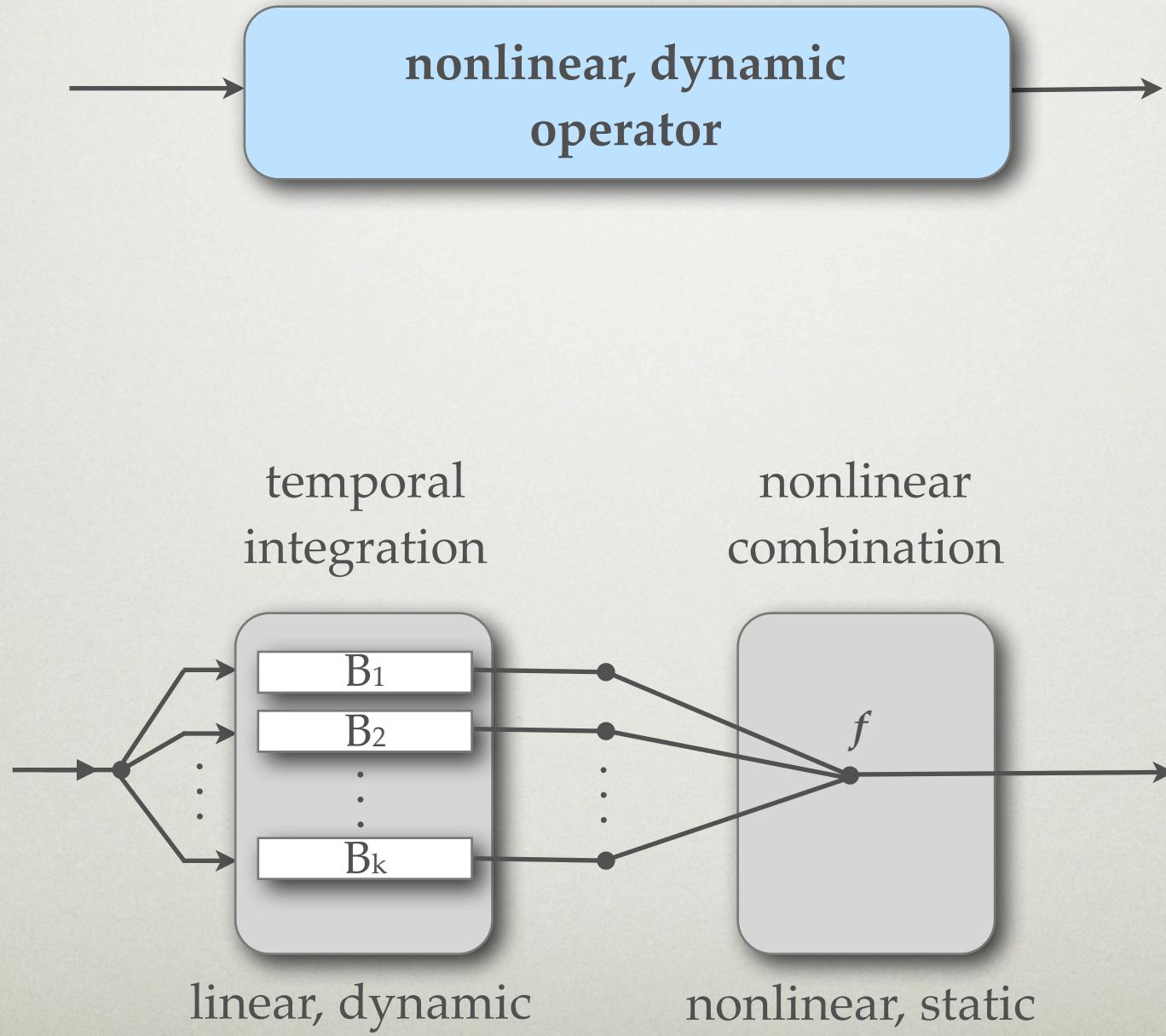
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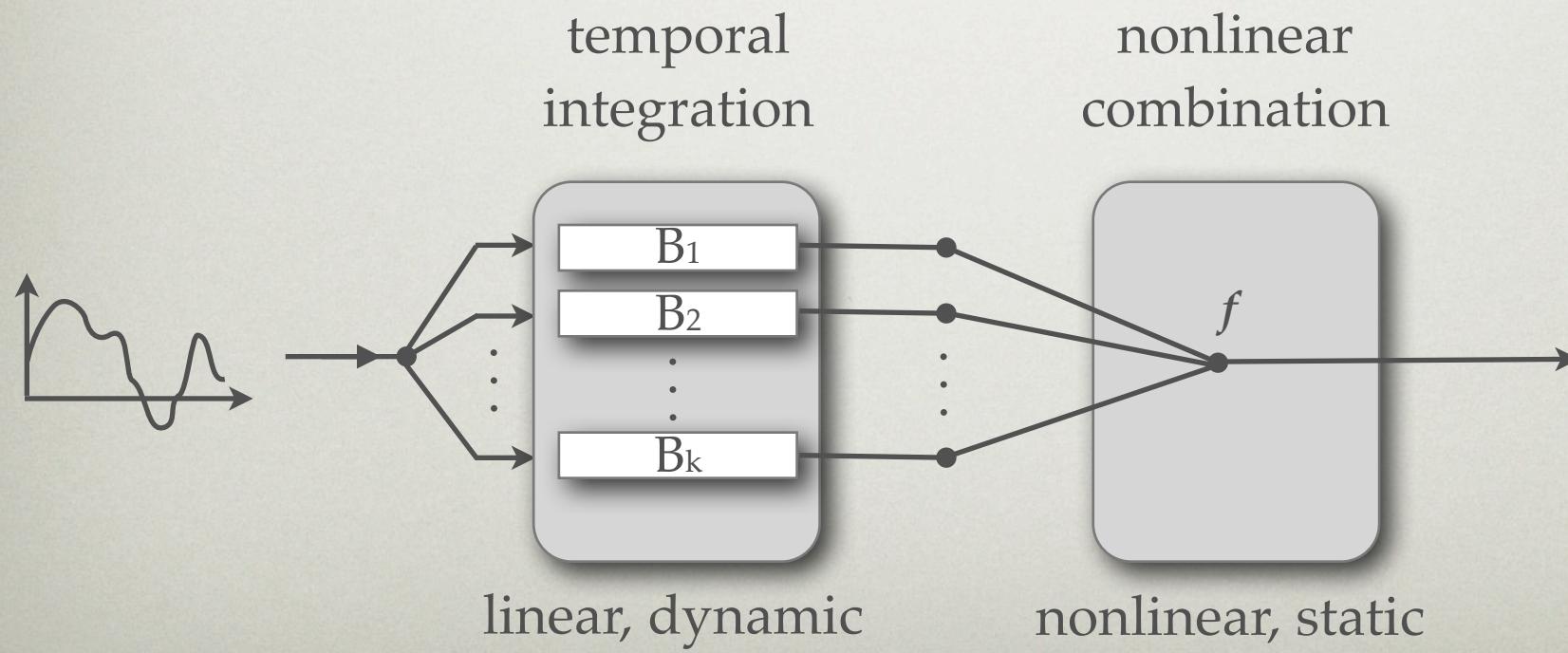
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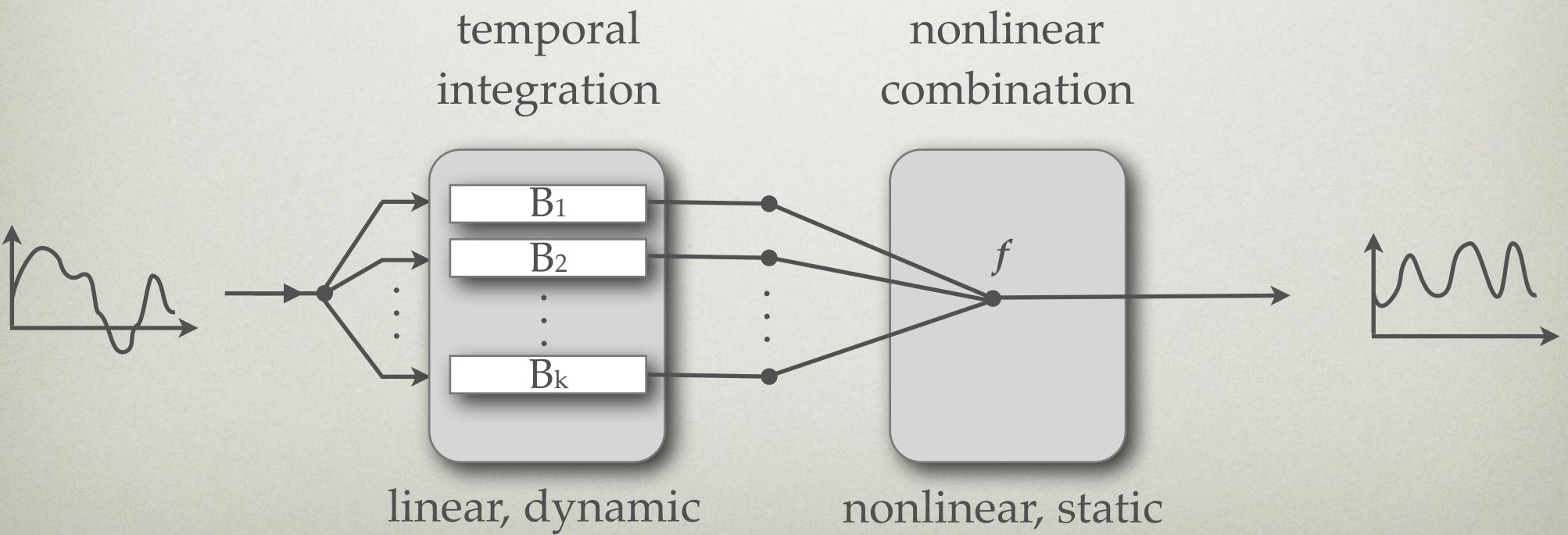
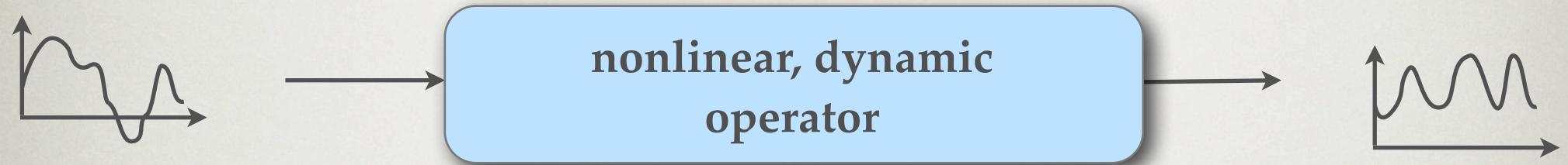
FIRST THEORETICAL MODEL



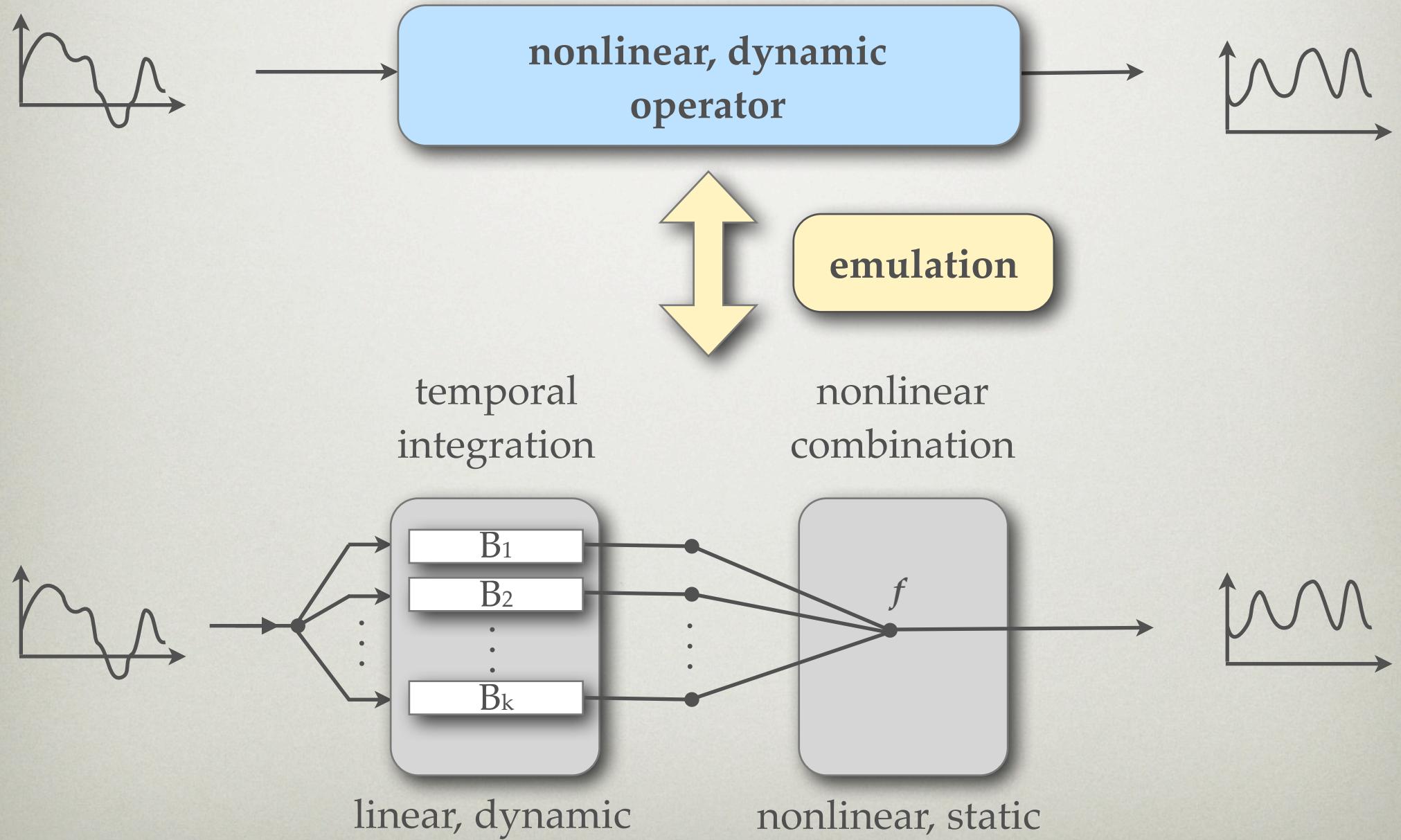
FIRST THEORETICAL MODEL



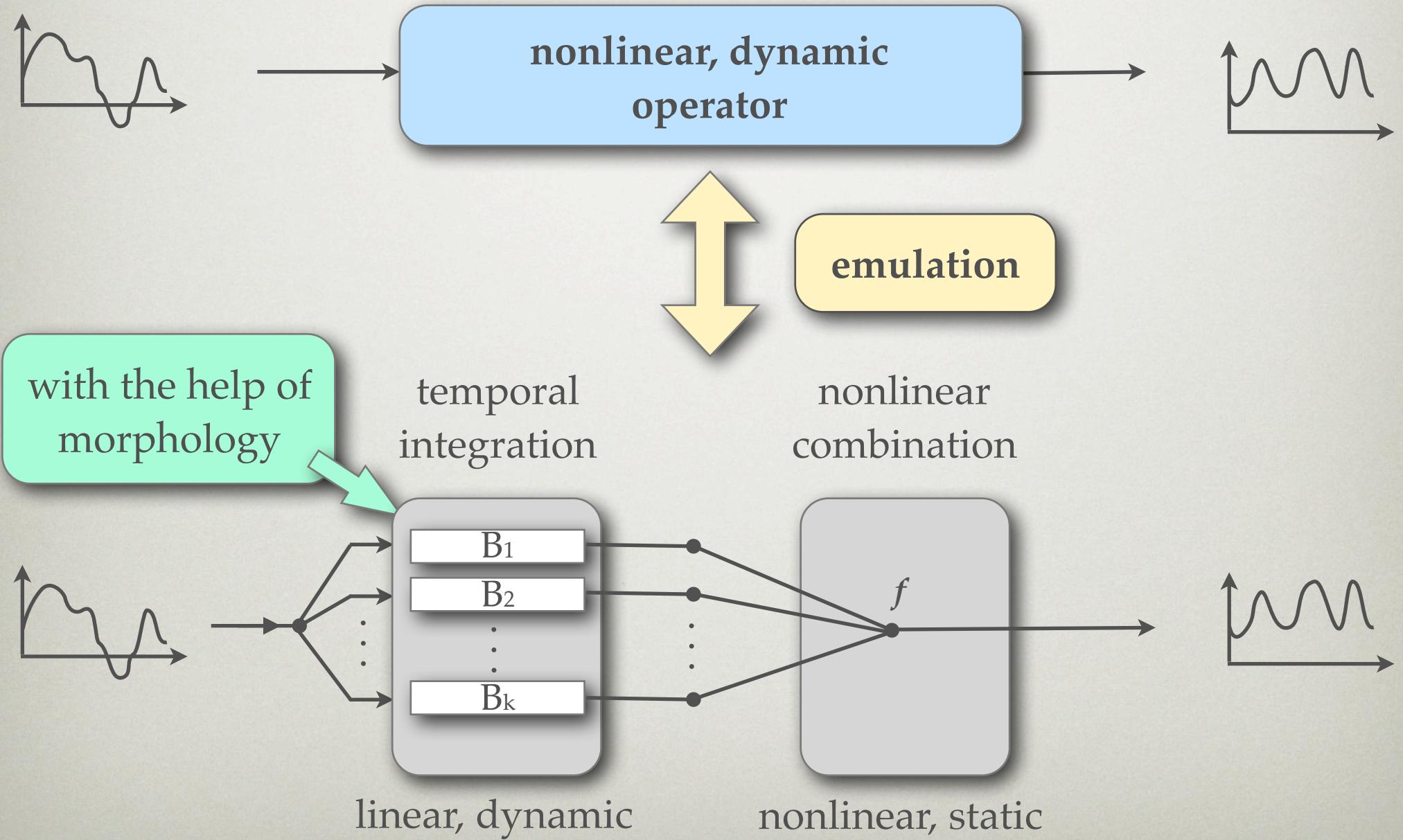
FIRST THEORETICAL MODEL



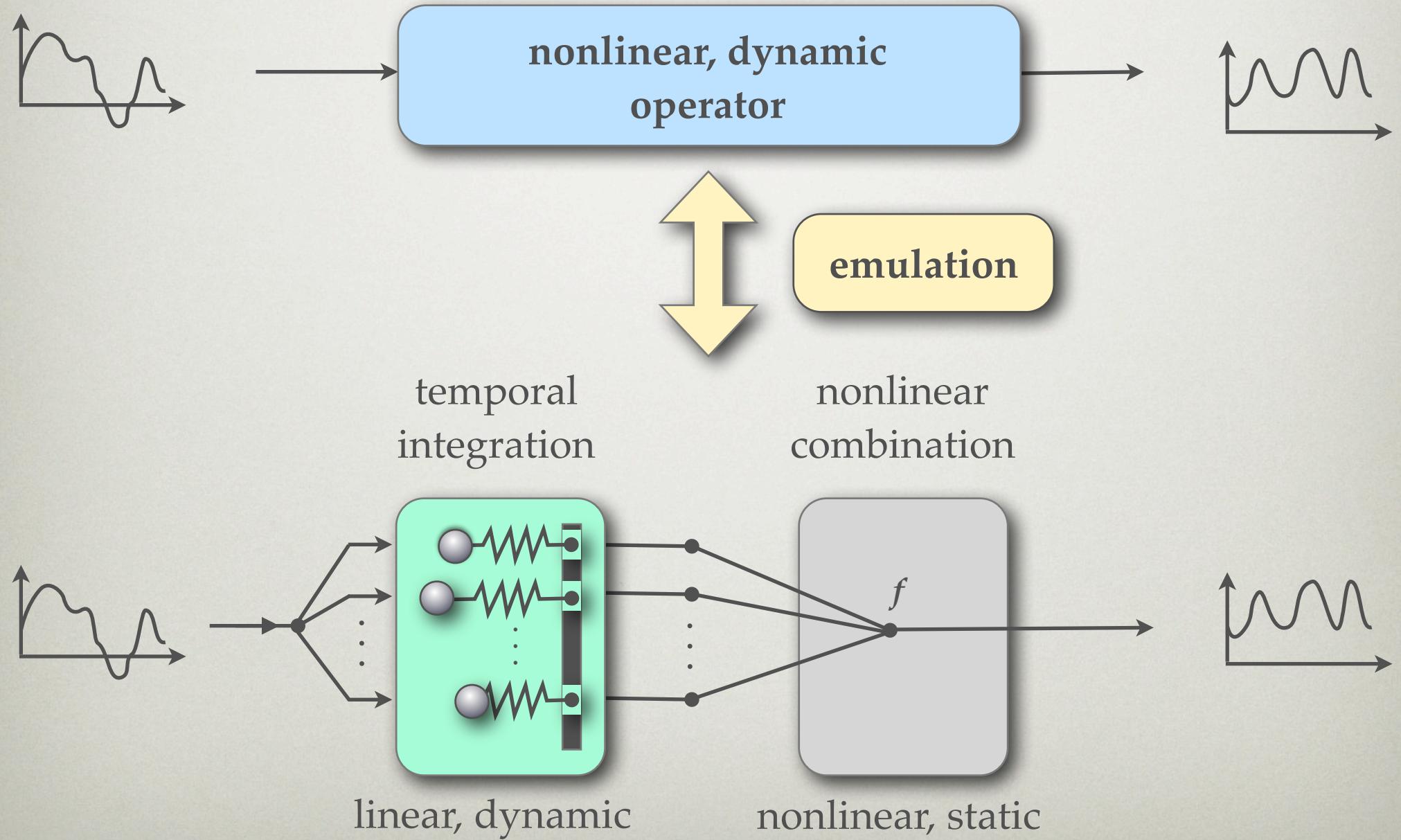
FIRST THEORETICAL MODEL



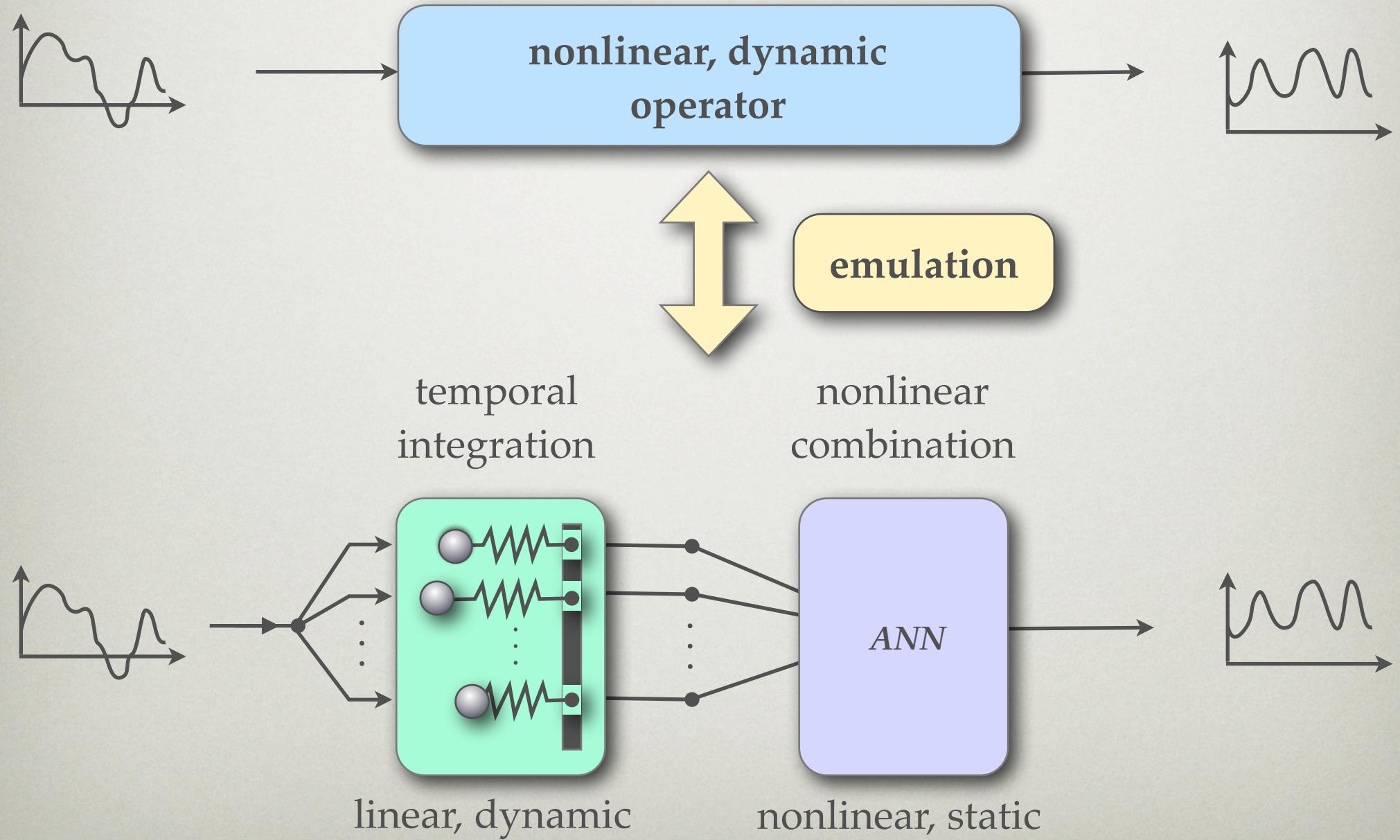
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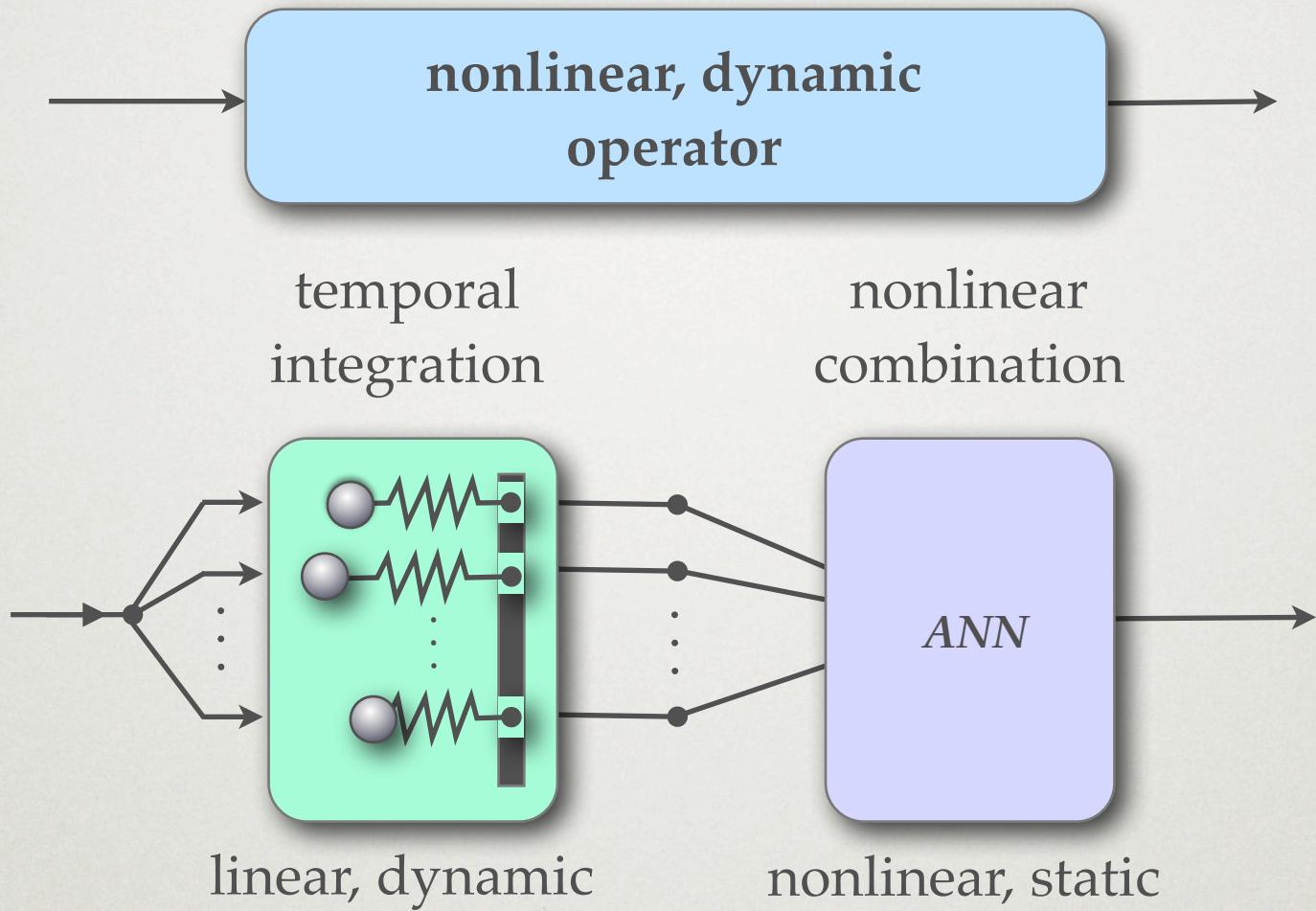
FIRST THEORETICAL MODEL



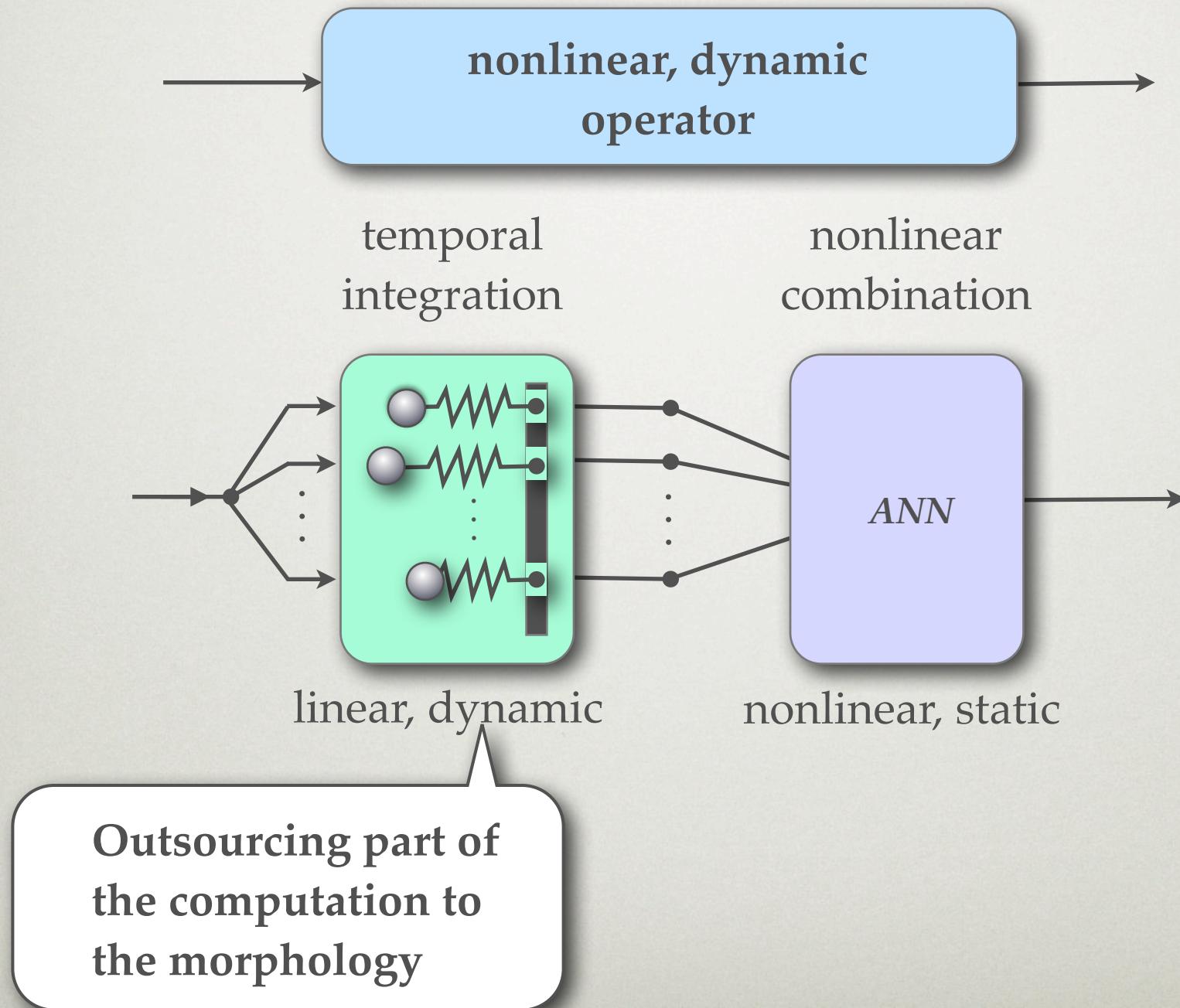
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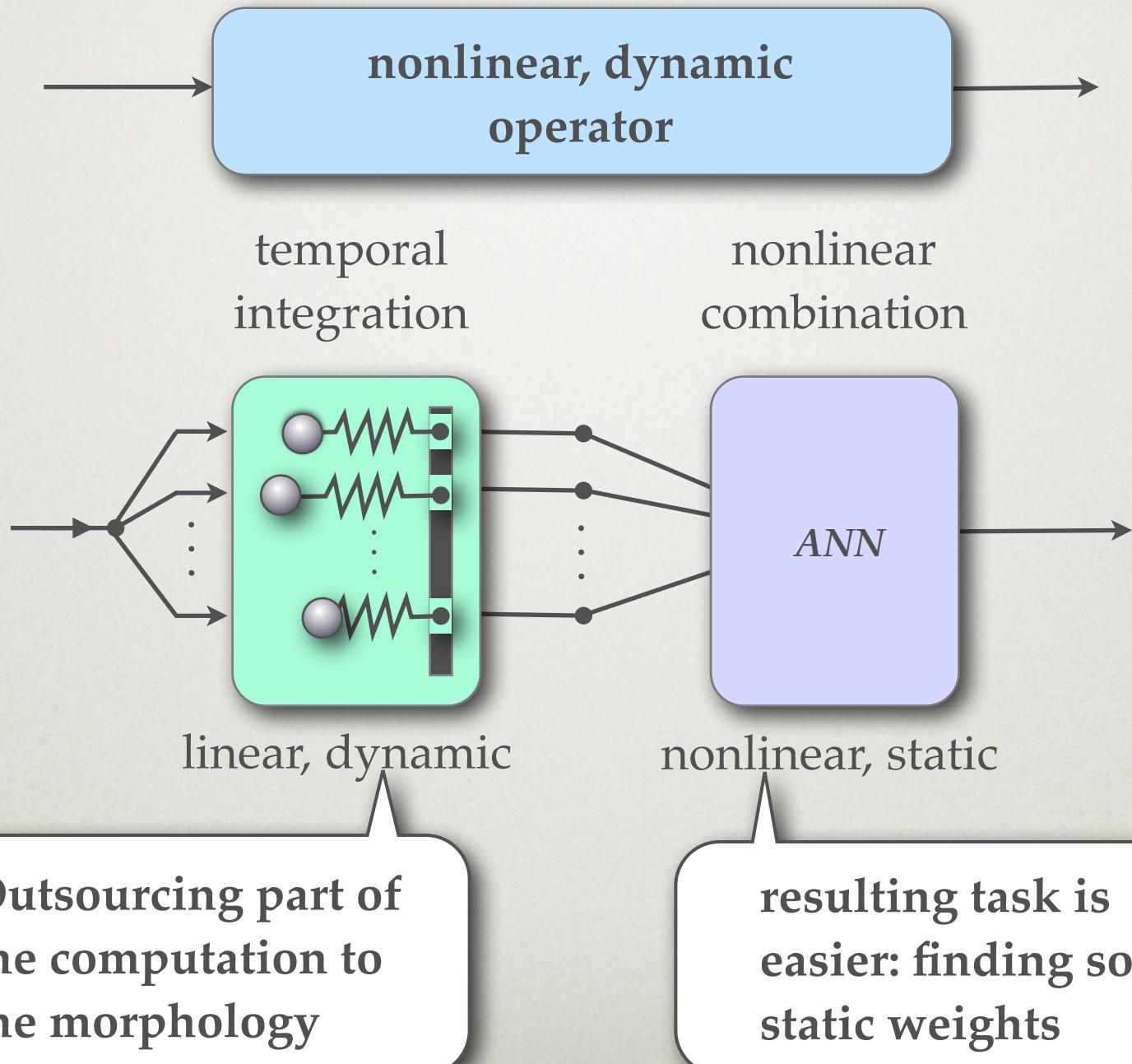
REMARKABLE CONCLUSION



