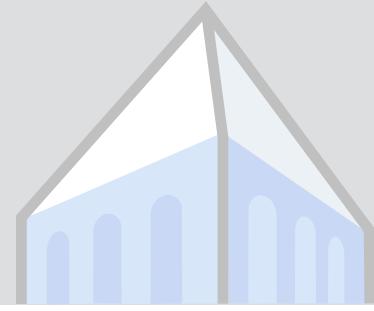
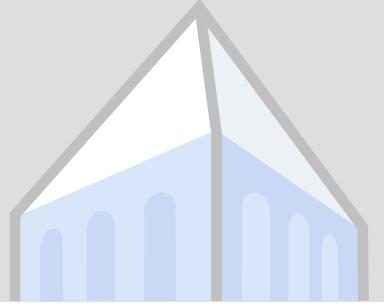


# Learning from Language



Jacob Andreas



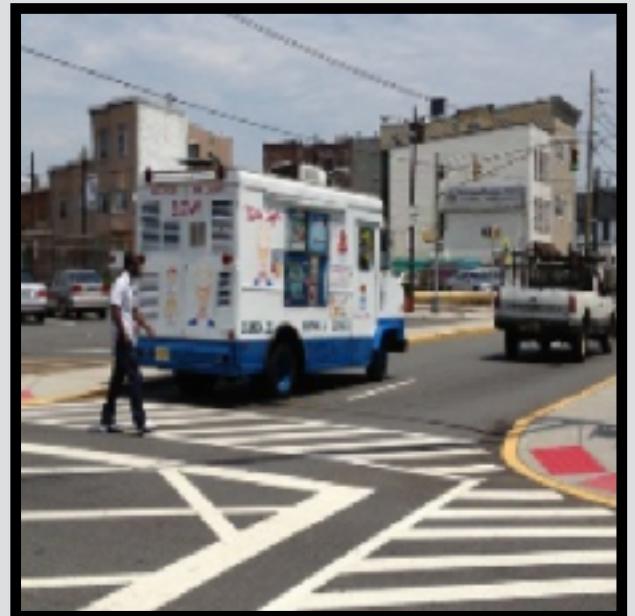
# Doing things with language





# Doing things with language

*Who is left of  
the truck?*



*A man with a  
white shirt and  
black pants.*





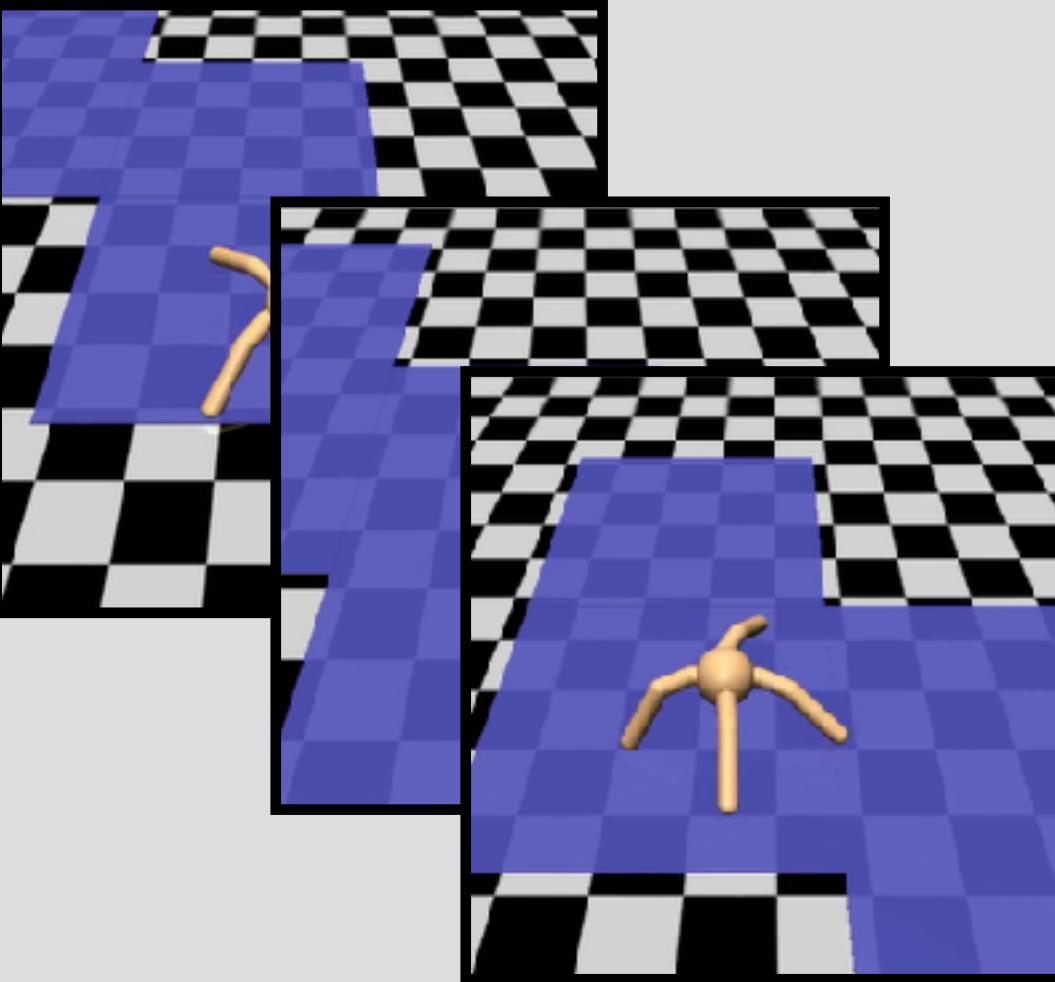
# Doing things with language

*Who is left of  
the truck?*

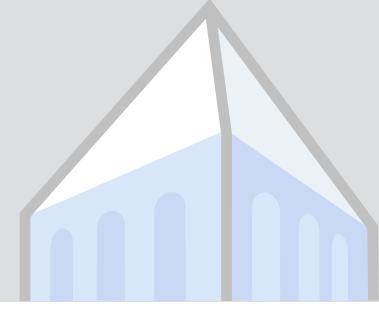


*A man with a  
white shirt and  
black pants.*

*Go up, then go left.*



# Doing things with language

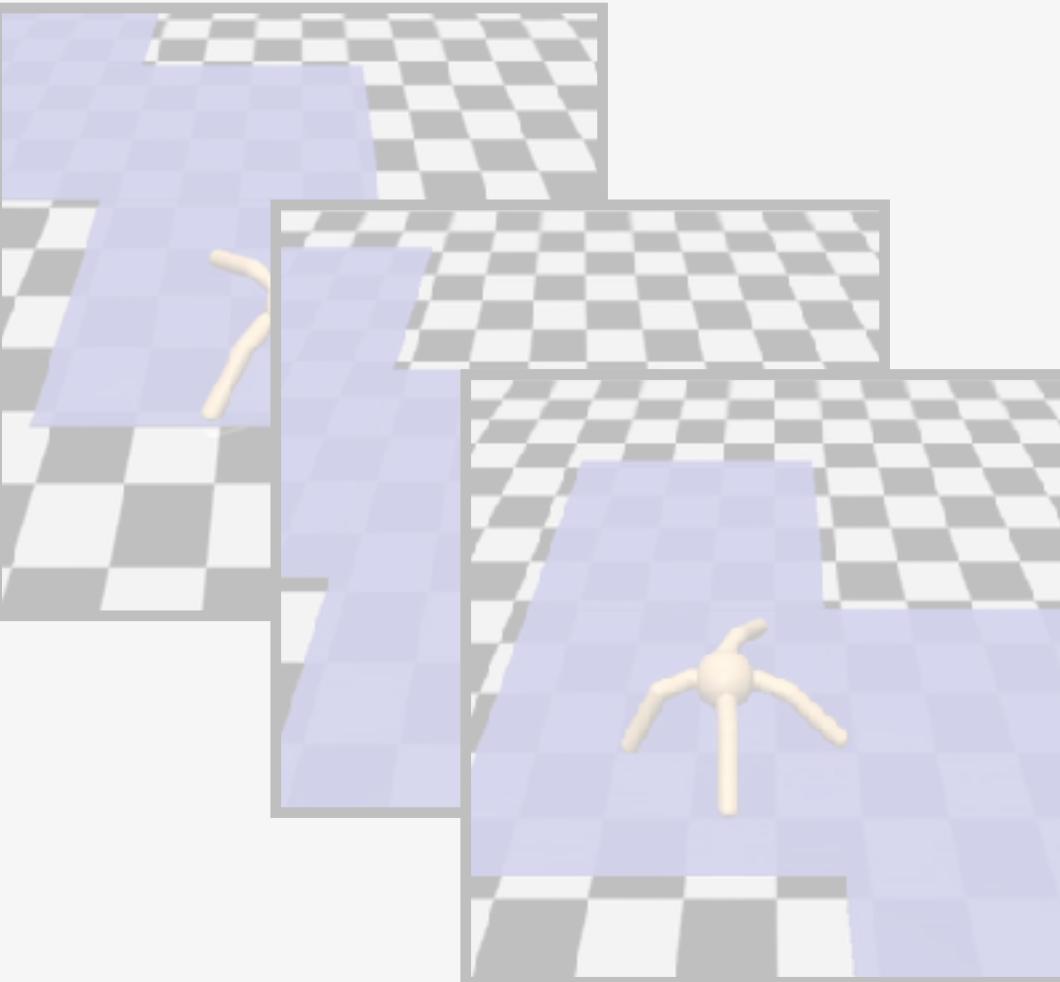


*Who is left of  
the truck?*



*A man with a  
white shirt and  
black pants.*

*Go up, then go left.*



*The hooded oriole  
is a large bird with  
black wings.*



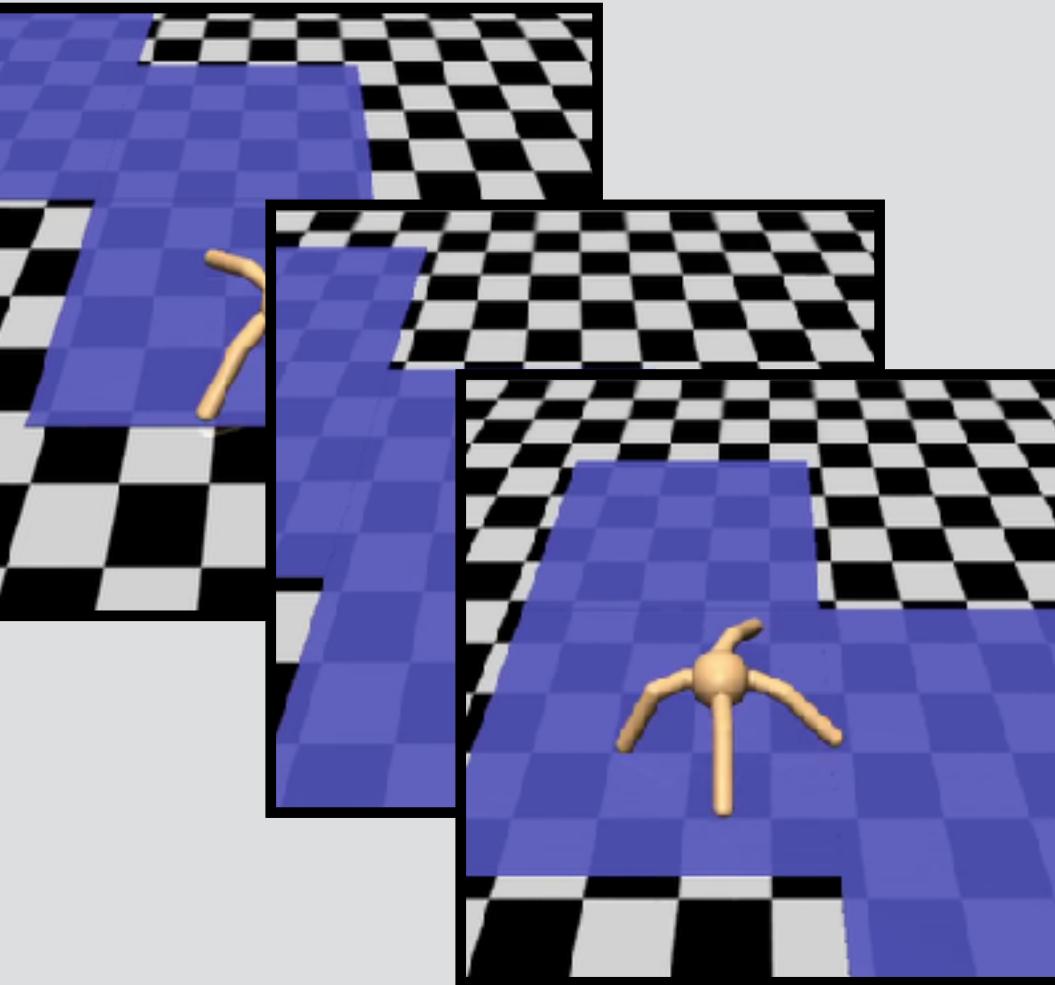
# Doing things with language

*Who is left of  
the truck?*



*A man with a  
white shirt and  
black pants.*

*Go up, then go left.*

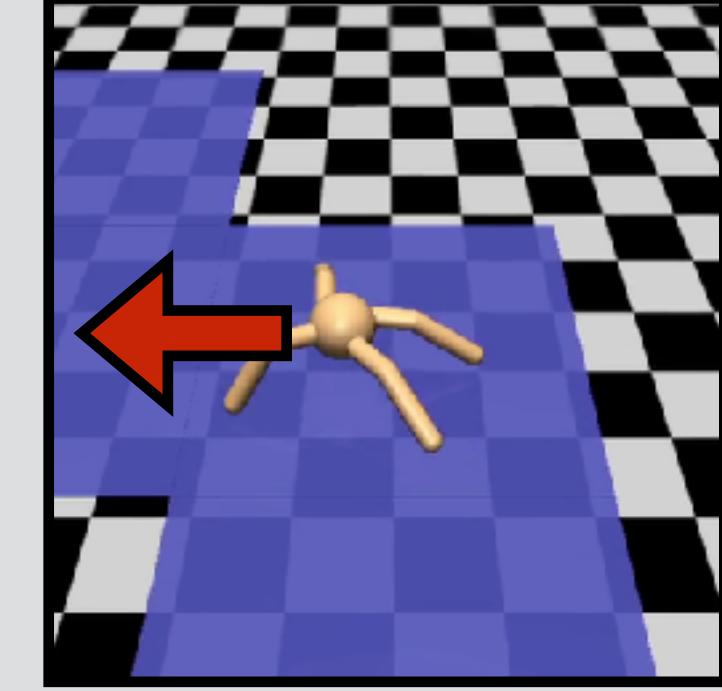


*The hooded oriole  
is a large bird with  
black wings.*

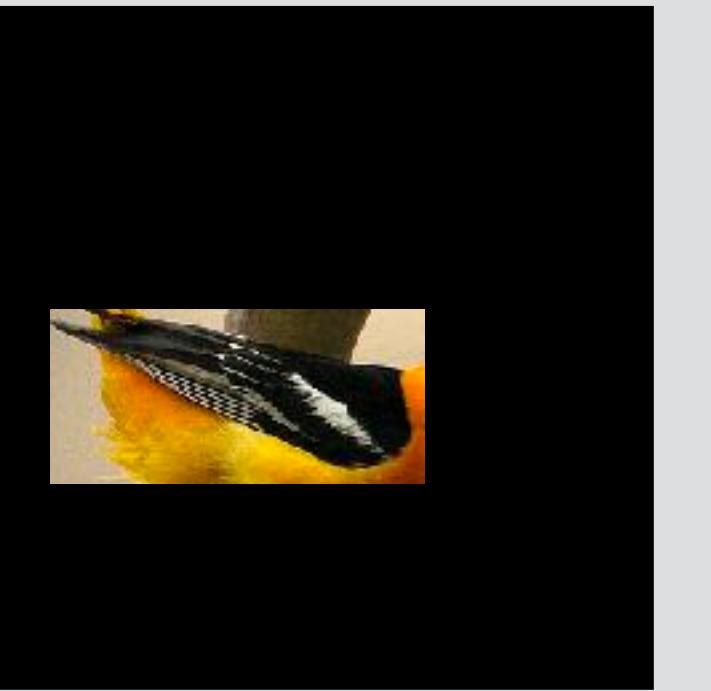


# Words and primitives

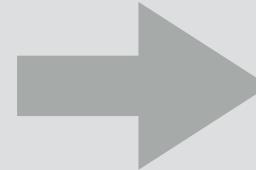
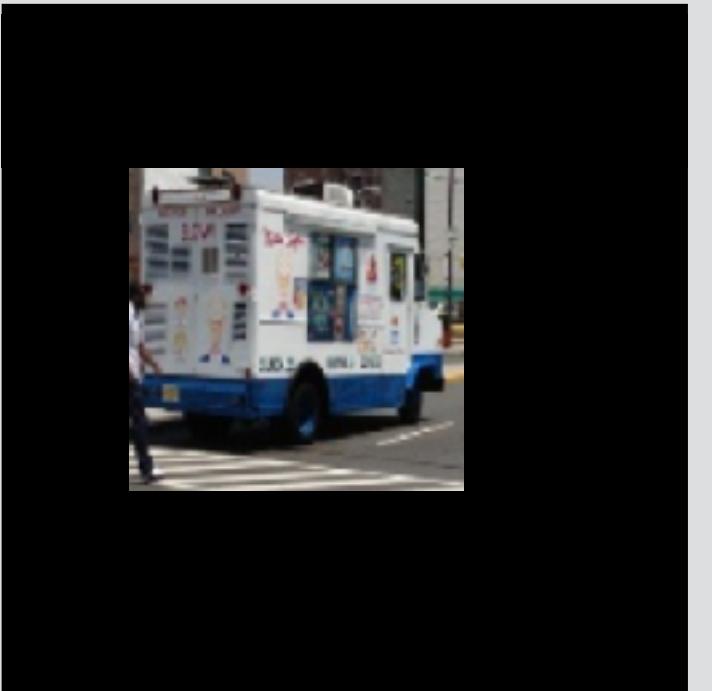
left



color



*black*

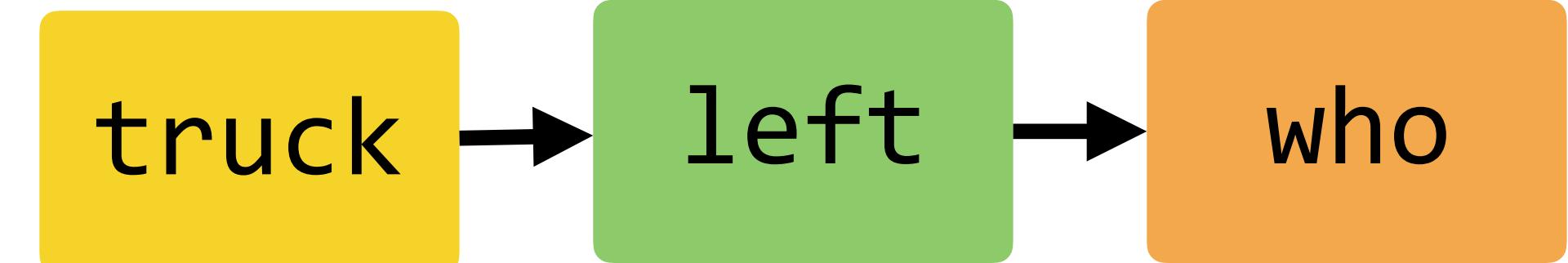


*white*

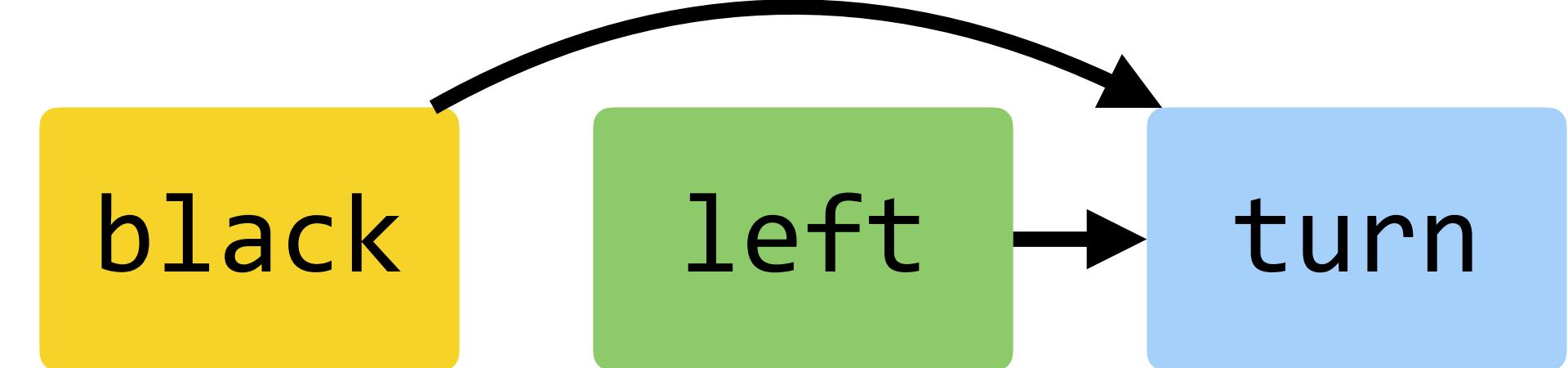


# Syntax and composition

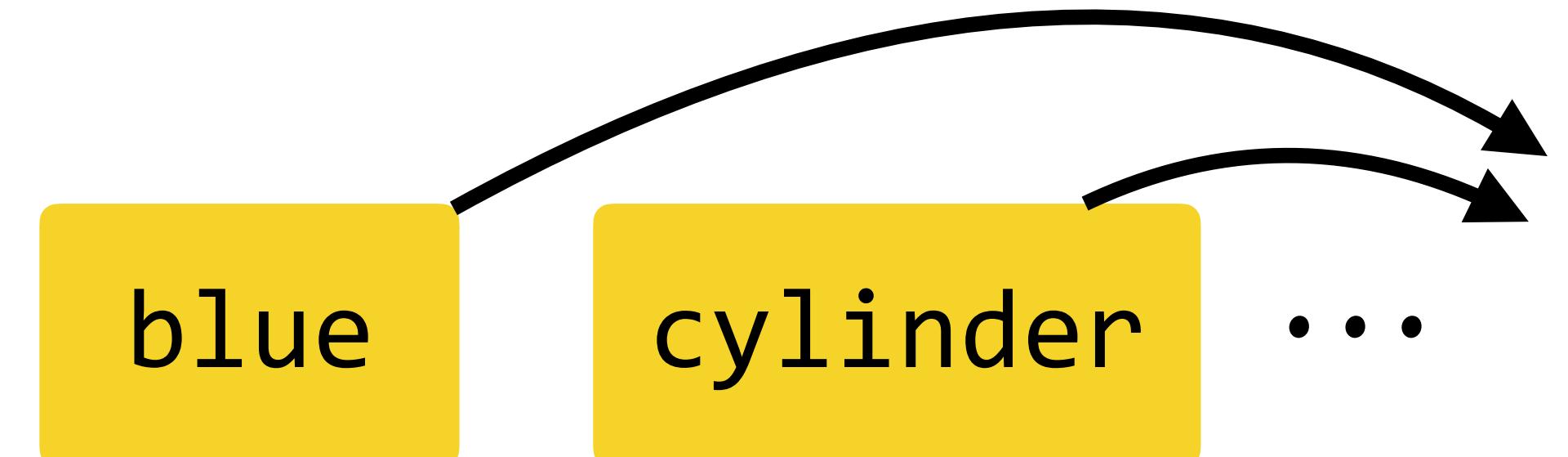
[Who is [left of the truck]]?

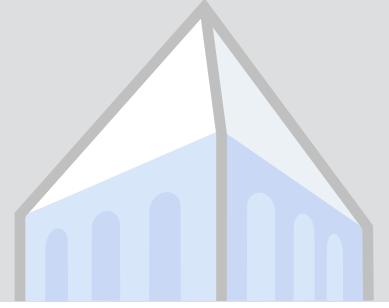


[Turn [left] [at the black hallway]].

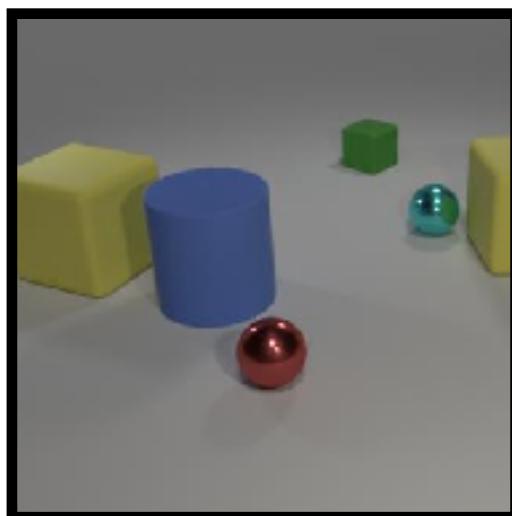
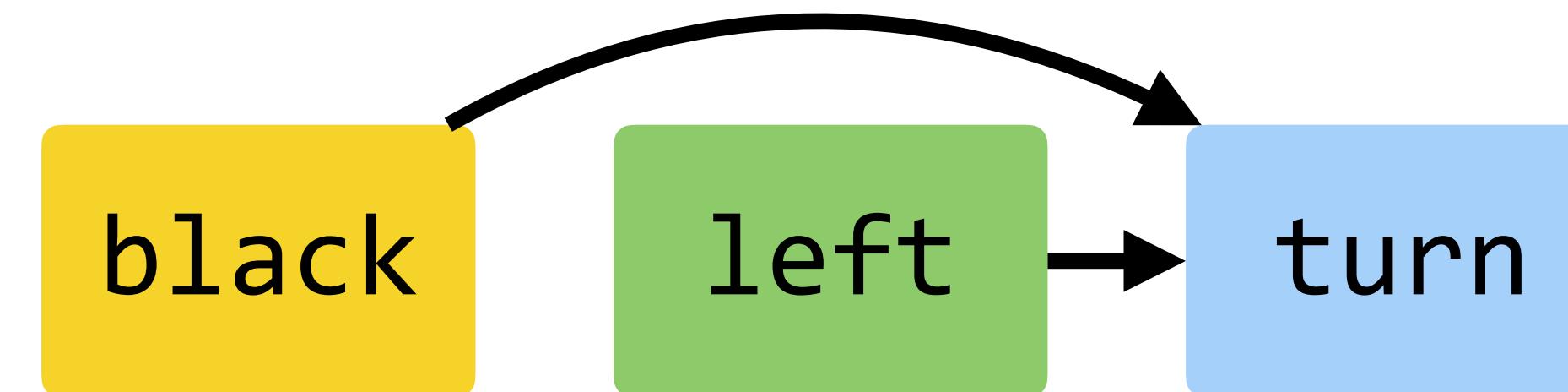
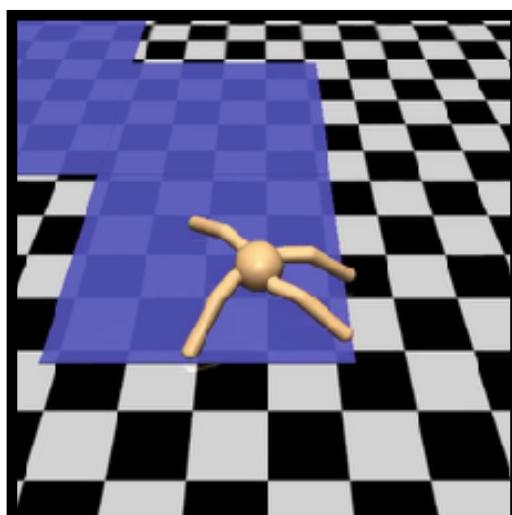
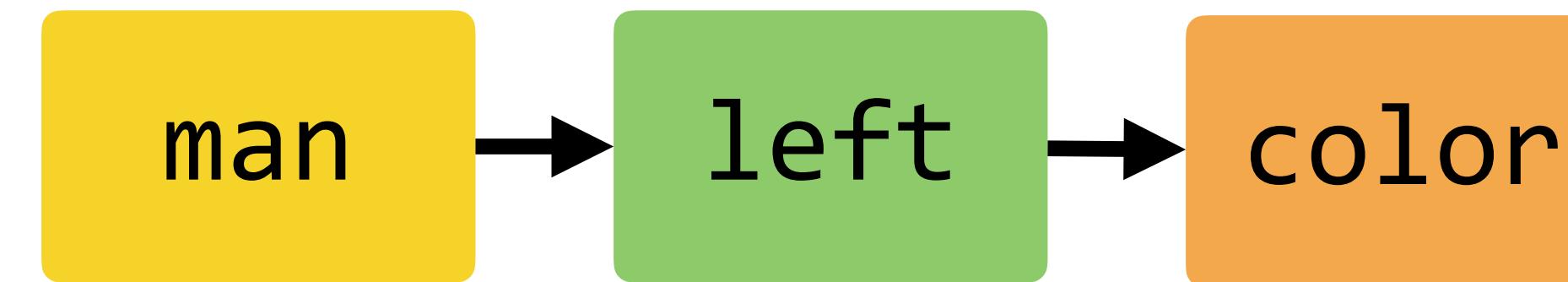


[Does the [blue cylinder] have the [same material as the [big block [on the right side of [the red metallic thing]]]]?]



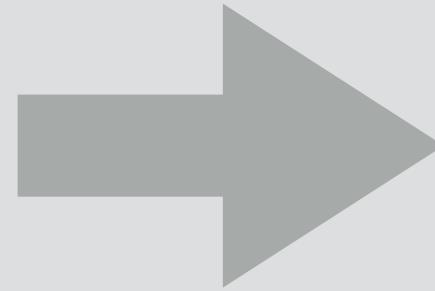
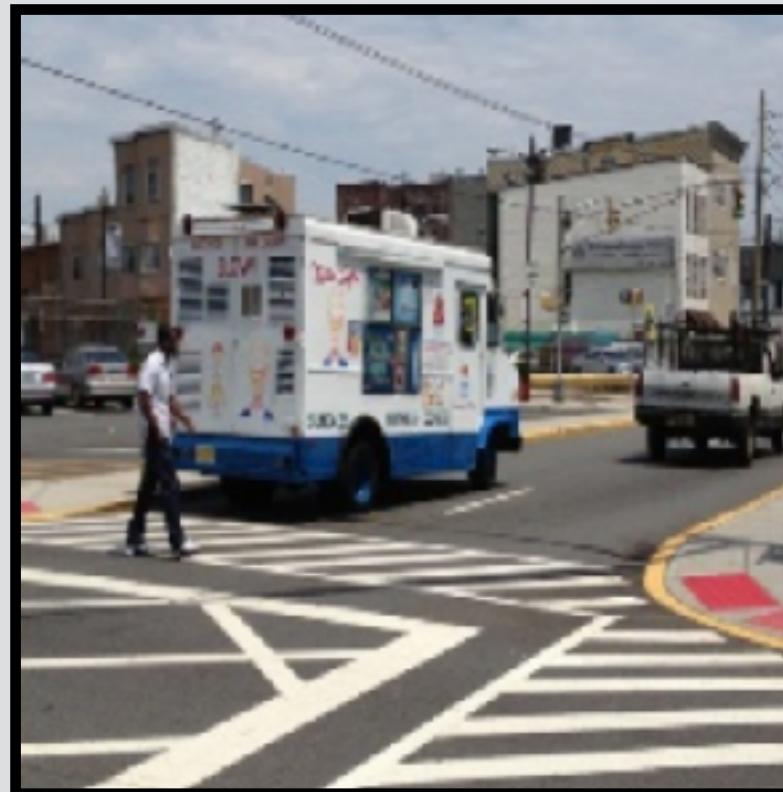


# Learning reusable abstractions



# LANGUAGE & REASONING

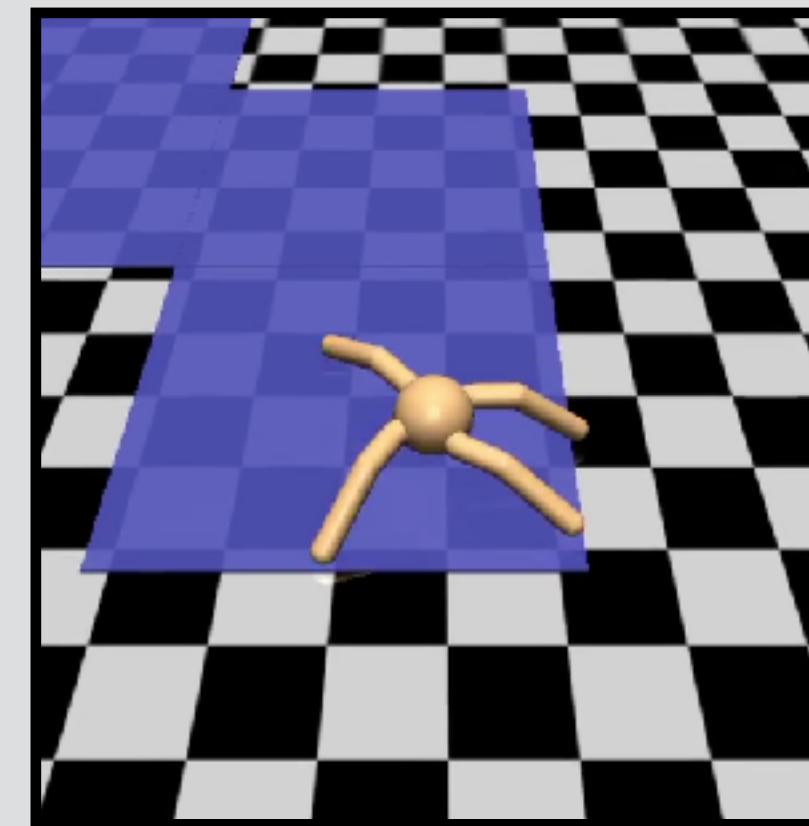
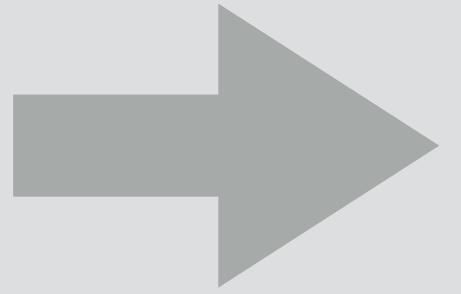
*What does the truck  
on the left sell?*



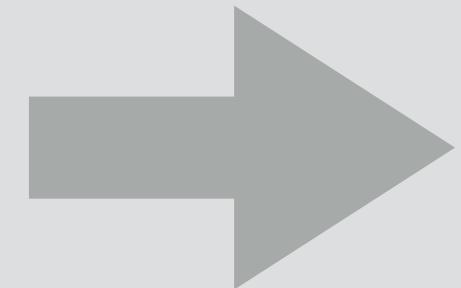
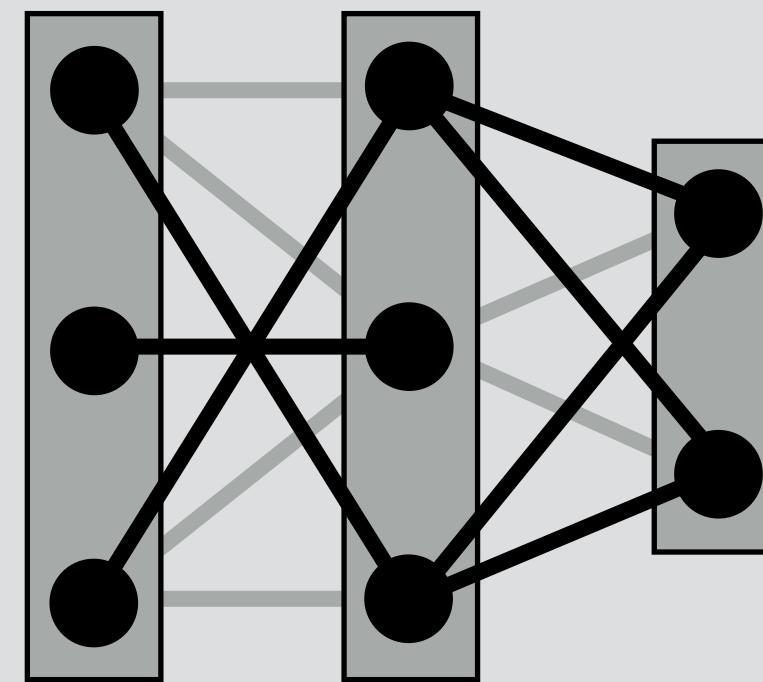
*ice cream*

# LANGUAGE & LEARNING

*Go up, then go left.*



# LANGUAGE & BELIEF



*large bird,  
black wings*

# LANGUAGE & REASONING

## LEARNING BELIEF

**A** et al. *Neural Module Networks*. CVPR 16.

**A** et al. *Learning to Compose Neural Networks for Question Answering*. NAACL 16.

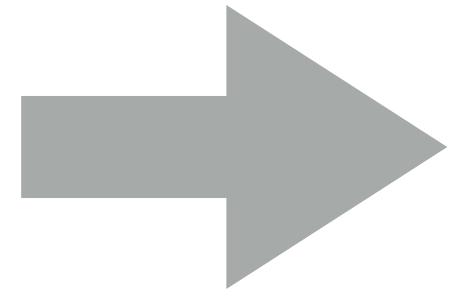
Hu, Rohrbach, **A** et al. *Modeling Relationships in Referential Expressions [...]*. CVPR 17.

Hu, **A** et al. *Learning to Reason: End-to-End Module Networks [...]*. ICCV 17.

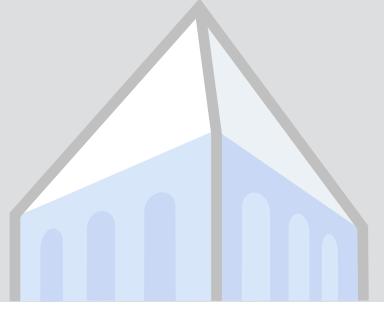


# Answering questions

*What color is  
the necktie?*



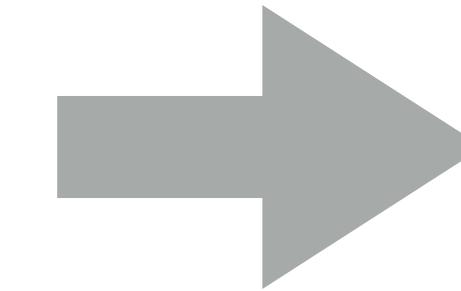
*yellow*



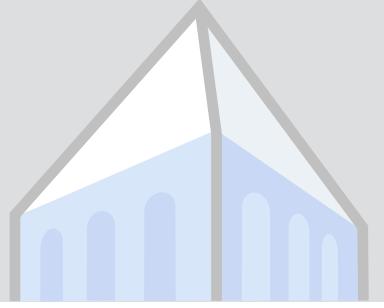
# Answering questions

*What rivers  
are in South  
Carolina?*

name	type	coastal
<i>Columbia</i>	city	no
<i>Cooper</i>	river	yes
<i>Charleston</i>	city	yes



*Cooper*



# Answering questions

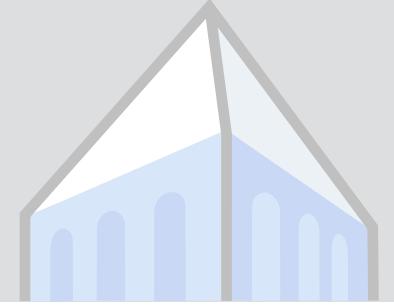
*What rivers are in South Carolina?*

$\lambda x. \text{river}(x) \wedge \text{in}(x, \text{SC})$

name	type	coastal
<i>Columbia</i>	city	no
<b>Cooper</b>	river	yes
<i>Charleston</i>	city	yes

**prolog**

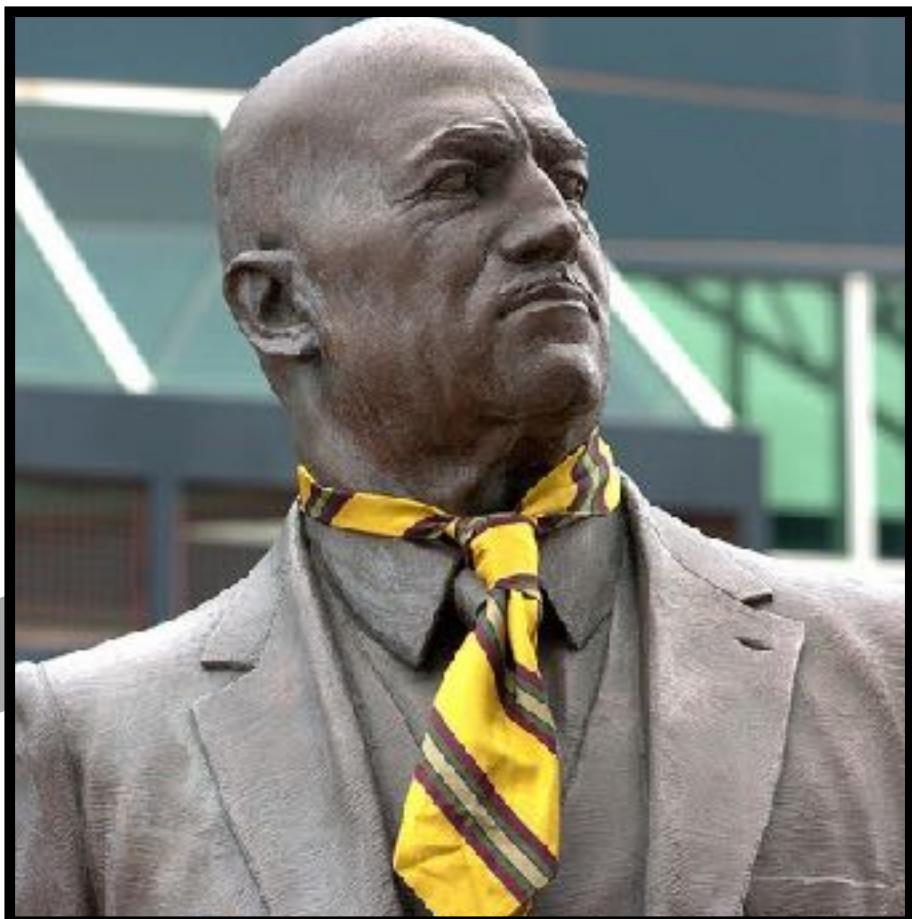
*Cooper*



# Answering questions

*What color is  
the necktie?*

$\lambda x. \exists y.$   
`color-of(x, y)`  
 $\wedge$  `necktie(y)`



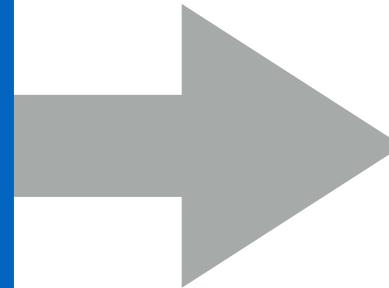
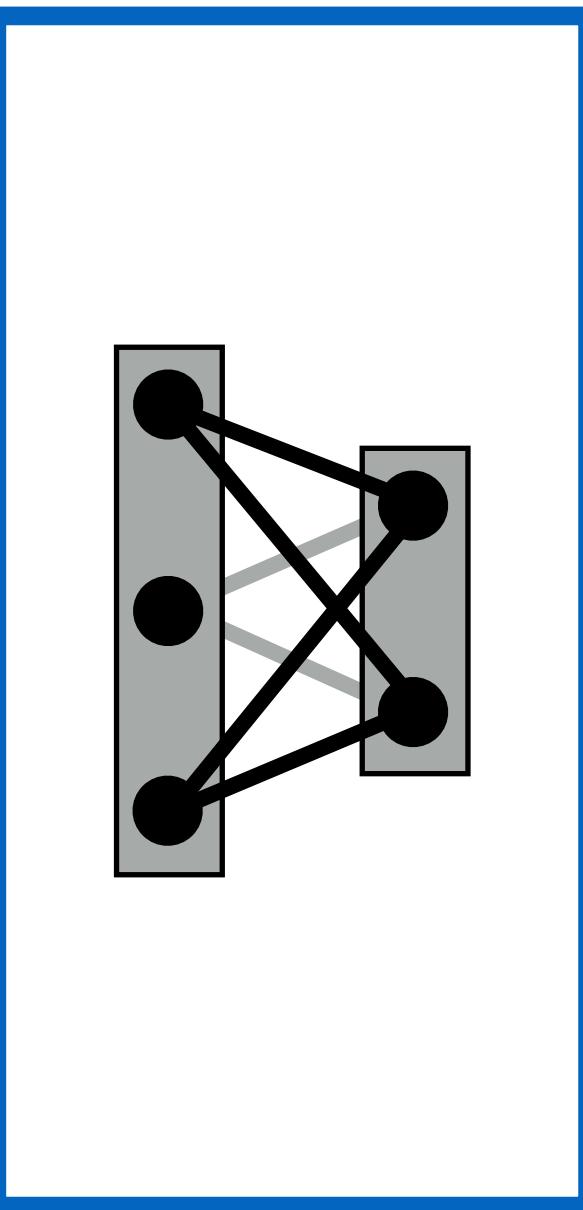
???

*yellow*



# Answering questions

*What color is  
the necktie?*

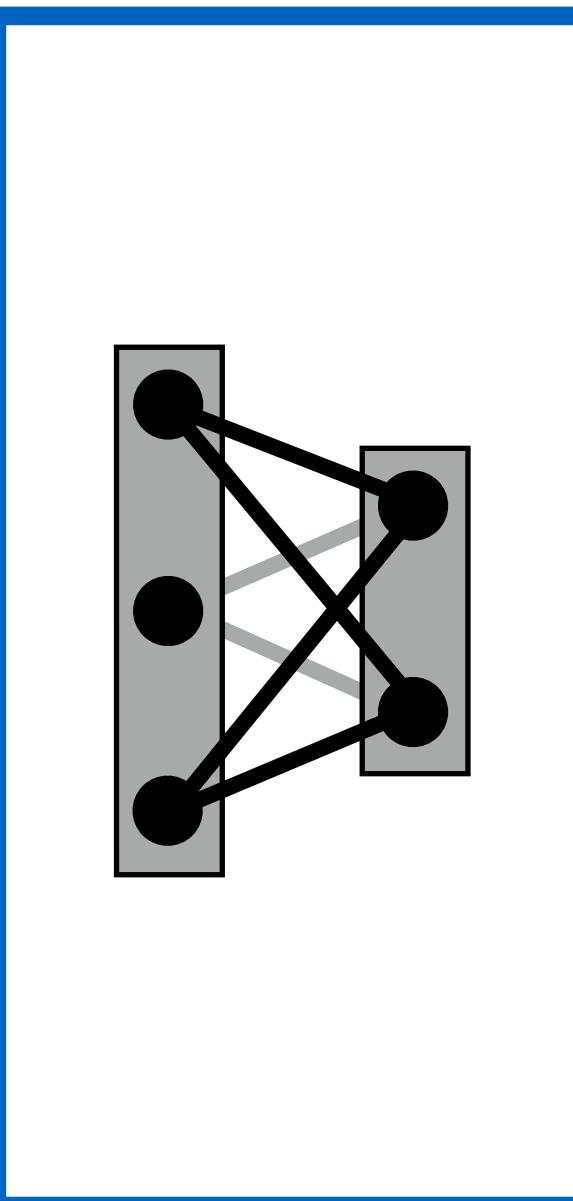


*yellow*

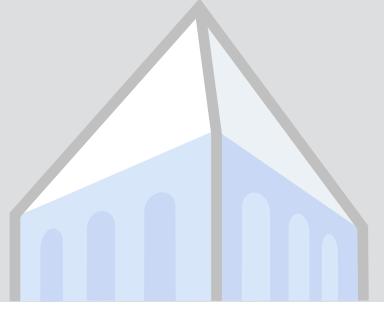


# Answering questions

*What color is  
the necktie?*

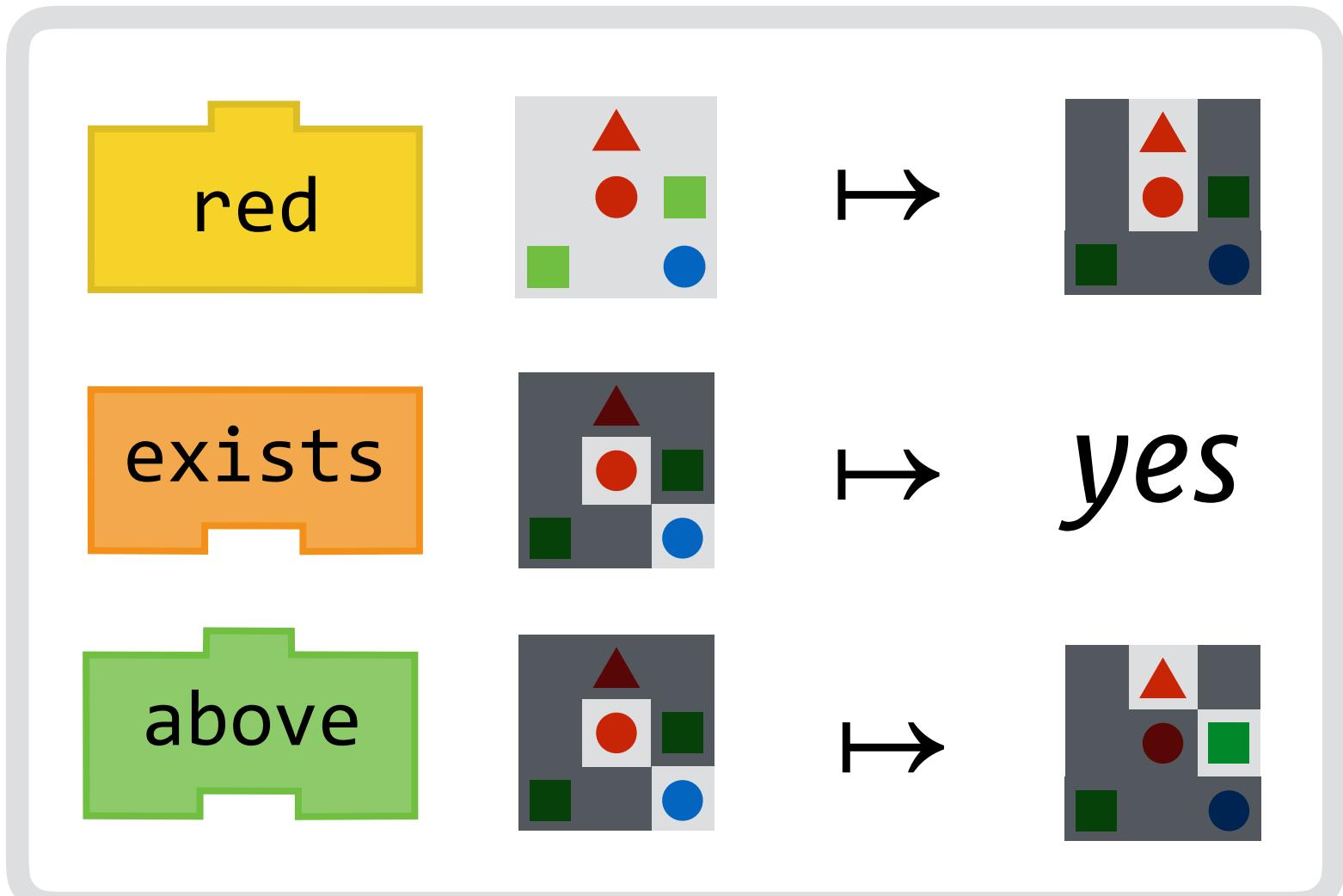
$$\lambda x. \exists y. \text{color-of}(x, y) \wedge \text{necktie}(y)$$


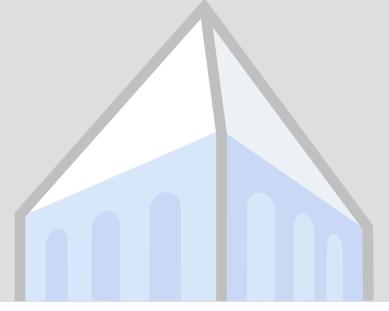
*yellow*



# Neural module networks

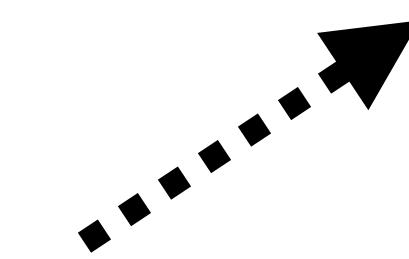
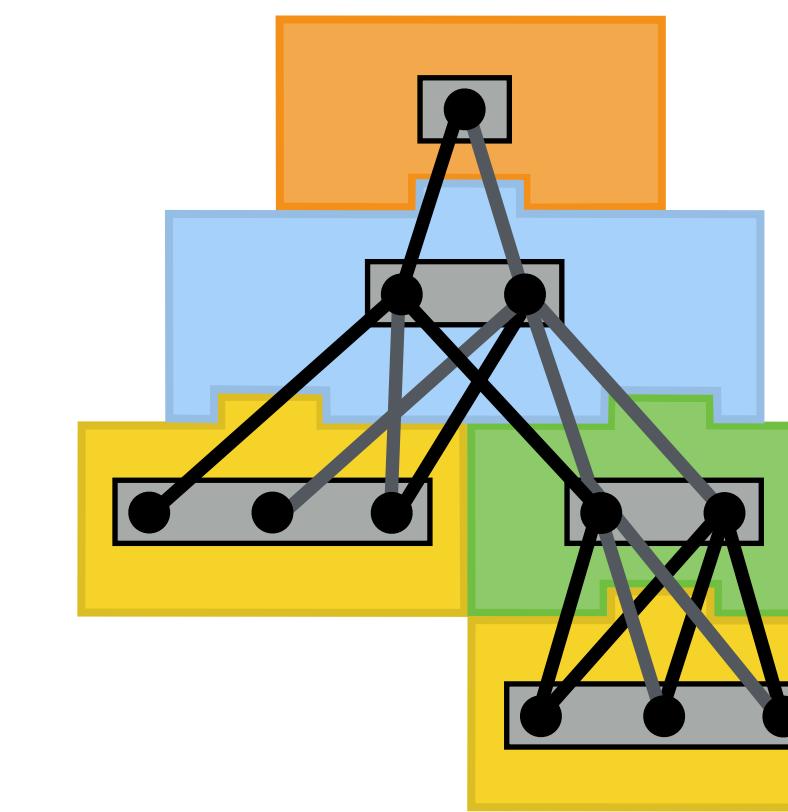
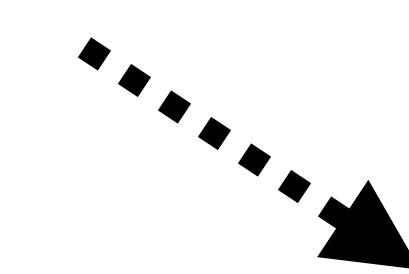
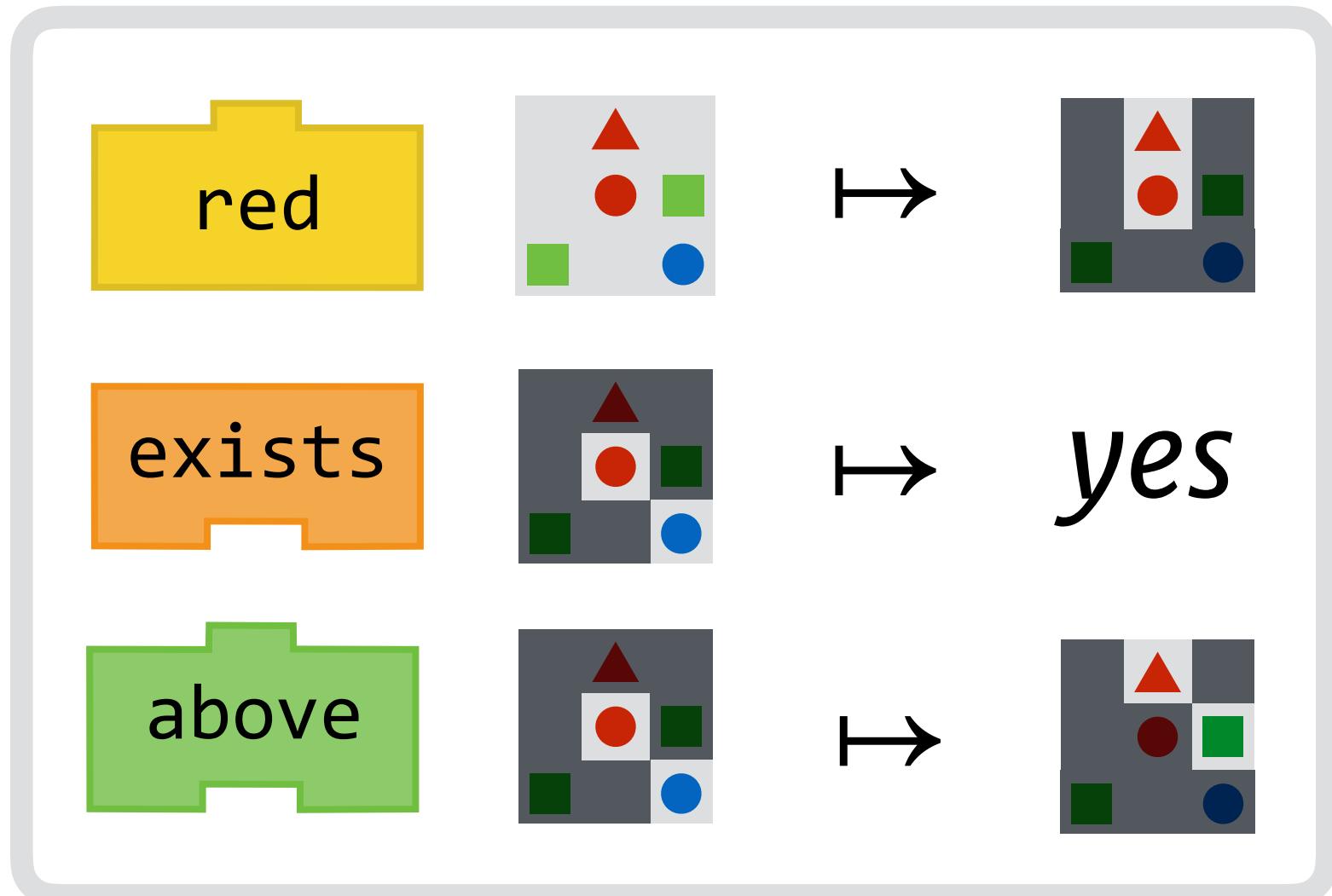
*Is there a red shape  
above a circle?*





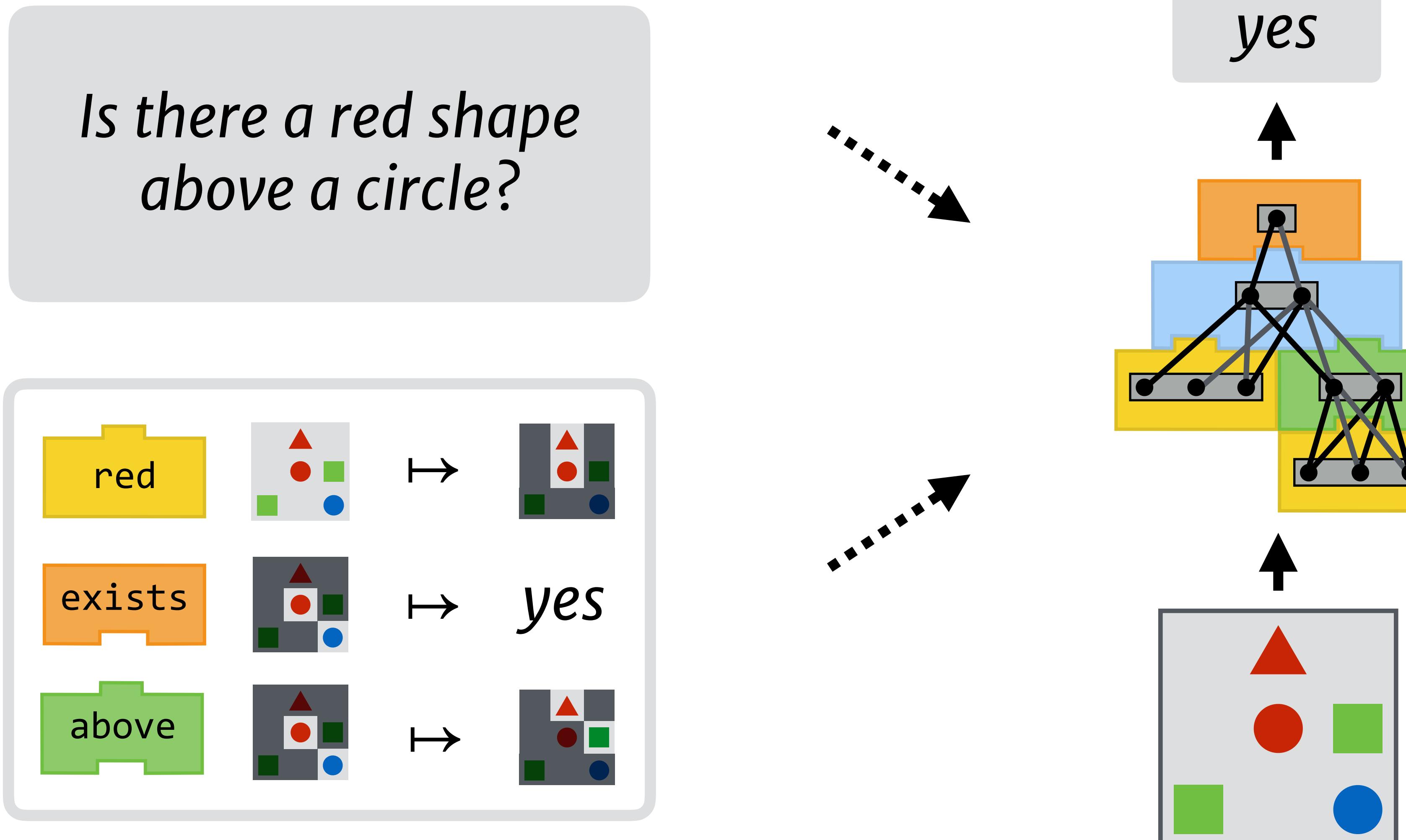
# Neural module networks

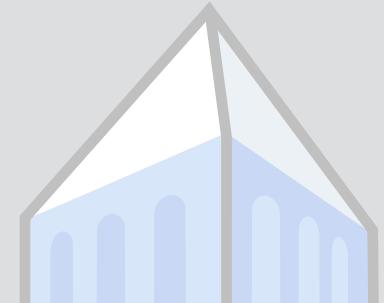
*Is there a red shape  
above a circle?*





