

Learning to Control Self-Assembling Morphologies

Generalization via Modularity



Deepak
Pathak*



Chris
Lu*



Trevor
Darrell



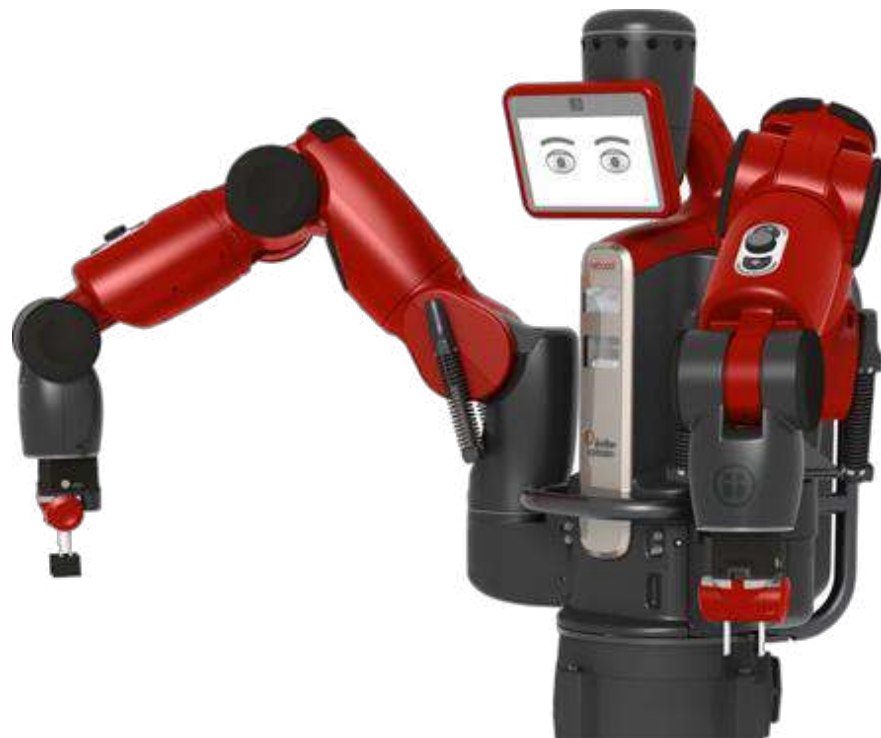
Phillip
Isola



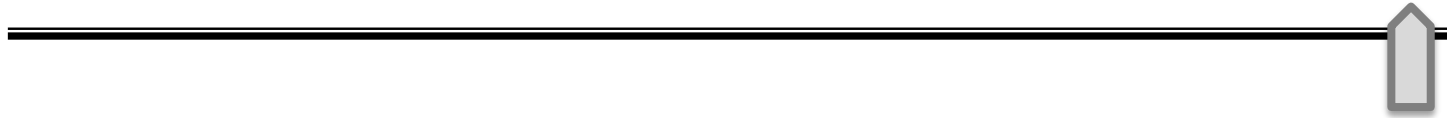
Alyosha
Efros

* equal contribution

How do we train a robot?







- Multiple tasks
- Expert demonstrations
- Rewards, labels
- ...

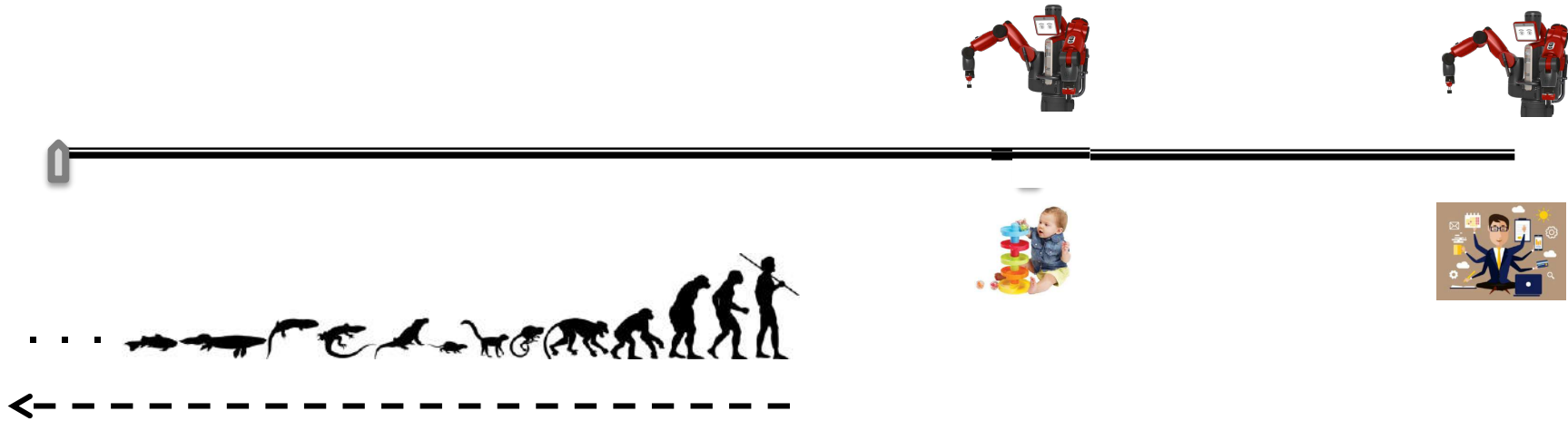


- Self-supervision
- Curious exploration
- Learning “common sense”
- ...



- Multiple tasks
- Expert demonstrations
- Rewards, labels
- ...



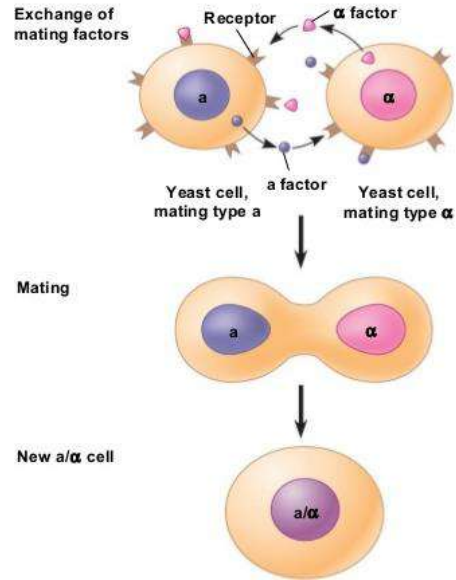


... even earlier?

Single to Multicellular

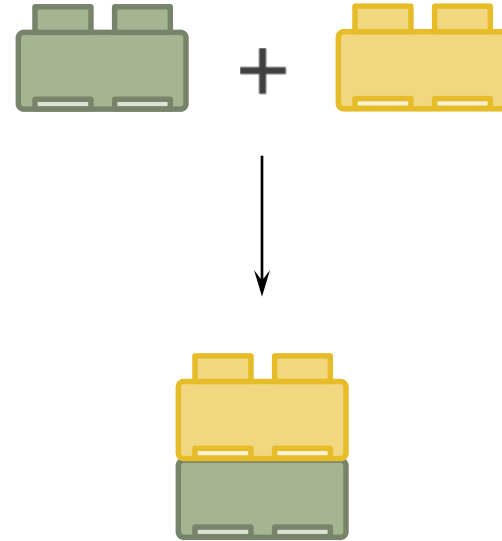
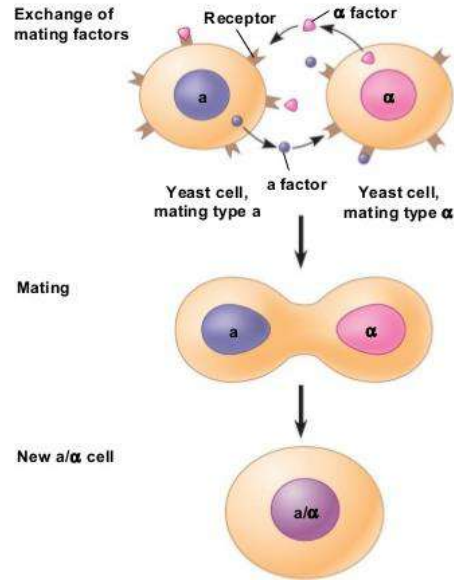
Single to Multicellular