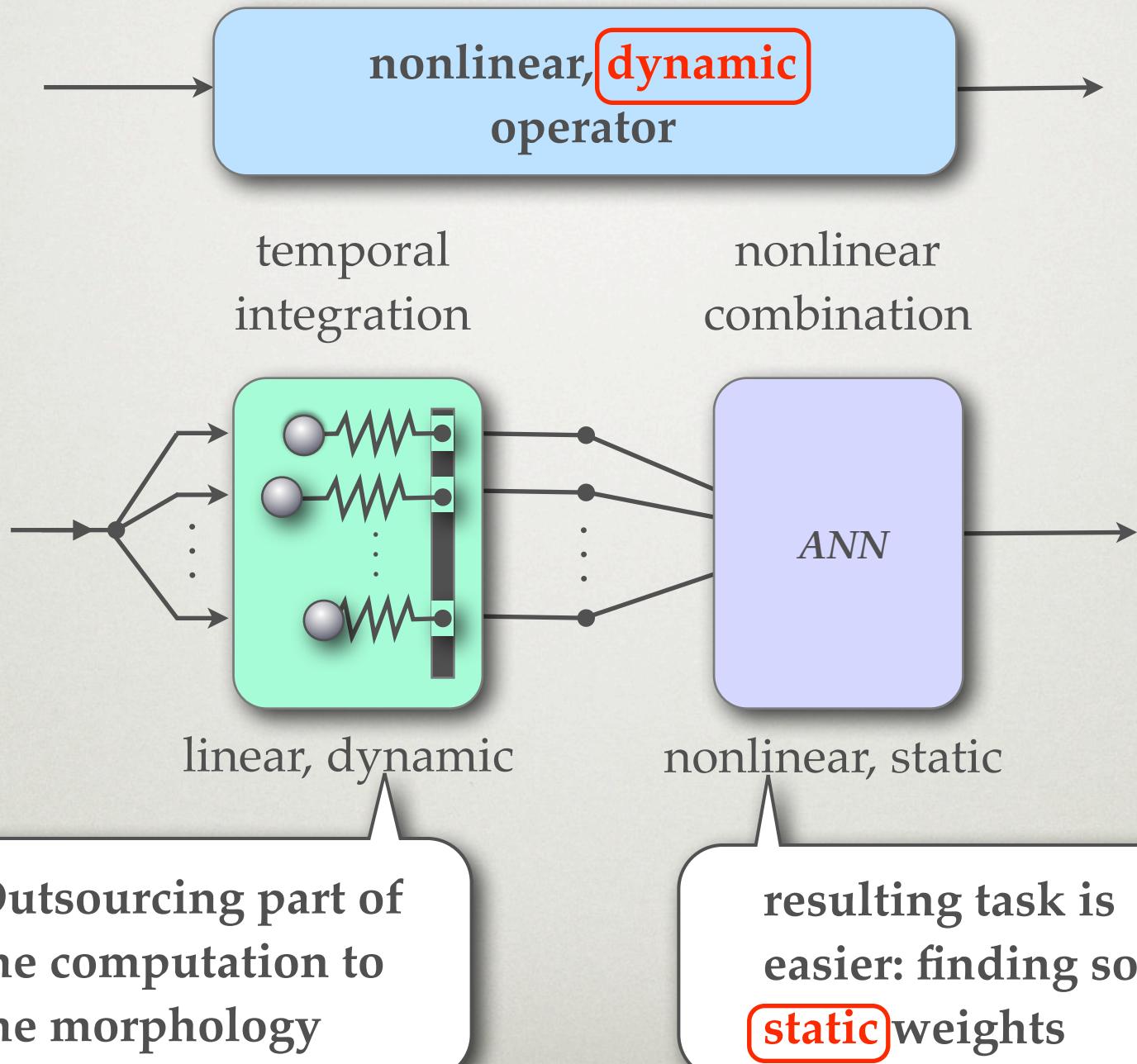
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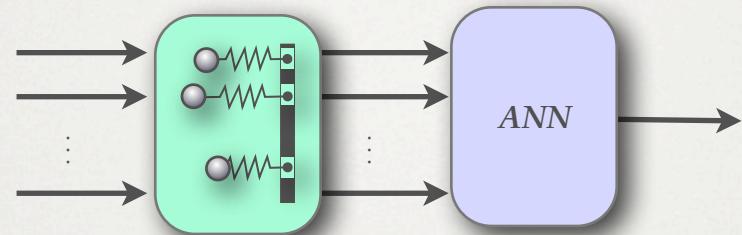
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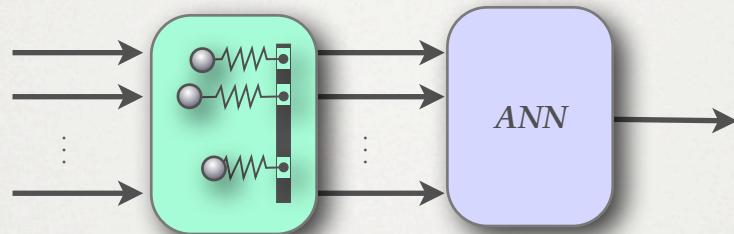
REMARKABLE CONCLUSION



REMARKS

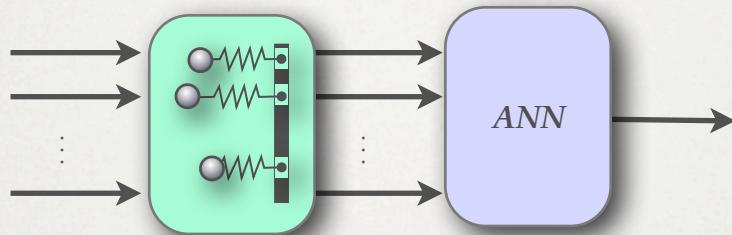


REMARKS



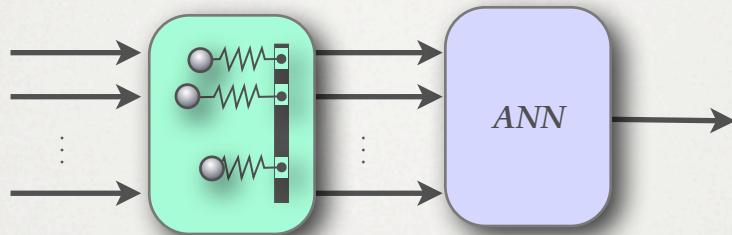
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REMARKS



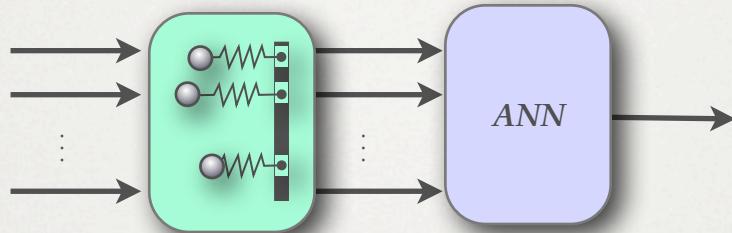
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REMARKS



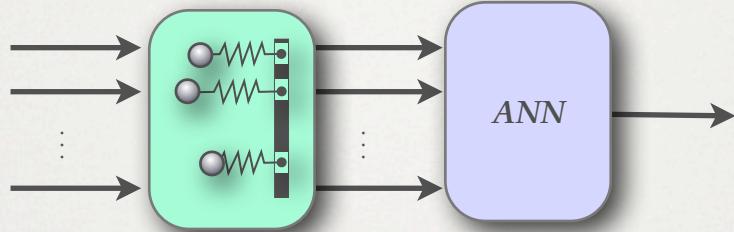
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REMARKS



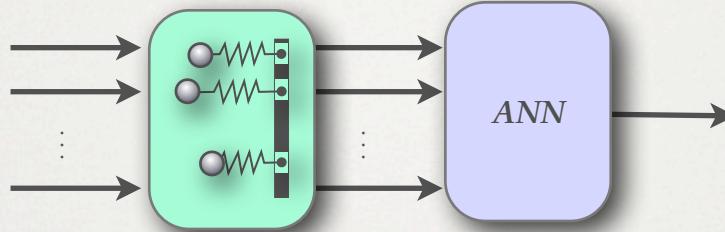
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REMARKS

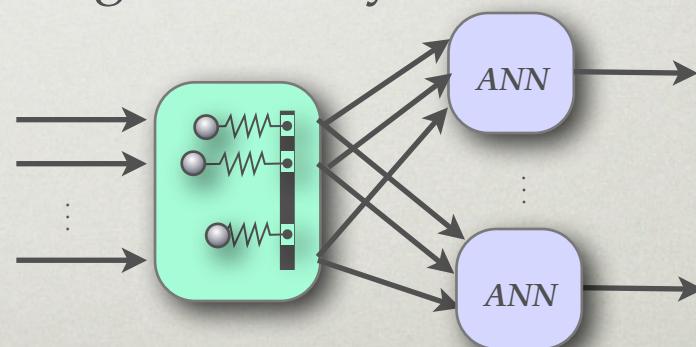


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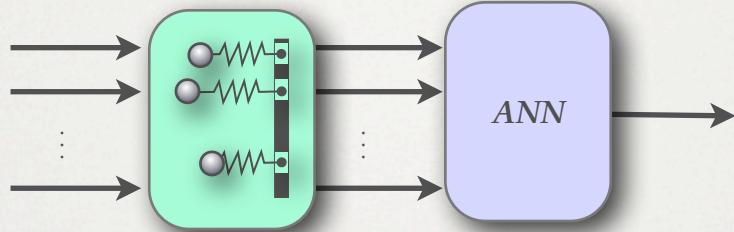
REMARKS



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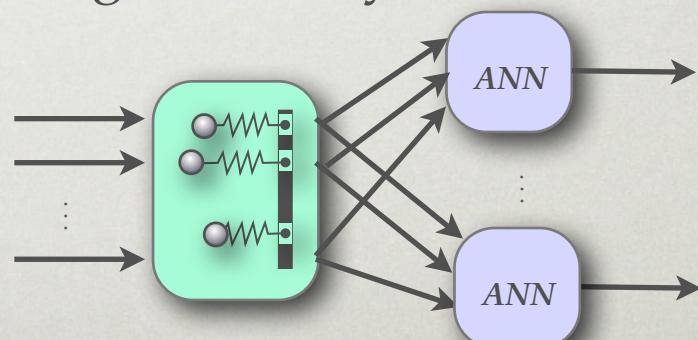


REMARKS

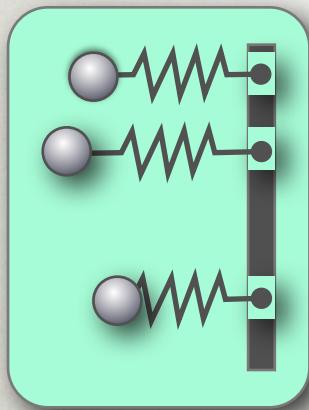


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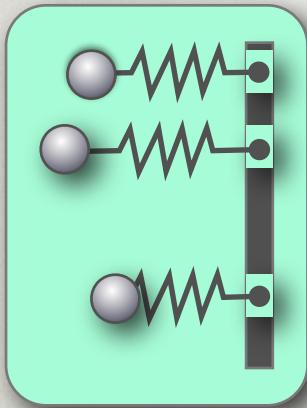
exploitation of the body



COMPUTATIONAL POWER



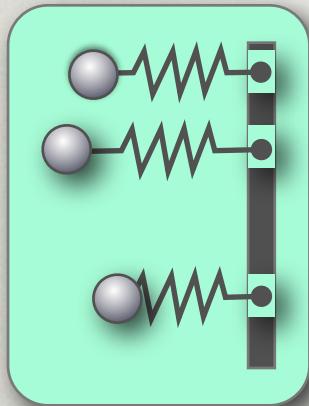
COMPUTATIONAL POWER



Has to **integrate** information over time (fading memory)

Has to **separate** signals

COMPUTATIONAL POWER

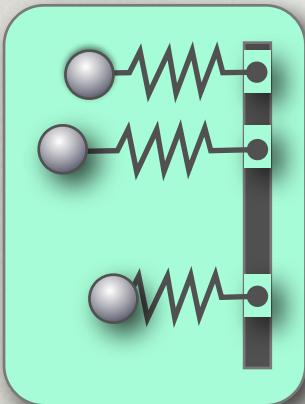


- compliance is important

Has to **integrate** information over time (fading memory)

Has to **separate** signals

COMPUTATIONAL POWER

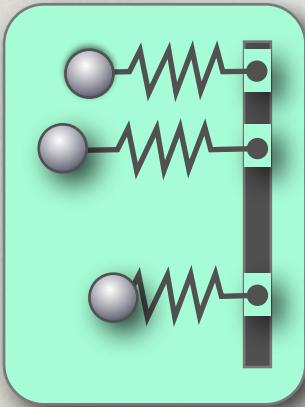


- compliance is important
- The number of mass-spring systems should be high

Has to **integrate** information over time (fading memory)

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COMPUTATIONAL POWER



- compliance is important
- The number of mass-spring systems should be high
- The diversity of mass-spring systems is important (i.e., different physical parameters)

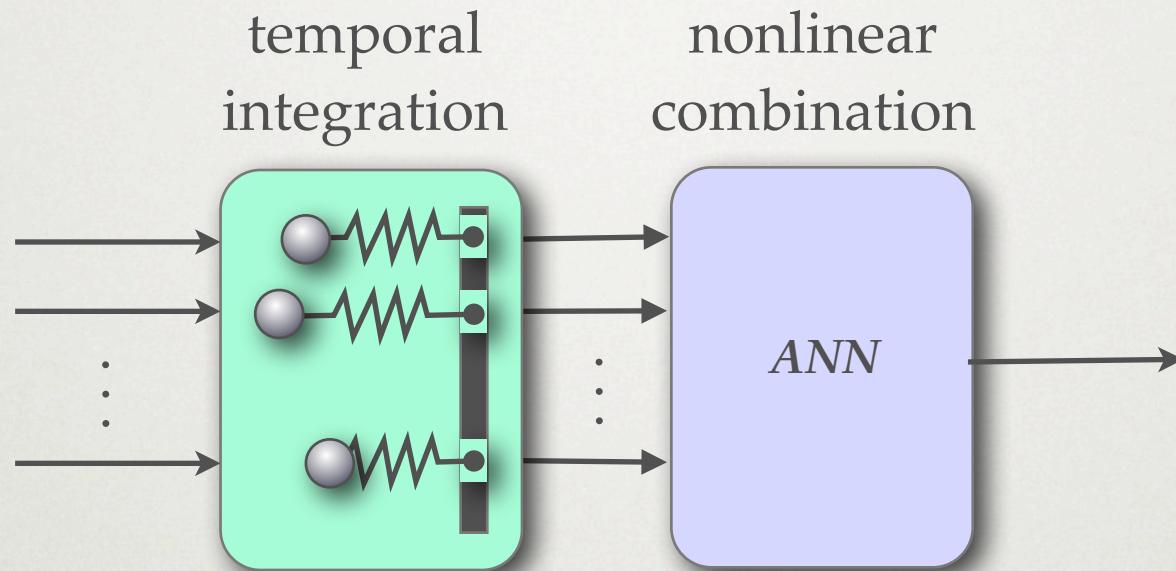
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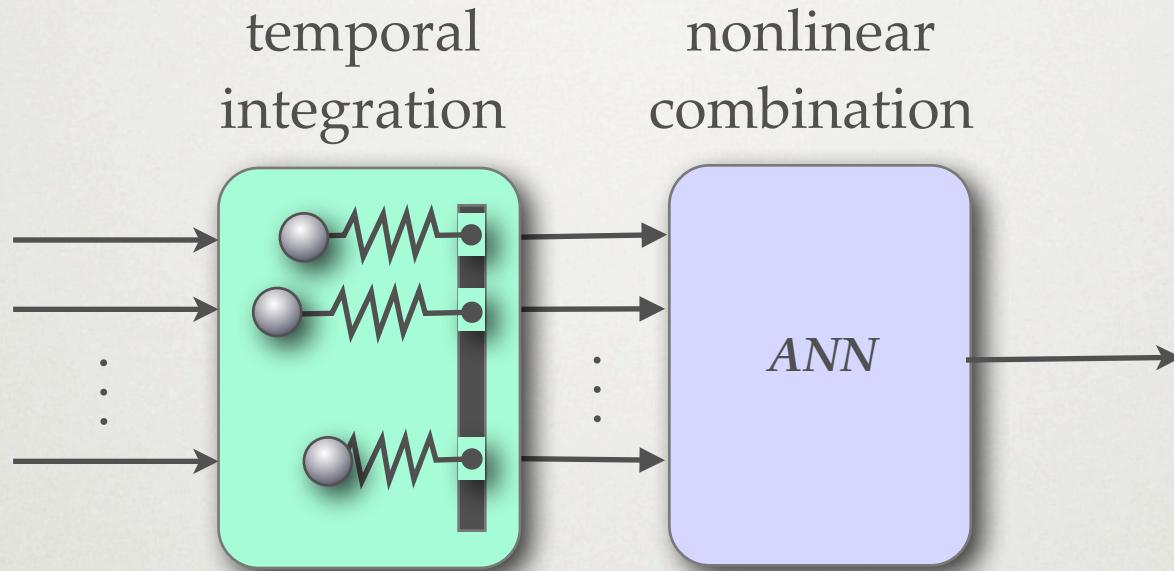
soft robots



CAN THE PHYSICAL BODY DO MORE?

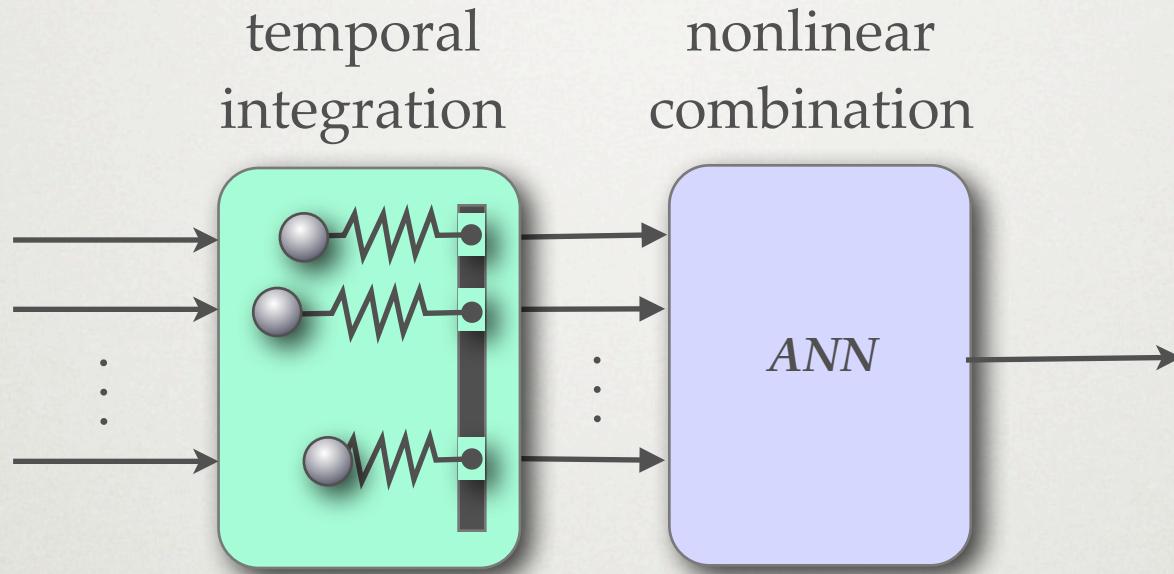


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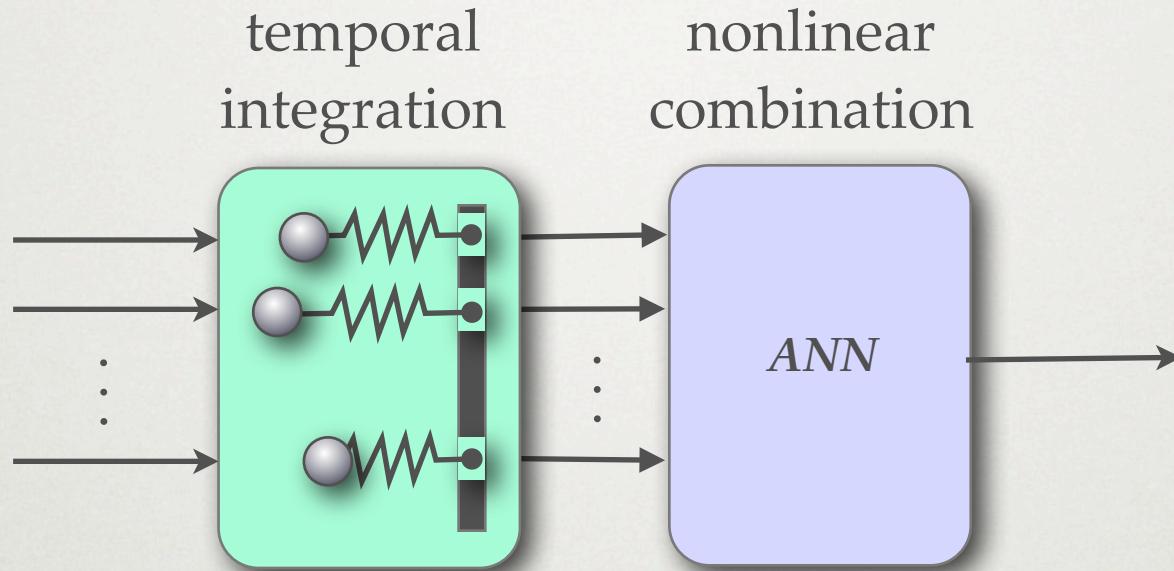
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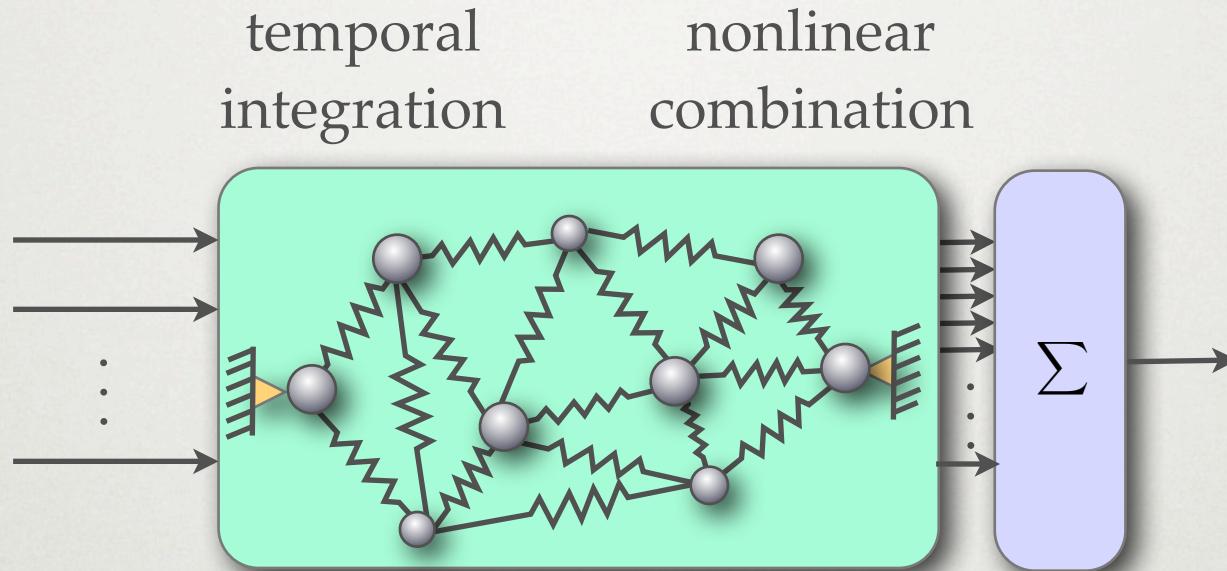
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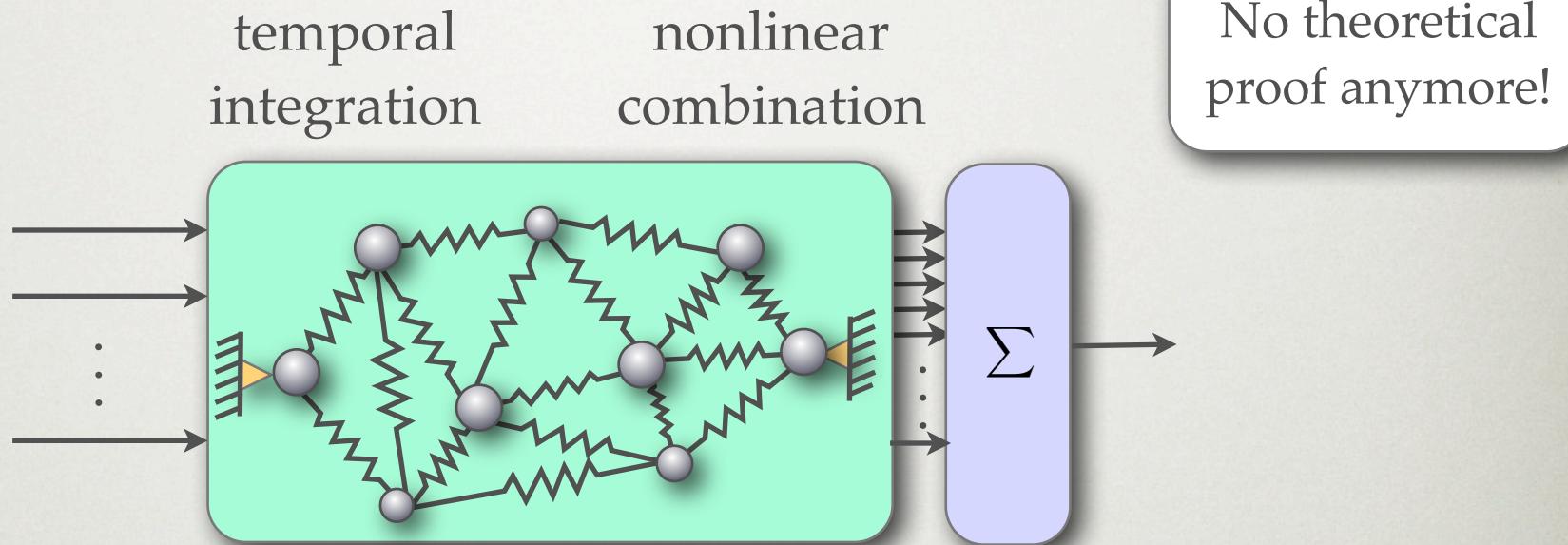
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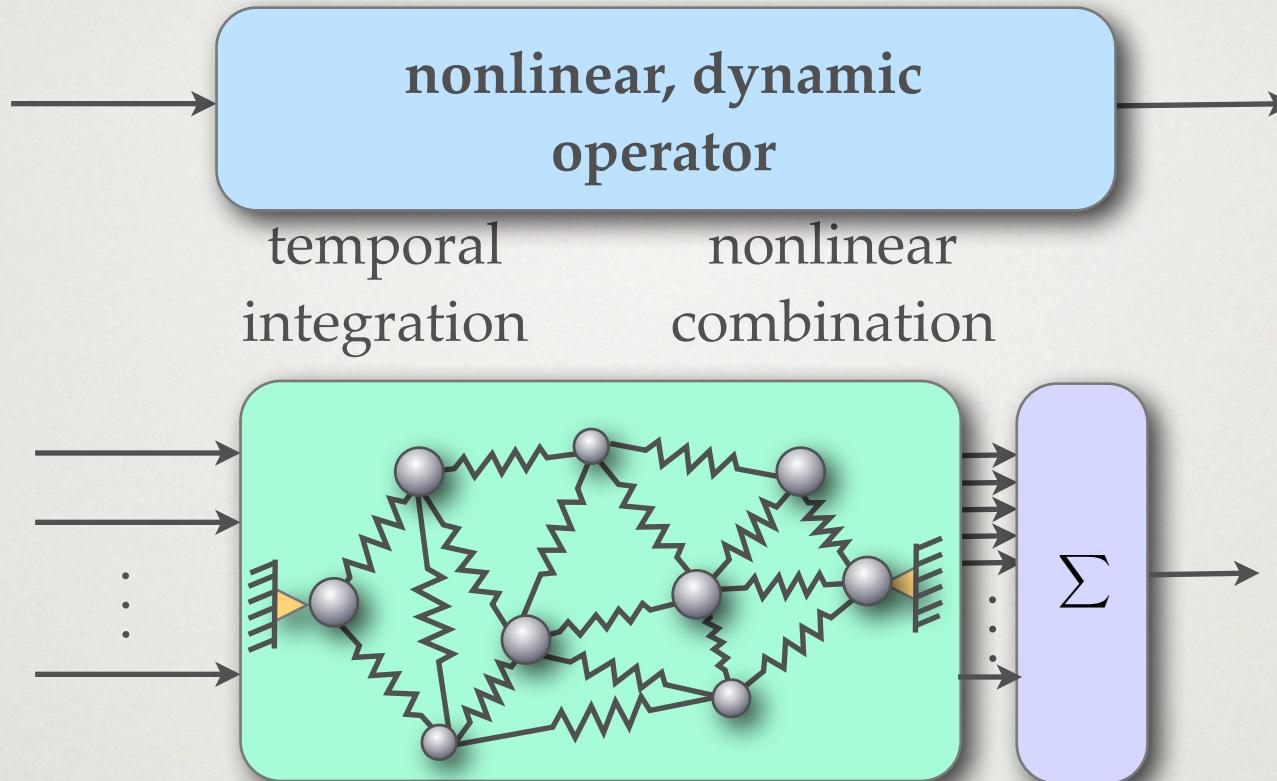
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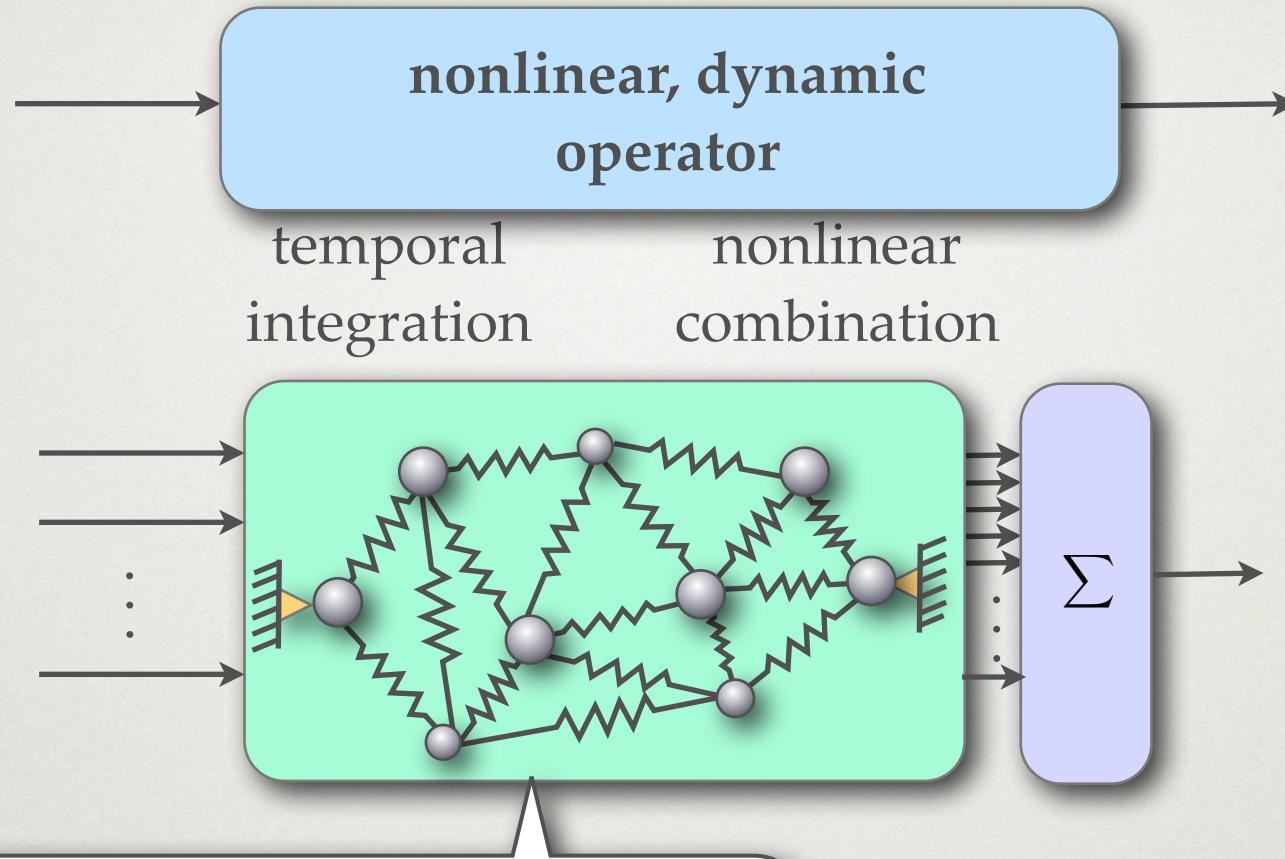