# Neural module networks

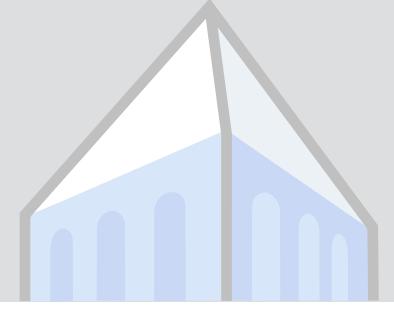




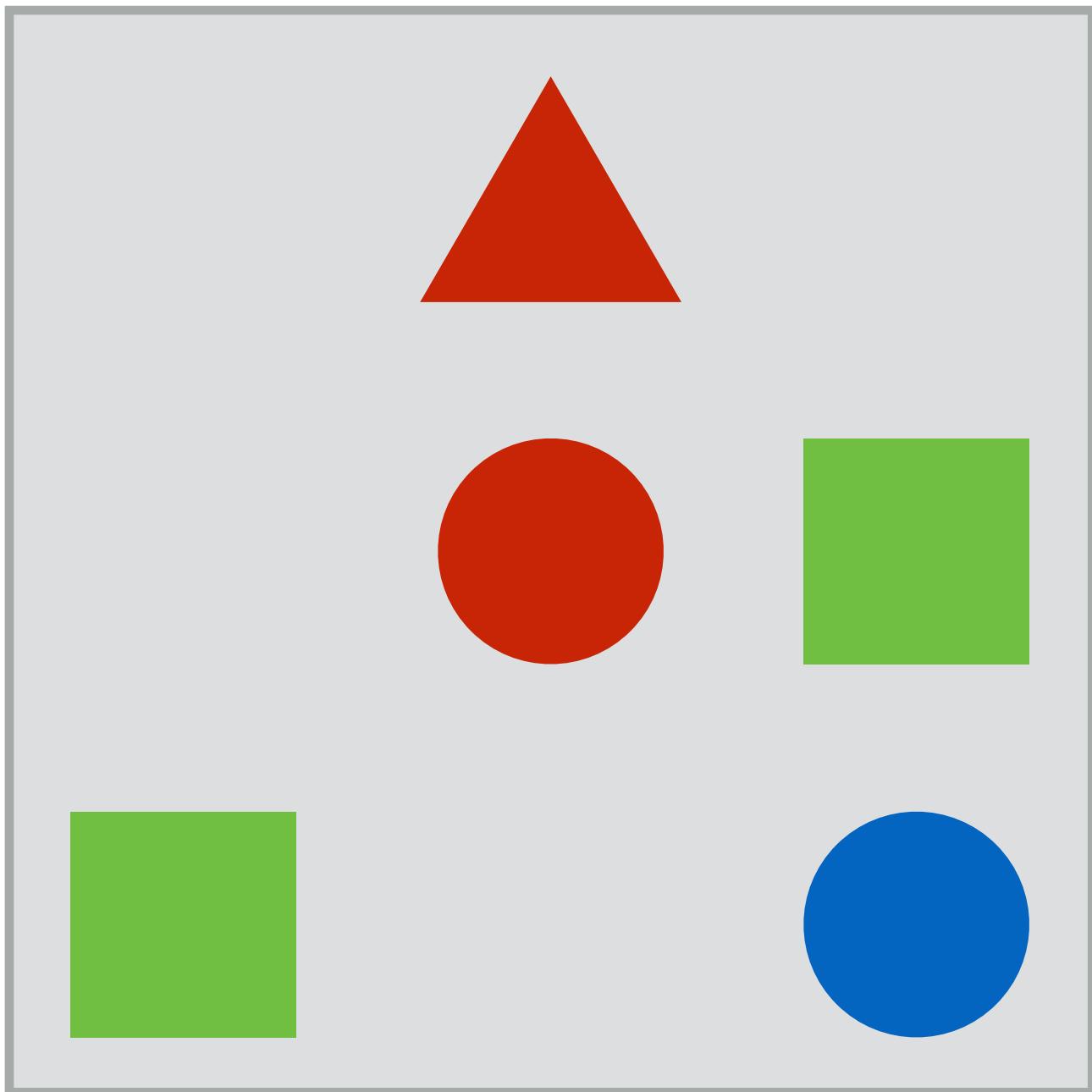
# Perceptual primitives



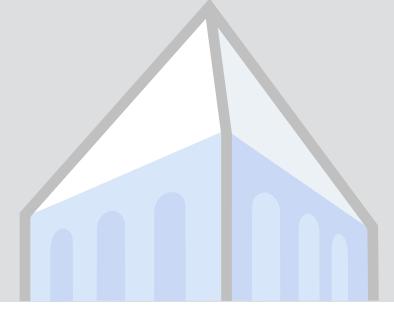
*What color is the necktie?*



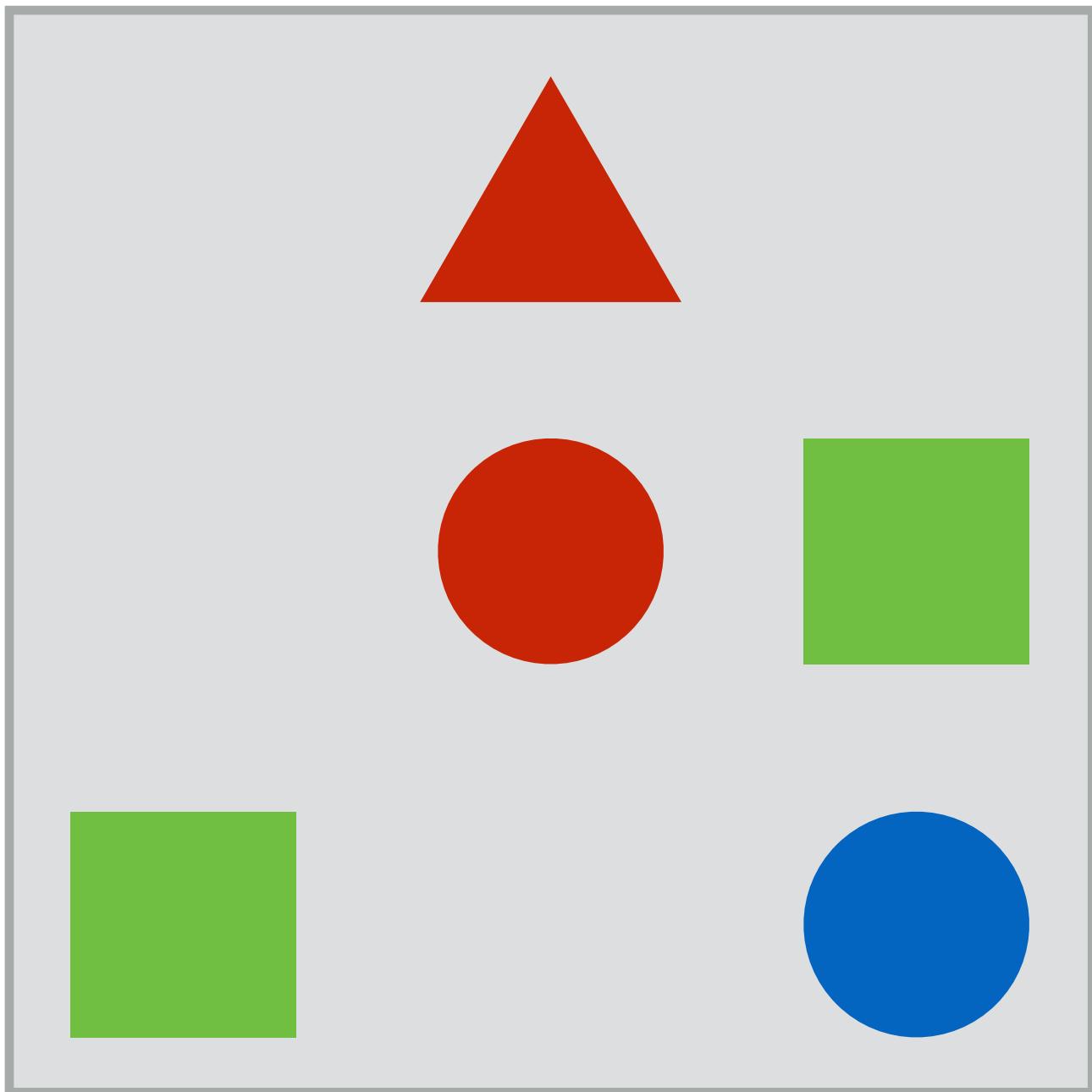
# Perceptual primitives



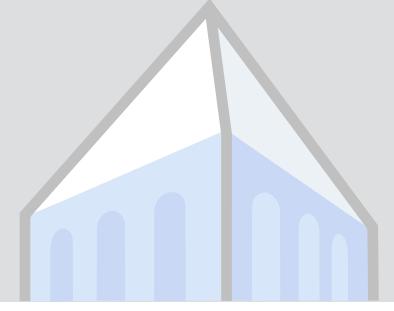
*Is there a red shape above a circle?*



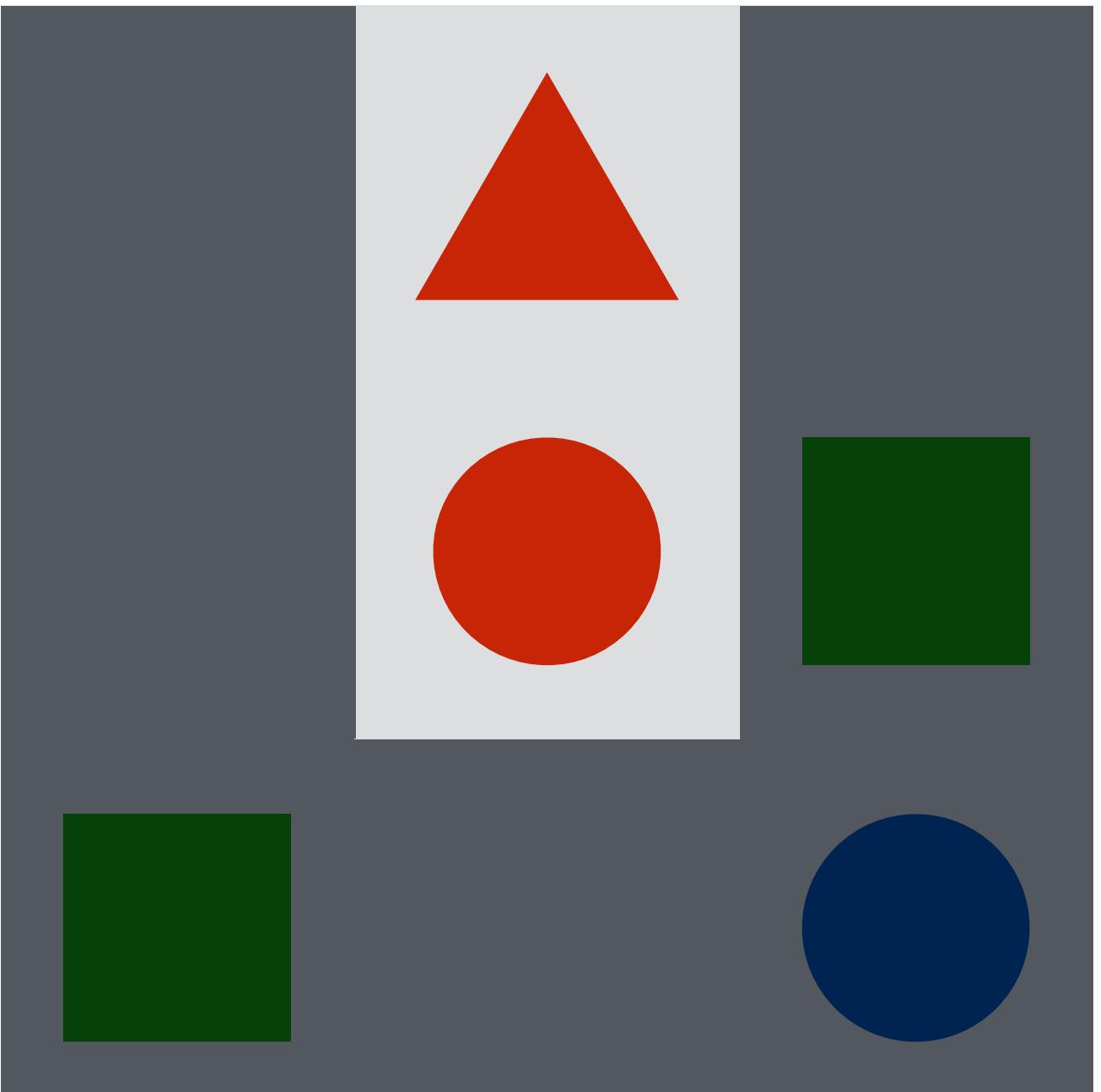
# Perceptual primitives



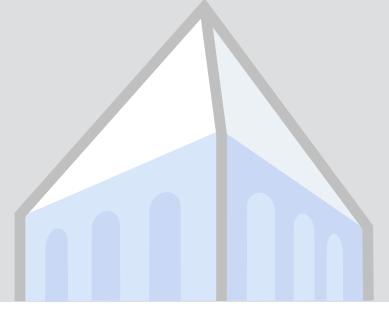
*Is there a **red** shape above a circle?*



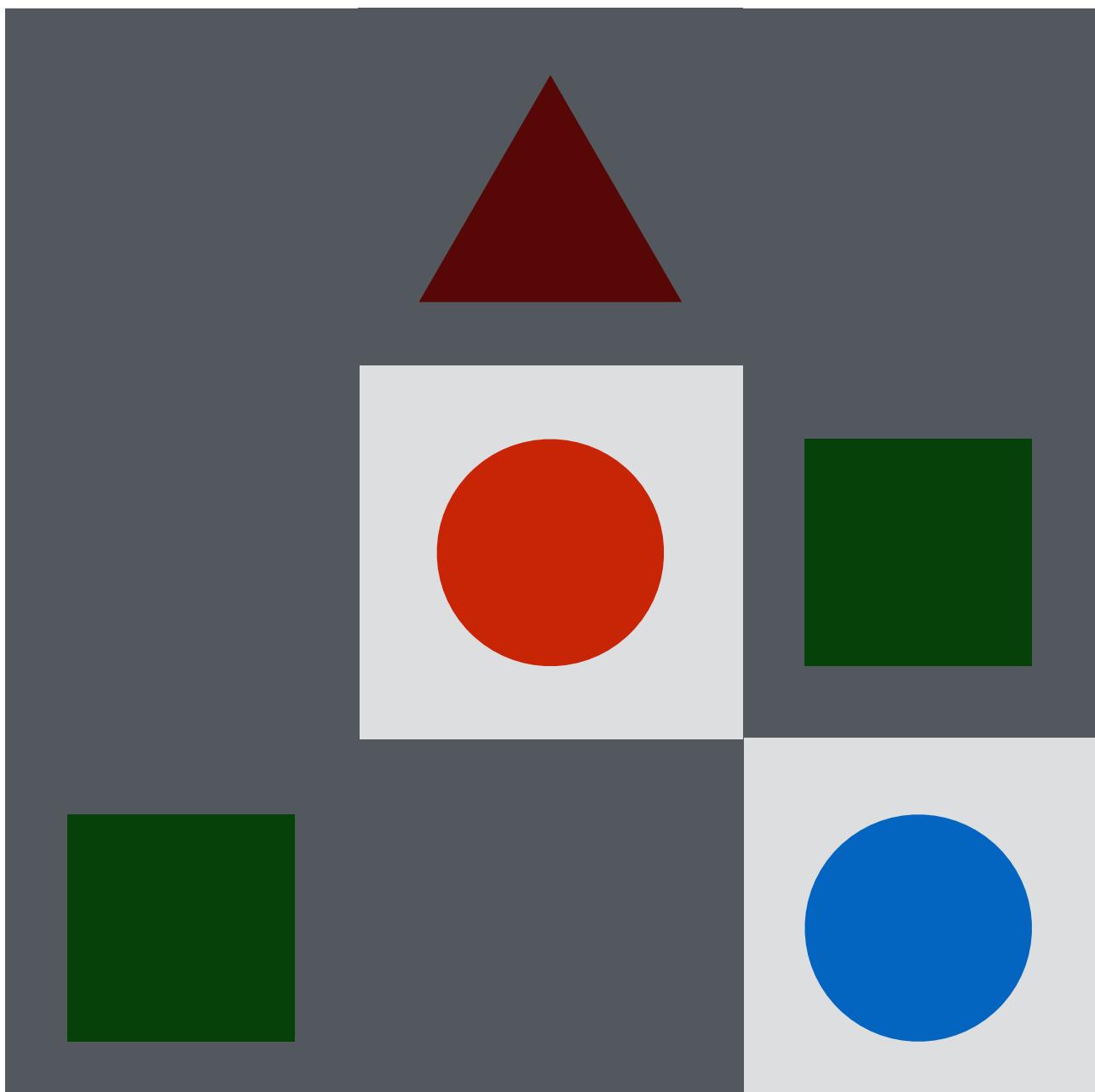
# Perceptual primitives



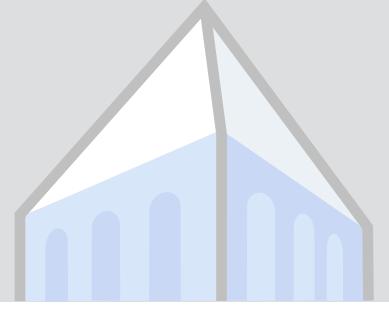
*Is there a **red** shape above a circle?*



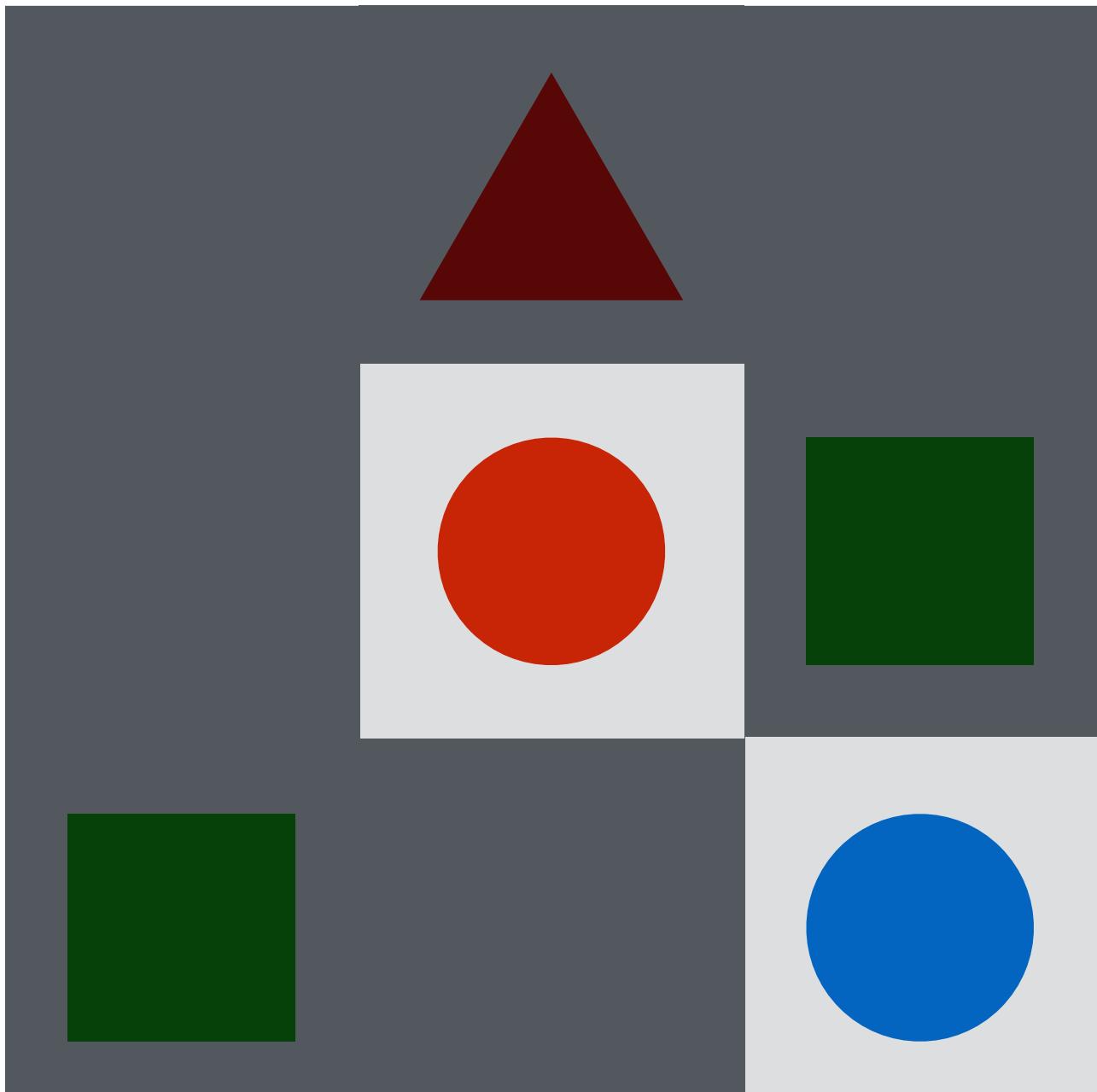
# Perceptual primitives



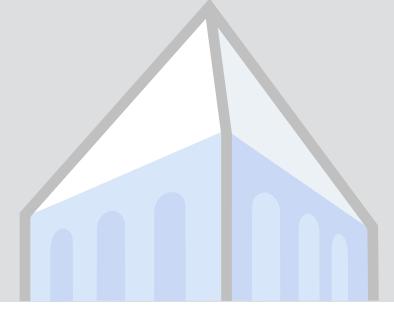
*Is there a red shape above a circle?*



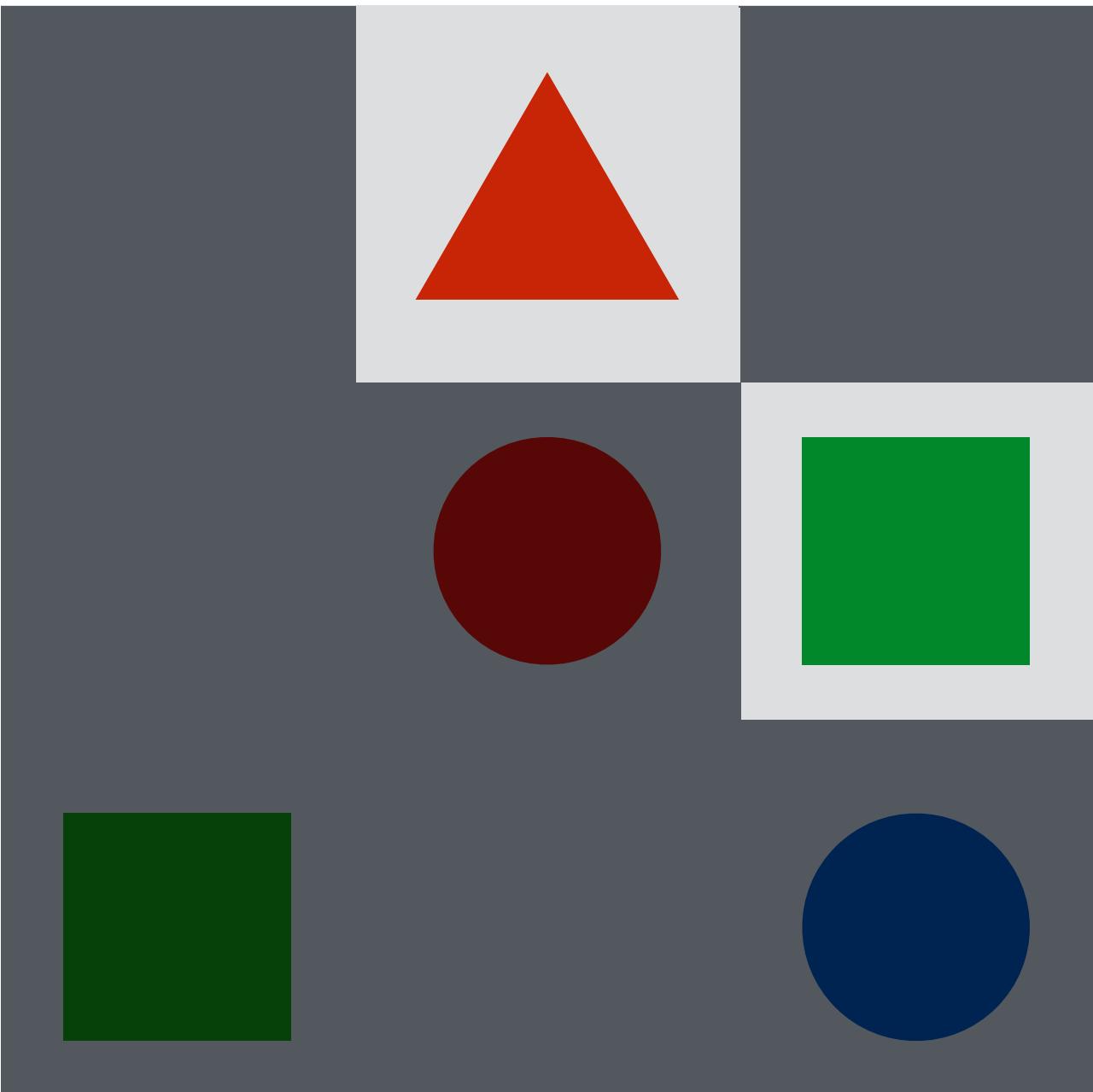
# Perceptual primitives



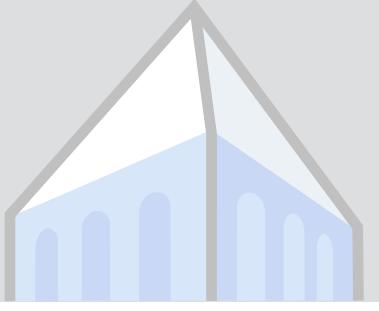
*Is there a red shape above a circle?*



# Perceptual primitives

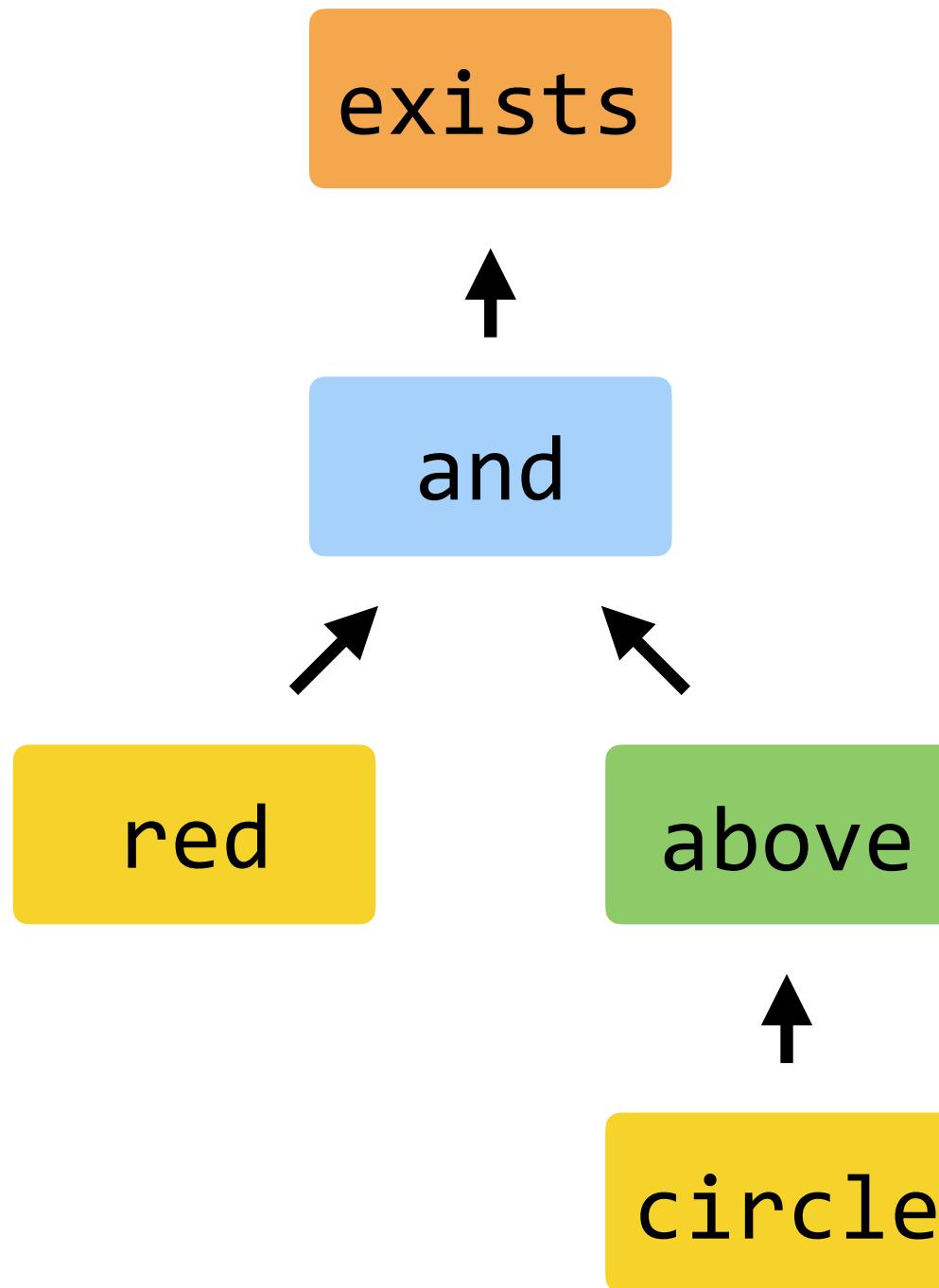
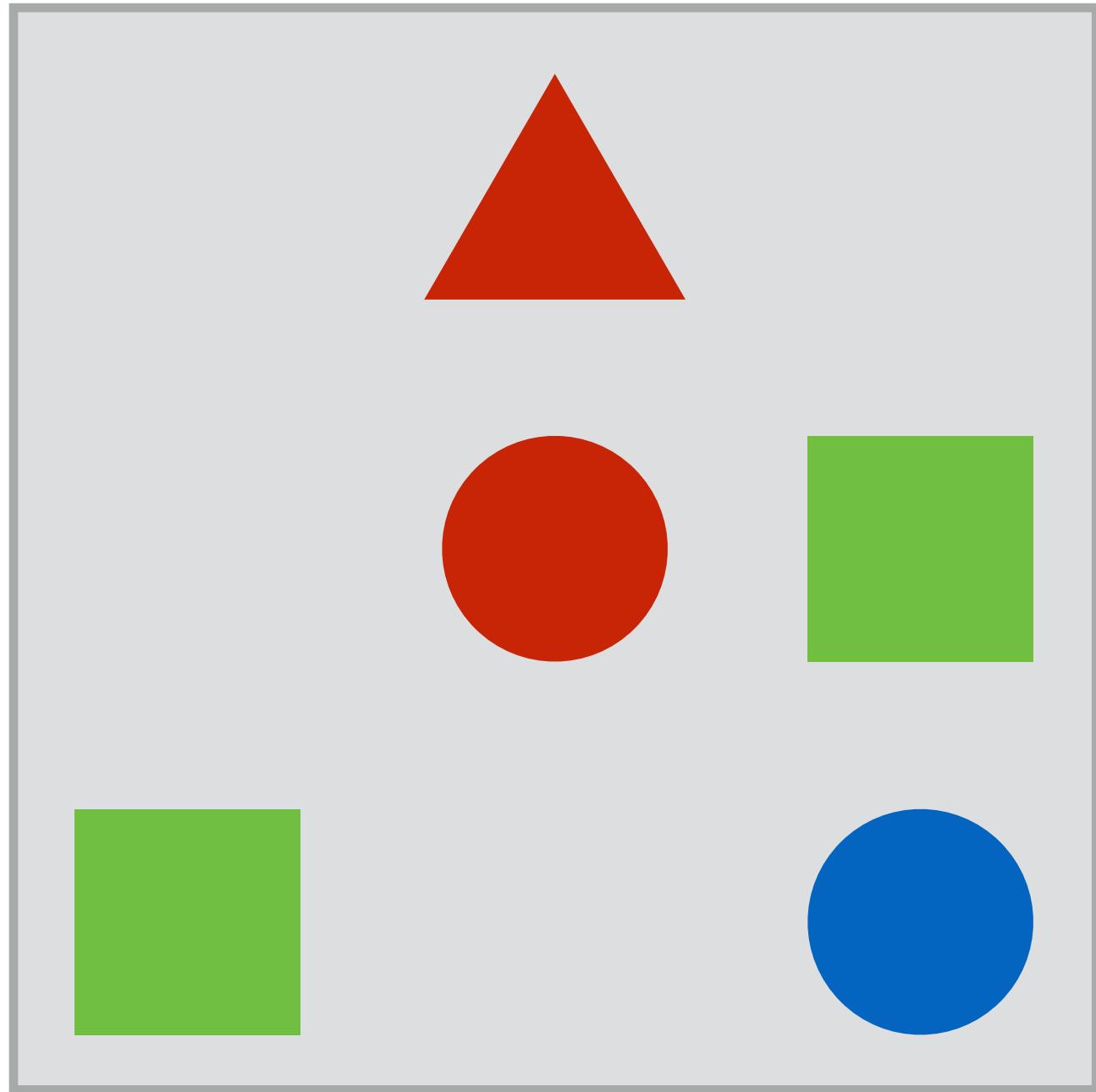


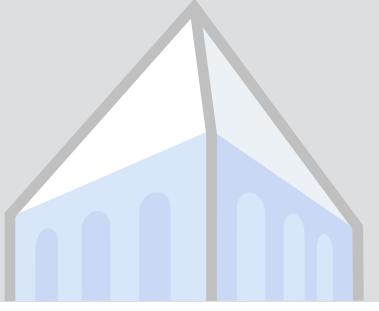
*Is there a red shape above a circle?*



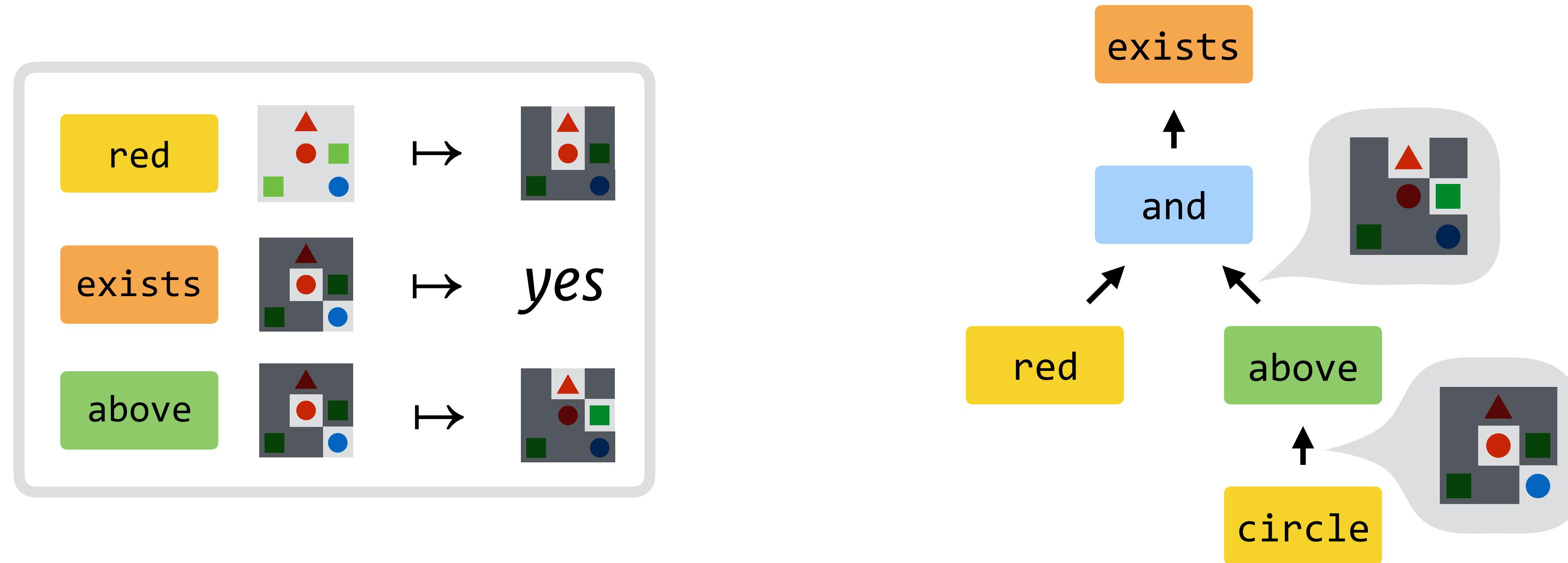
# Meanings are computations

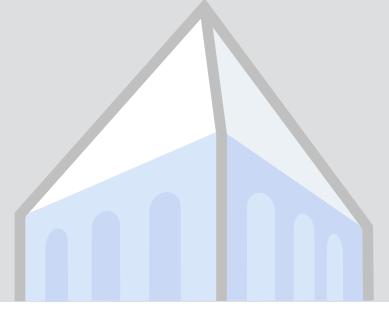
*Is there a red shape above a circle?*





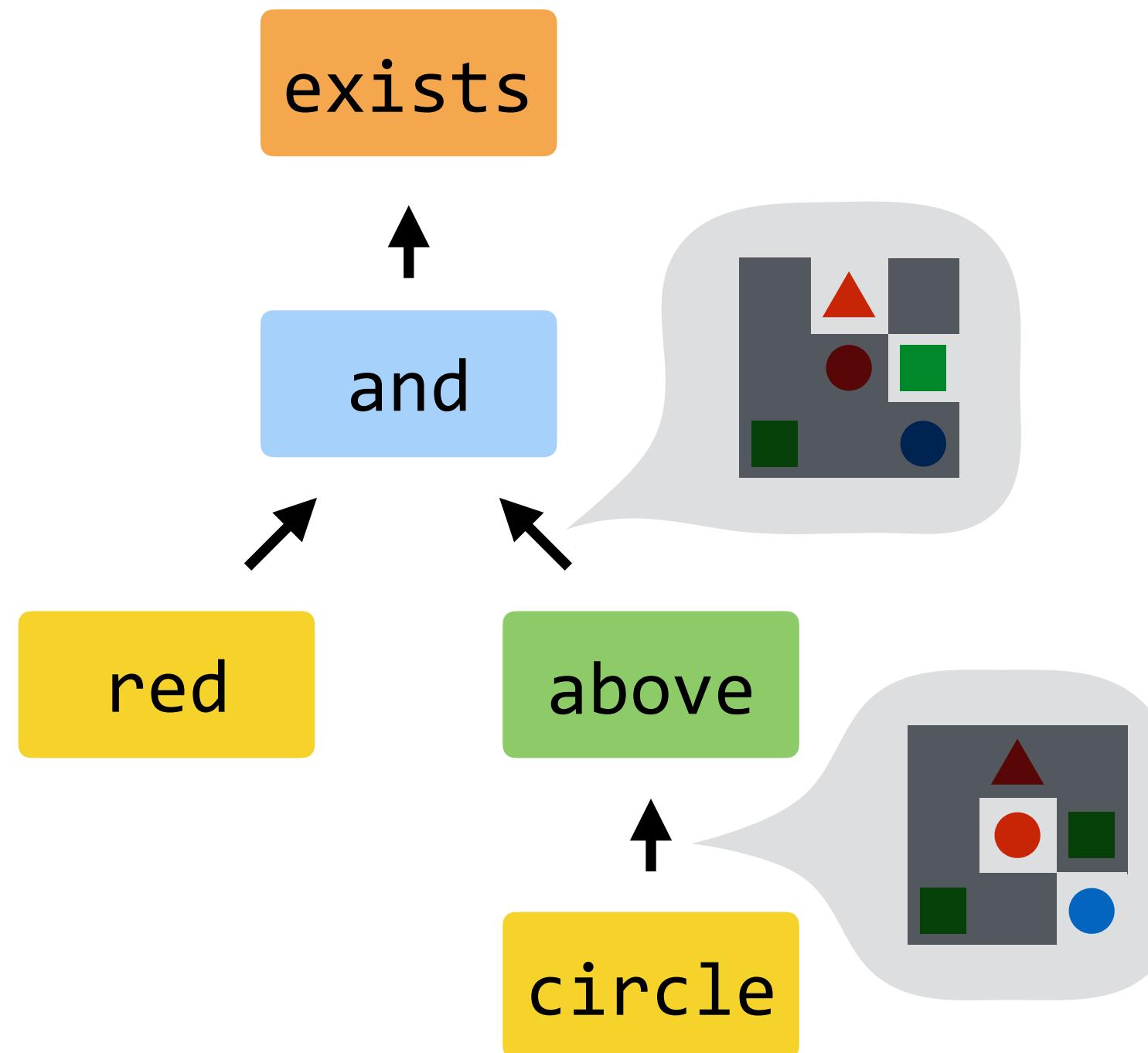
# Meanings are computations

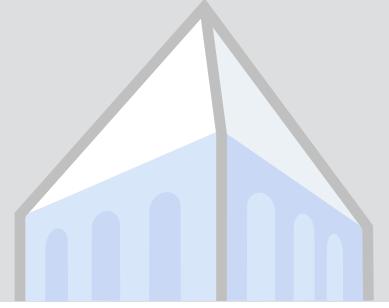




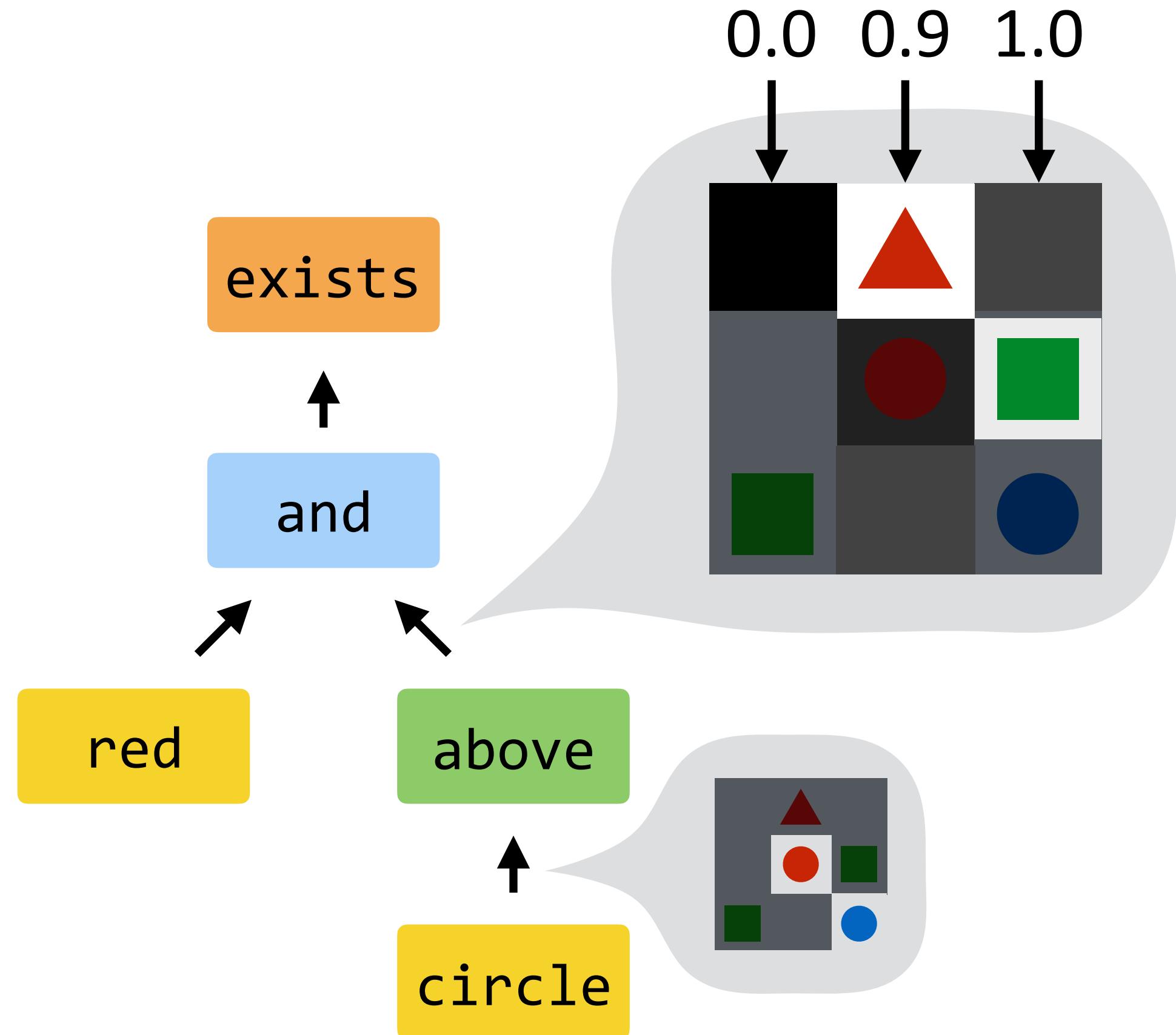
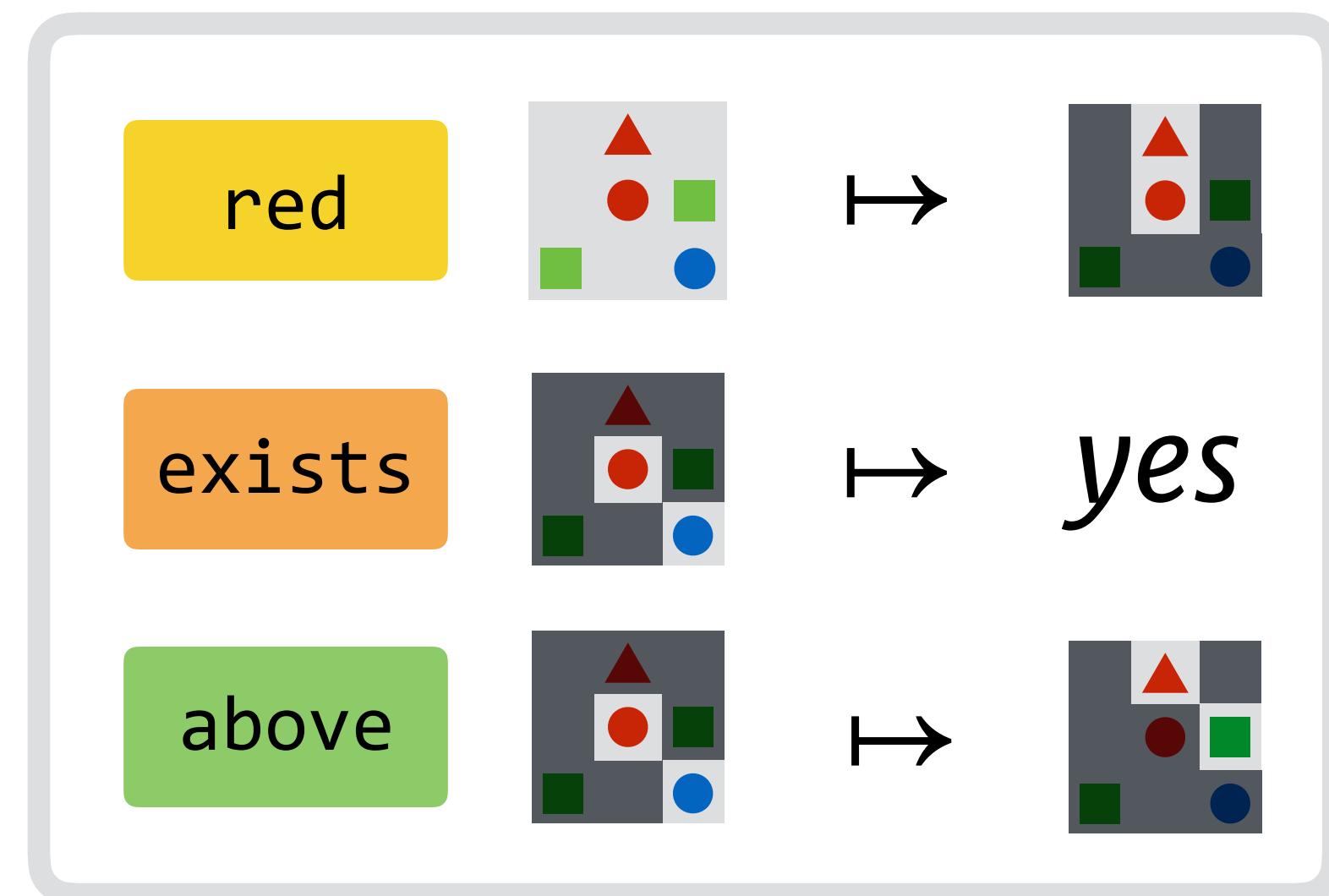
# Learning compositional operators

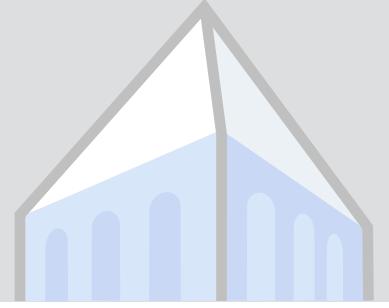
```
shapes.where(_.color == "red")  
  
d => d.nonEmpty ? true : false  
  
d => d.map(_.neighborAbove)
```



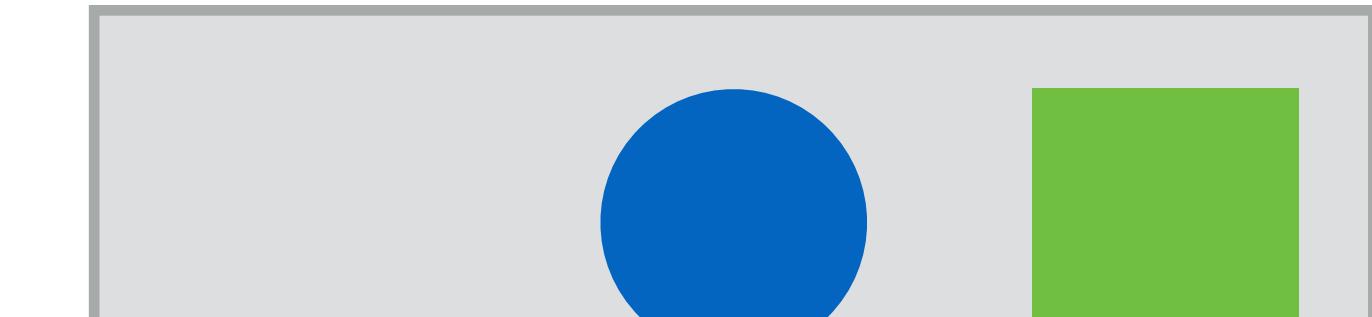
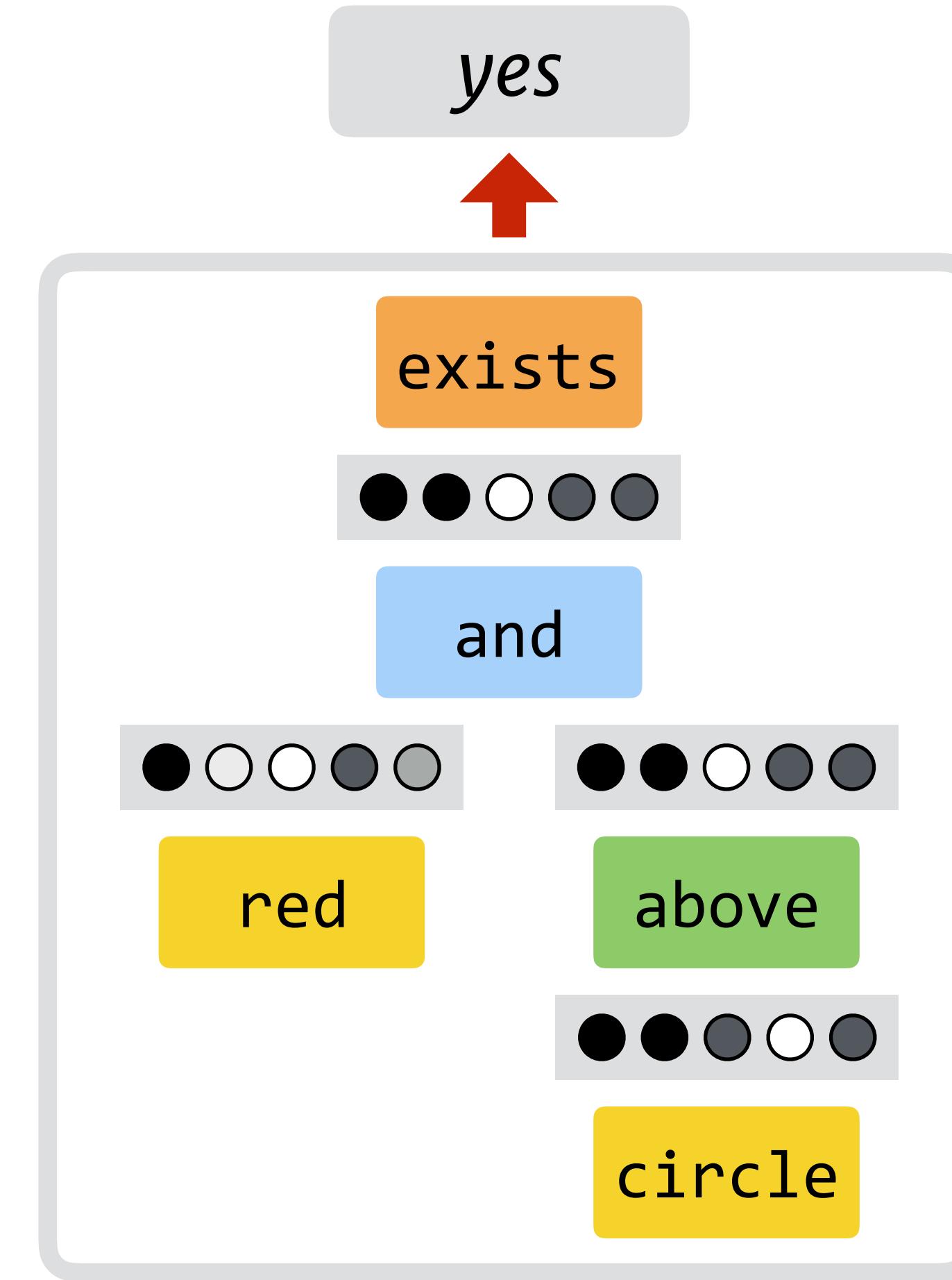
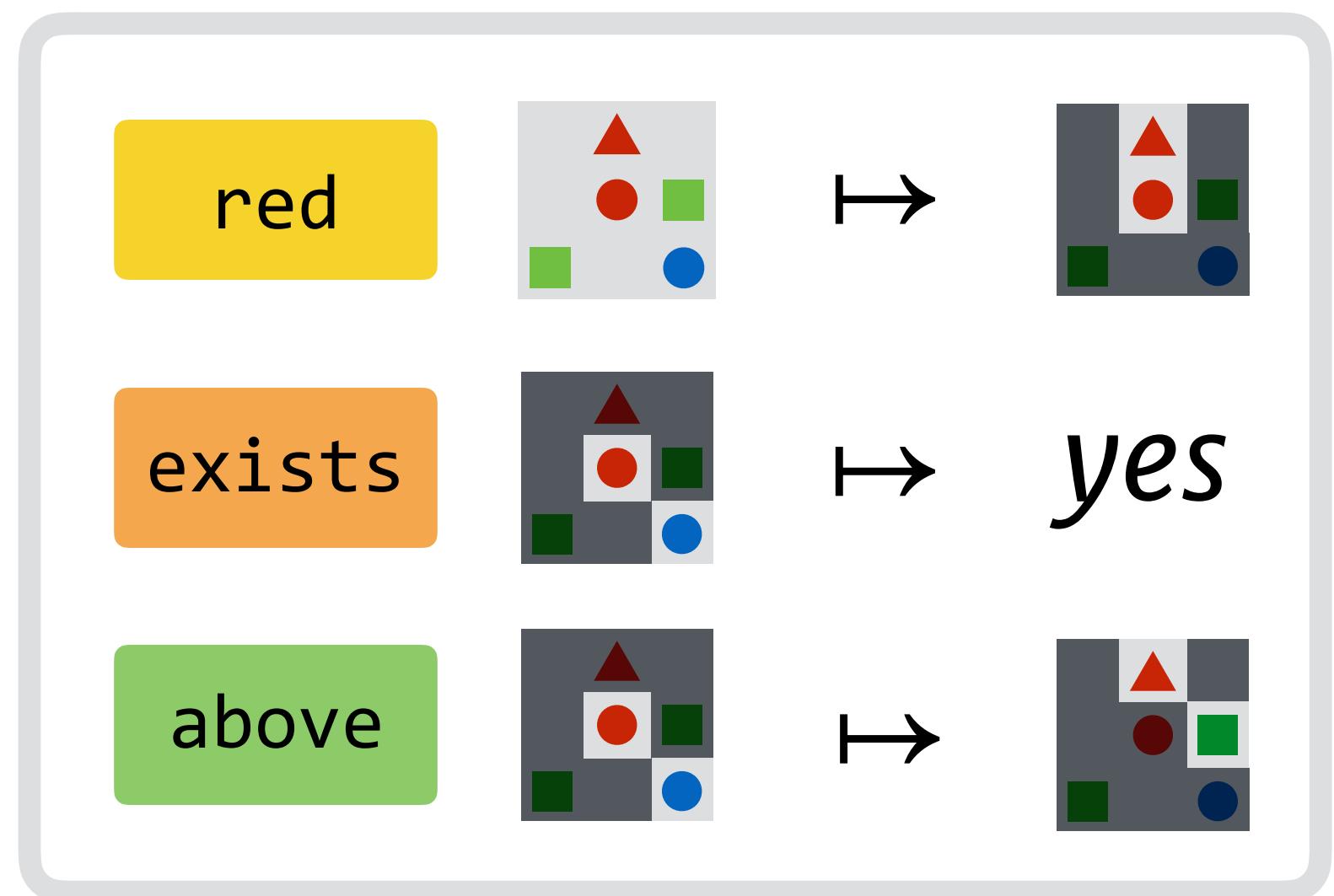


# Learning compositional operators



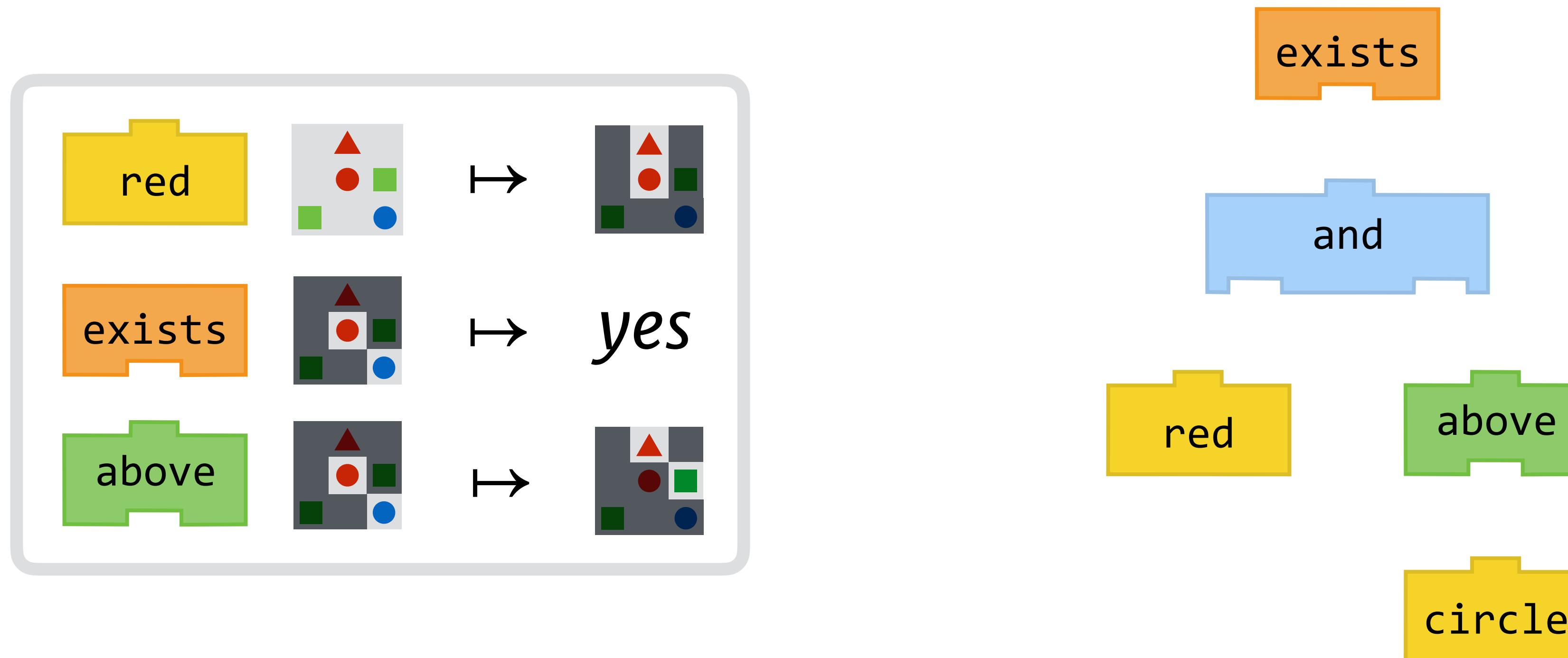


# Learning compositional operators



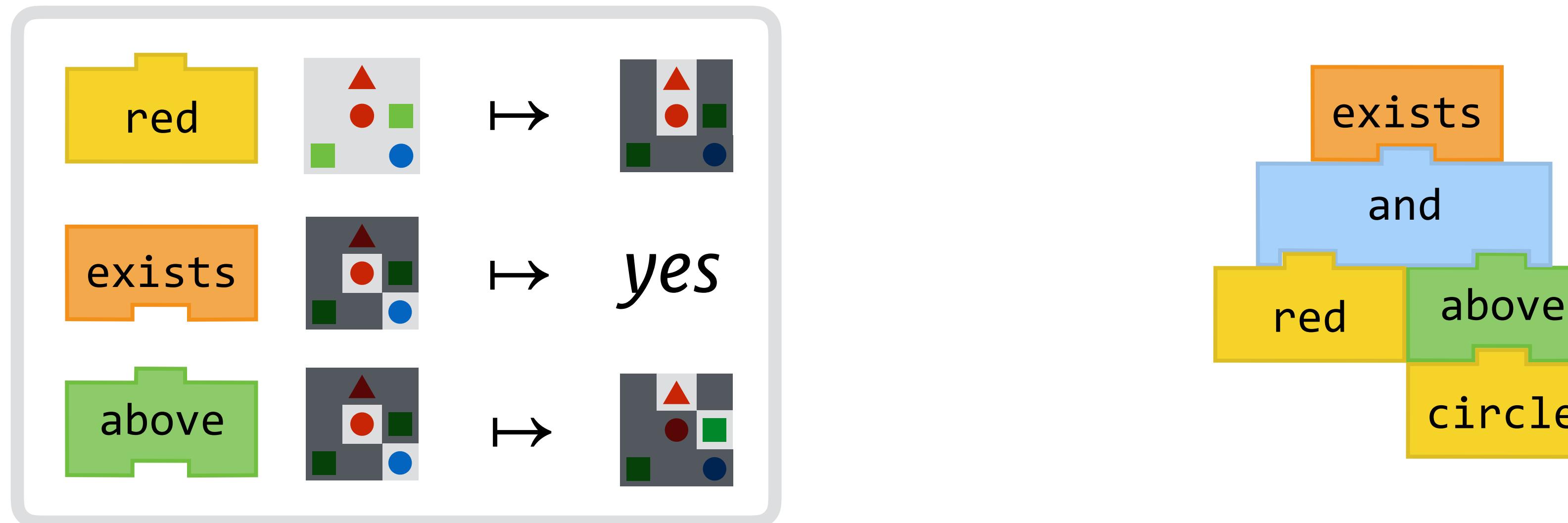


# Composing neural networks

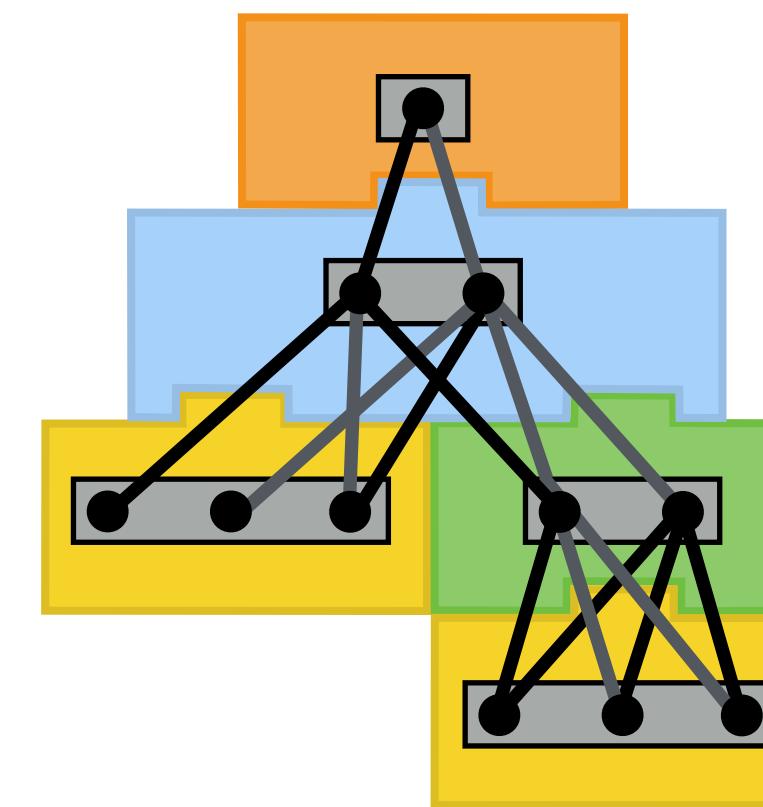
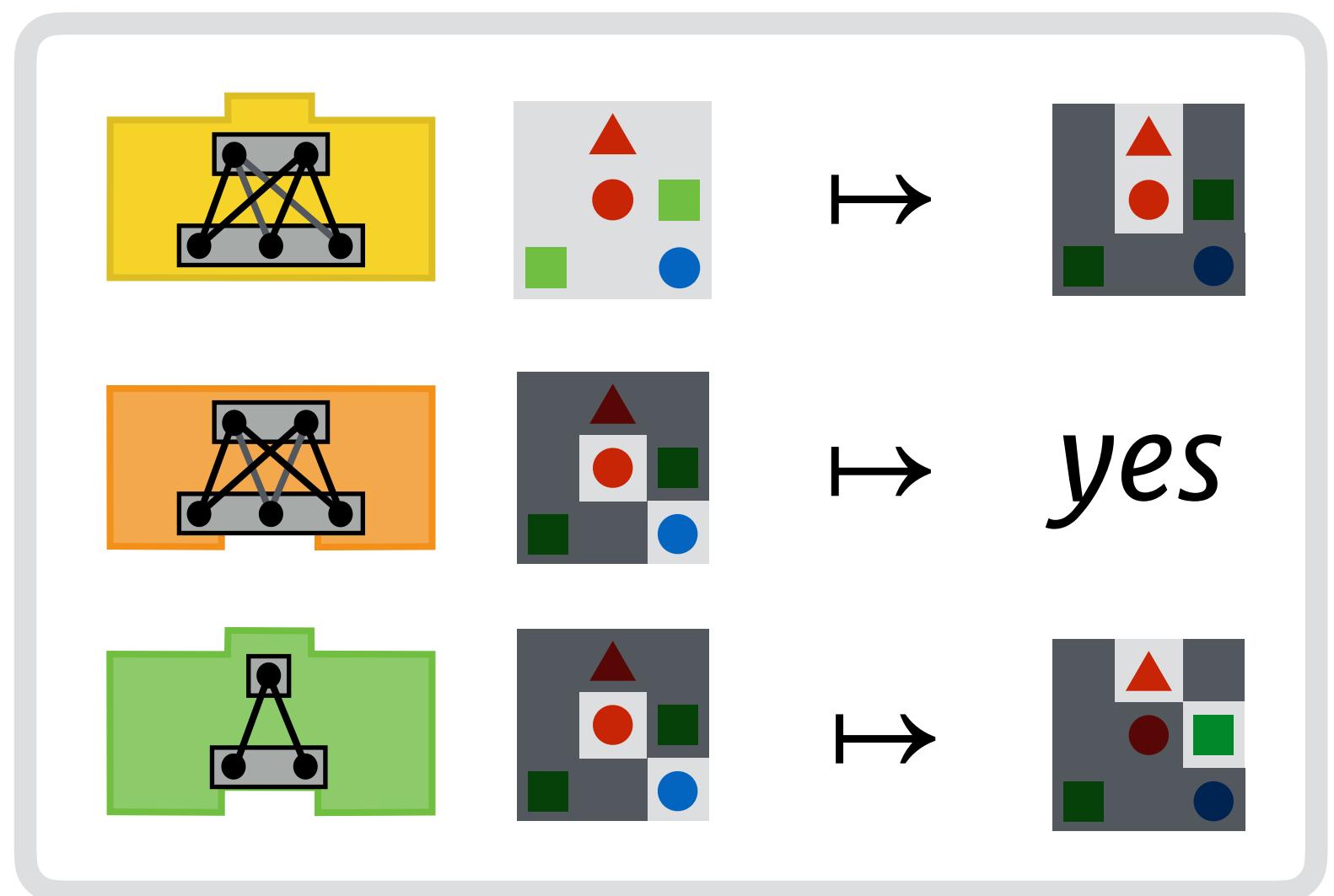




