



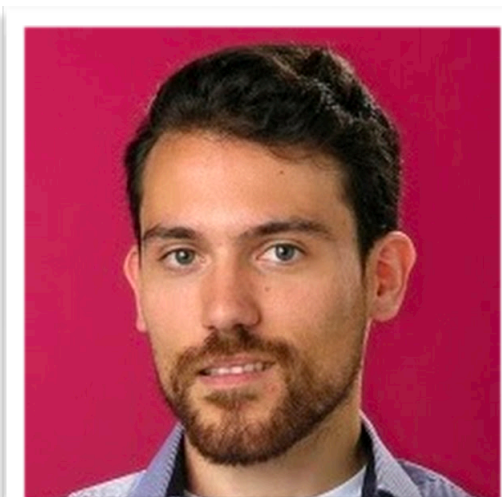
Structured agents for physical construction



(Wednesday posters, Pacific Ballroom #36)



**Victor
Bapst***



**Alvaro
Sanchez-Gonzalez***



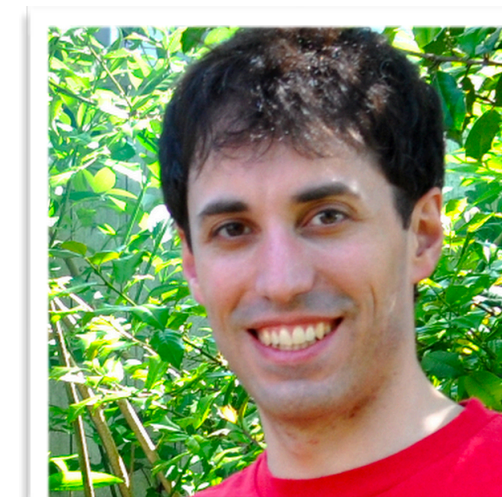
Carl
Doersch



Kim
Stachenfeld



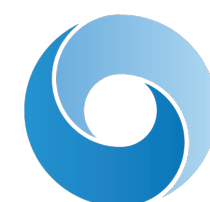
Pushmeet
Kohli



Peter
Battaglia



Jessica
Hamrick



DeepMind

**equal contribution*

Humans are a “Construction Species”



Humans are a “Construction Species”



ELEMENTS	
Hydrogen	Strontian
Nitrogen	Barytes
Carbon	Iridium
Oxygen	Zinc
Phosphorus	Cobalt
Sulphur	Lithium
Magnesia	Silver
Lime	Gold
Soda	Platina
Potash	Mercury

No.	No.	No.	No.	No.	No.	No.	No.
H 1	F 8	Cl 15	Co & Ni 22	Br 29	Pd 36	I 42	Pt & Ir 48
Li 2	Na 9	K 16	Cu 23	Rb 30	Ag 37	Cs 44	Os 49
B 3	Mg 10	Ca 17	Zn 24	Sr 31	Cd 38	Ba & V 45	Hg 49
Bo 4	Al 11	Cr 19	Y 25	Ce & La 33	U 40	Ta 46	Tl 47
C 5	Si 12	Ti 18	In 26	Zr 32	Sn 39	W 47	Pb 48
N 6	P 13	Mn 20	As 27	Di & Mo 34	Sb 41	Nb 47	Bi 48
O 7	S 14	Fe 21	Se 28	Ro & Ru 35	Te 43	Au 49	Th 49

Reihen	Gruppe I. R ⁰	Gruppe II. R ⁰	Gruppe III. R ⁰	Gruppe IV. RH ⁴ R ⁰	Gruppe V. RH ⁵ R ⁰	Gruppe VI. RH ⁶ R ⁰	Gruppe VII. RH ⁷ R ⁰	Gruppe VIII. R ⁰
1	II=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,8	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	--=44	Ti=48	V=51	Cr=52	Mn=55	Po=60, Co=59, Ni=59, Cu=63
5	(Cu=63)	Zn=65	--=68	--=72	As=75	Se=78	Br=80	
6	Rb=86	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	--=100	Hu=104, Rh=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Co=140				
9	(-)							
10			?Er=178	?La=180	Ta=182	W=184		Os=195, Ir=193, Pt=198, Au=197
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208			
12				Th=231		U=240		