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REMARKABLE CONCLUSION

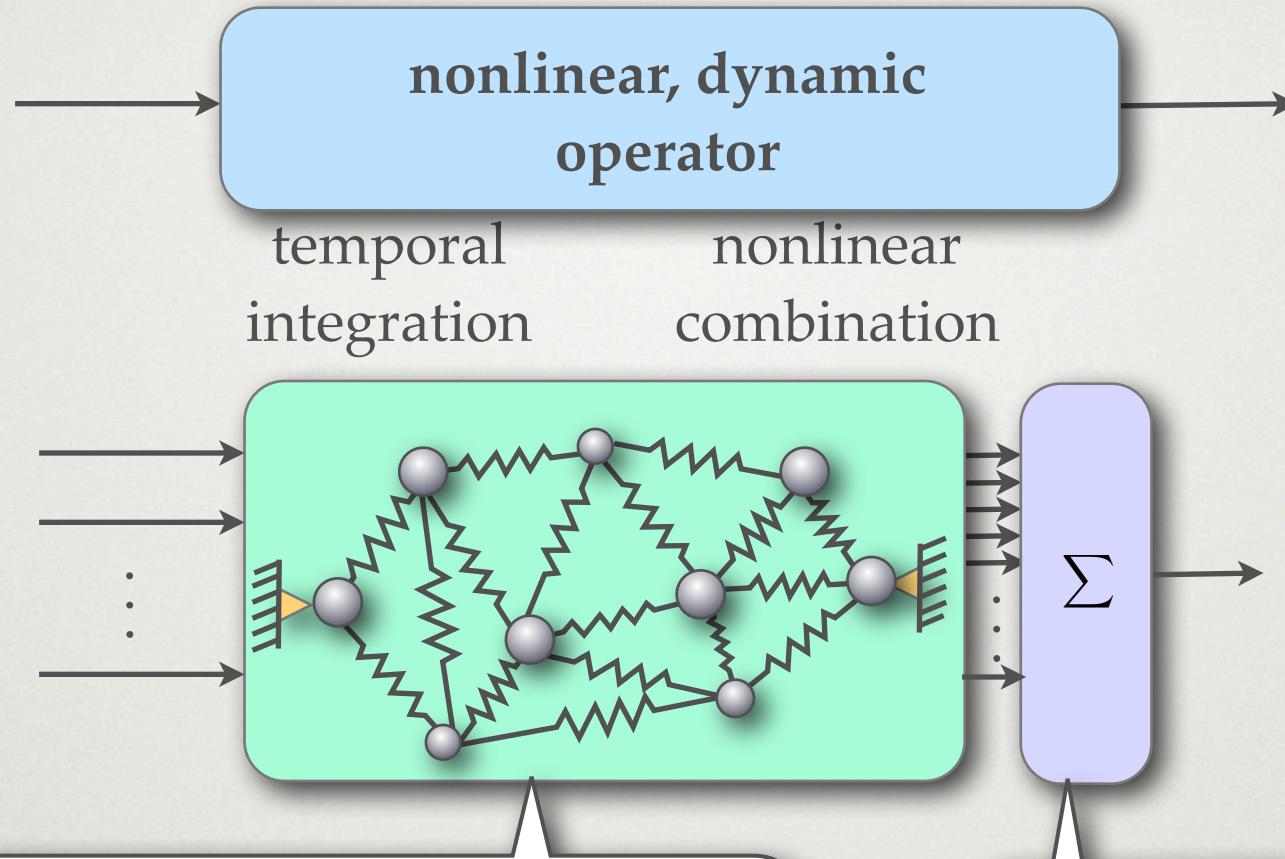


REMARKABLE CONCLUSION



Outsourcing big part of the computation to the morphology

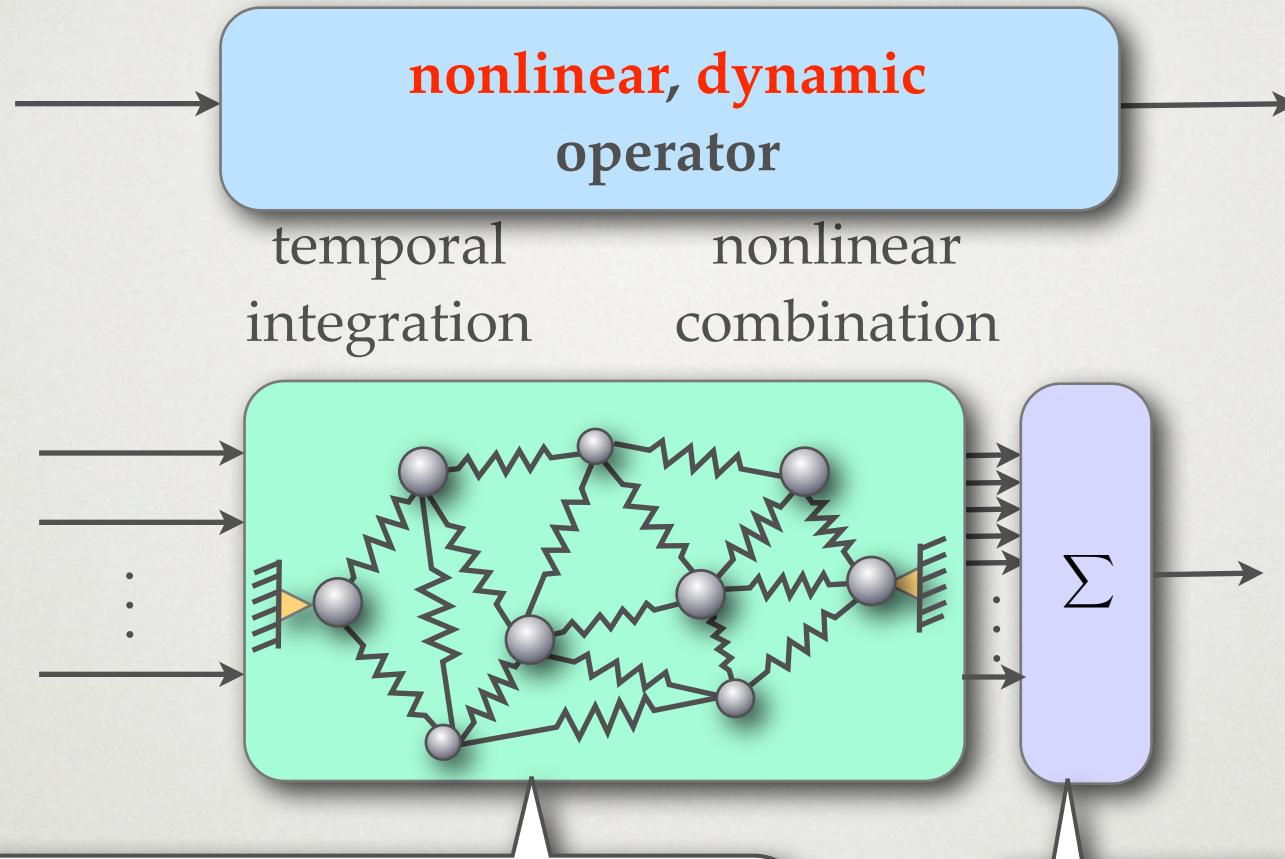
REMARKABLE CONCLUSION



Outsourcing big part of the computation to the morphology

resulting task is easier:
linear regression

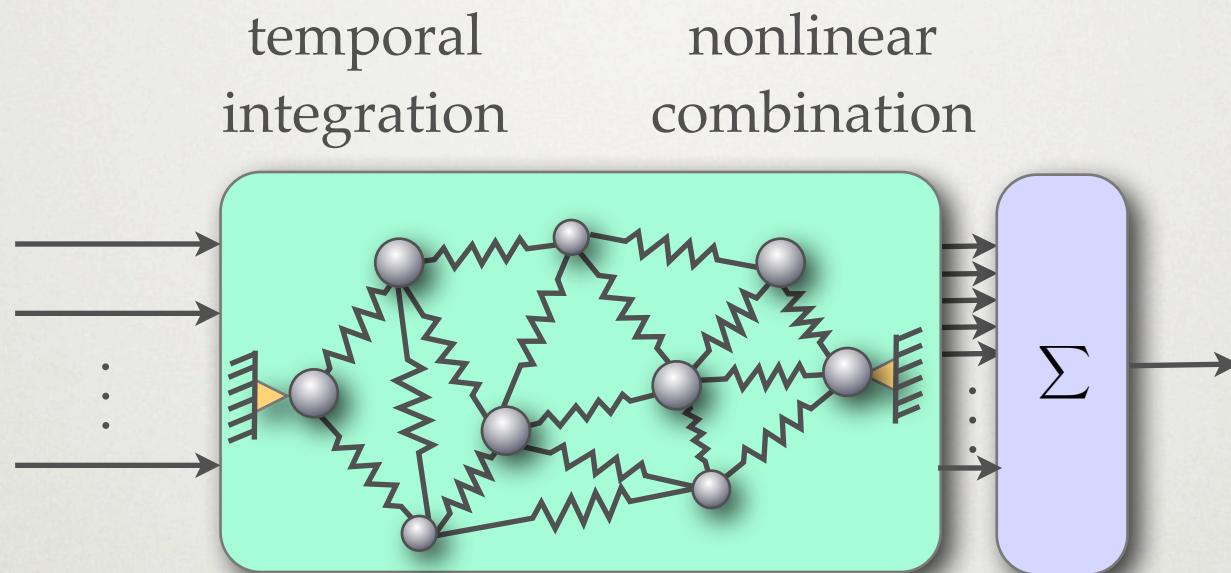
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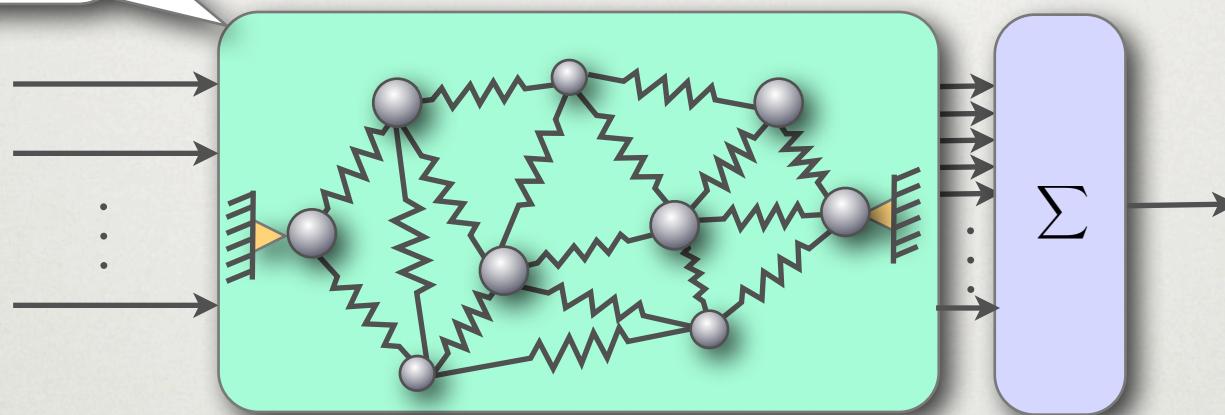


REMARKABLE CONCLUSION

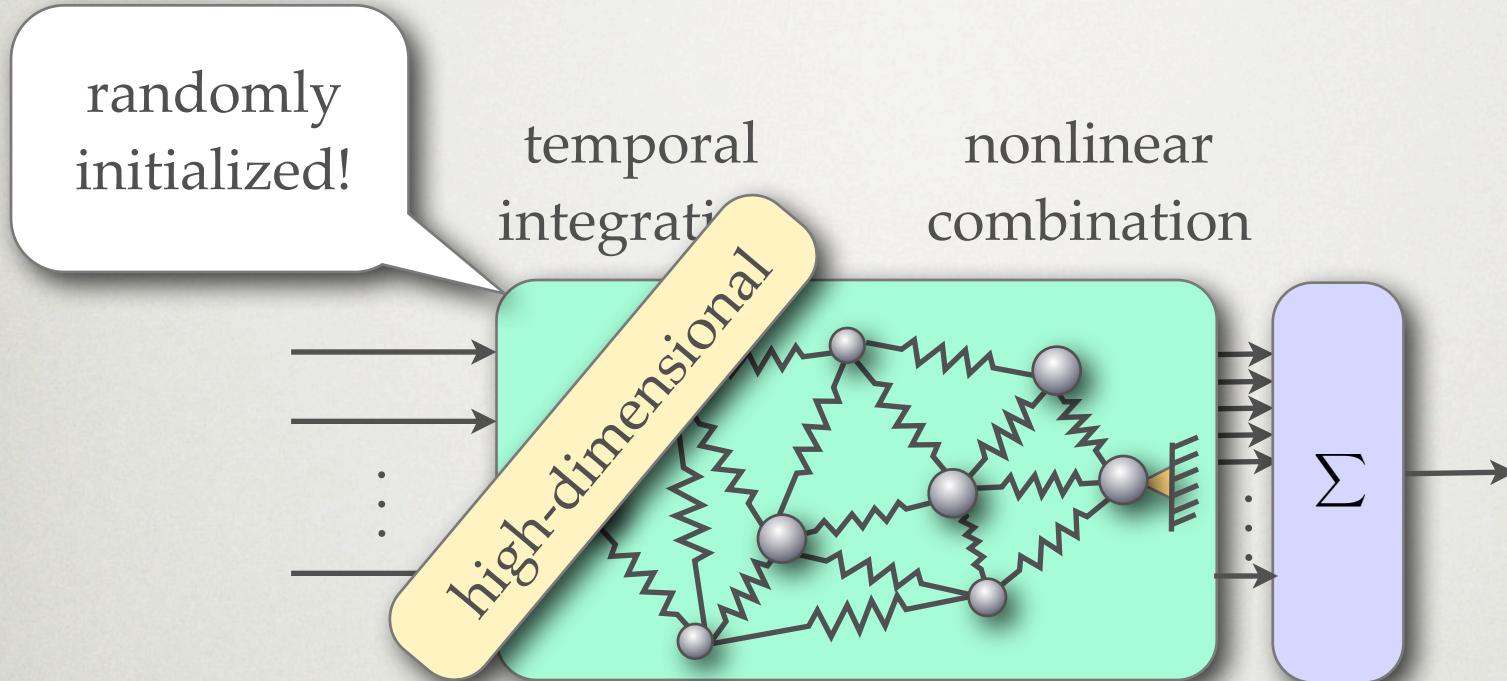
randomly
initialized!

temporal
integration

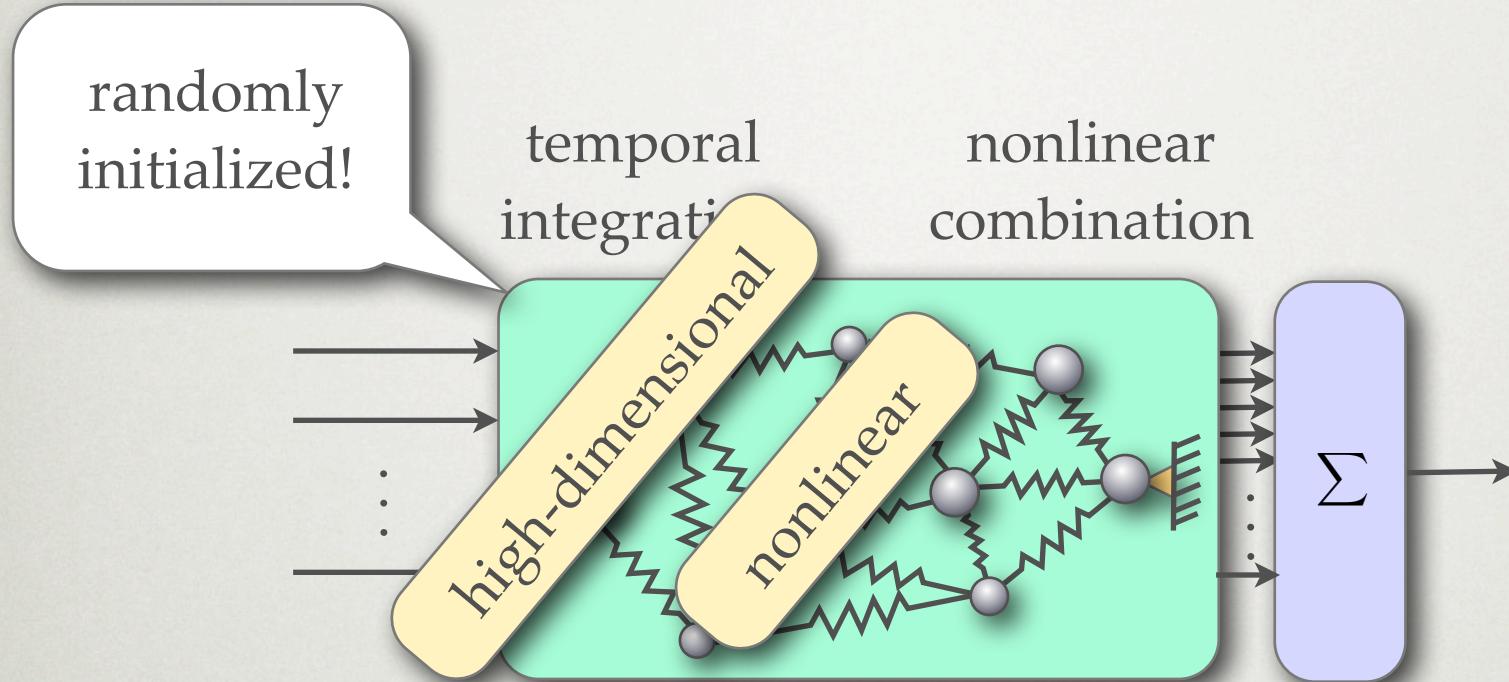
nonlinear
combination



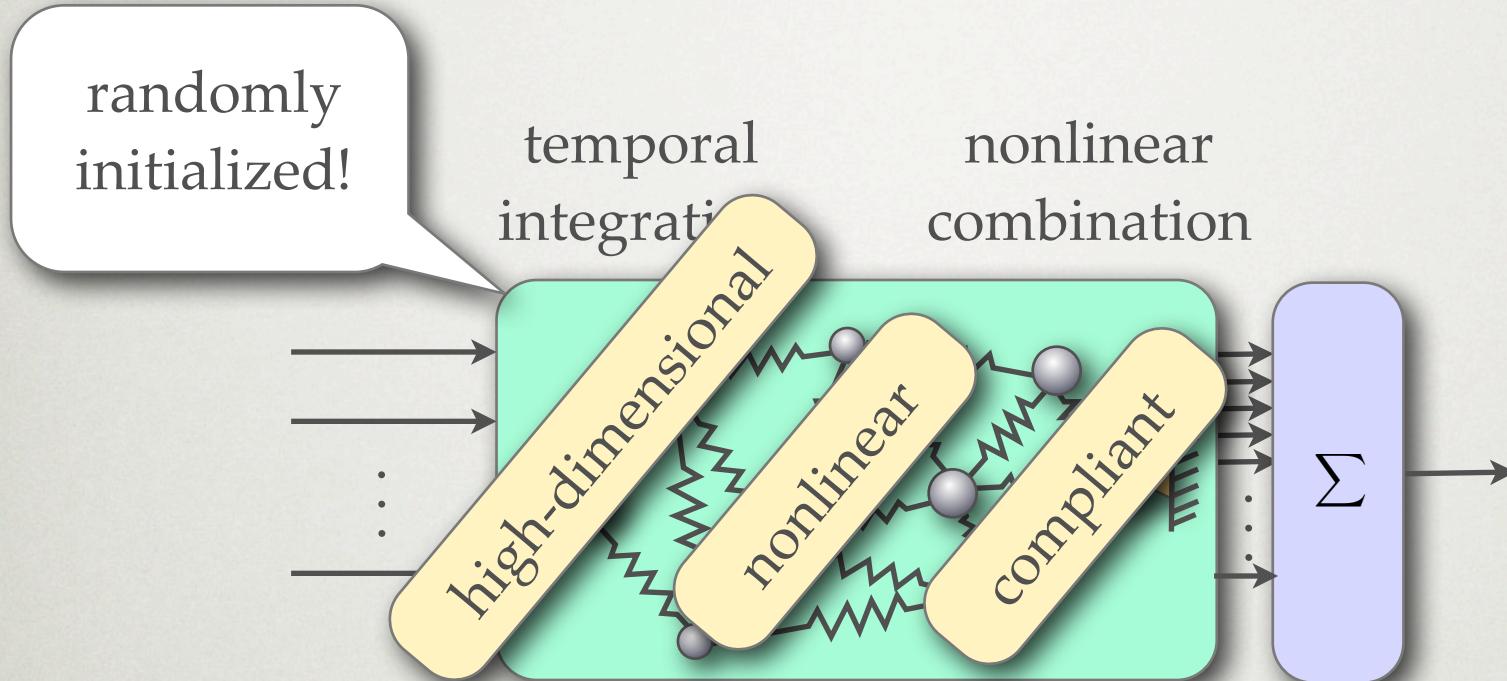
REMARKABLE CONCLUSION



REMARKABLE CONCLUSION



REMARKABLE CONCLUSION



REMARKABLE CONCLUSION

high-dimensional

nonlinear

compliant

REMARKABLE CONCLUSION

high-dimensional

nonlinear

compliant



I don't like that!

REMARKABLE CONCLUSION

high-dimensional

nonlinear

compliant

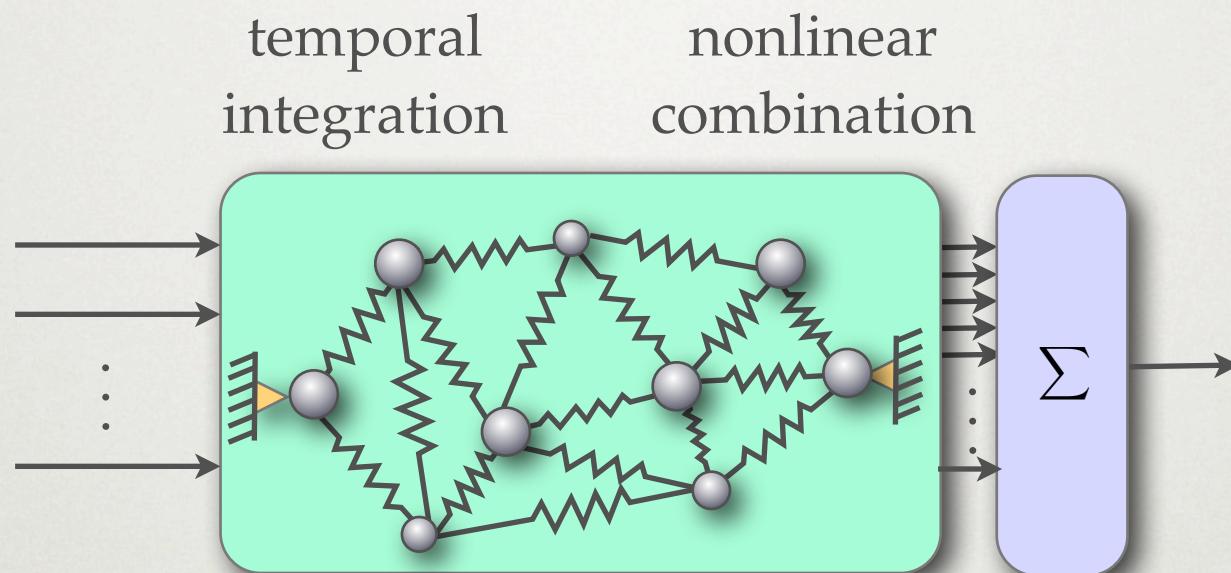


I don't like that!

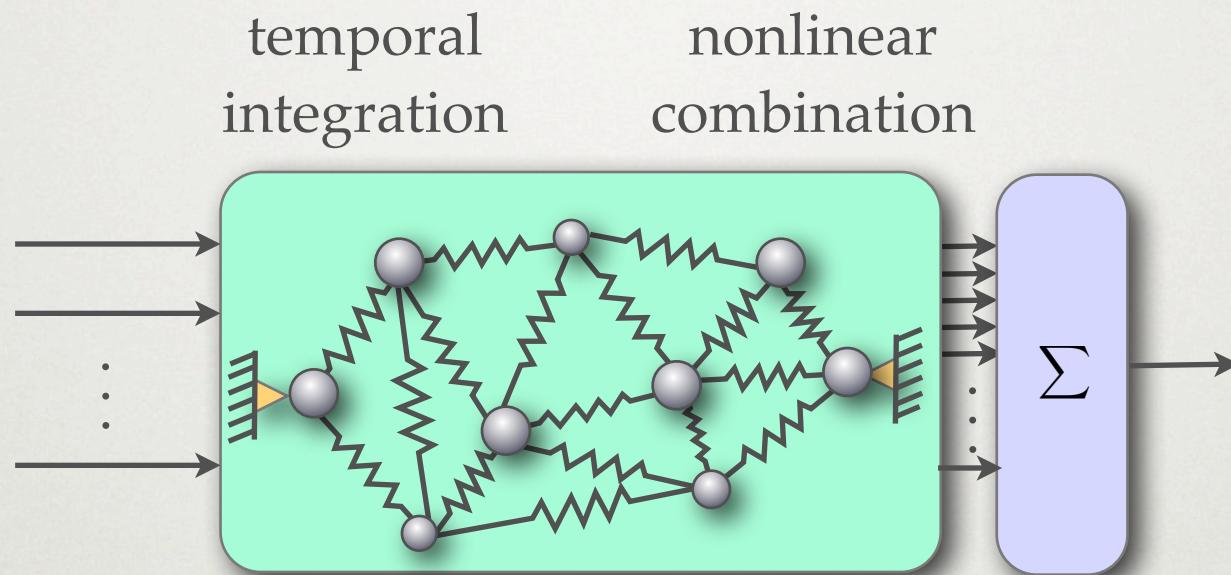


Actually, I do like
that!

LIMITATION

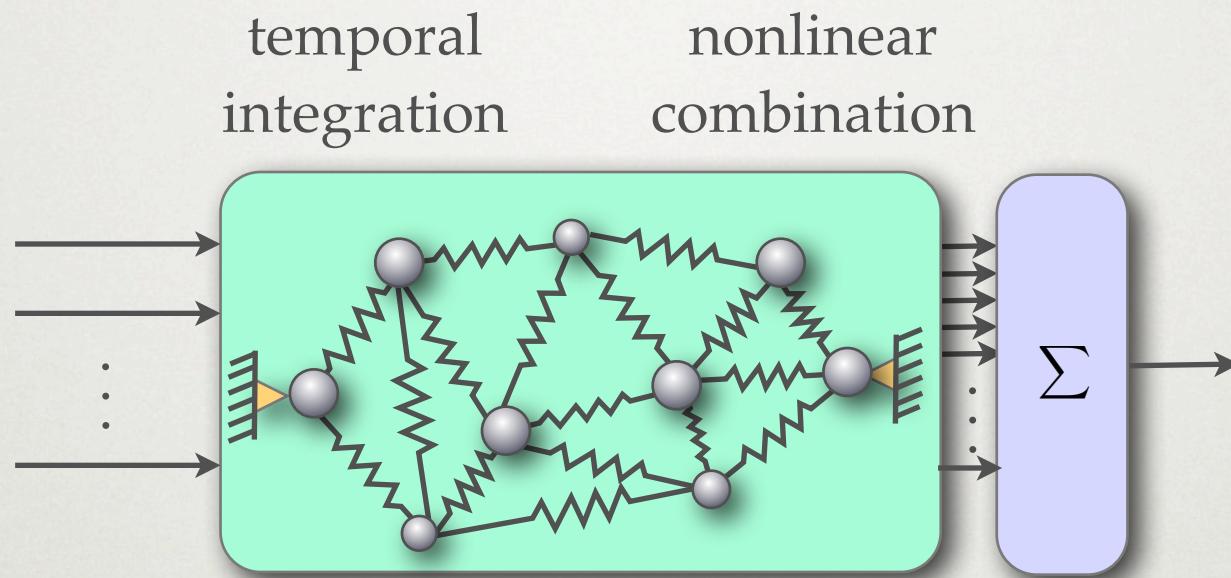


LIMITATION



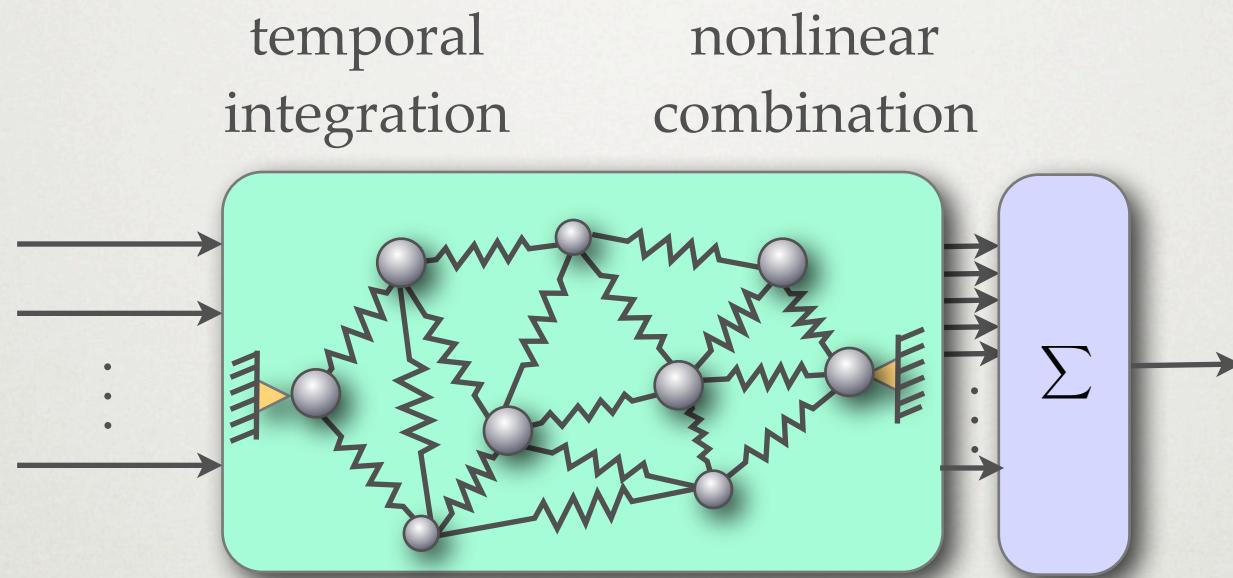
- The theoretical model is limited to **time-invariant operators with fading memory**