competition → *collaboration*



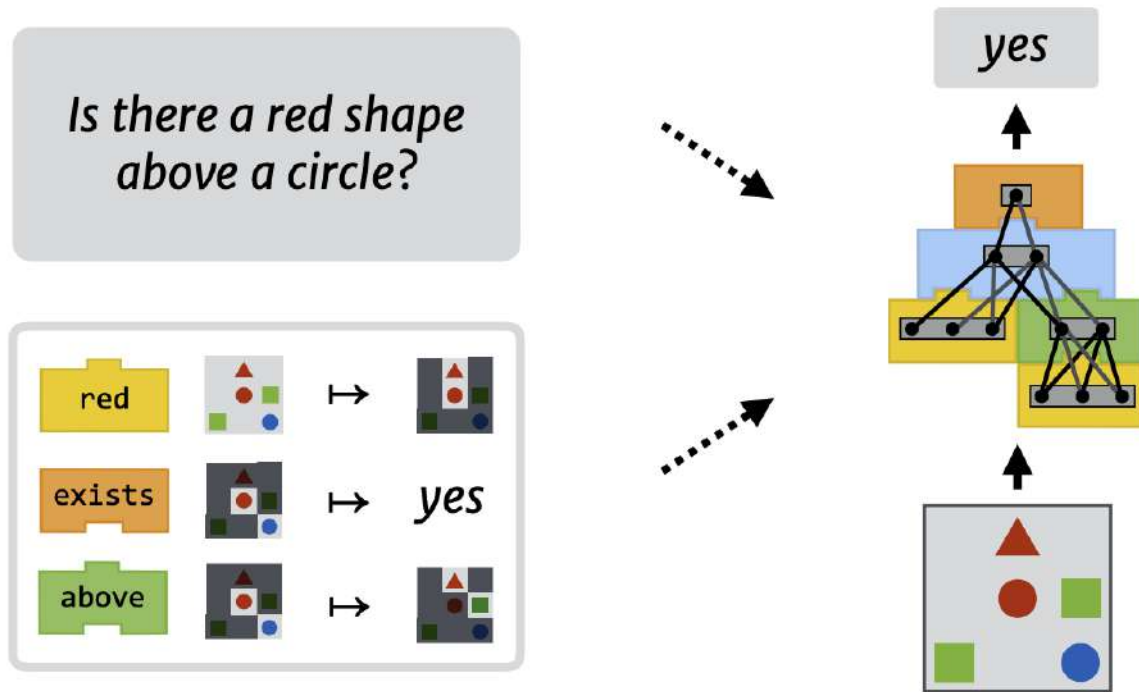
Single to Multicellular

competition \rightarrow *collaboration*



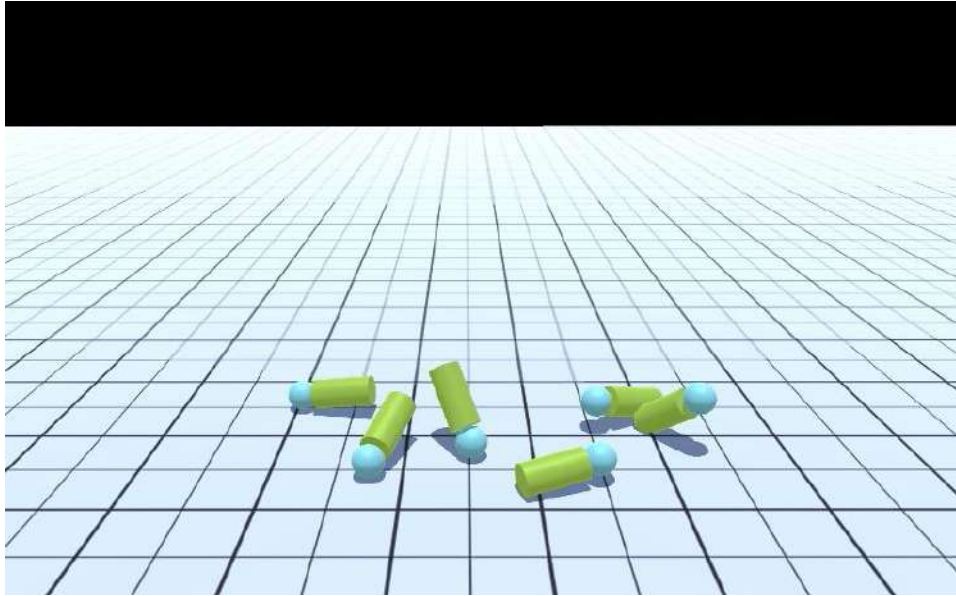
shared objective

Compositionality has been useful in language ...

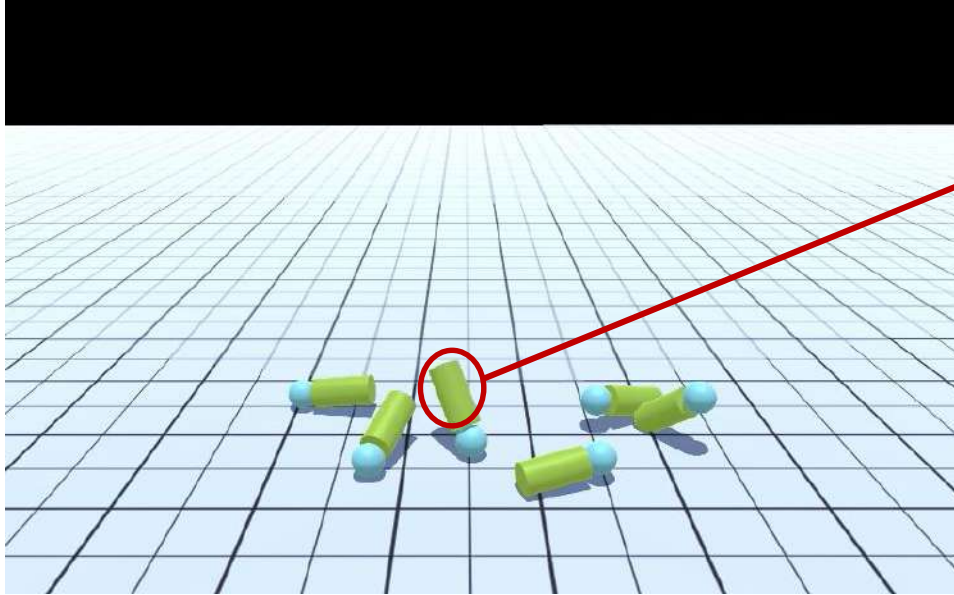


How to implement compositionality in hardware?

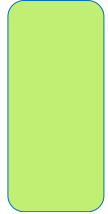
Modular Co-evolution of Control and Morphology



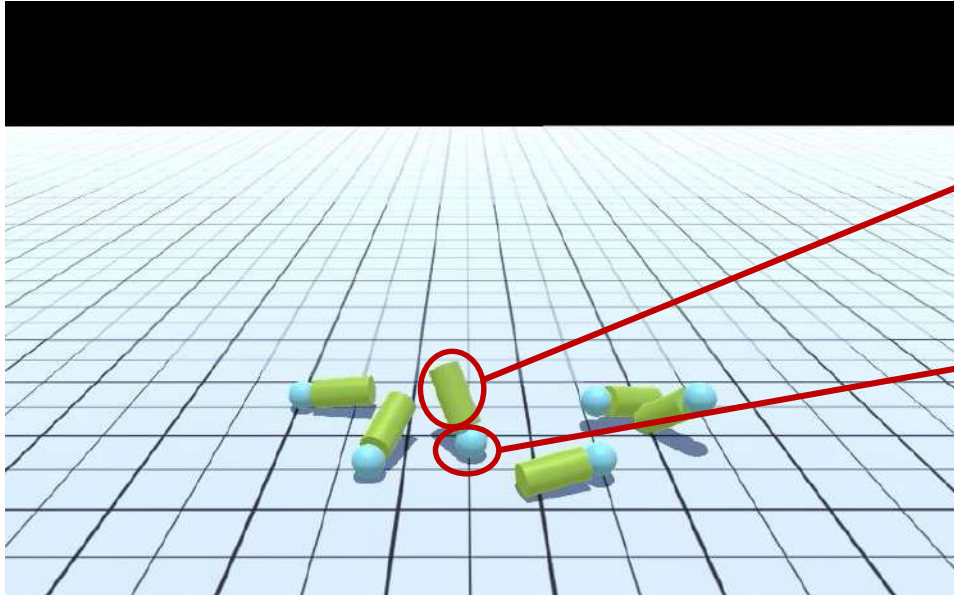
Modular Co-evolution of Control and Morphology