# Composing neural networks

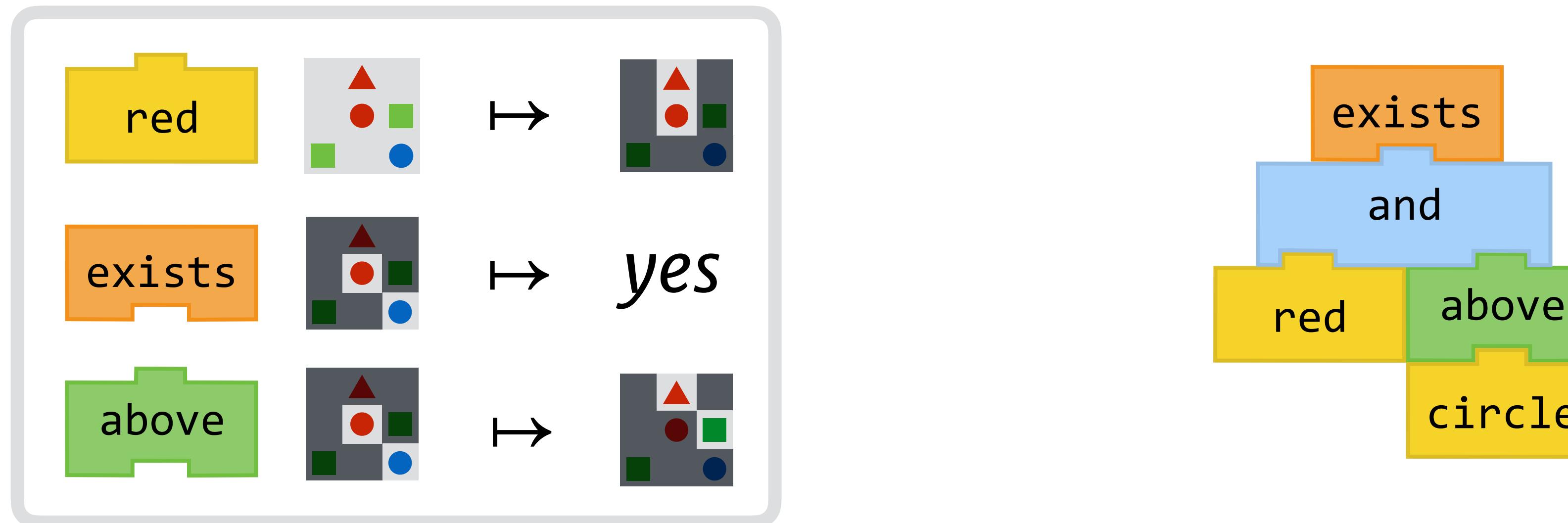


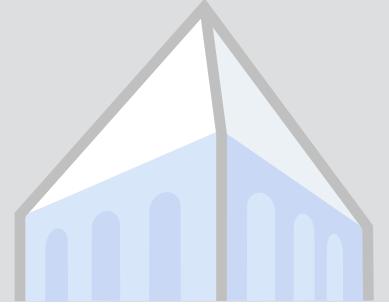
# Composing neural networks



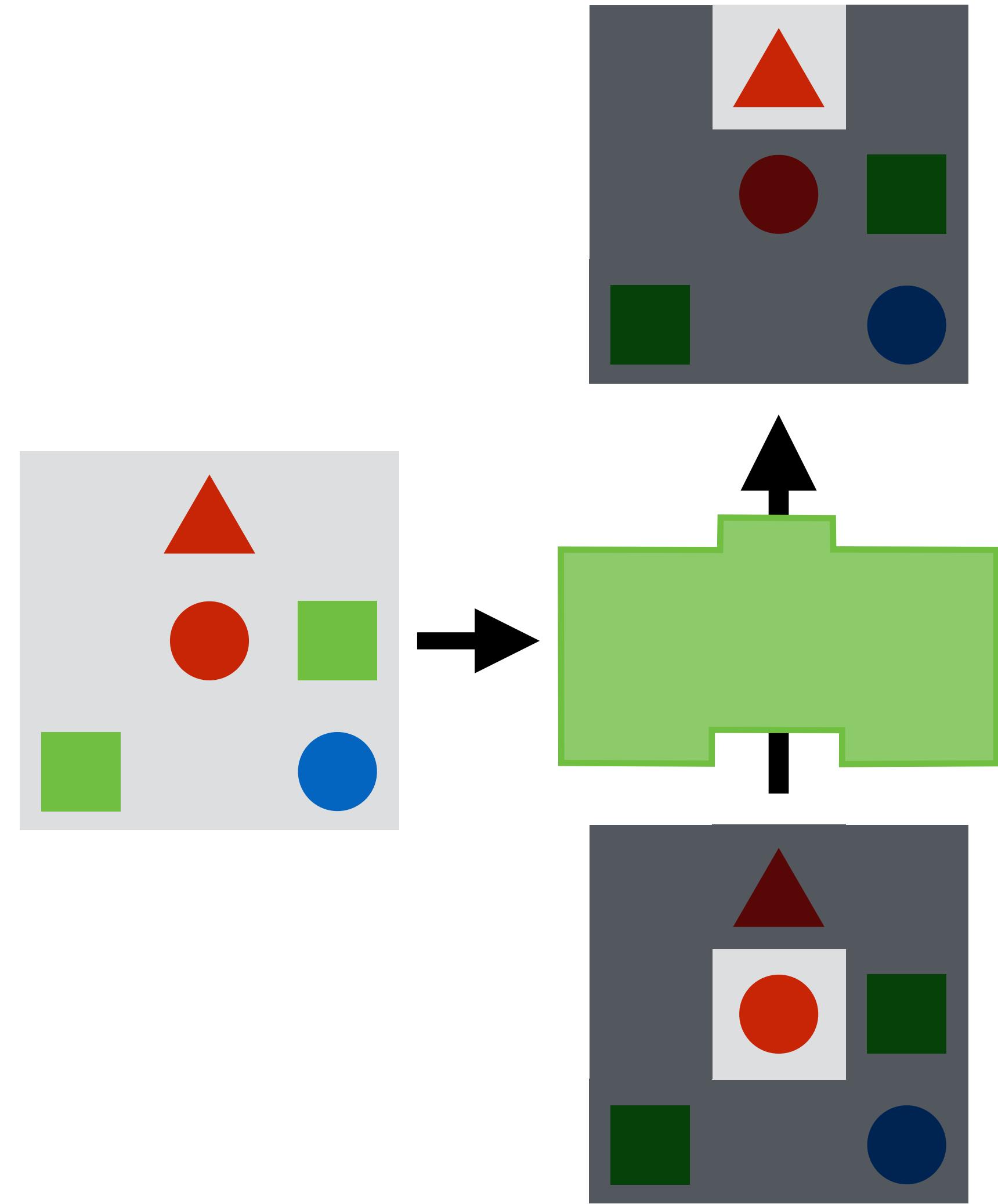


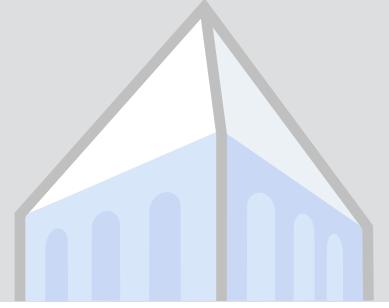
# Composing neural networks



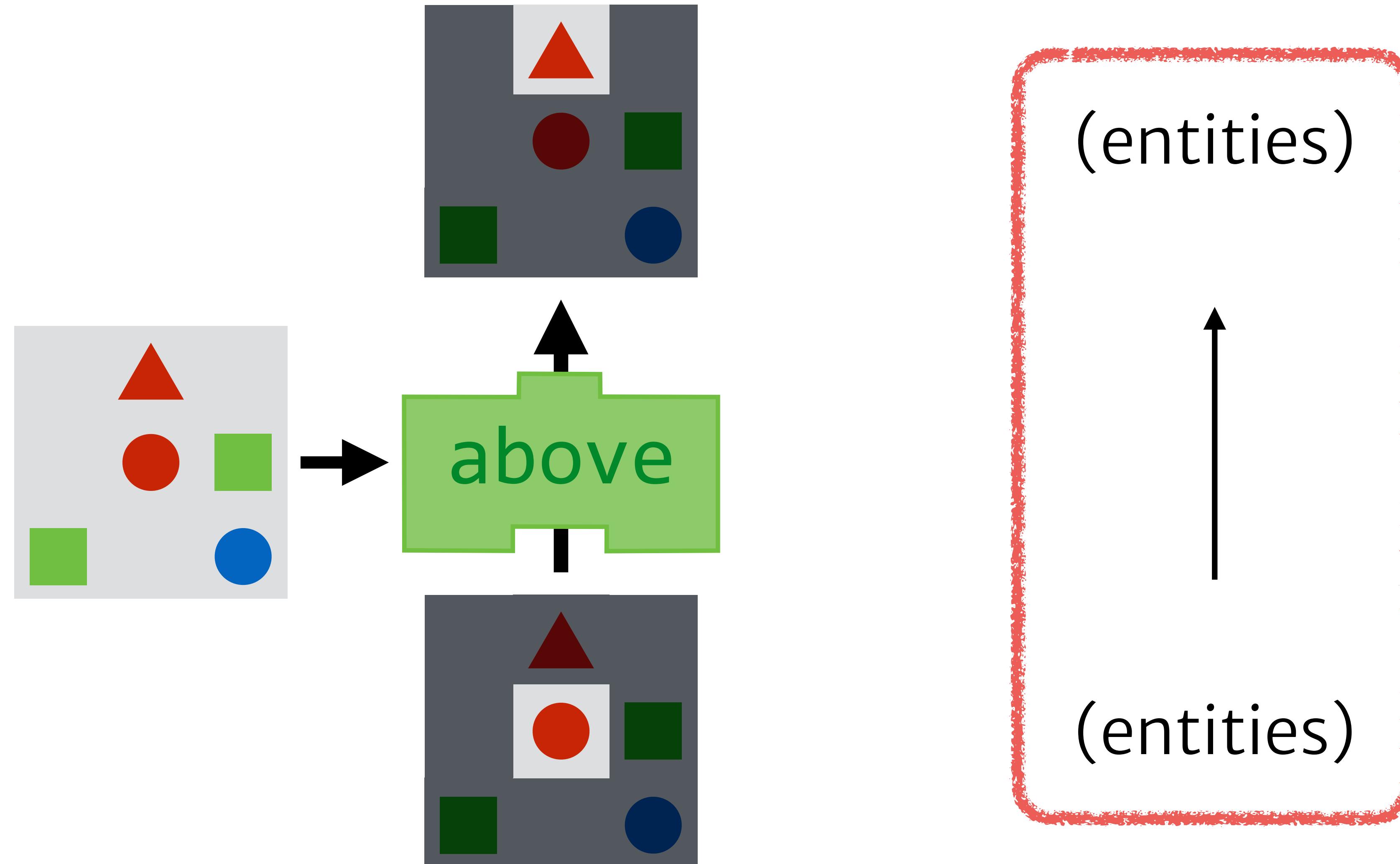


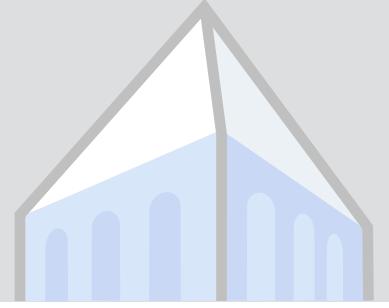
# Anatomy of a module: Types



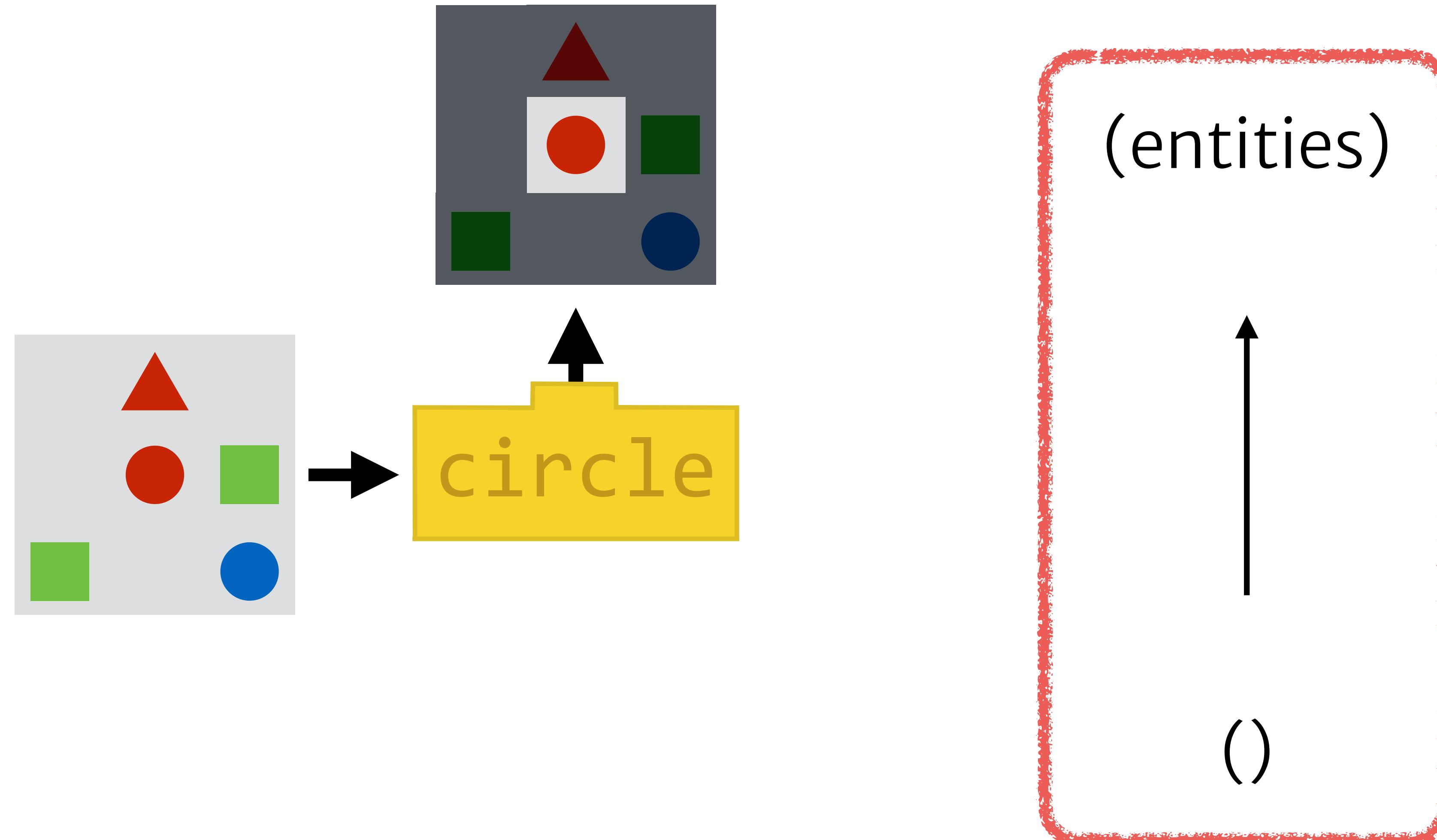


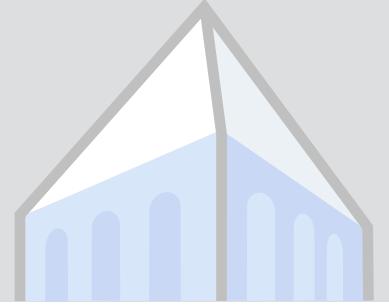
# Anatomy of a module: Types



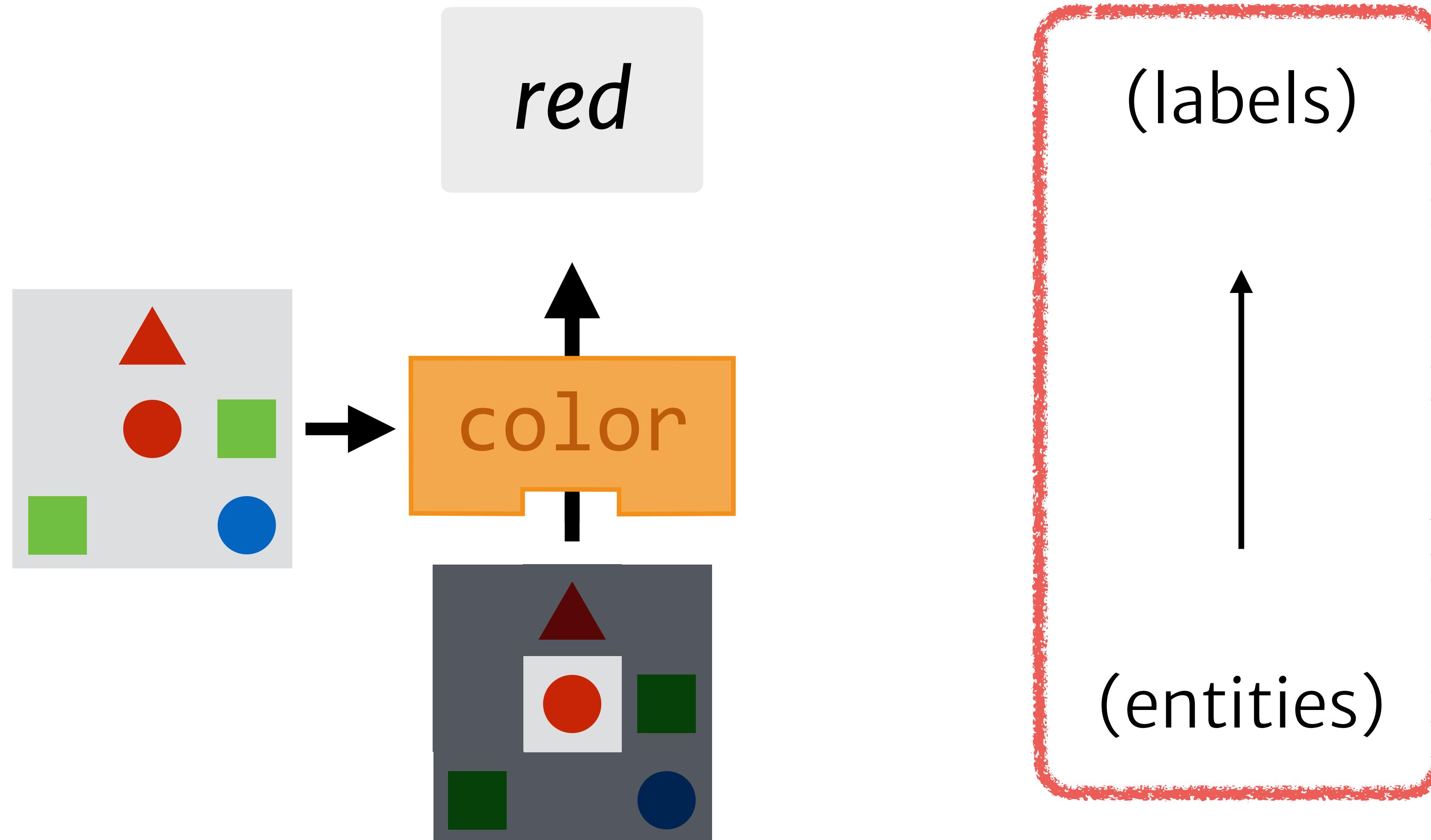


# Anatomy of a module: Types



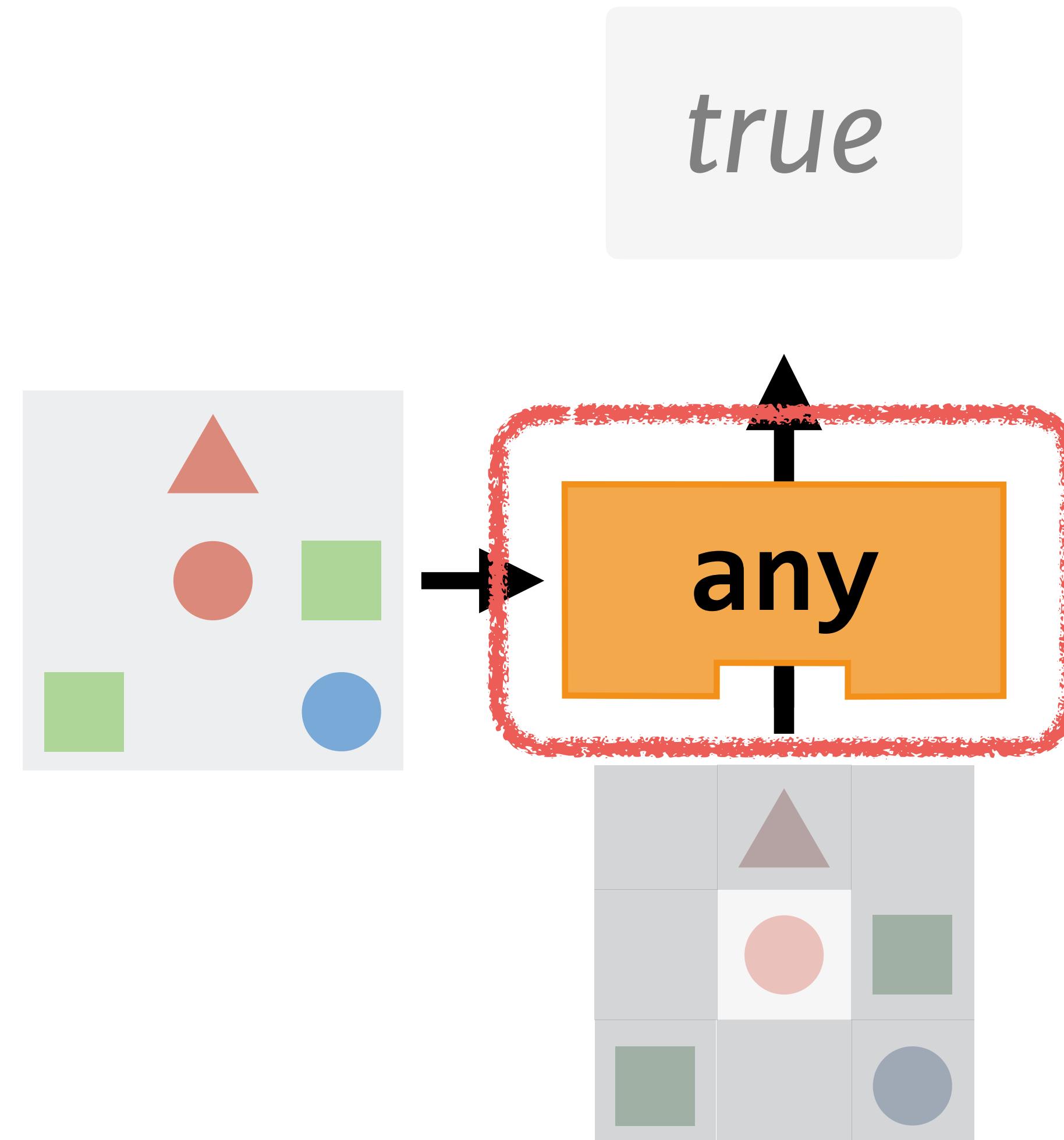


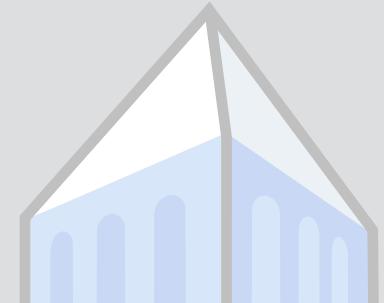
# Anatomy of a module: Types



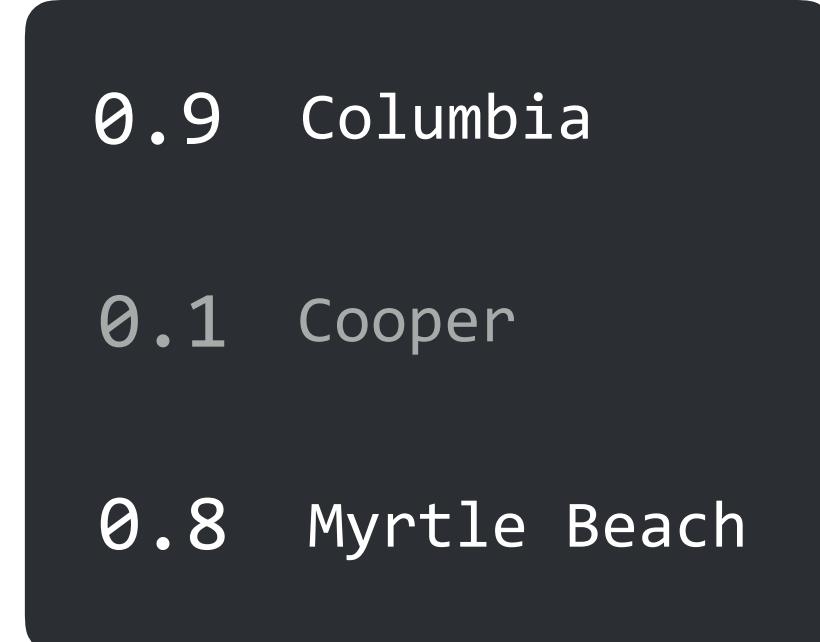
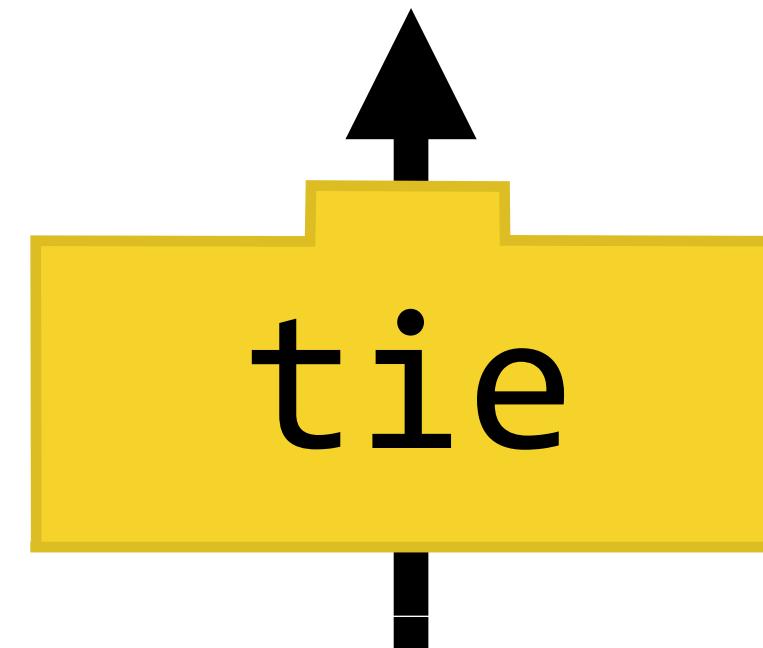
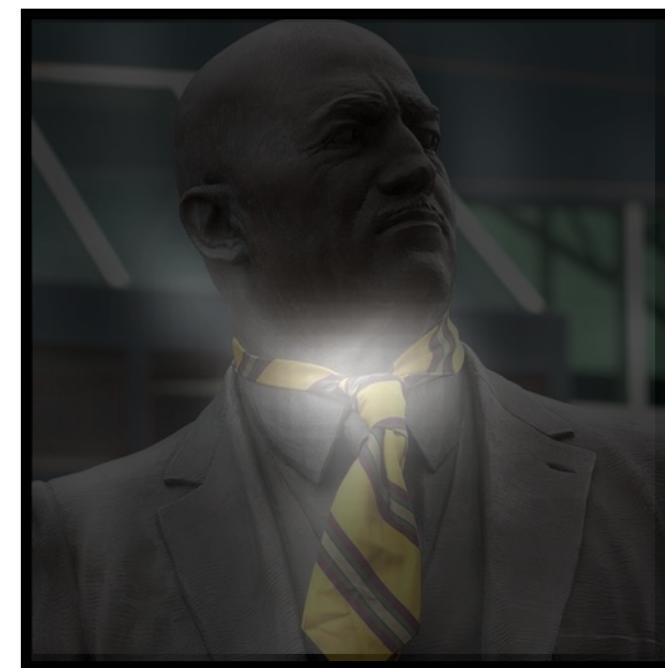


# Anatomy of a module: Parameters





# Anatomy of a module



0.9 Columbia  
0.1 Cooper  
0.8 Myrtle Beach

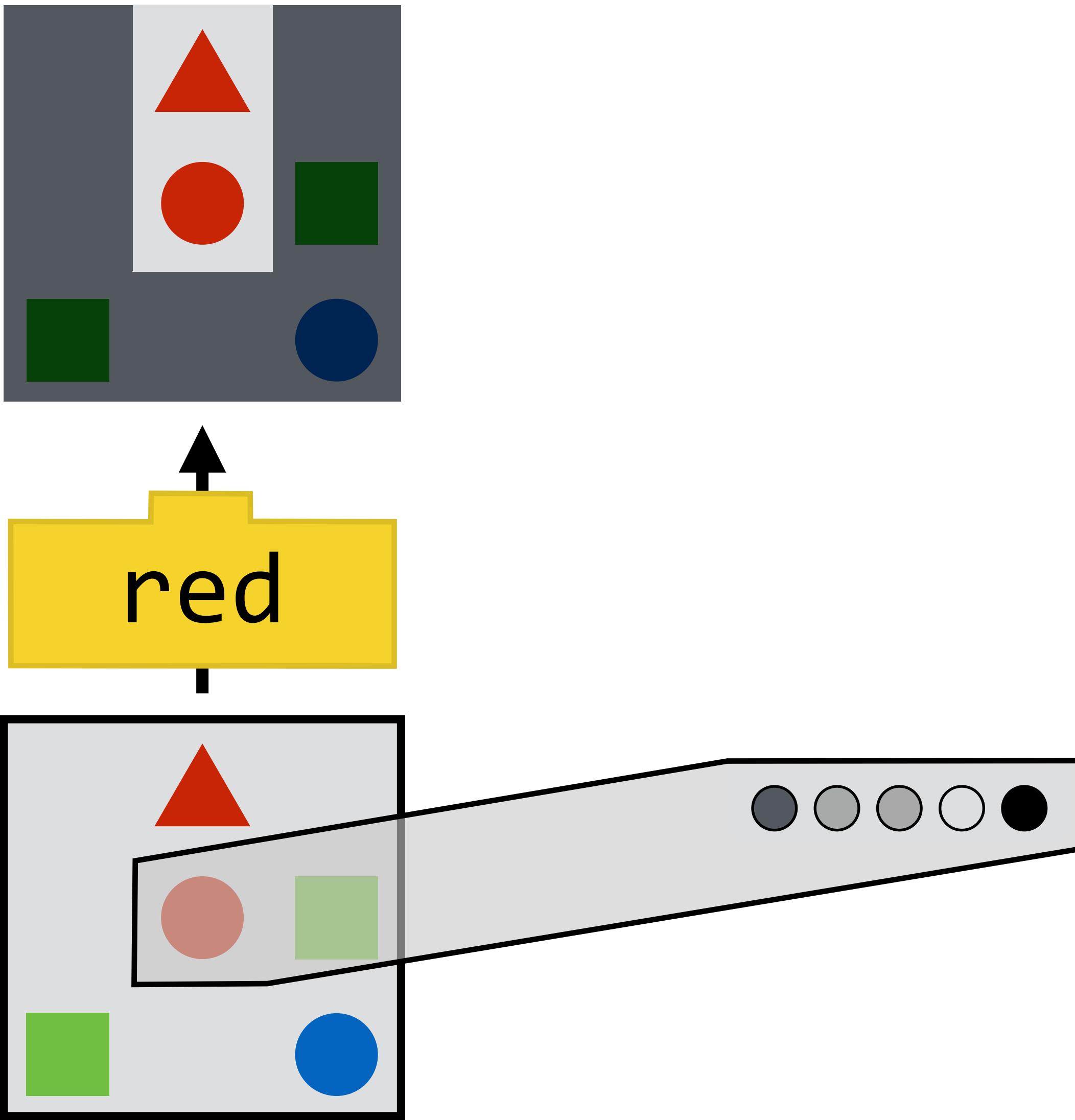
city



name	type	coastal
<i>Columbia</i>	city	no
<i>Cooper</i>	river	yes
<i>Myrtle Beach</i>	city	yes

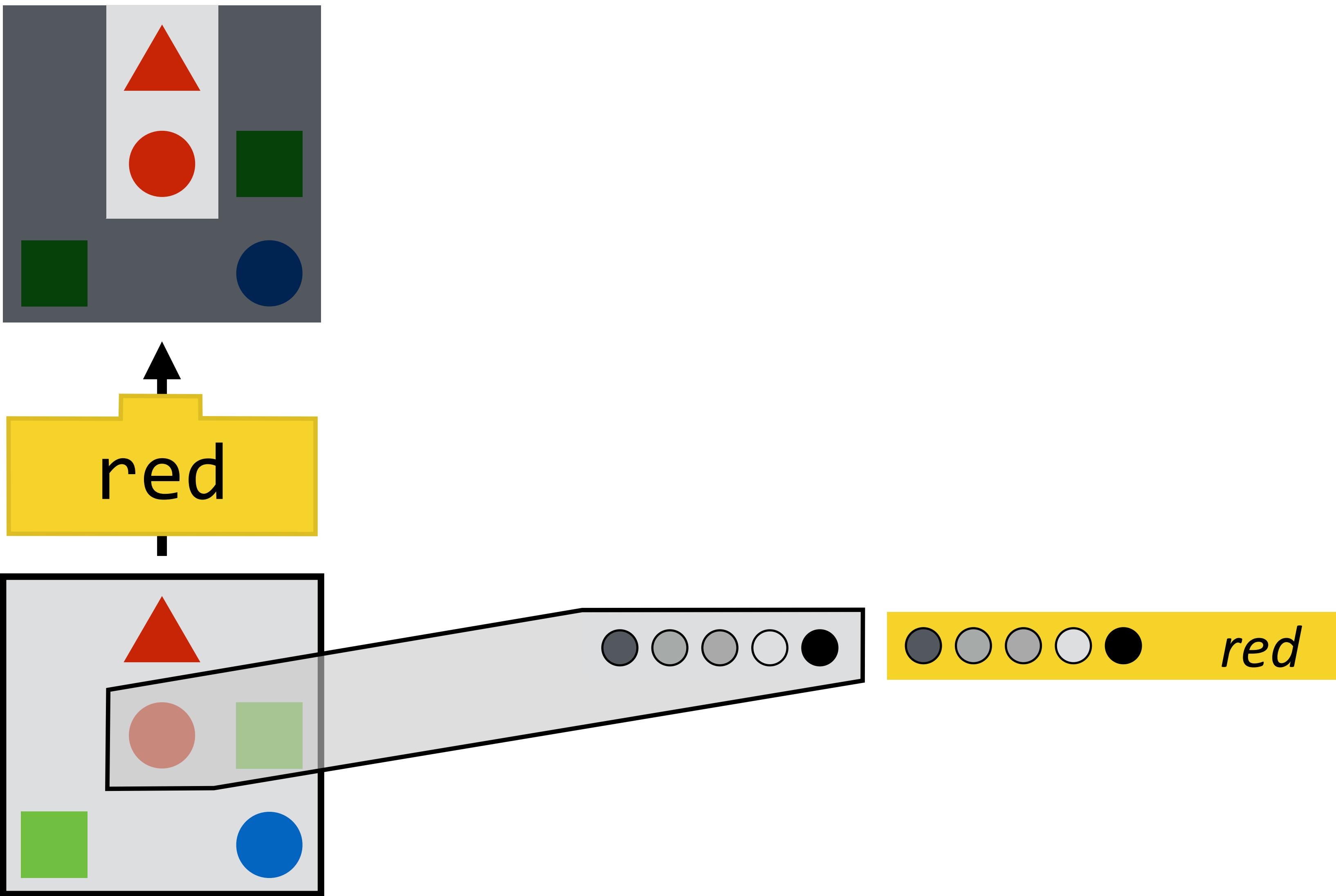


# Simple predicates



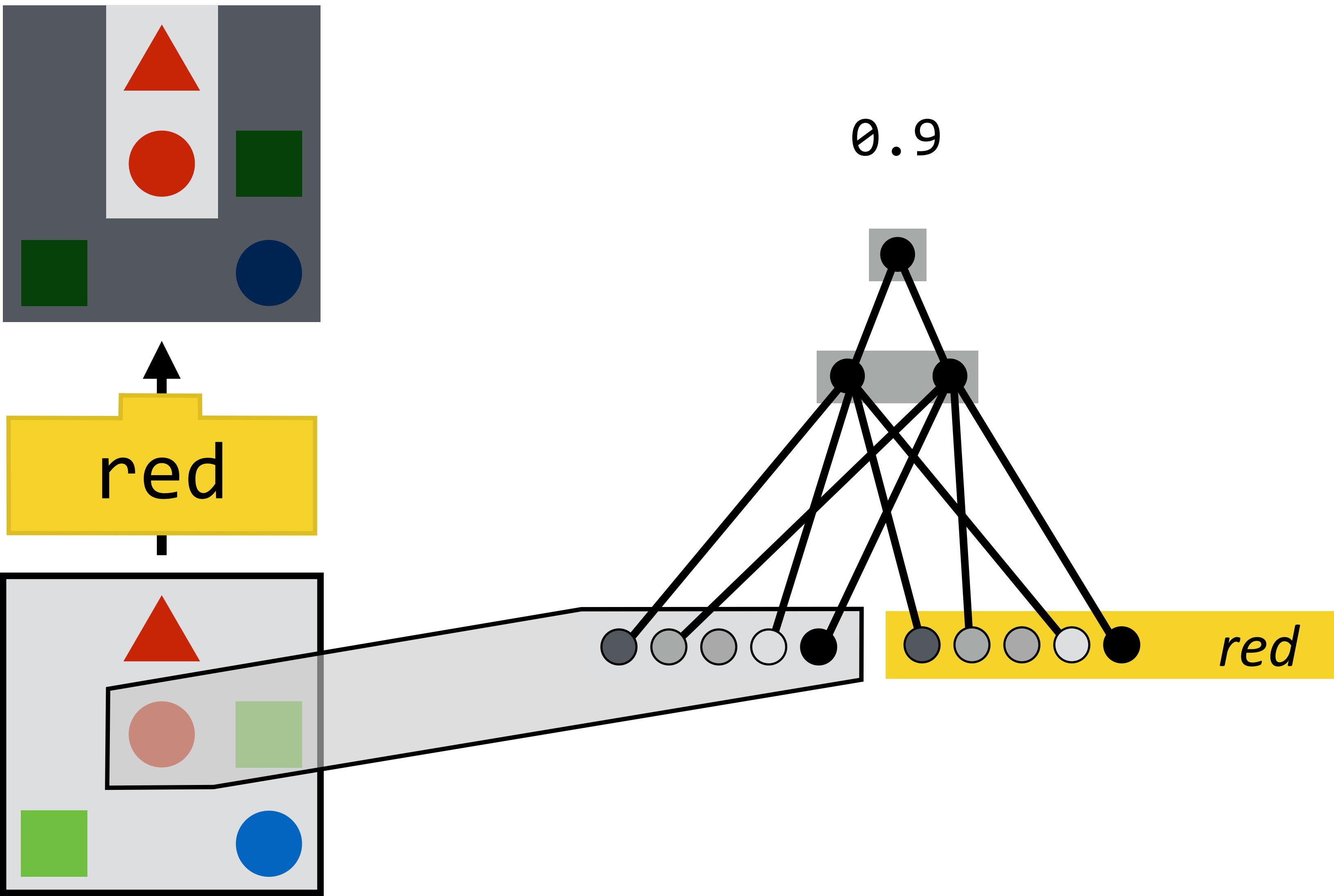


# Simple predicates



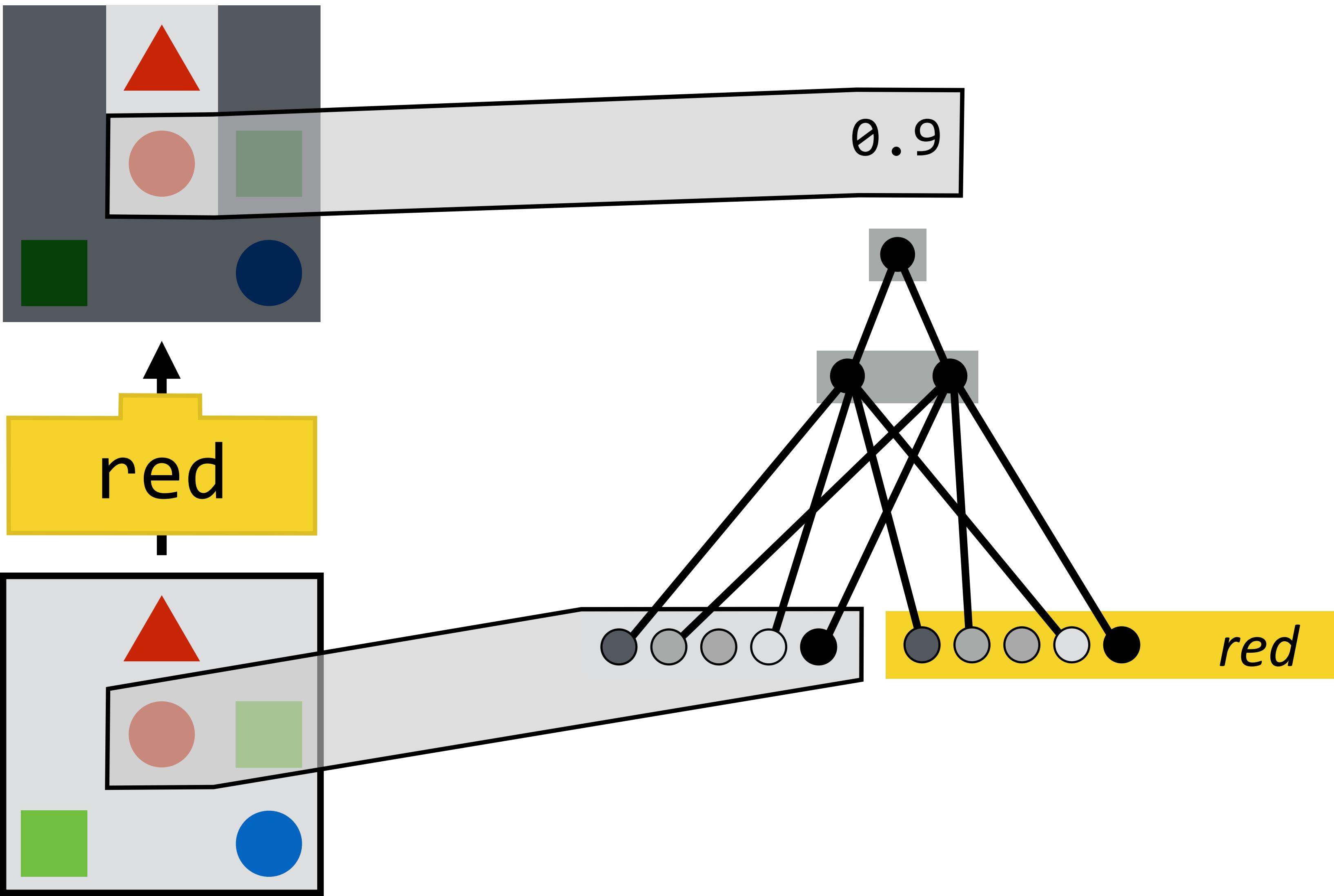


# Simple predicates

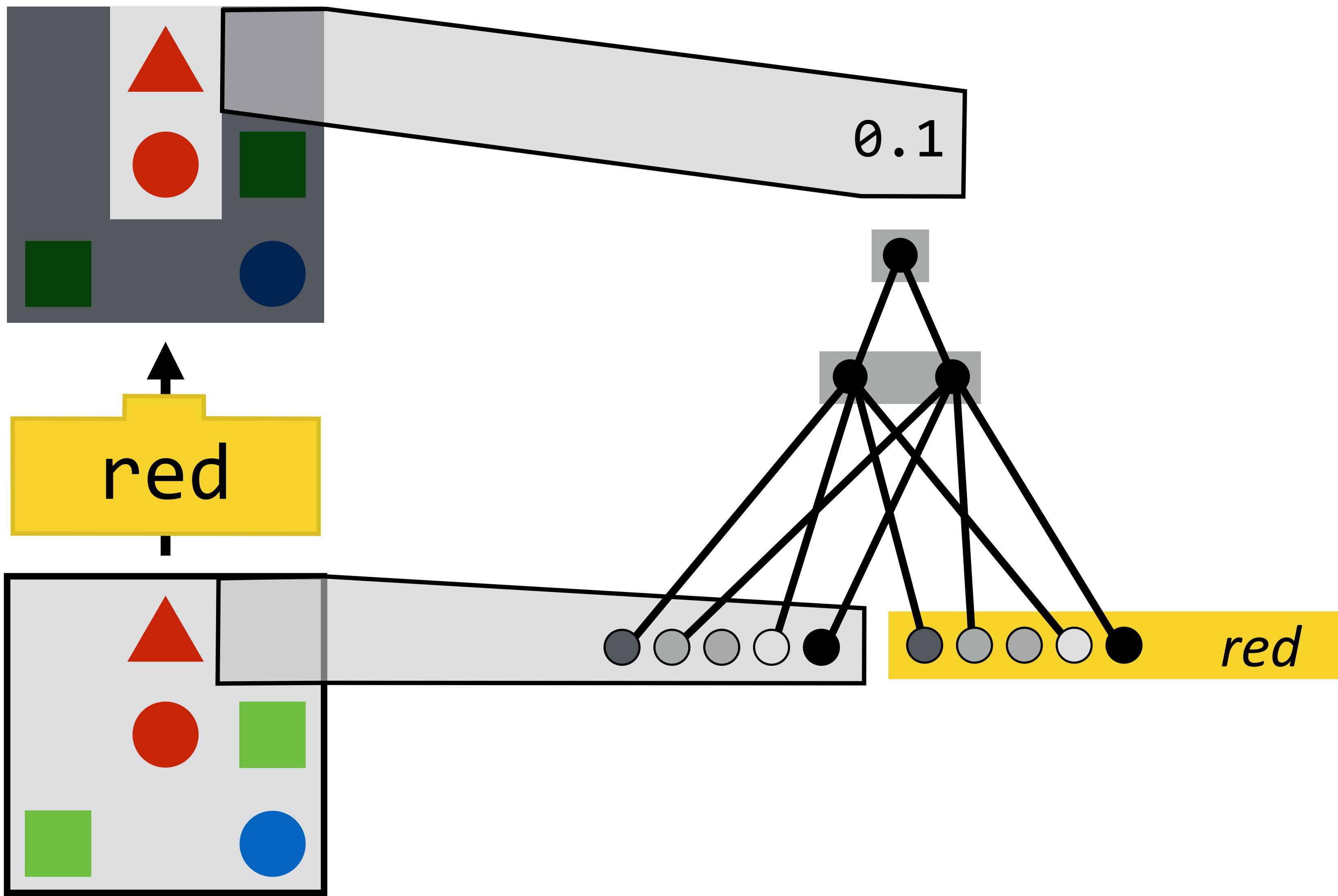




# Simple predicates

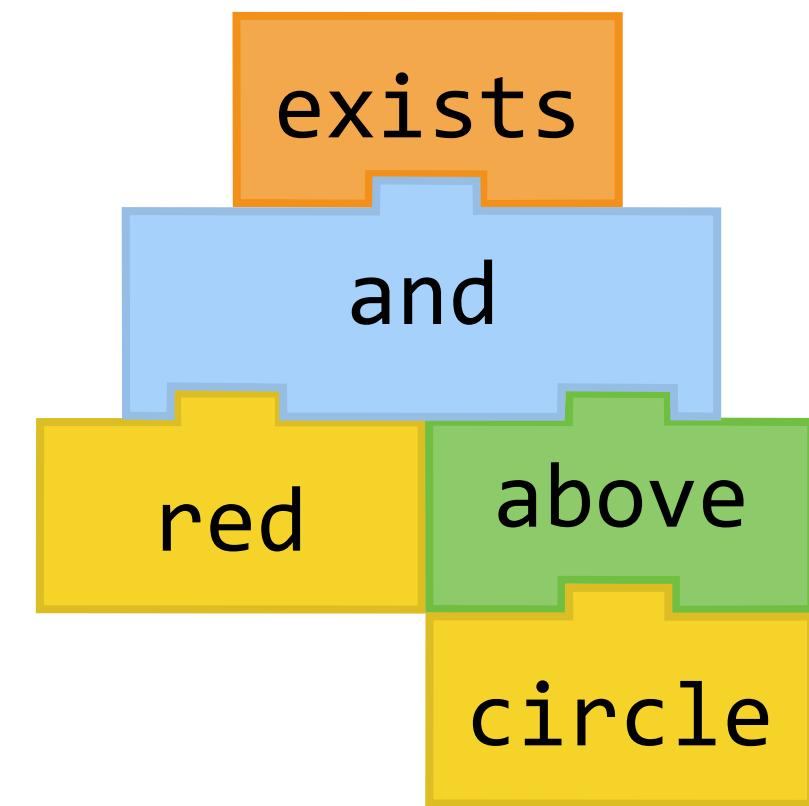


# Simple predicates

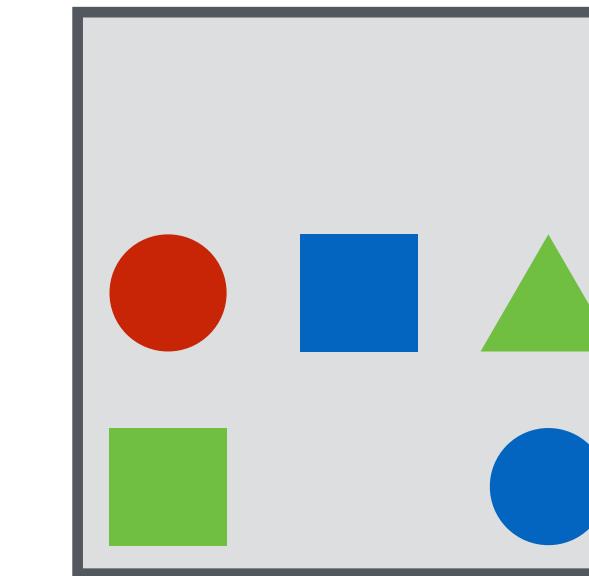
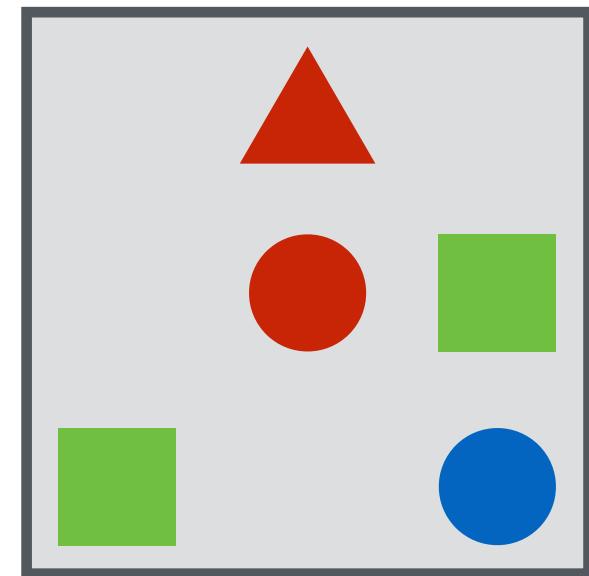
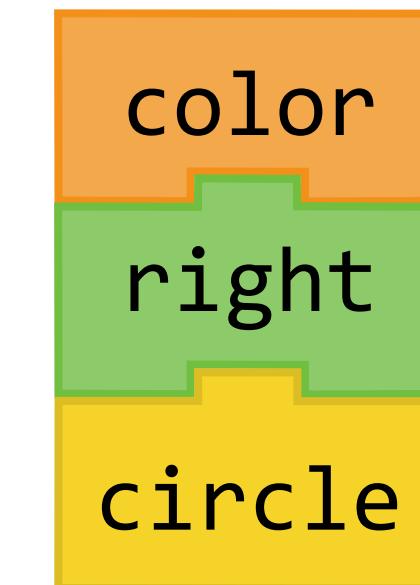


# Learning

yes



blue

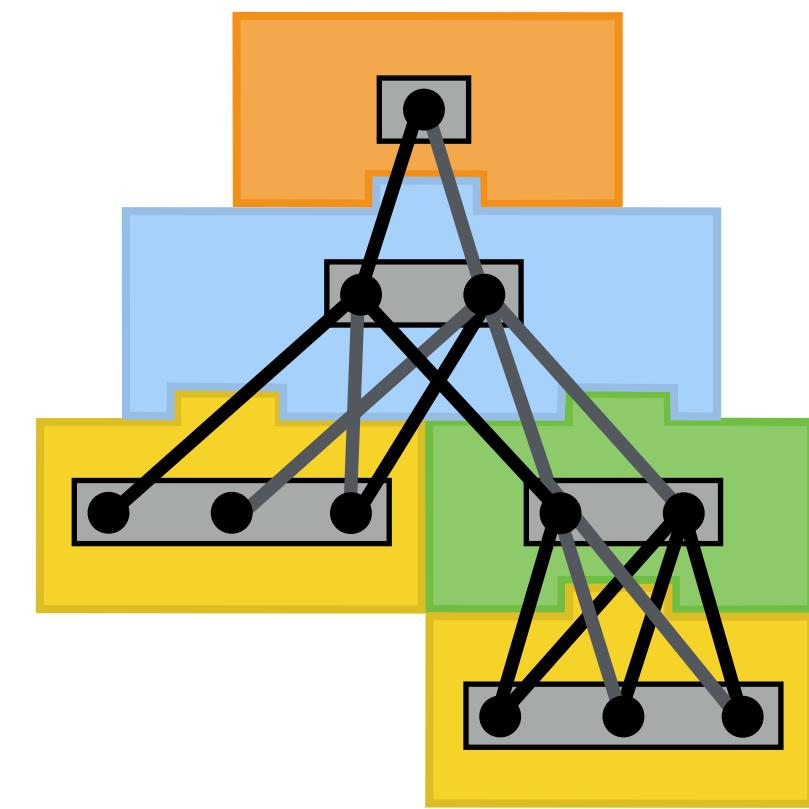


*Is there a red shape above a circle?*

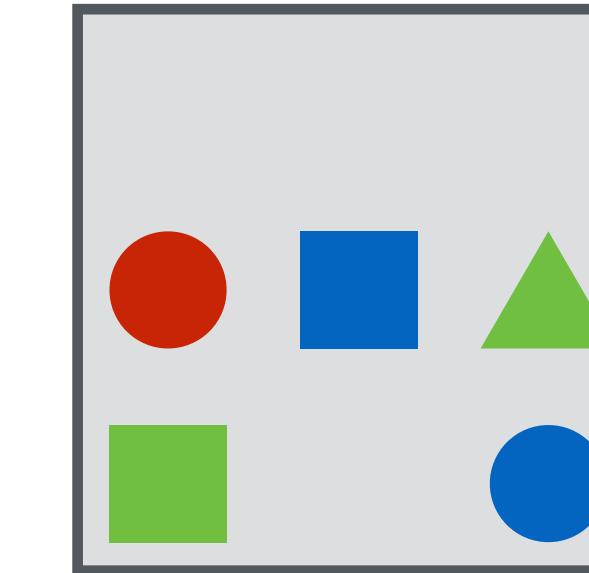
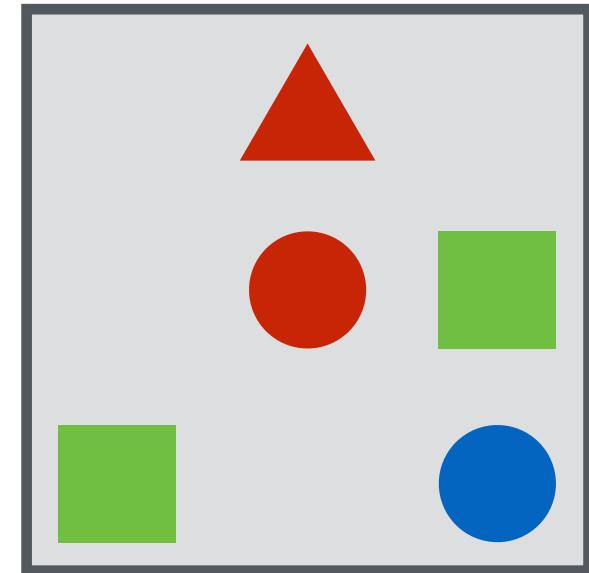
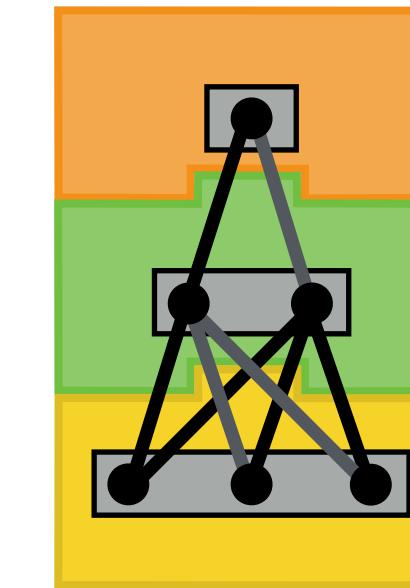
*What color is the shape right of a circle?*

# Learning

yes



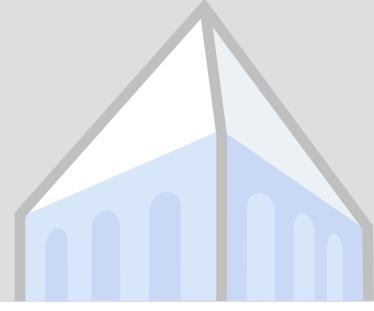
blue



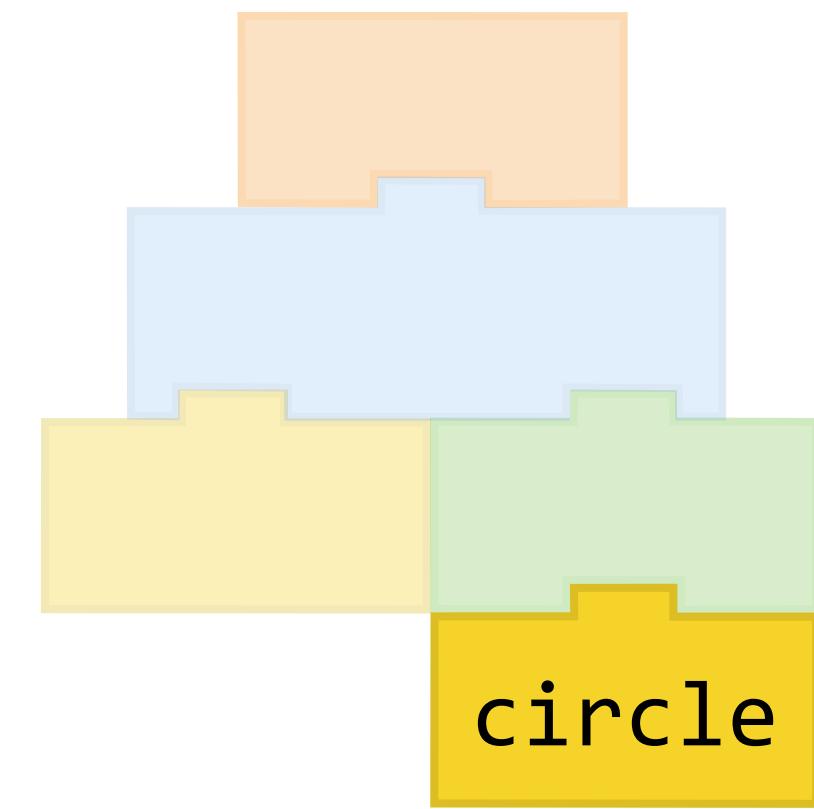
*Is there a red shape above a circle?*

*What color is the shape right of a circle?*

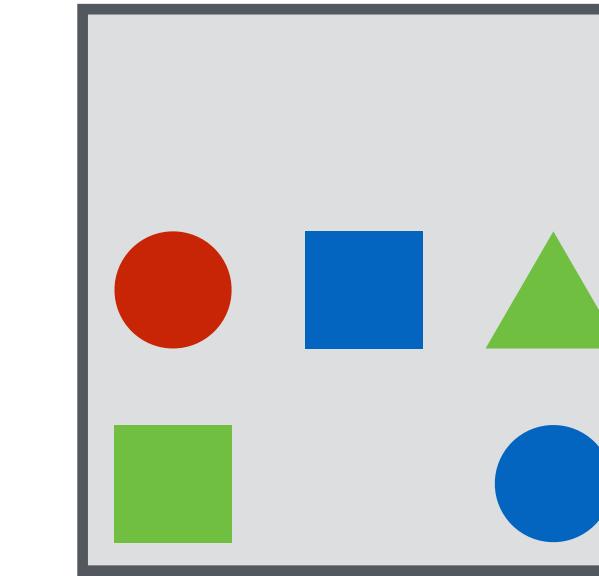
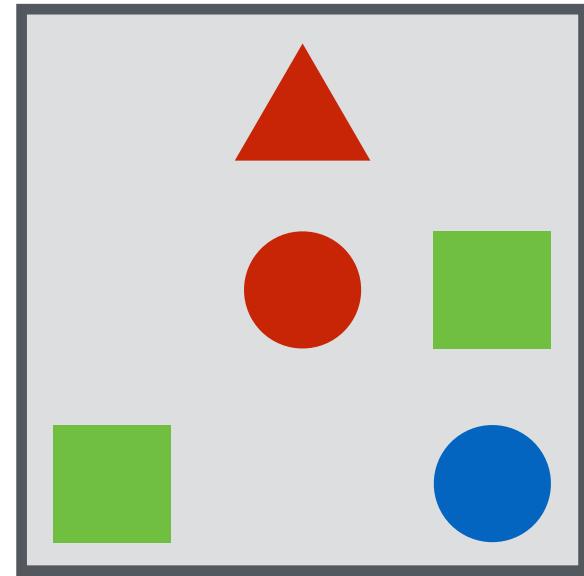
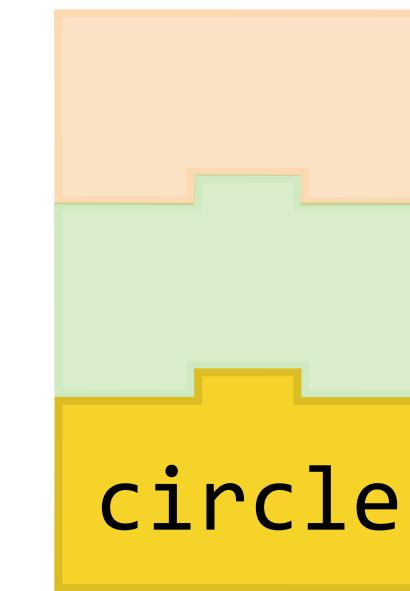
# Parameter tying



yes



blue



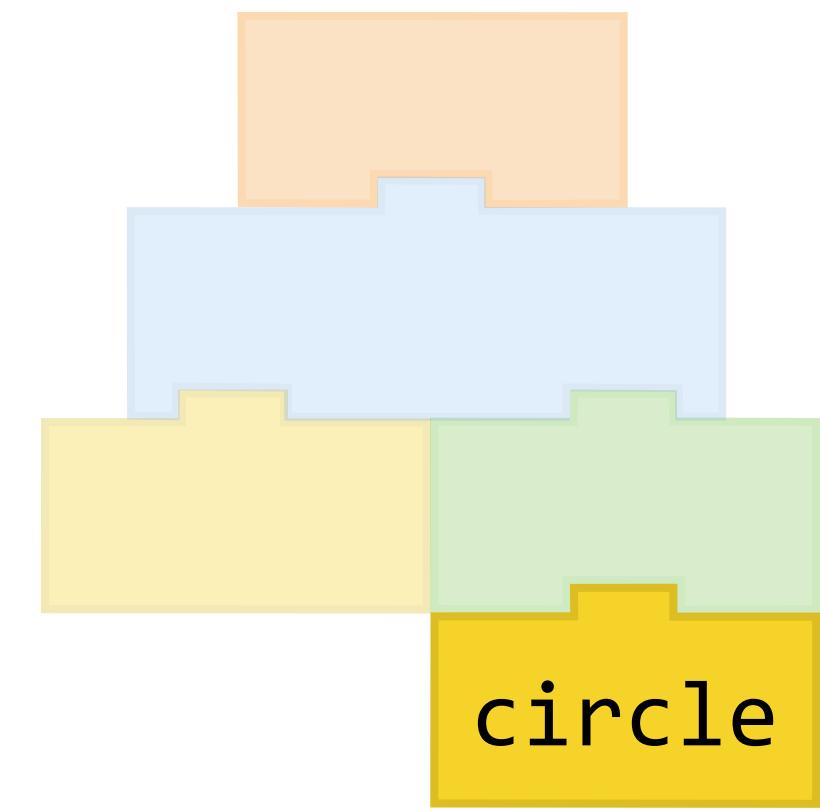
*Is there a red shape above a circle?*

*What color is the shape right of a circle?*

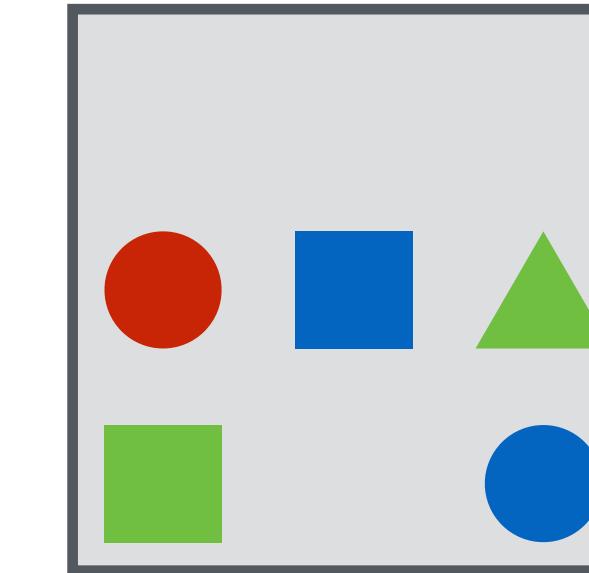
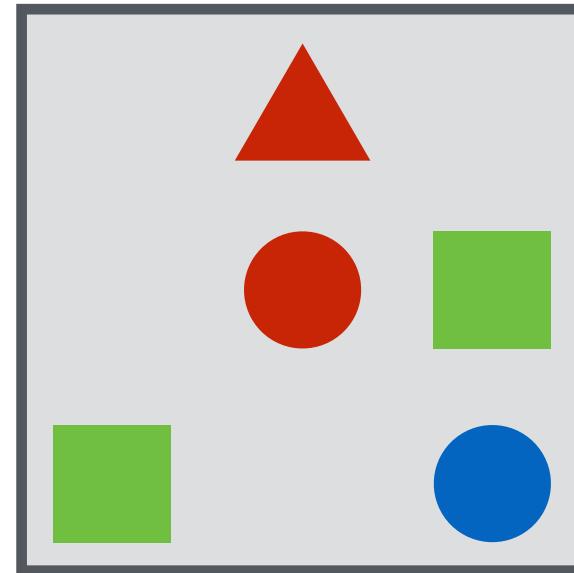
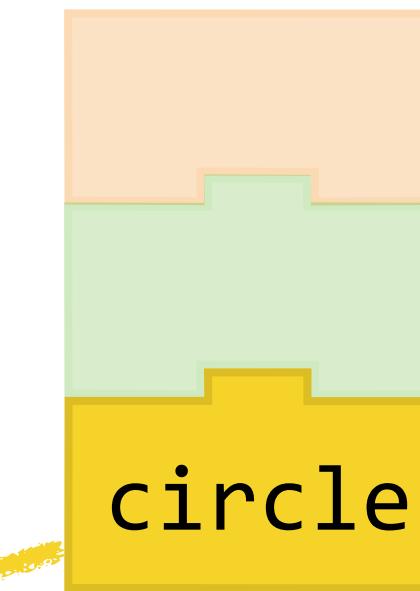
# Parameter tying



yes



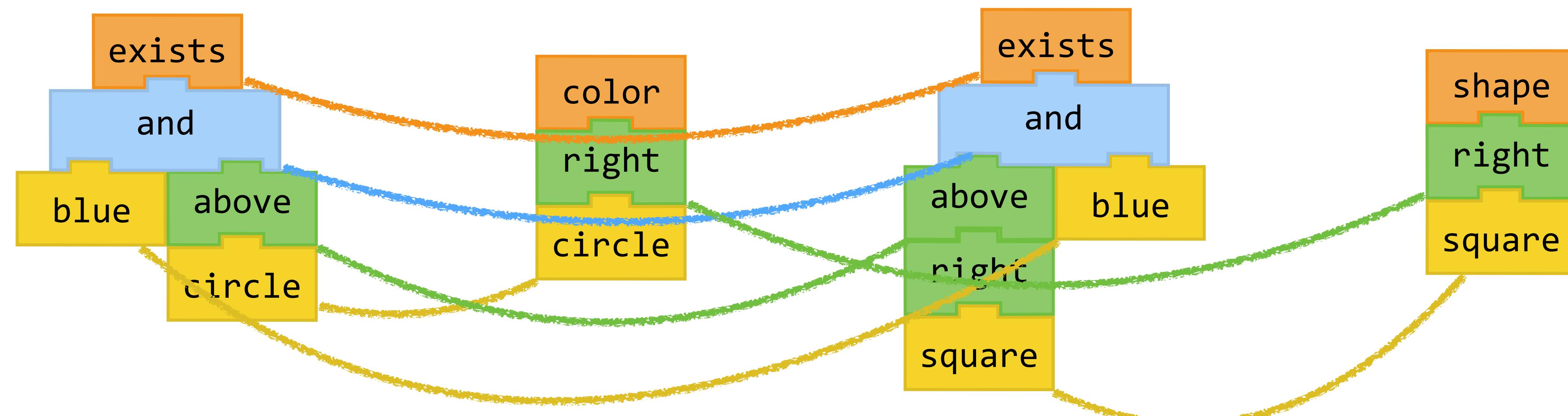
blue



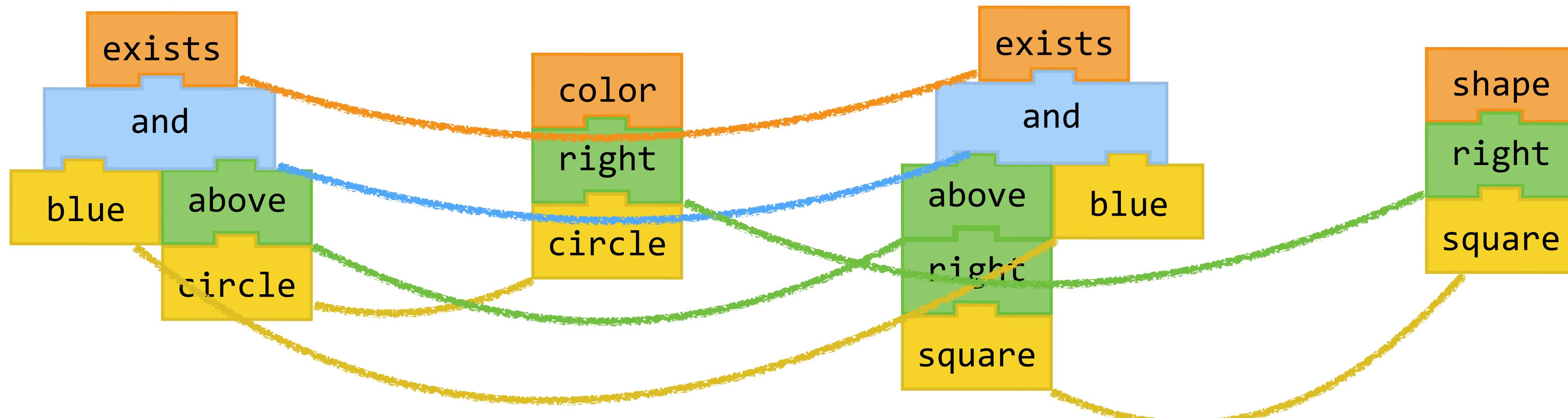
*Is there a red shape above a circle?*

*What color is the shape right of a circle?*

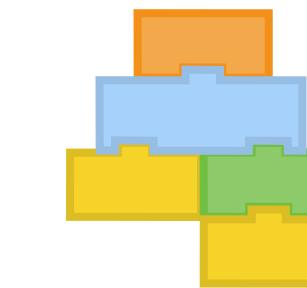
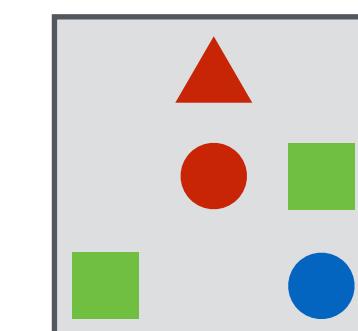
# EXTREME parameter tying



# EXTREME parameter tying

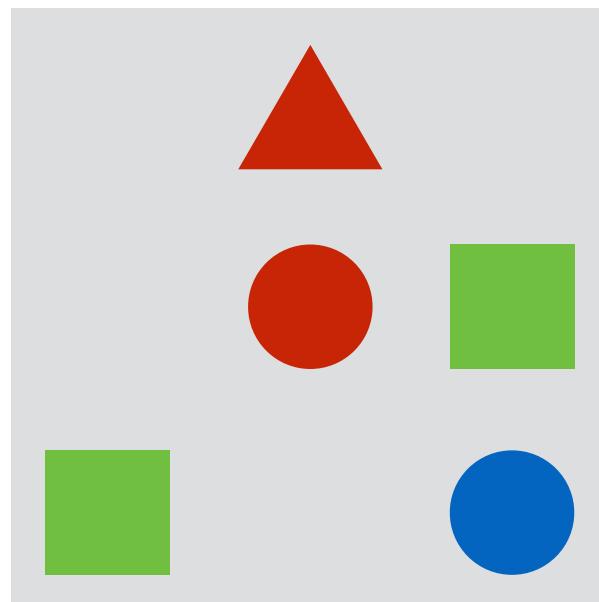


$$\arg \max_W \sum \log p(\text{yes} | \text{ } , \text{ } ; W)$$

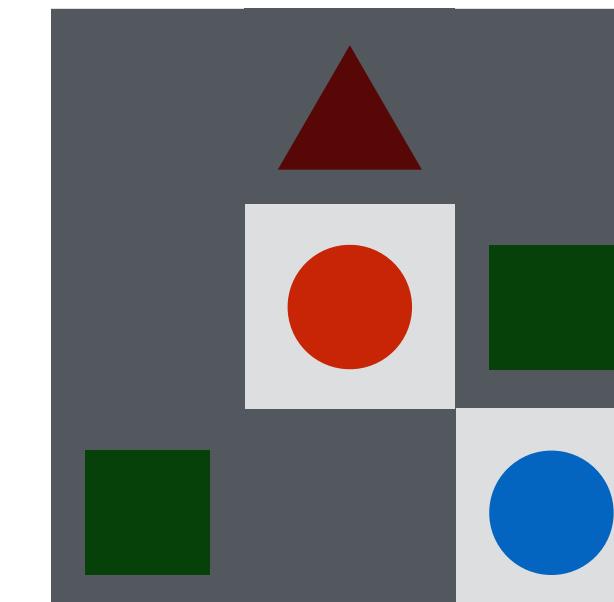




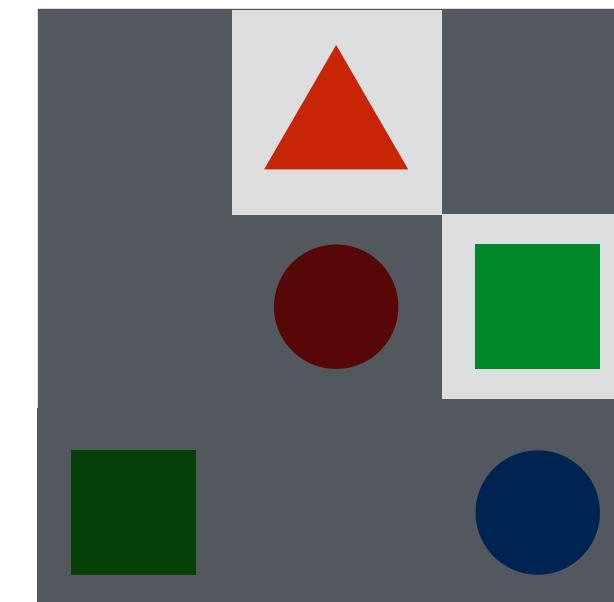
# Learning with fixed layouts is easy!



circle



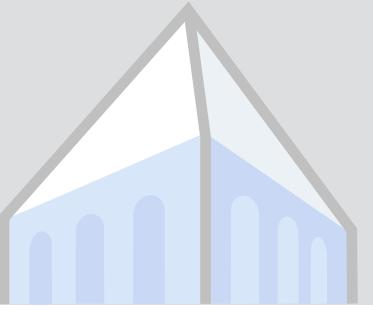
above



any

true

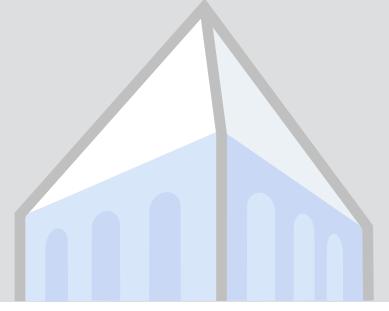
Module specialization is driven entirely by context!