LIMITATION



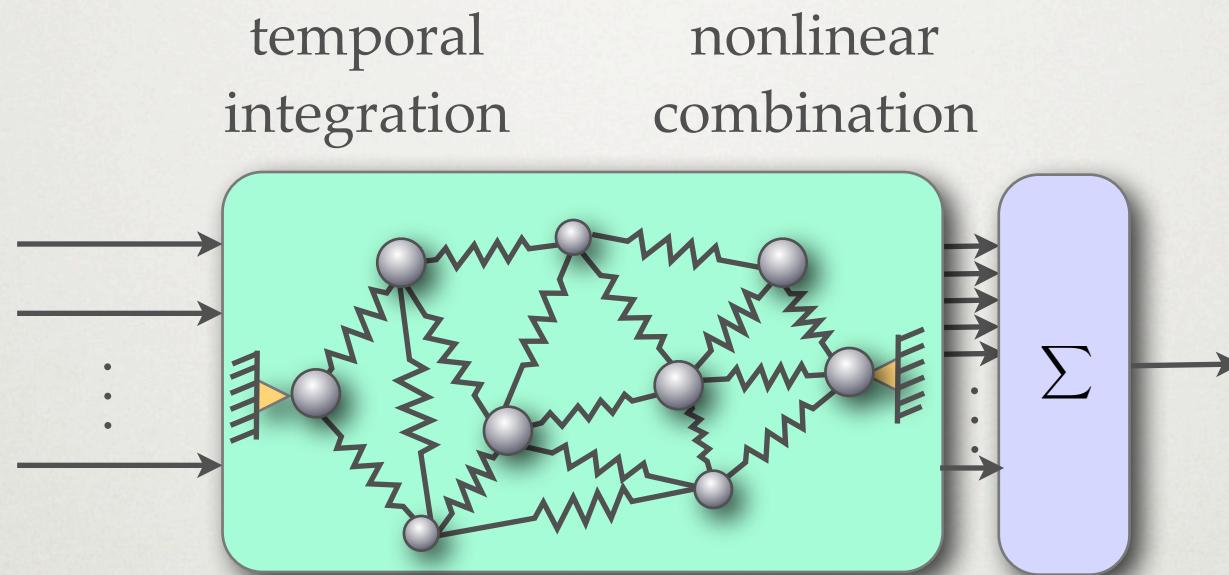
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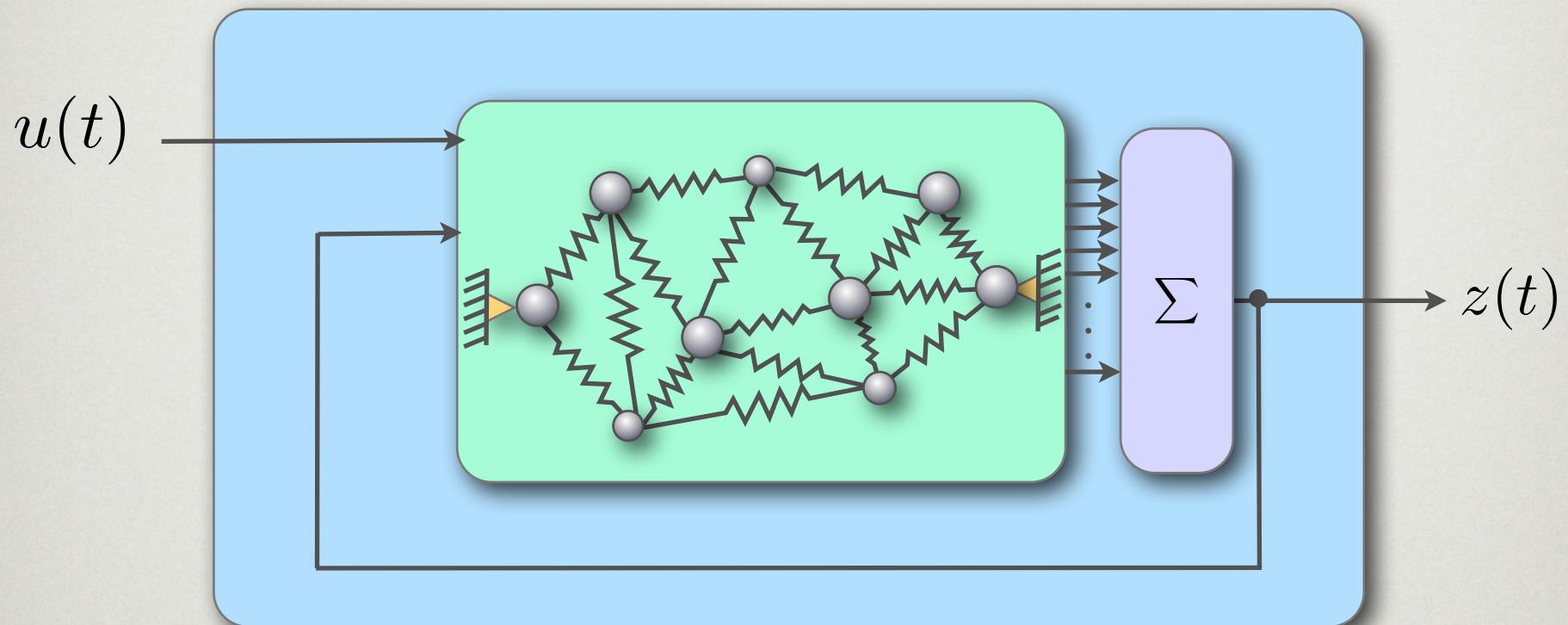
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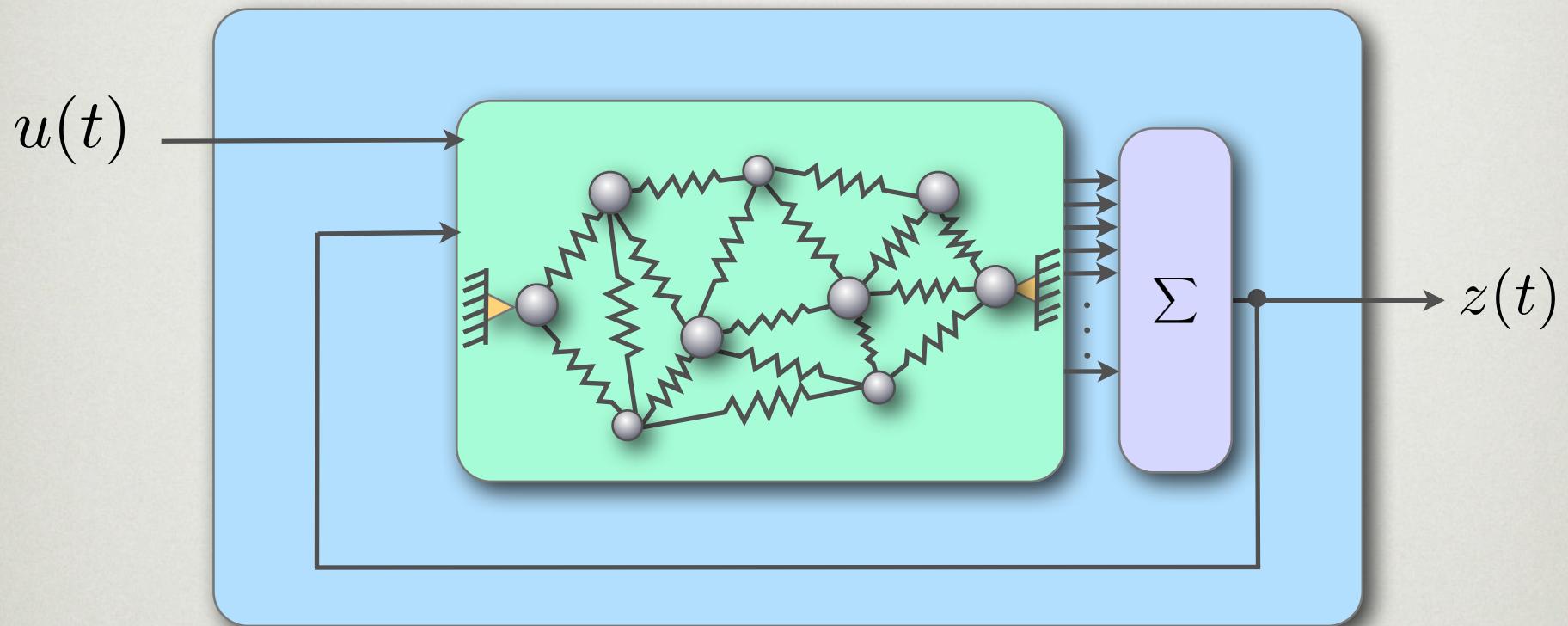


- The theoretical model is limited to **time-invariant operators with fading memory**
- Persistent memory is of interest too, or limit cycles for locomotion
- **Another theory is needed!**
- based on feedback linearization from control theory

SECOND THEORETICAL MODEL

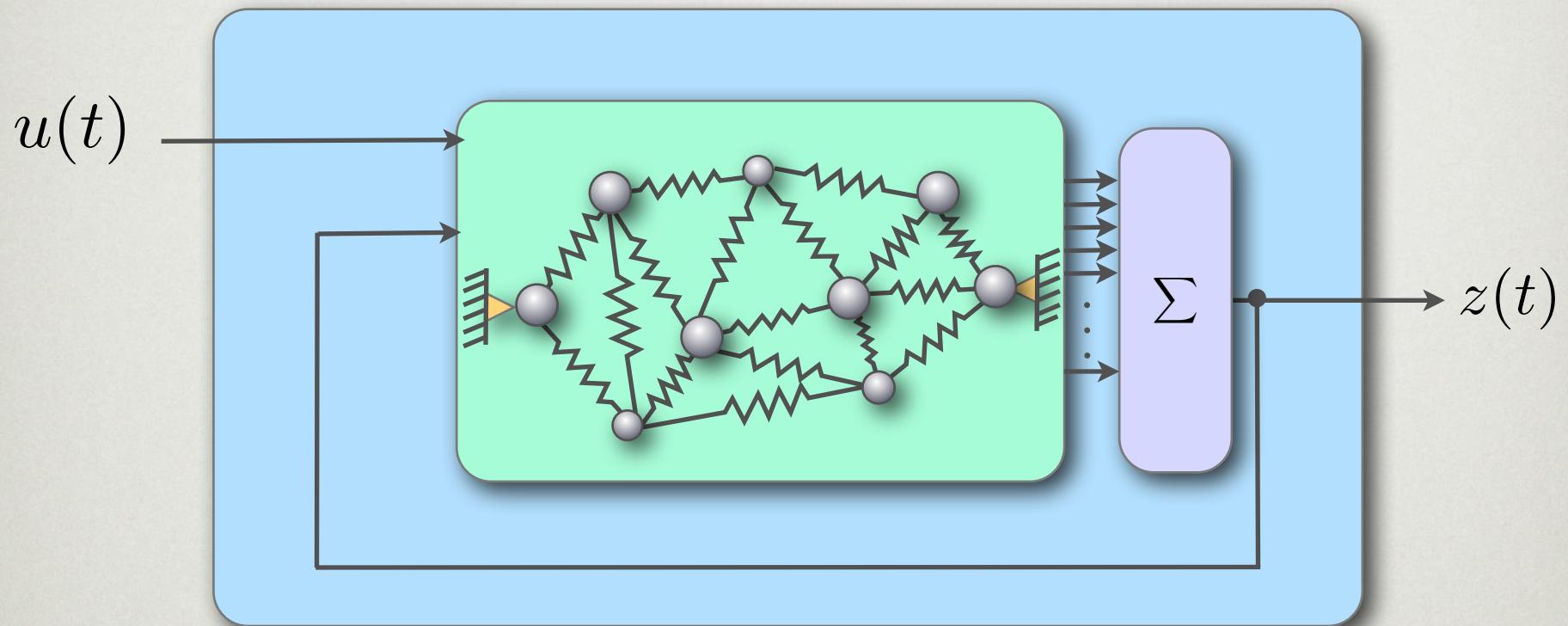


SECOND THEORETICAL MODEL



$$u(t) \rightarrow z(t)^{(n)} = G(z(t), z(t)', \dots, z(t)^{(n-1)}) + u(t) \rightarrow z(t)$$

SECOND THEORETICAL MODEL



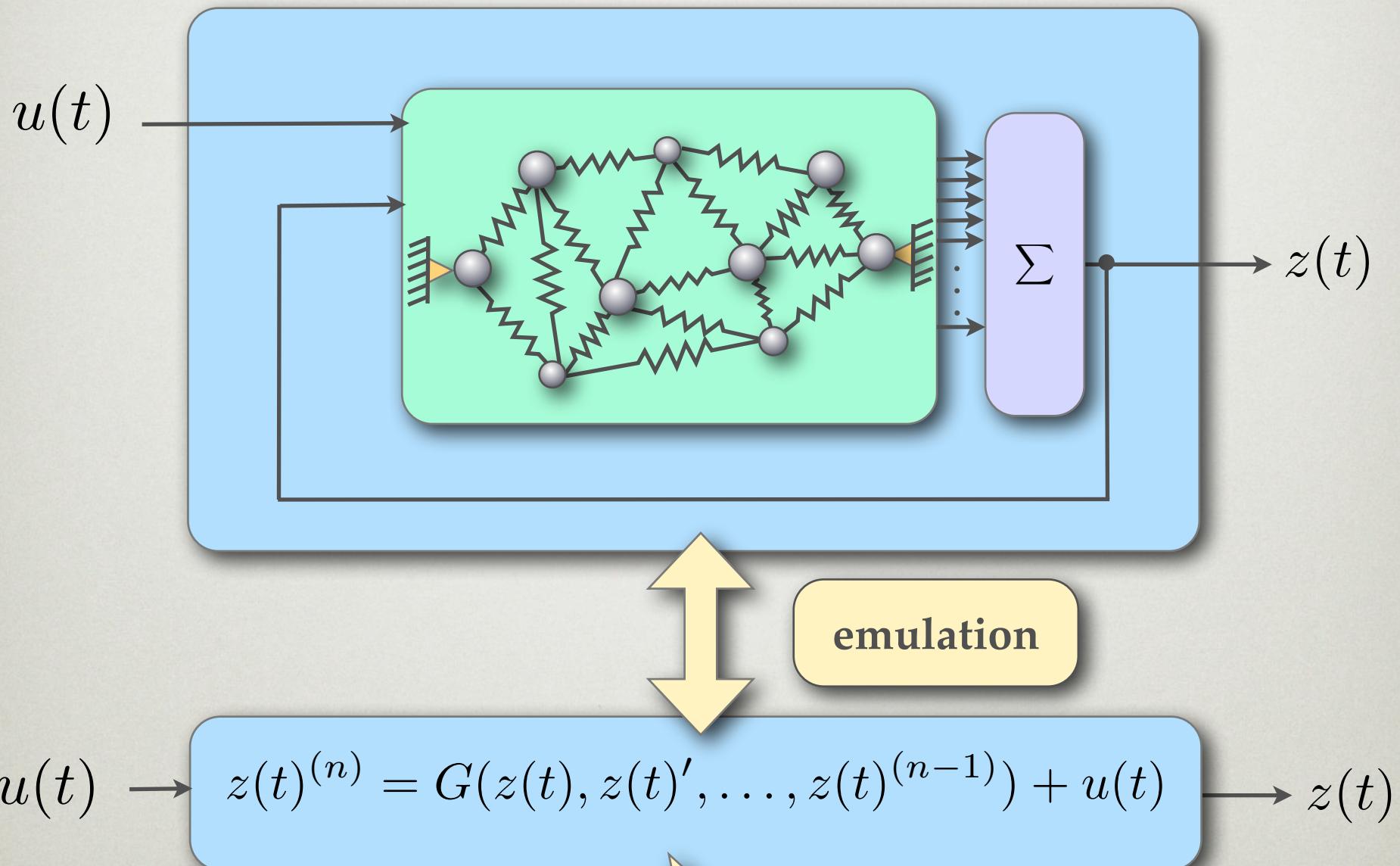
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Hauser et al.

"The role of feedback in morphological computation with compliant bodies" Biological Cybernetics, 2012

encodes our computation

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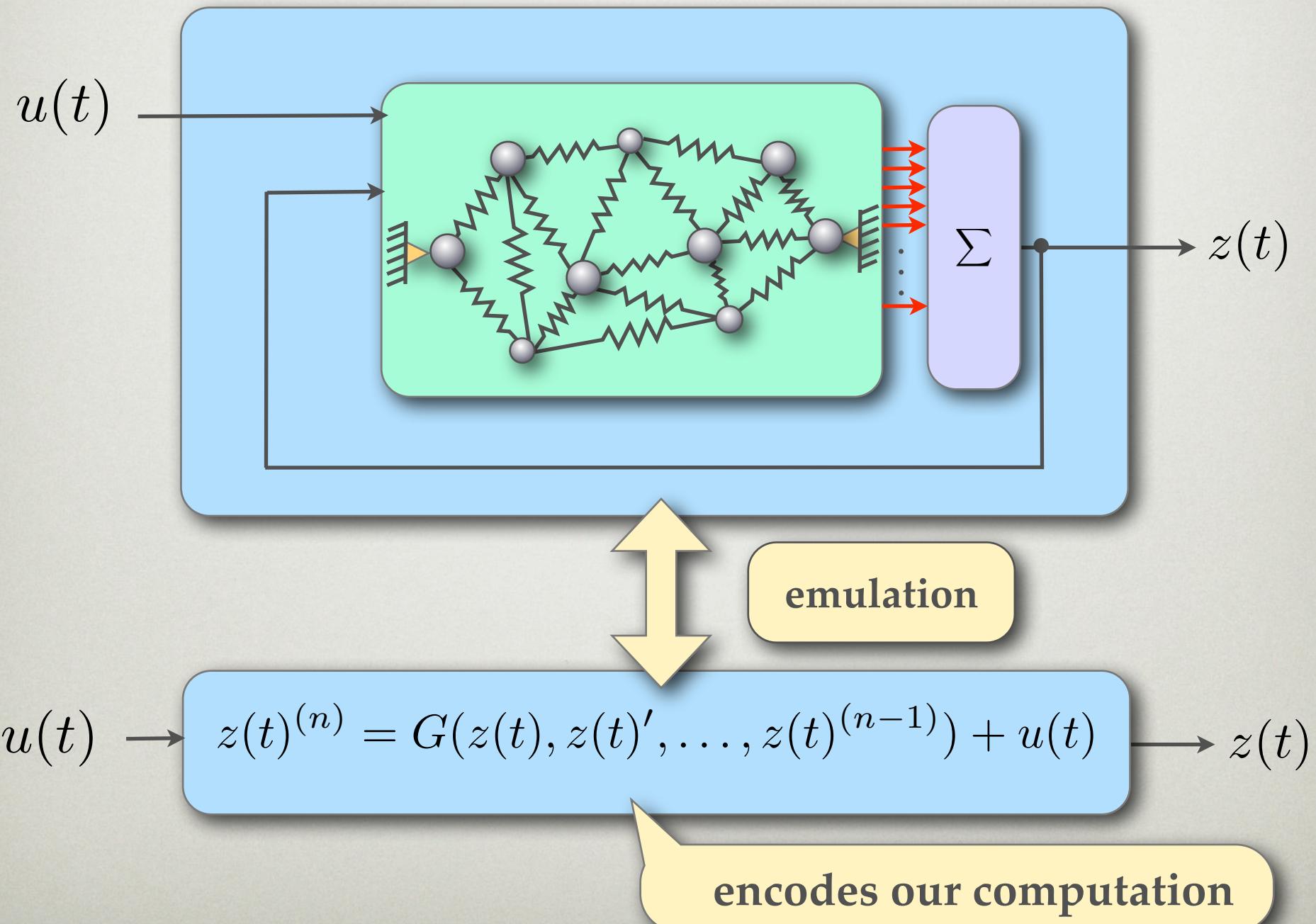


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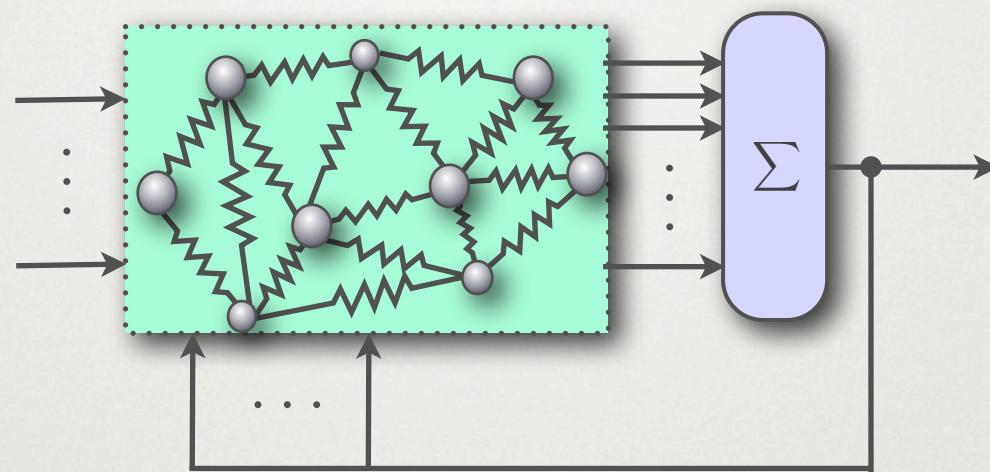
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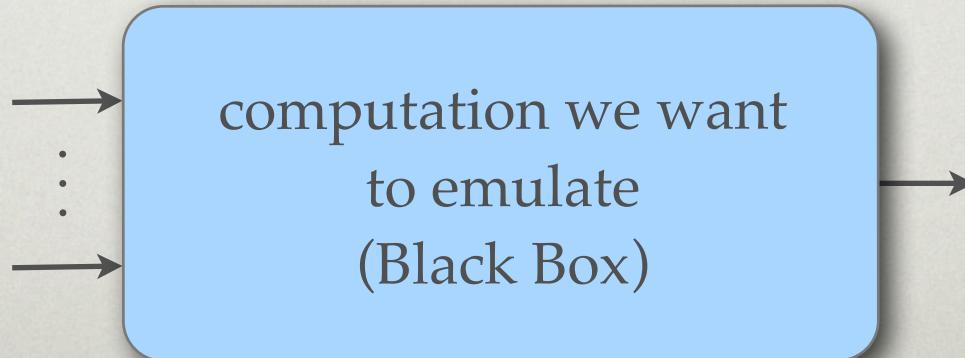
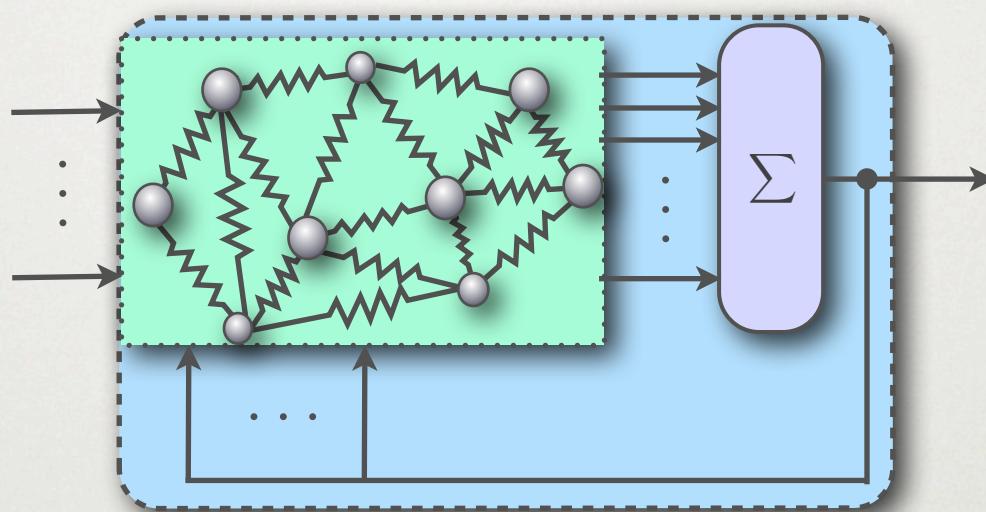
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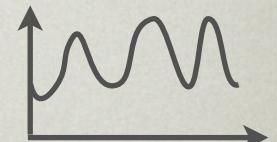
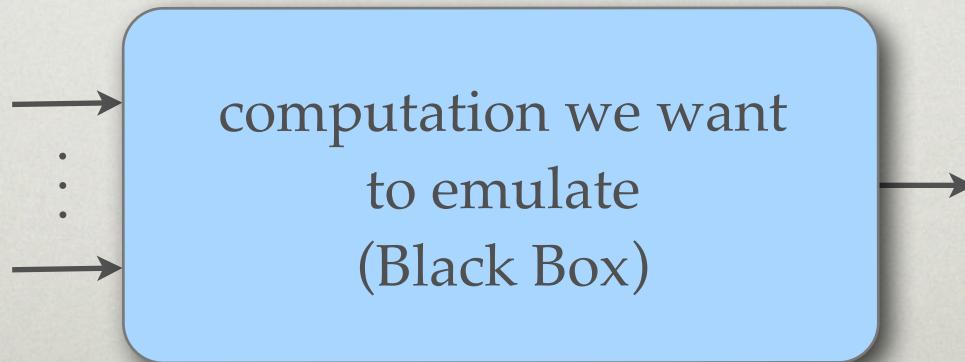
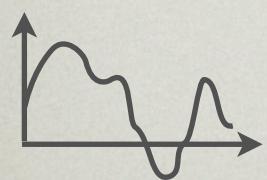
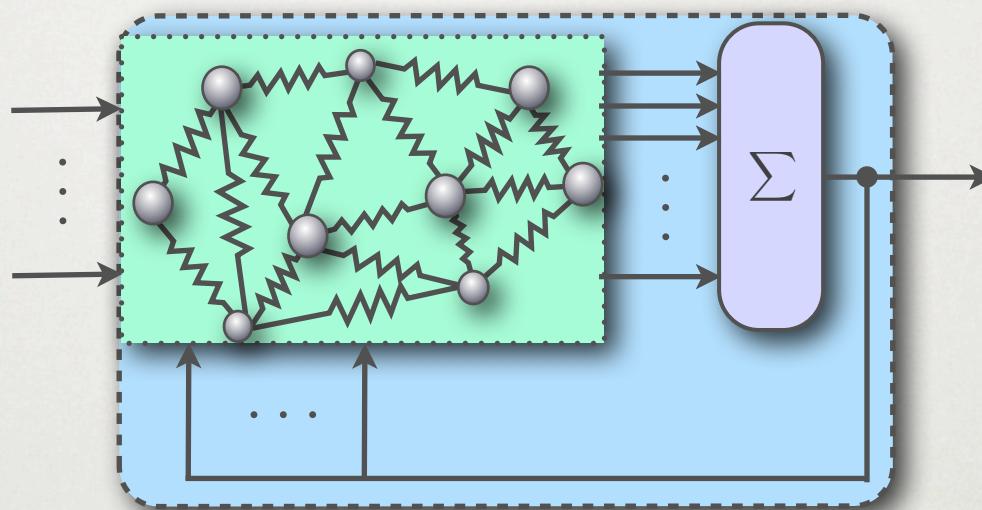
LEARNING SETUP



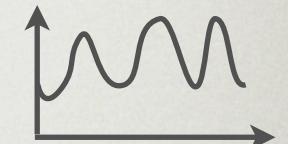
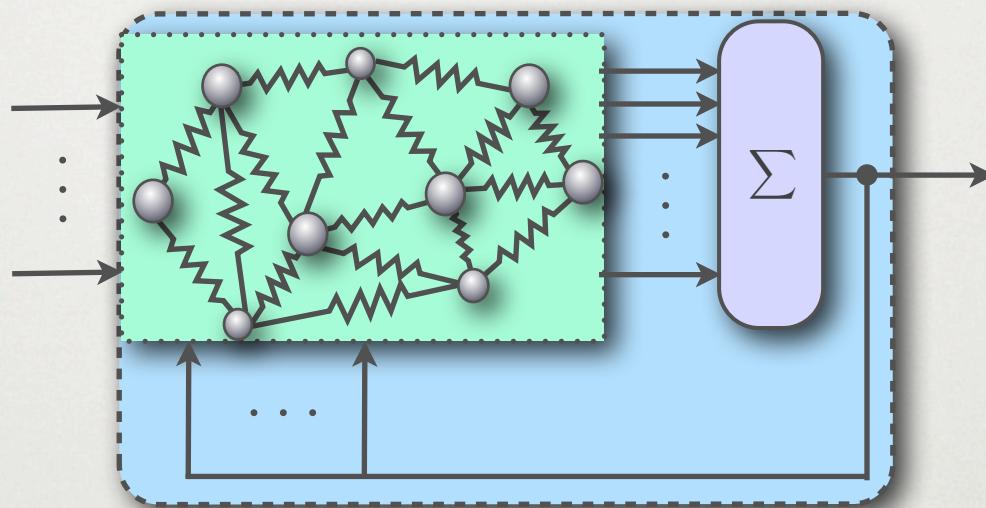
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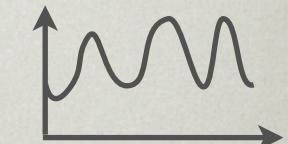
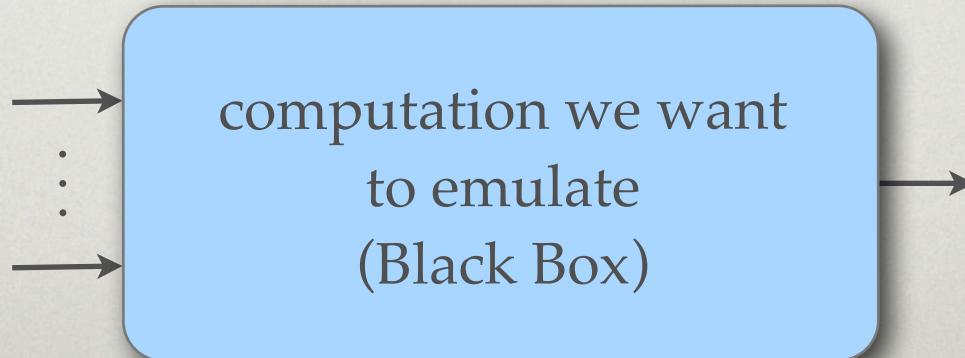
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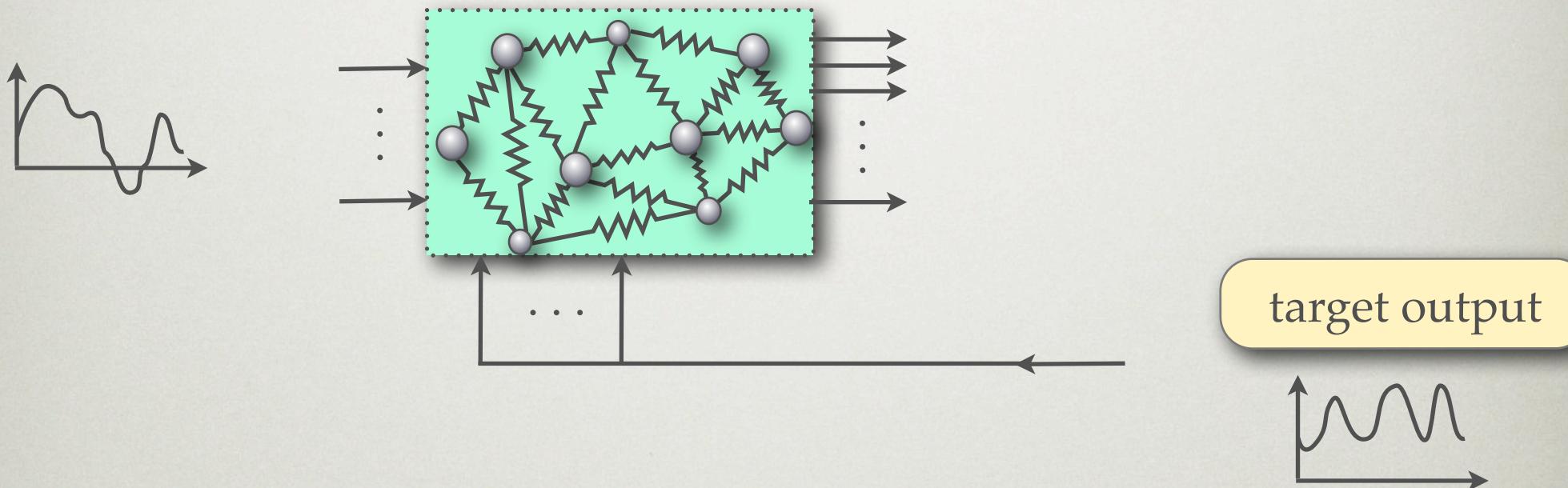
LEARNING SETUP