Cylindrical Limb

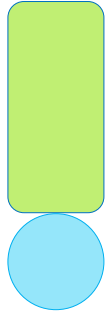


Modular Co-evolution of Control and Morphology

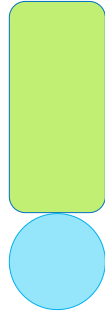


Cylindrical Limb

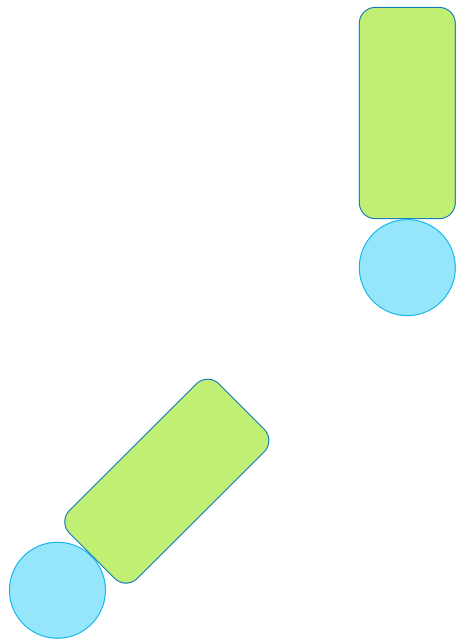
Configurable Motor Joint



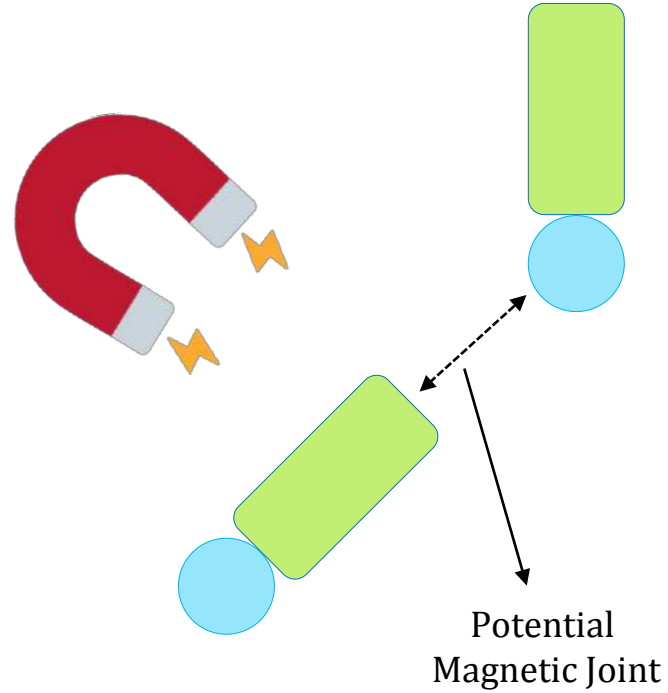
Modular Co-evolution of Control and Morphology



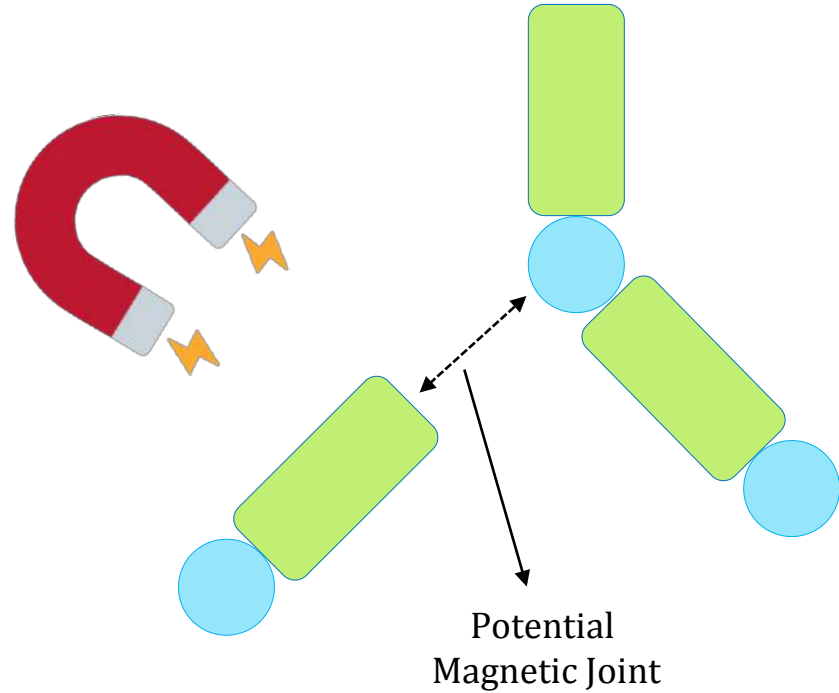
Modular Co-evolution of Control and Morphology



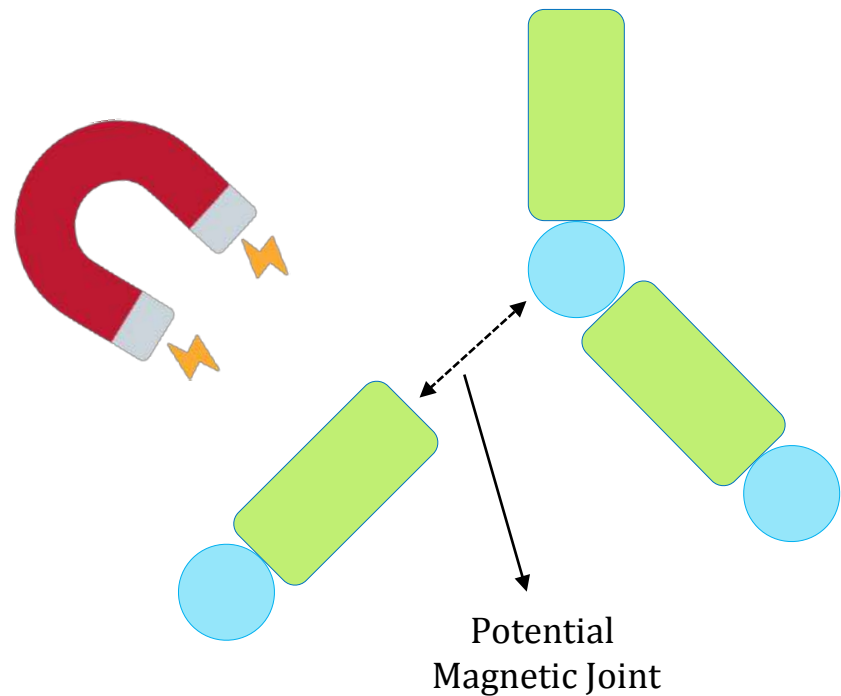
Modular Co-evolution of Control and Morphology



Modular Co-evolution of Control and Morphology

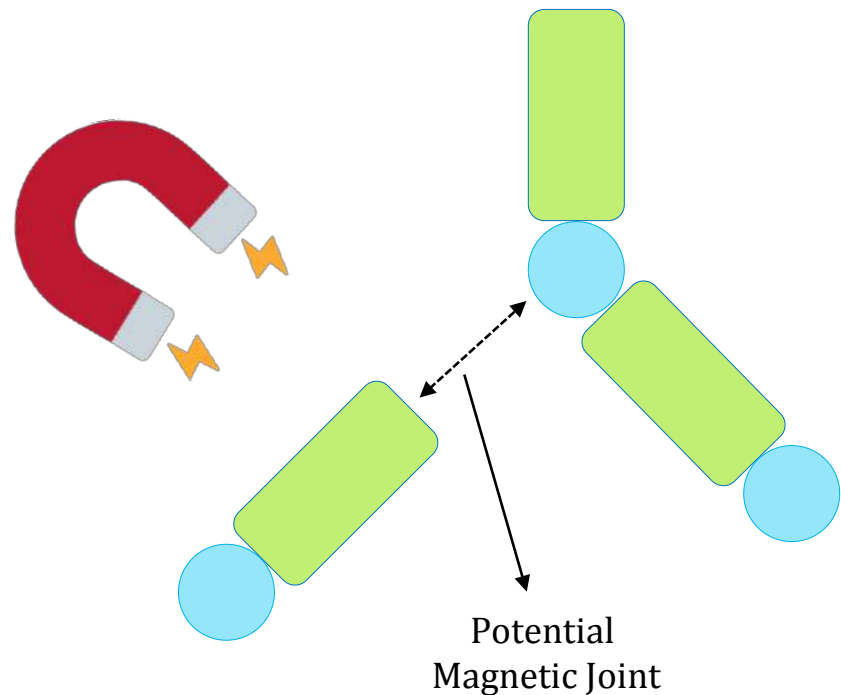


Modular Co-evolution of Control and Morphology



Acts as single agent upon joining
Rewards are shared!

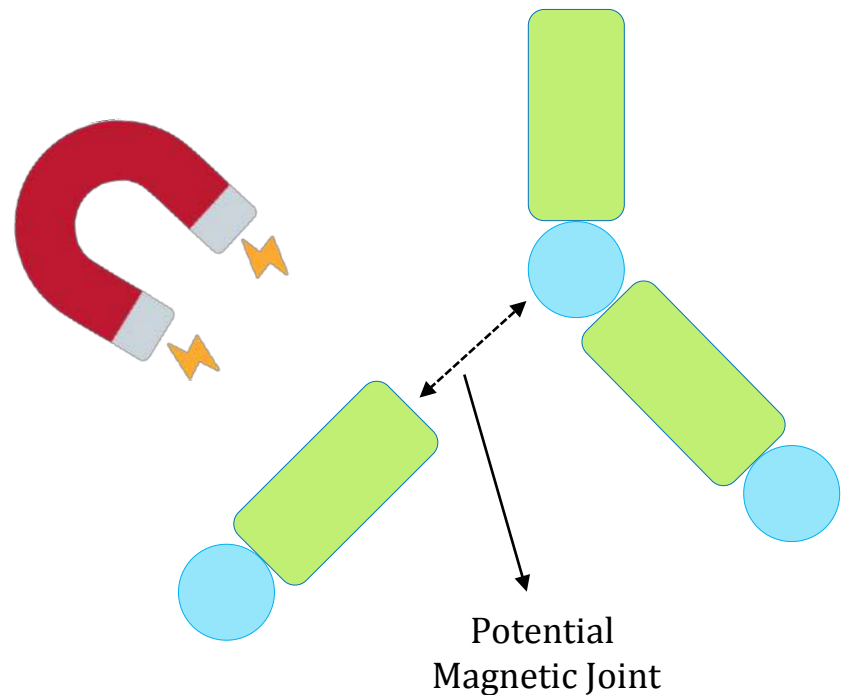
Modular Co-evolution of Control and Morphology



Acts as single agent upon joining
Rewards are shared!