# Learning with fixed layouts is easy!



Module specialization is driven entirely by context!

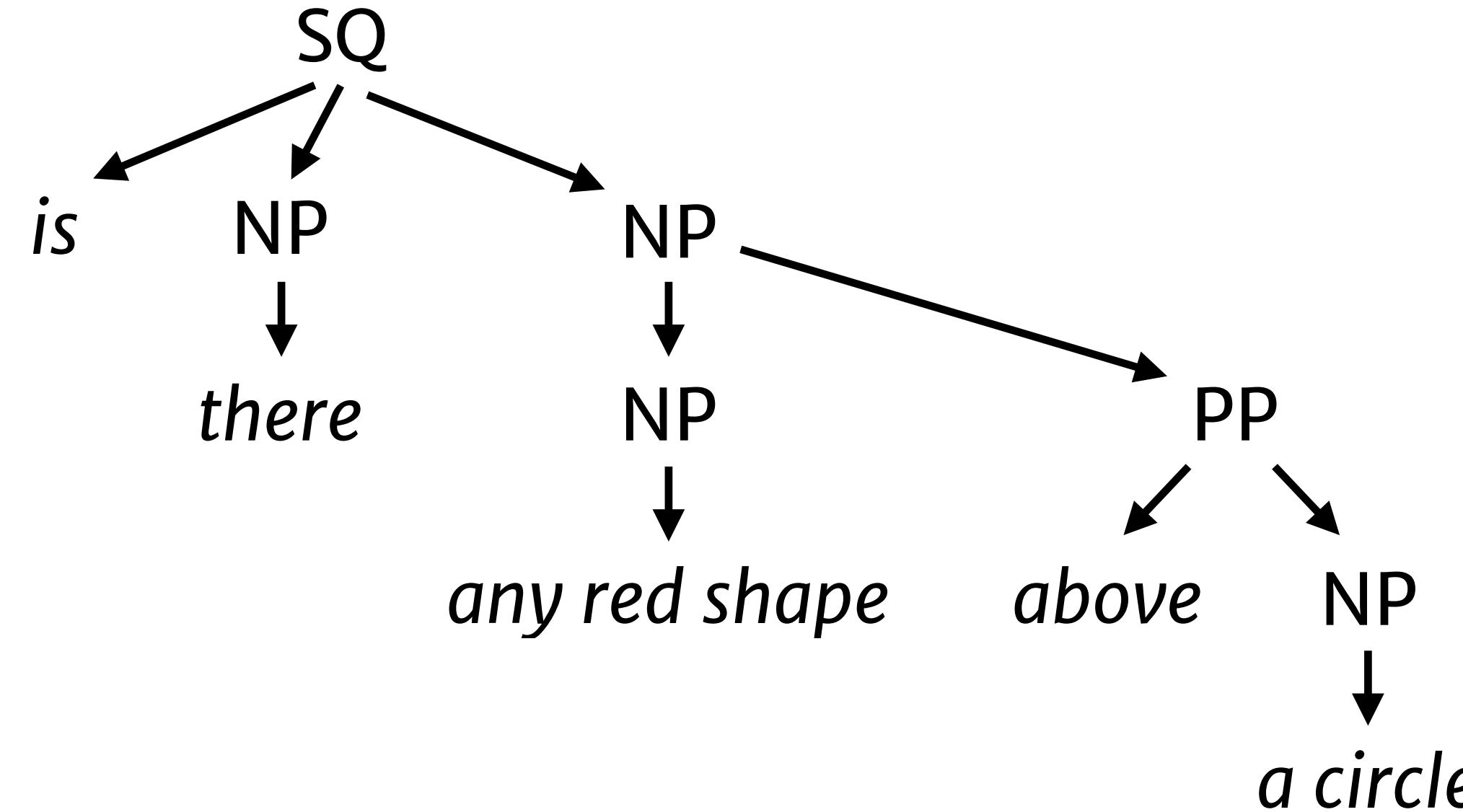


# Where do network structures come from?

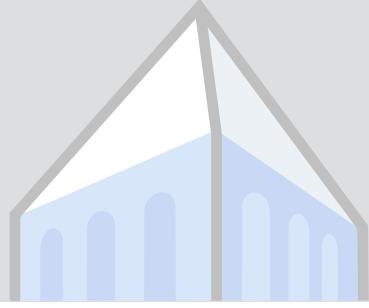
*Is there any red shape above a circle?*



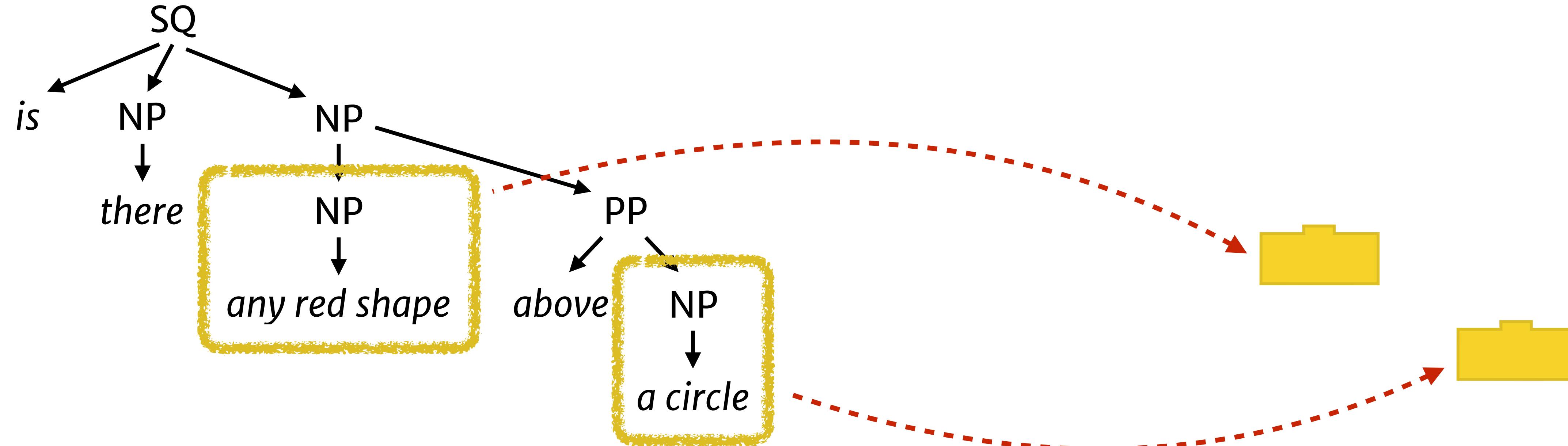
# Where do network structures come from?



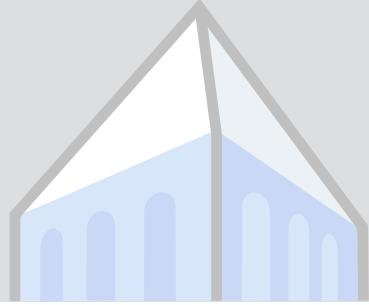
*Is there any red shape above a circle?*



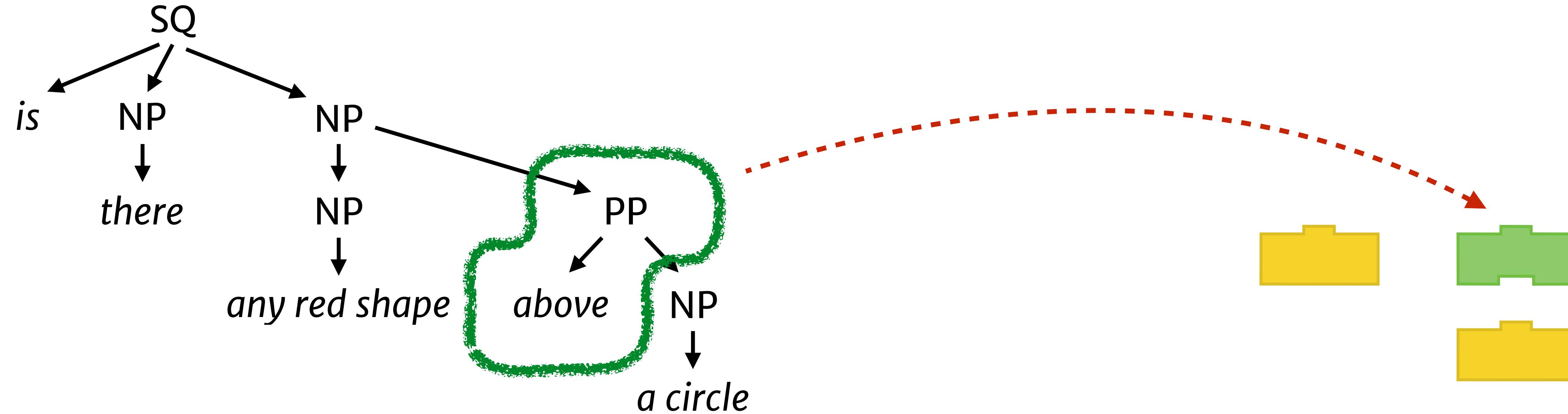
# Where do network structures come from?



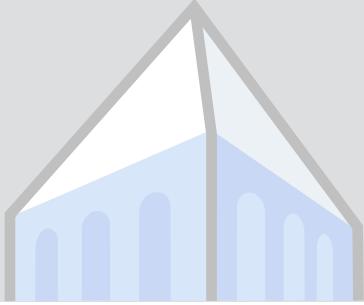
*Is there any red shape above a circle?*



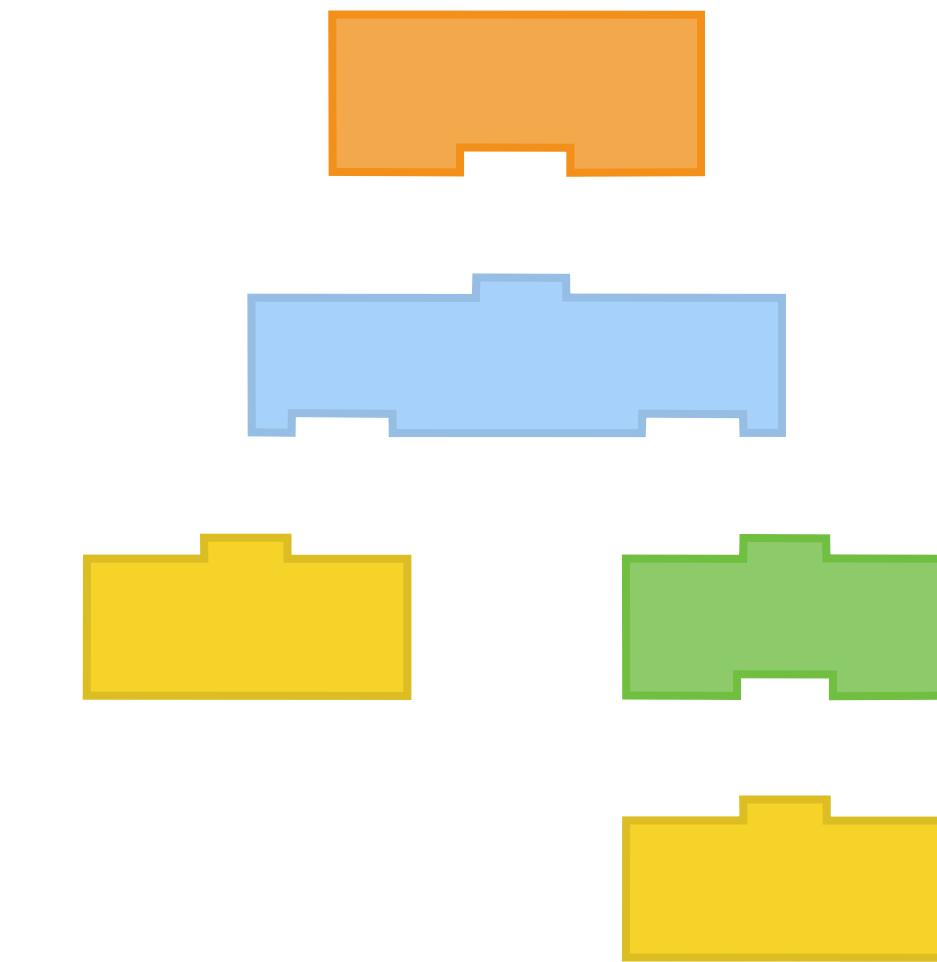
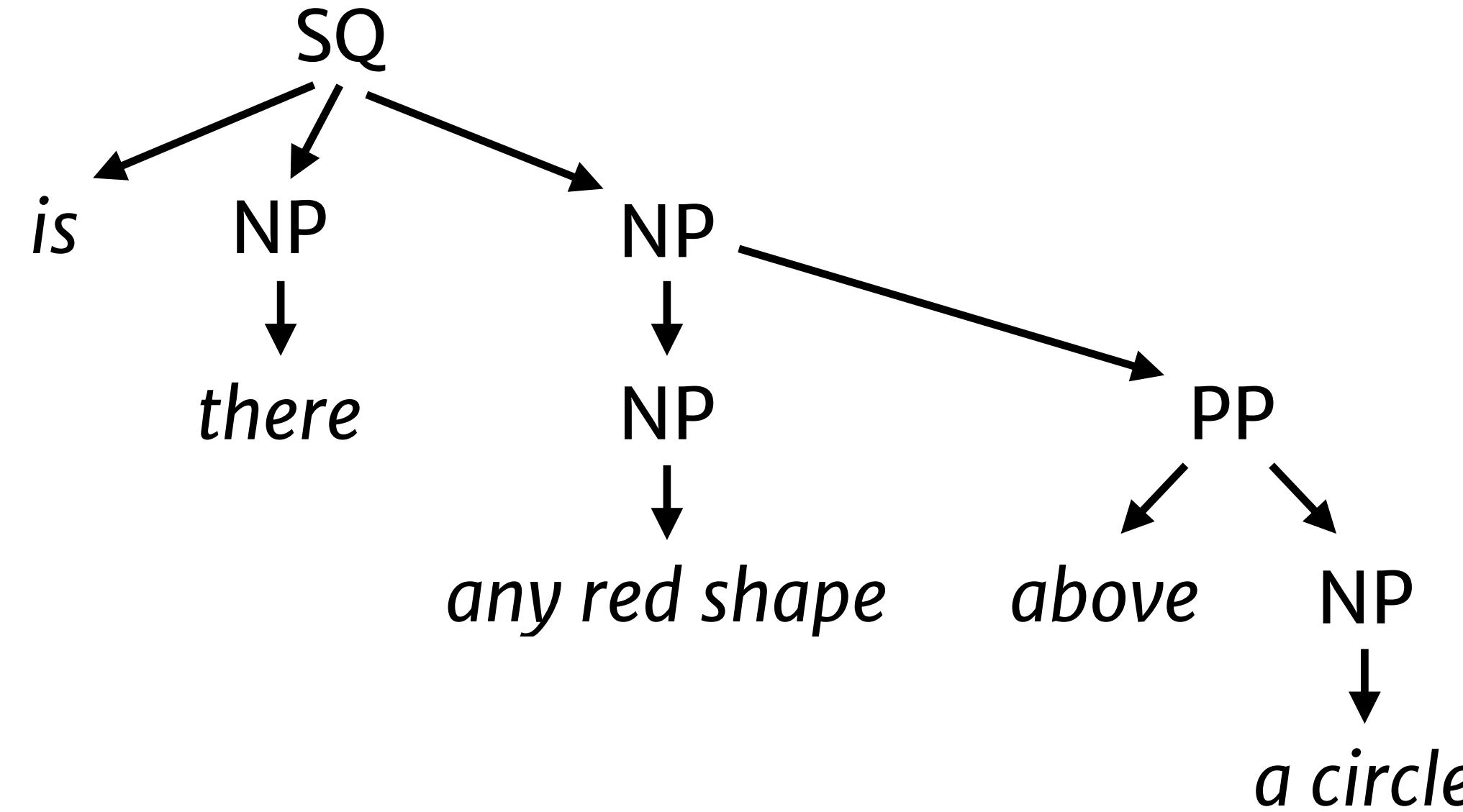
# Where do network structures come from?



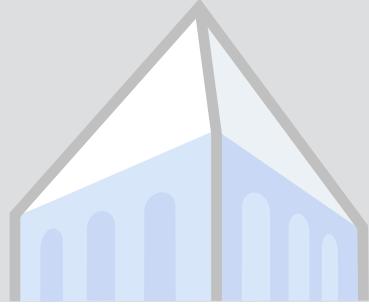
*Is there any red shape above a circle?*



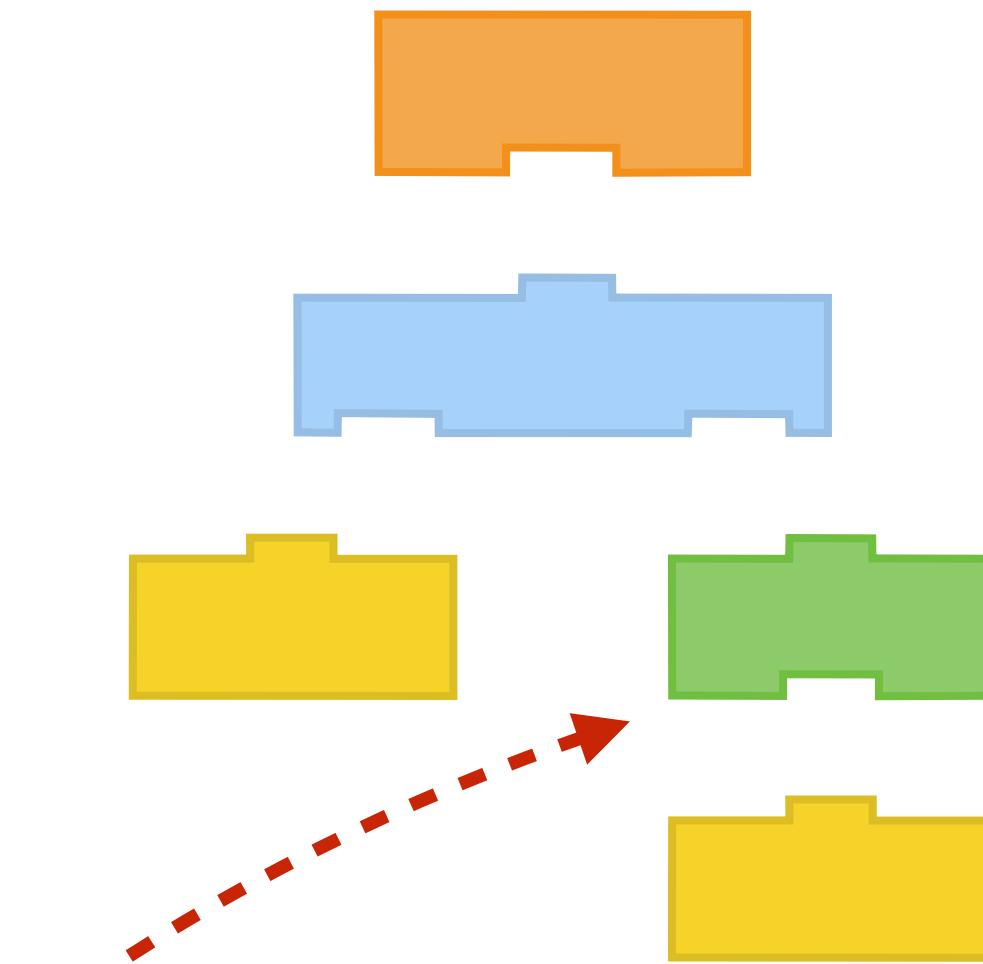
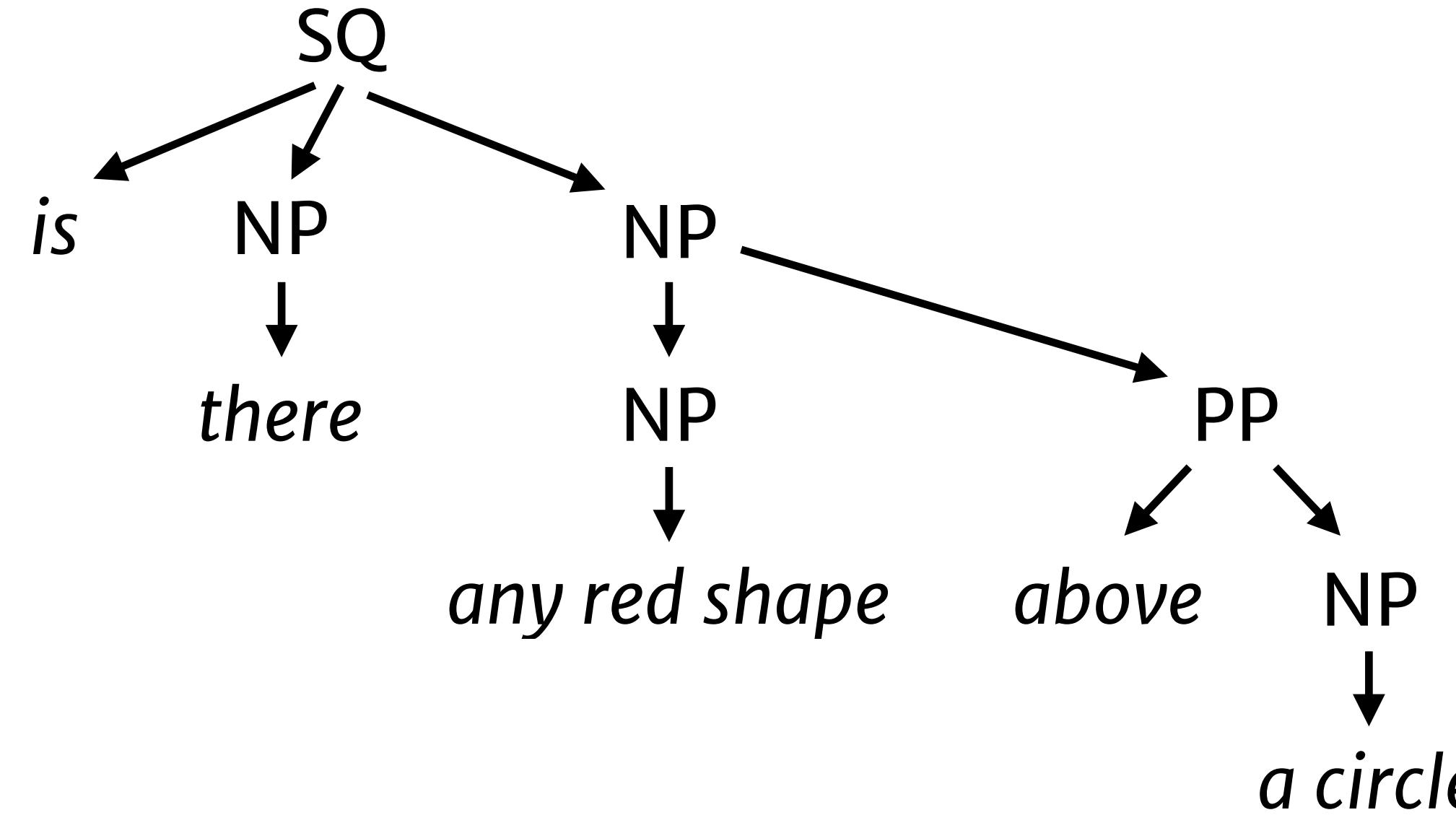
# Where do network structures come from?



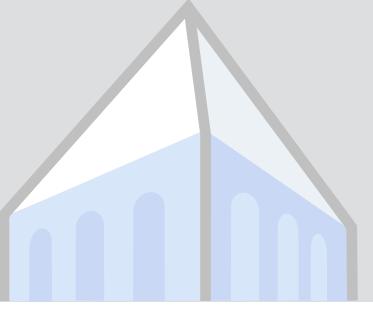
*Is there any red shape above a circle?*



# Where do network structures come from?

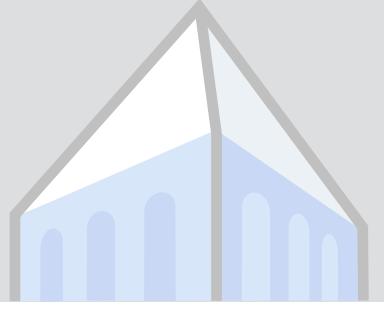


Is there any red shape above a circle?



# Where do network structures come from?

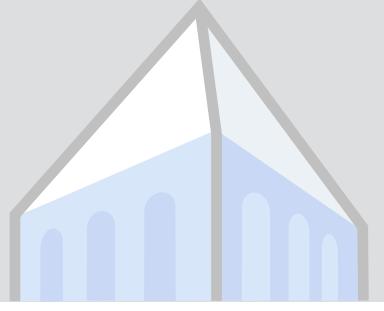
hard choice of layouts and answers



# Where do network structures come from?

hard choice of layouts and answers

$$\arg \max_{\theta} \mathbb{E} \log p(\text{ans} | \text{ques}, \text{net})$$



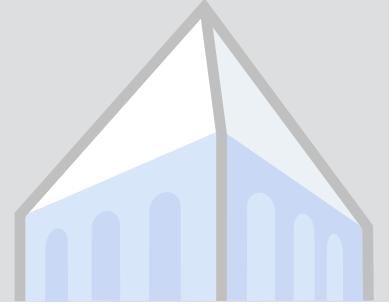
# Where do network structures come from?

hard choice of layouts and answers

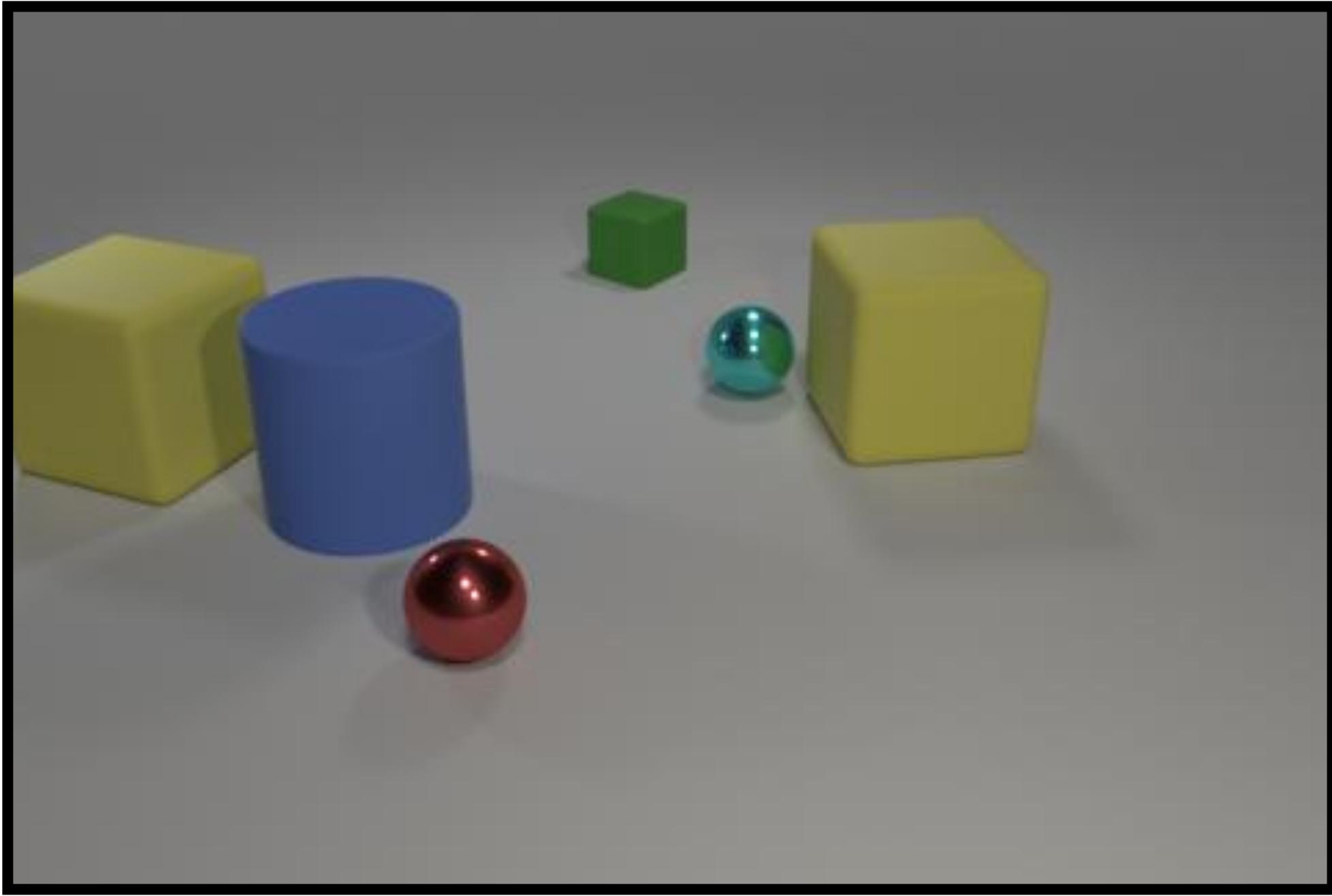
$$\arg \max_{\theta} \mathbb{E} \log p(\text{ans} | \text{ques}, \text{layout})$$

hybrid supervised / policy gradient

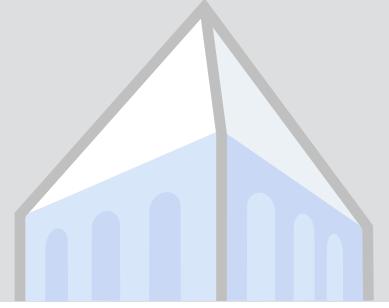
$$\begin{aligned} \nabla \mathbb{E} r \approx & \nabla \log p(\text{ans} | \text{layout}, \text{ques}) + \\ & \lambda (\nabla \log p(\text{layout} | \text{ques})) \cdot \log p(\text{ans} | \text{layout}, \text{ques}) \end{aligned}$$



# Experimental evaluation



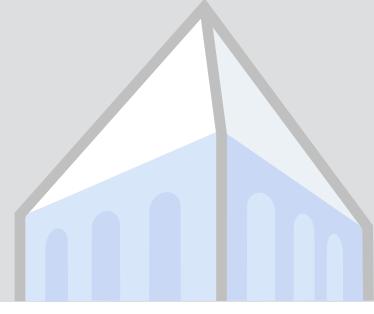
*Does the blue cylinder have the same material as the big block on the right side of the red metallic thing?*



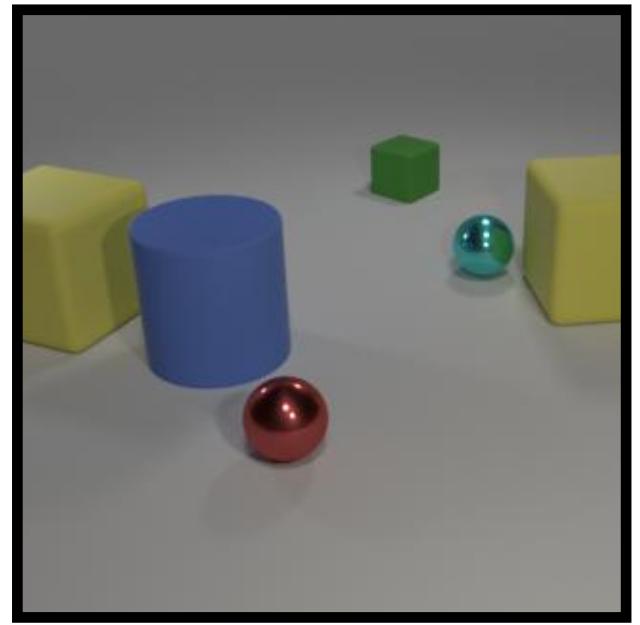
# Experimental evaluation



*What is in the sheep's ear?*



# Experimental evaluation [ARDK16a, HARDS17]



*How many other things are the same size as the cylinder?*

68.5

CNN +  
RNN

83.7  
NMN

96.9  
NMN  
[JH+17]



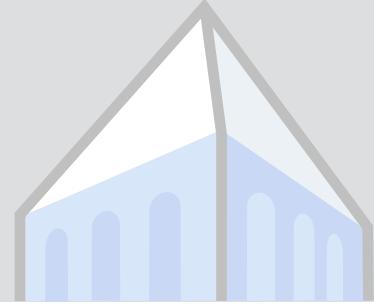
*What color is she wearing?*

62.5

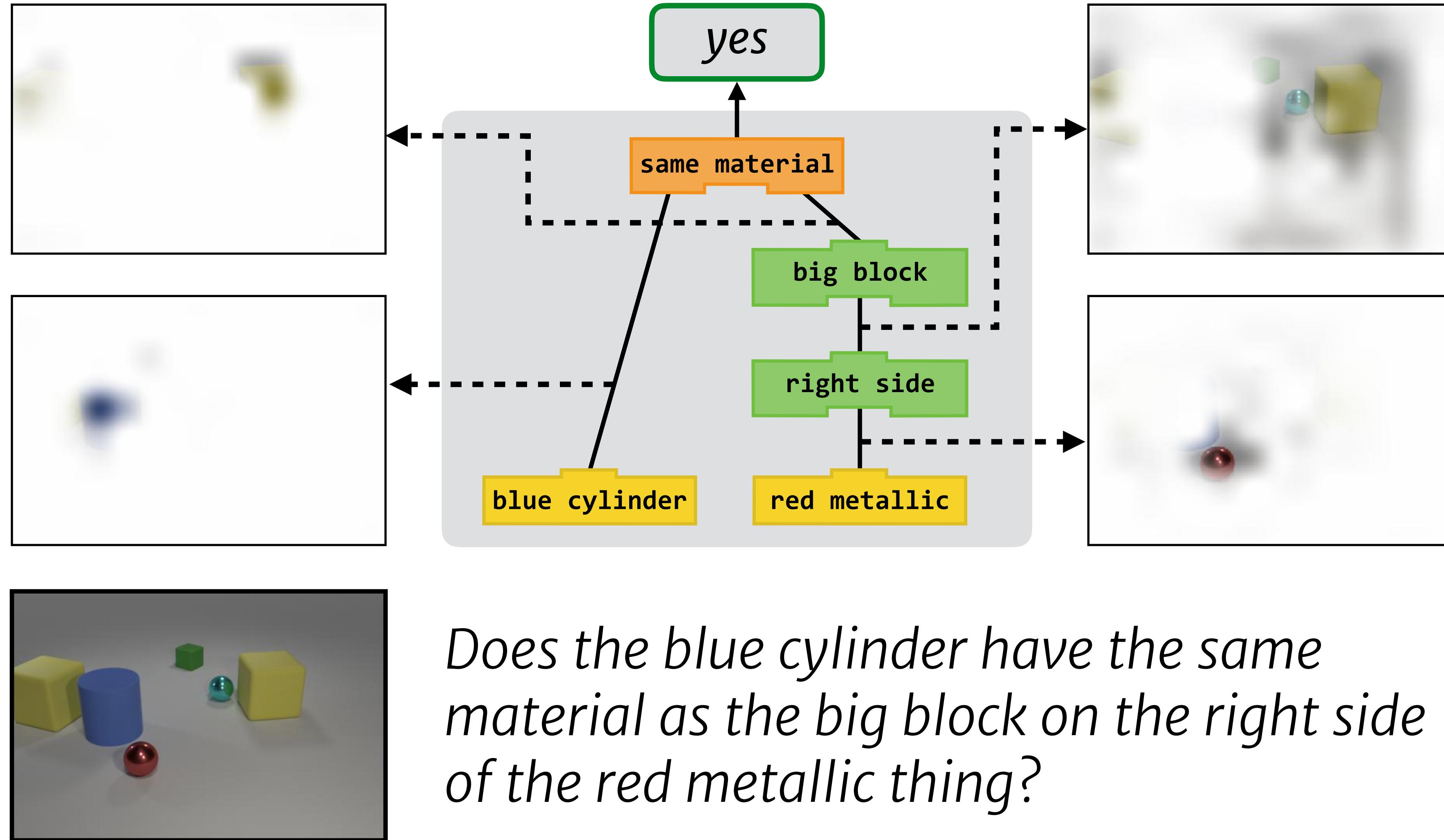
CNN +  
RNN

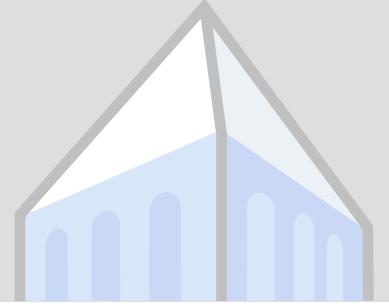
64.7  
MCB

64.9  
NMN

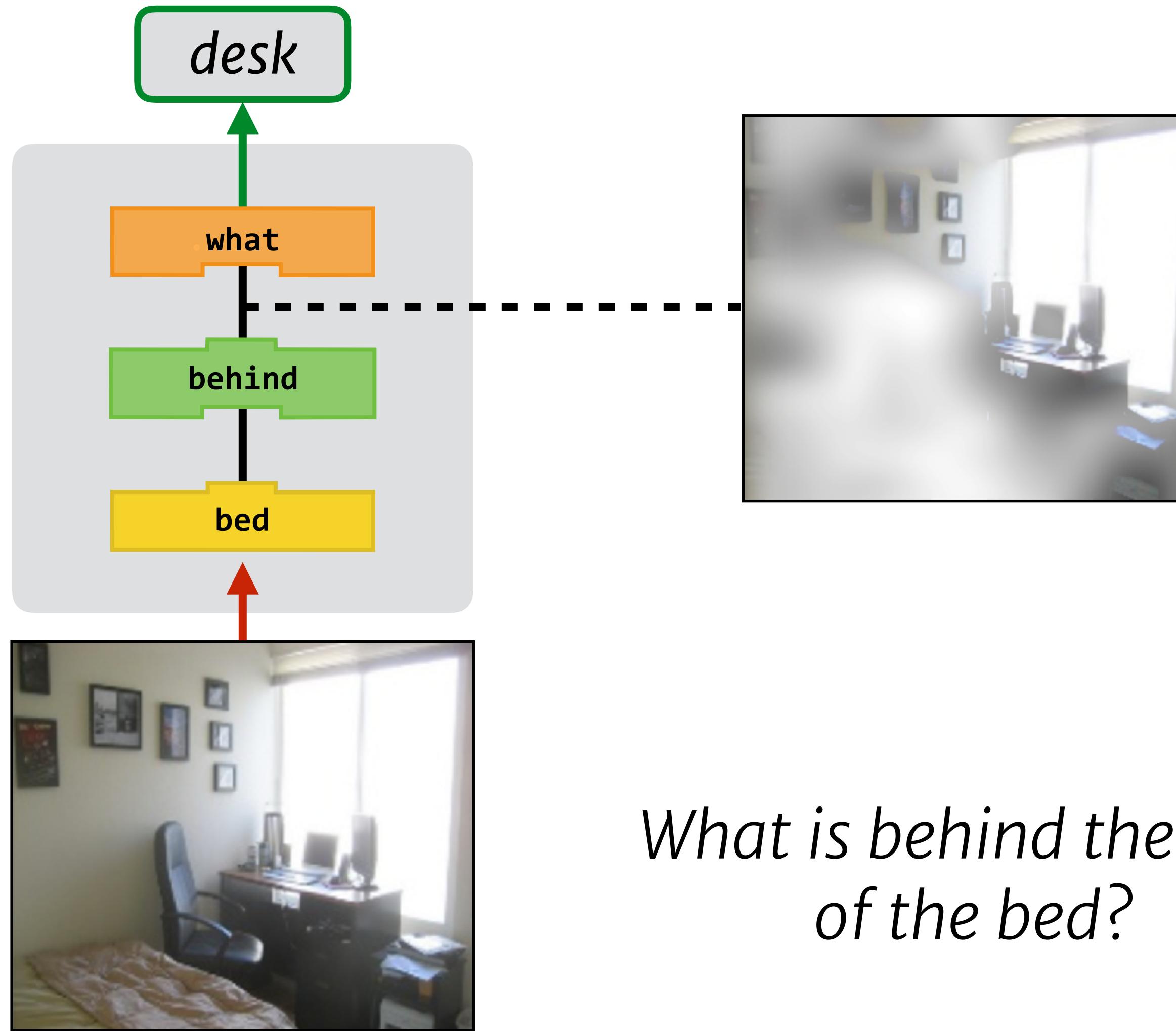


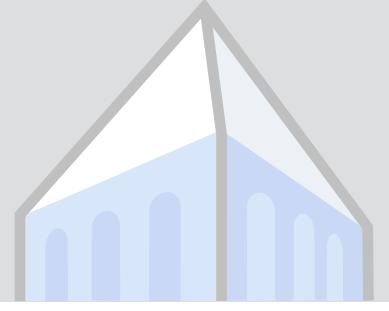
# Experimental evaluation [ARDK16a, HARDS17]





# Experimental evaluation [ARDK16a, HARDS17]





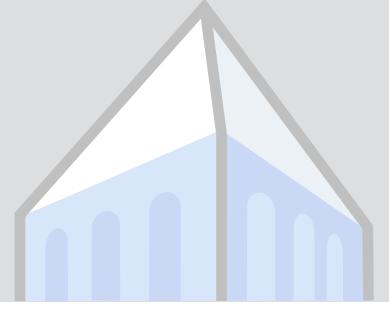
# NMNs and strong generalization [ARDK16a]

## TRAIN

*Is there anything left of a circle?  
Is there anything above a circle?*

## TEST

*Is there anything **above and left**  
of a circle?*



# NMNs and strong generalization [ARDK16a]

## TRAIN

*Is there anything left of a circle?  
Is there anything above a circle?*

## TEST

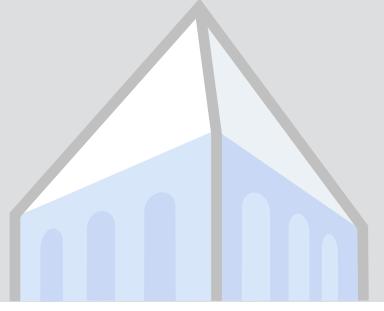
*Is there anything **above and left** of a circle?*

76.5

CNN + RNN

90.6

NMN



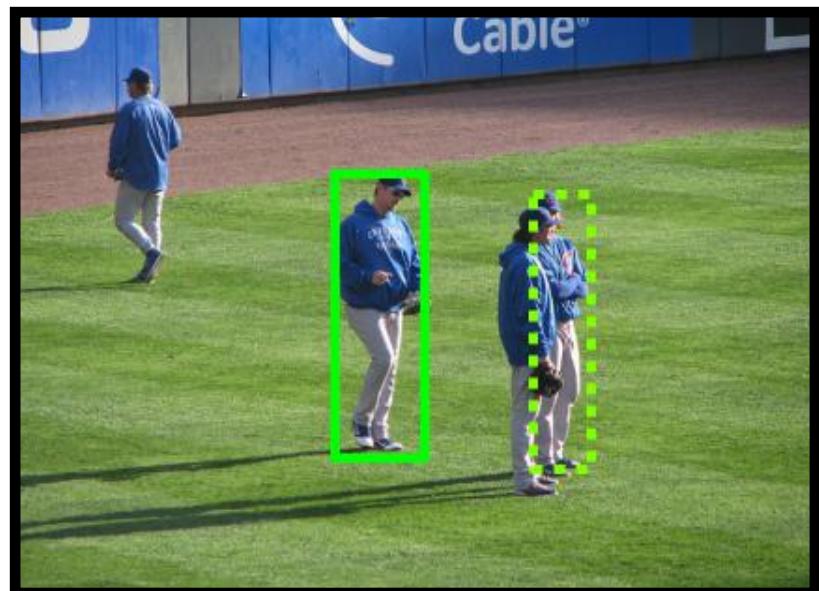
# NMNS for other tasks

*Is Key Largo  
an island?*

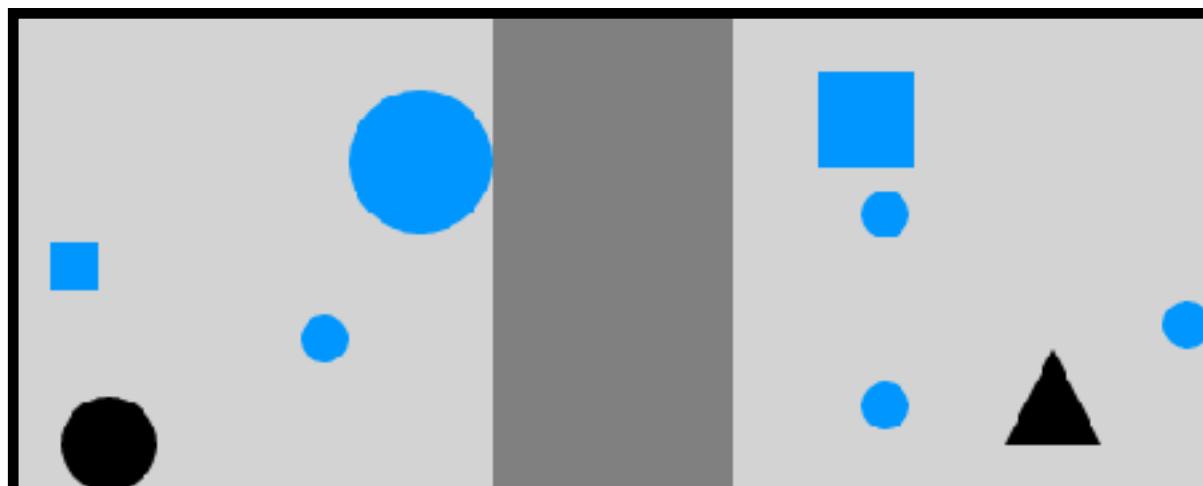
name	type	coastal	island
<i>Columbia</i>	city	no	no
<i>Cooper</i>	river	yes	no
<i>Charleston</i>	city	yes	no

[A, Rohrbach, Darrell, Klein; 16b]

*man in sunglasses  
walking towards  
two men*



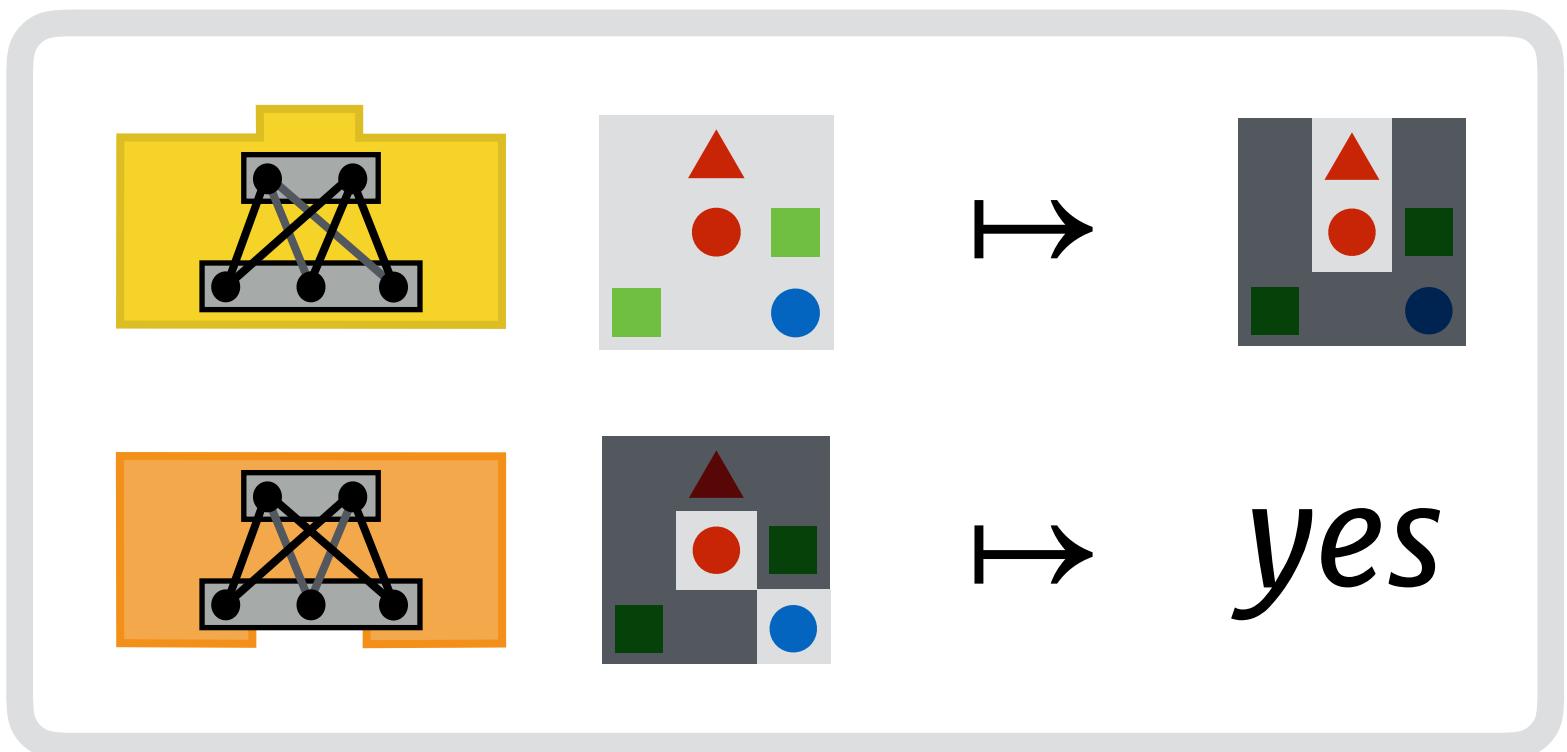
*There is exactly one  
black triangle not  
touching any edge.*



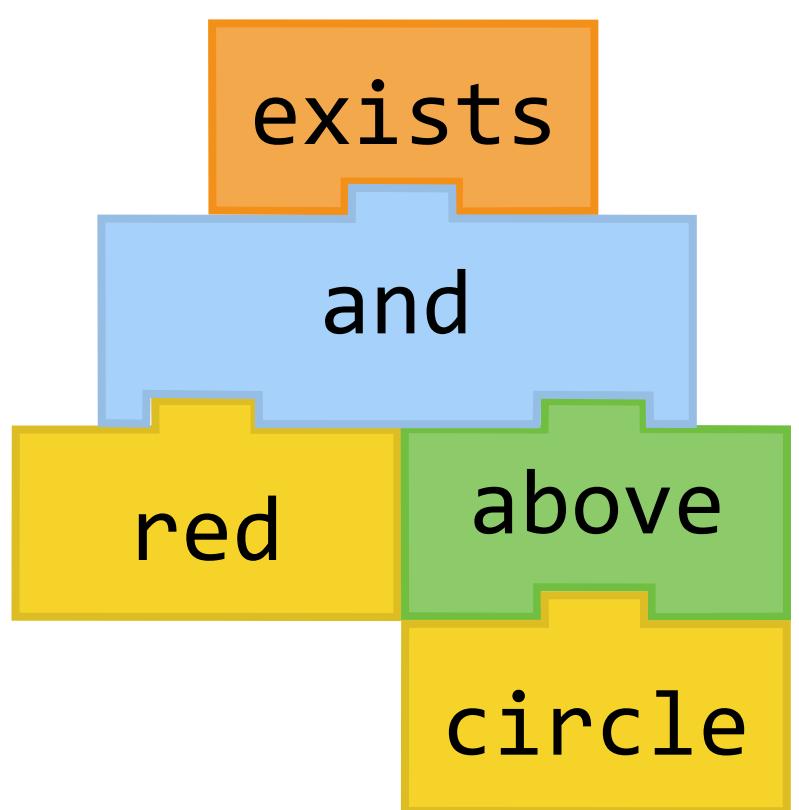
[Hu, Rohrbach, A, Darrell, Saenko; 17]  
[Cirik, Berg-Kirkpatrick, Morency; 18]  
[Yu, Lin, Shen, Yang, Lu, Bansal, Berg; 18]

[Suhr, Lewis, Artzi; 17]

# Lessons



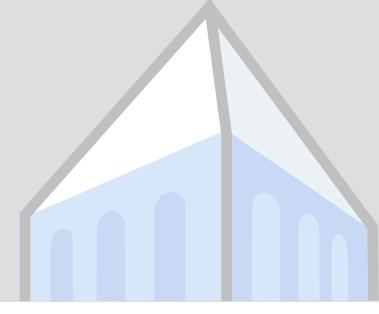
Linguistic structure lets us learn composable neural modules from weak supervision.



These modules allow us to more accurately interpret new statements, questions and references.

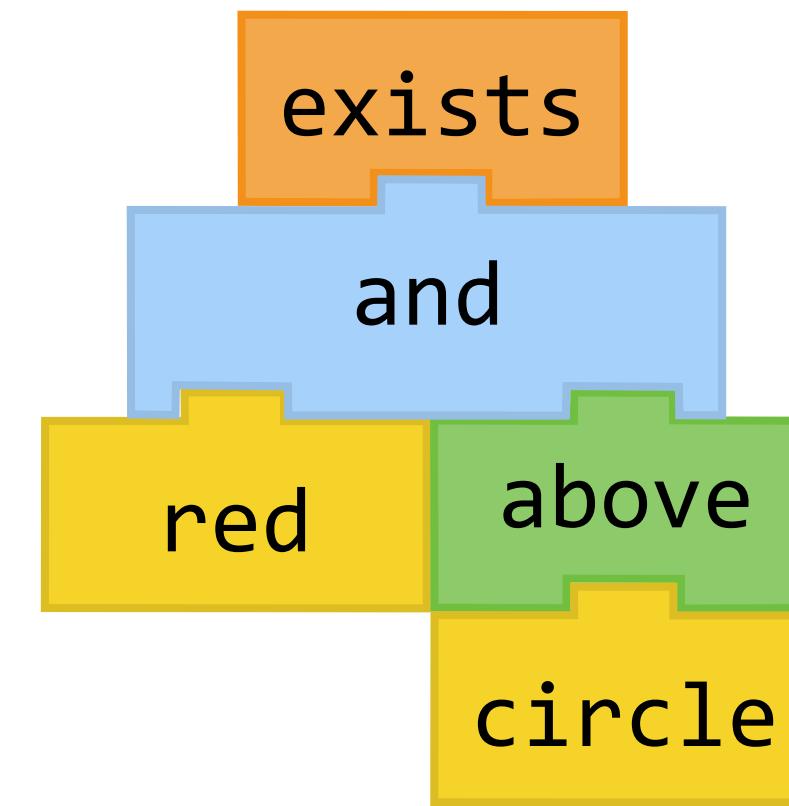
REASONING  
LANGUAGE & LEARNING  
BELIEF

A, Klein & Levine. *Modular Multitask Reinforcement Learning [...]*. ICML 17.