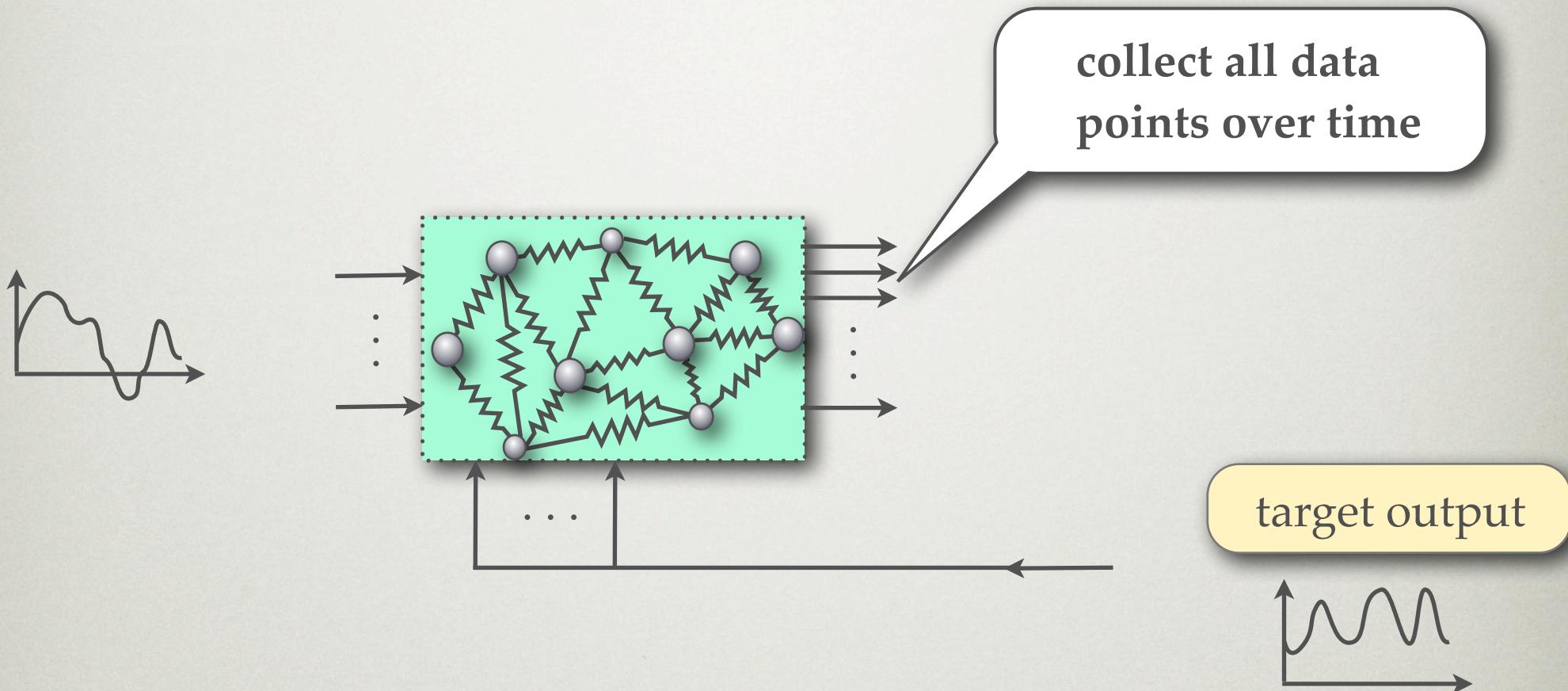
target output



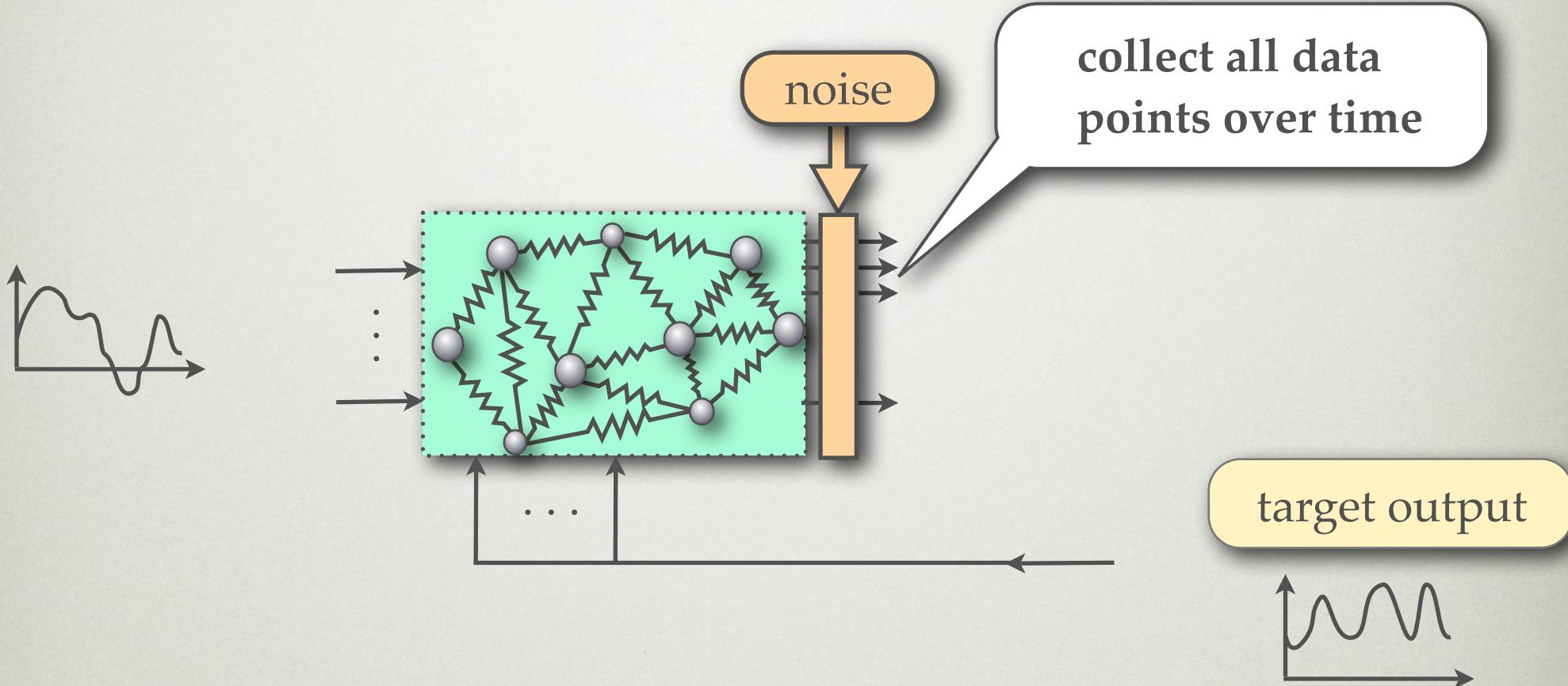
LEARNING SETUP



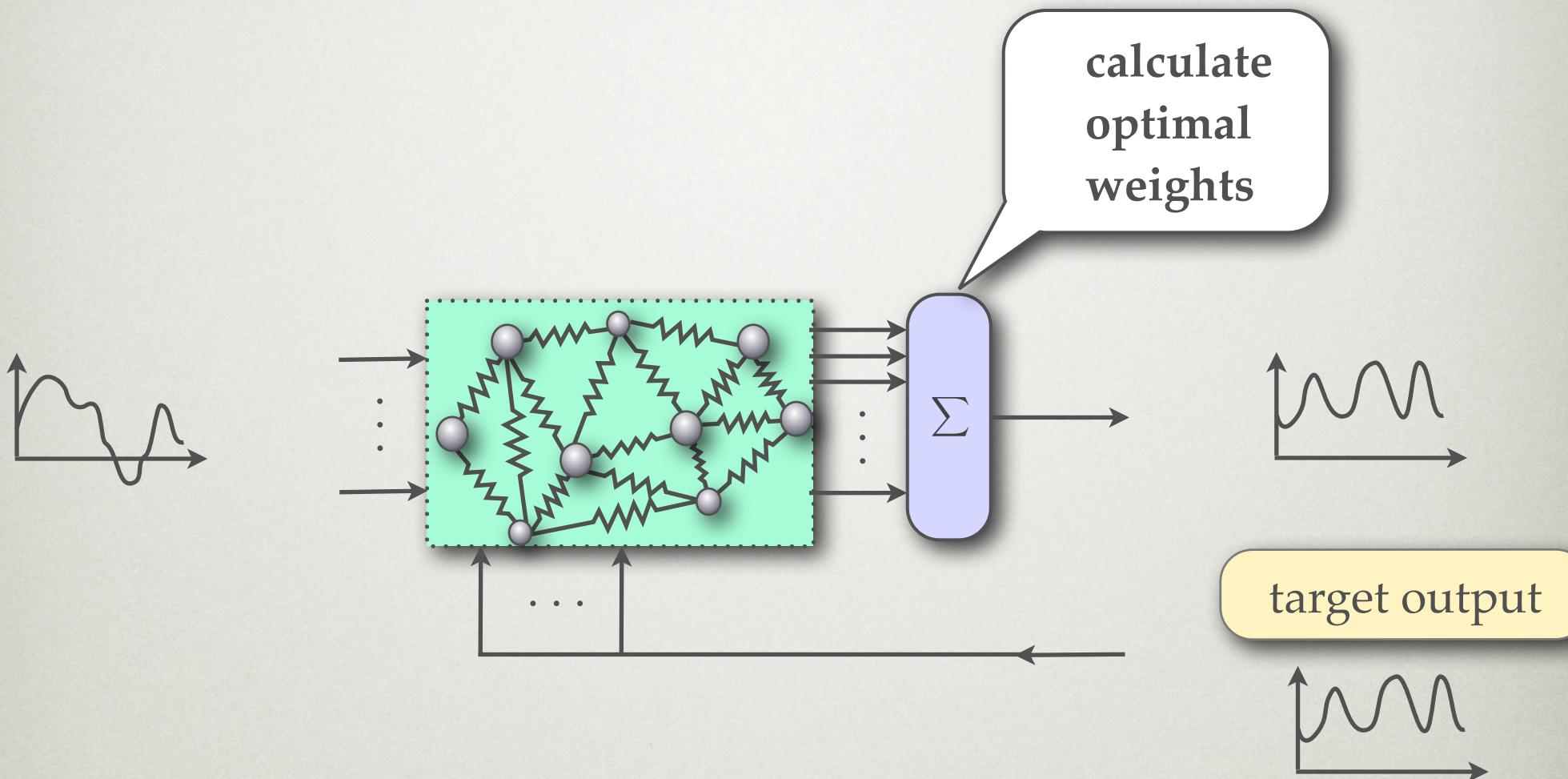
LEARNING SETUP



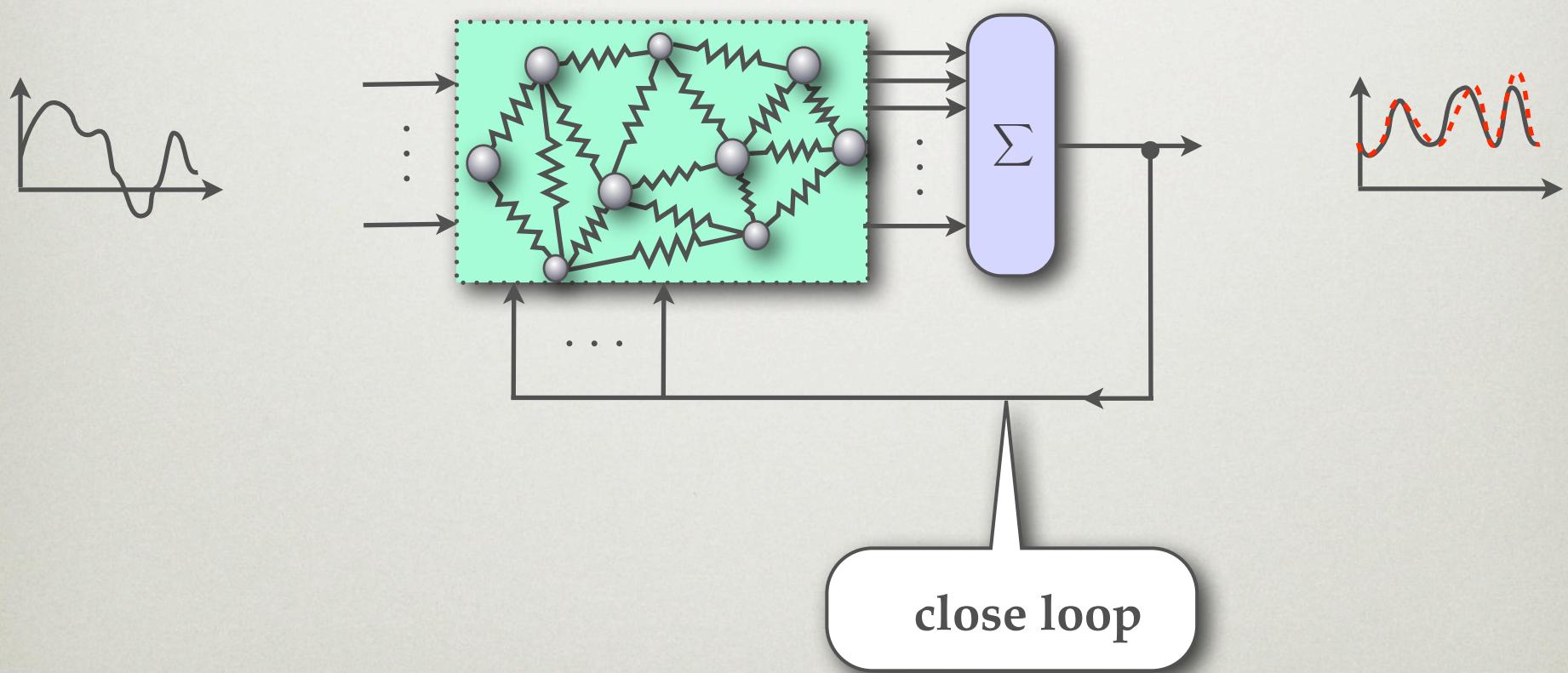
LEARNING SETUP



LEARNING SETUP



LEARNING SETUP



RESULTS

Input Dependent Limit Cycle

$$x'_1 = x_1 + x_2 - \varepsilon x_1(x_1^2 + x_2^2)$$

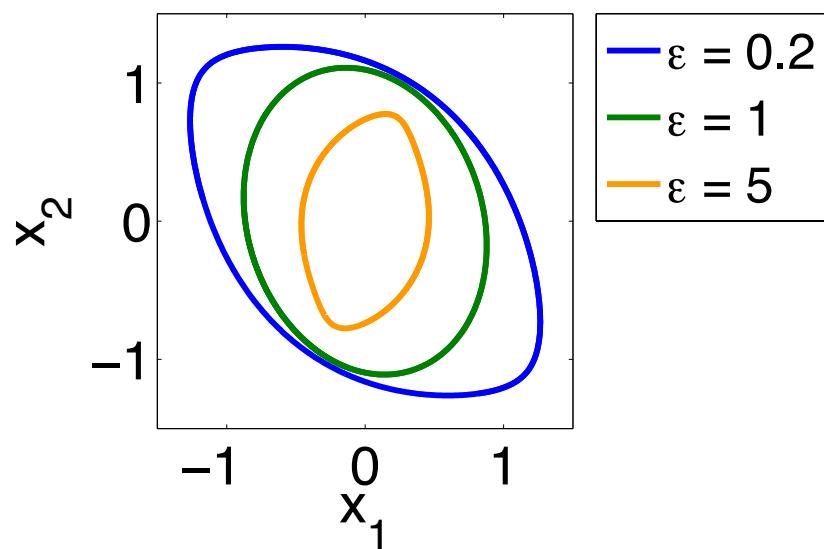
$$x'_2 = -2x_1 + x_2 - x_2(x_1^2 + x_2^2)$$

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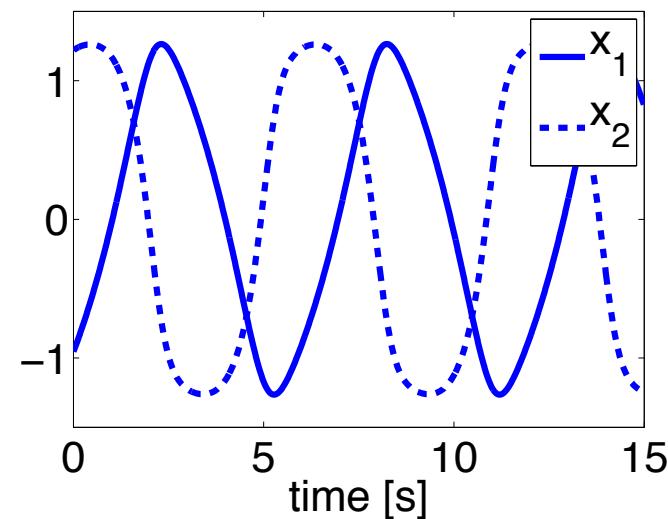
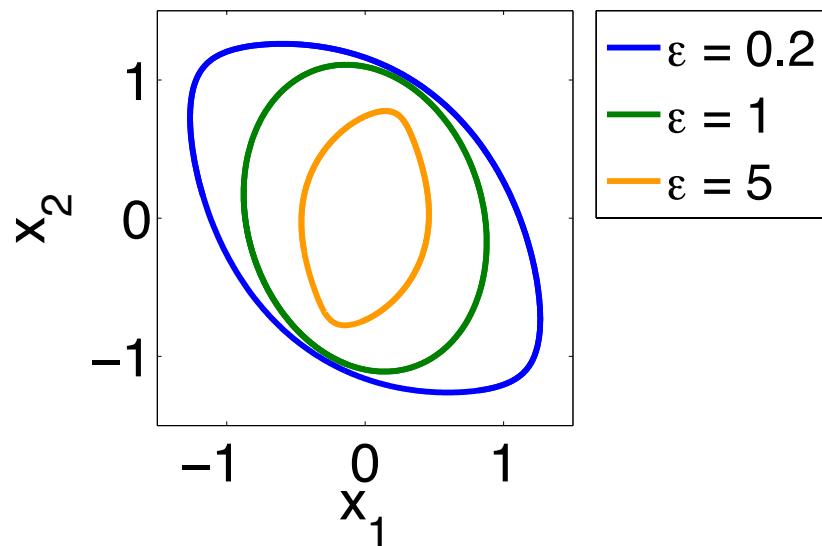


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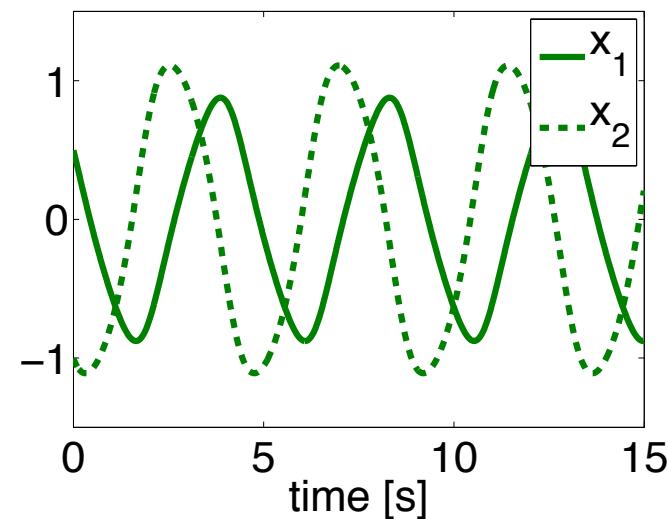
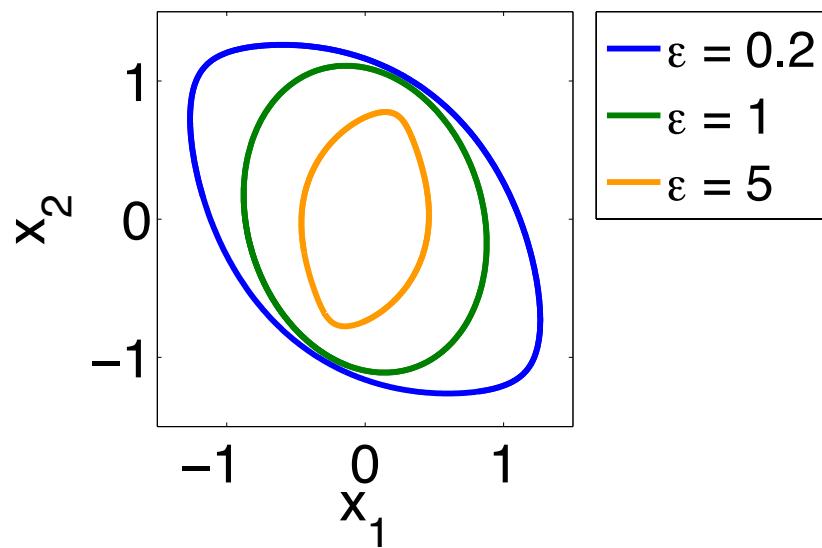


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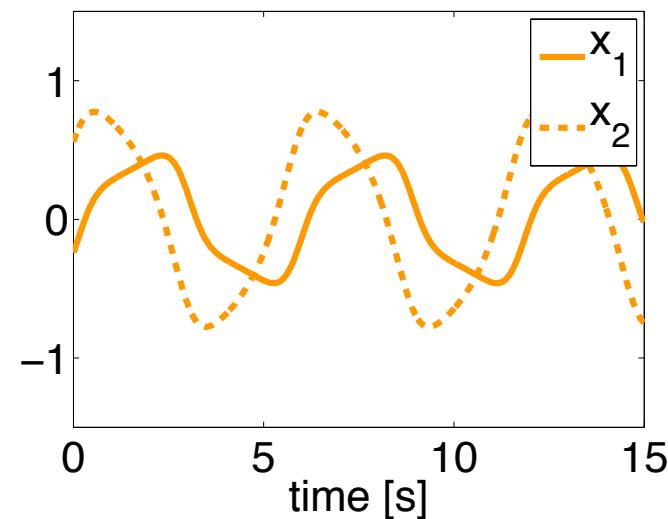
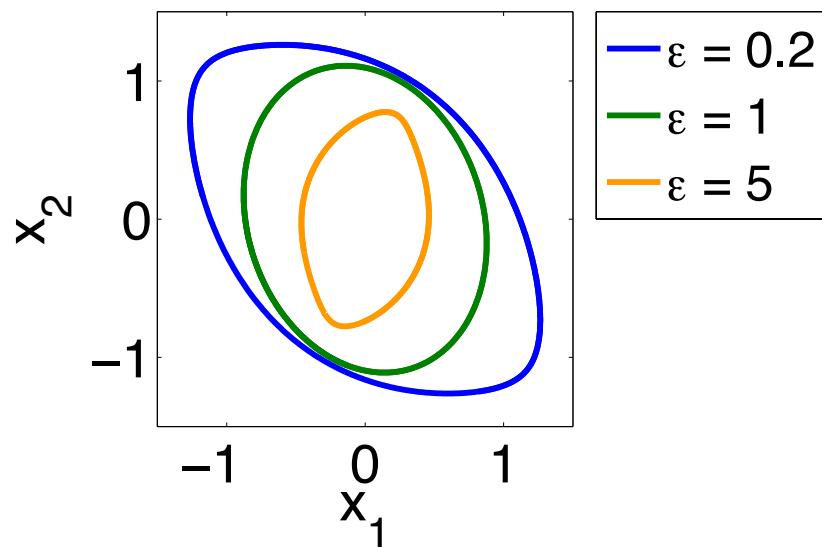


RESULTS

Input Dependent Limit Cycle

$$x'_1 = x_1 + x_2 - \varepsilon x_1(x_1^2 + x_2^2)$$

$$x'_2 = -2x_1 + x_2 - x_2(x_1^2 + x_2^2)$$



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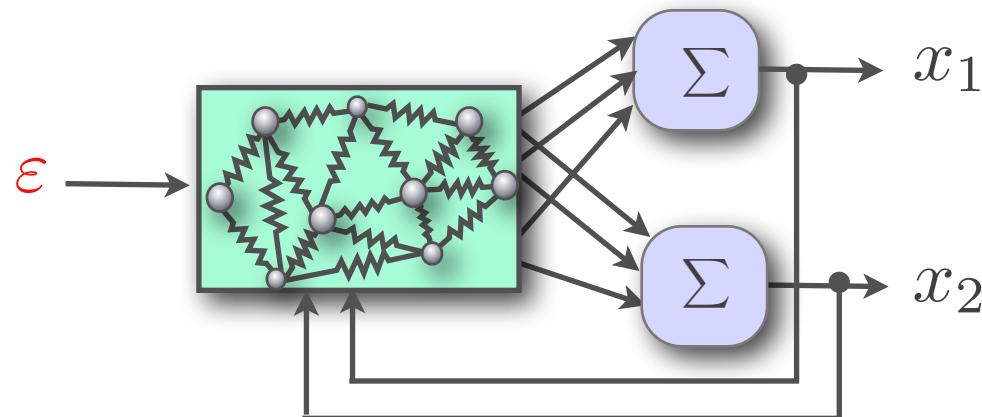
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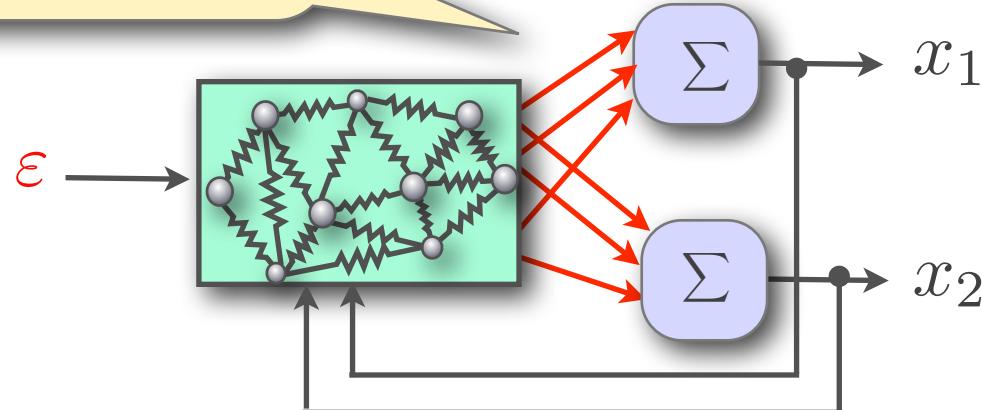
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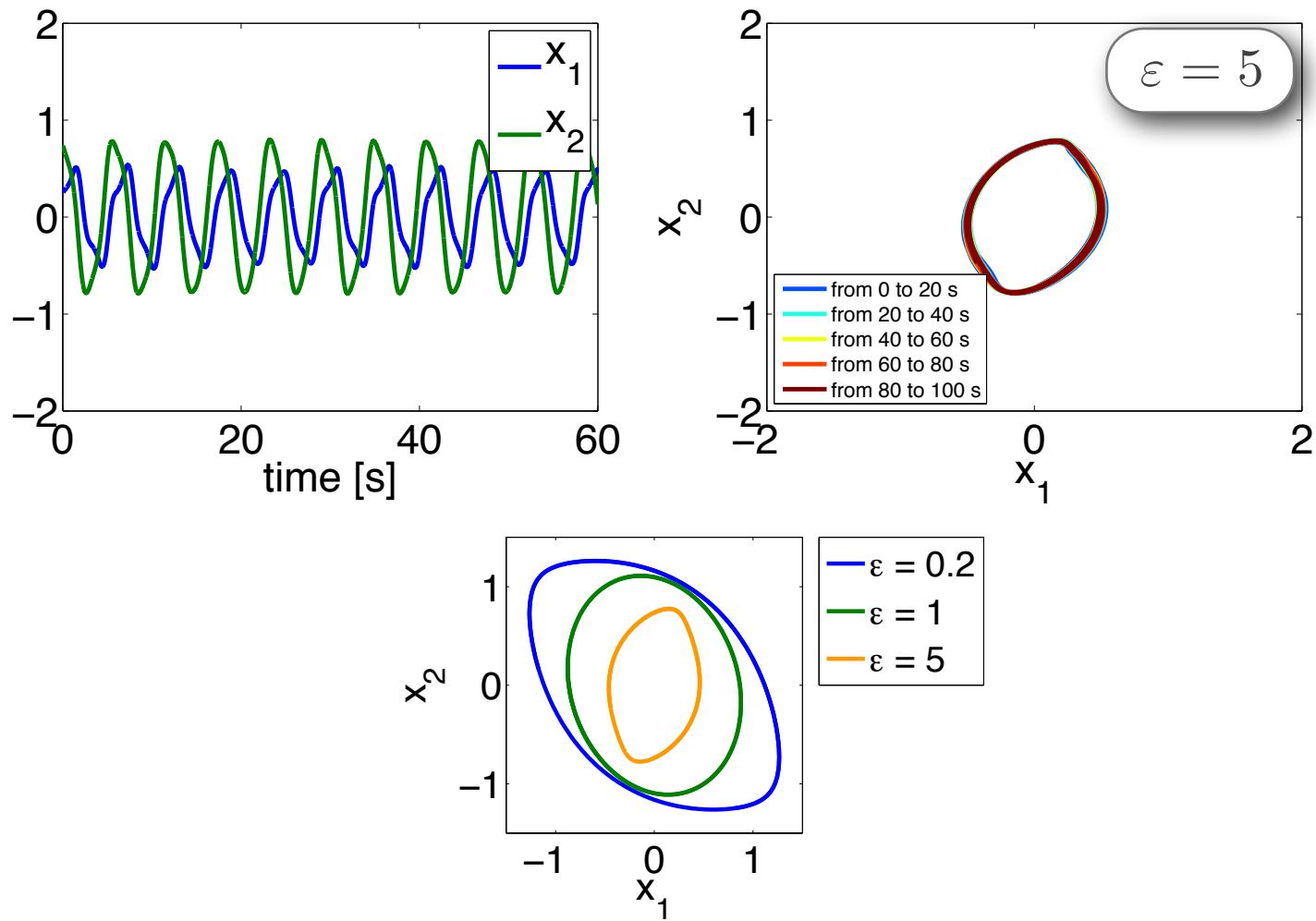
$$x'_2 = x_2 - x_2(x_1^2 + x_2^2)$$