- **Input** = *Local* Sensory State
- **Output** = Torques, Link, Unlink

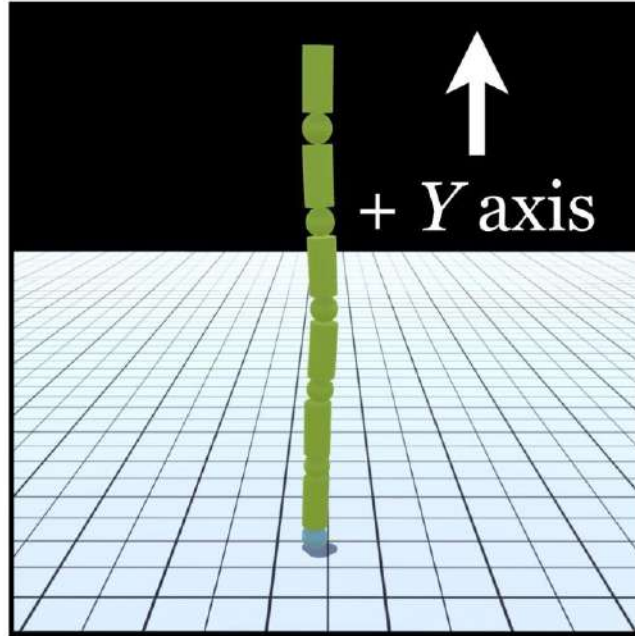
Modular Co-evolution of Control and Morphology



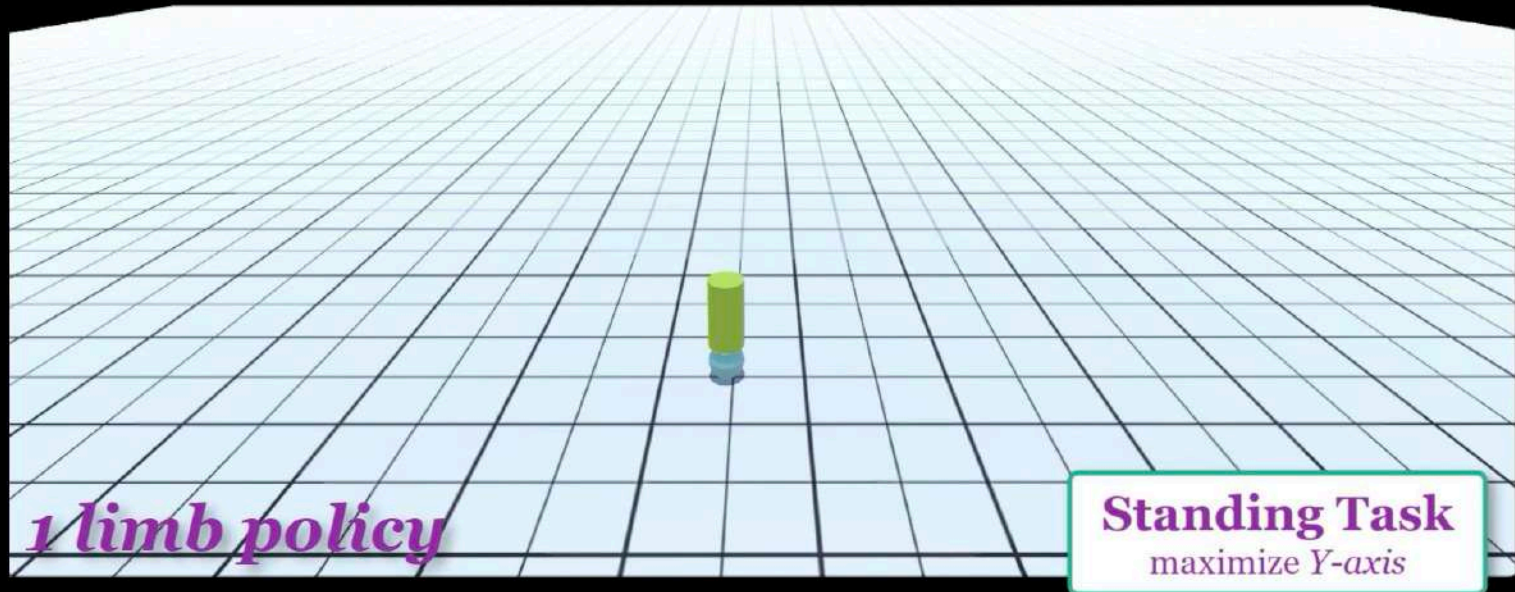
Acts as single agent upon joining
Rewards are shared!

- Input = *Local* Sensory State
- Output = Torques, Link, Unlink

Consider the task of “standing up” ...

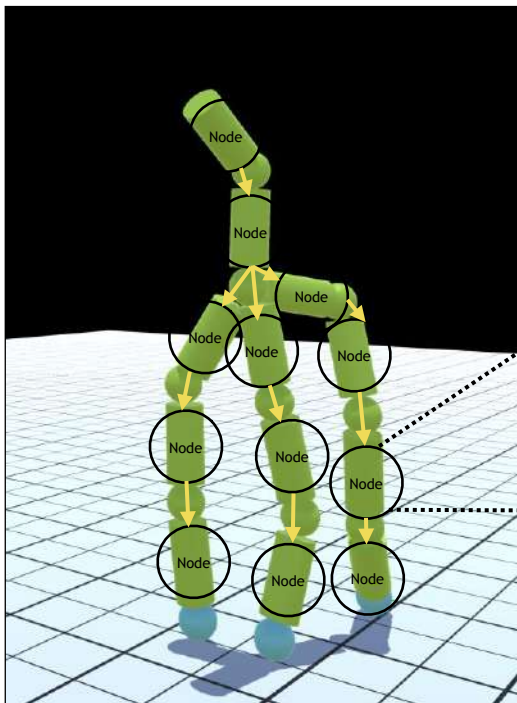


Vanilla Reinforcement Learning

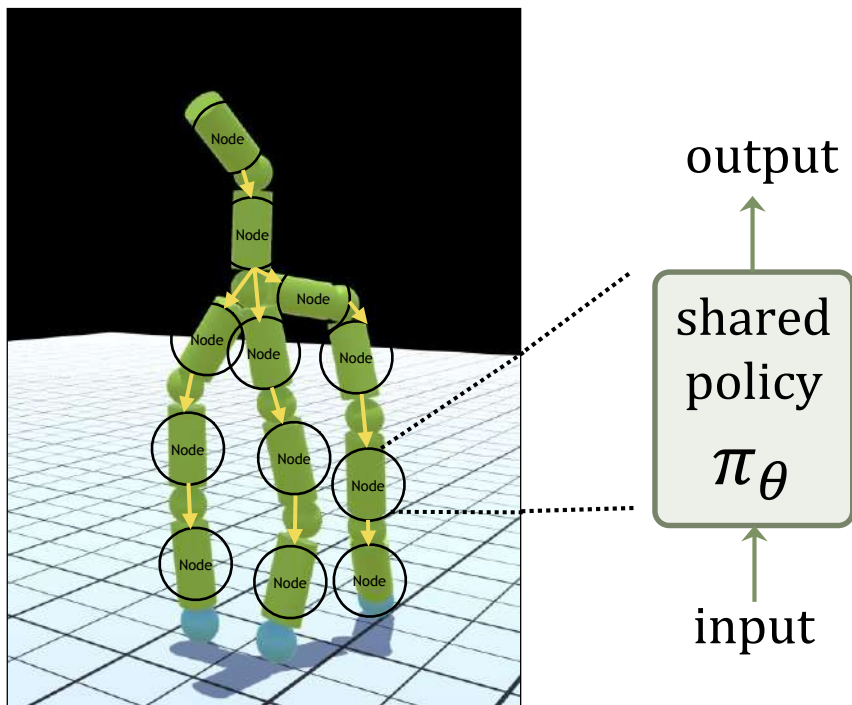


How to learn compositional controllers?