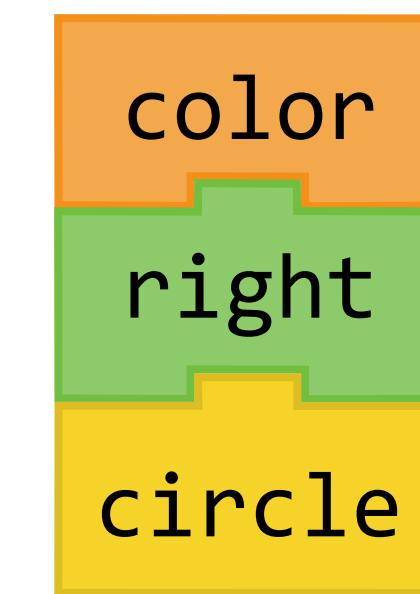
# Learning classifiers

yes



*Is there a red shape above a circle?*

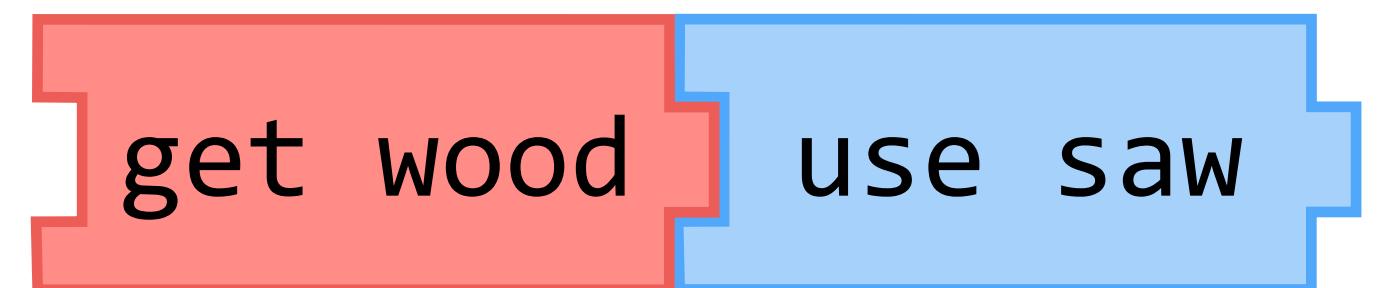
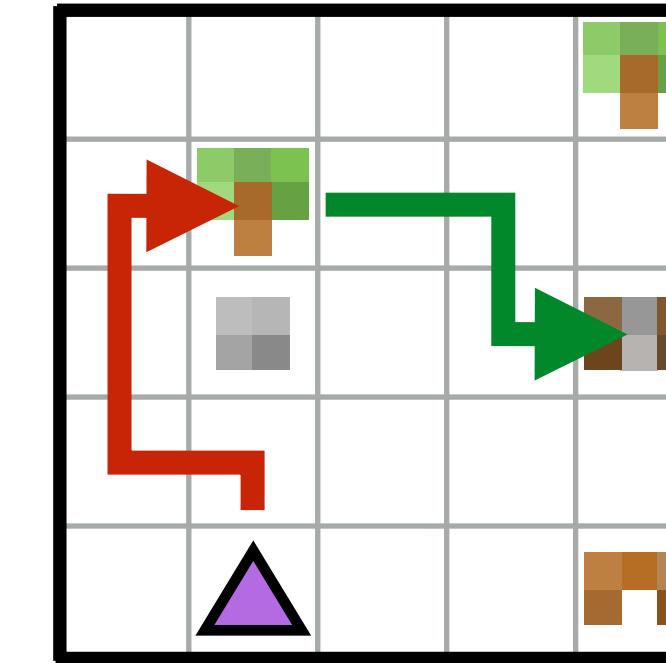
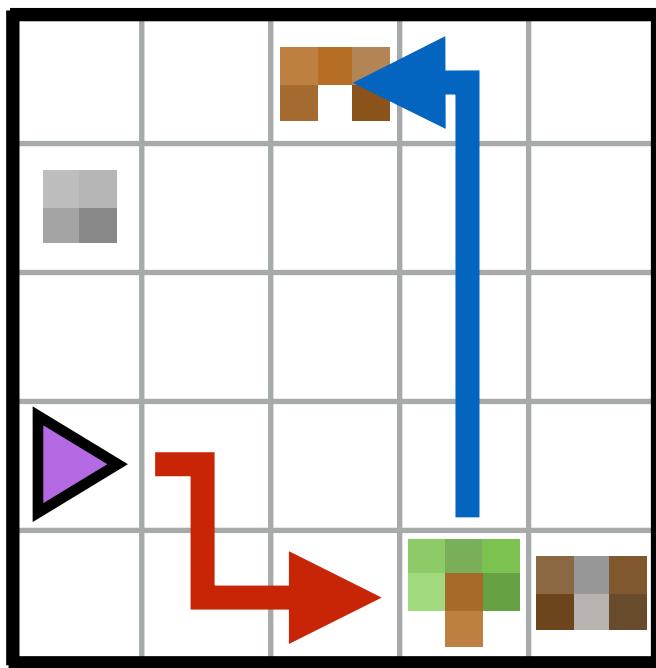
blue



*What color is the shape right of a circle?*

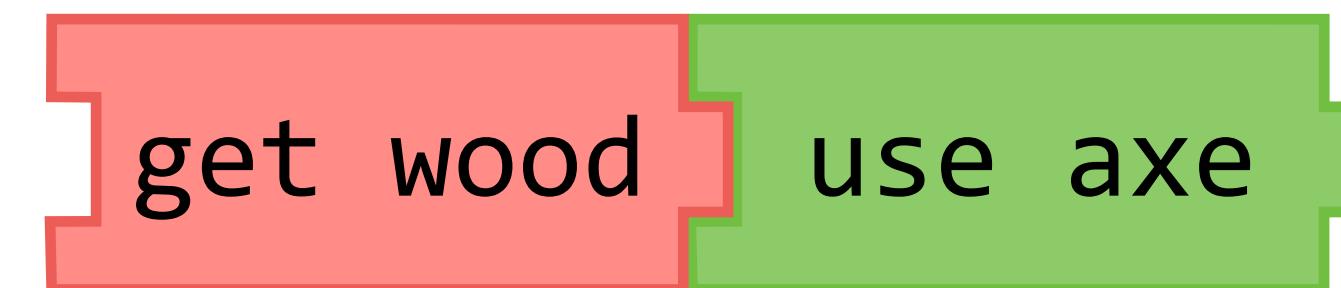


# Learning behaviors



get wood      use saw

*Make planks:  
get wood, then use a saw.*

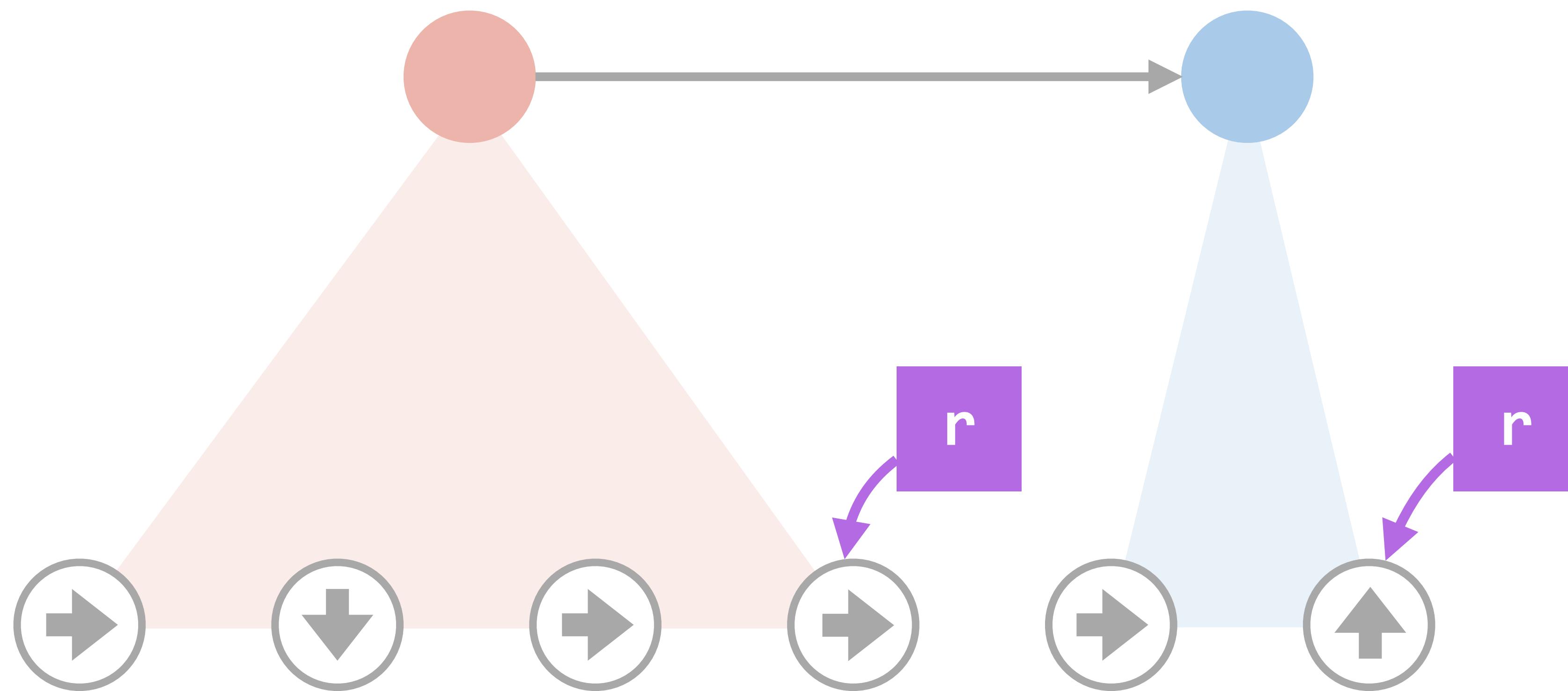


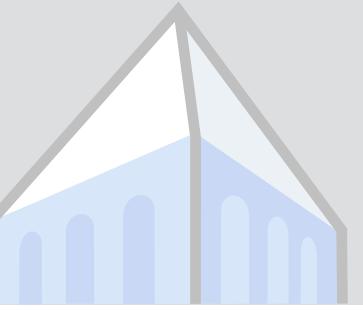
get wood      use axe

*Make sticks:  
get wood, then use an axe.*

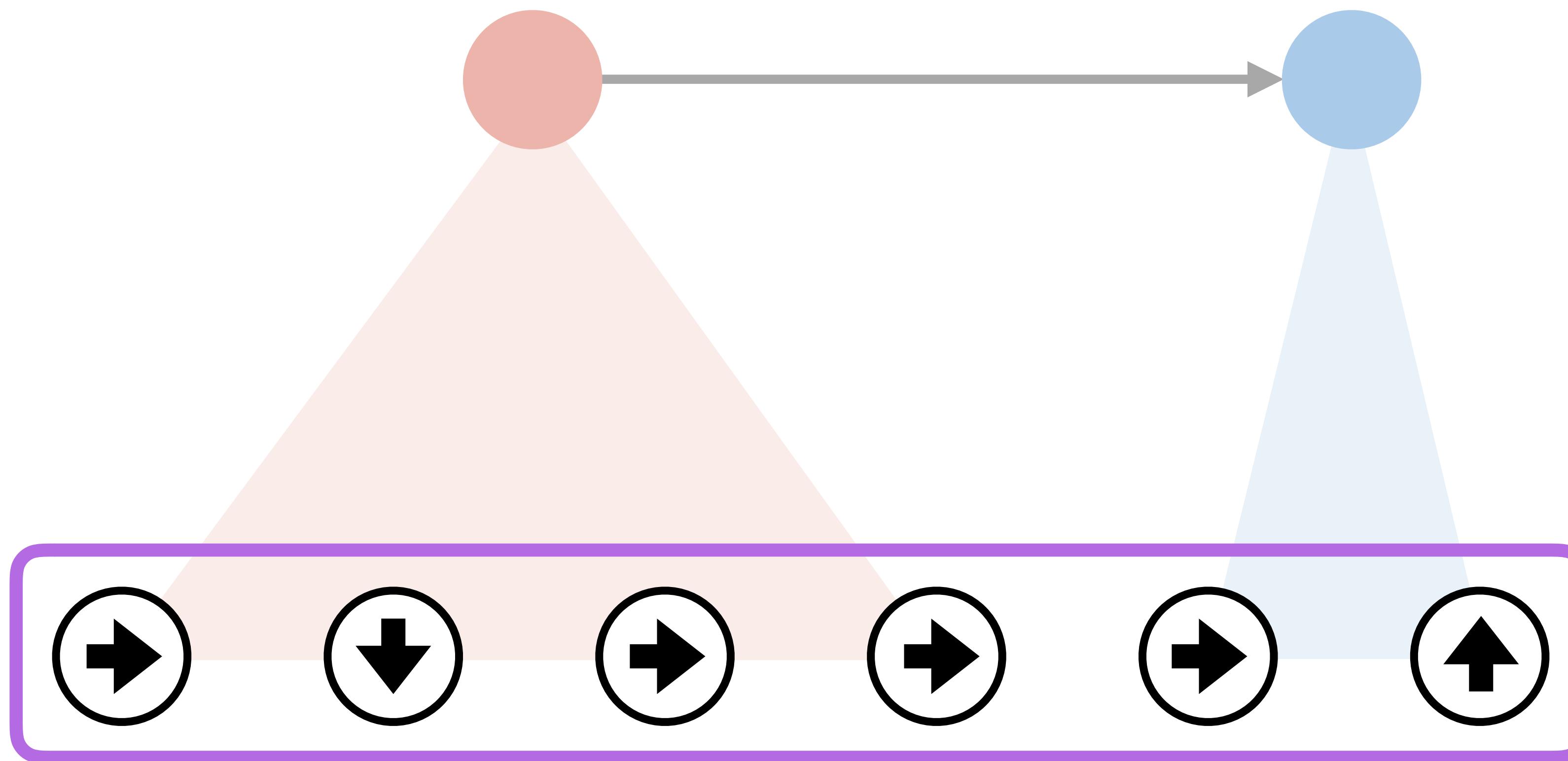


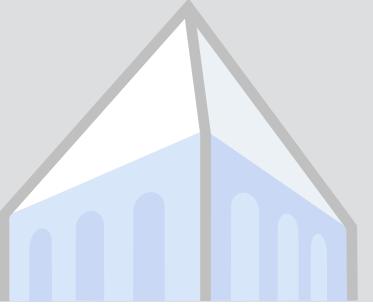
# Learning from intermediate rewards



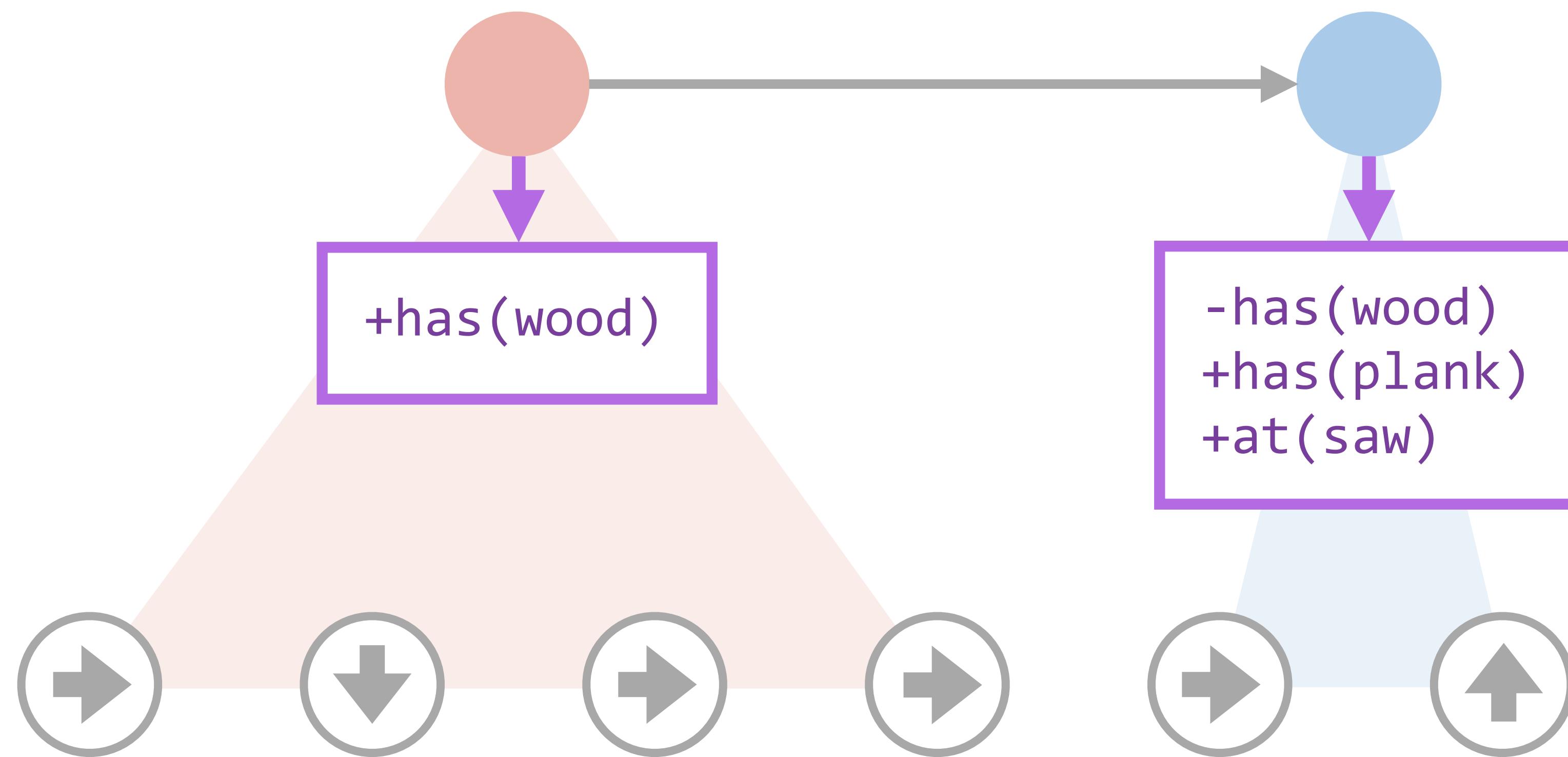


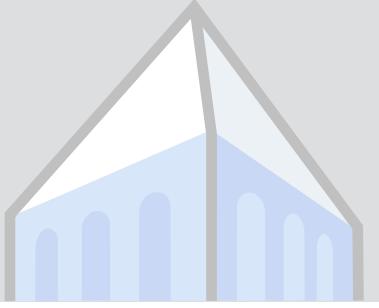
# Learning from demonstrations



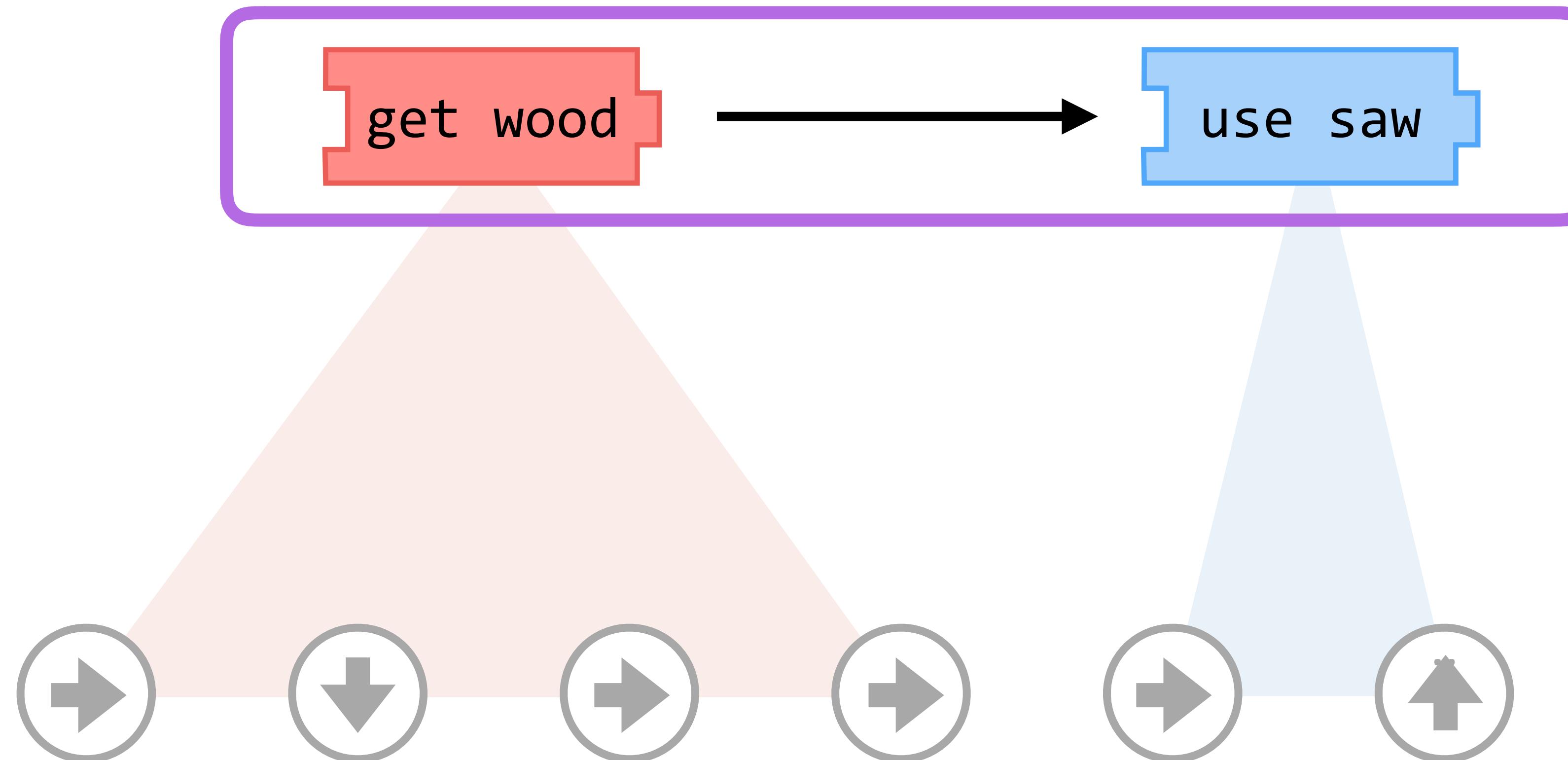


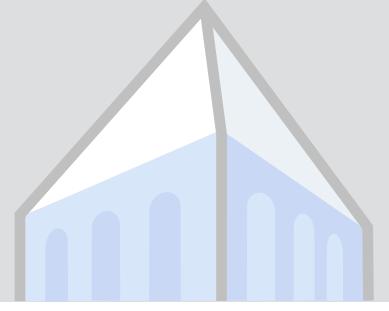
# Learning from intermediate rewards





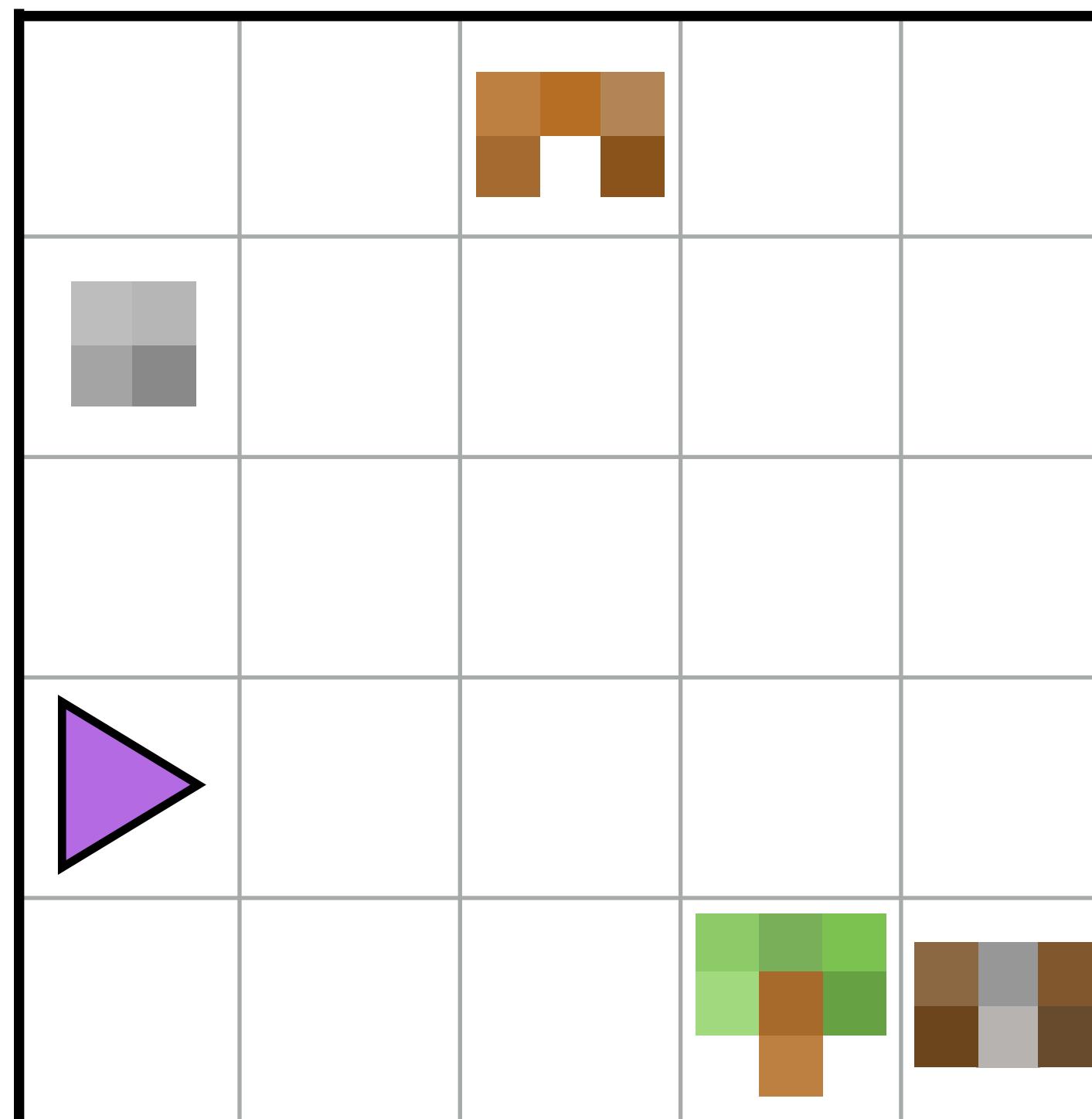
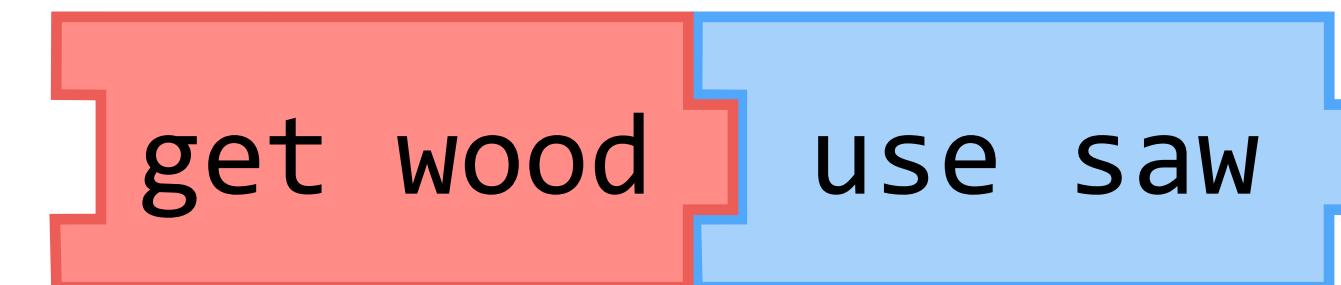
# Learning from sketches

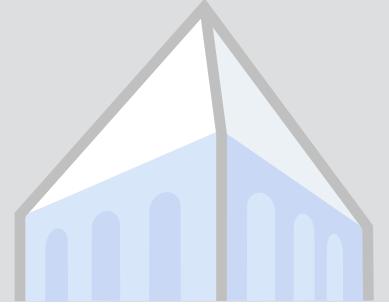




# Learning from sketches

*Make planks:*

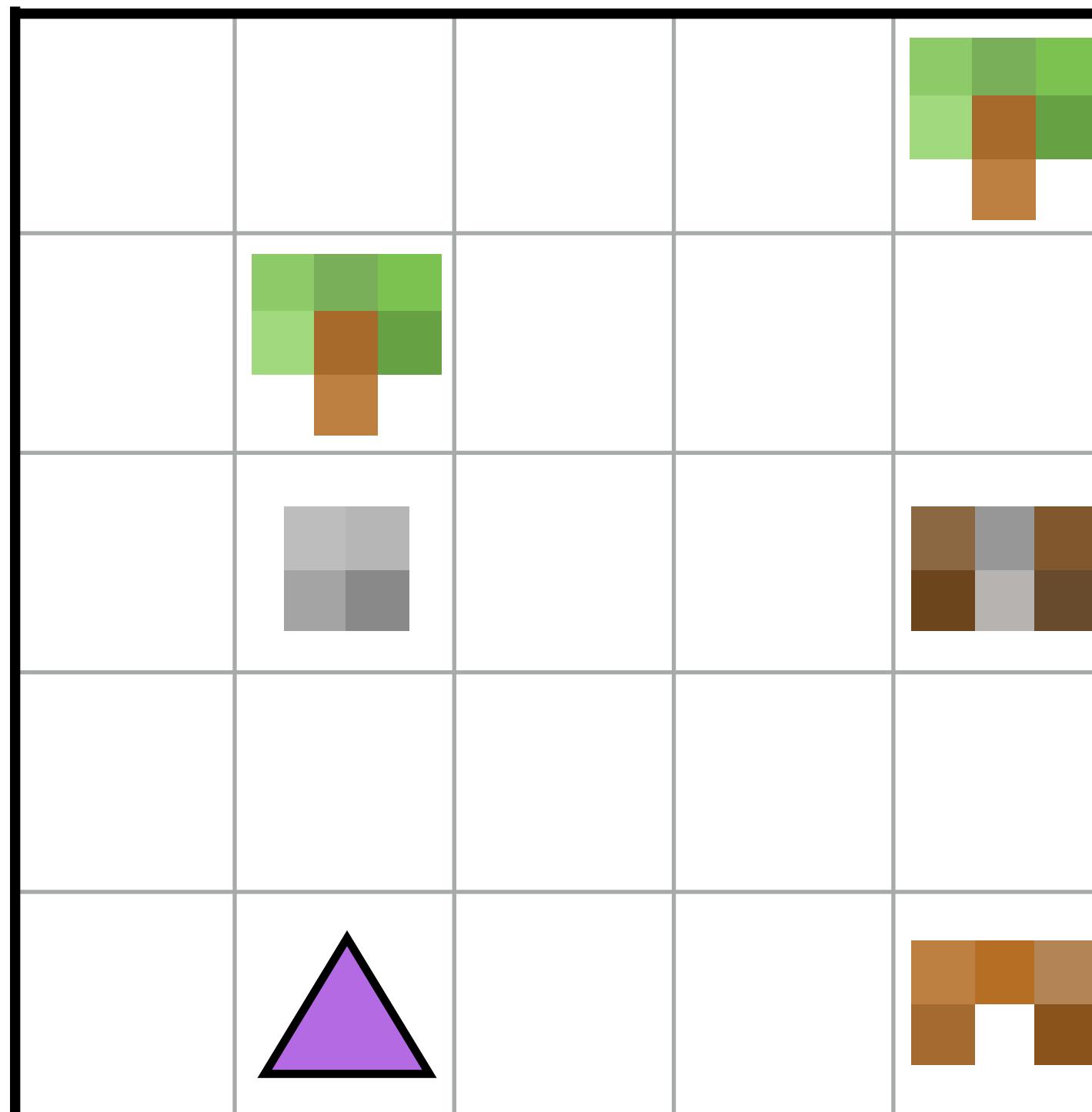




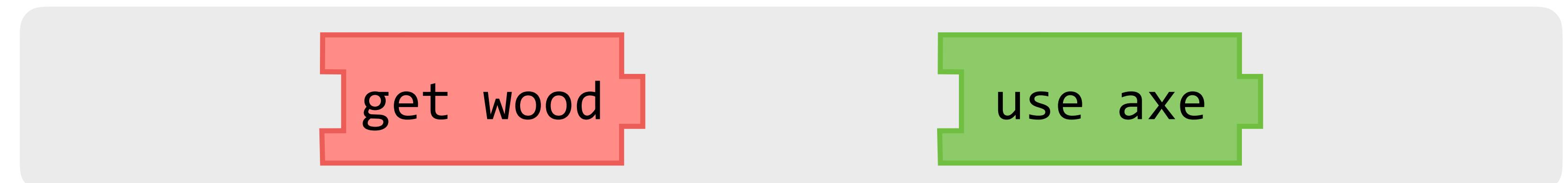
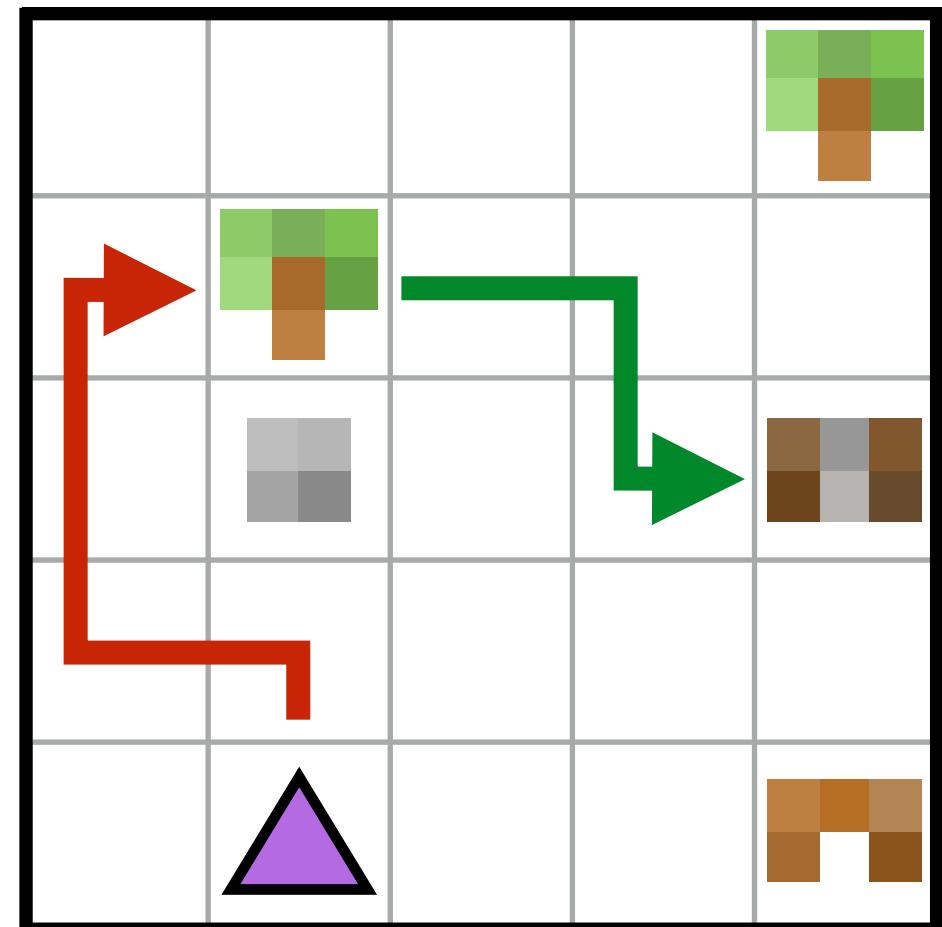
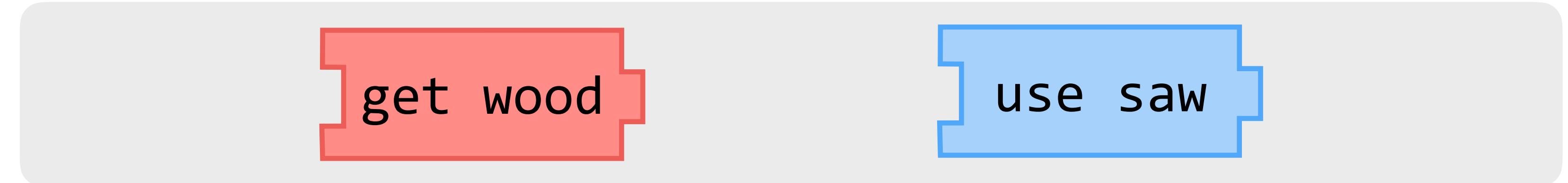
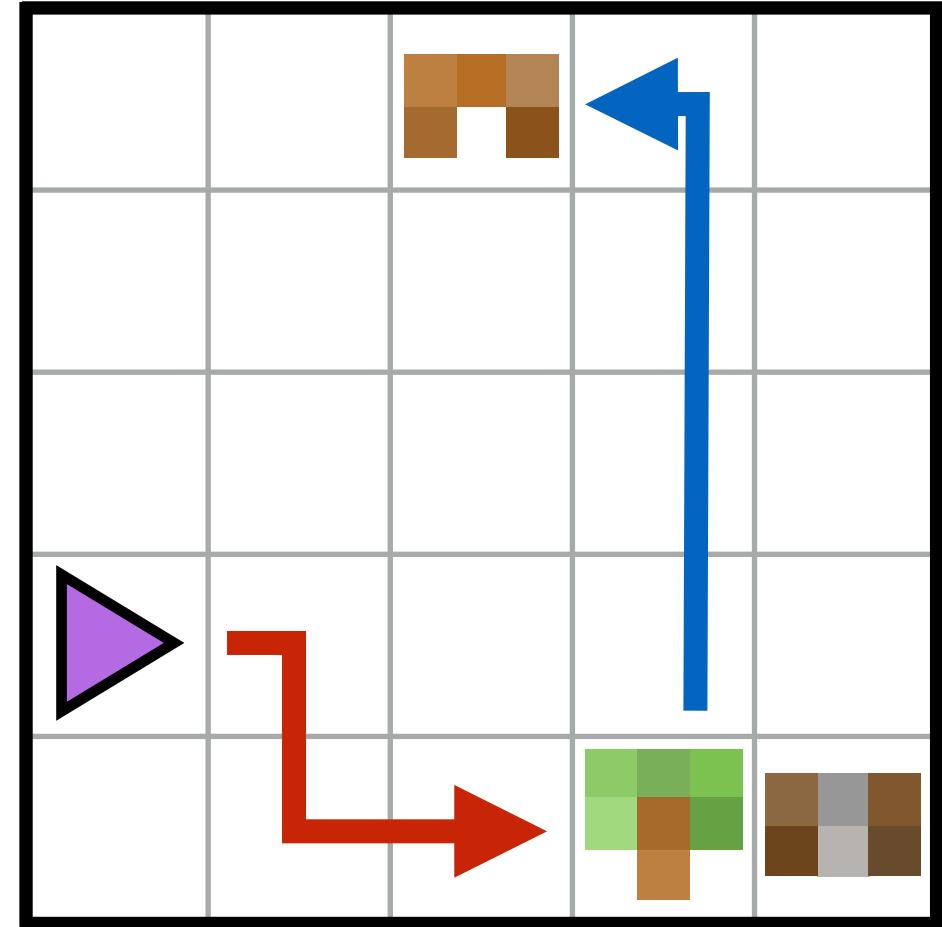
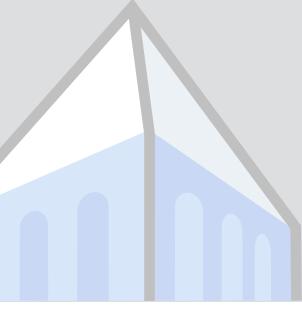
# Learning from sketches

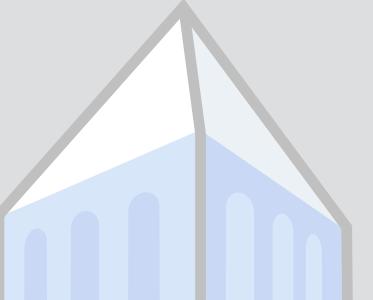
*Make sticks:*

get wood      use axe

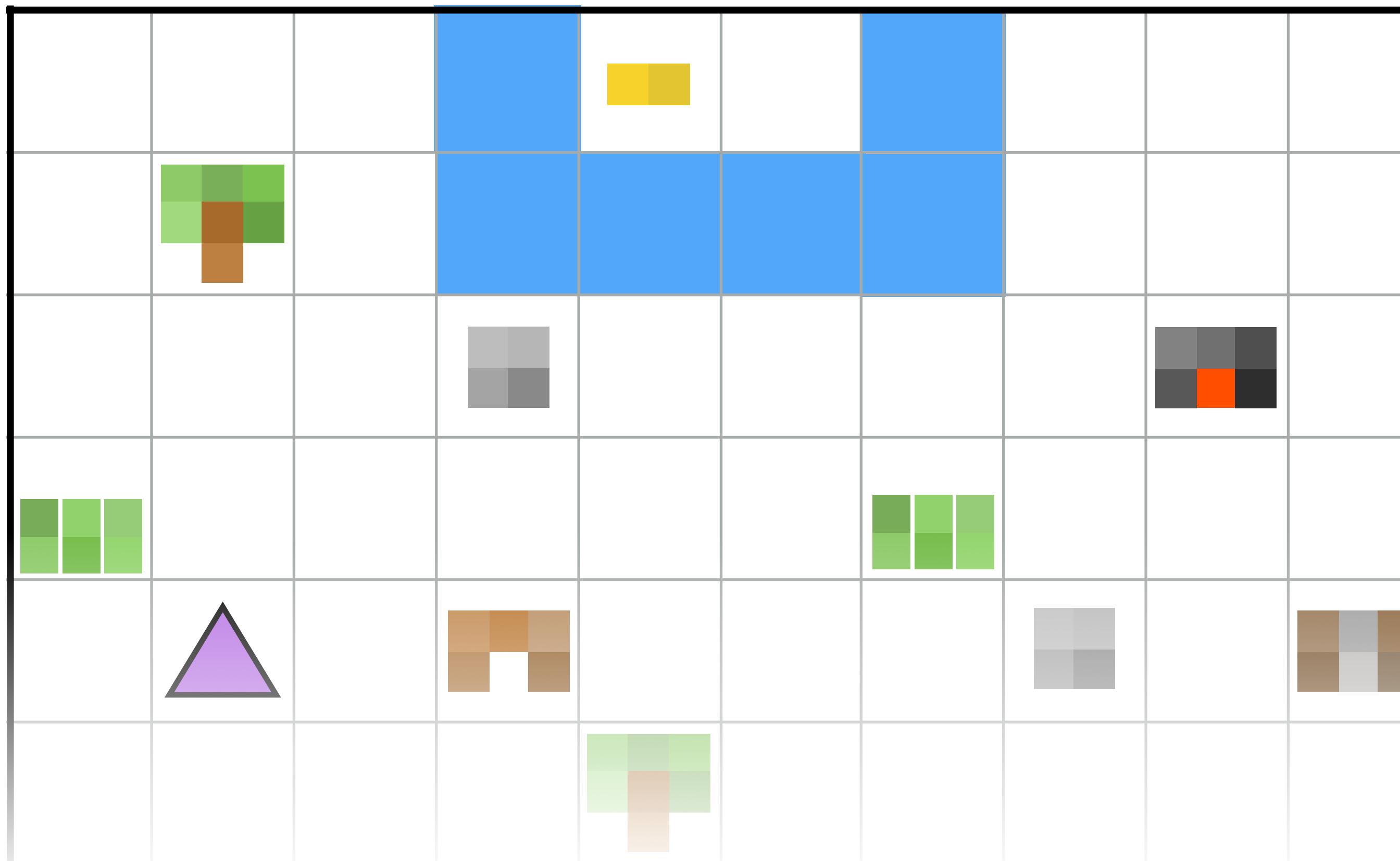


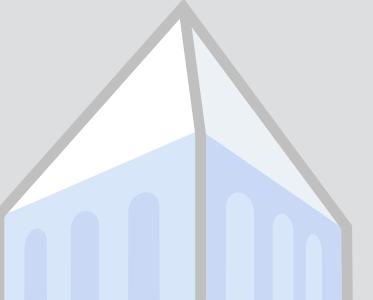
# Learning from sketches



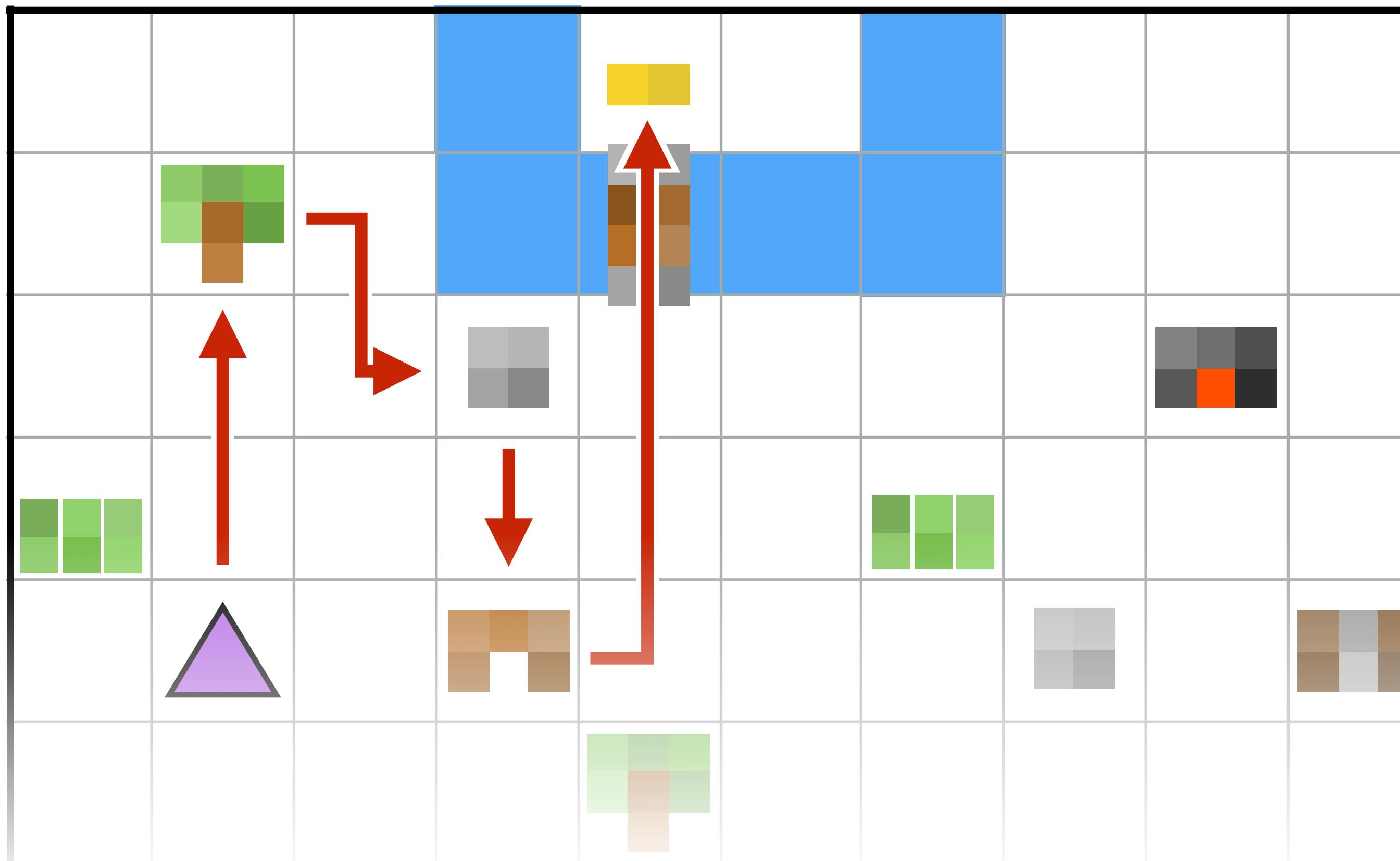


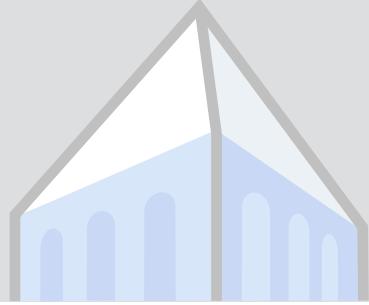
# Experiments: crafting game



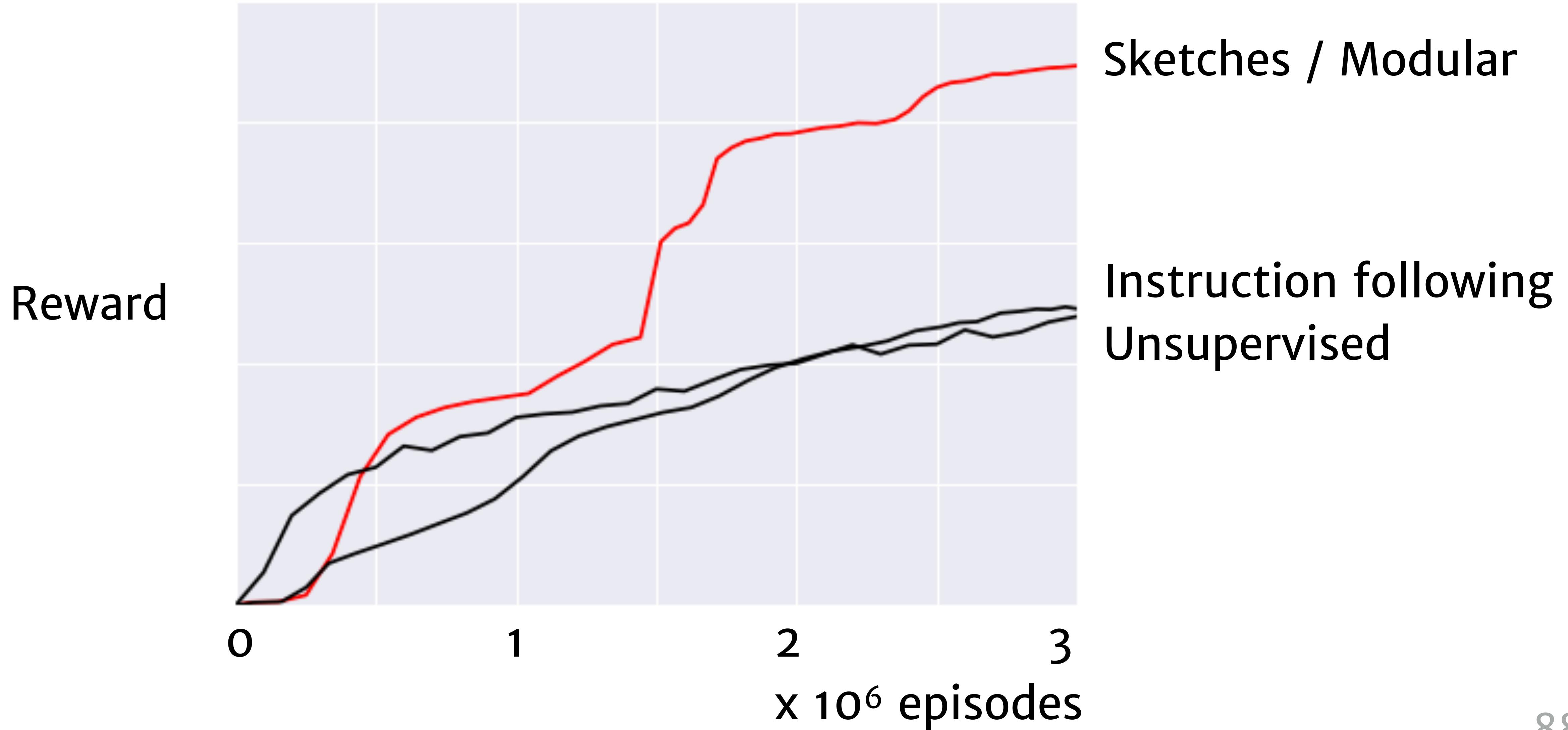


# Experiments: crafting game



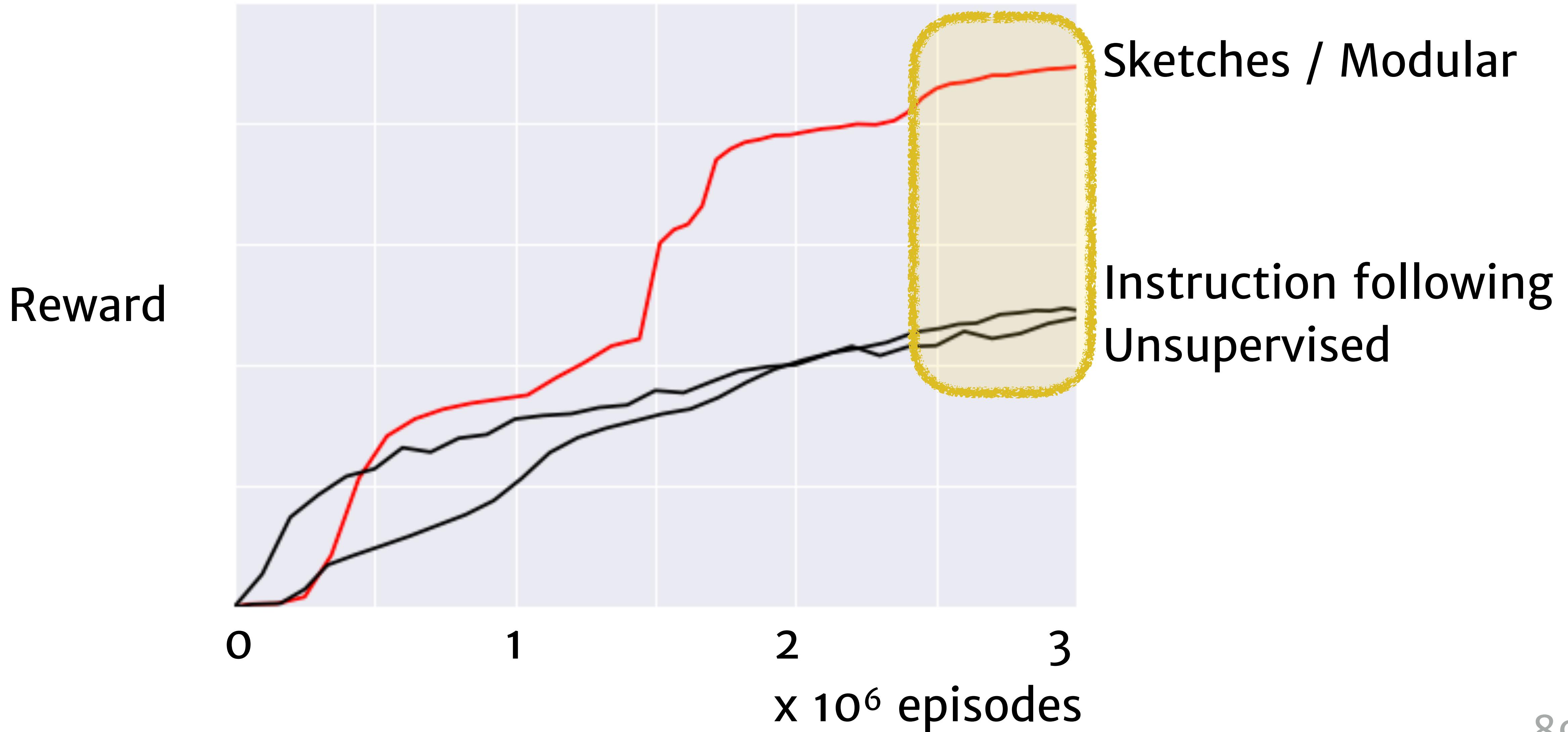


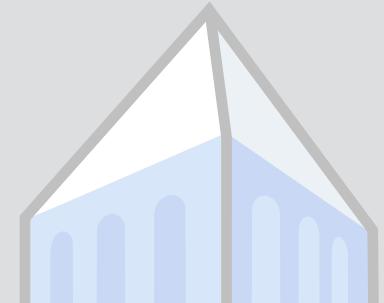
# Experiments: crafting game



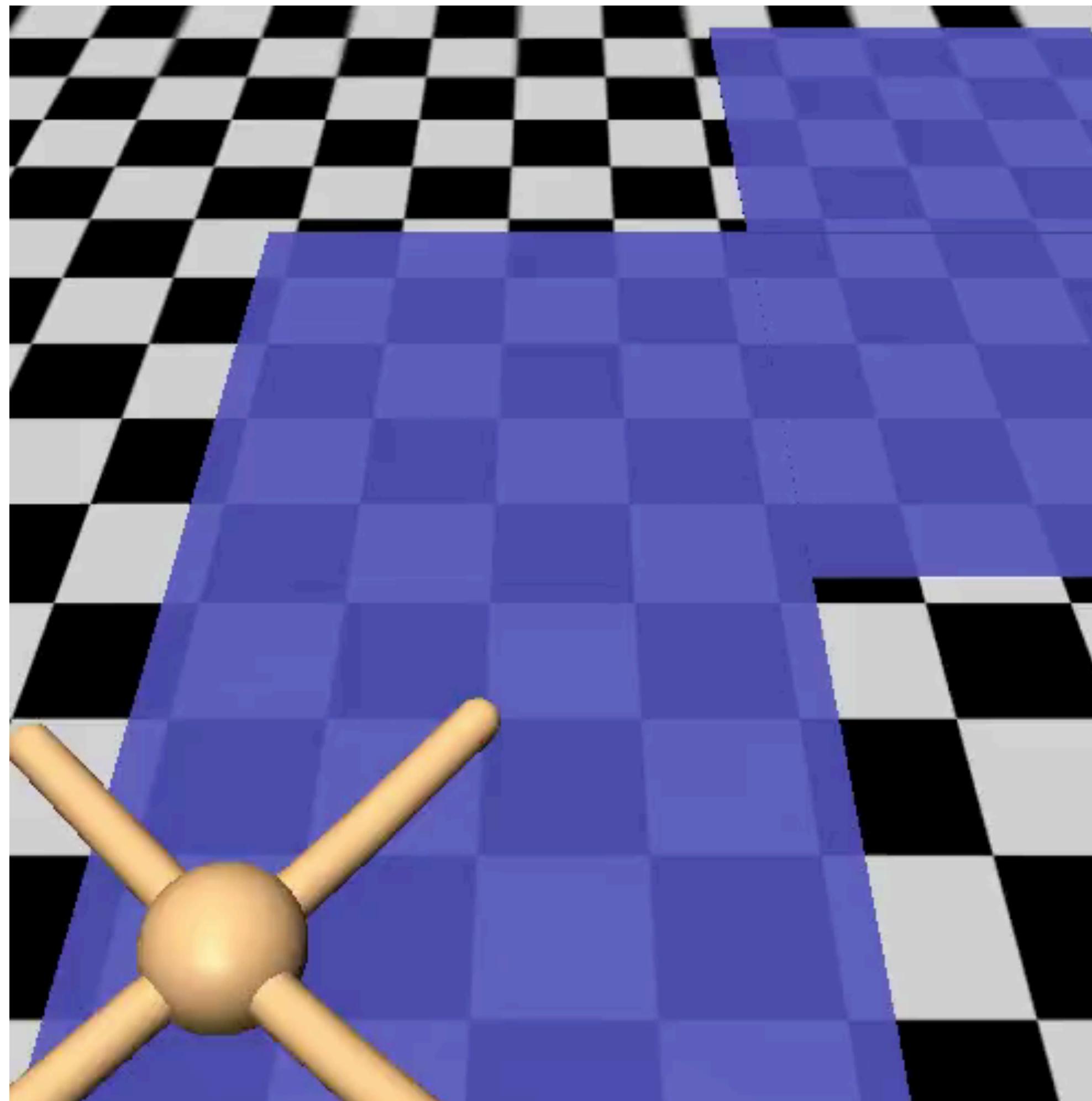


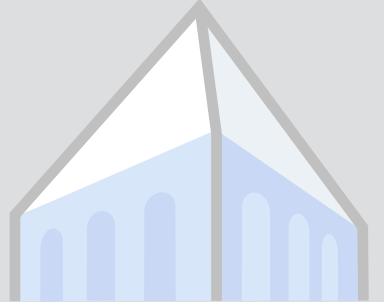
# Experiments: crafting game





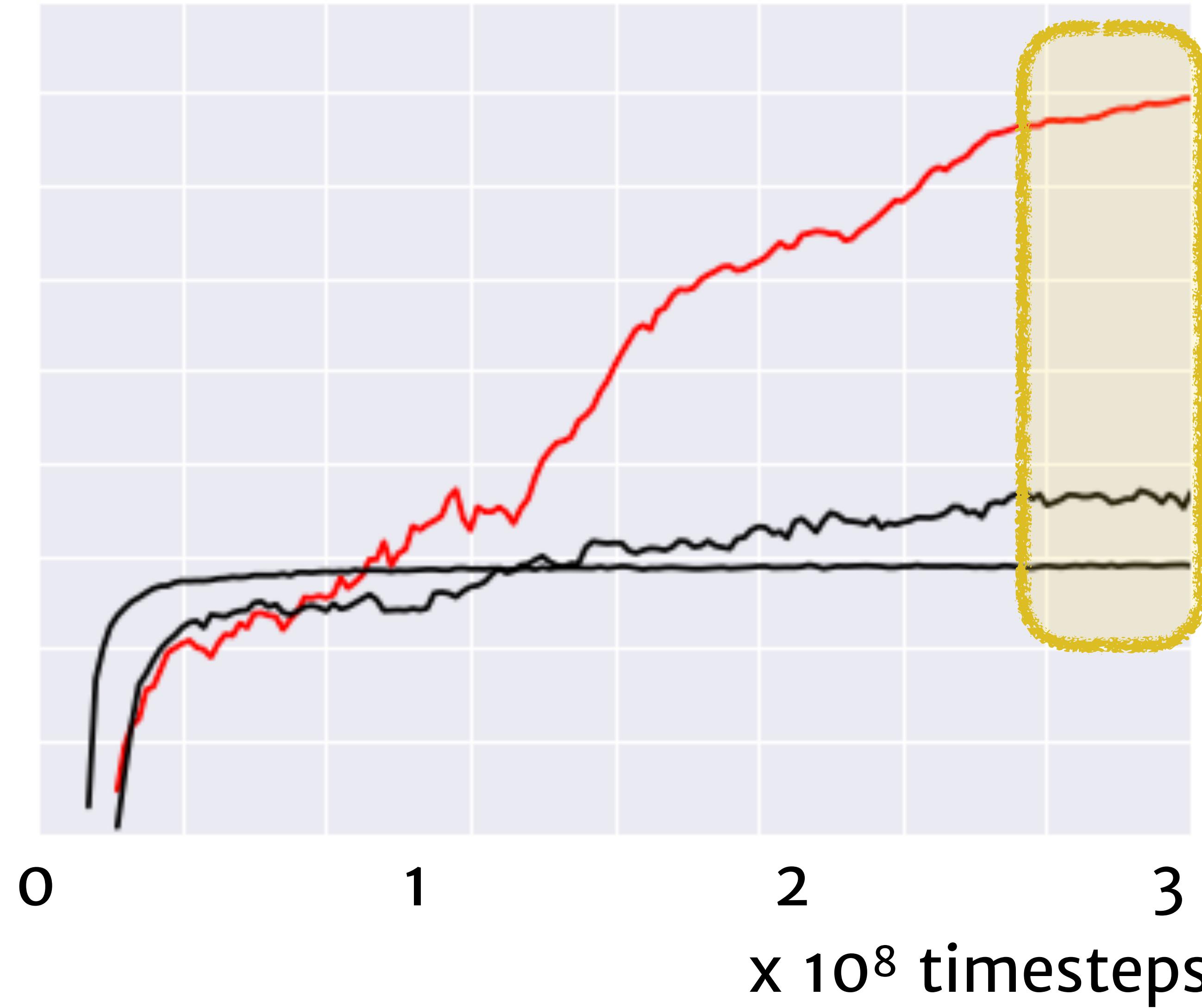
# Experiments: locomotion





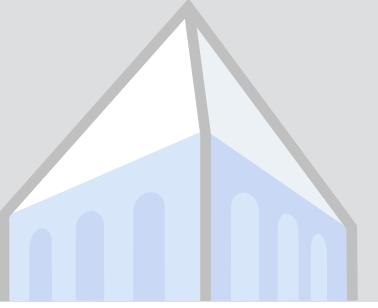
# Experiments: locomotion

log Reward



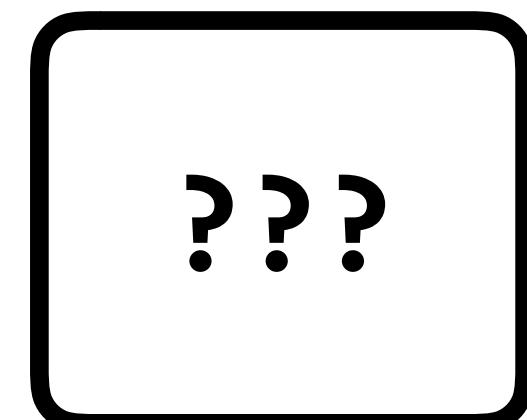
Sketches / Modular

Instruction following  
Unsupervised



# Fast adaptation

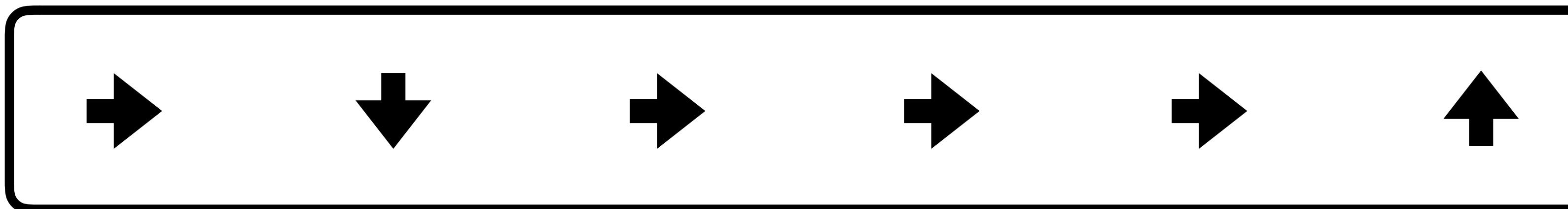
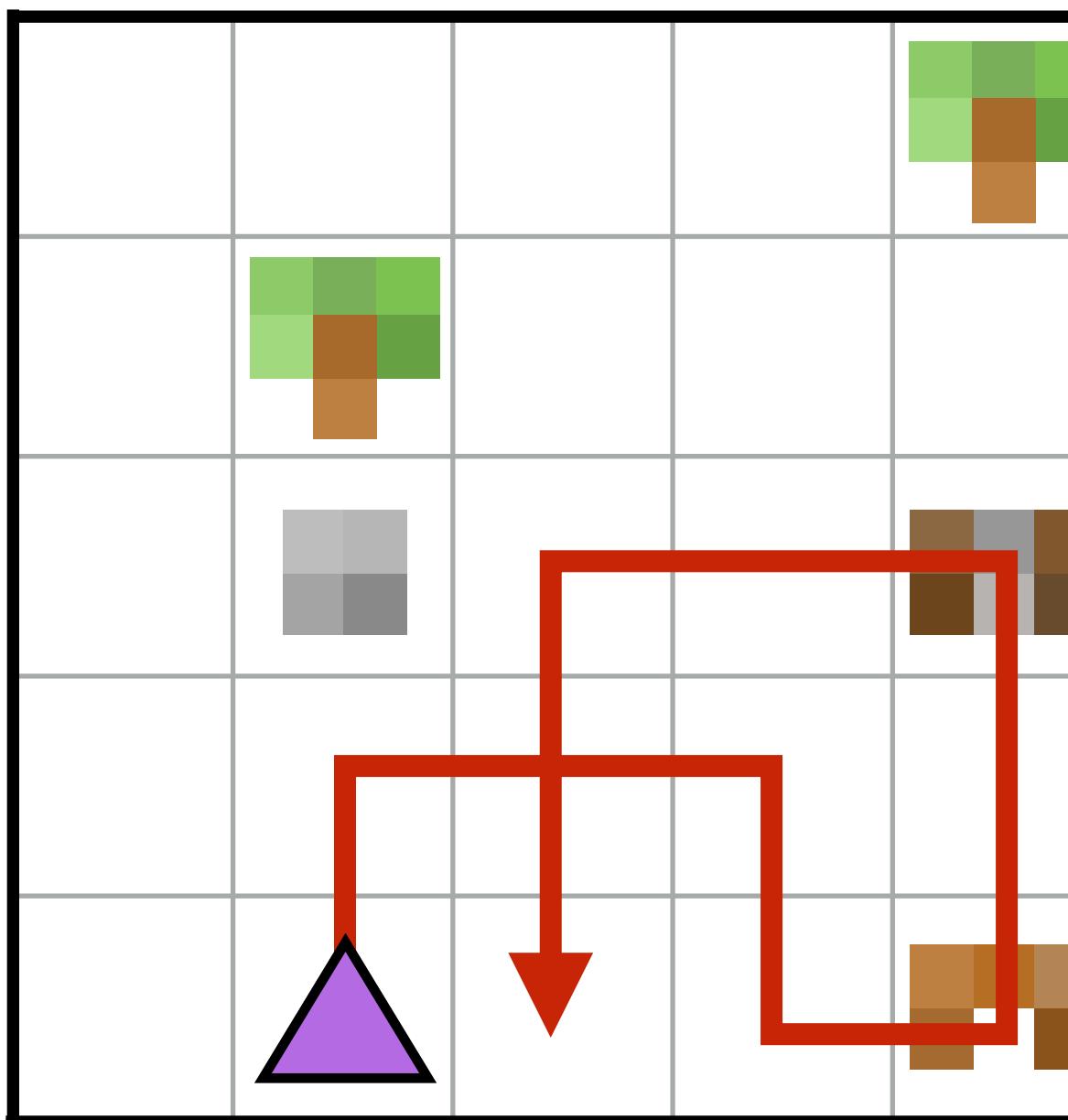
What if I don't get a sketch at test time?





# Fast adaptation

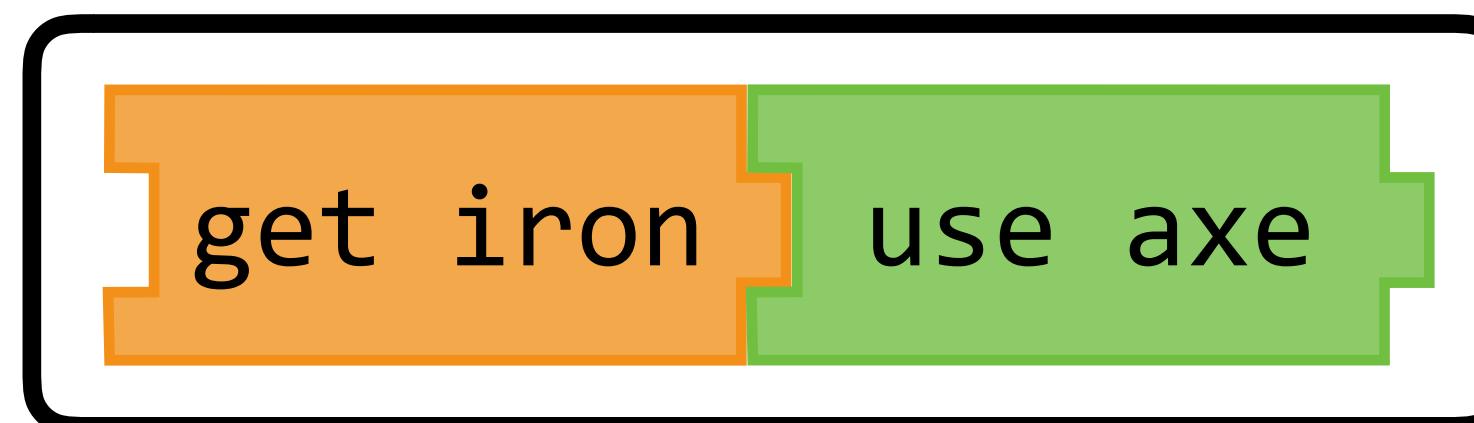
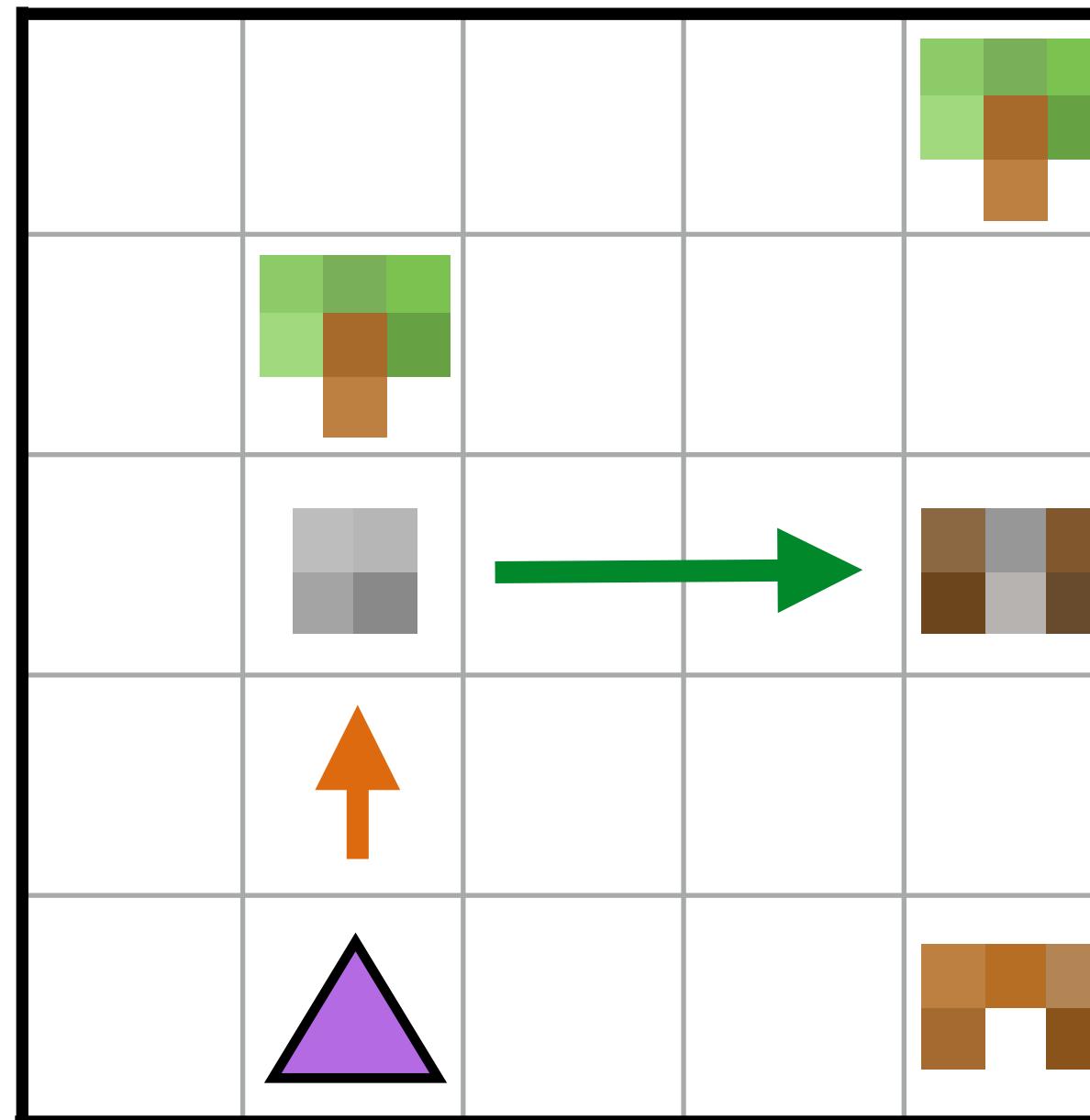
What if I don't get a sketch at test time?