one set of
weights for
all three ε



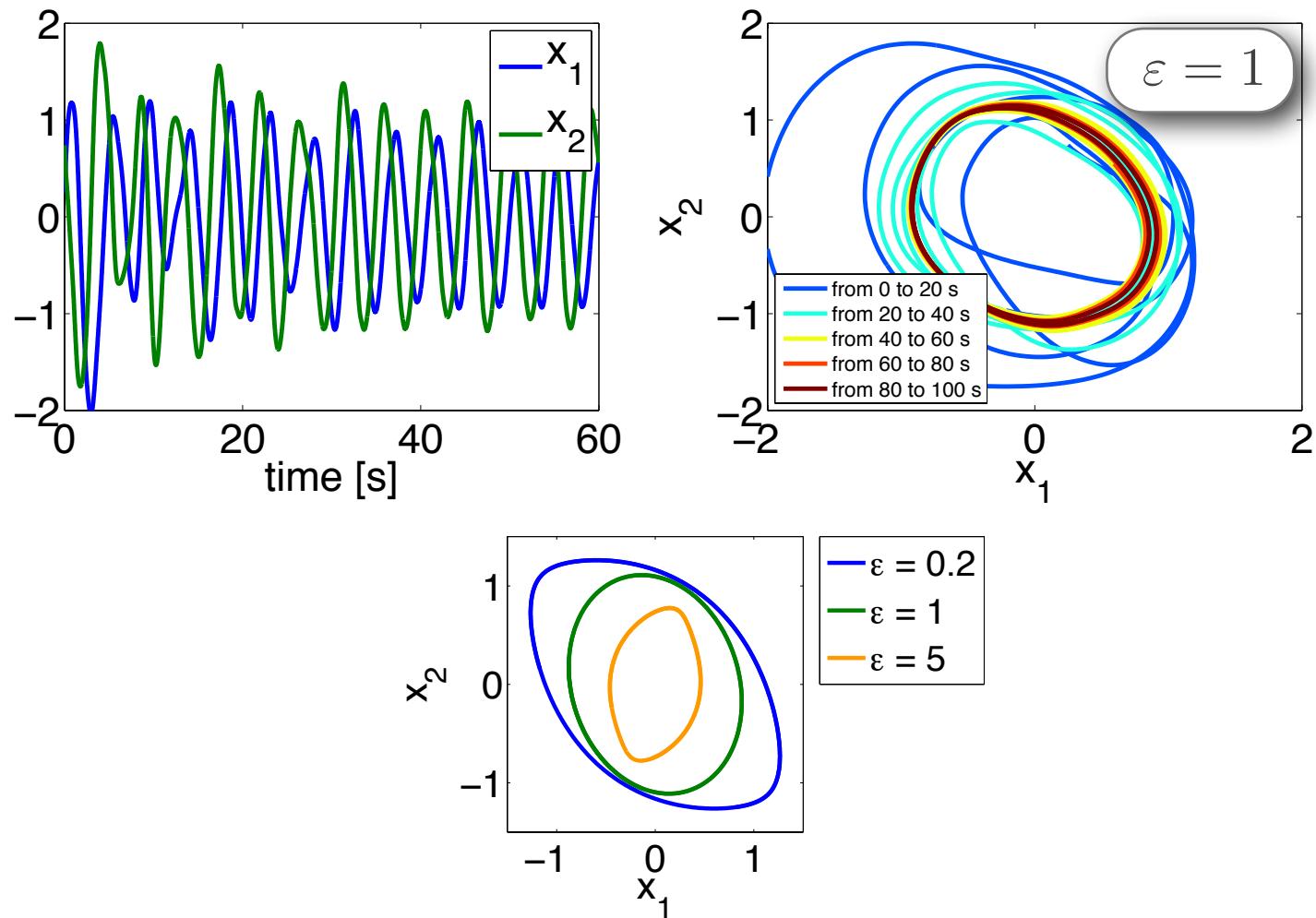
RESULTS

Input Dependent Limit Cycle



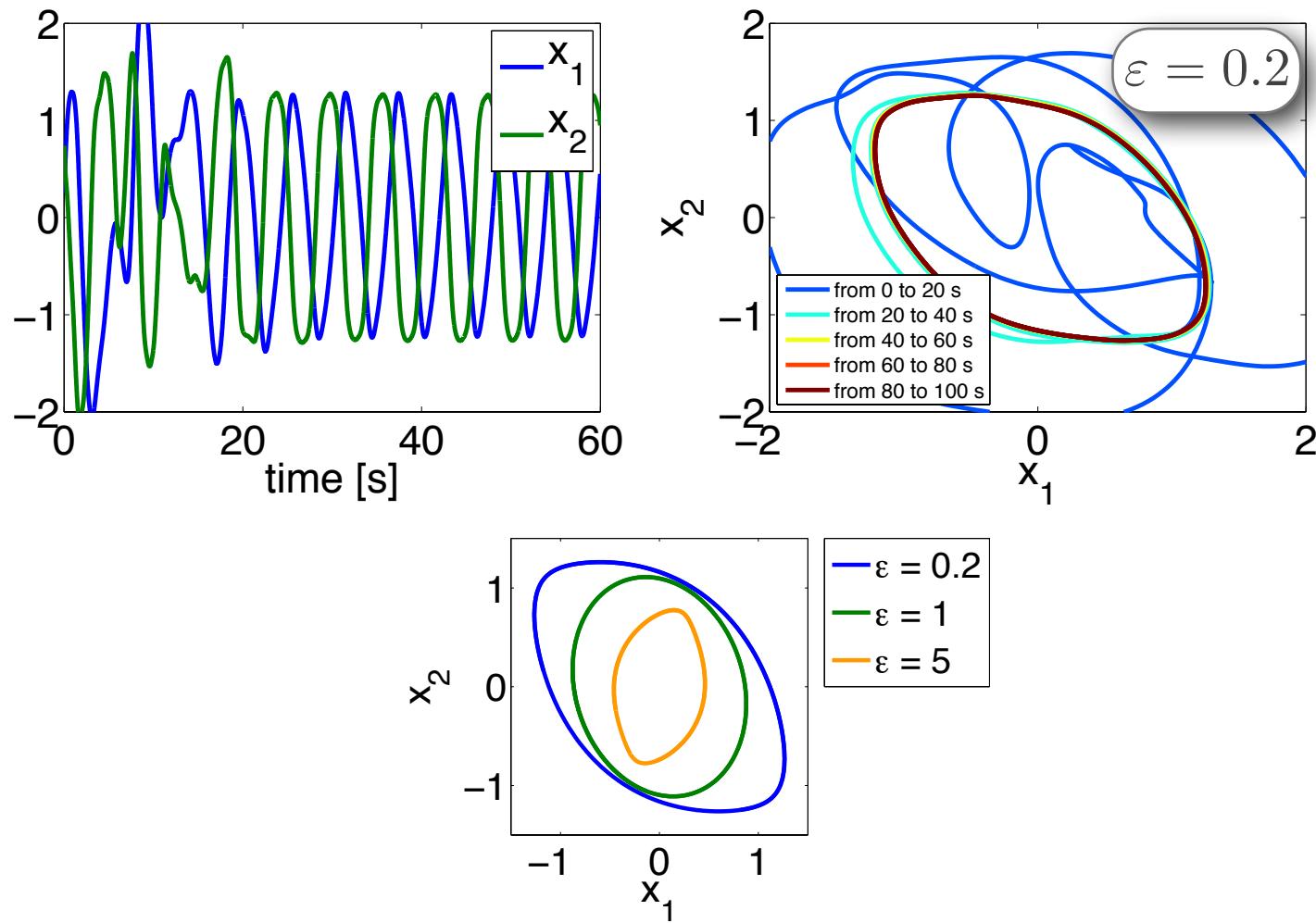
RESULTS

Input Dependent Limit Cycle

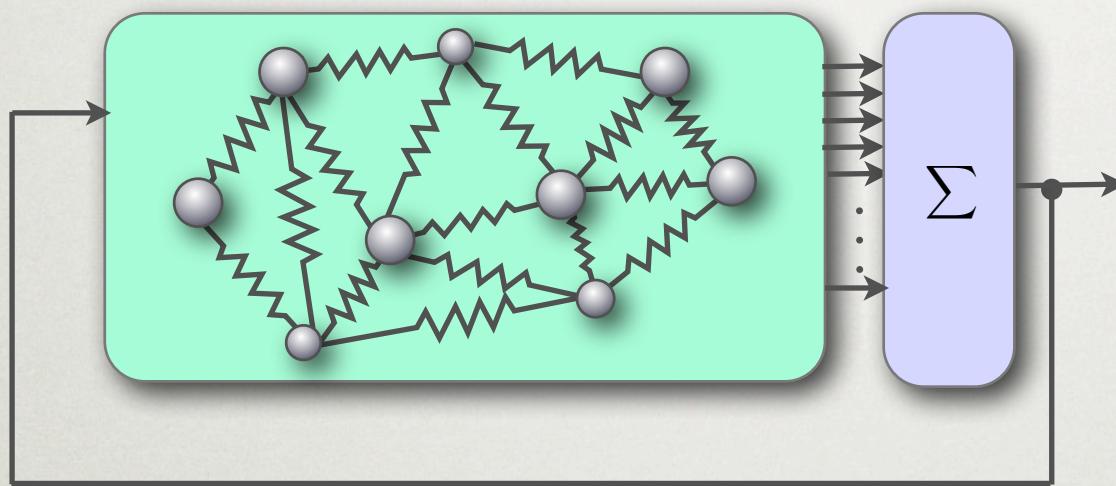


RESULTS

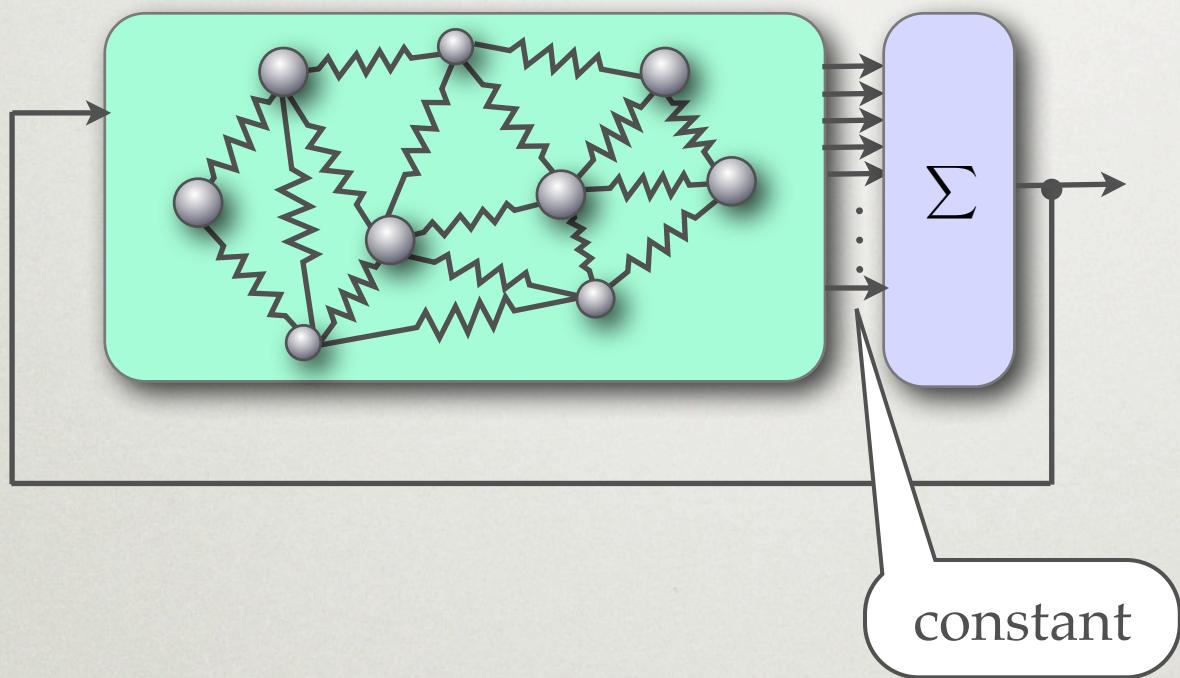
Input Dependent Limit Cycle



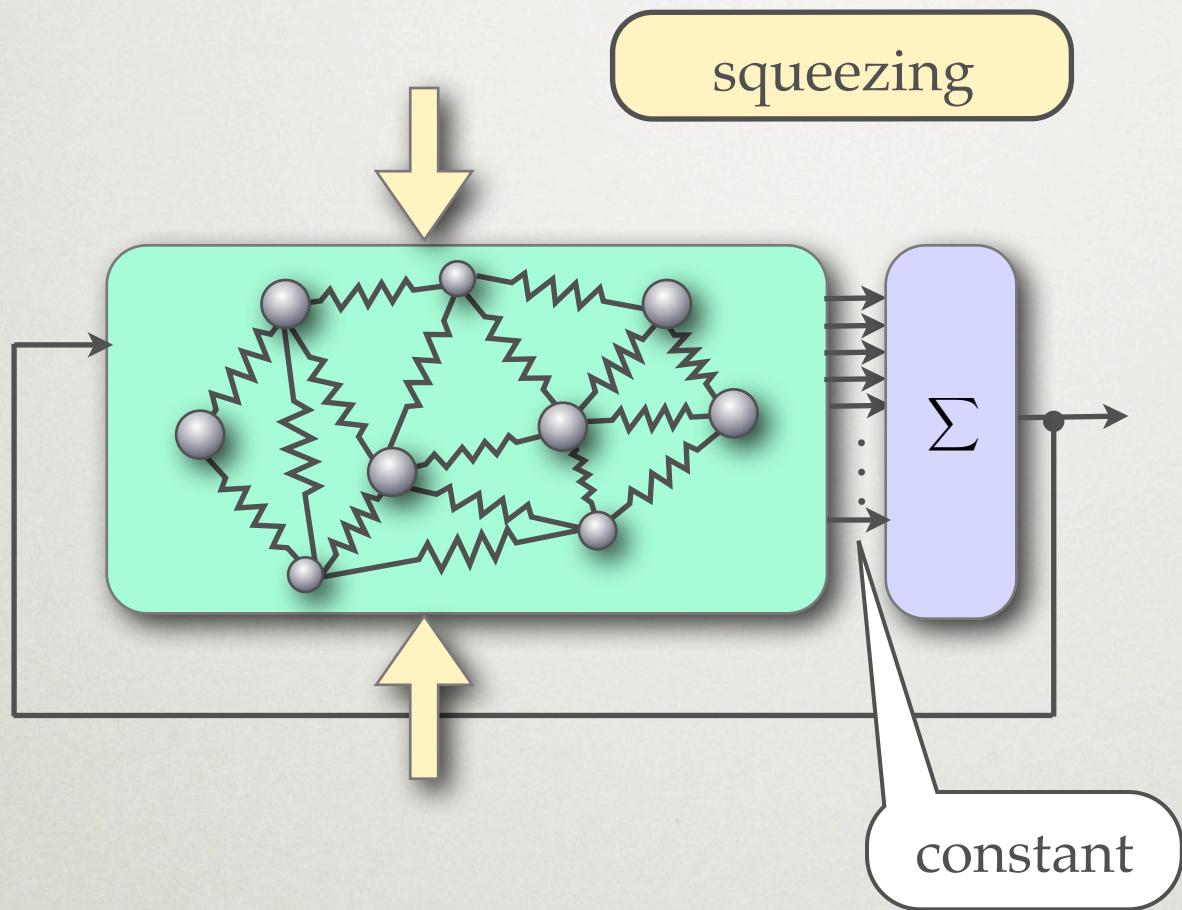
DISCUSSION



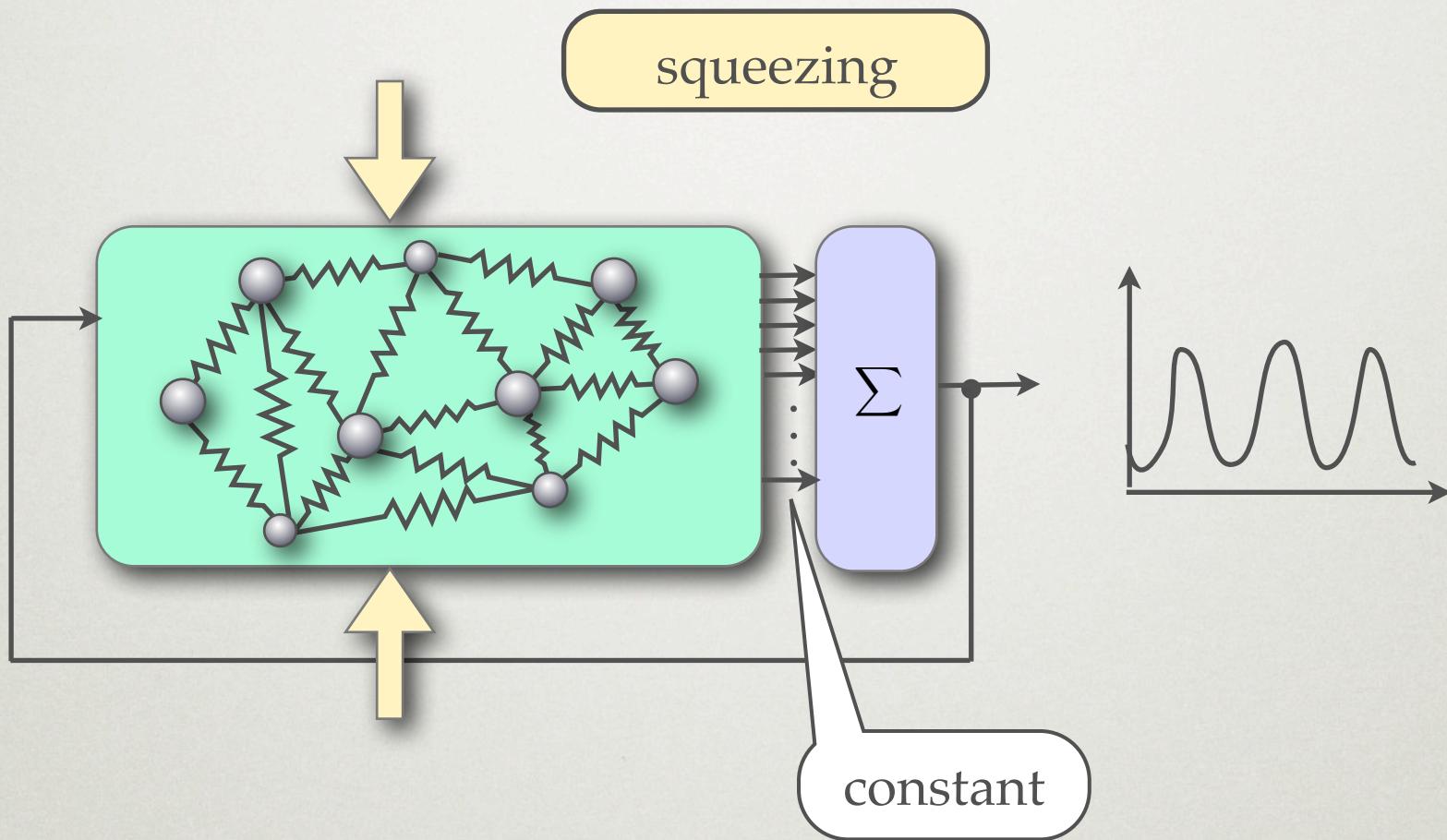
DISCUSSION



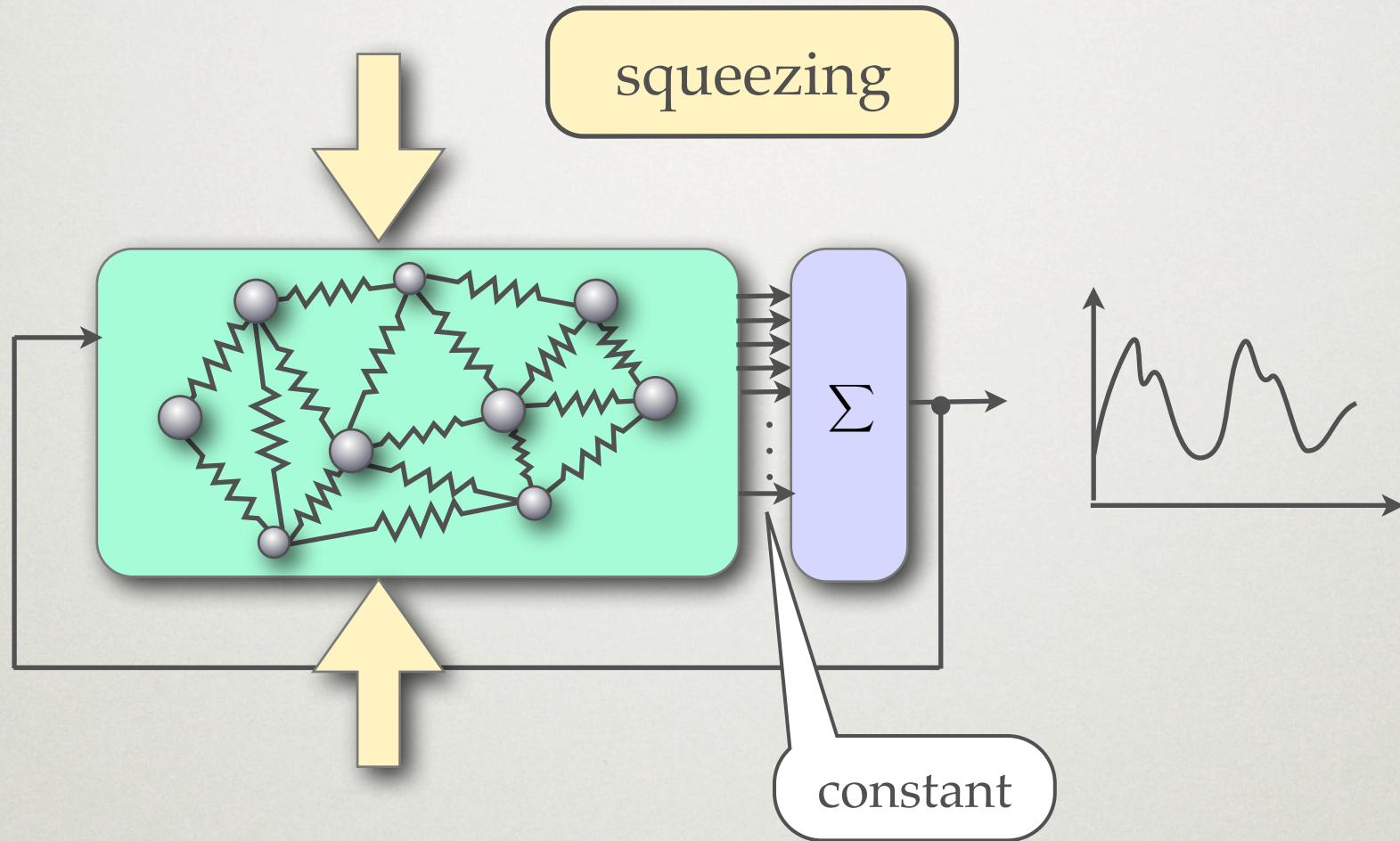
DISCUSSION



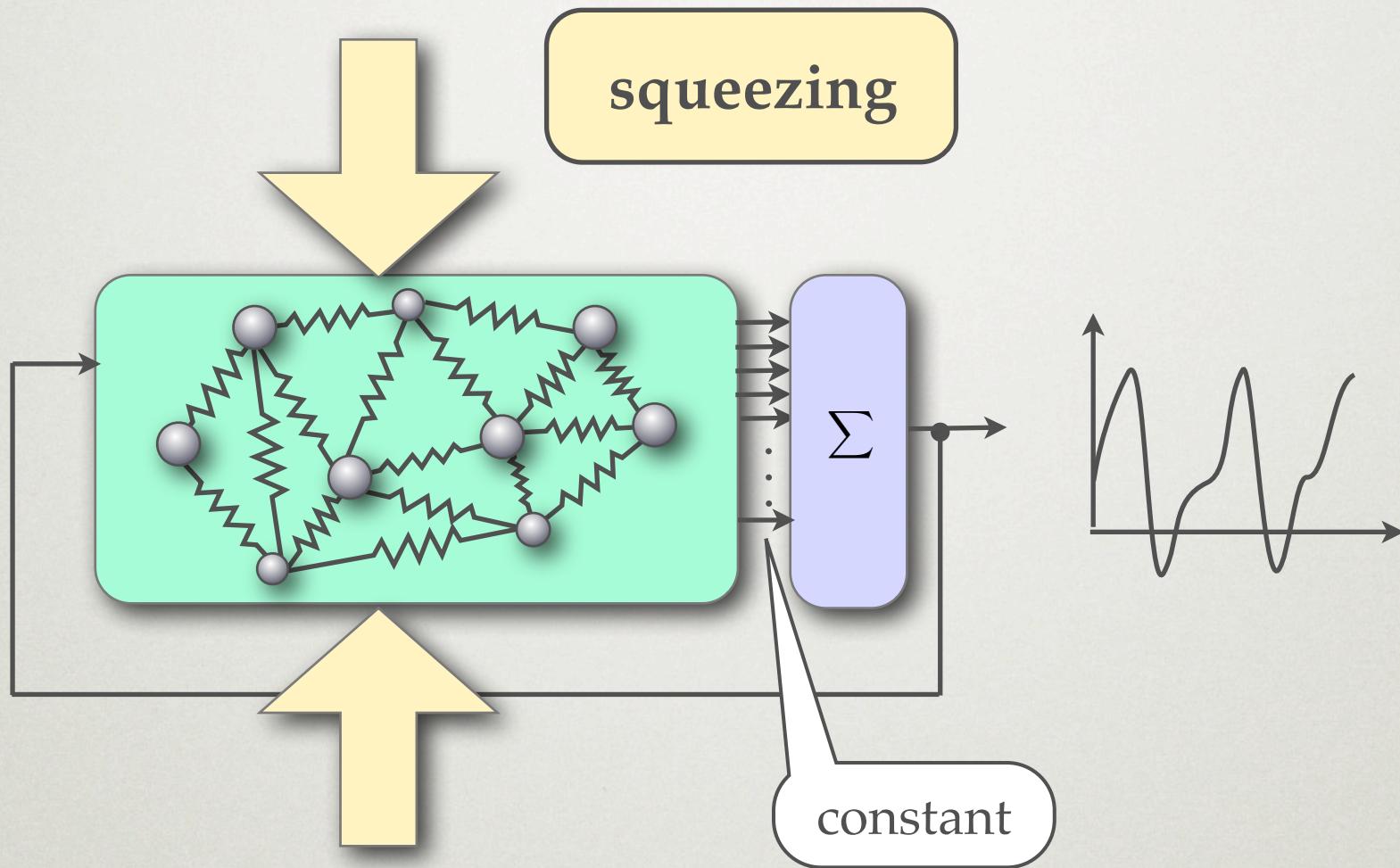
DISCUSSION



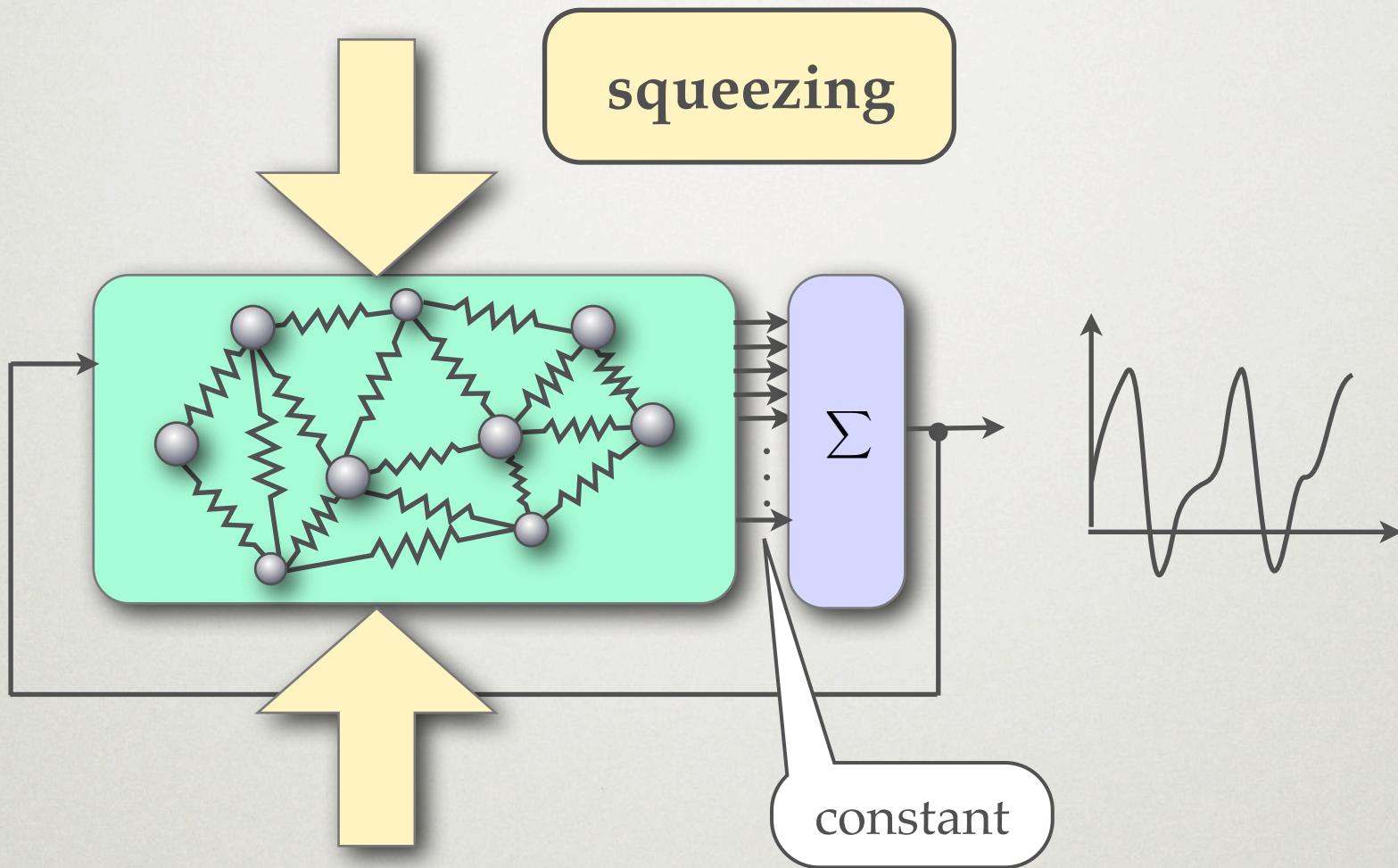
DISCUSSION



DISCUSSION

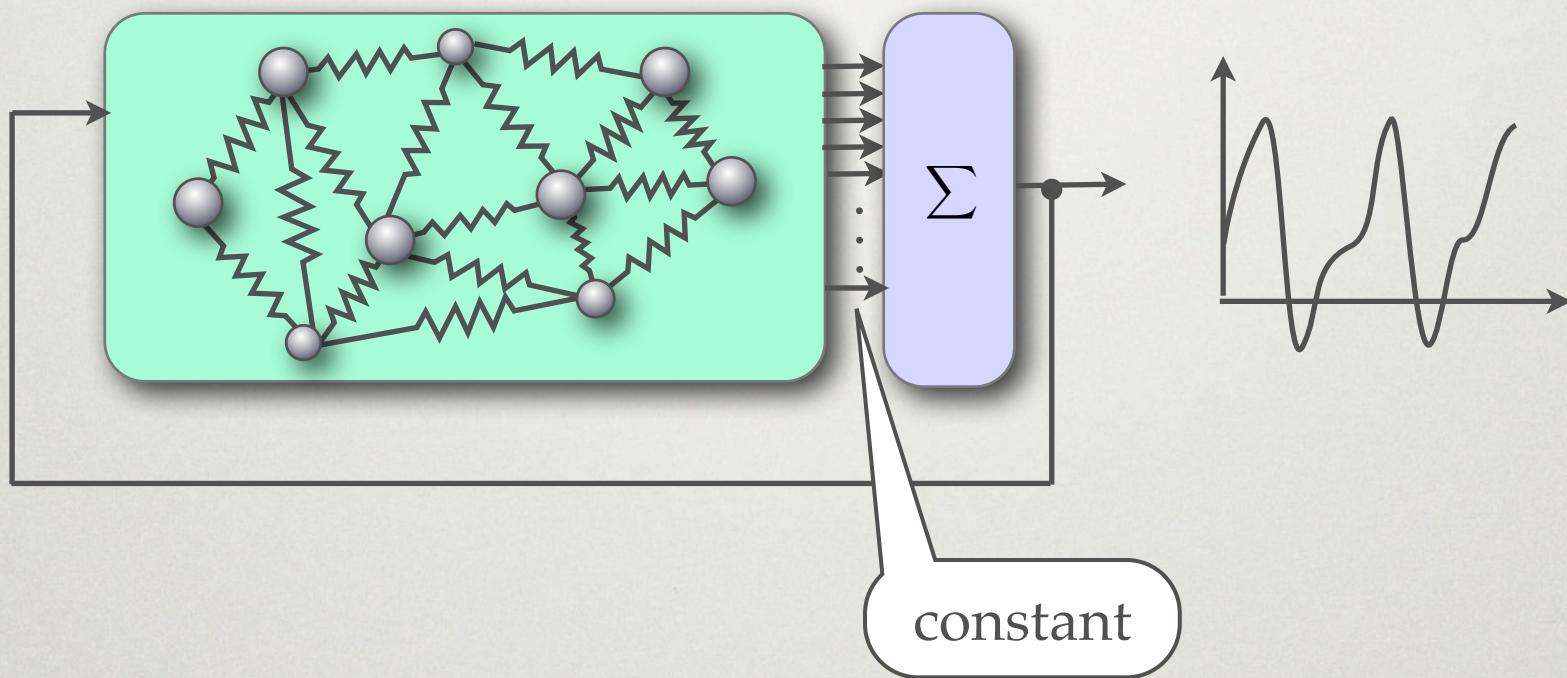


DISCUSSION



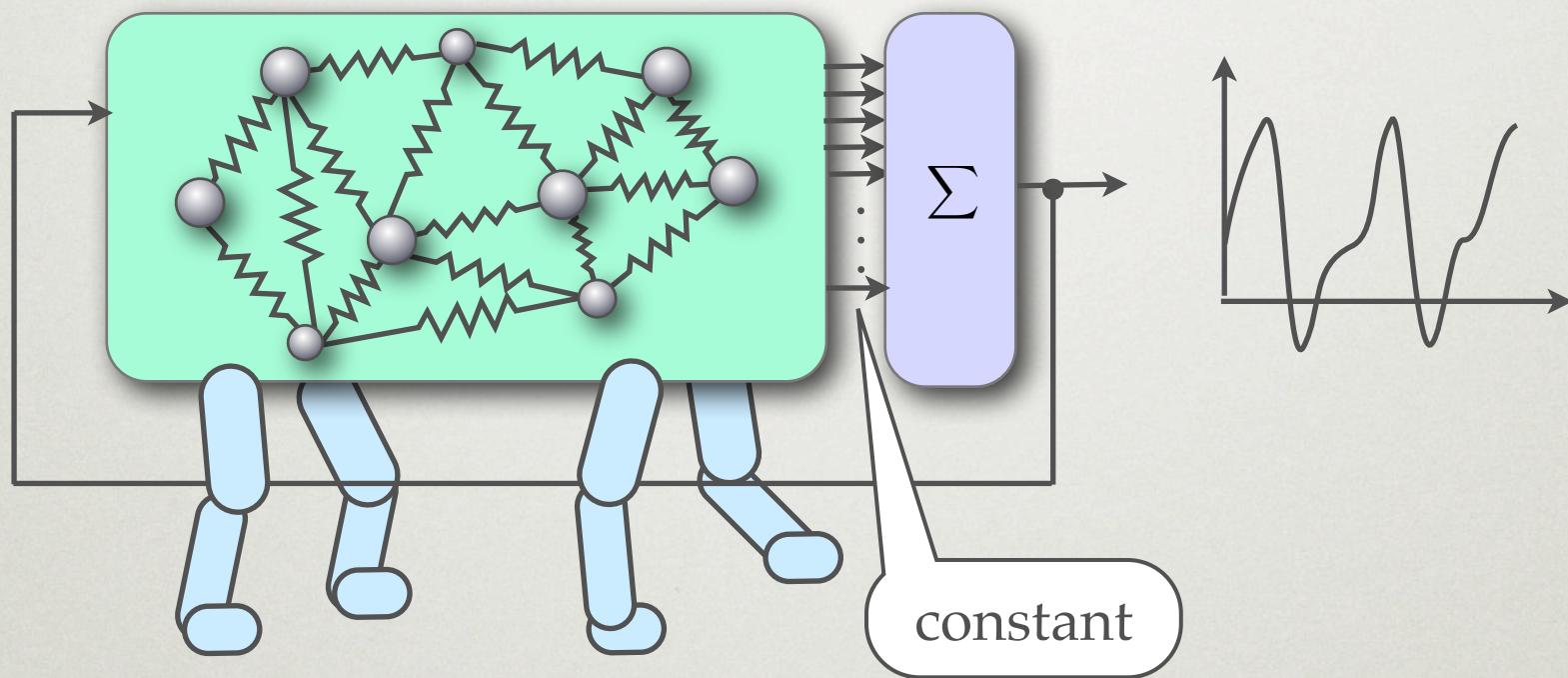
System is able to sense through its morphology!

DISCUSSION



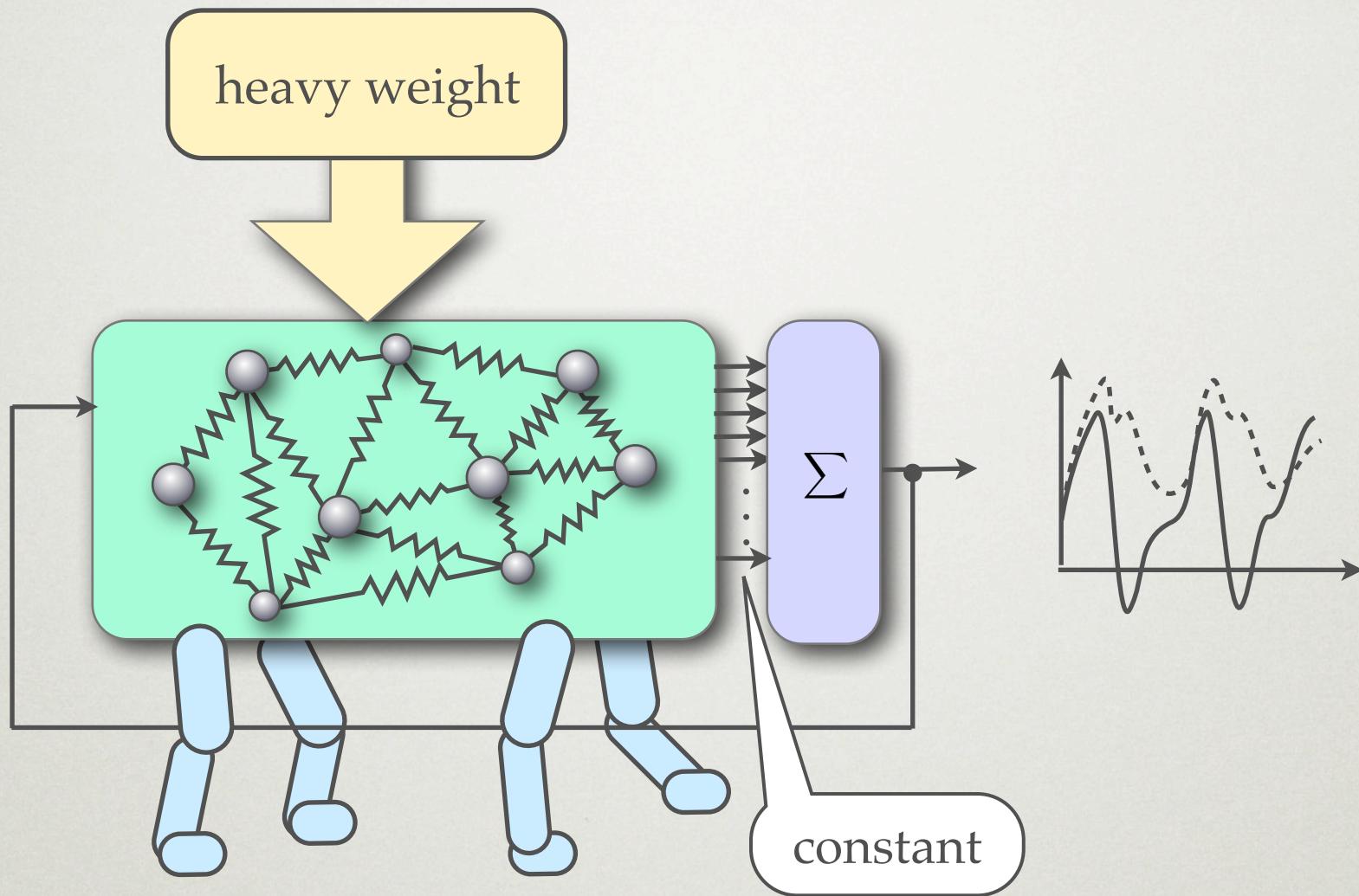
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DISCUSSION



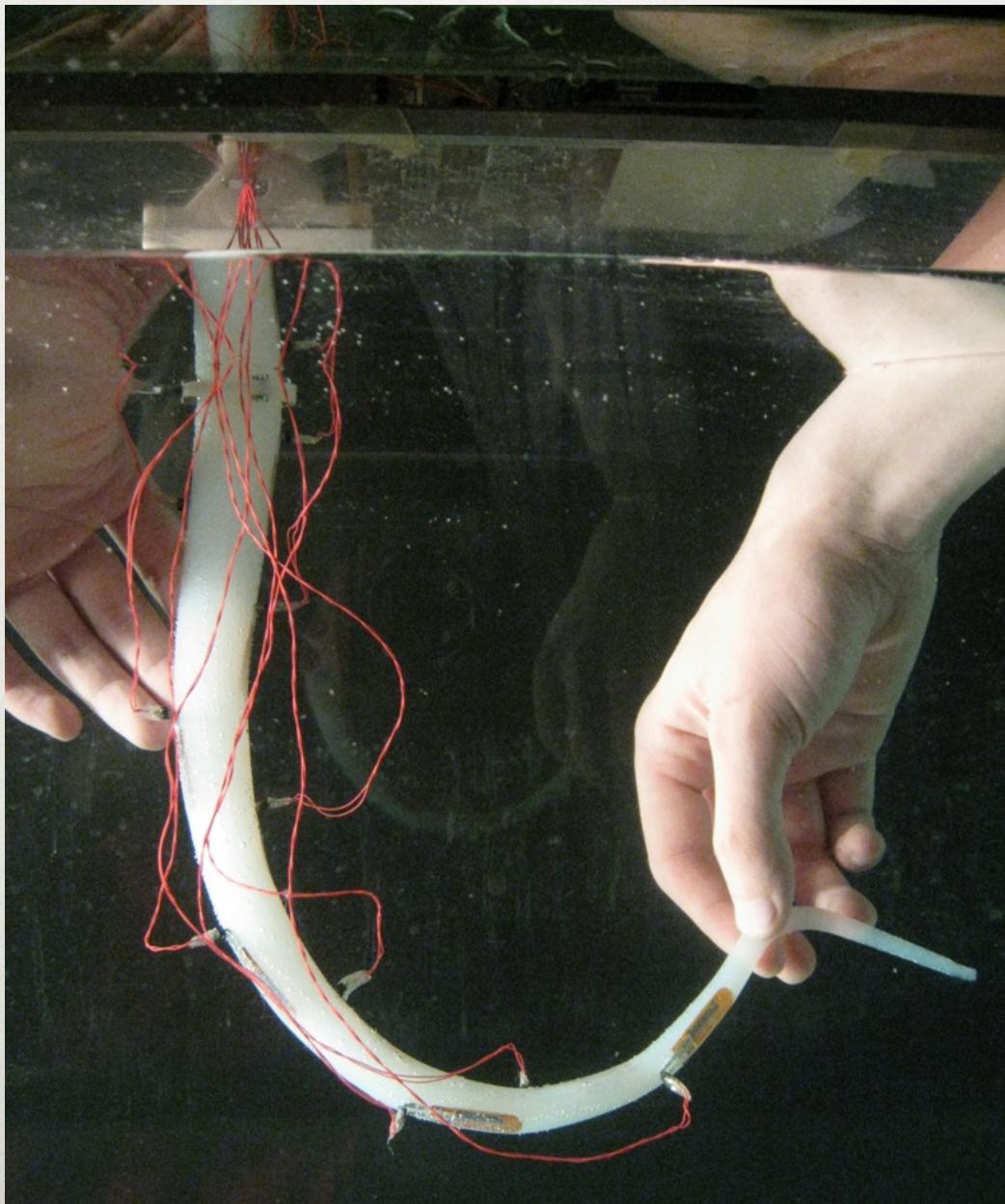
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DISCUSSION

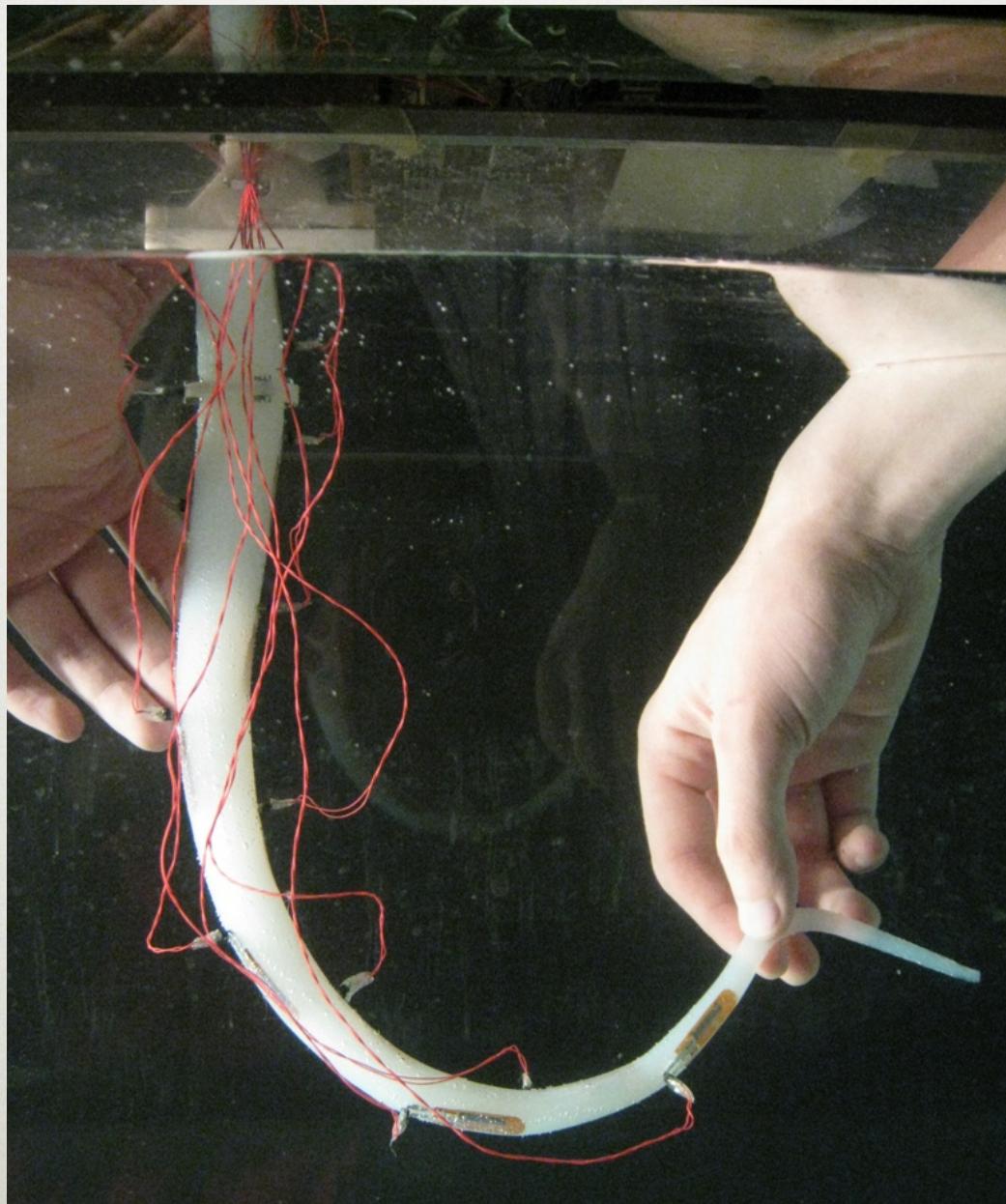


System is able to sense through its morphology!