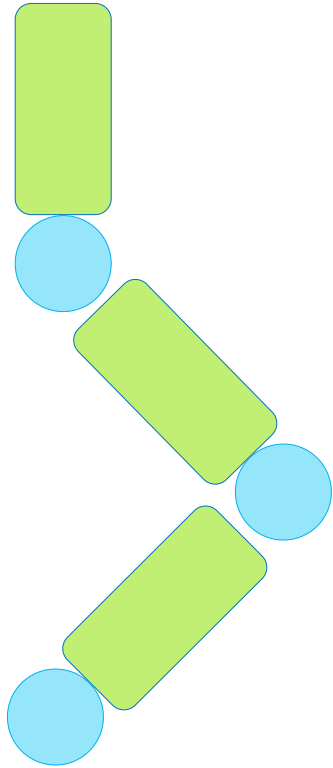
Idea: Shared policy network across limbs



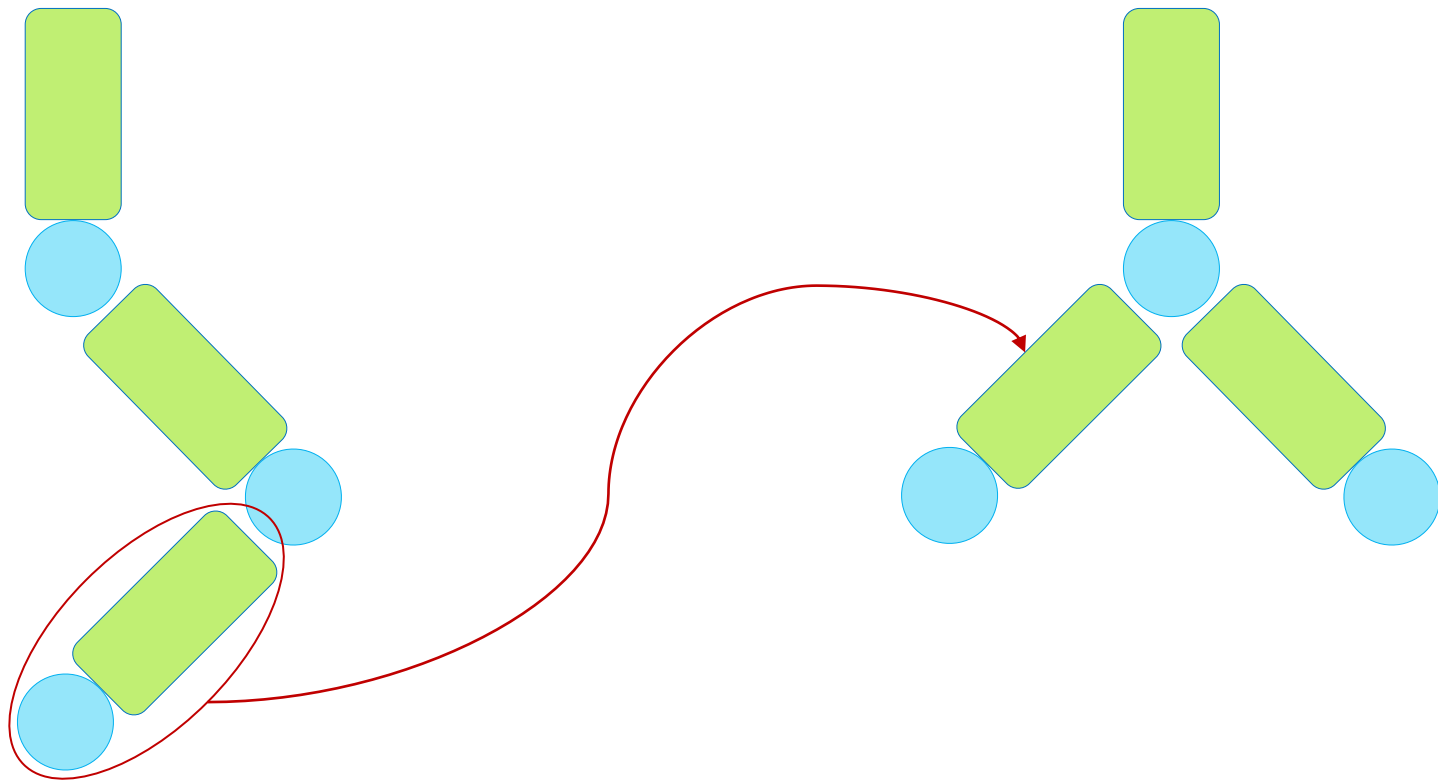
Idea: Shared policy network across limbs



How to adapt when morphology changes?

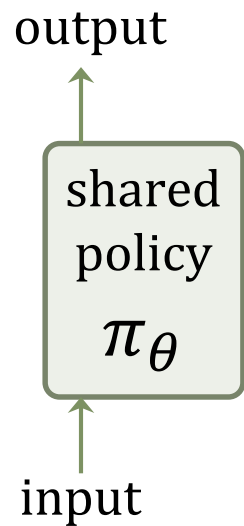


How to adapt when morphology changes?

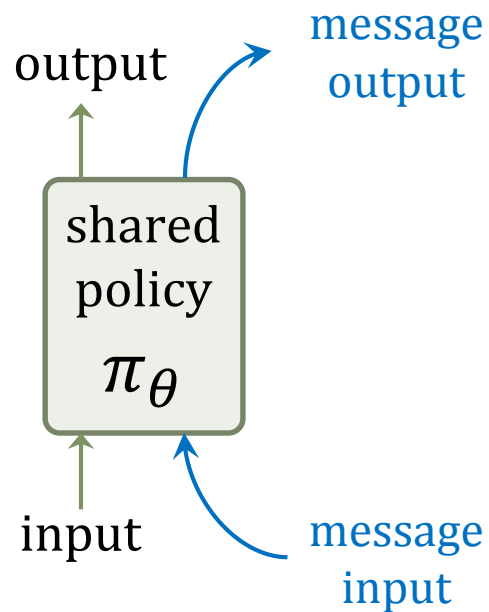


Network as reusable LEGO Blocks

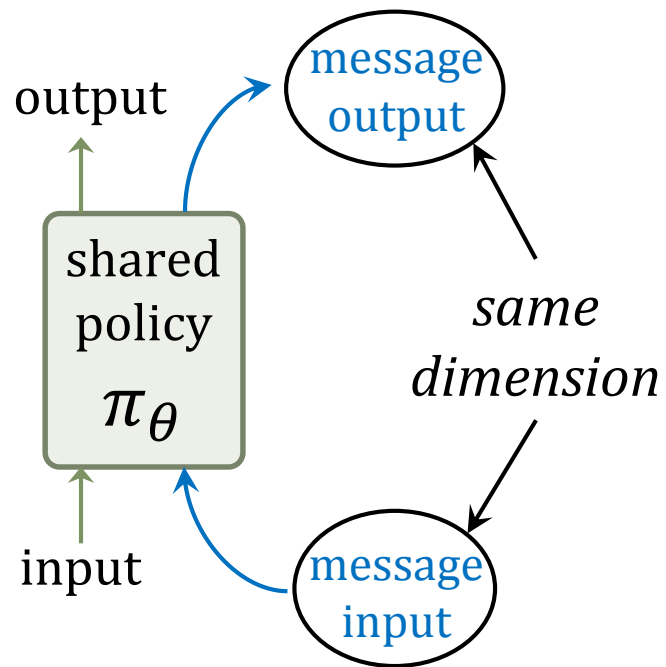
Network as reusable LEGO Blocks



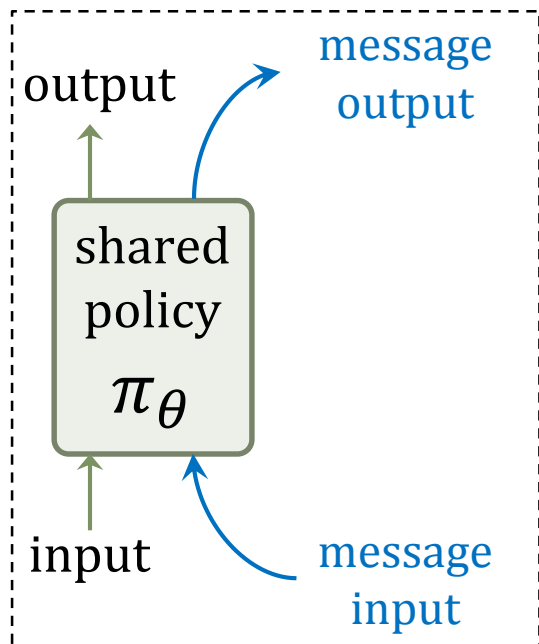
Network as reusable LEGO Blocks



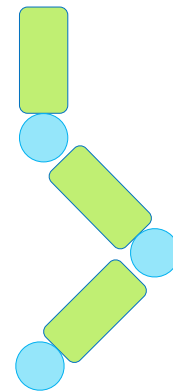
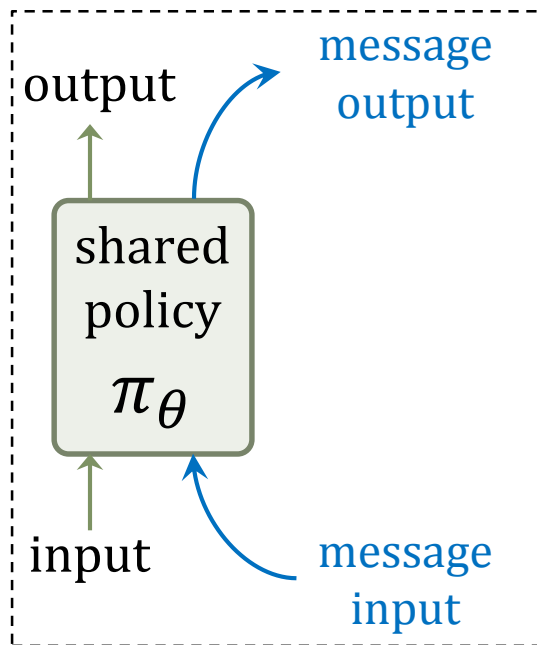
Network as reusable LEGO Blocks