# Fast adaptation

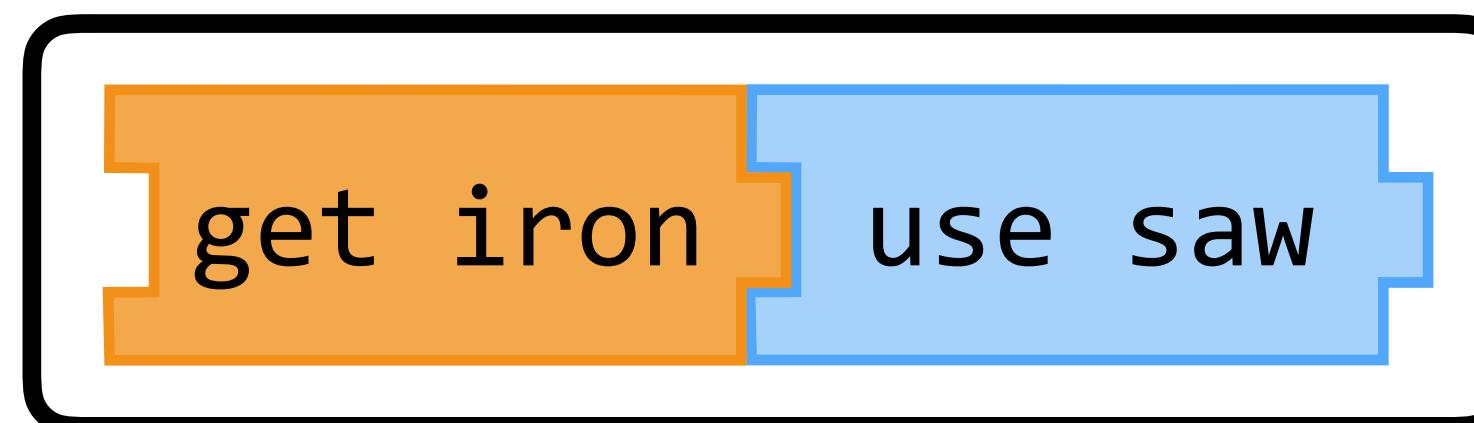
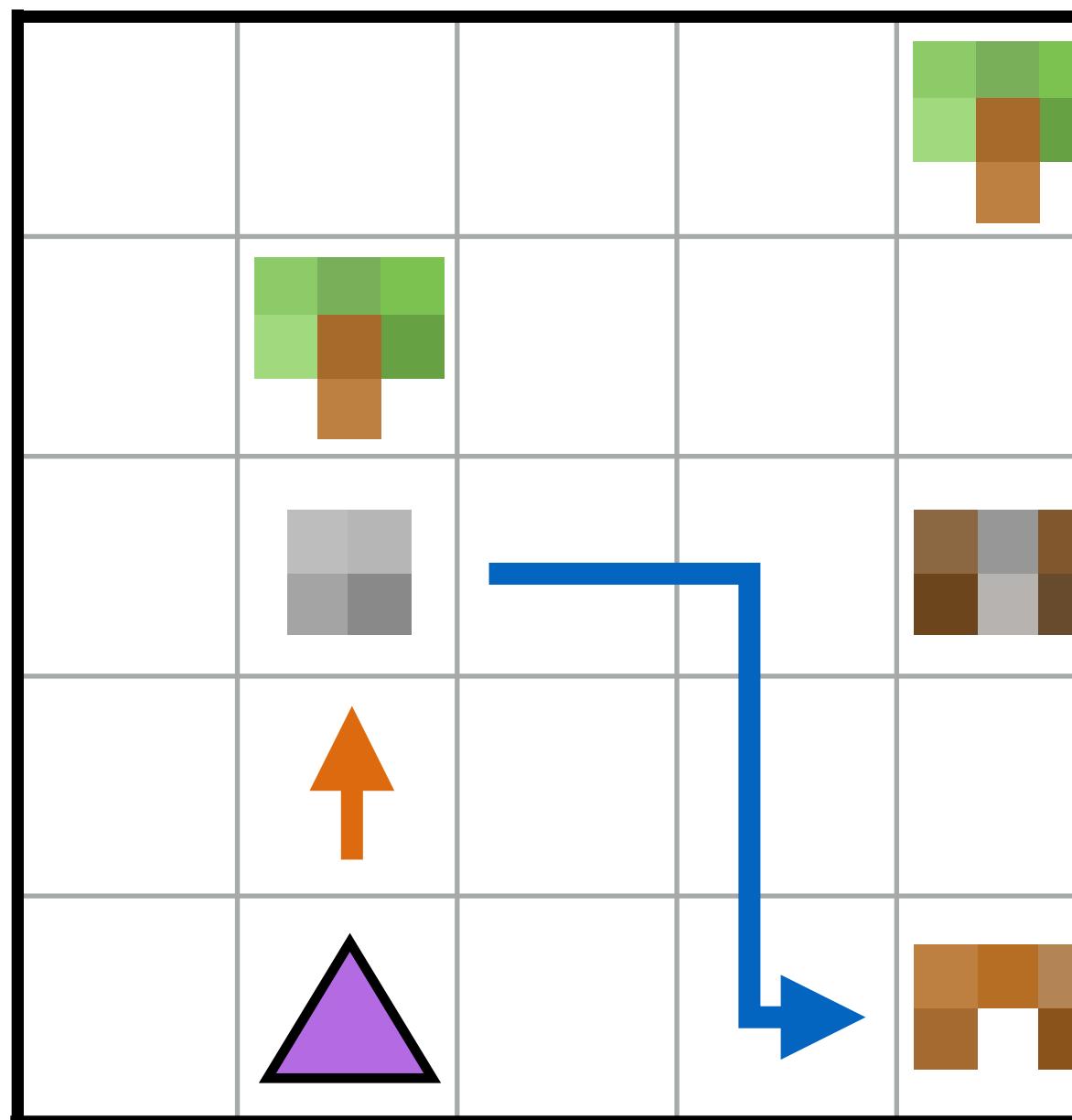
What if I don't get a sketch at test time?

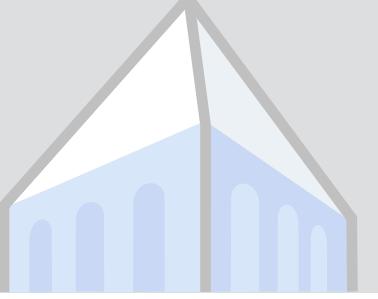




# Fast adaptation

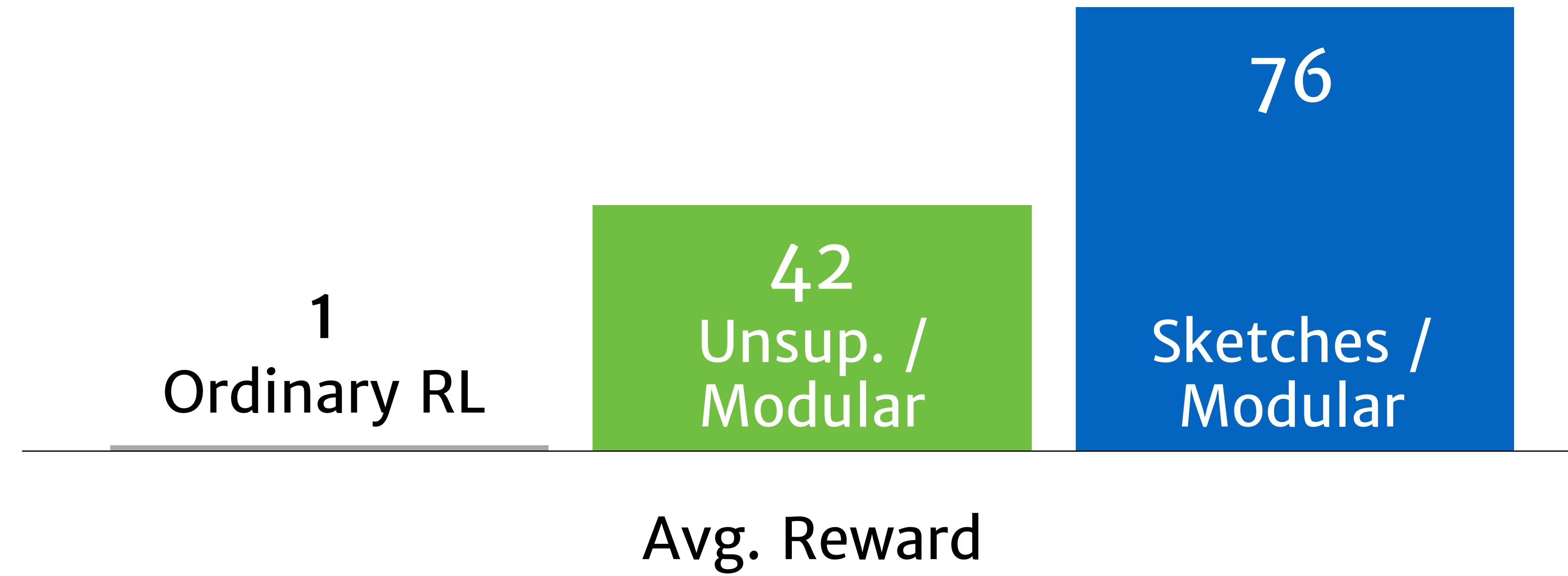
What if I don't get a sketch at test time?





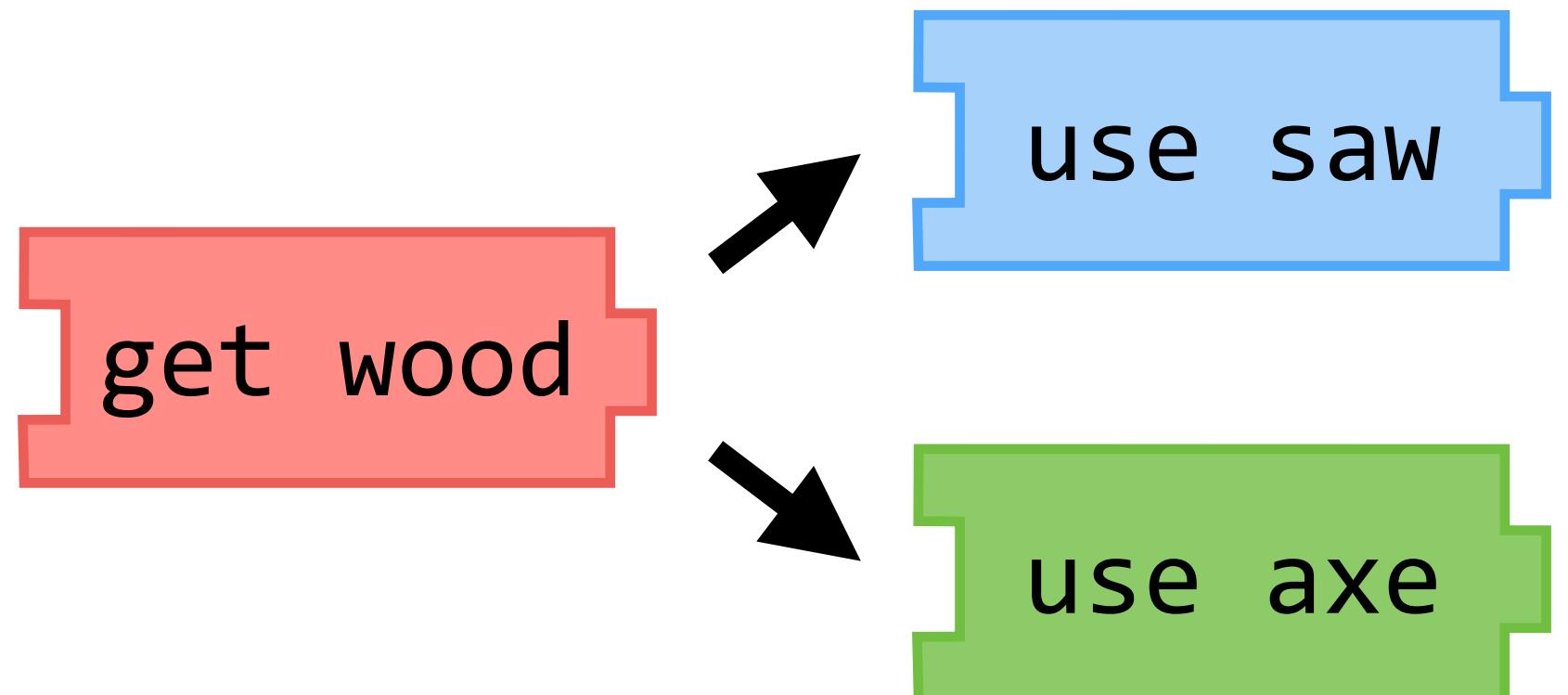
# Fast adaptation

What if I don't get a sketch at test time?





# Lessons



We can also learn modular behaviors from ungrounded “sketches” of abstract plans.

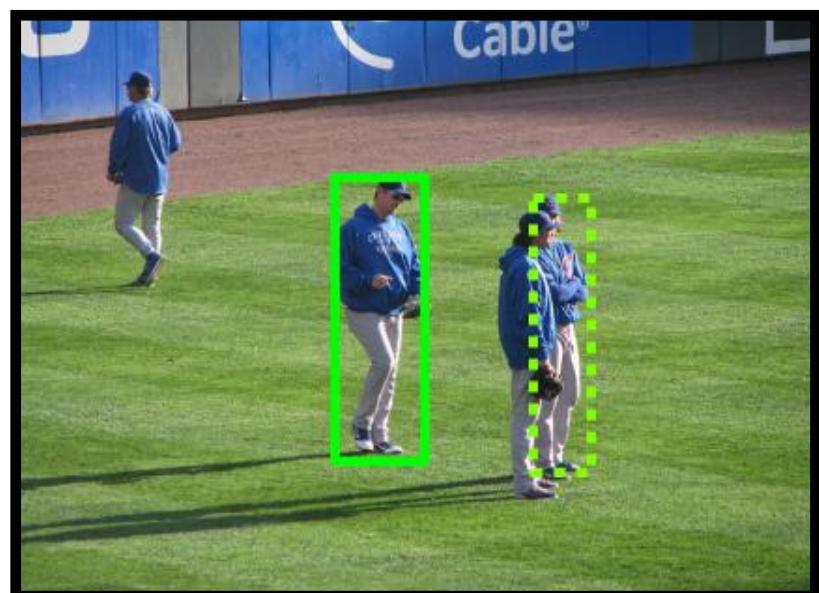
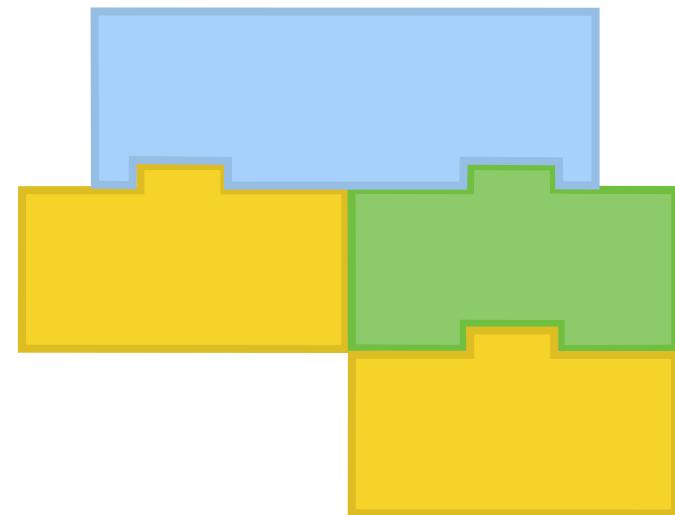
We can use these modules to help reinforcement learning even when sketches are not available.



# Beyond “tasks”

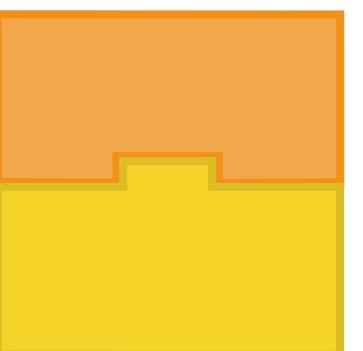
## LOCALIZATION

*Man in glasses  
near two men.*



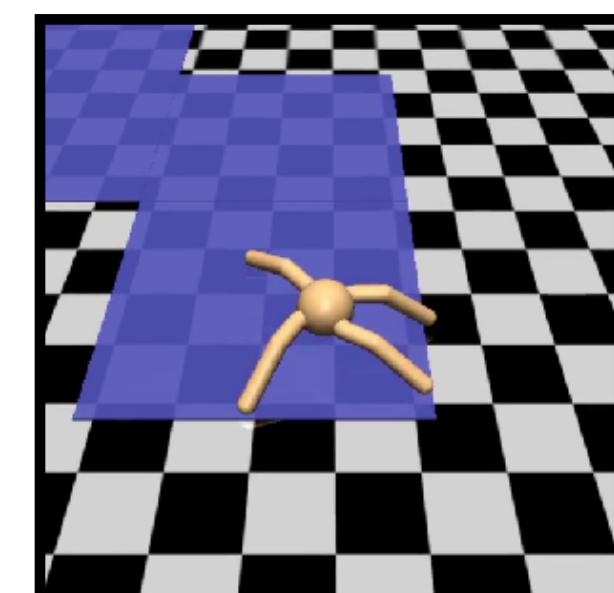
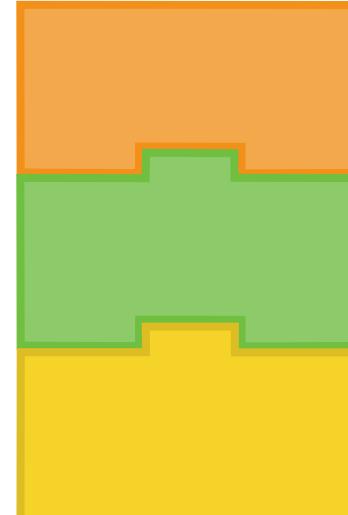
## Q&A

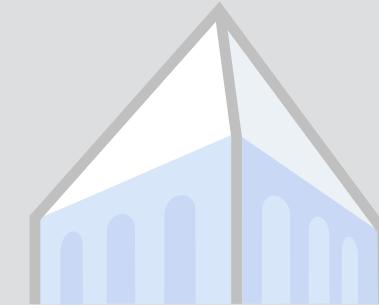
*How many  
men?*



## POLICY SEARCH

*go near the  
corner*





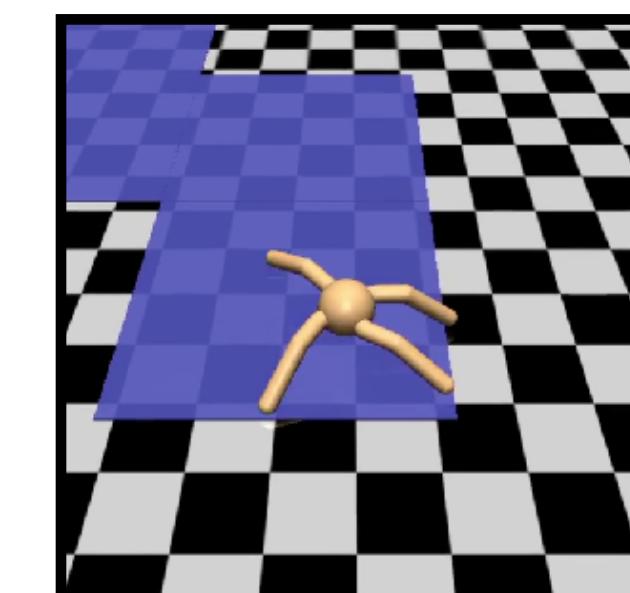
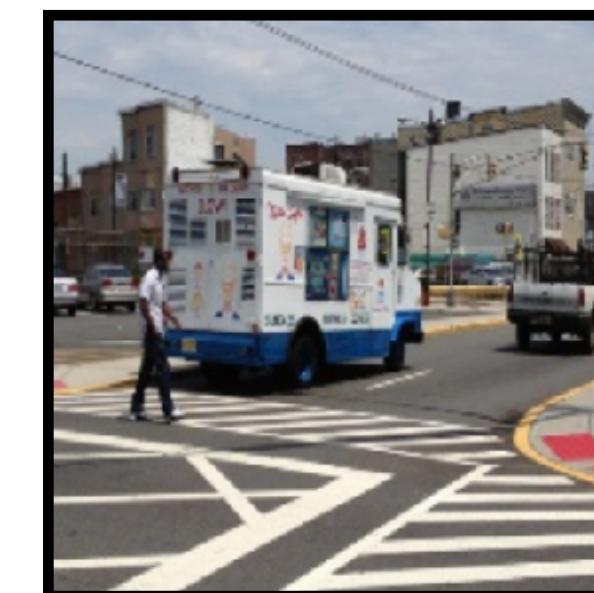
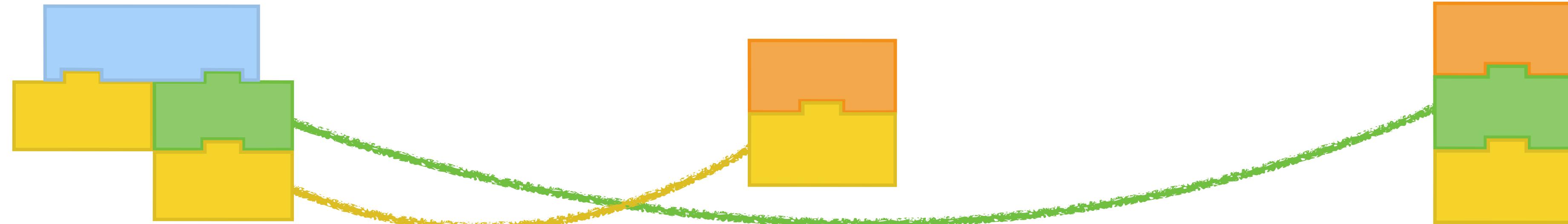
# Toward a model of everything

## LANGUAGE LEARNING

*Man in glasses  
near two men.*

*How many  
men?*

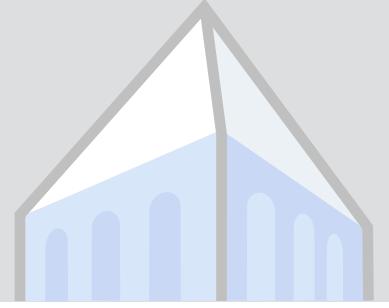
*go near the  
corner*



REASONING  
LEARNING

# LANGUAGE & BELIEF

- A & Klein. *Reasoning about Pragmatics with Neural Listeners and Speakers*. EMNLP 16.
- A, Drăgan & Klein. *Translating Neuralese*. ACL 17.
- A & Klein. *Analogs of Linguistic Structure in Deep Representations*. EMNLP 17.
- Fried, A & Klein. *Unified Pragmatic Models for Generating and Following [...]*. NAACL 18.

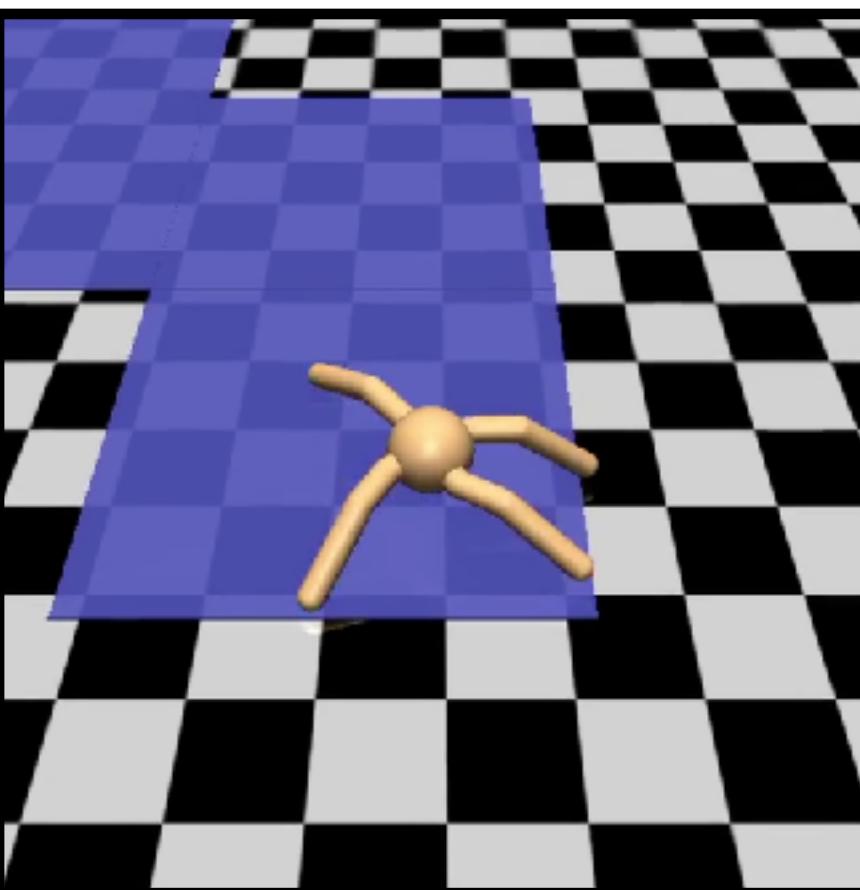


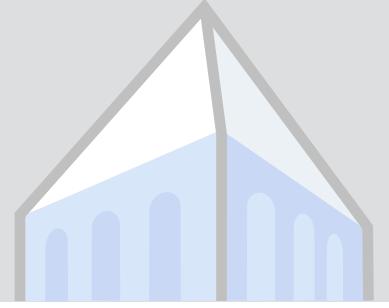
# Interpreting language

*What kind of  
bird is this?*



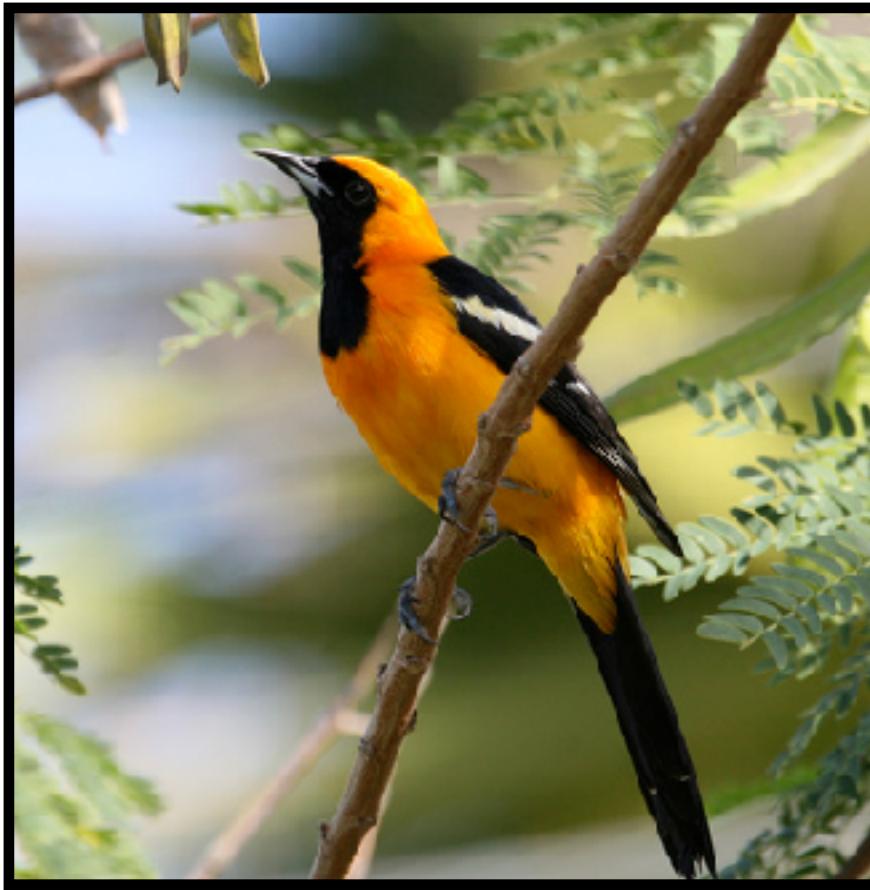
*What are you  
going to do?*





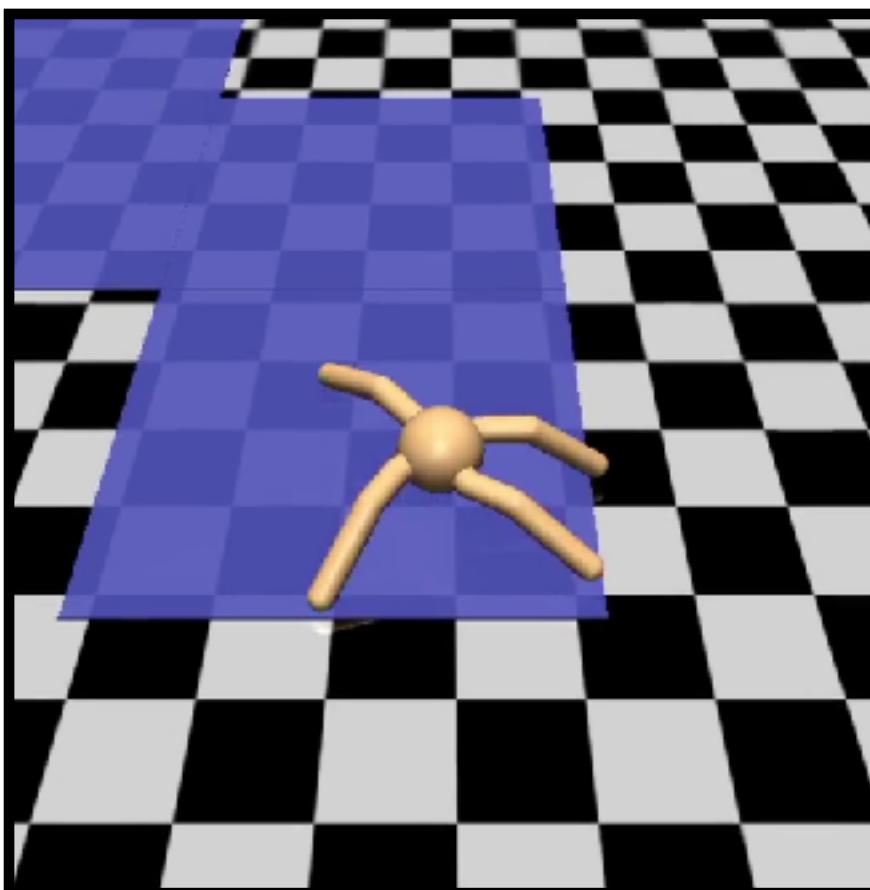
# Generating “language”

*What kind of  
bird is this?*

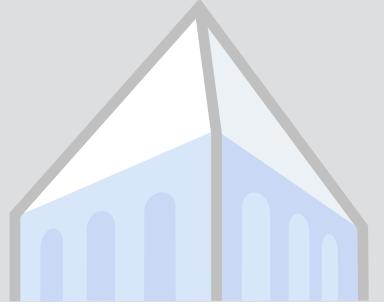


oriole

*What are you  
going to do?*

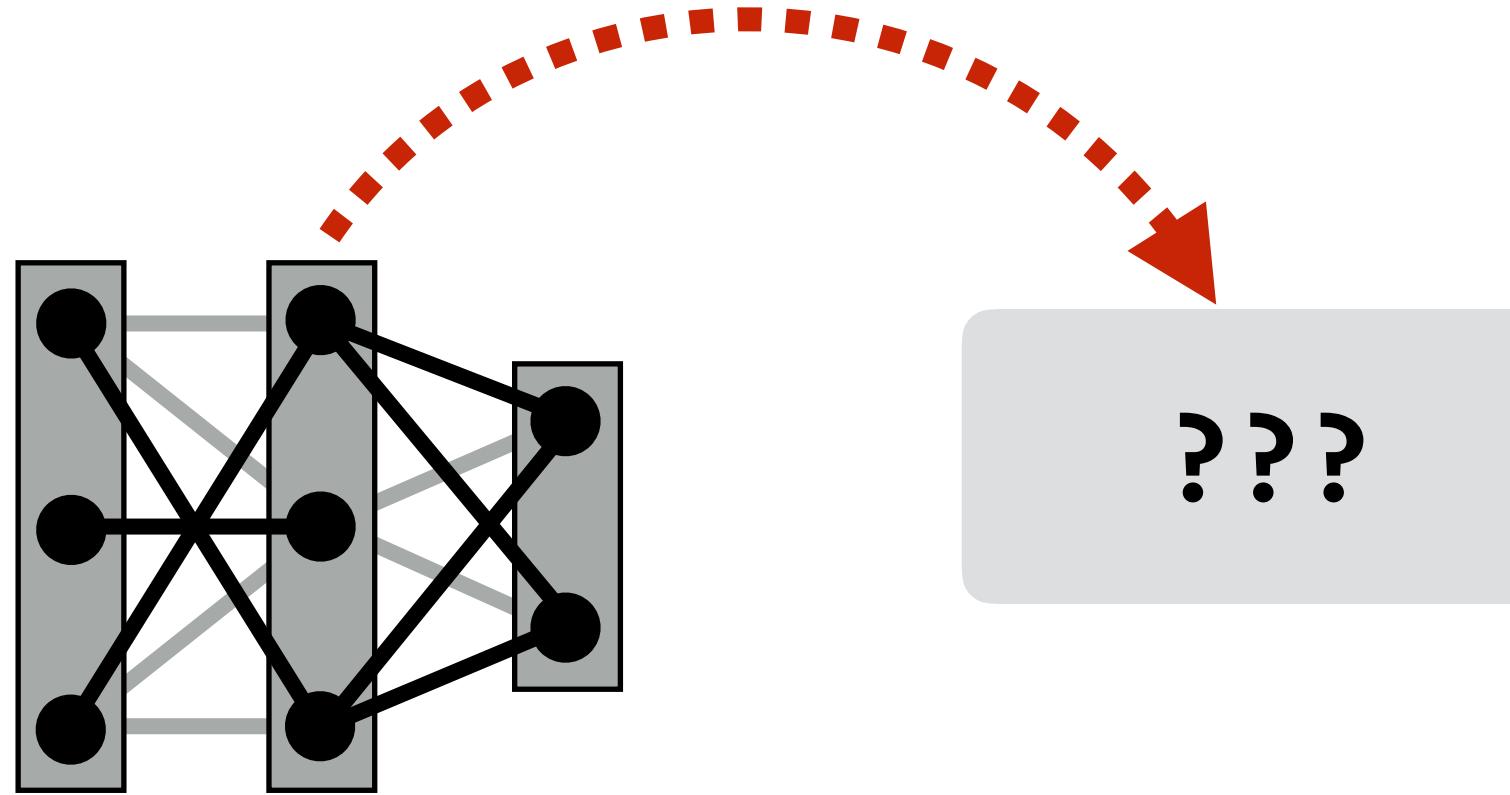


[GO NORTH, GO WEST]

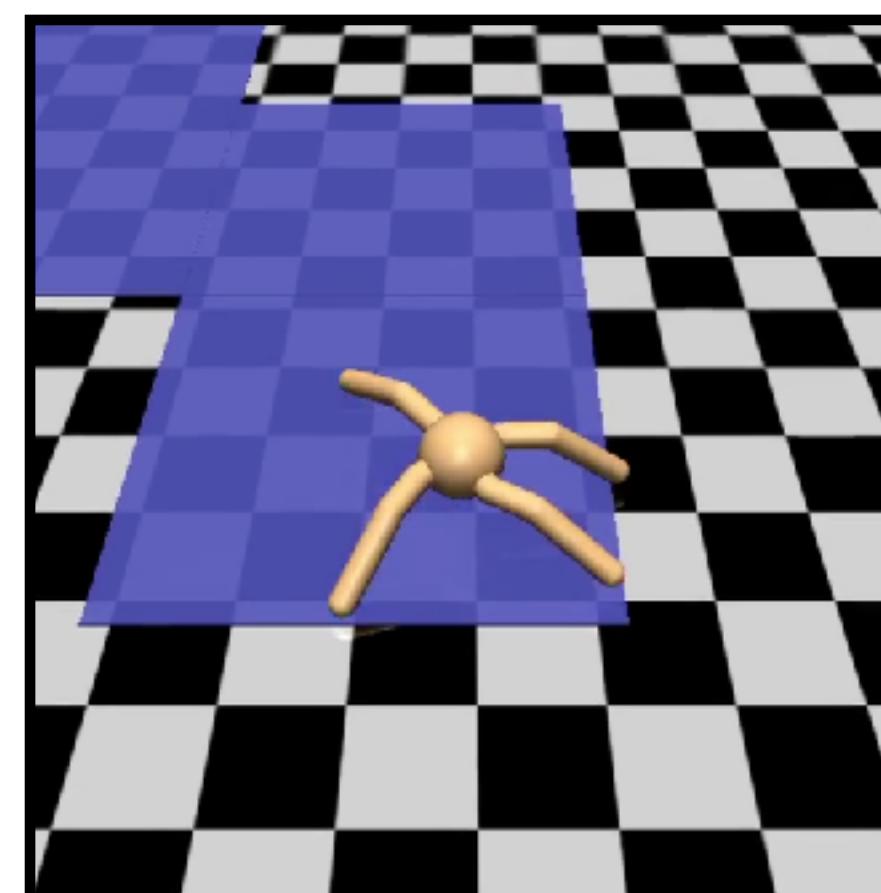


# Generating “language”

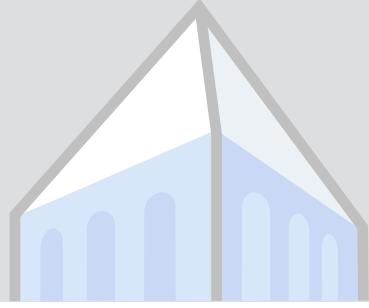
*What kind of  
bird is this?*



*What are you  
going to do?*

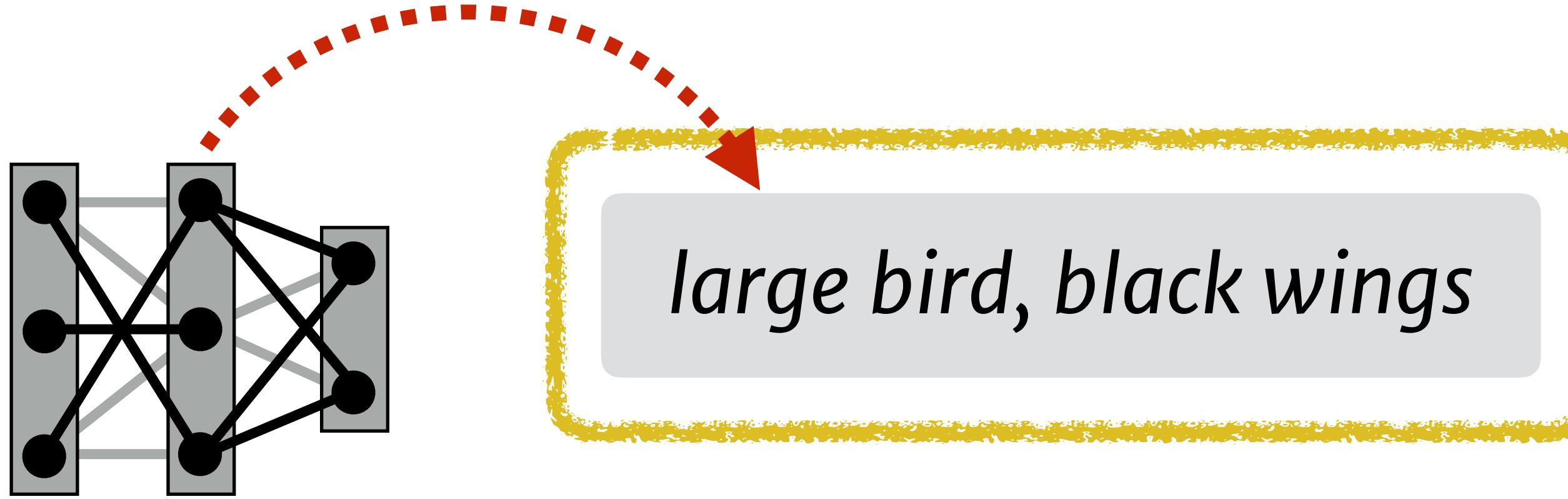


[GO NORTH, GO WEST]



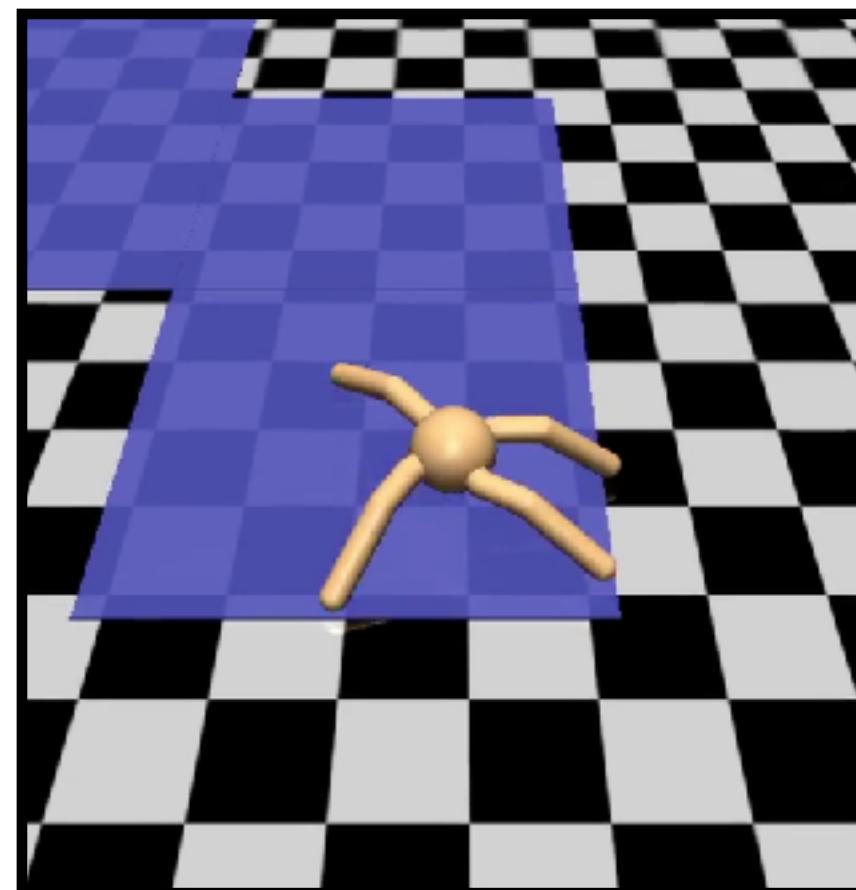
# Generating informative language

*What kind of  
bird is this?*

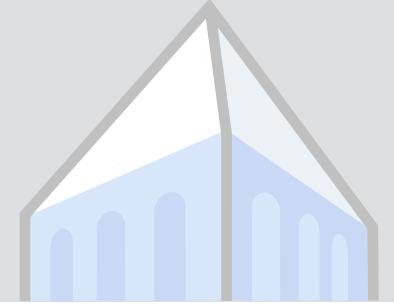


*large bird, black wings*

*What are you  
going to do?*



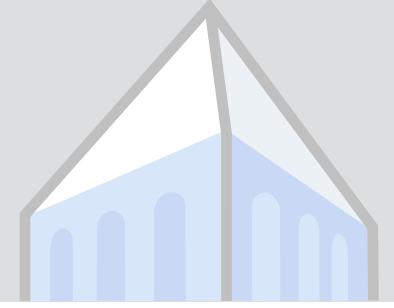
*Reach the end of the  
blue path.*



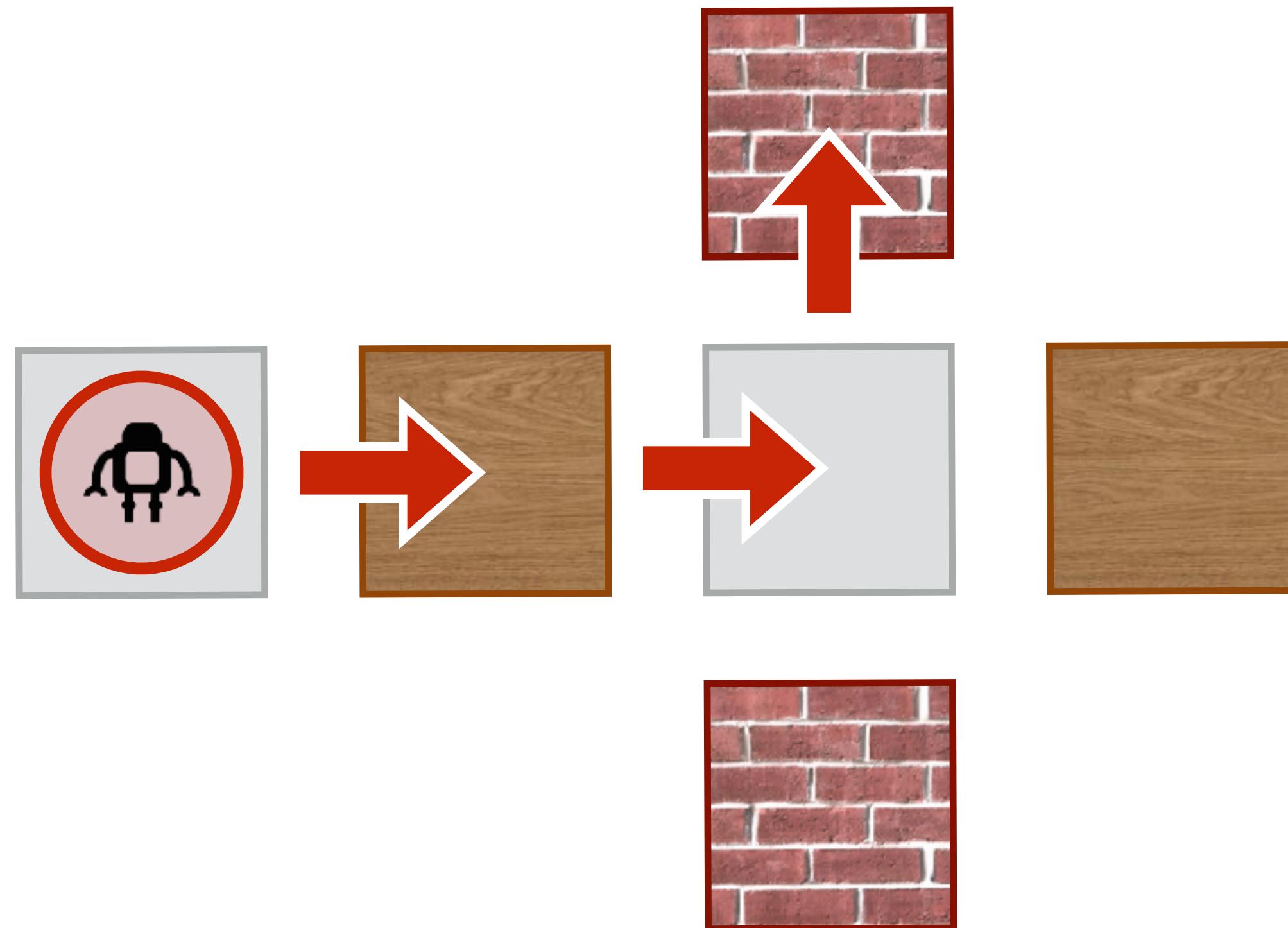
# Explaining behaviors



[MacMahon et al. 06, Daniele et al. 17]

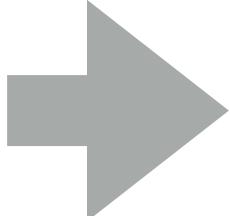
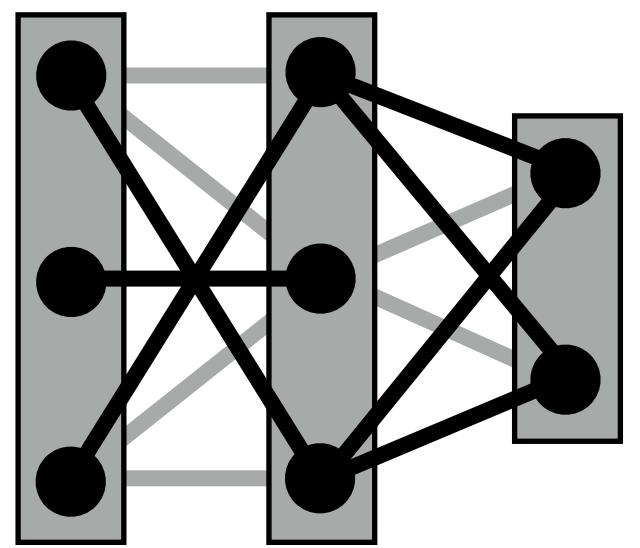
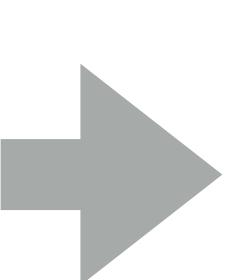


# Explaining behaviors





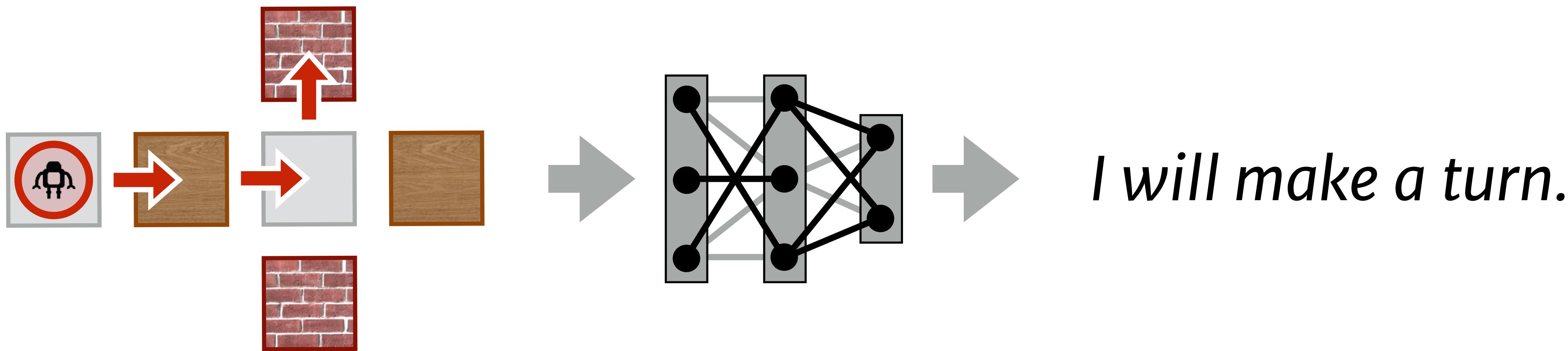
# Image captioning



*A group of young men  
playing a game of soccer.*

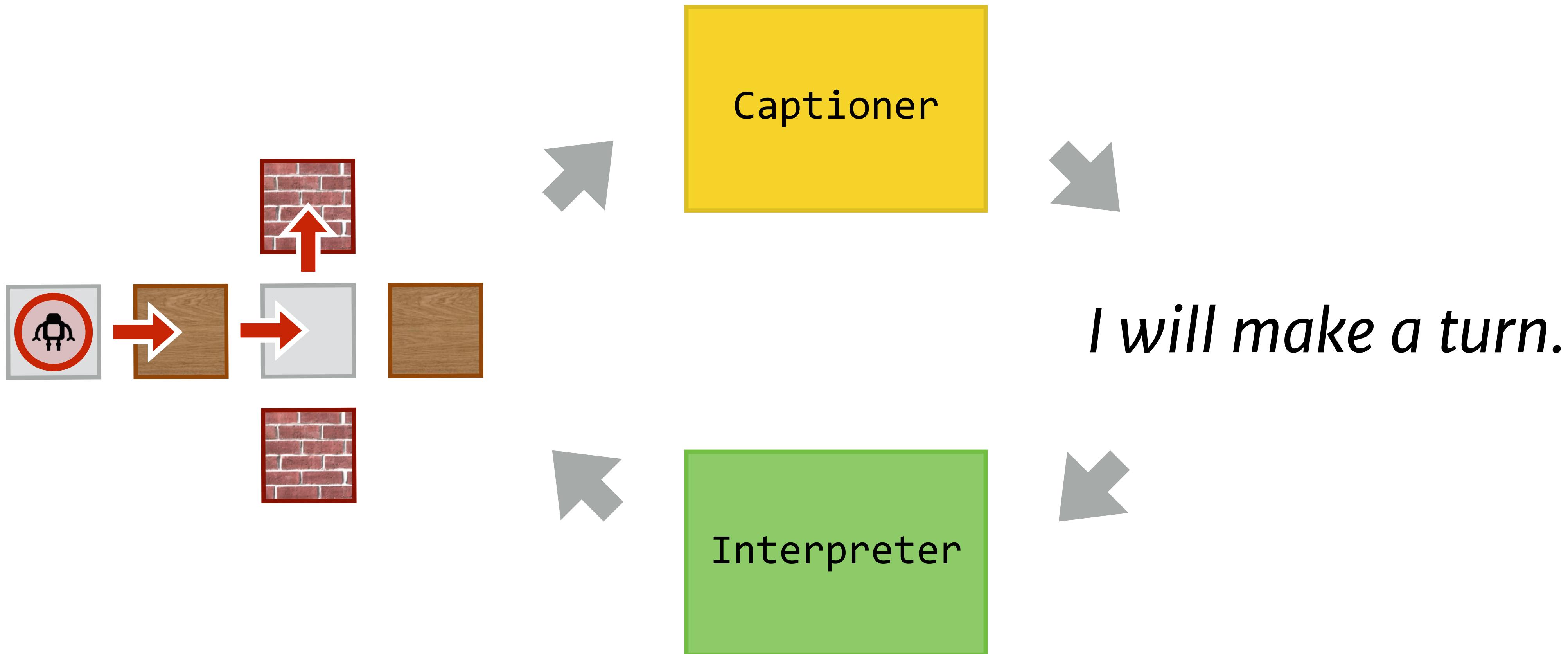


# Image captioning



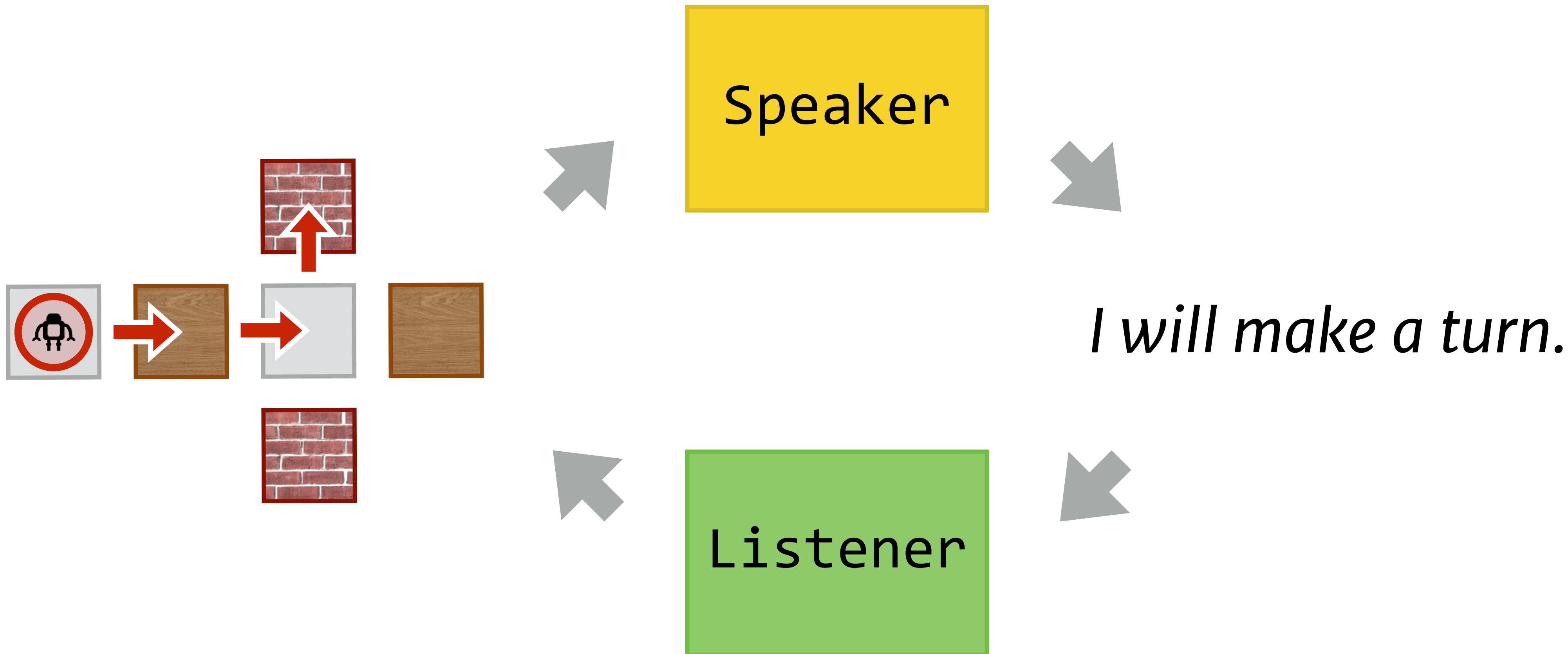


# Reasoning about outcomes



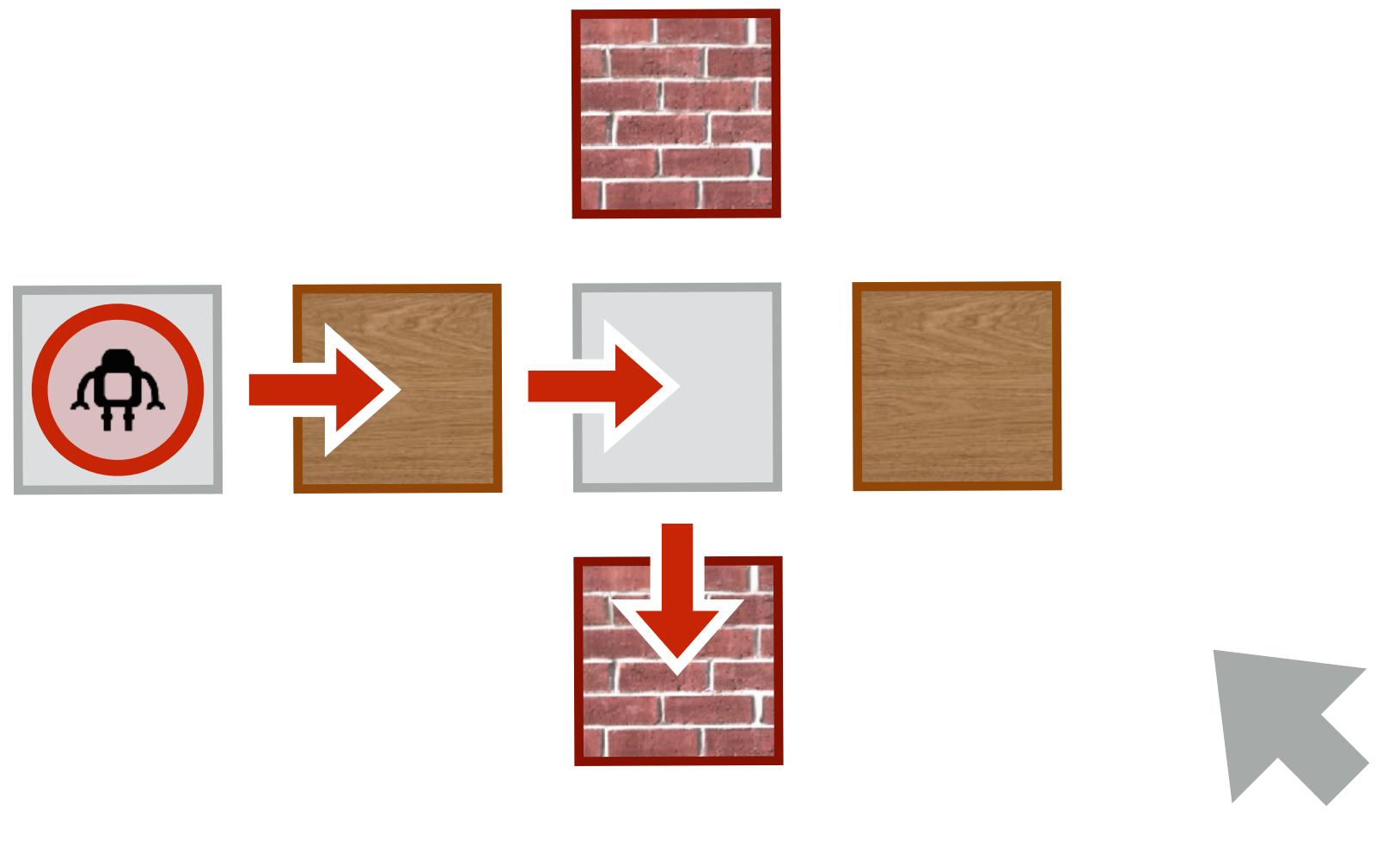


# Reasoning about outcomes





# Reasoning about outcomes

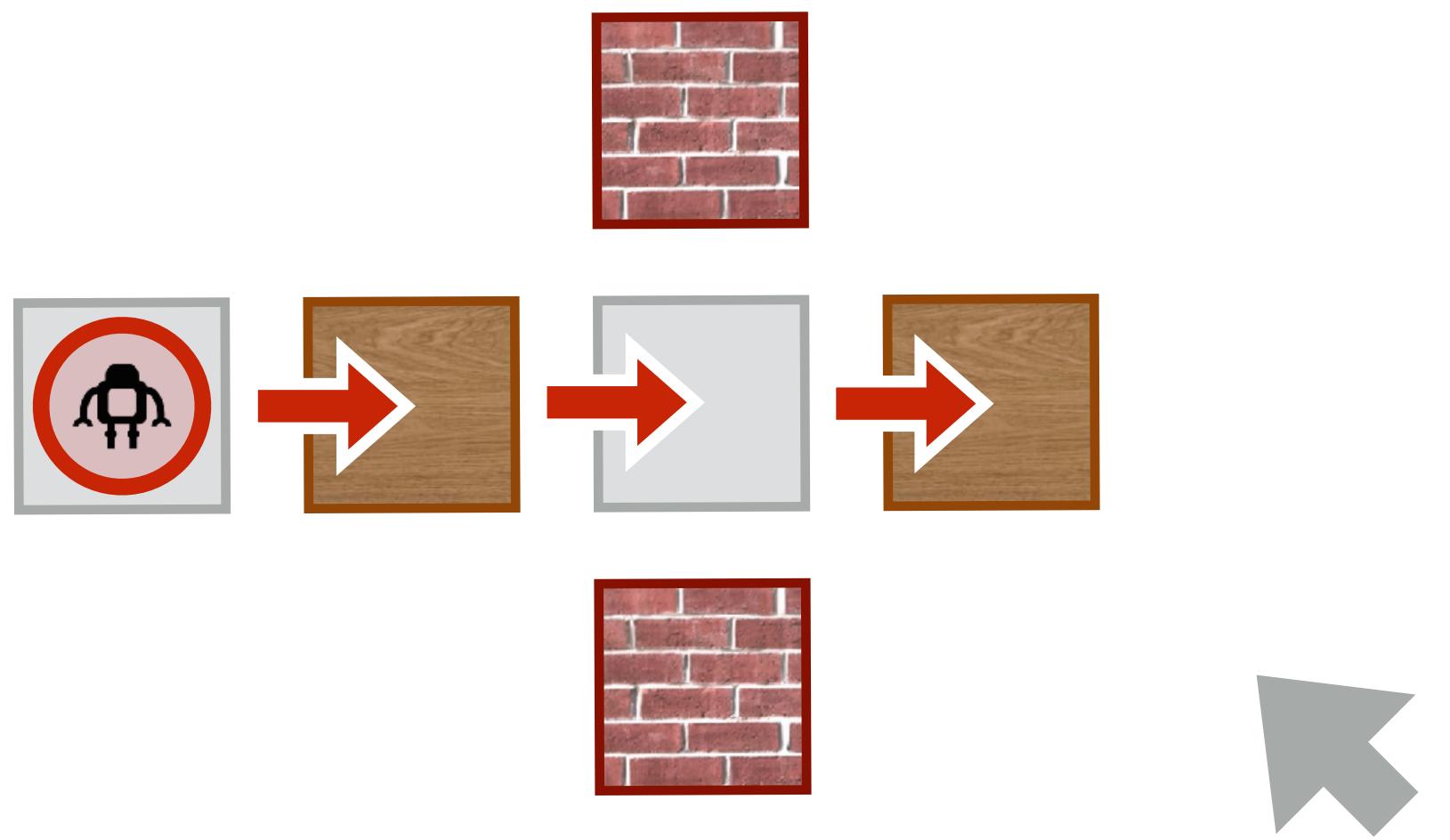


*I will make a turn.*

Listener



# Reasoning about outcomes

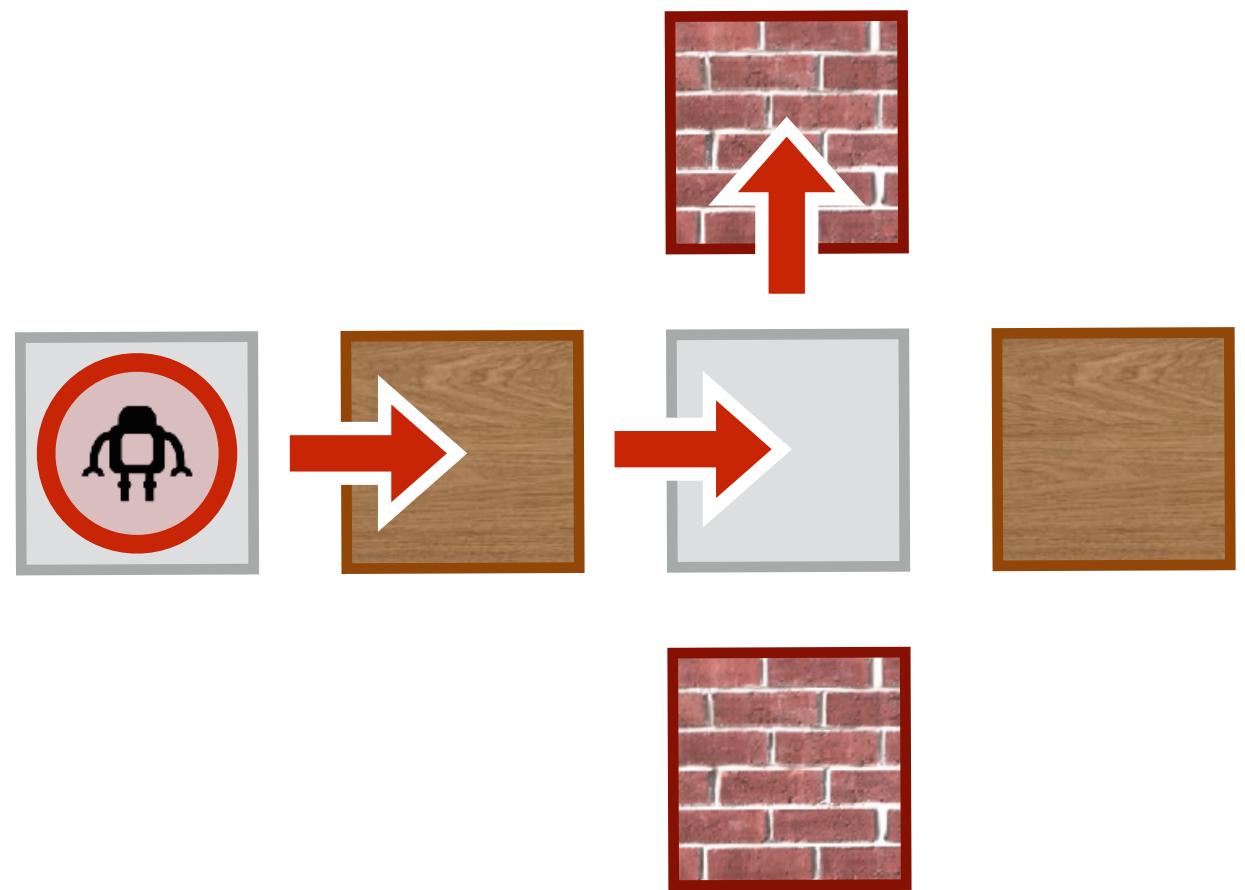


*I will go straight through.*

Listener



# Reasoning about outcomes

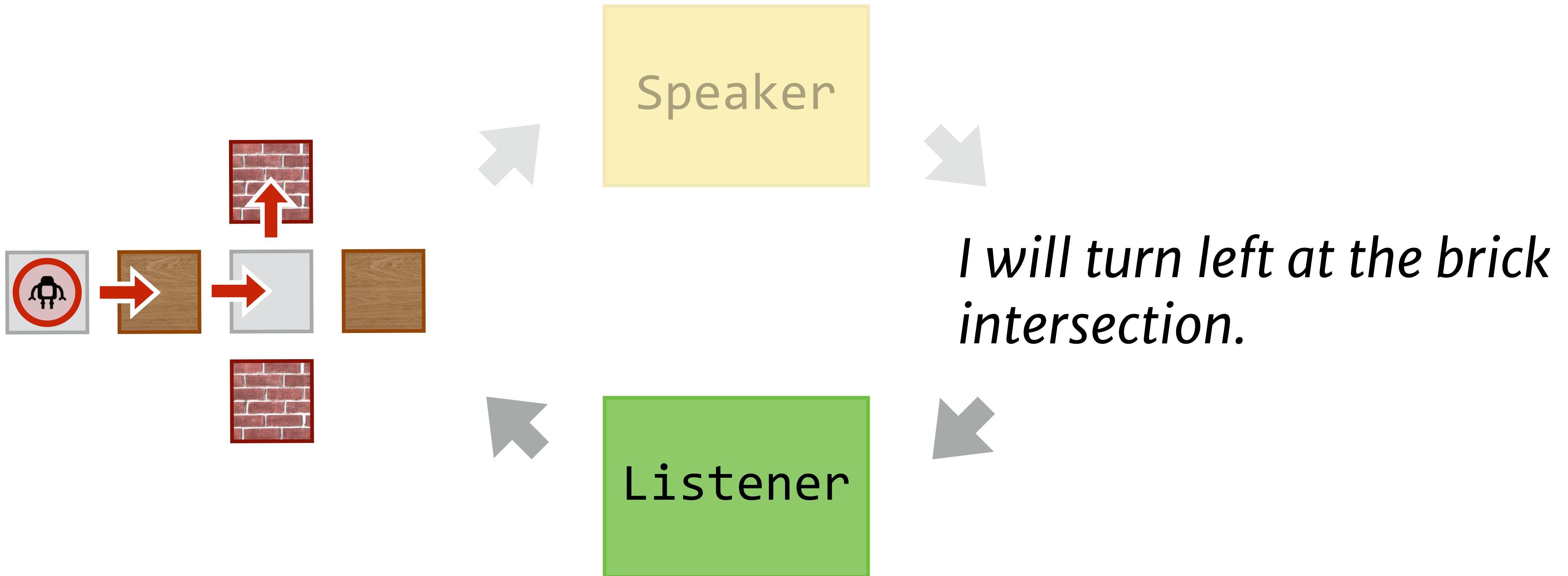


Listener

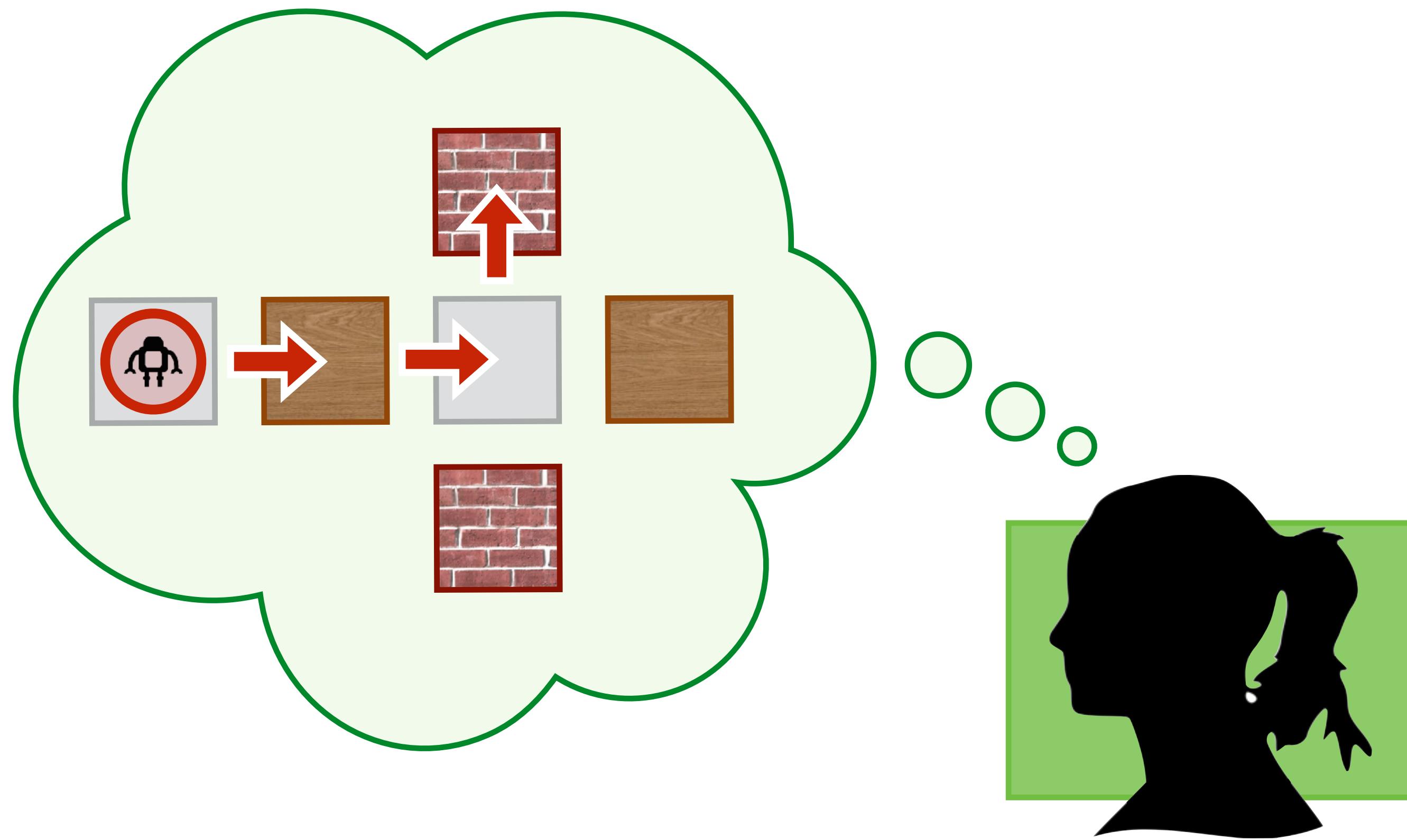
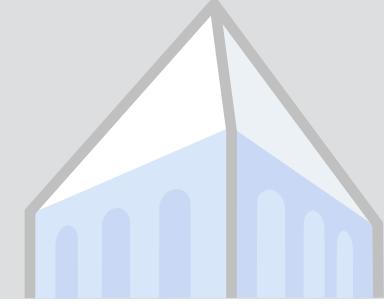
*I will turn left at the brick intersection.*