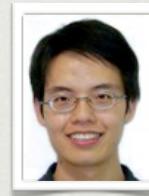
APPLICATION IN SOFT ROBOTICS



APPLICATION IN SOFT ROBOTICS



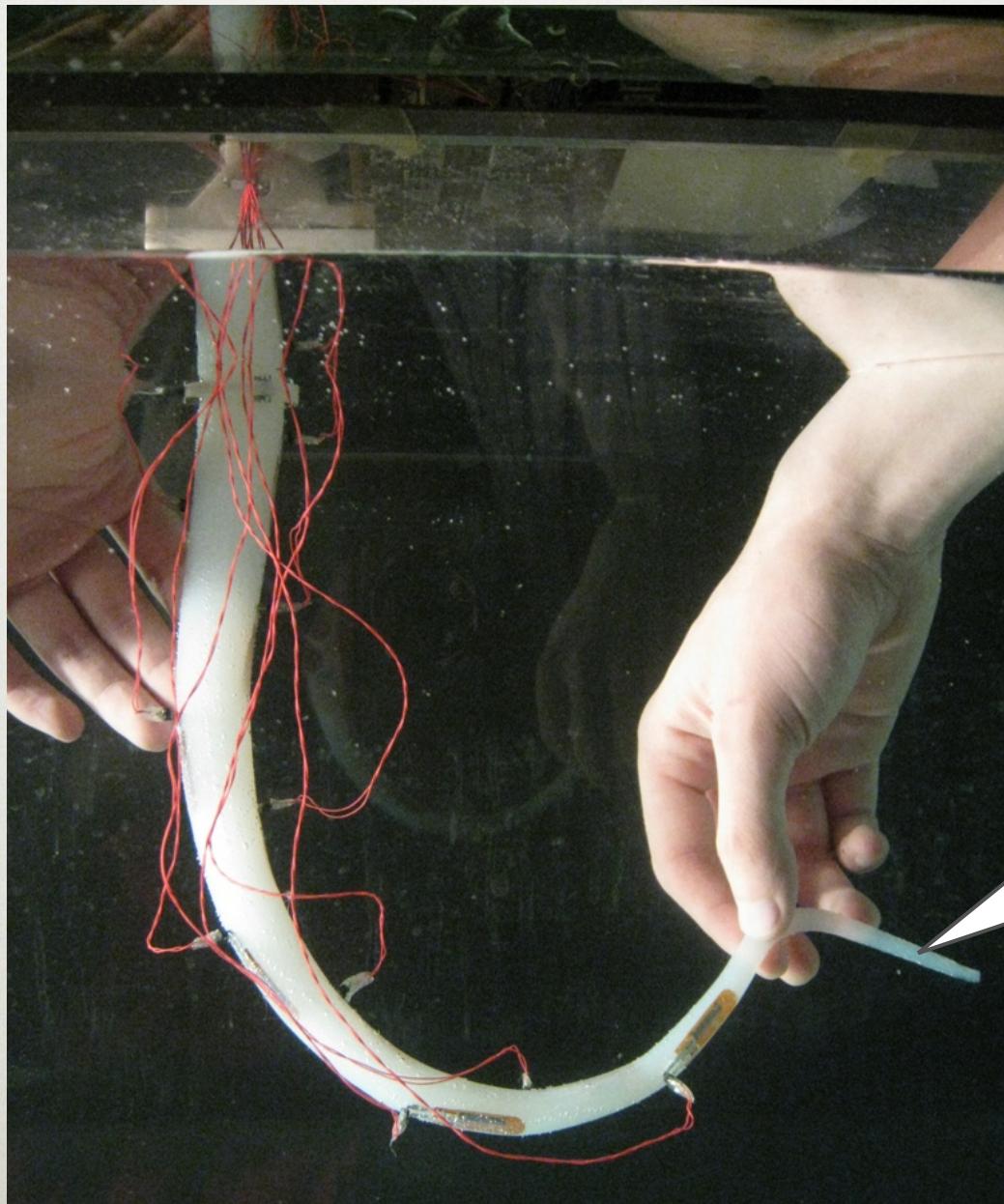
Kohei
Nakajima



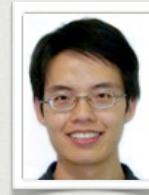
Tao Li



APPLICATION IN SOFT ROBOTICS



Kohei
Nakajima

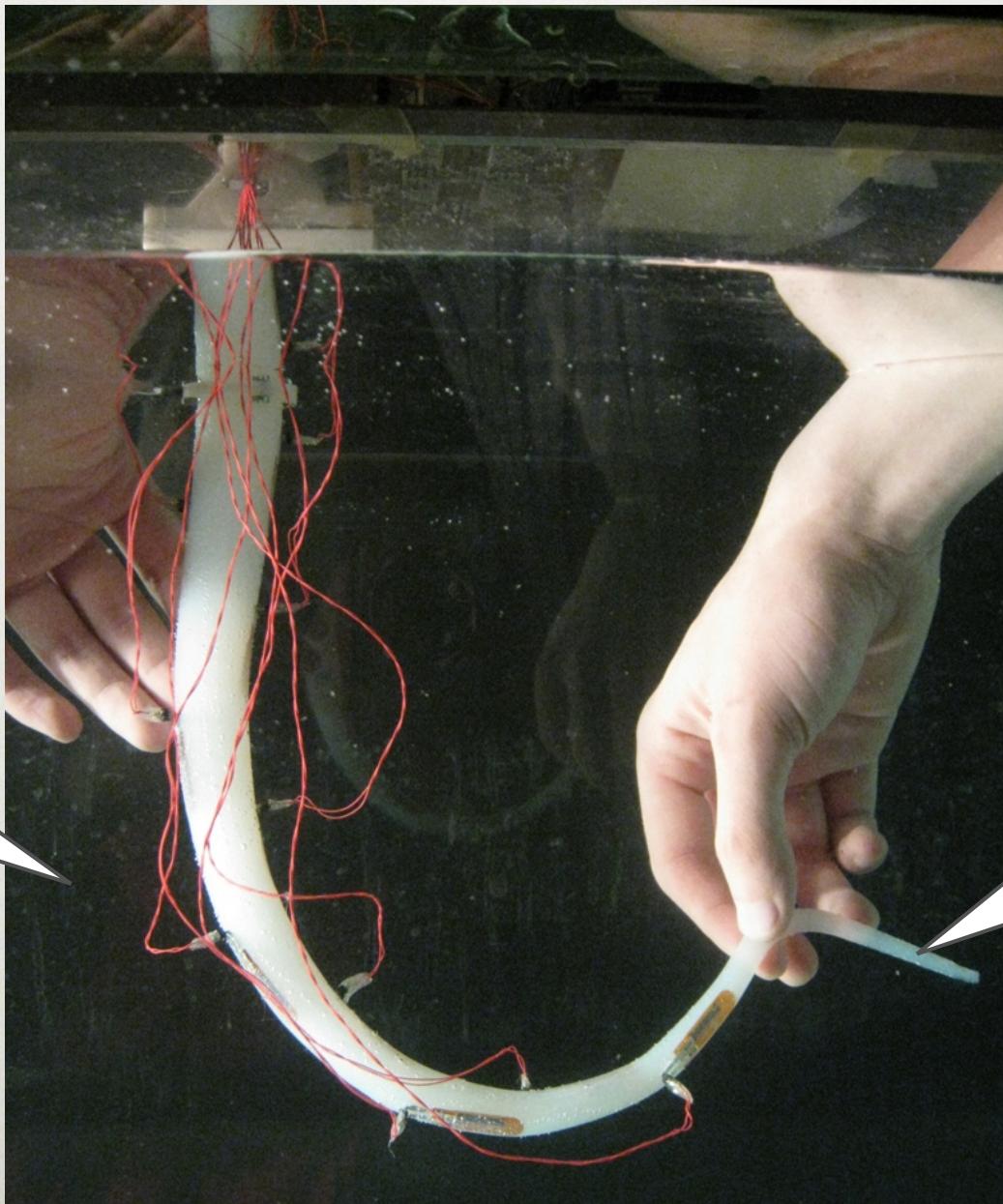


Tao Li

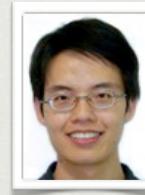
soft (passive)
silicone structure



APPLICATION IN SOFT ROBOTICS



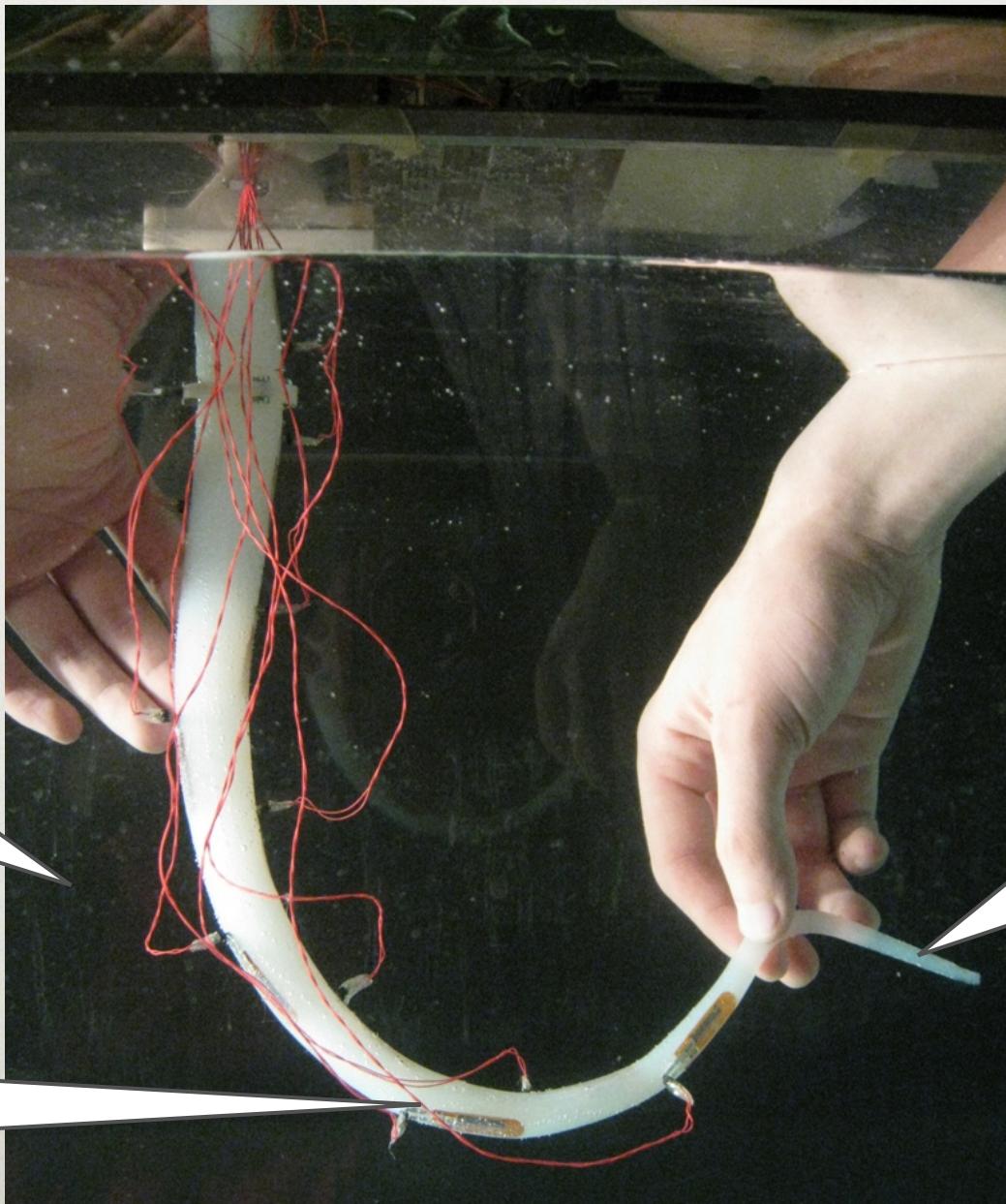
Kohei
Nakajima



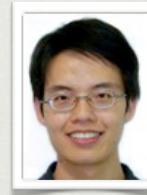
Tao Li



APPLICATION IN SOFT ROBOTICS



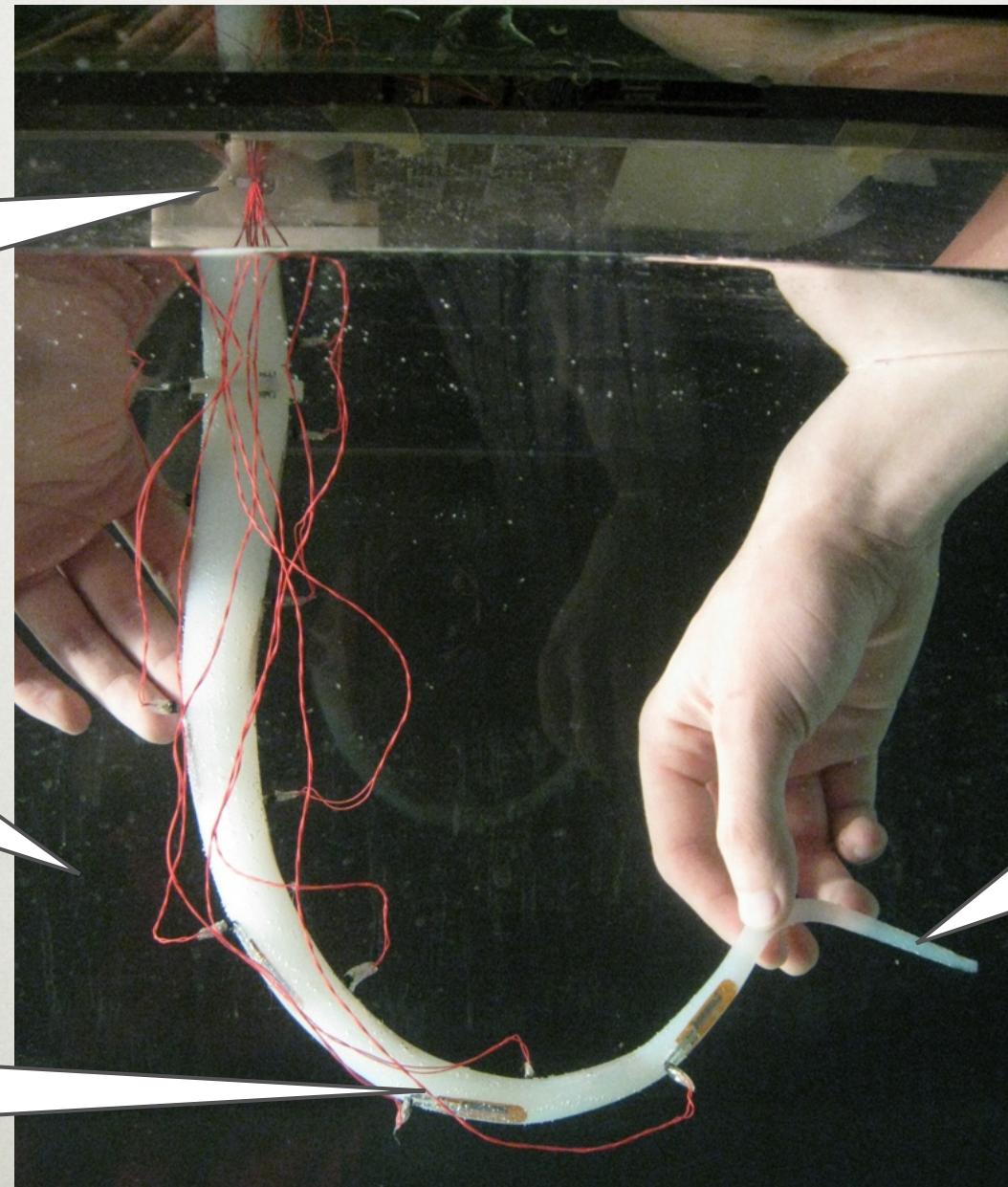
Kohei
Nakajima



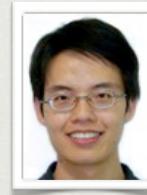
Tao Li



APPLICATION IN SOFT ROBOTICS



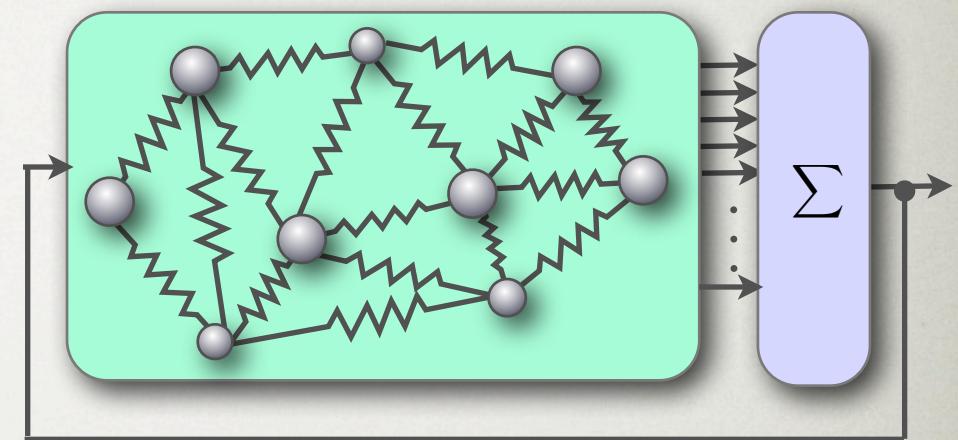
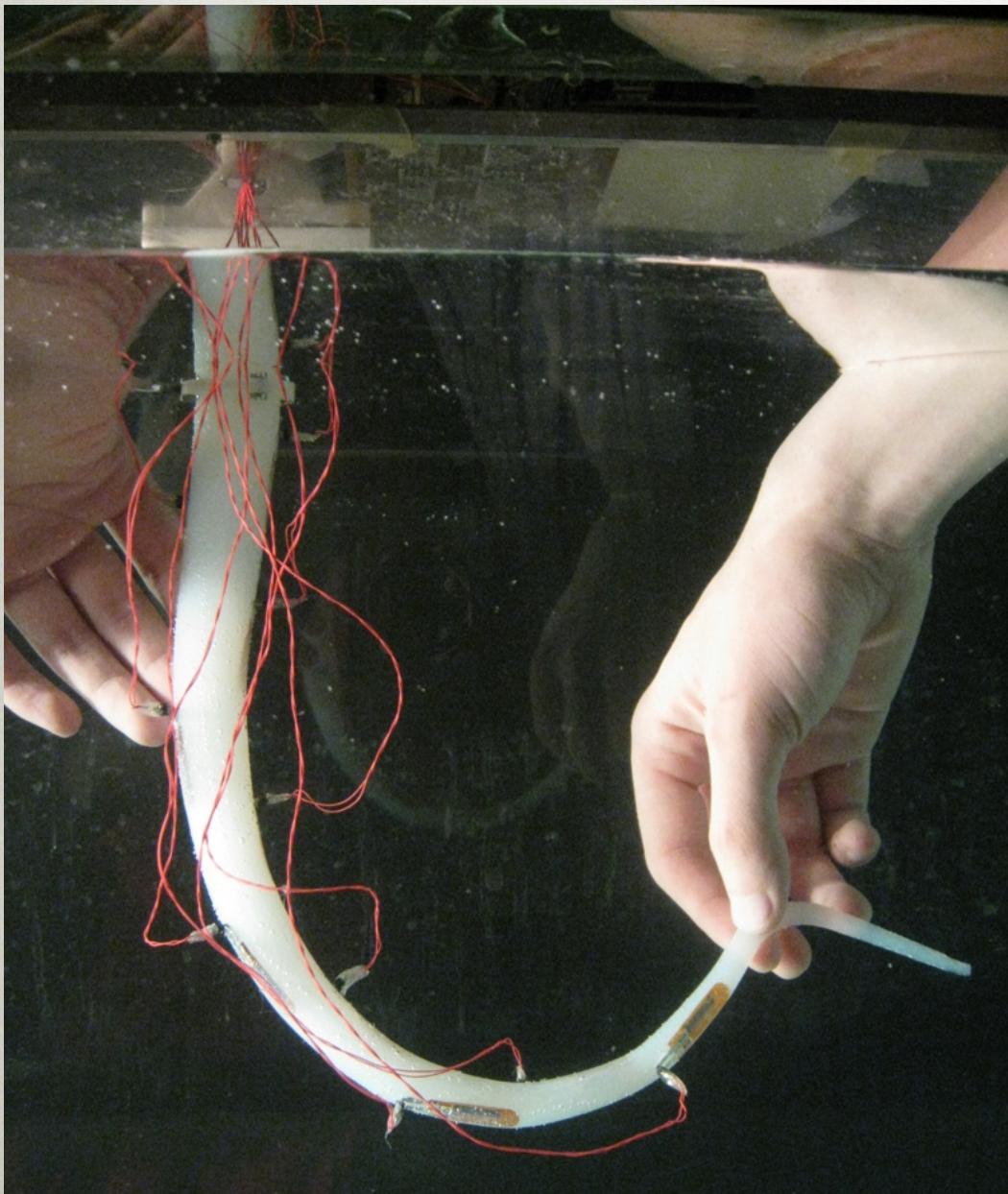
Kohei
Nakajima



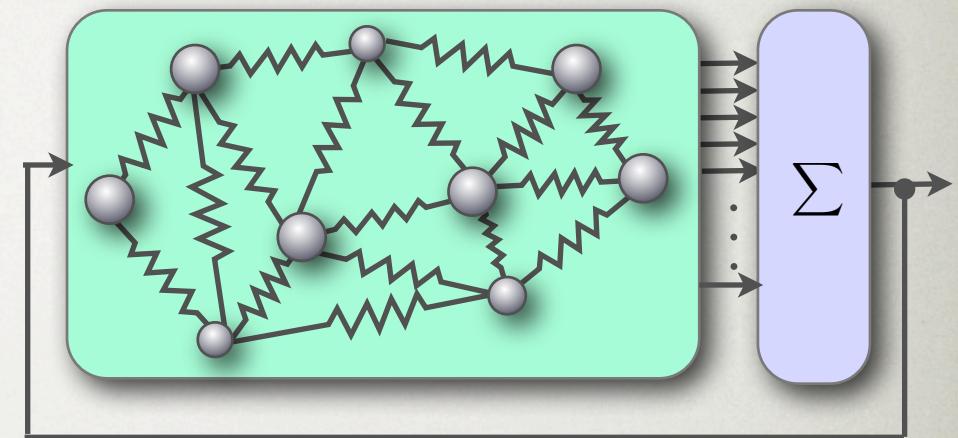
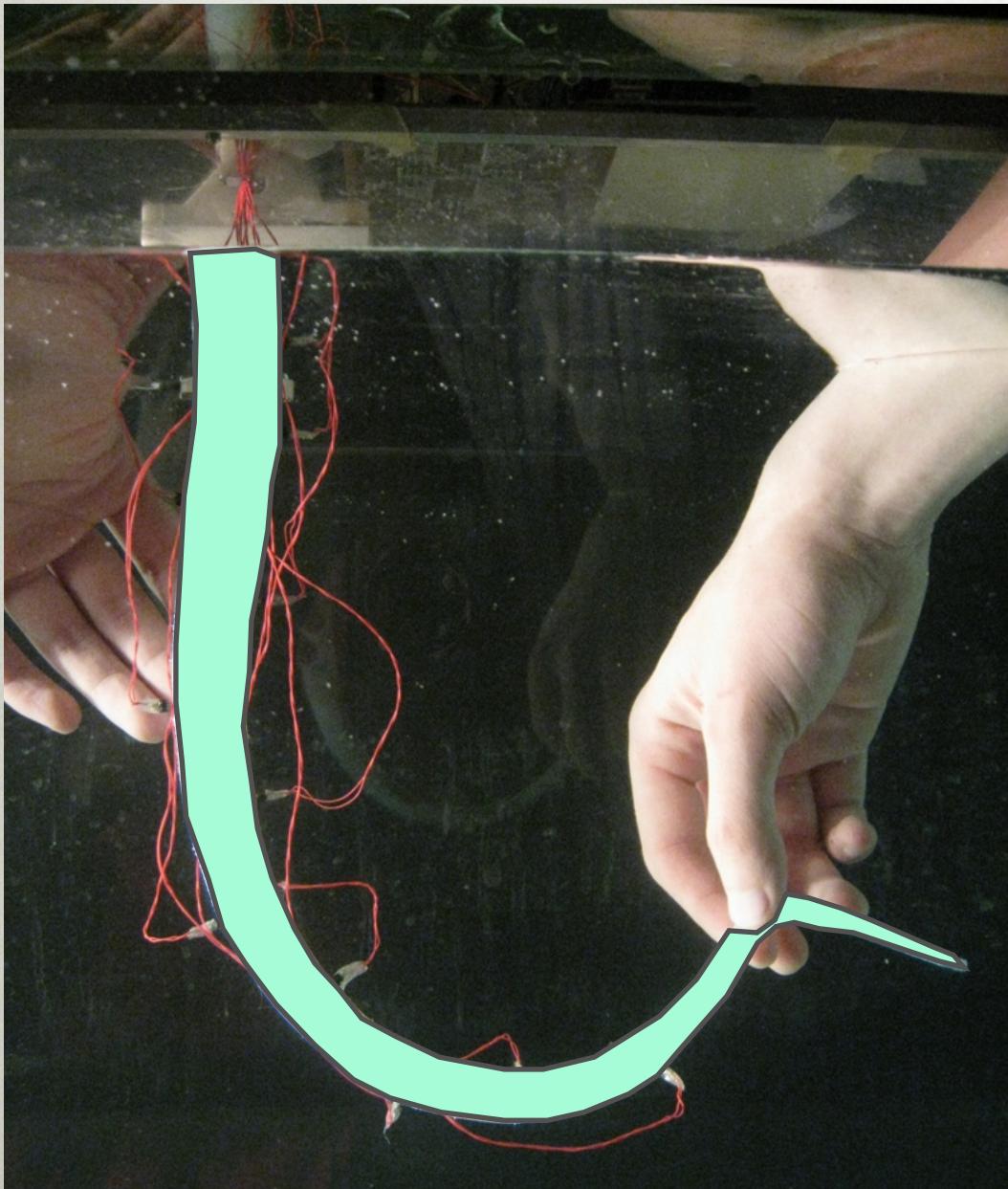
Tao Li