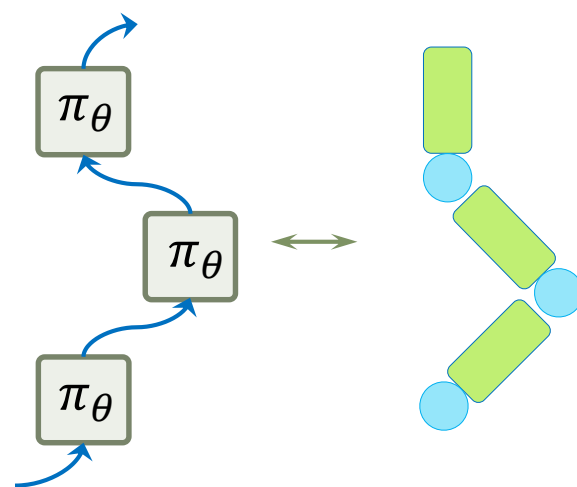
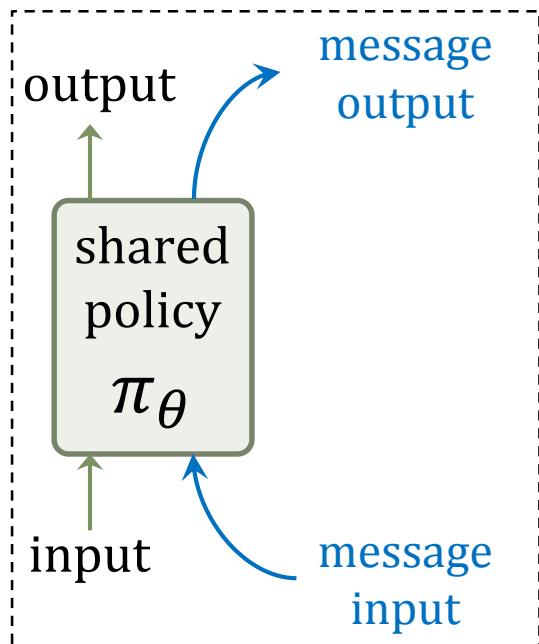
Network as reusable LEGO Blocks



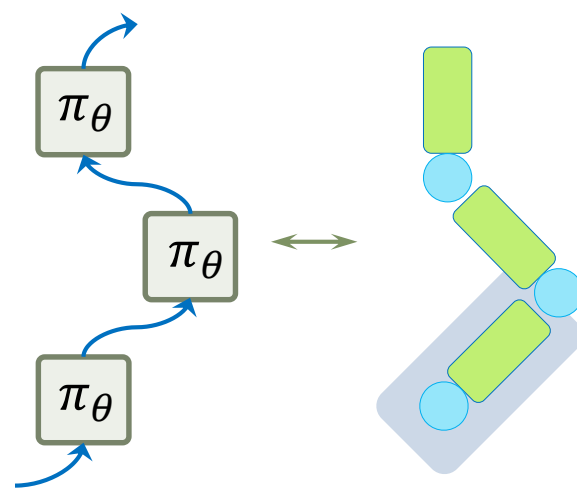
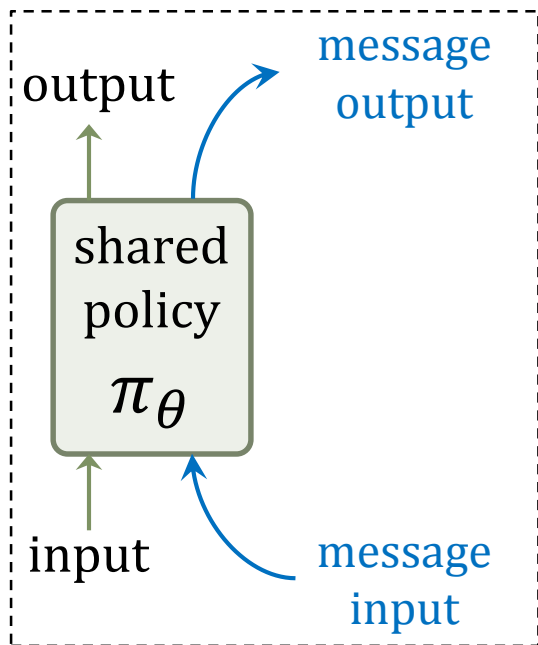
Network as reusable LEGO Blocks



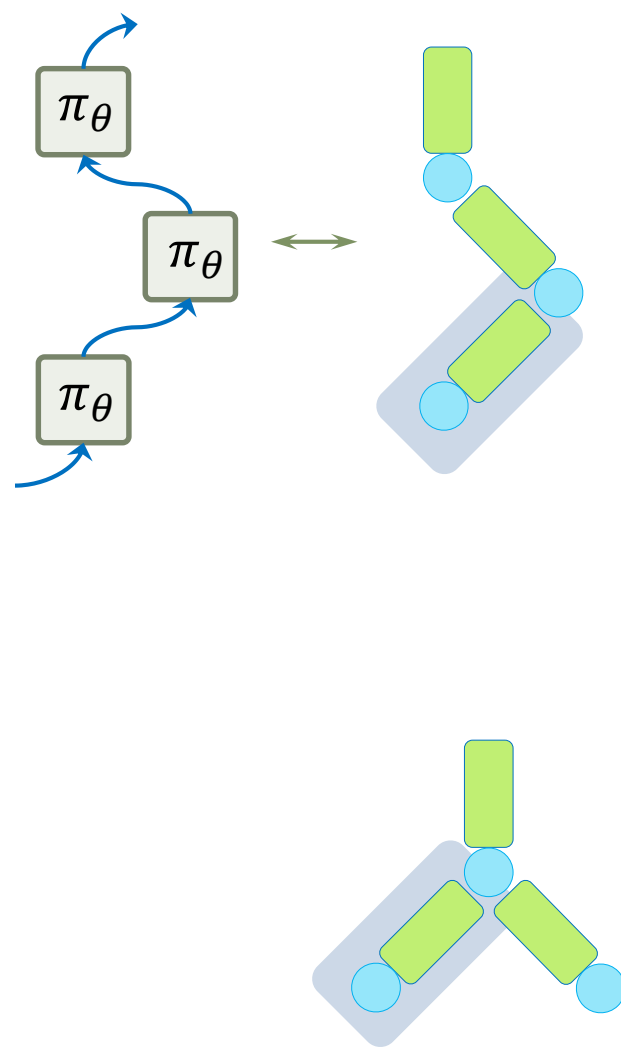
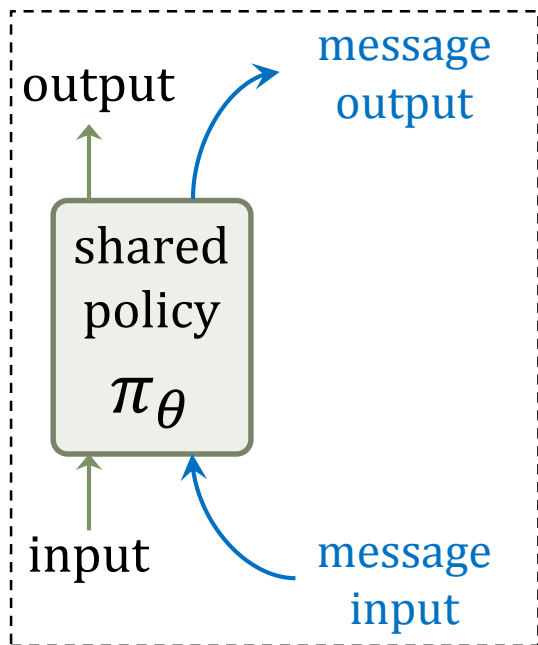
Network as reusable LEGO Blocks