# Reasoning about outcomes

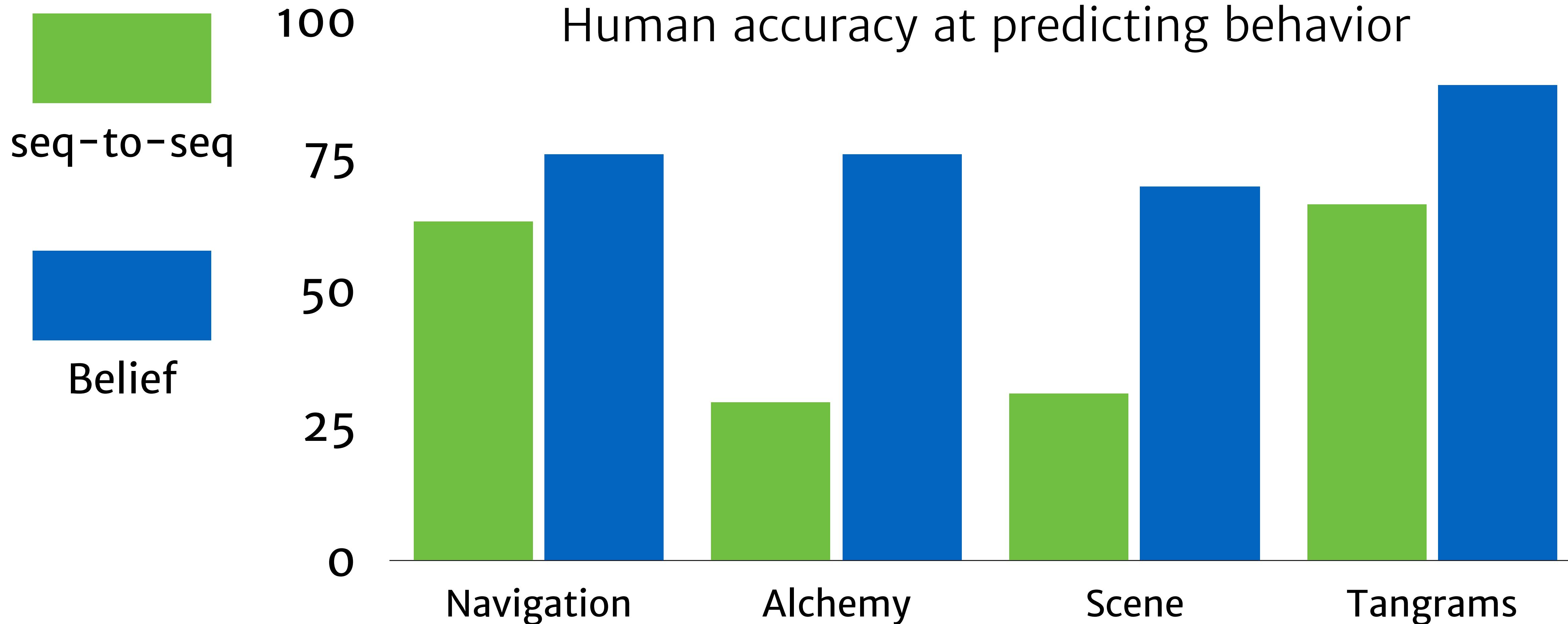


# Reasoning about belief



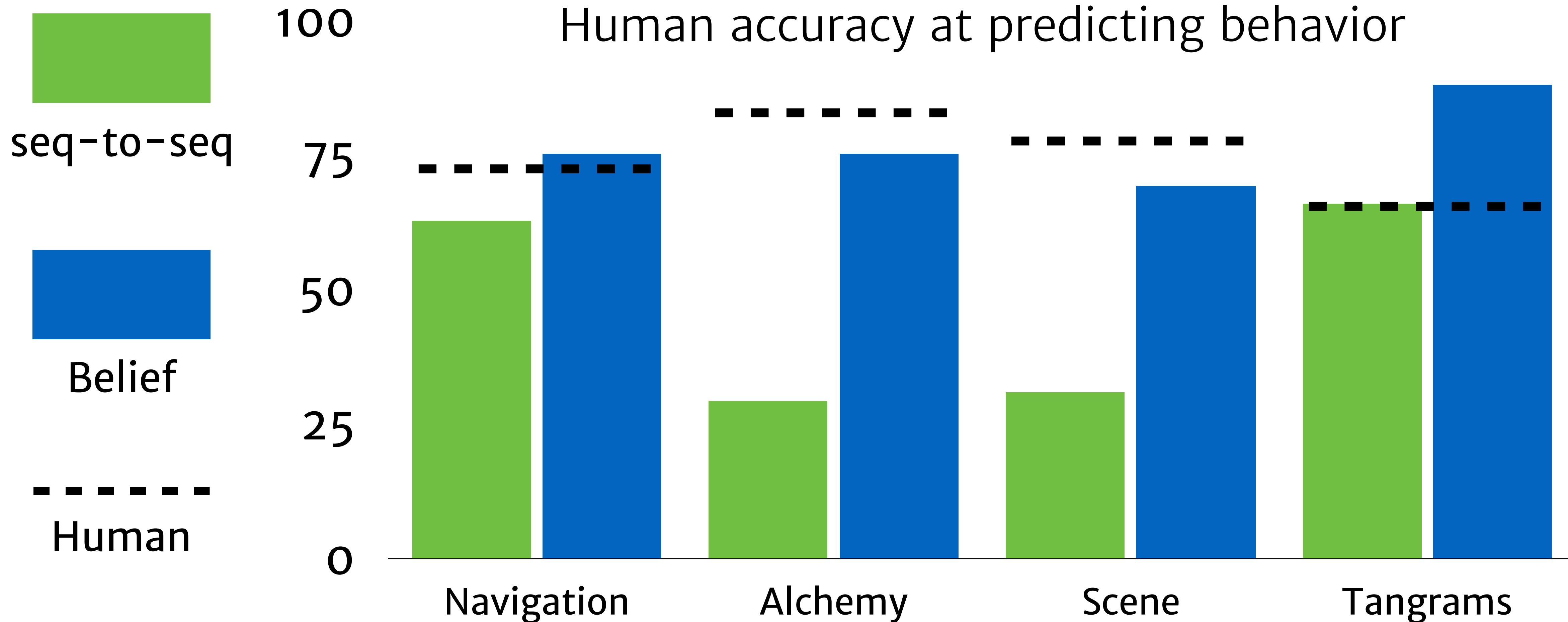


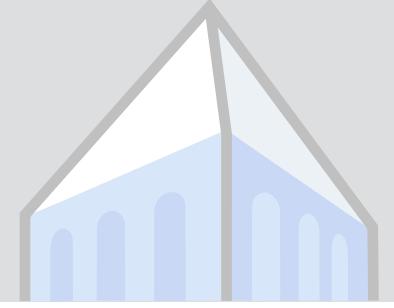
# Experimental results [FAK18]



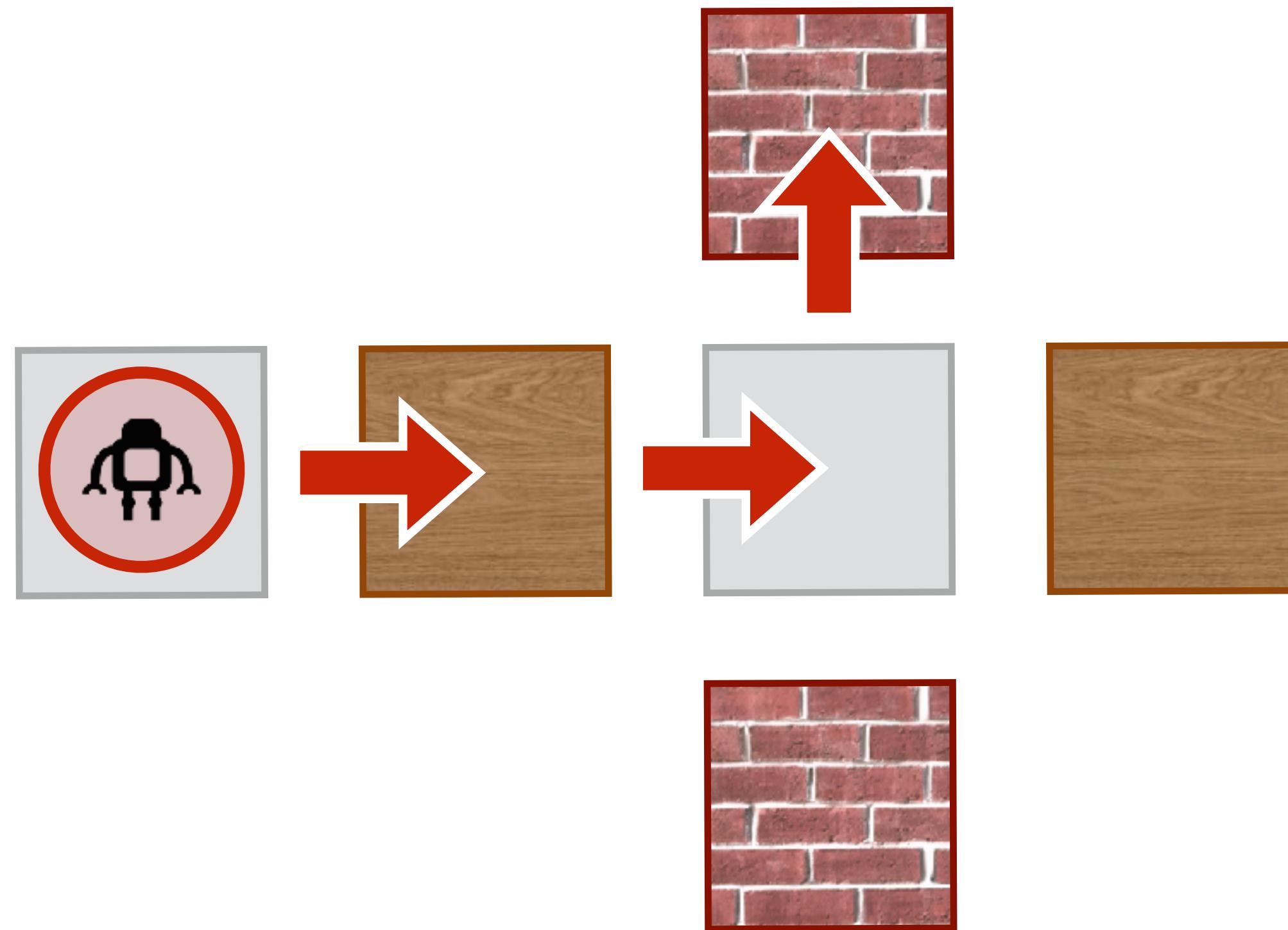


# Experimental results [FAK18]



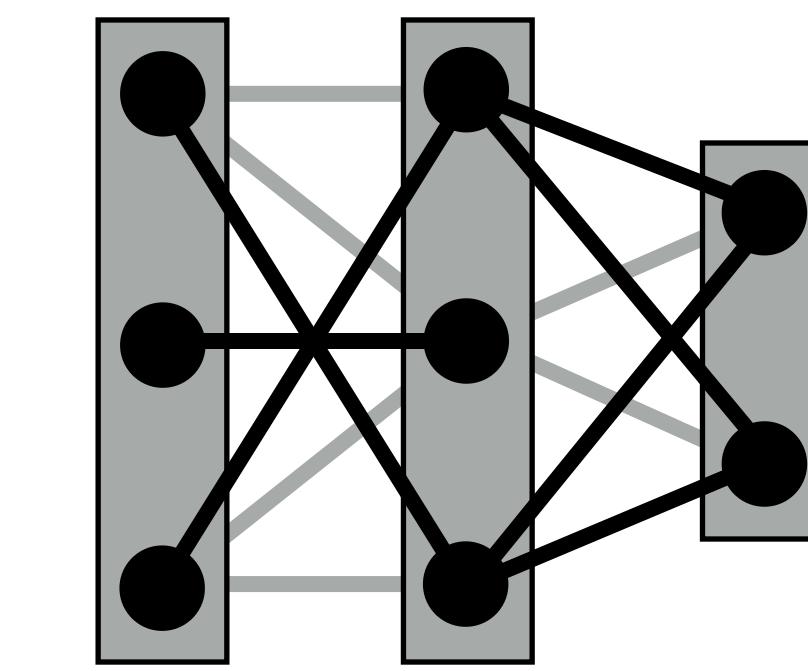
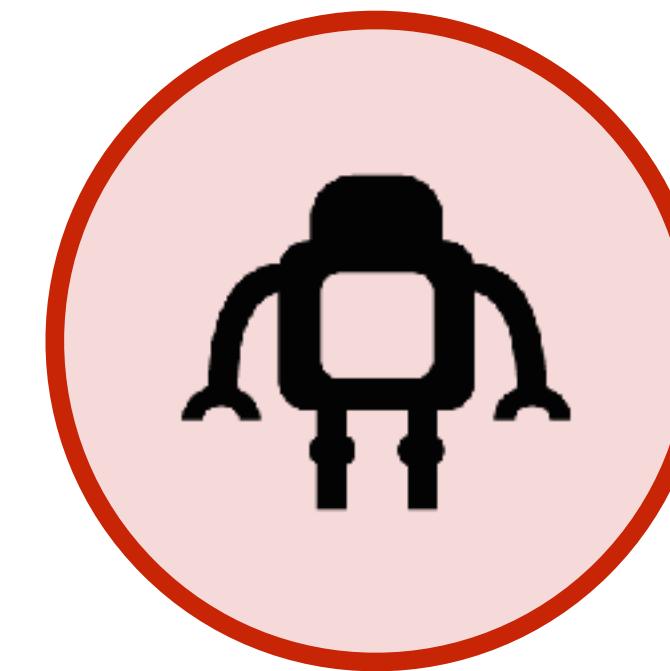


# Explaining behaviors

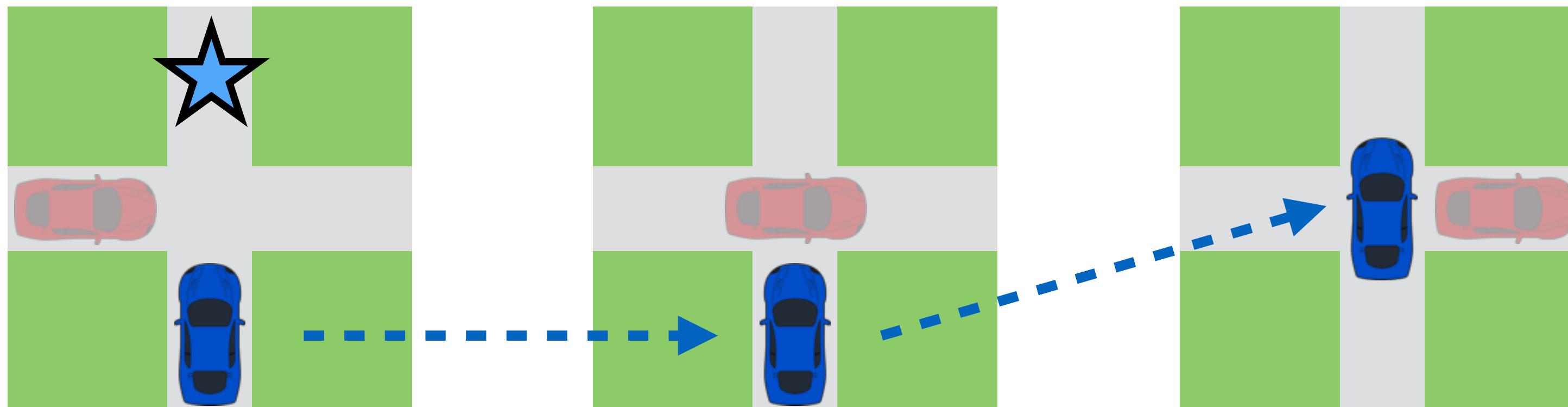
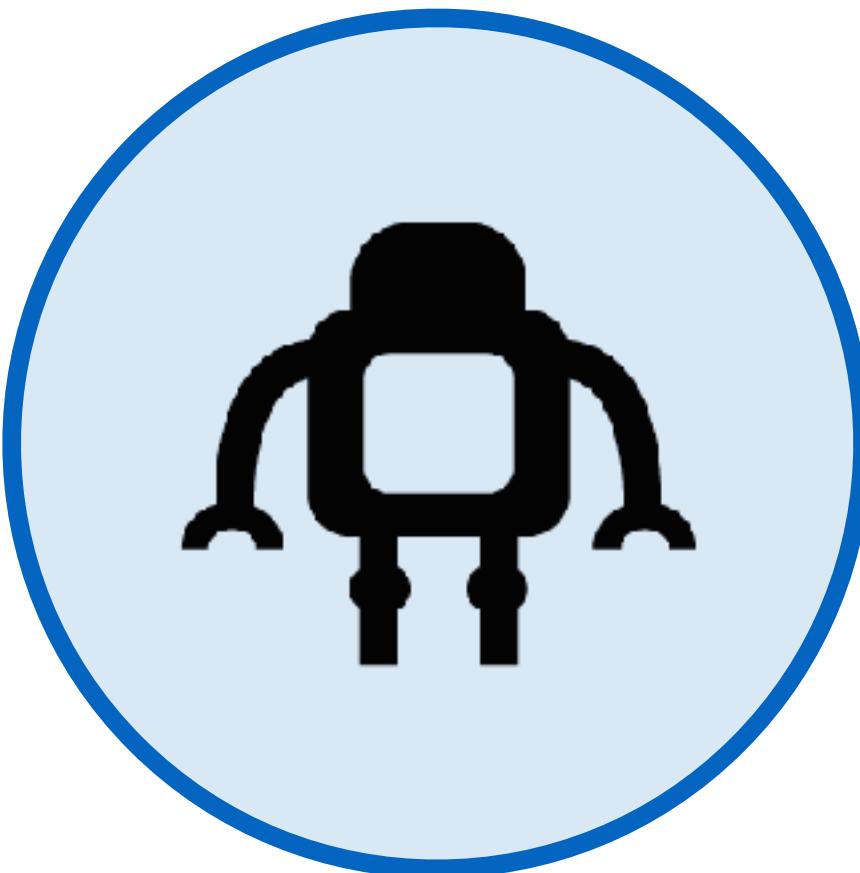
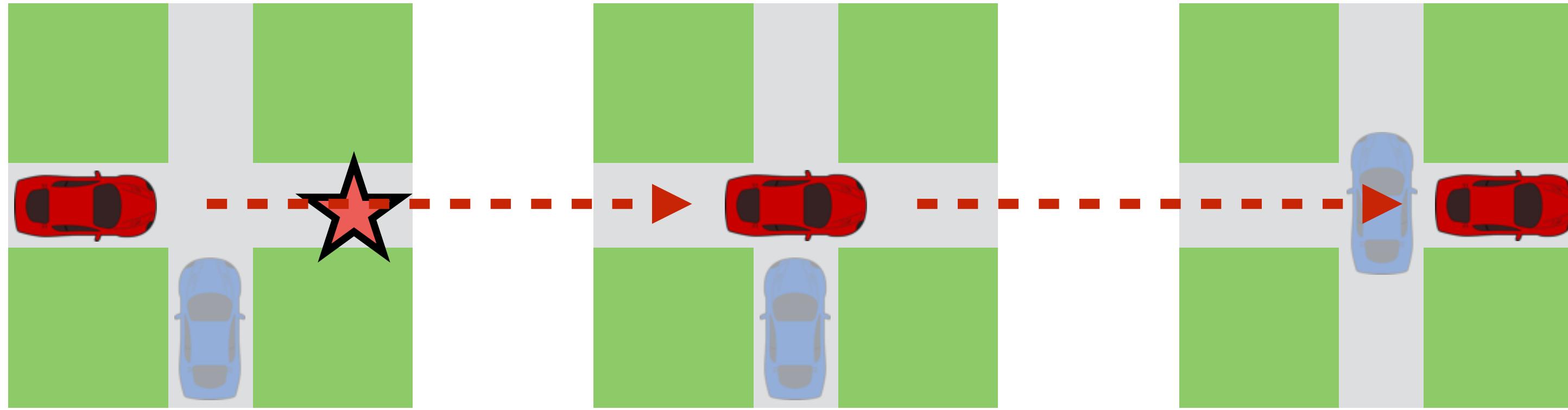
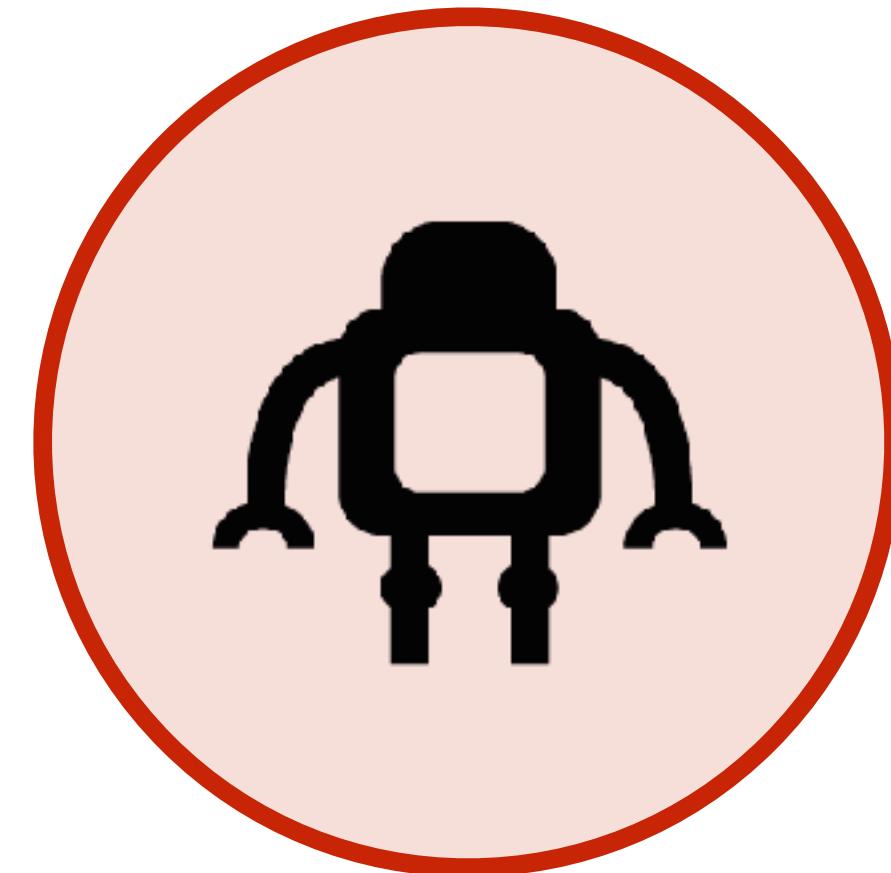




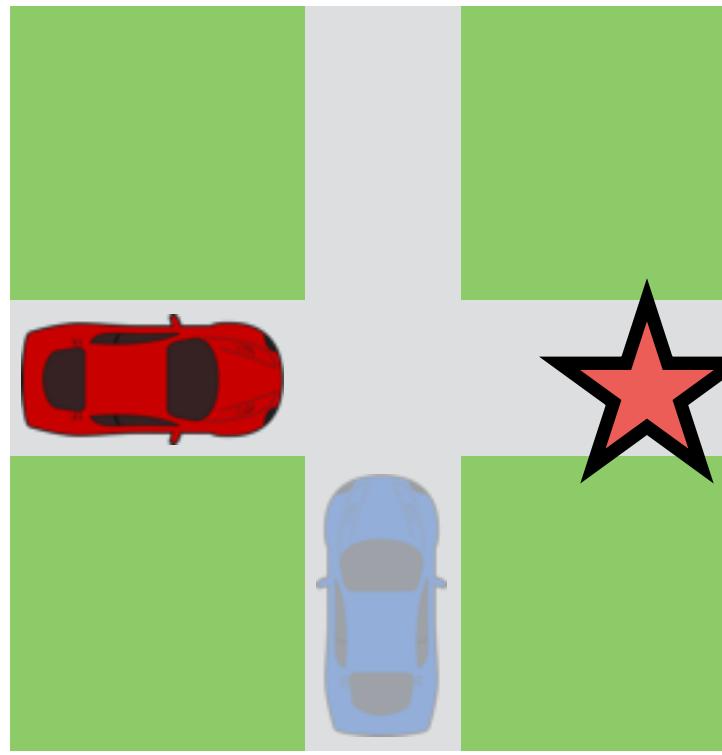
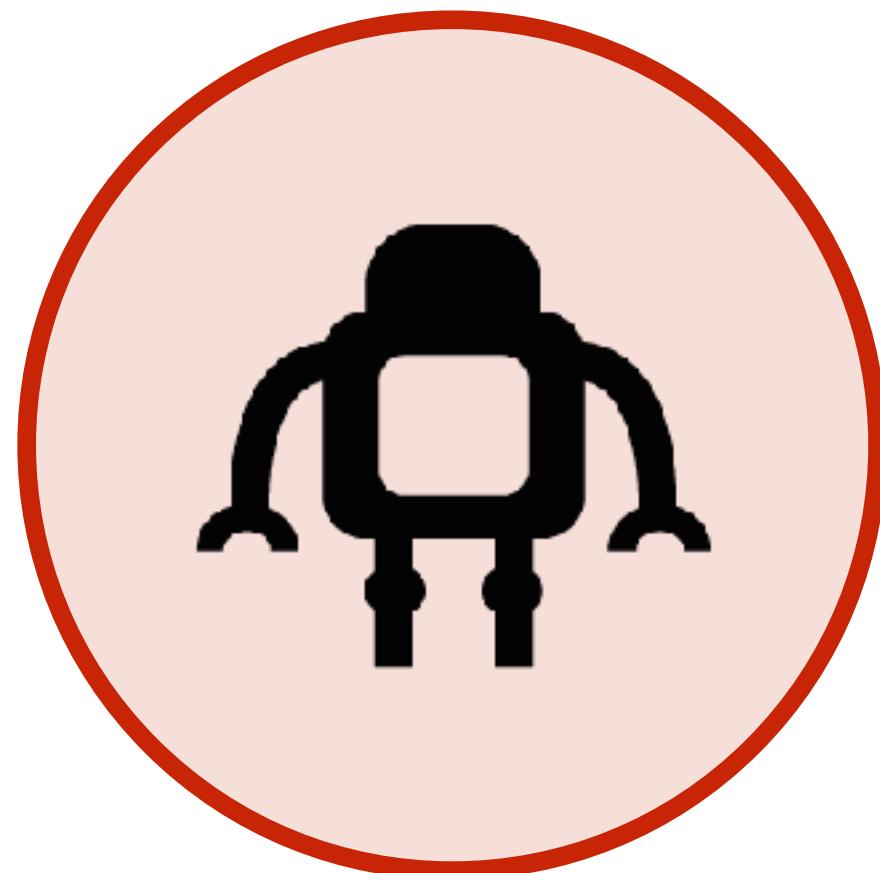
# Explaining models



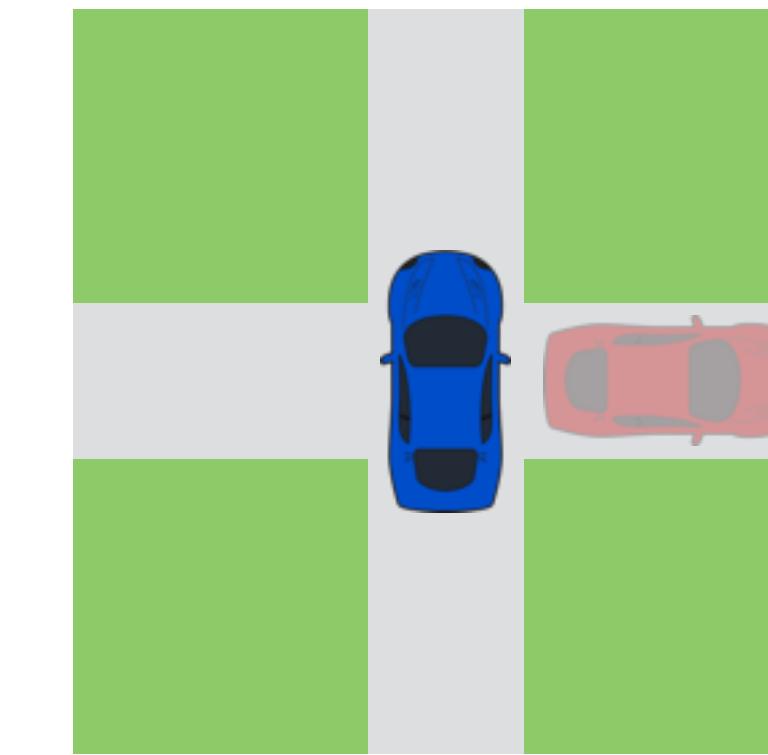
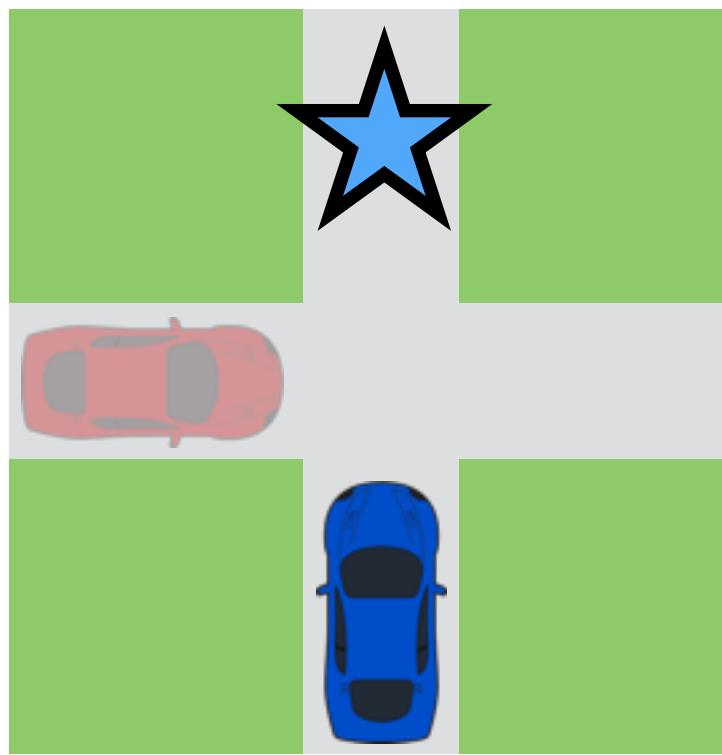
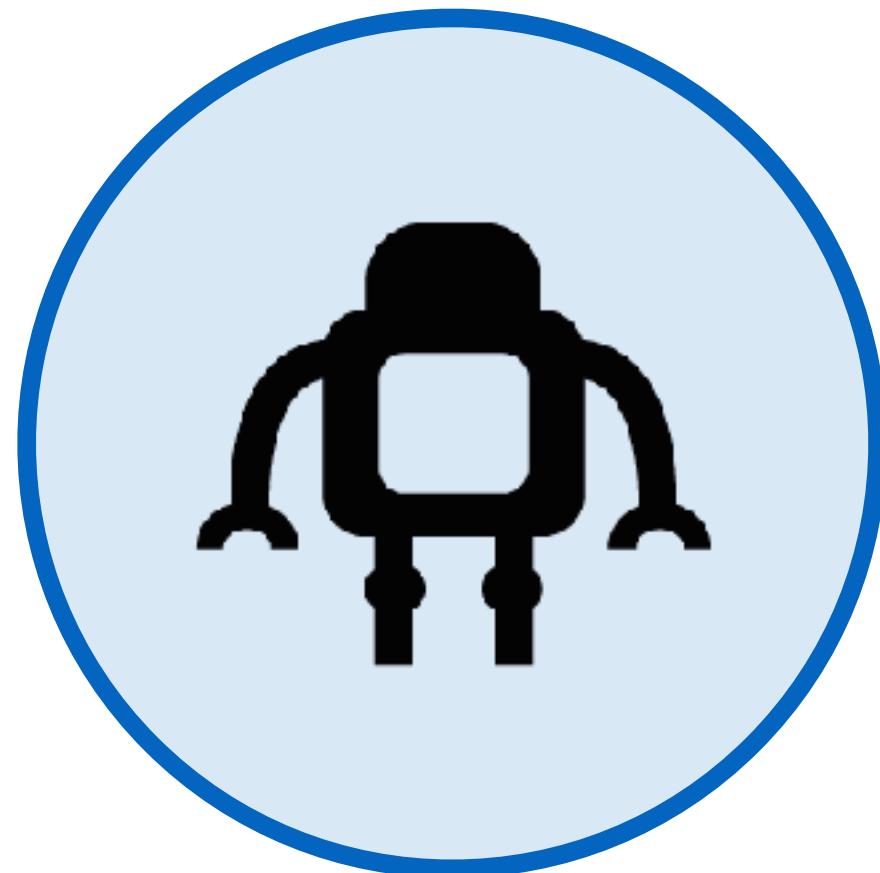
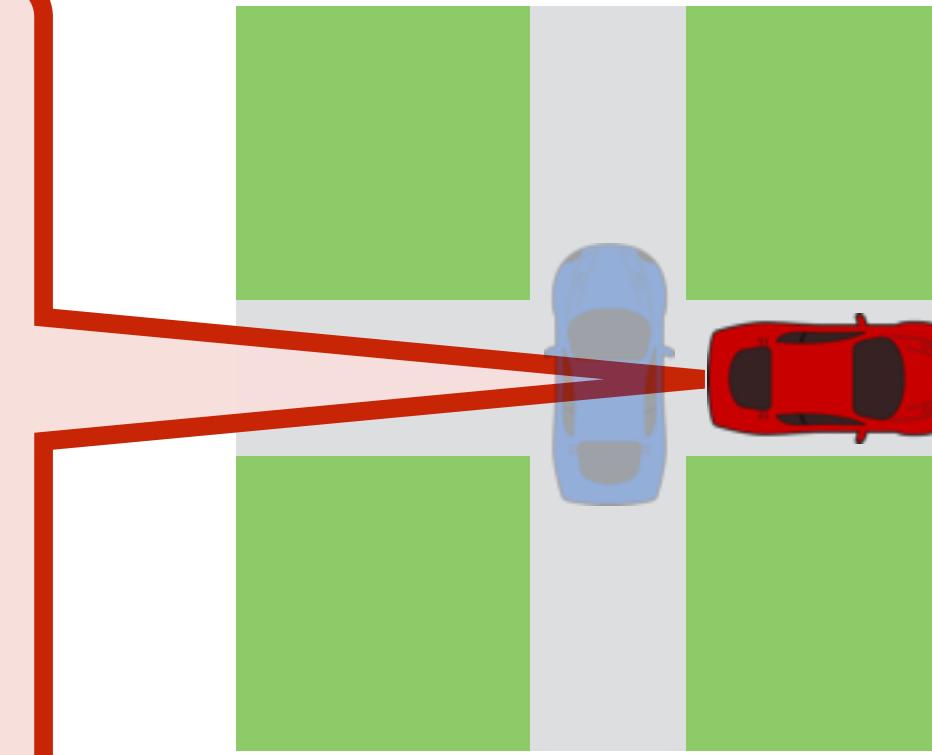
# Multi-agent communication

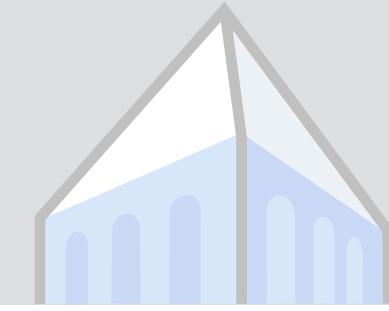


# Neuralese

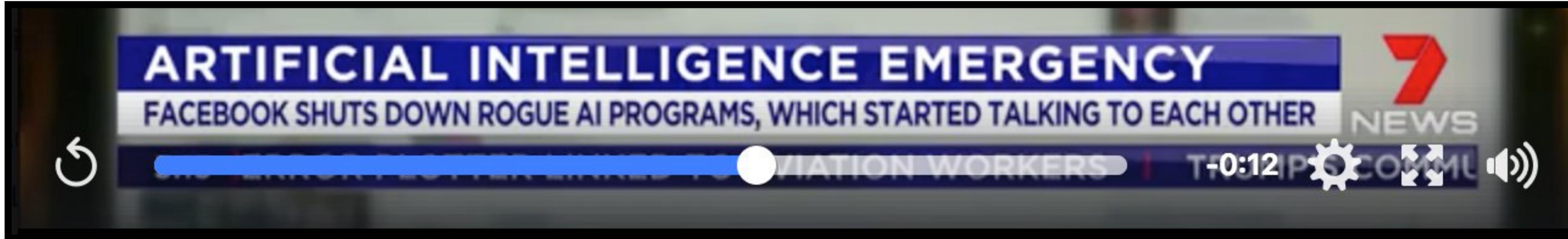


1.0	2.3
-0.3	0.4
-1.2	1.1





# Communication and behavior



**ROBOSTOP** Facebook shuts off AI experiment after two robots begin speaking in their OWN language only they can understand

Experts have called the incident exciting but also incredibly scary

By James Beal and Andy Jebring  
1st August 2017, 12:03 am | Updated: 2nd August 2017, 4:56 am

**Elon Musk's lab forced bots to create their own language**



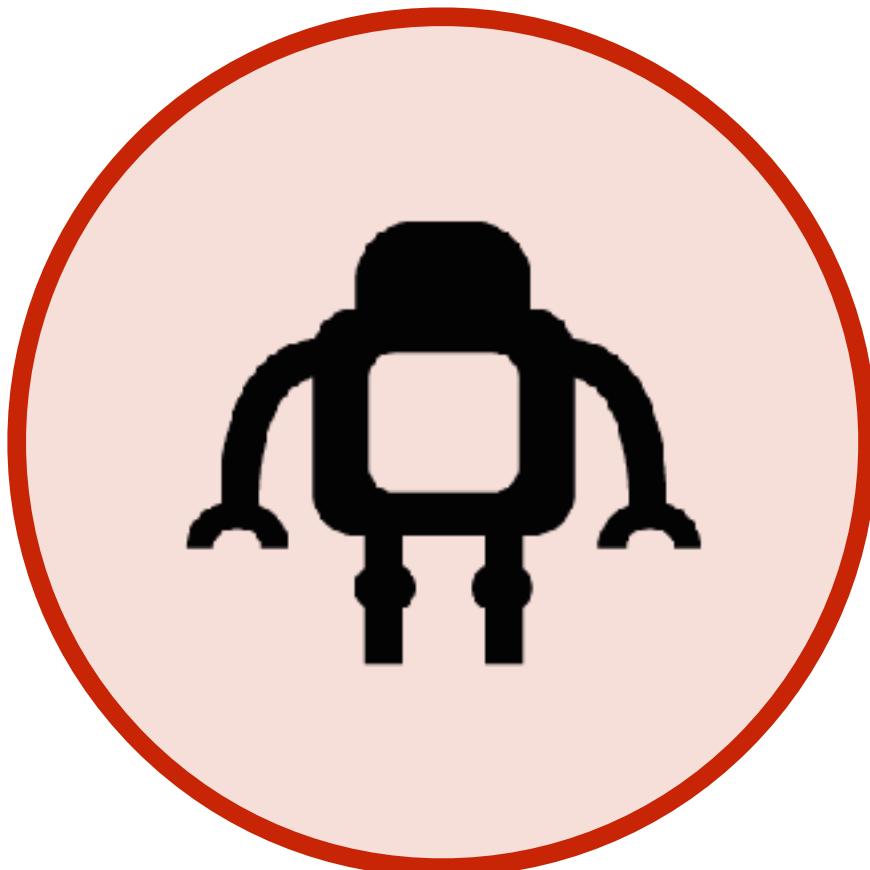
Mike Wehner [@MikeWehner](#)  
March 19th, 2017 at 9:01 AM

[Share](#)

[Tweet](#)

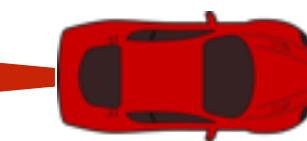


# Translating neuralese



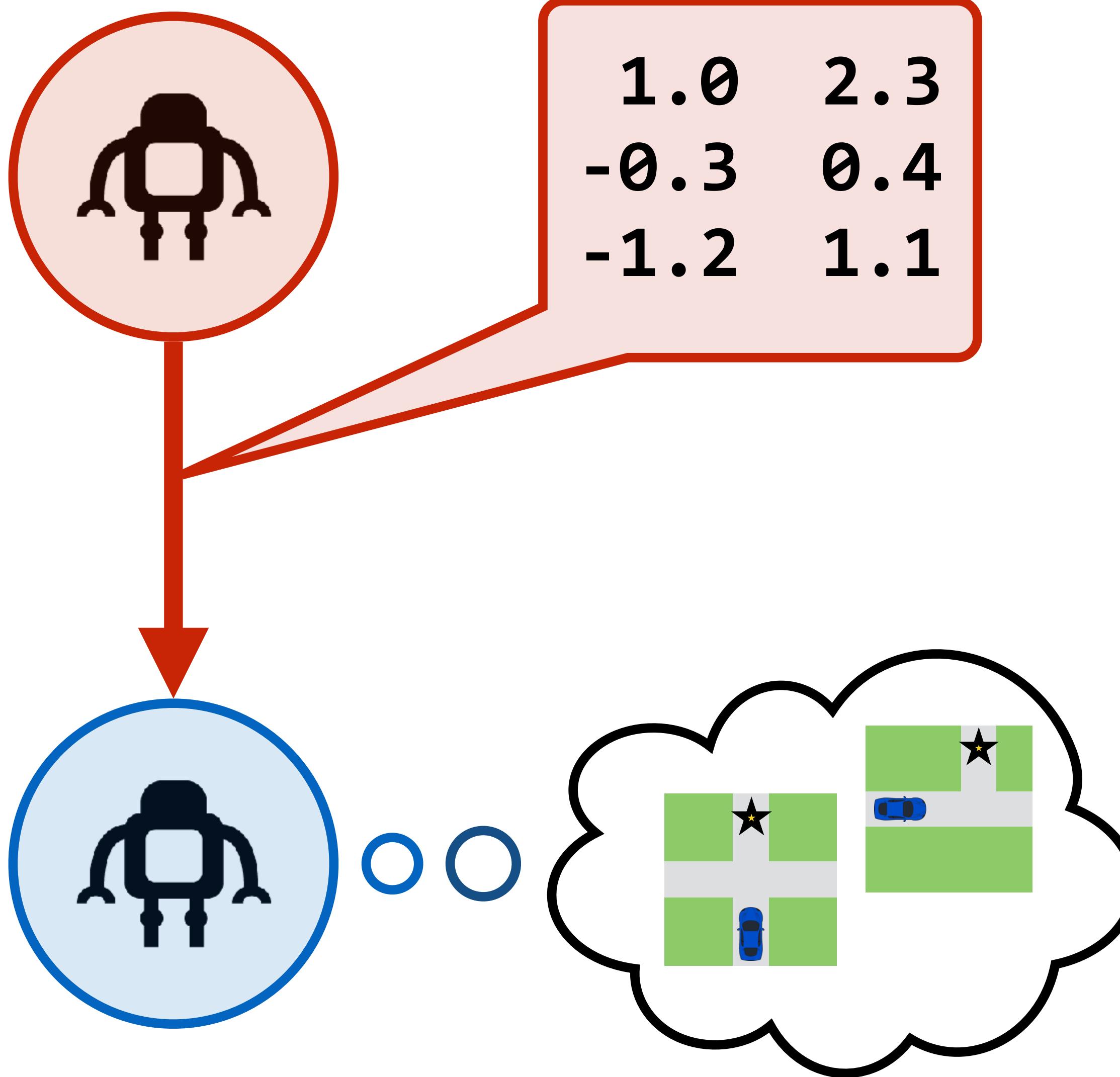
1.0	2.3
-0.3	0.4
-1.2	1.1

*all clear*

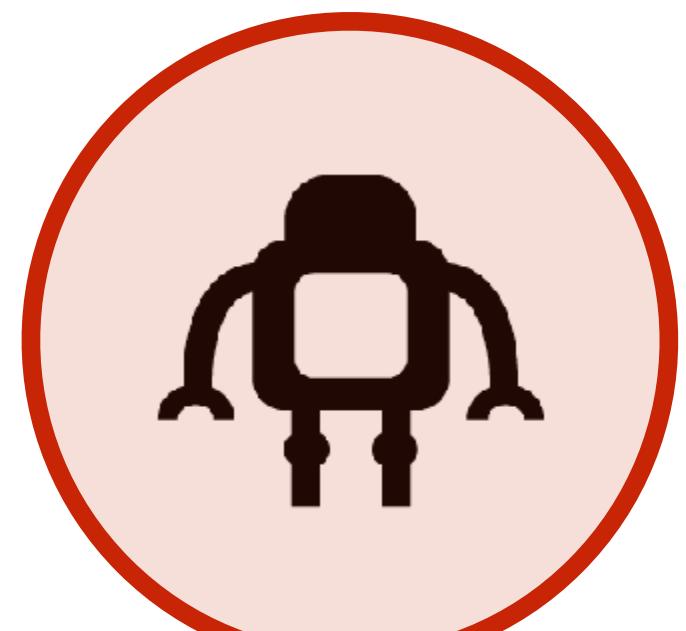
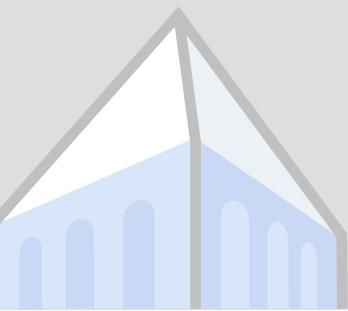




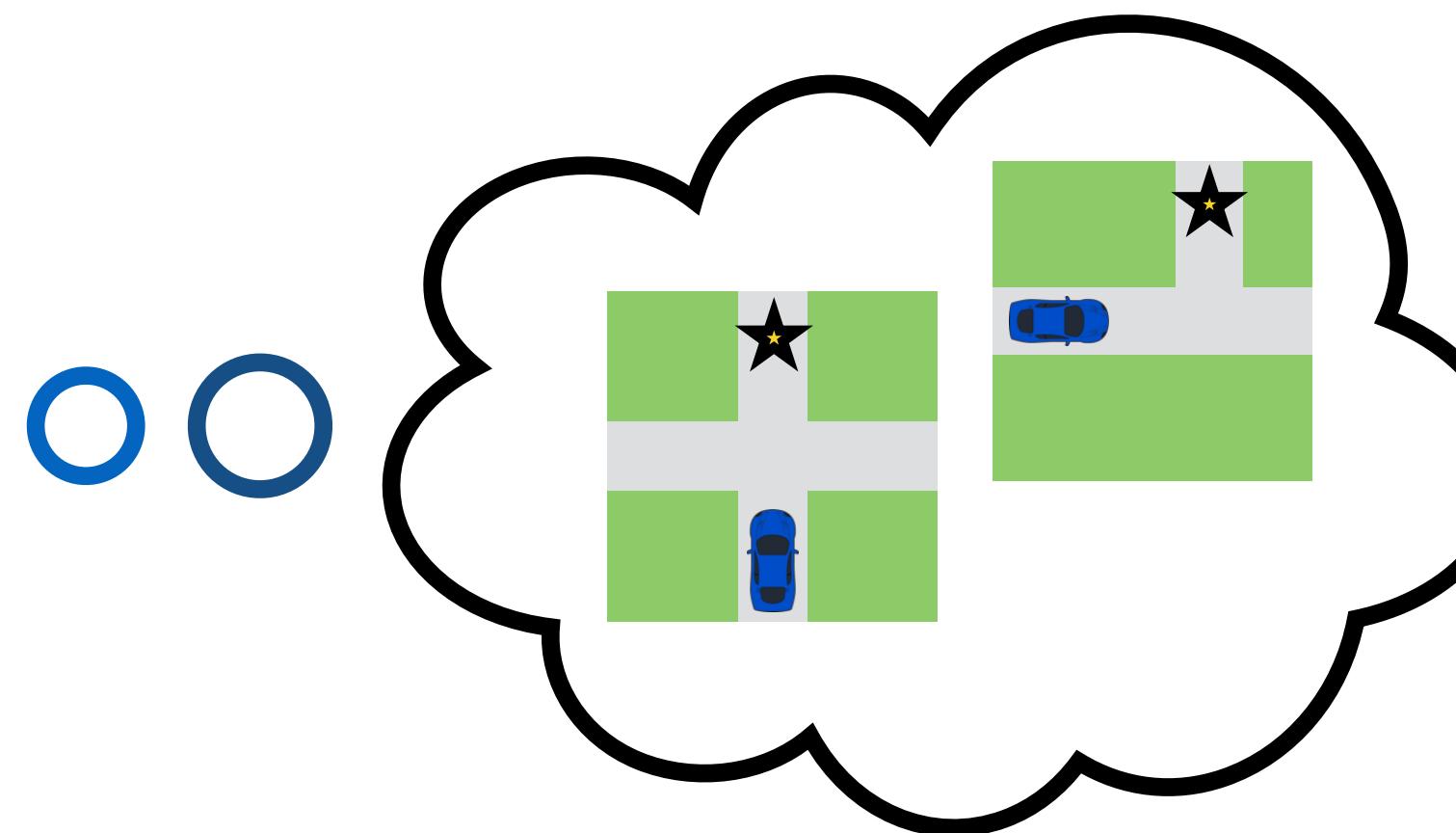
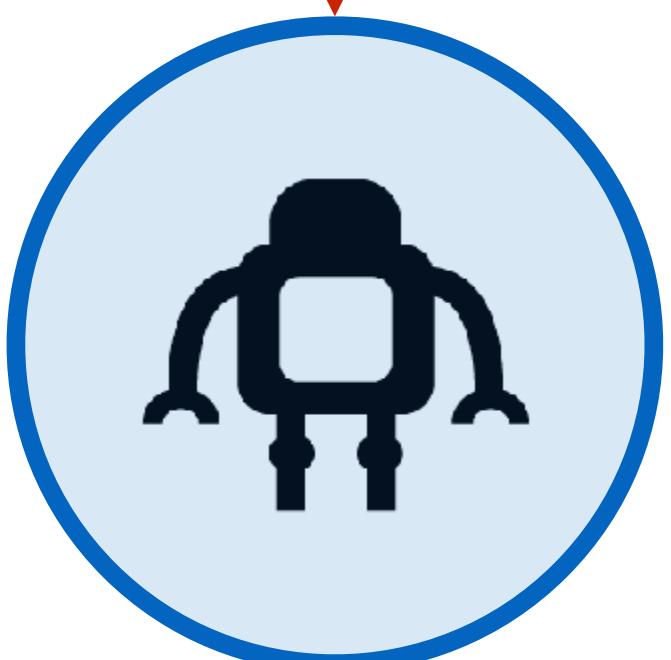
# Translating via belief