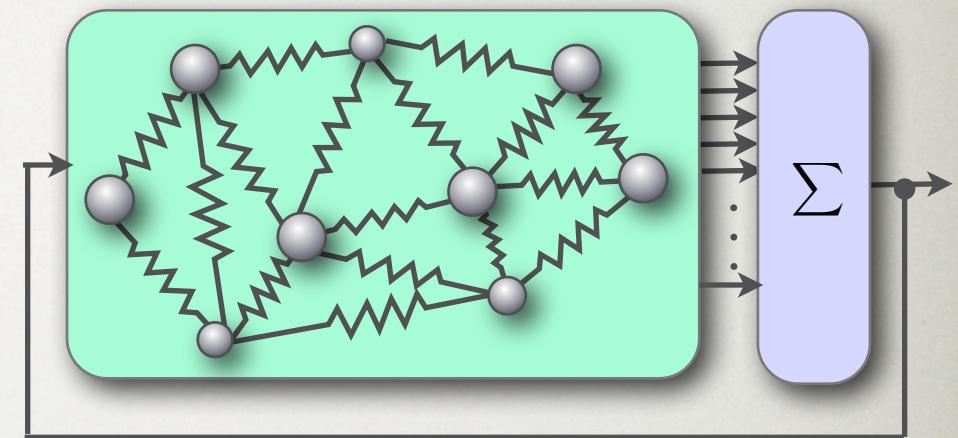
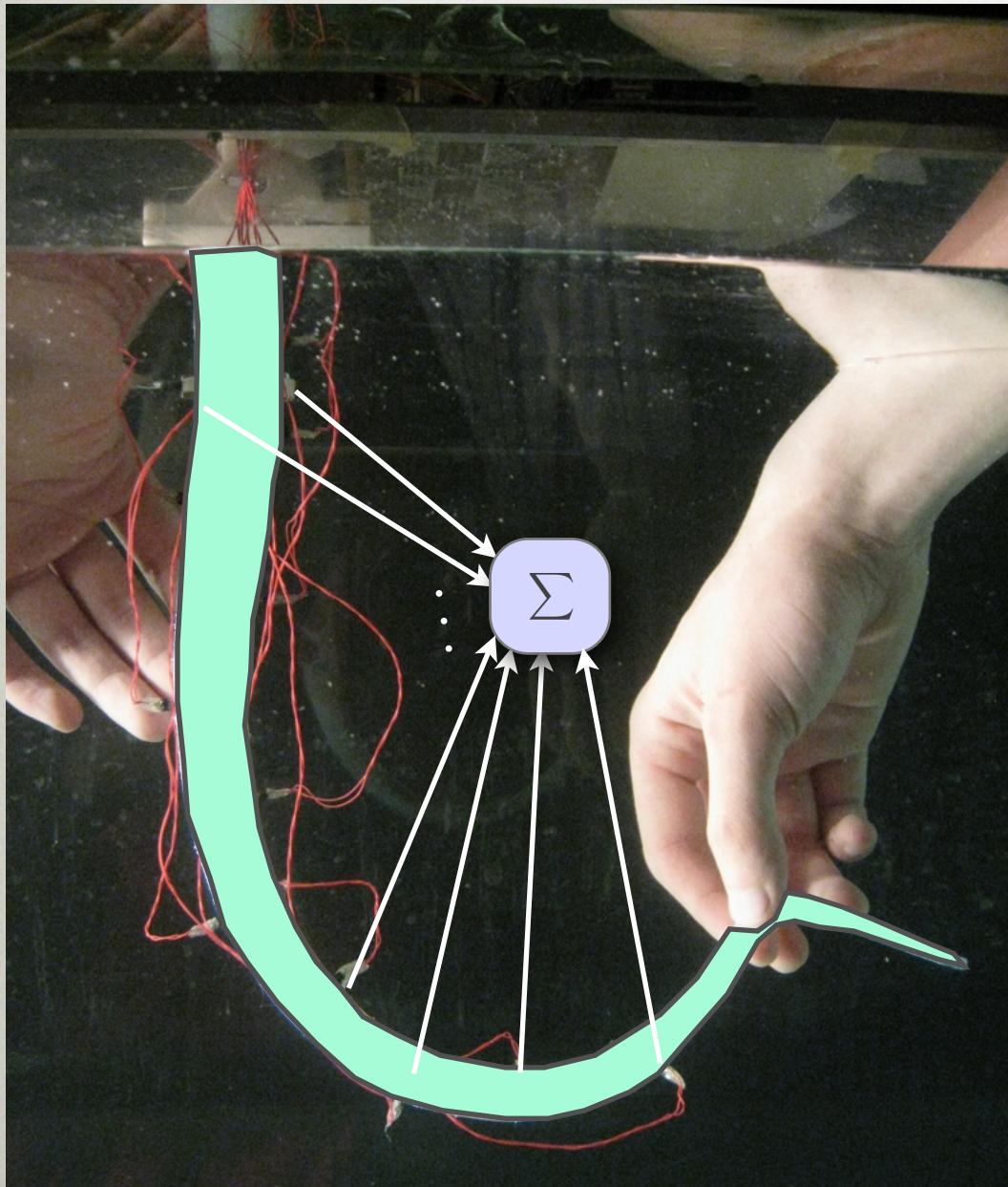
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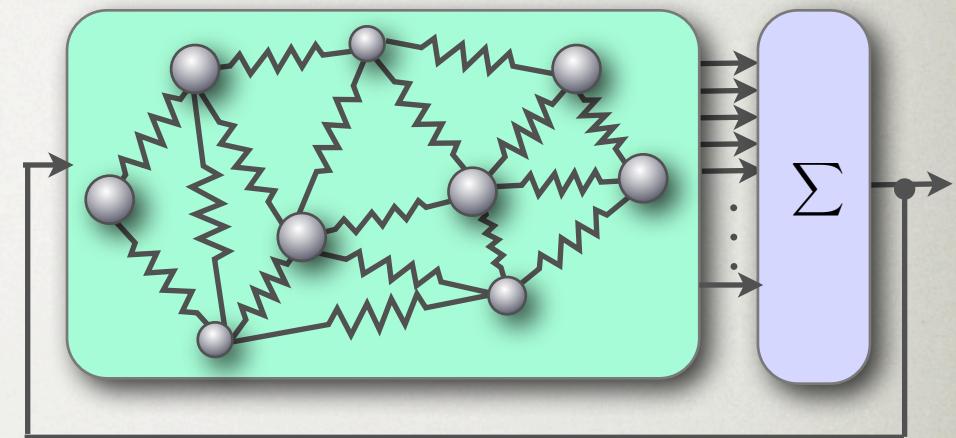
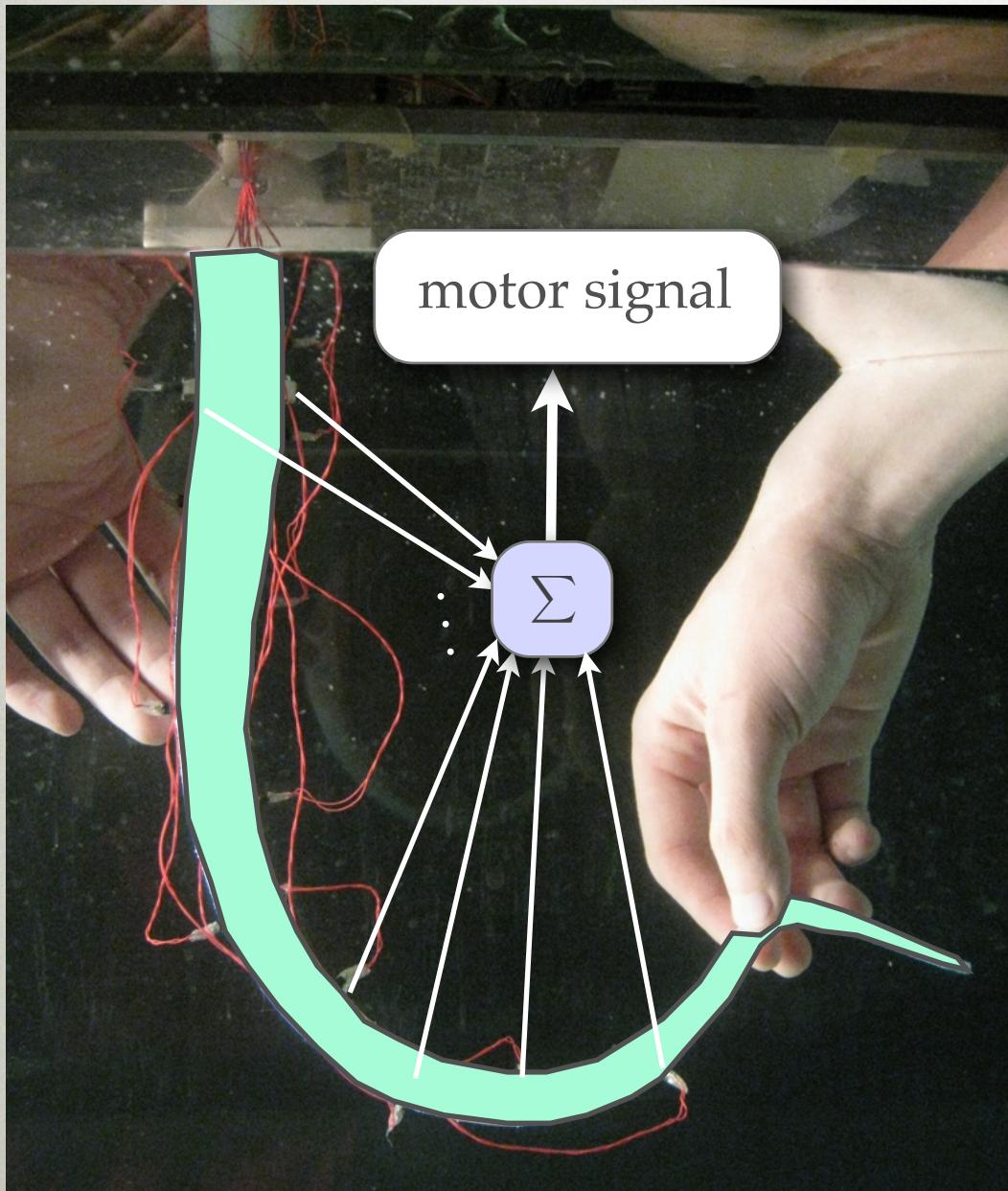
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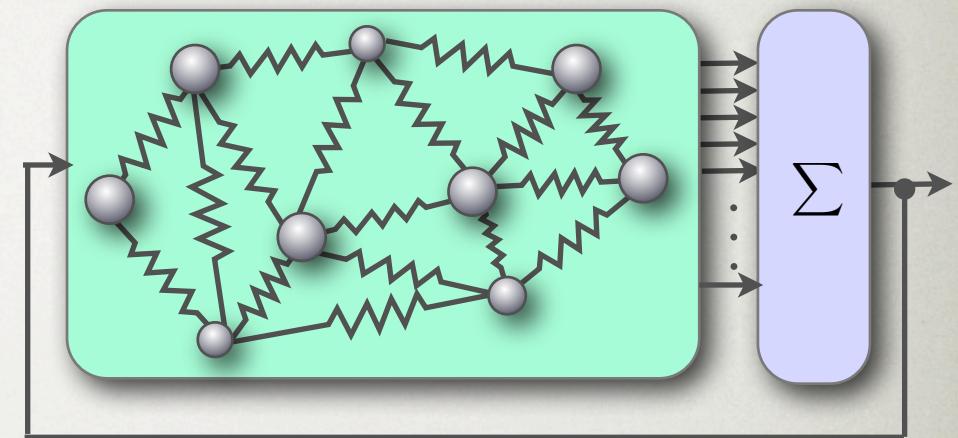
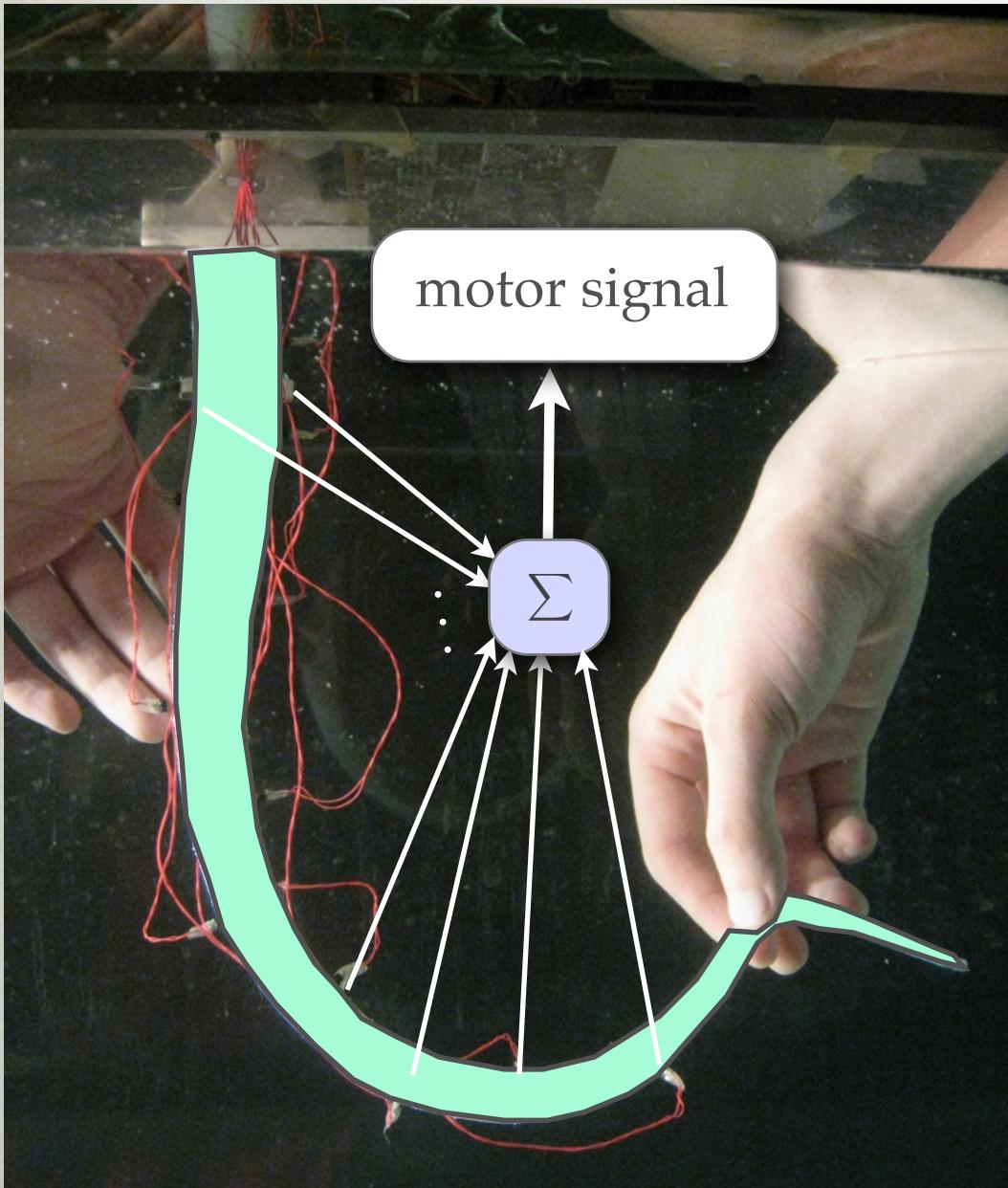
APPLICATION IN SOFT ROBOTICS



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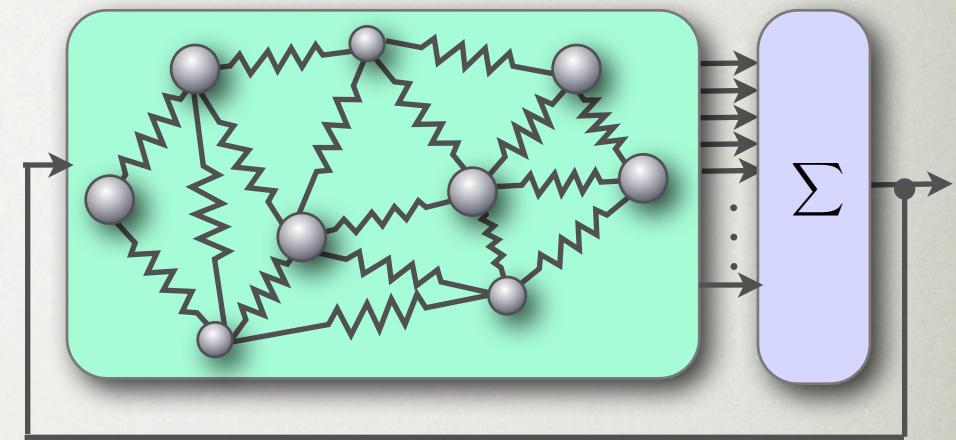
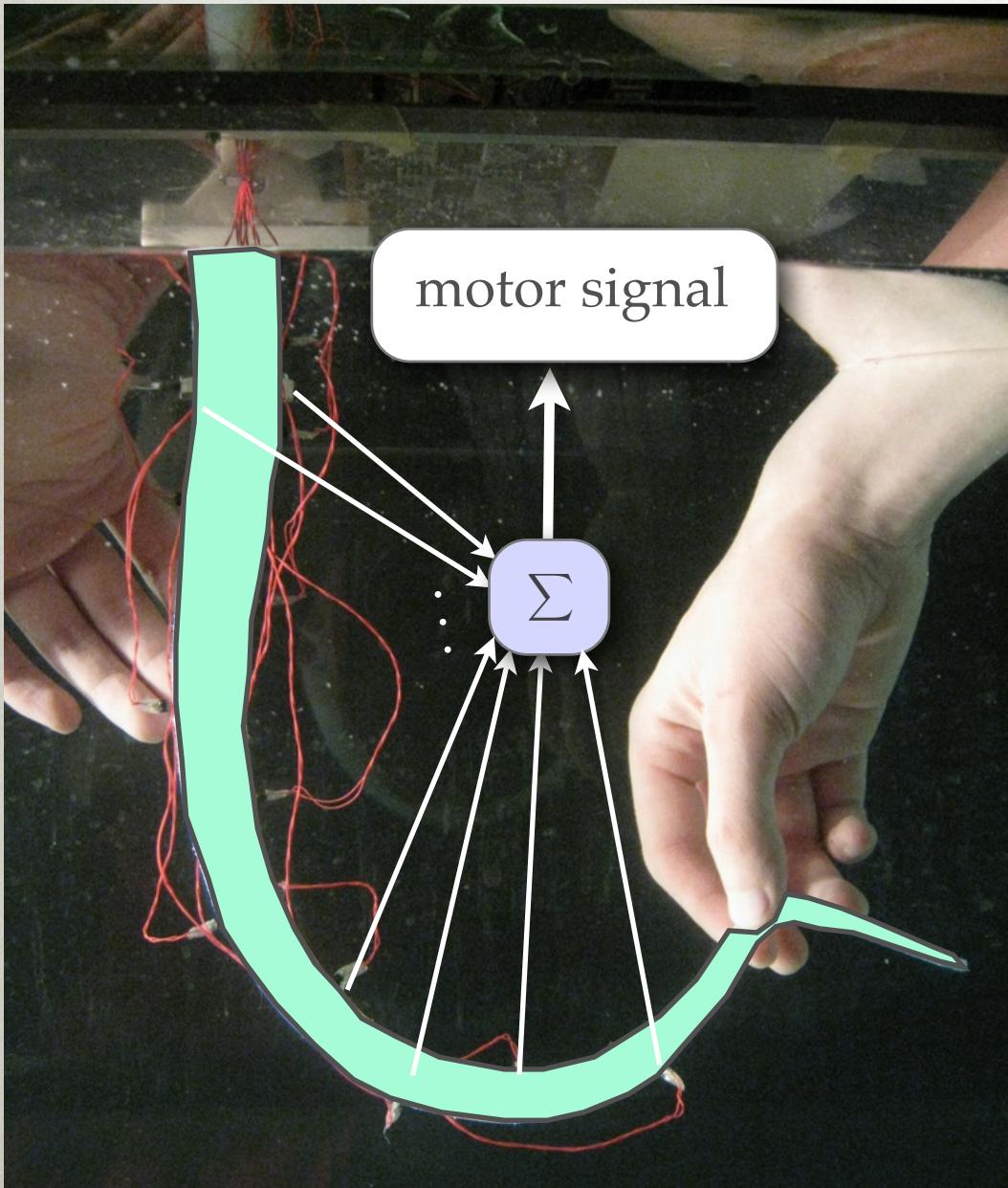


APPLICATION IN SOFT ROBOTICS



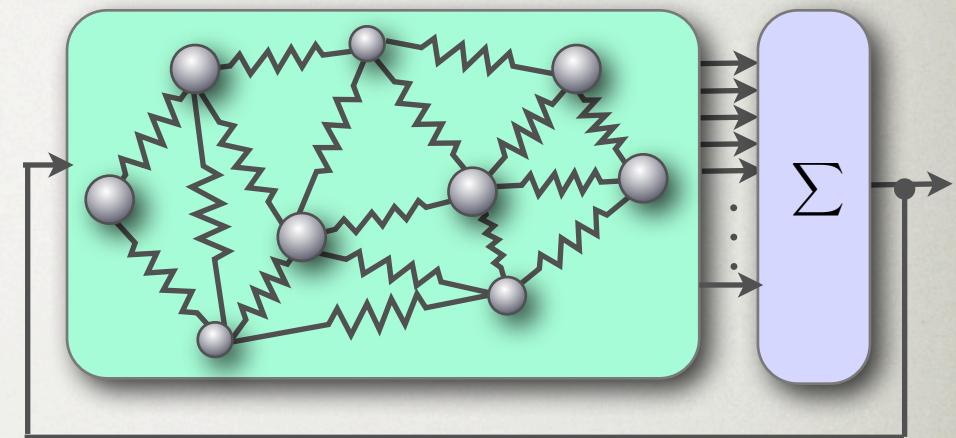
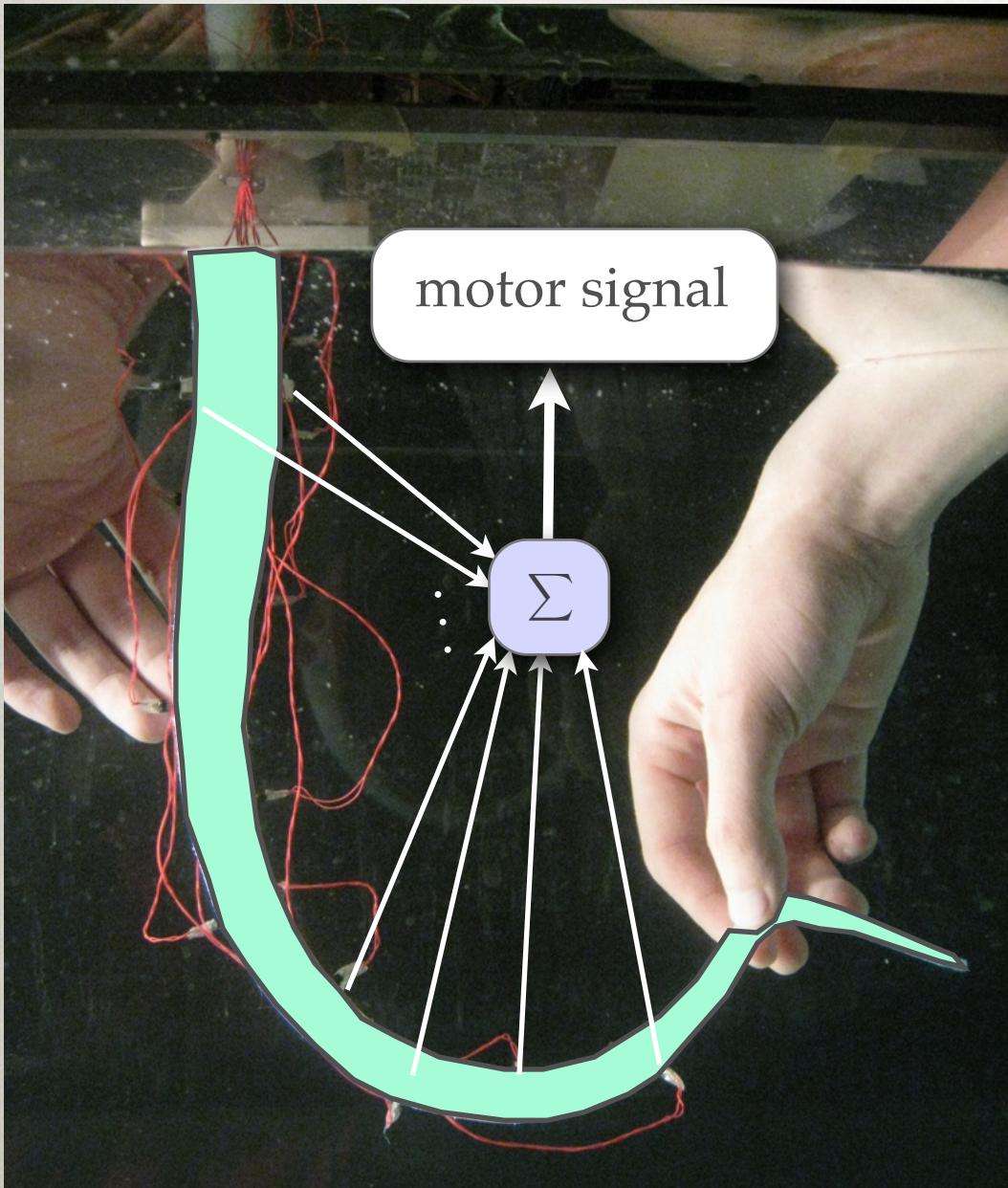
- exploitation of the body

APPLICATION IN SOFT ROBOTICS



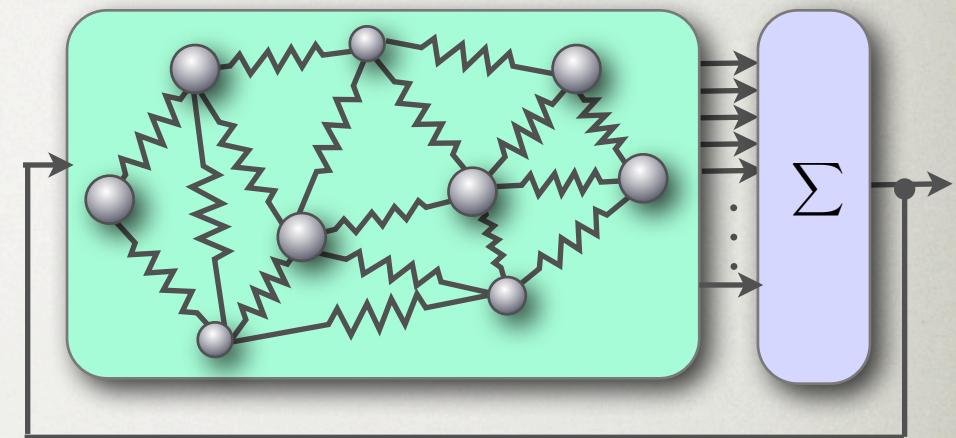
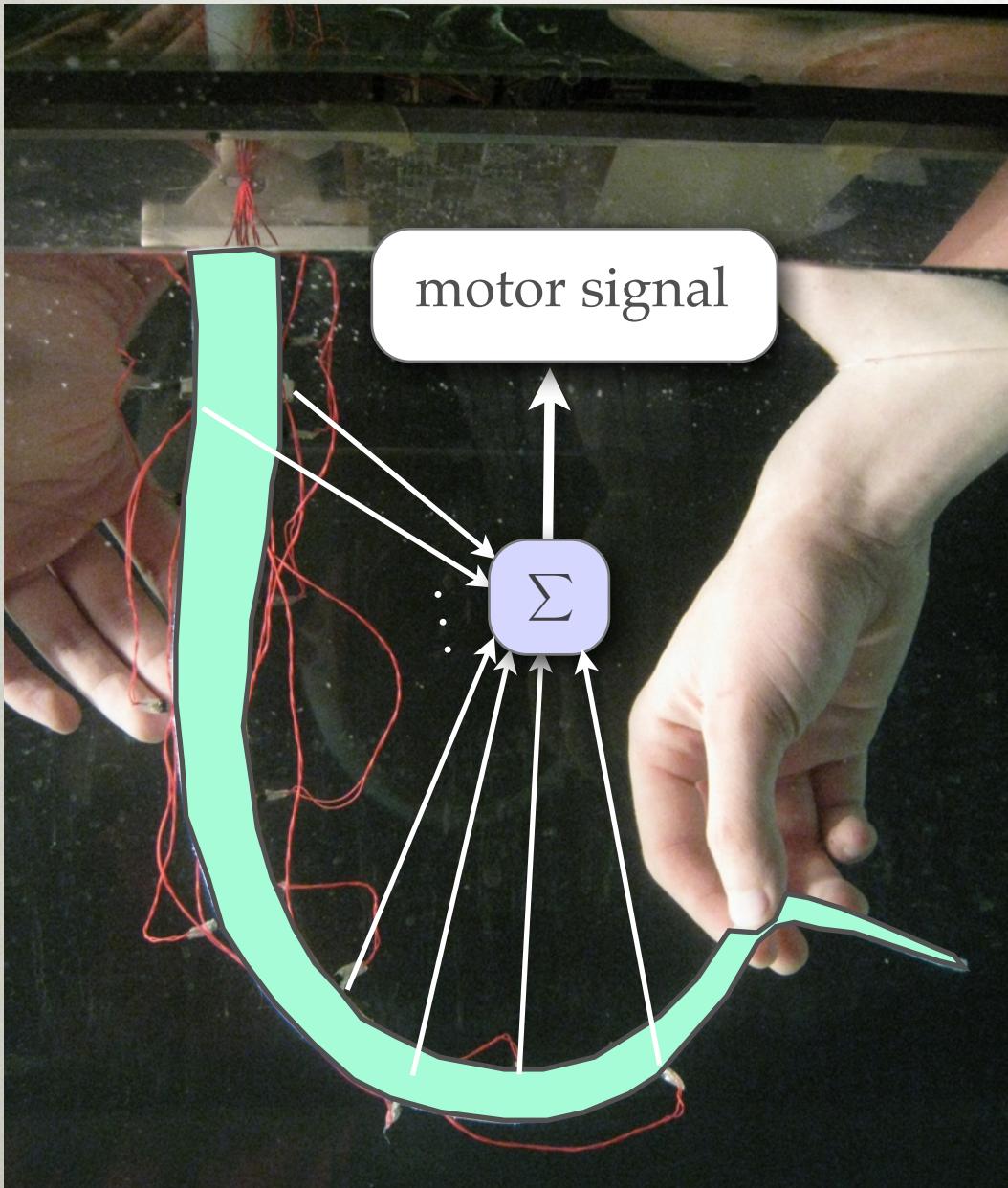
- exploitation of the body
- nonlinear and memory

APPLICATION IN SOFT ROBOTICS



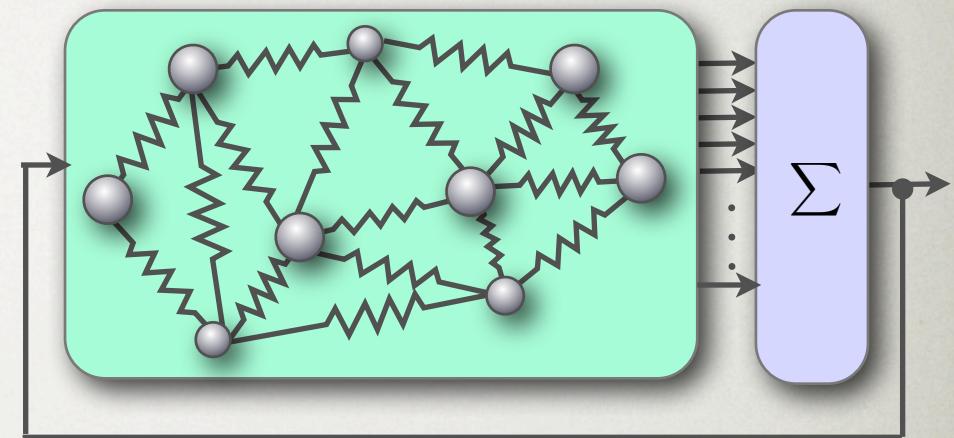
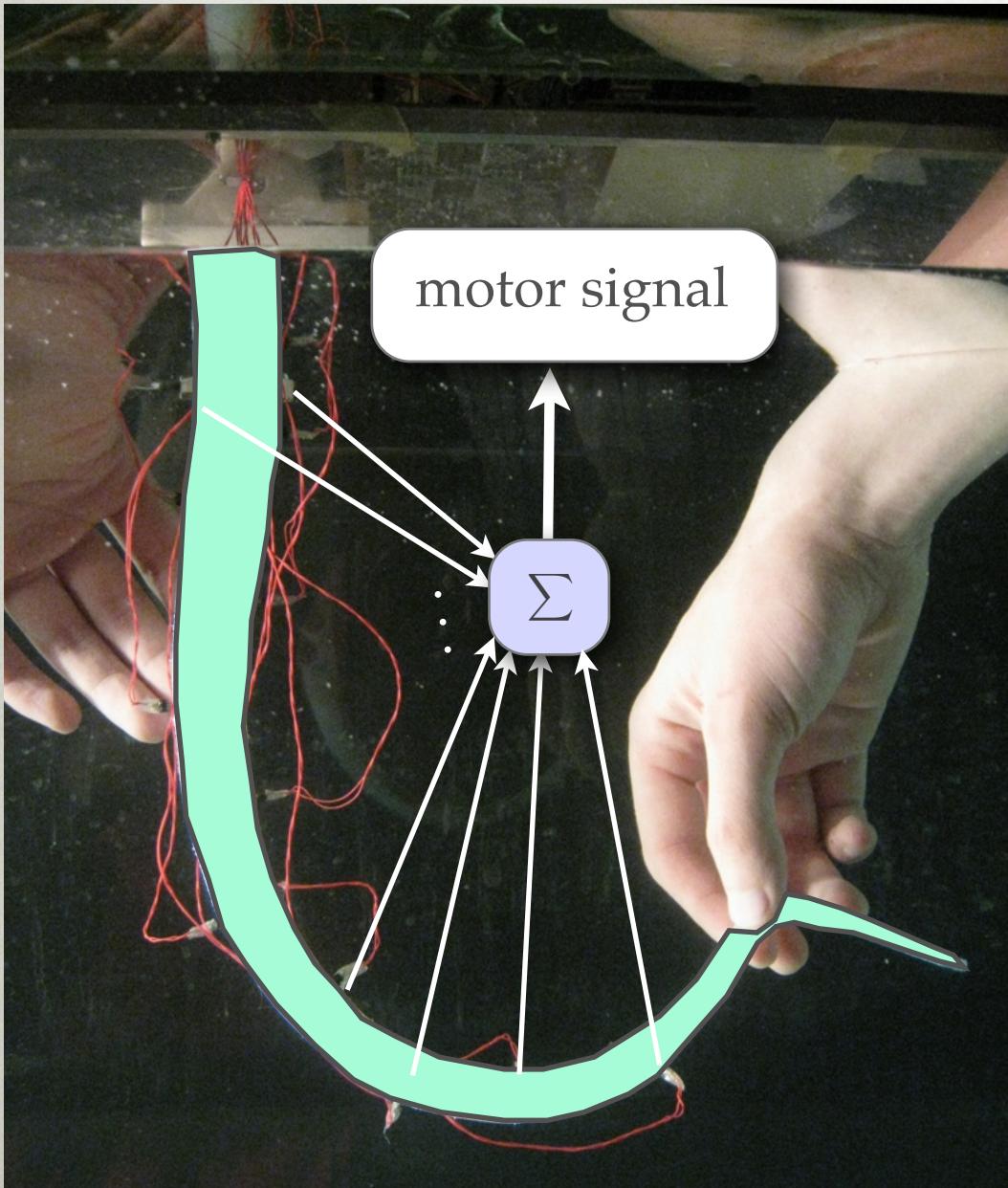
- exploitation of the body
- nonlinear and memory
- noise comes from the sensors

APPLICATION IN SOFT ROBOTICS



- exploitation of the body
- nonlinear and memory
- noise comes from the sensors
- sensors, water and even motor is part of the morphology

APPLICATION IN SOFT ROBOTICS



- exploitation of the body
- nonlinear and memory
- noise comes from the sensors
- sensors, water and even motor is part of the morphology
- able to produce robust limit cycle

APPLICATION IN SOFT ROBOTICS



TAKE HOME MESSAGES

TAKE HOME MESSAGES

1

Outsourcing computation to the physical body facilitates computation/control

TAKE HOME MESSAGES

1

Outsourcing computation to the physical body facilitates computation/control

2

High-dimensionality, nonlinearity, compliance, and noise are your friends!

TAKE HOME MESSAGES

1

Outsourcing computation to the physical body facilitates computation/control

2

High-dimensionality, nonlinearity, compliance, and noise are your friends!

3

Computational exploitation is a way to control soft robots (without “knowing” their body)

THANK YOU VERY MUCH FOR YOUR ATTENTION!



Rolf Pfeifer



Rudolf M. Füchslin



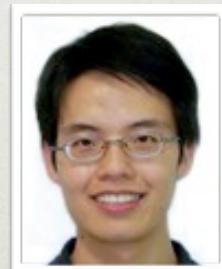
Auke Ijspeert



Wolfgang Maass



Kohei Nakajima



Tao Li

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Hauser, Helmut, Auke J. Ijspeert, Rudolf M. Füchslin, Rolf Pfeifer, and Wolfgang Maass. "**Towards a theoretical foundation for morphological computation with compliant bodies**" Biological Cybernetics 105, no. 5-6 (2011): 355-370. [\[pdf\]](#)

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Hauser, Helmut, Hidenobu Sumioka, Rudolf M. Füchslin, and Rolf Pfeifer. "**Introduction to the special issue on morphological computation**" Artificial life 19, no. 1 (2013): 1-8.

EU project OCTOPUS, <http://www.octopusproject.eu/>

EU project LOCOMORPH, <http://www.locomorph.eu/>