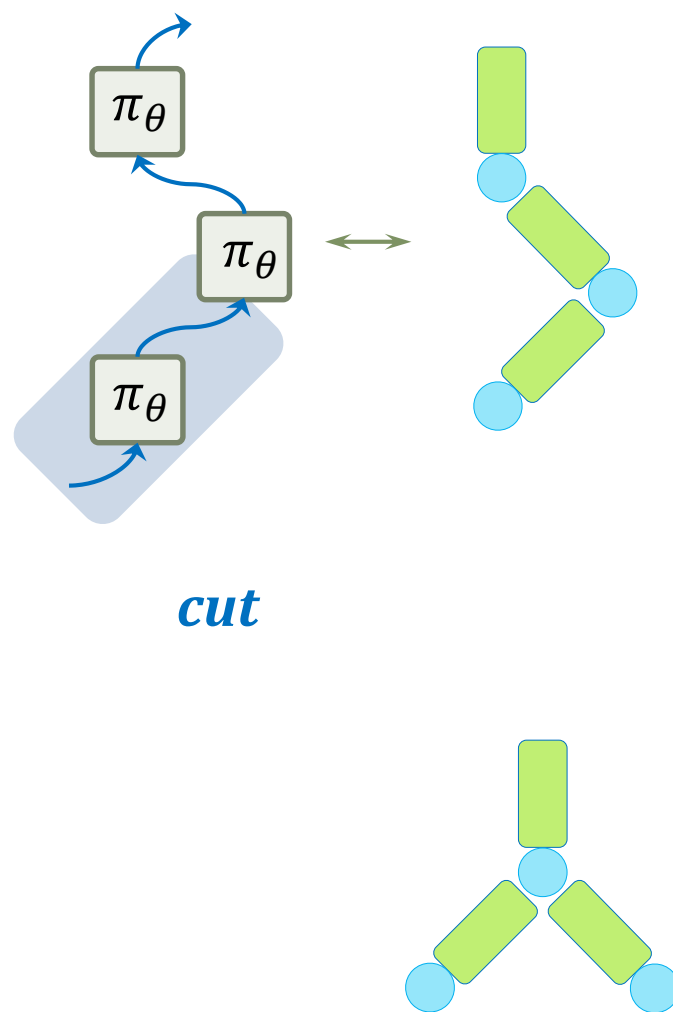
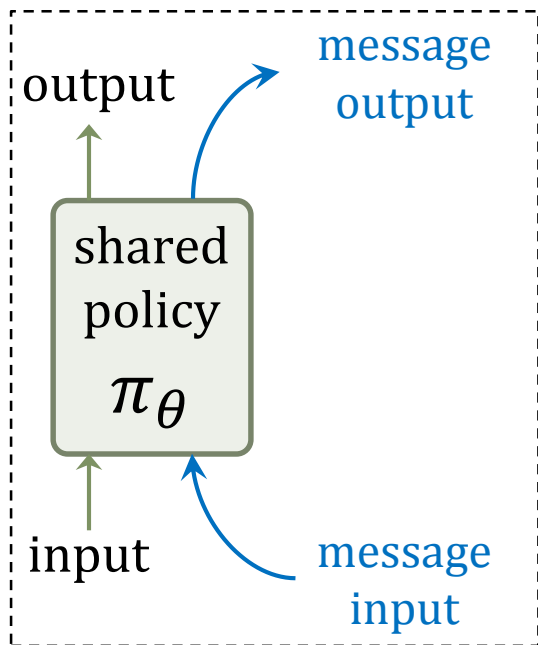
Network as reusable LEGO Blocks



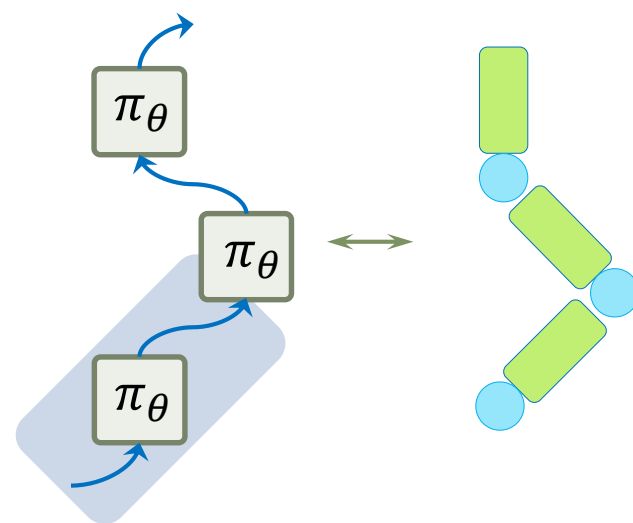
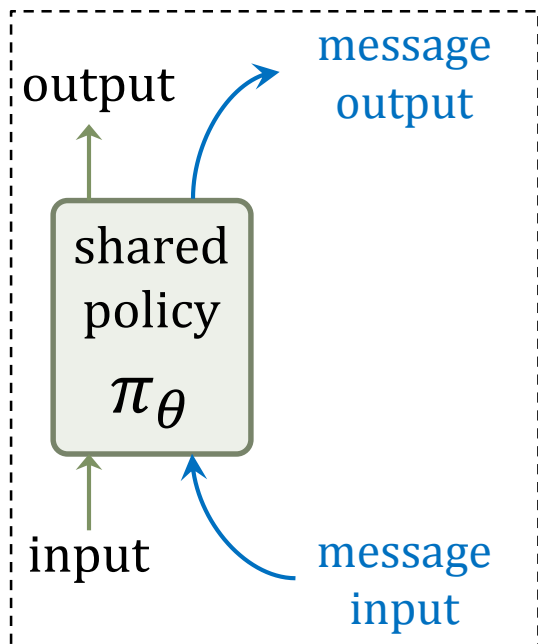
Network as reusable LEGO Blocks