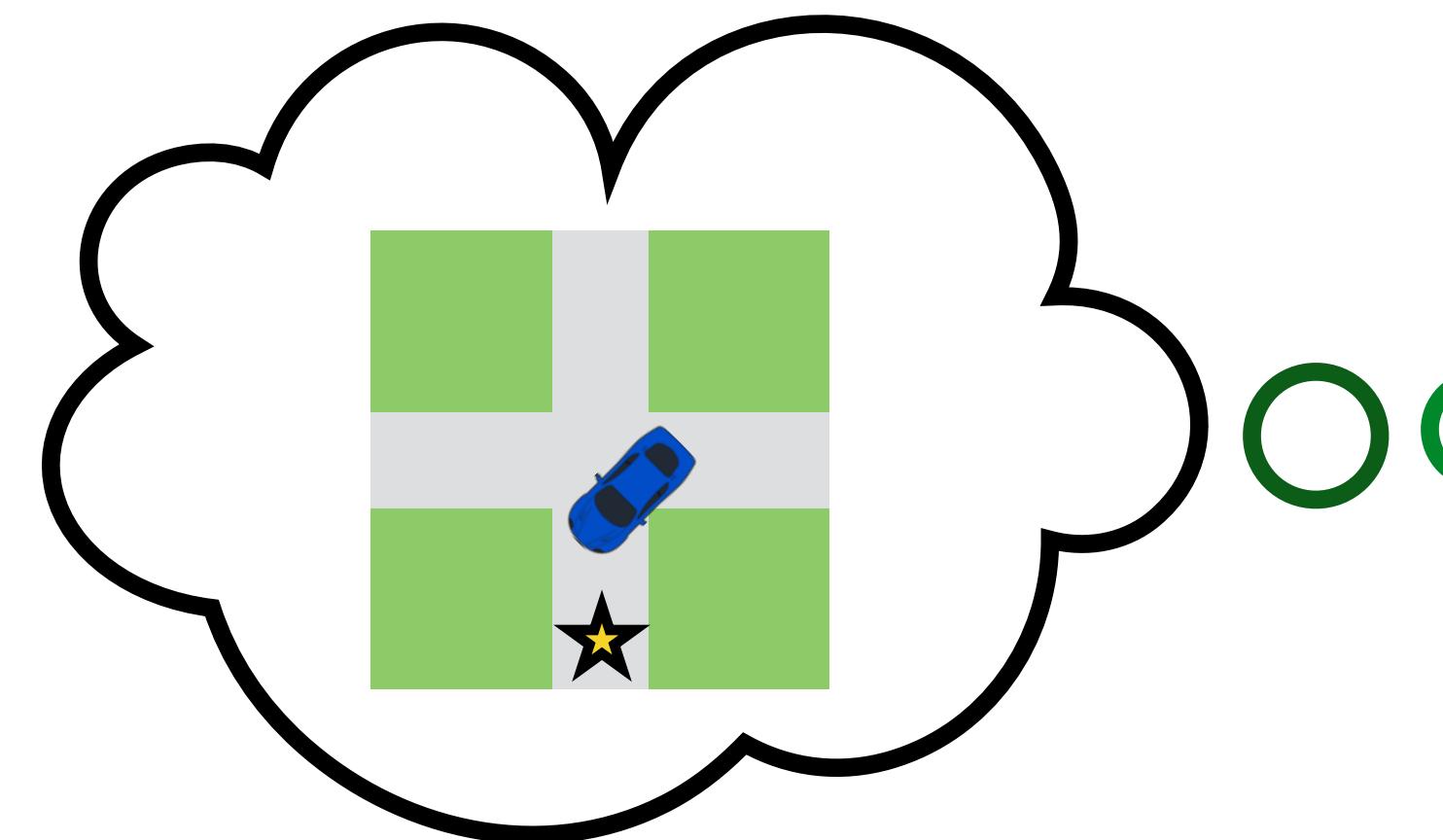
# Translating via belief



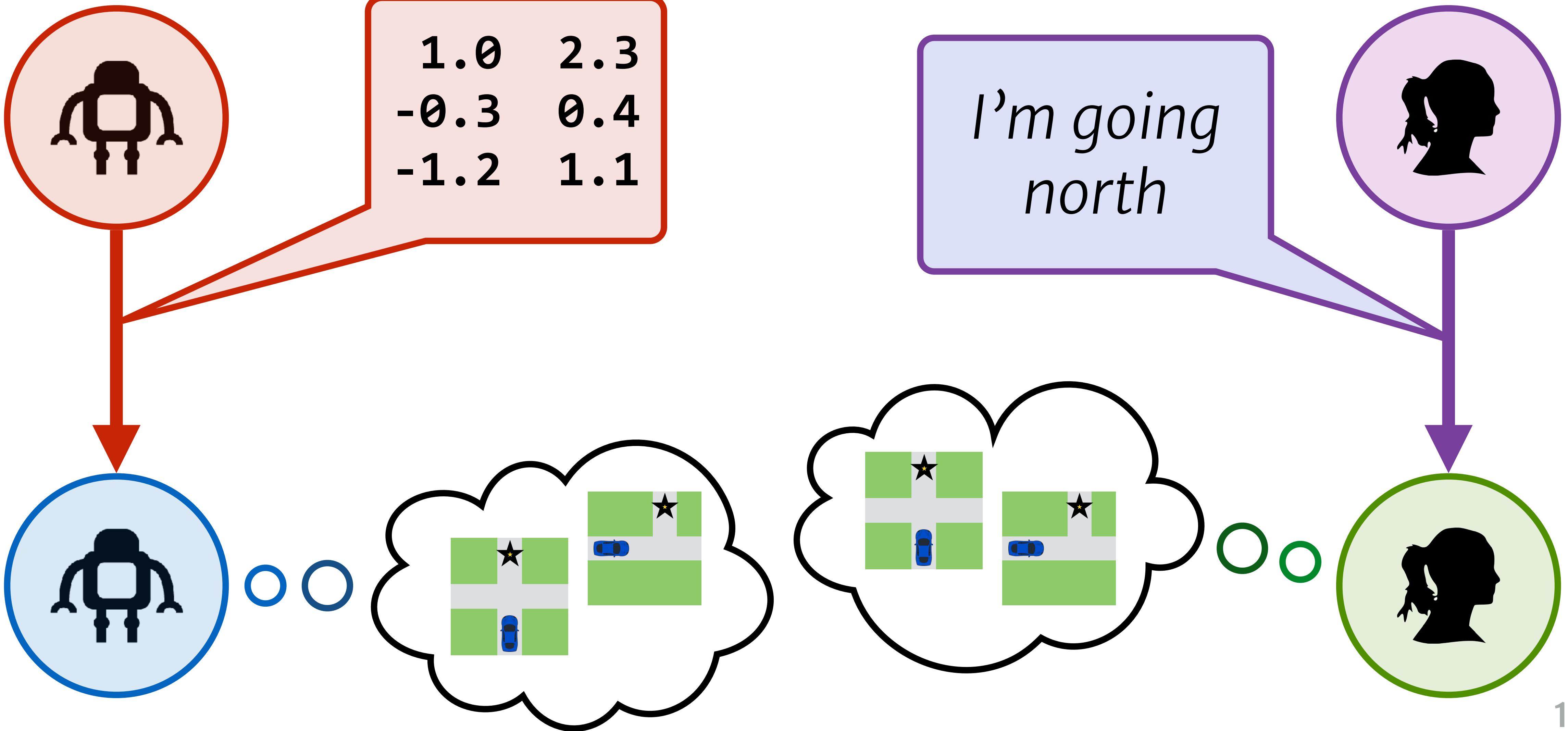
1.0	2.3
-0.3	0.4
-1.2	1.1



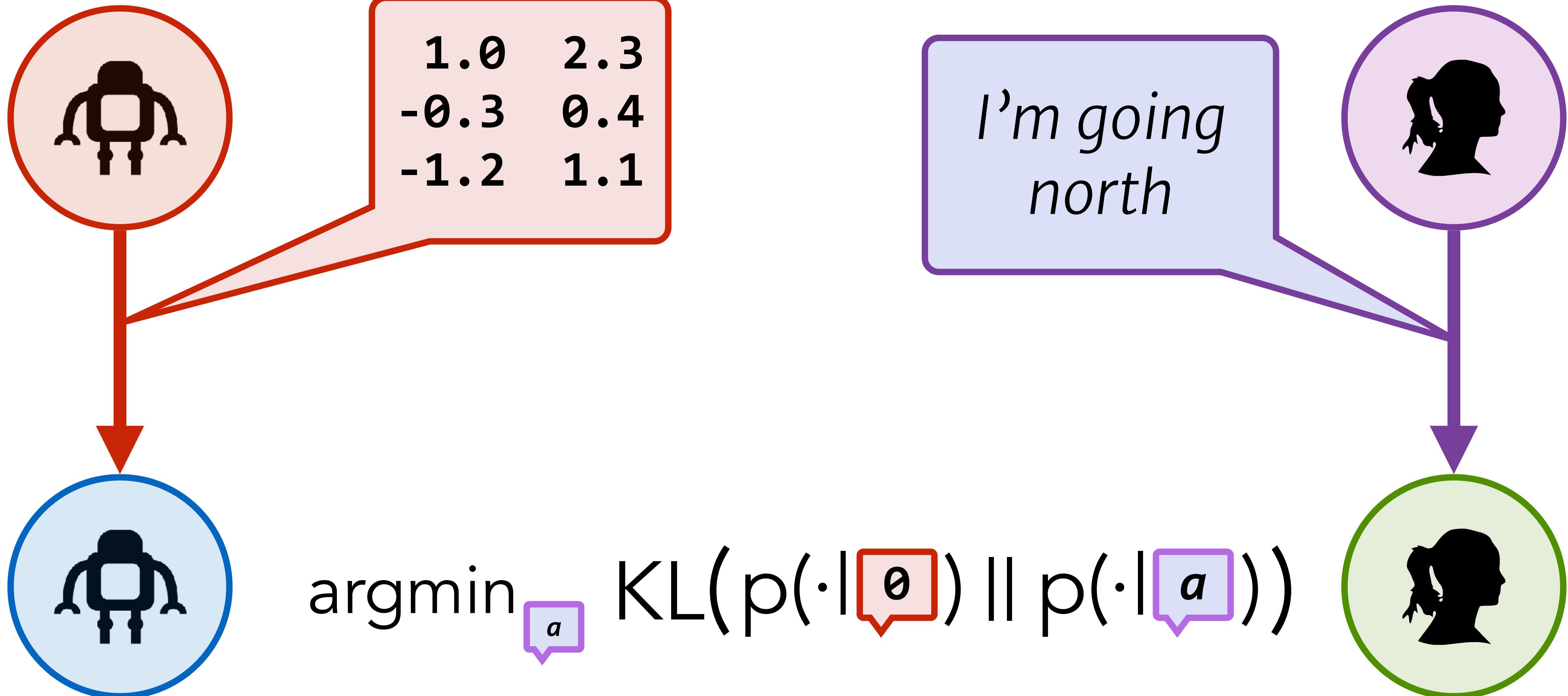
*in the  
intersection*

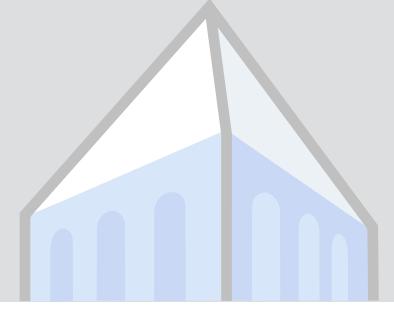


# Translating via belief

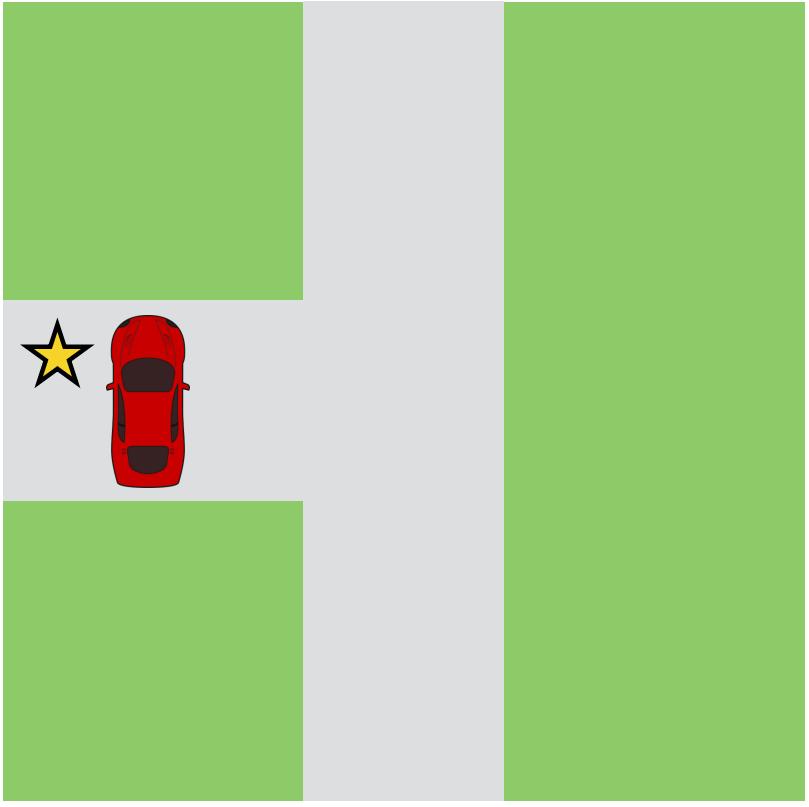


# Translating via belief

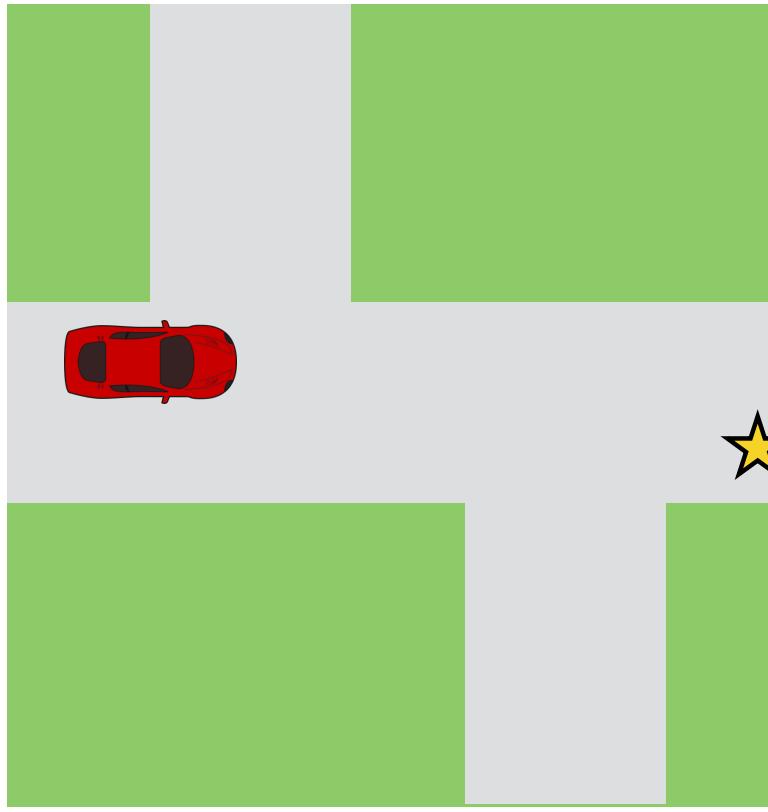




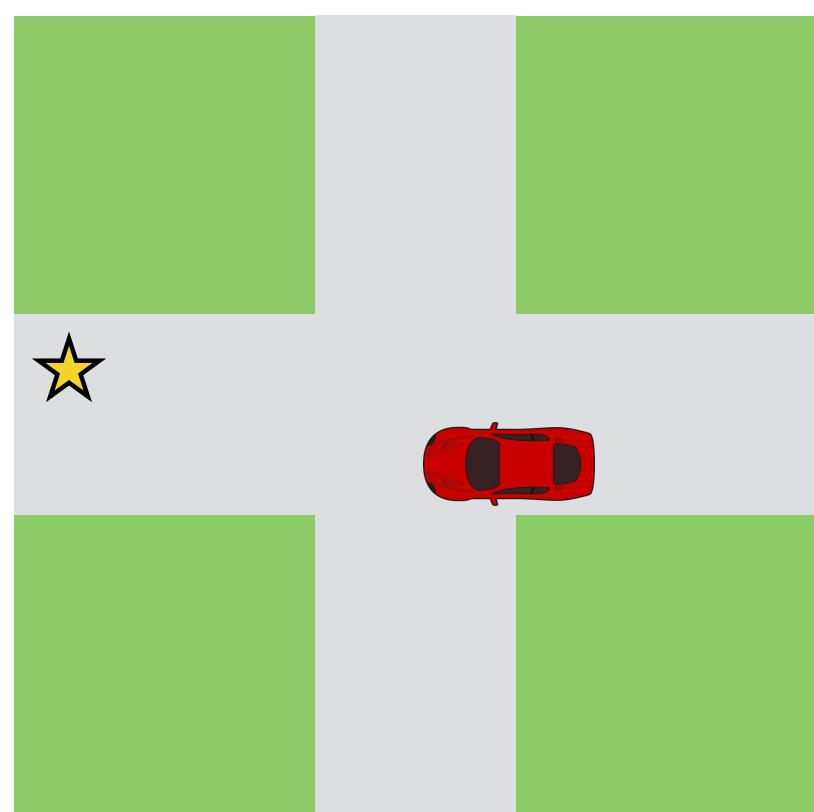
# Example translations



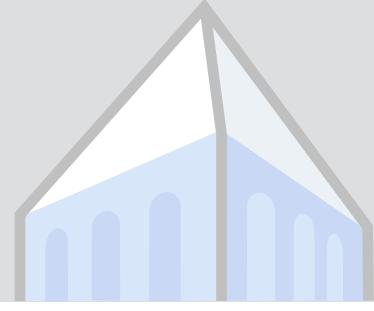
*at goal  
done  
left to top*



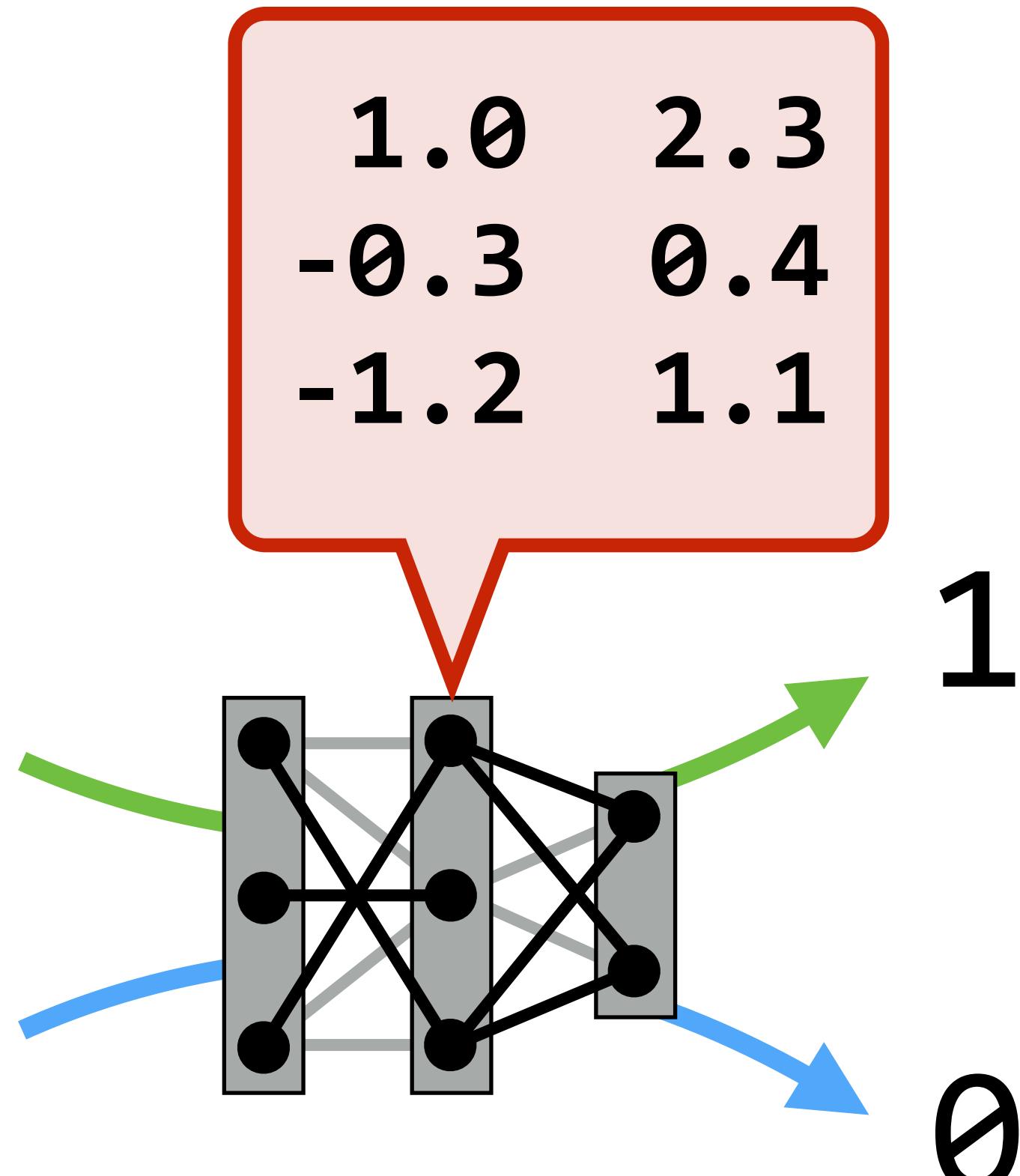
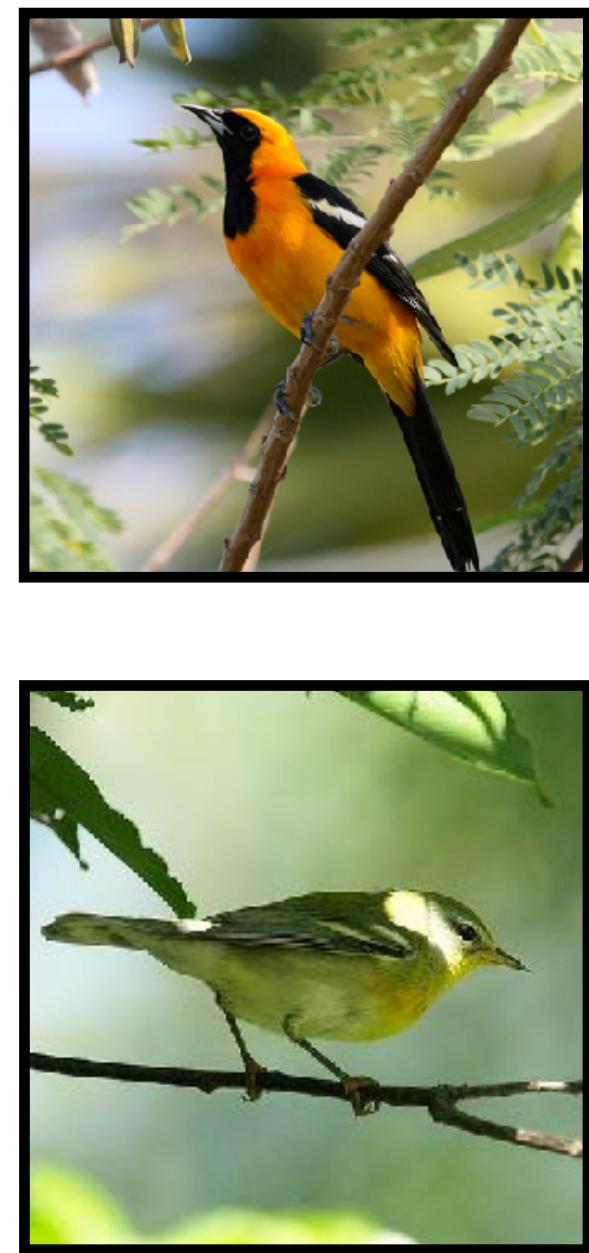
*you first  
following  
going down*



*going in intersection  
proceed  
going*

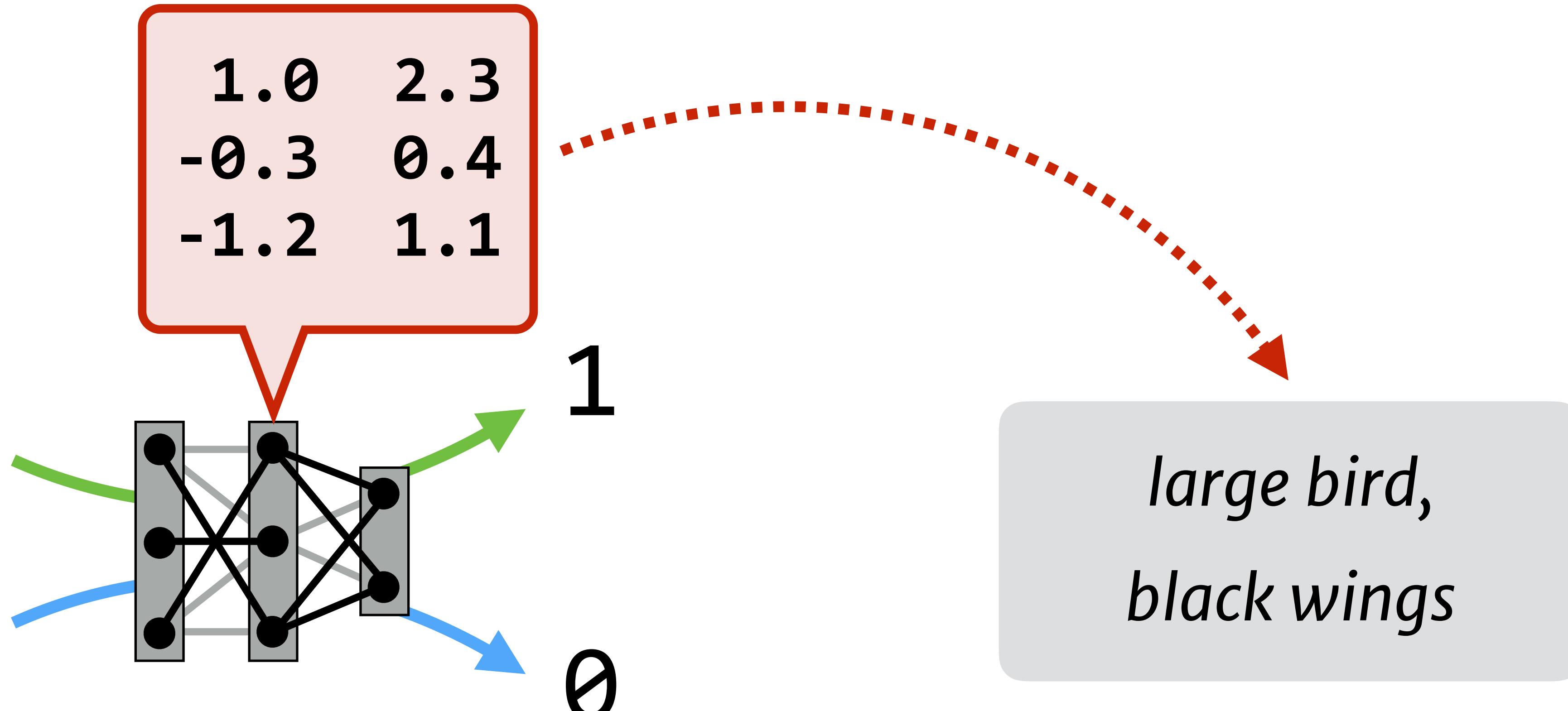
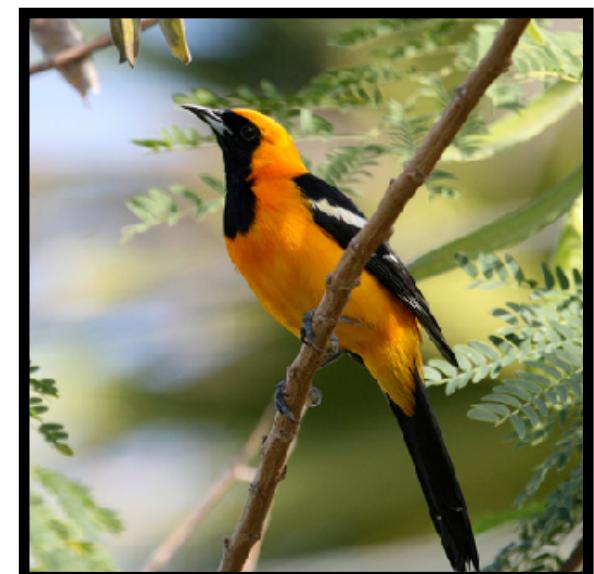


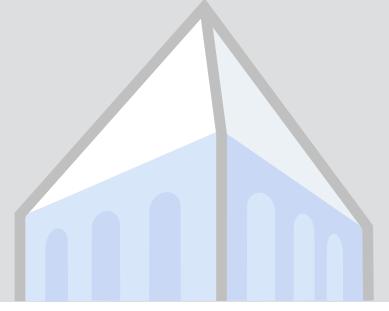
# Translating deep representations





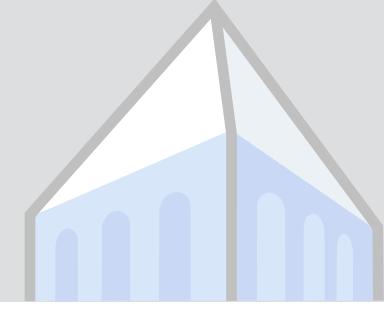
# Translating deep representations





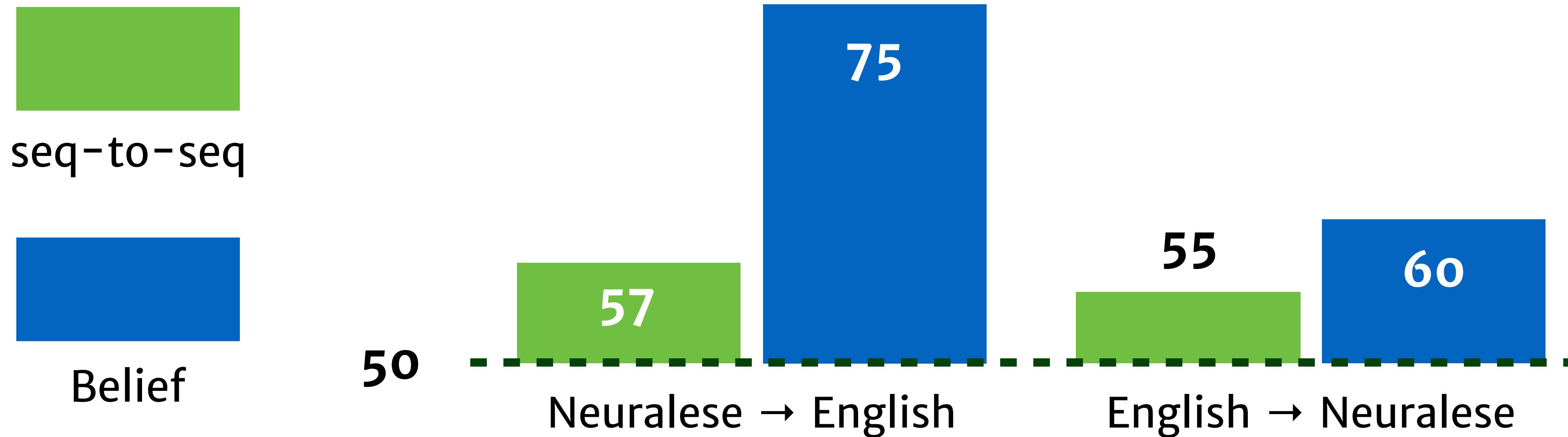
# Translation games [ADK17]

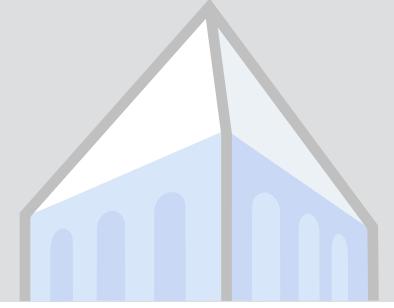
**PROPOSITION:** For agents cooperating via an approximately belief-preserving translation layer, we can bound loss relative to agents with a common language.



# Translation games [ADK17]

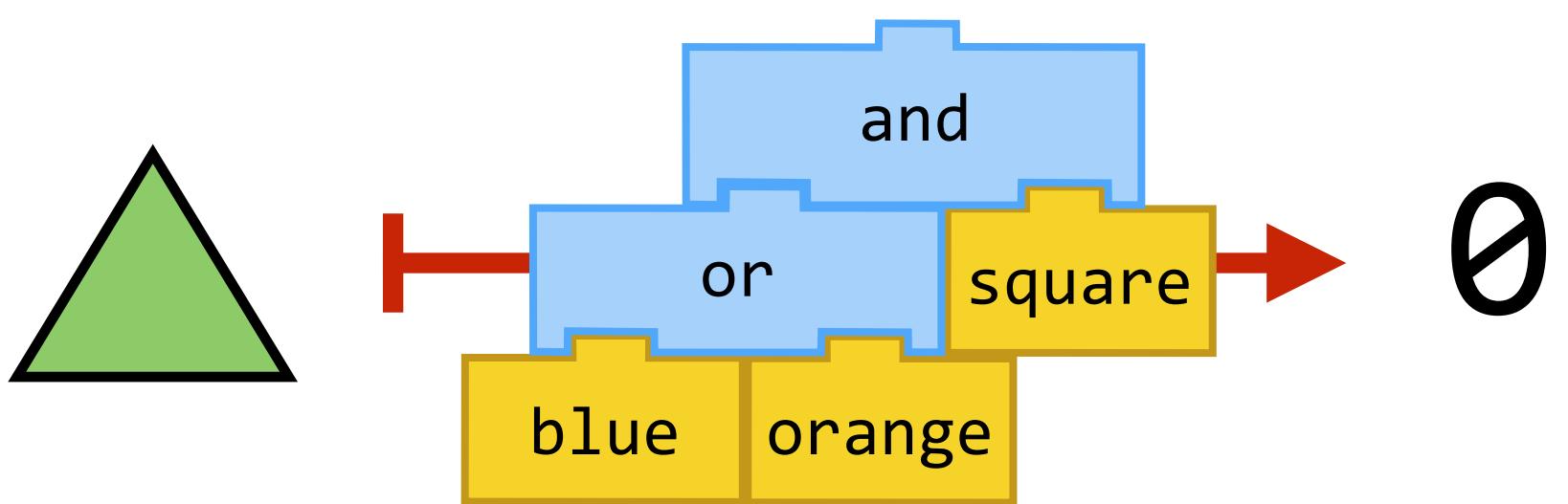
**PROPOSITION:** For agents cooperating via an approximately belief-preserving translation layer, we can bound loss relative to agents with a common language.





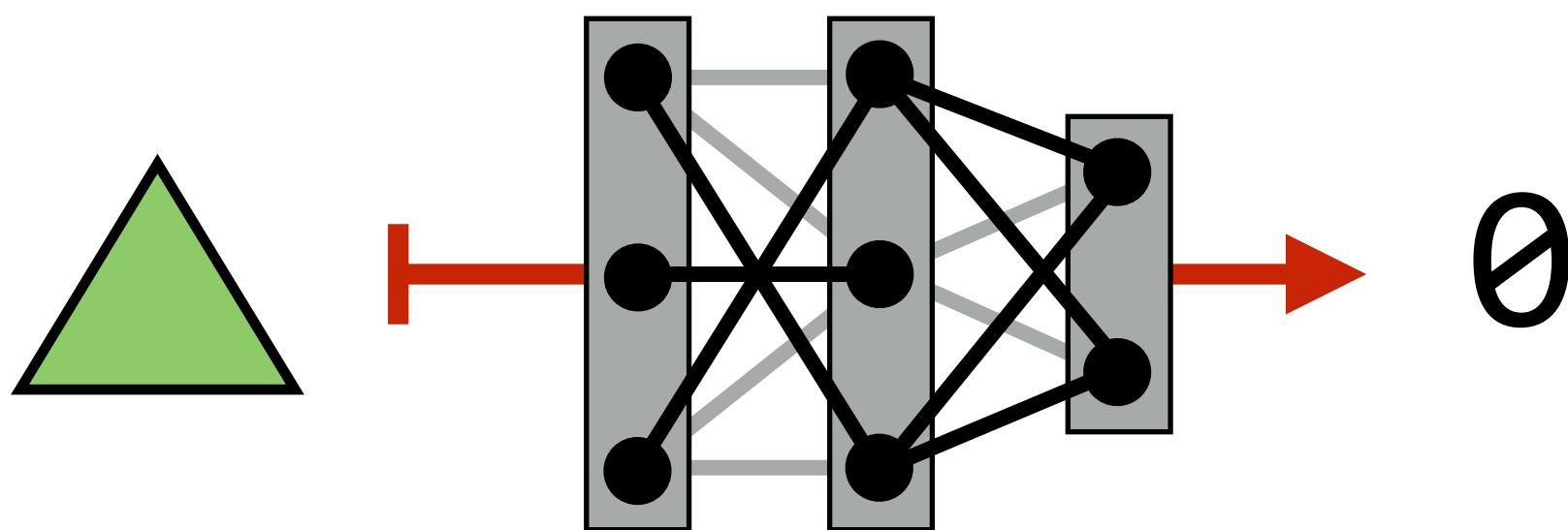
# Explaining classifiers

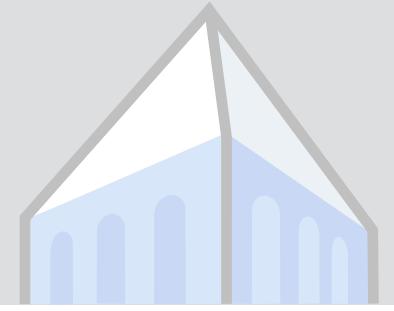
Interpreted language



*blue and orange squares*

Learned classifier





# Learning compositional operators

???

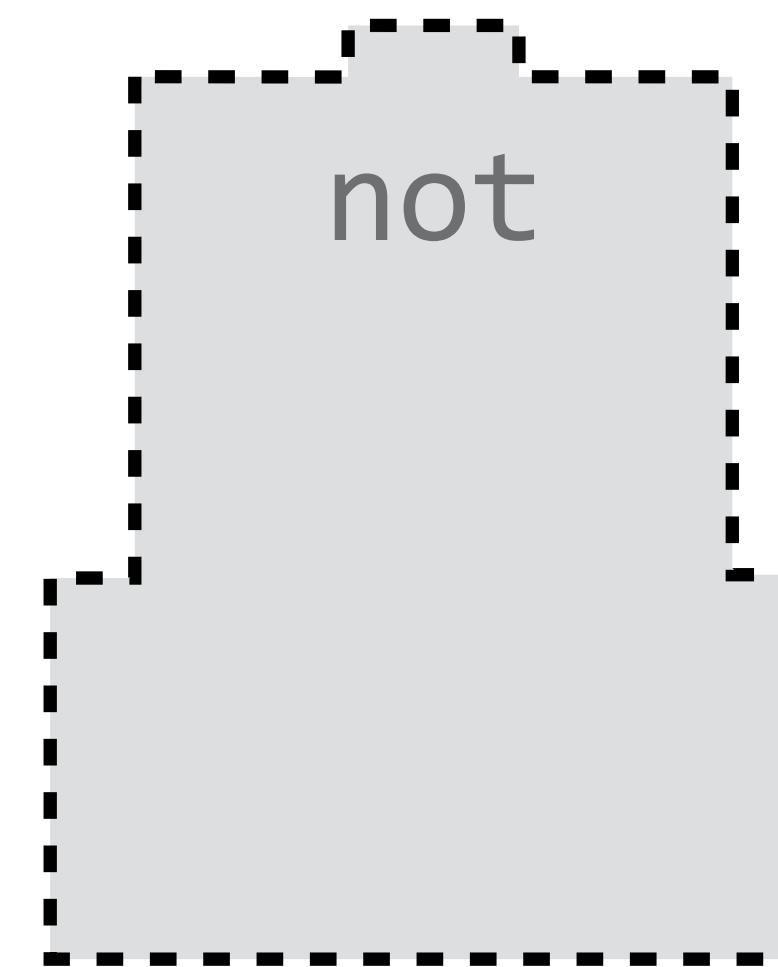
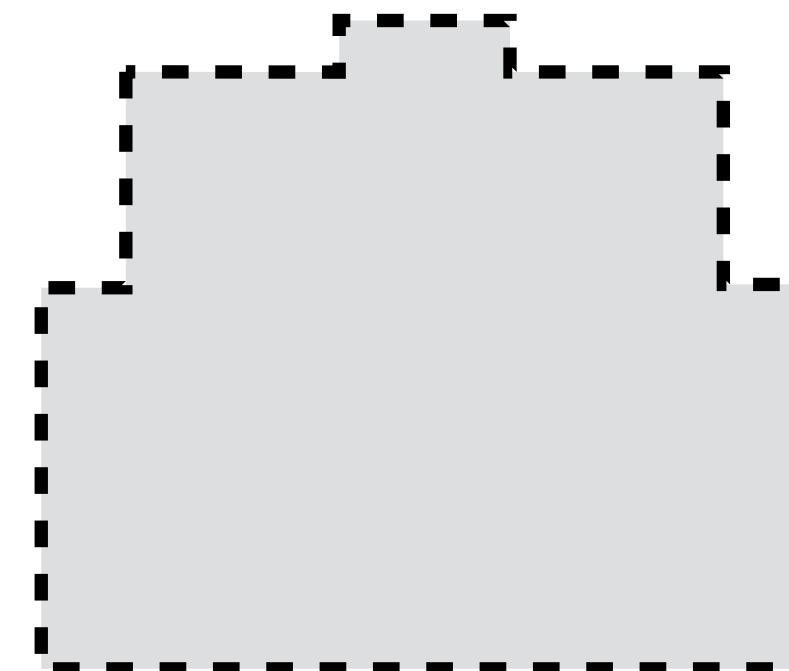
=

1.4 -0.3 -0.5

not

0.1 -0.3 0.5

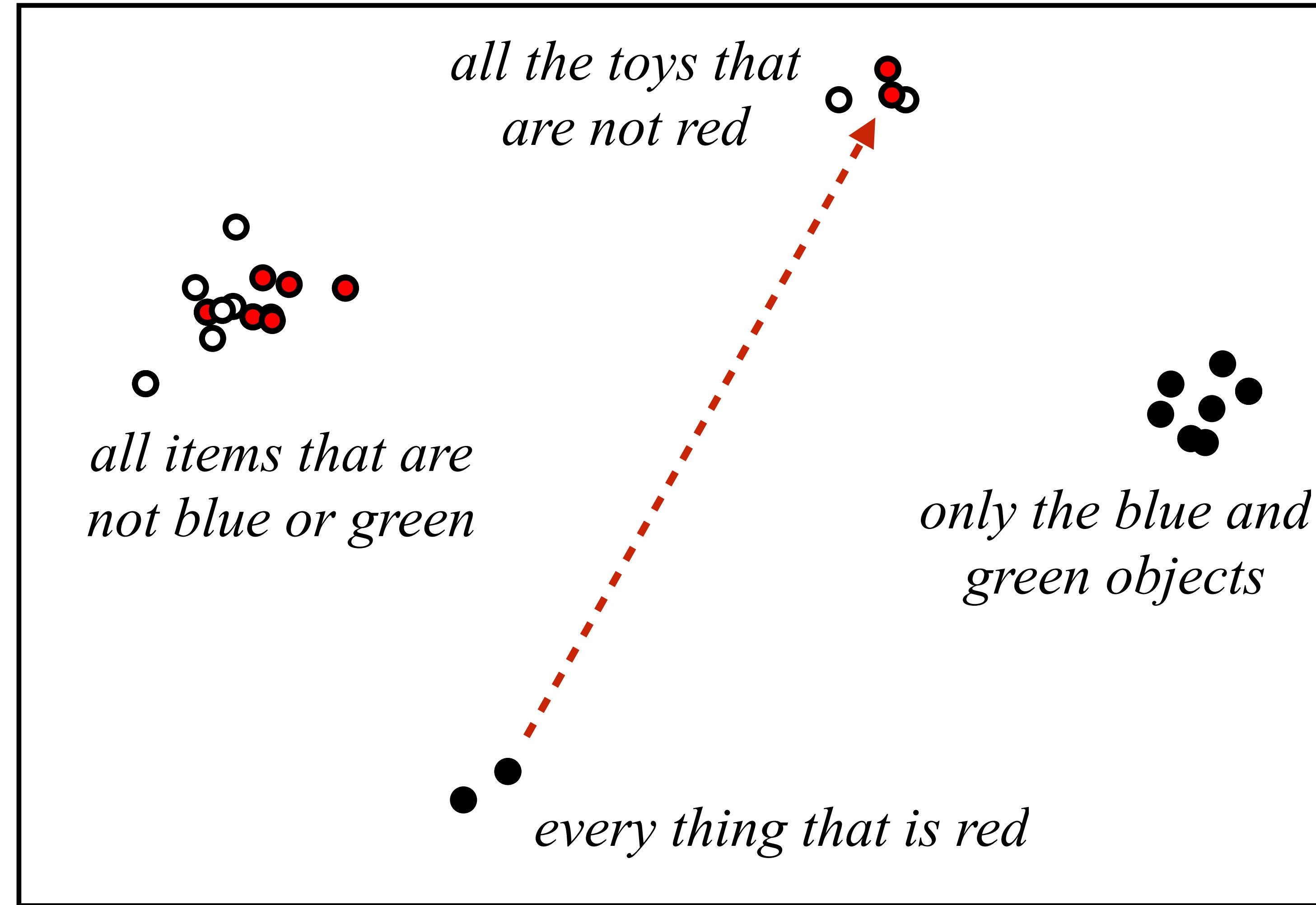
not



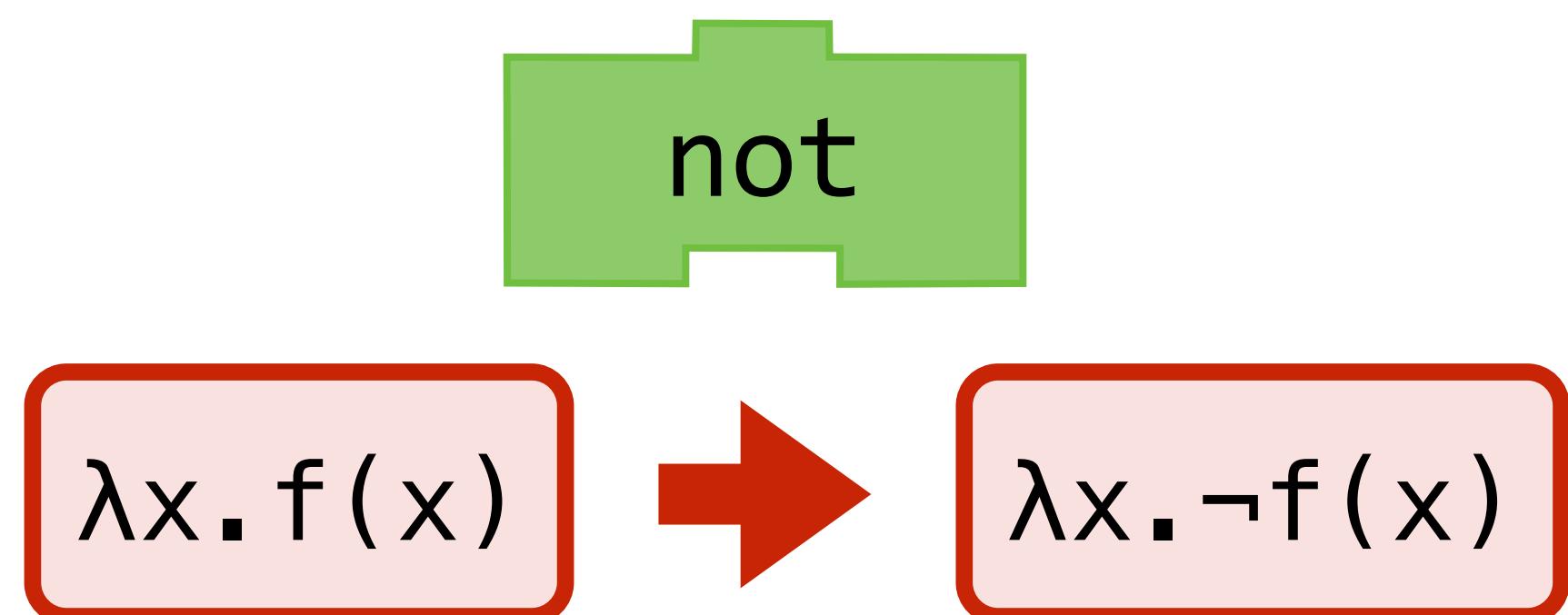
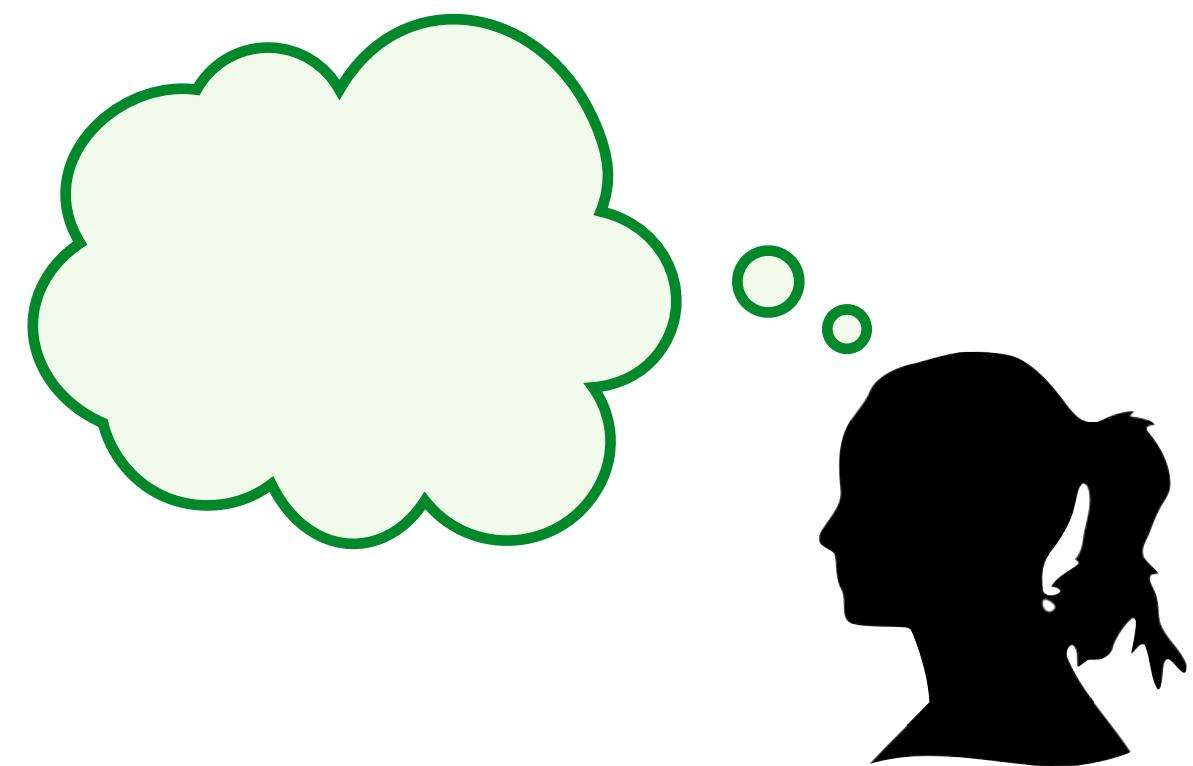


# Learning negation [AK17]

● Input  
● Predicted  
○ True

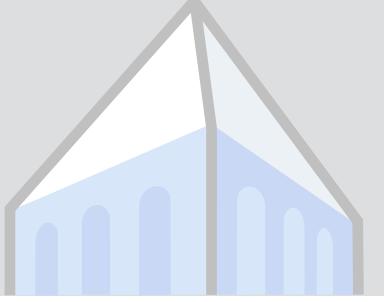


# Lessons

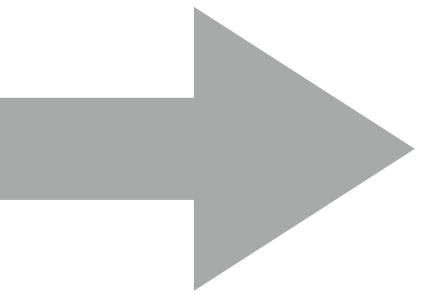
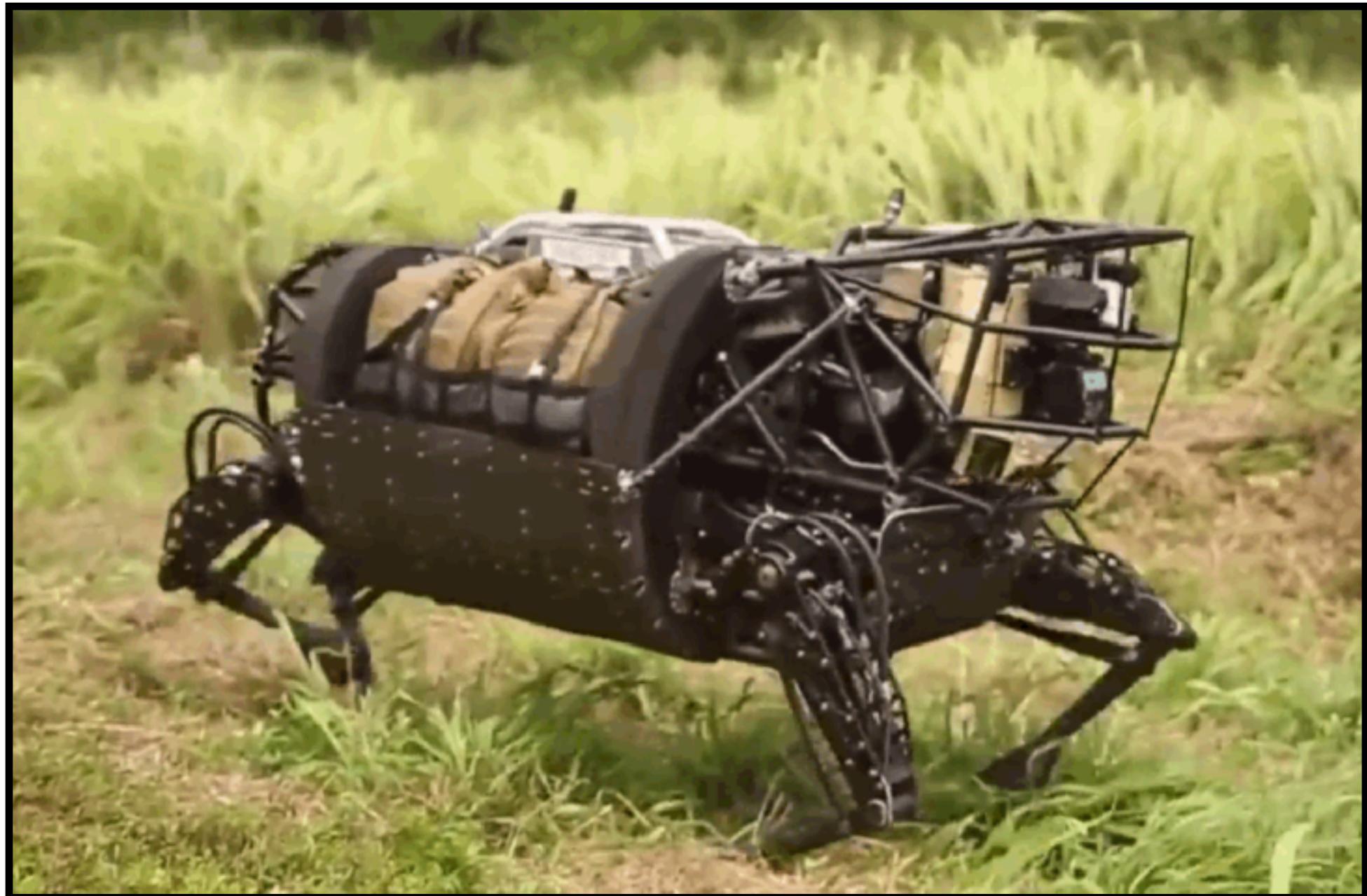


Explicitly modeling listener beliefs helps us build informative models for language generation.

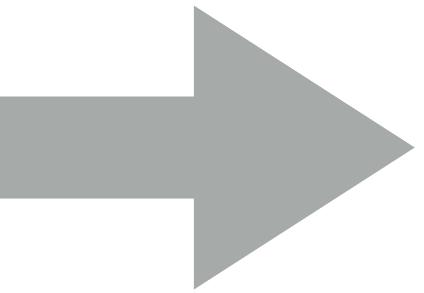
Language lets us find interpretable compositional operators in black-box deep models.



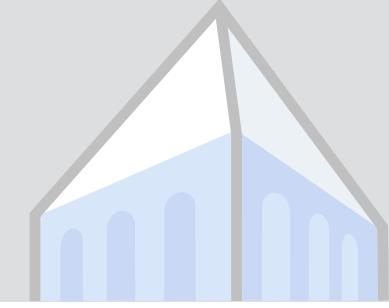
# Safe exploration



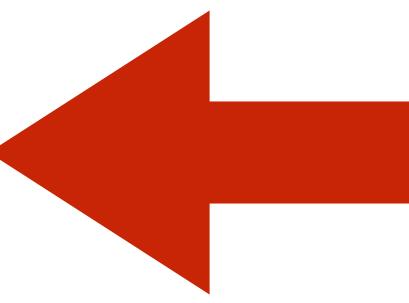
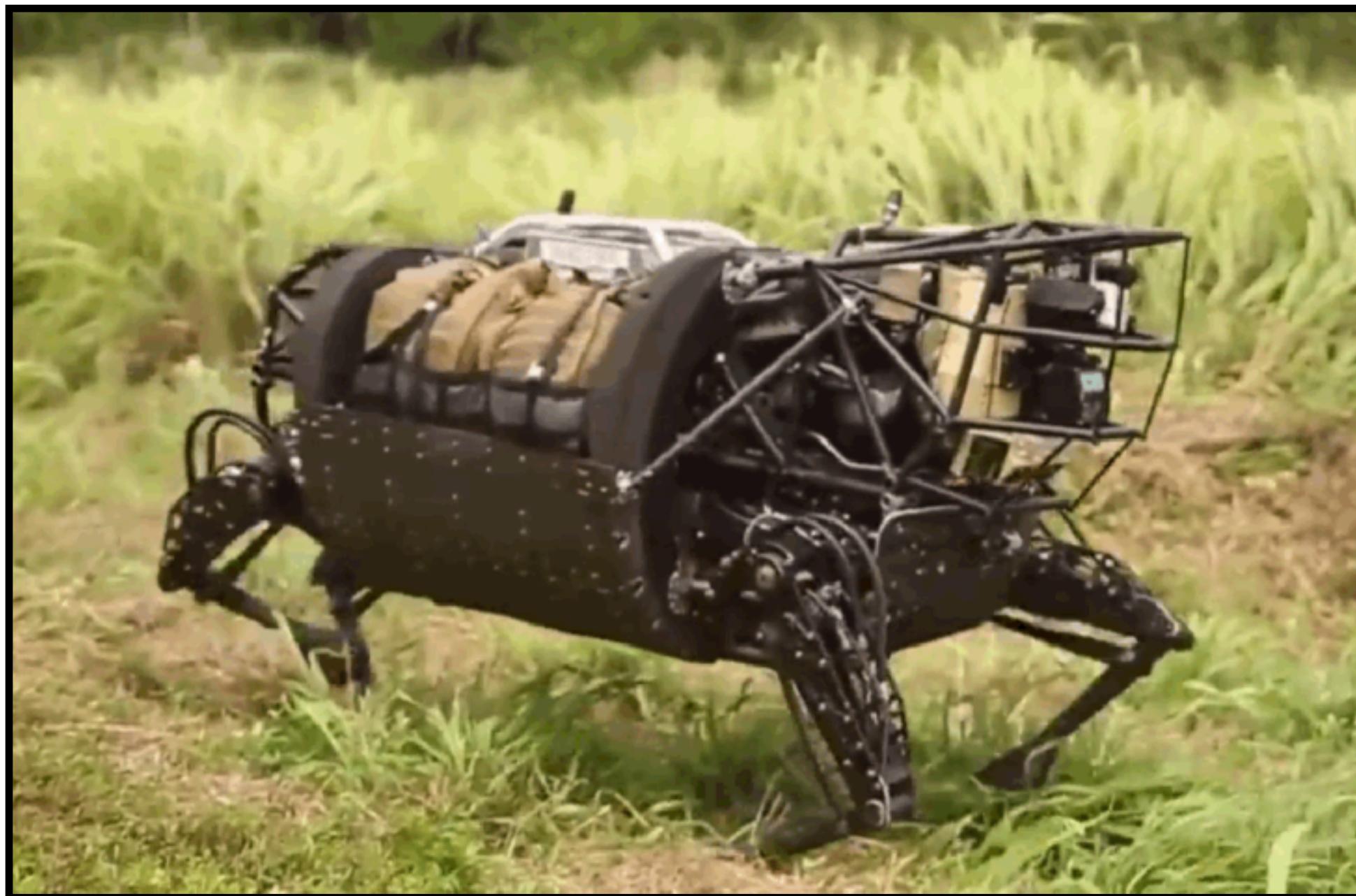
*I will wiggle my front left leg.*



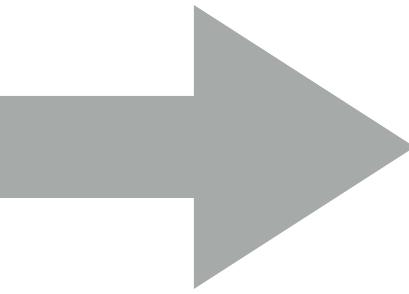
*I will sprint 300 meters forward.*



# Demonstrating competence

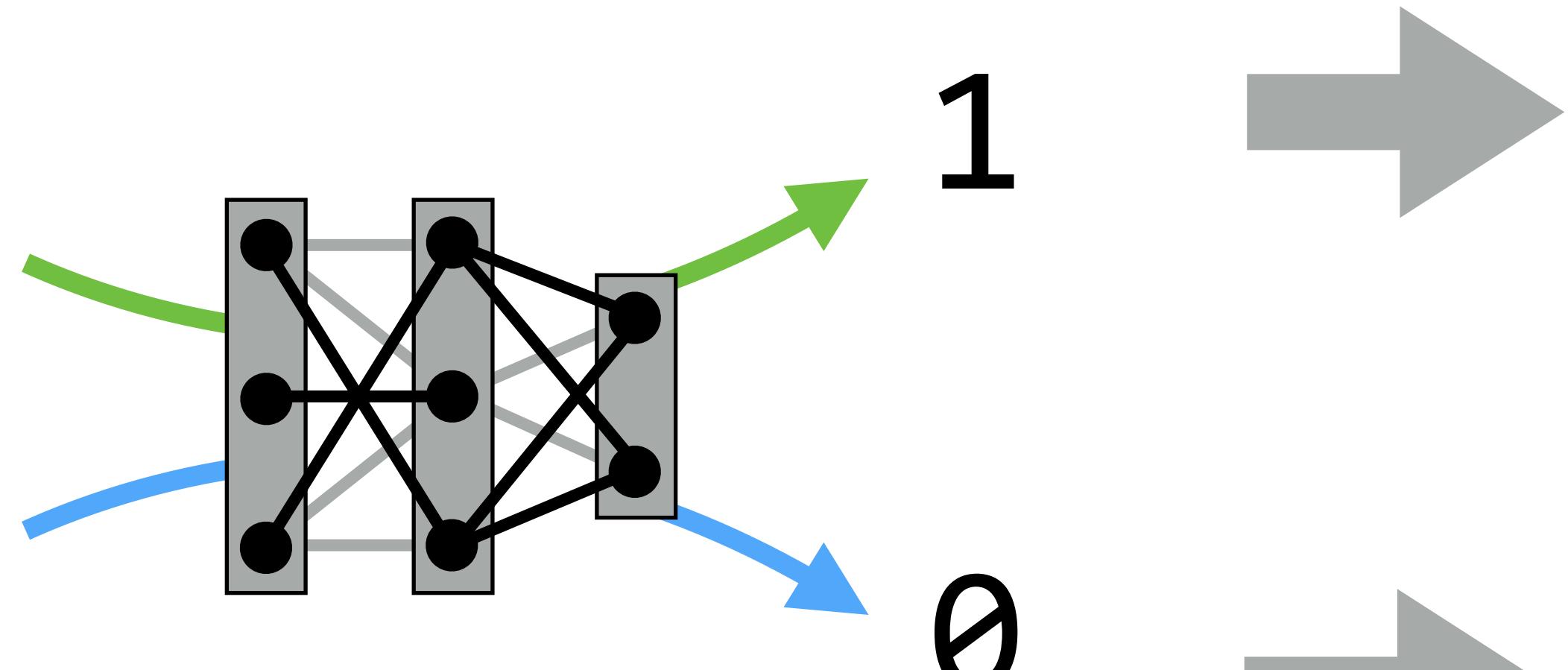
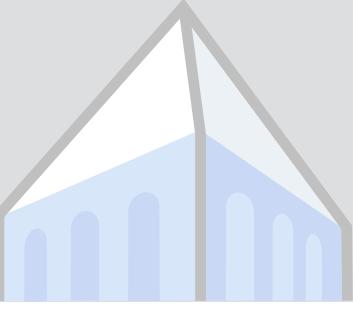


*Defuse the bomb.*



*I will cut open the box and snip the blue wire while avoiding the red one.*

# Explaining limitations

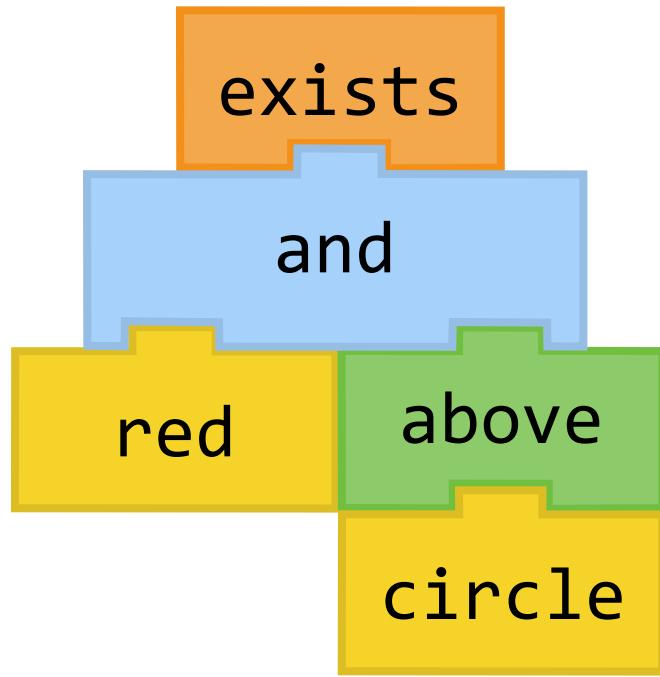


*All western  
tanagers have  
yellow heads.*

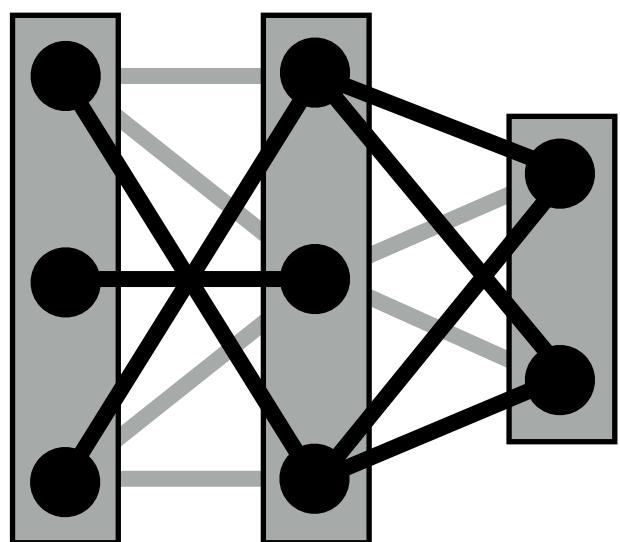
*I can't tell the  
difference between  
ravens and crows.*



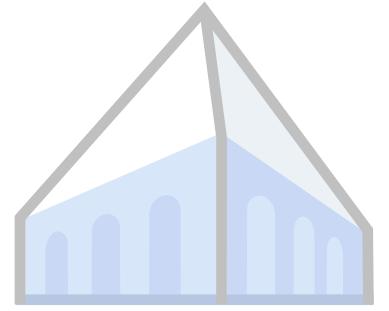
# Last lessons



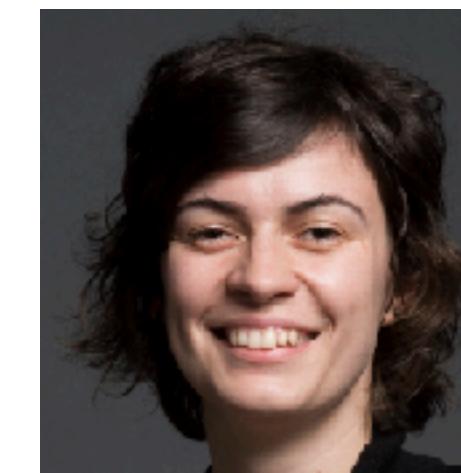
The structure of language helps us design models that reflect the compositional structure of the world.



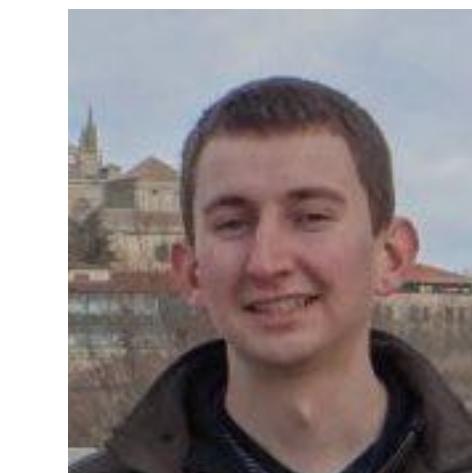
These models provide more accurate and interpretable learning for language processing and more.



Trevor  
Darrell



Anca  
Drăgan



Daniel  
Fried



Dan  
Klein



Ronghang  
Hu



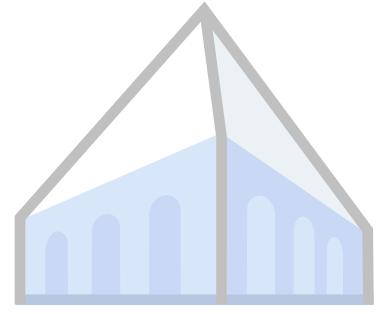
Sergey  
Levine



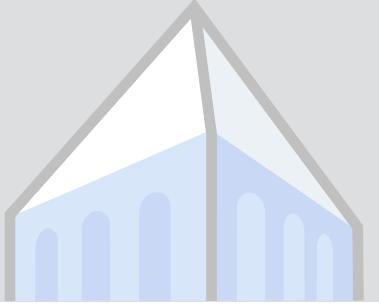
Marcus  
Rohrbach



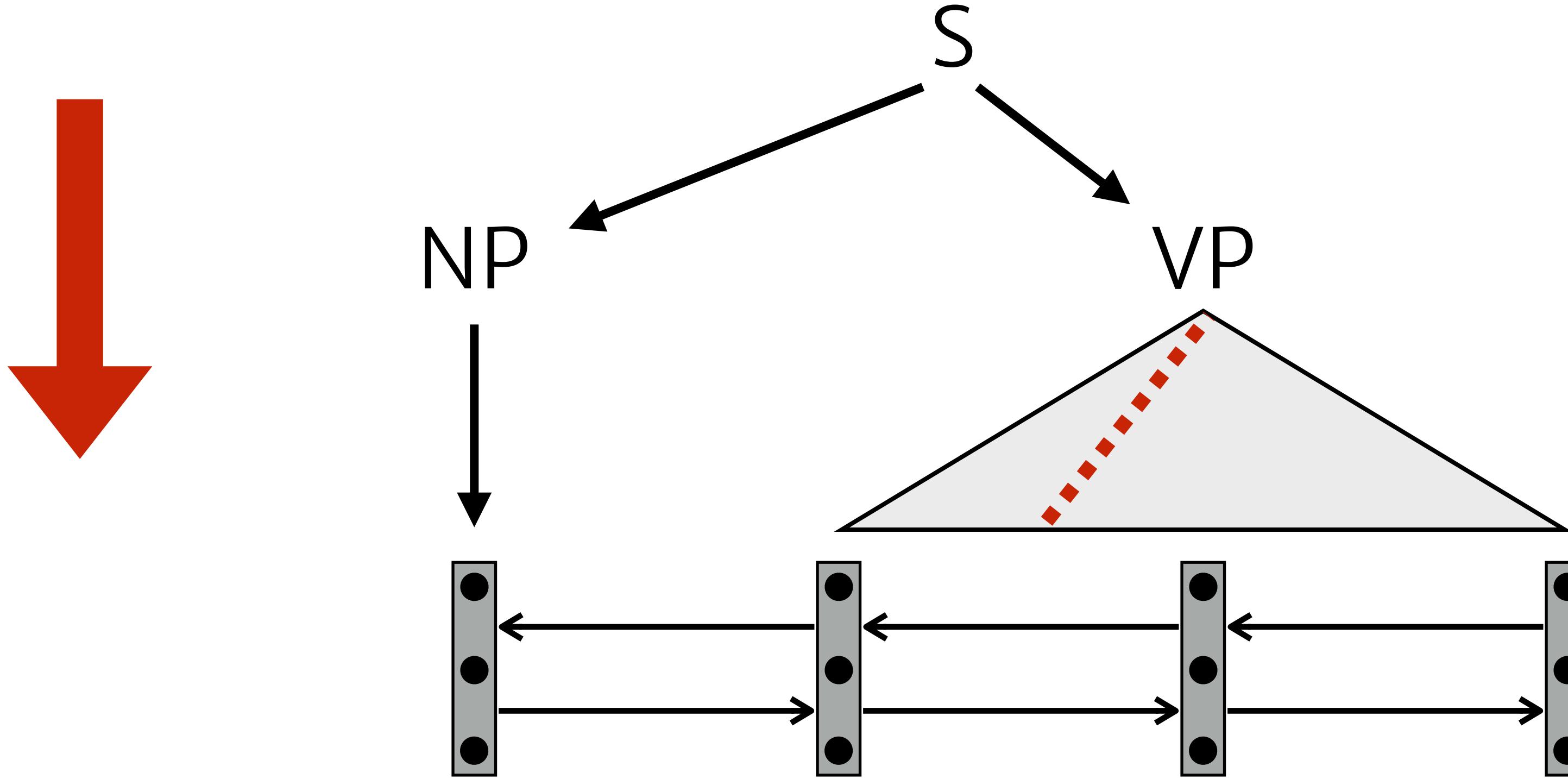
Kate  
Saenko



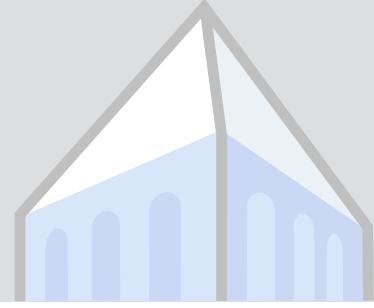
thank  
you



# Bonus parse tree [AK14, SAK17]

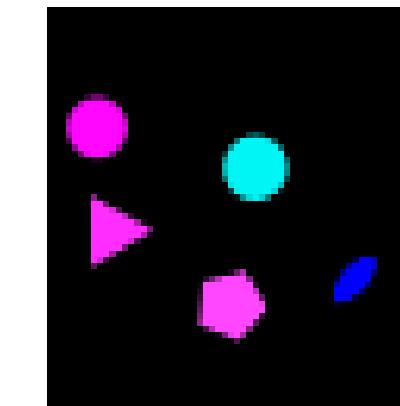


*She     enjoys     playing     tennis*



# Learning with latent language [AKL18]

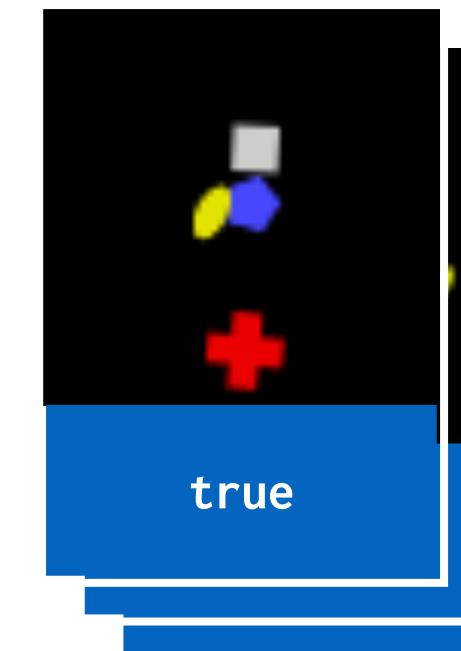
language  
learning



there is a pink pentagon

true

concept  
learning



there is a  
green square

0.0

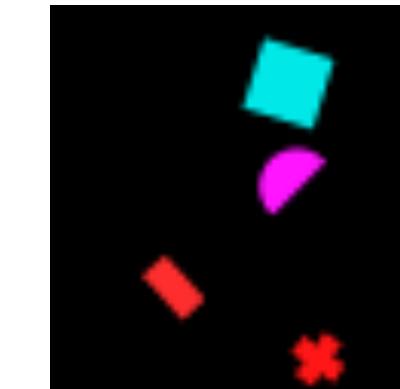
a gray square is  
above a square

0.2

a red cross is  
below a square

0.9

evaluation



a red cross is  
below a square

0.8

true