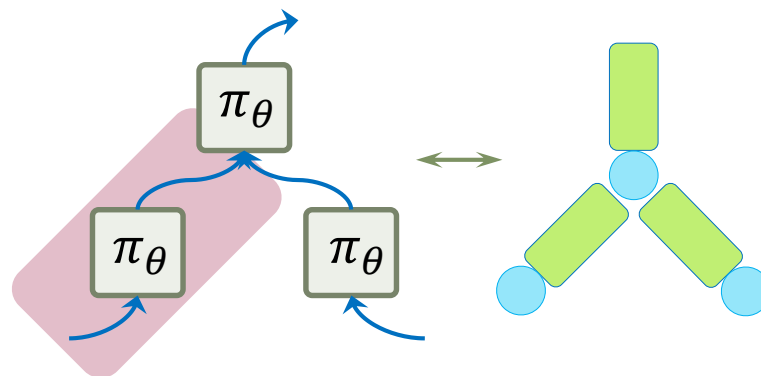
Network as reusable LEGO Blocks



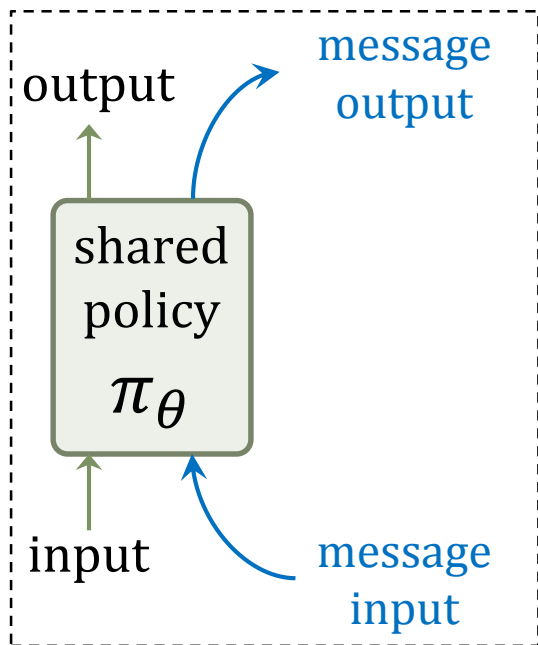
Network as reusable LEGO Blocks



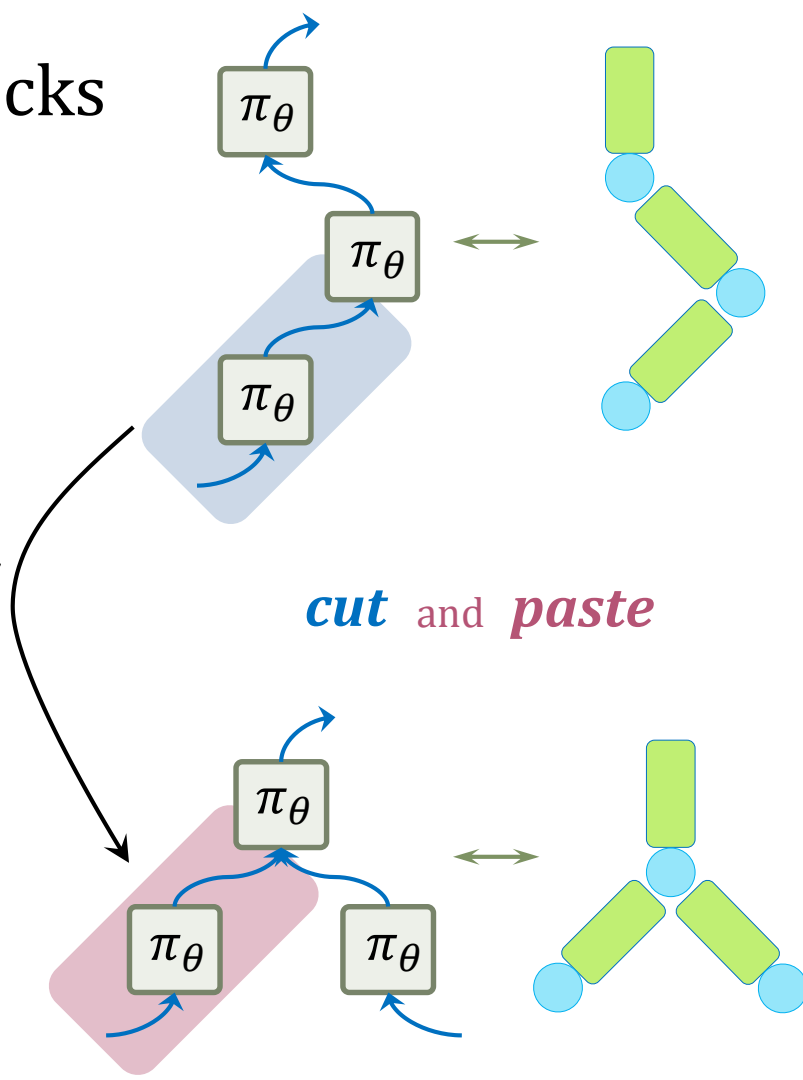
cut and *paste*



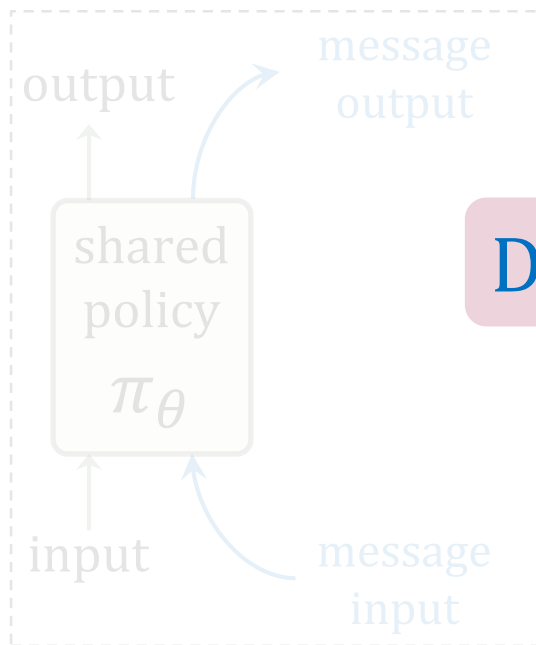
Network as reusable LEGO Blocks



*adaptation by
conditioning*



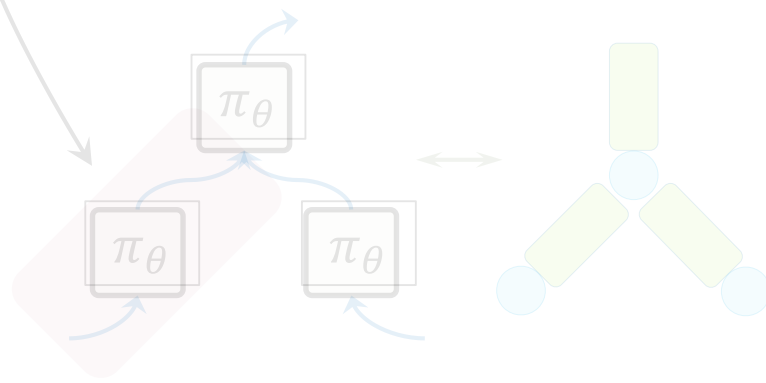
Network as reusable LEGO Blocks



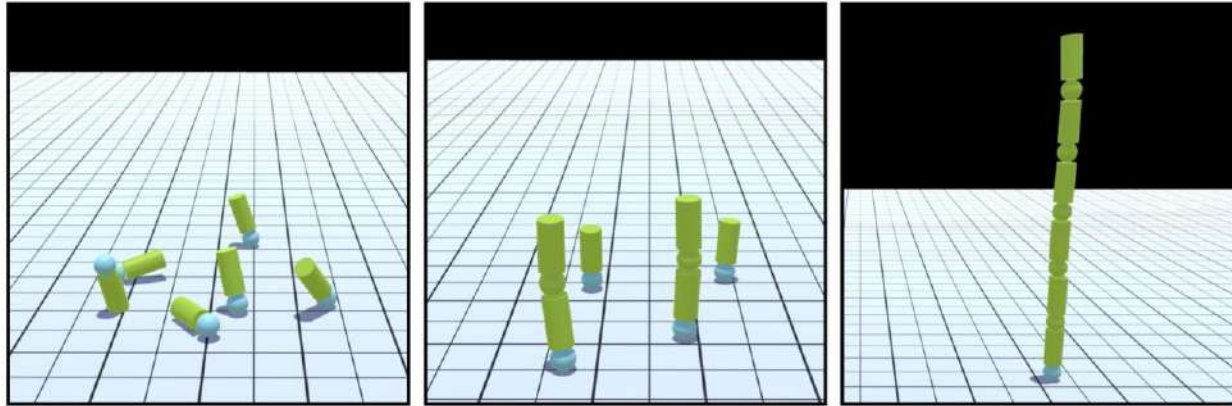
Dynamic Graph Networks

conditioning

cut and *paste*



BTW, basically curriculum learning but in hardware



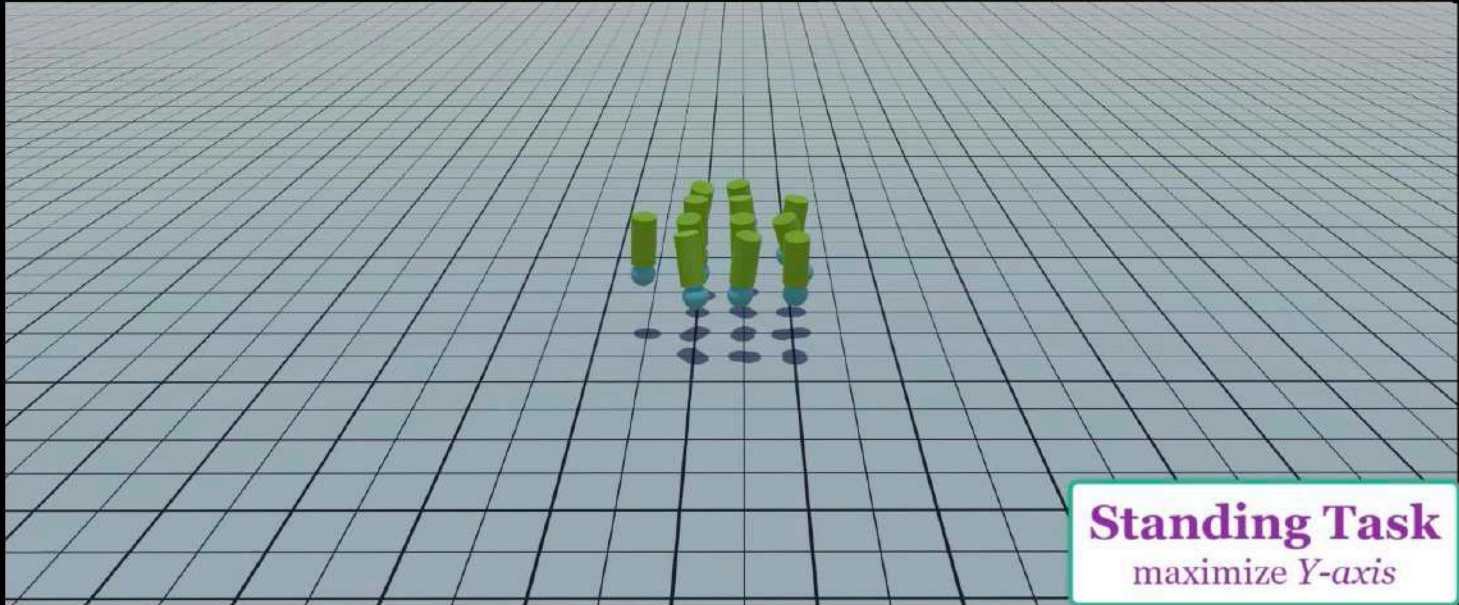
training



How well does it generalize?

Generalization w/o Fine-tuning

twice as many limbs





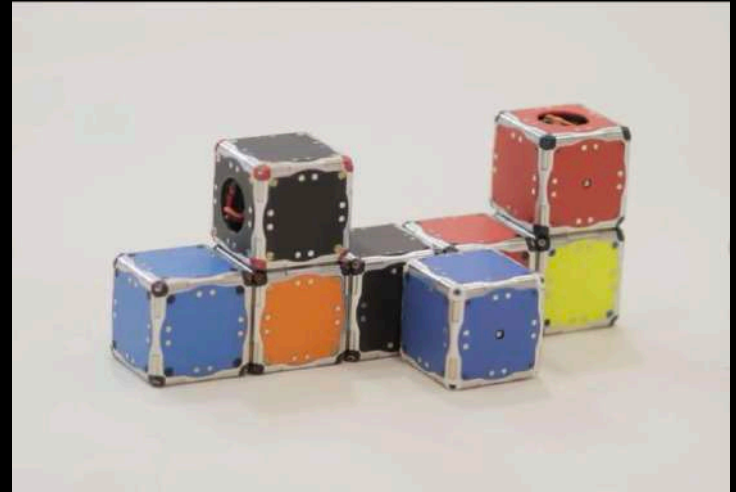


a bit crazy... is it even possible in real world?

Self-Assembling Robots in the Real World



[Mark Yim's Lab at UPenn]



[Daniela Rus's Lab at MIT]

Also: [Modular Snake Robot – Howie Choset's Lab at CMU]

code & data at

<https://people.eecs.berkeley.edu/~pathak/>

Poster # 197

Today (Tues)!!

Thank You!