Periodic table																																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																												
Hydrogen 1 H 1.008																	Helium 2 He 4.0026																												
Lithium 3 Li 6.94	Beryllium 4 Be 9.0122															Boron 5 B 10.81	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.183																								
Sodium 11 Na 22.990	Magnesium 12 Mg 24.305															Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.45	Argon 18 Ar 39.948																								
Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.887	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.630	Arsenic 33 As 74.922	Selenium 34 Se 78.971	Bromine 35 Br 79.904	Krypton 36 Kr 83.798																												
Rubidium 37 Rb 85.468	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc (98)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Tellurium 52 Te 127.60	Iodine 53 I 126.90	Xenon 54 Xe 131.29																												
Caesium 55 Cs 132.91	Barium 56 Ba 137.33	Lanthanum 57 La 138.91	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08	Gold 79 Au 196.97	Mercury 80 Hg 200.59	Thallium 81 Tl 204.38	Lead 82 Pb 207.2	Bismuth 83 Bi 208.98	Polonium 84 Po (209)	Astatine 85 At (210)	Radon 86 Rn (222)																												
Francium 87 Fr (223)	Radium 88 Ra (226)	Actinium 89 Ac (227)	Rutherfordium 104 Rf (261)	Dubnium 105 Db (262)	Seaborgium 106 Sg (263)	Bohrium 107 Bh (264)	Hassium 108 Hs (265)	Mtlerium 109 Mt (266)	Darmstadtium 110 Ds (267)	Roentgenium 111 Rg (268)	Copernicium 112 Cn (269)	Nihonium 113 Nh (270)	Flerovium 114 Fl (271)	Moscovium 115 Mc (272)	Livermorium 116 Lv (273)	Tennessee 117 Ts (274)	Oganesson 118 Og (276)																												
<table border="1"> <thead> <tr> <th>Cerium 58 Ce 140.12</th> <th>Praseodymium 59 Pr 140.91</th> <th>Neodymium 60 Nd 144.24</th> <th>Promethium 61 Pm (145)</th> <th>Samarium 62 Sm 150.36</th> <th>Europium 63 Eu 151.96</th> <th>Gadolinium 64 Gd 157.25</th> <th>Terbium 65 Tb 158.93</th> <th>Dysprosium 66 Dy 162.50</th> <th>Holmium 67 Ho 164.93</th> <th>Erbium 68 Er 167.26</th> <th>Thulium 69 Tm 168.93</th> <th>Ytterbium 70 Yb 173.05</th> <th>Lutetium 71 Lu 174.97</th> </tr> </thead> <tbody> <tr> <td>Thorium 90 Th 232.04</td> <td>Protactinium 91 Pa 231.04</td> <td>Uranium 92 U 238.03</td> <td>Nephtunium 93 Np (237)</td> <td>Plutonium 94 Pu (244)</td> <td>Americium 95 Am (243)</td> <td>Curium 96 Cm (247)</td> <td>Berkelium 97 Bk (247)</td> <td>Californium 98 Cf (251)</td> <td>Einsteinium 99 Es (252)</td> <td>Fermium 100 Fm (257)</td> <td>Mendelevium 101 Md (258)</td> <td>Nobelium 102 No (259)</td> <td>Lawrencium 103 Lr (260)</td> </tr> </tbody> </table>																		Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm (145)	Samarium 62 Sm 150.36	Europium 63 Eu 151.96	Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05	Lutetium 71 Lu 174.97	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Nephtunium 93 Np (237)	Plutonium 94 Pu (244)	Americium 95 Am (243)	Curium 96 Cm (247)	Berkelium 97 Bk (247)	Californium 98 Cf (251)	Einsteinium 99 Es (252)	Fermium 100 Fm (257)	Mendelevium 101 Md (258)	Nobelium 102 No (259)	Lawrencium 103 Lr (260)
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Humans are a “Construction Species”



Physical construction: the ability to compose **objects**, subject to physical **dynamics**, in order to serve a **function**.

Contributions

Contributions

1. A suite of challenging physical ***construction tasks***

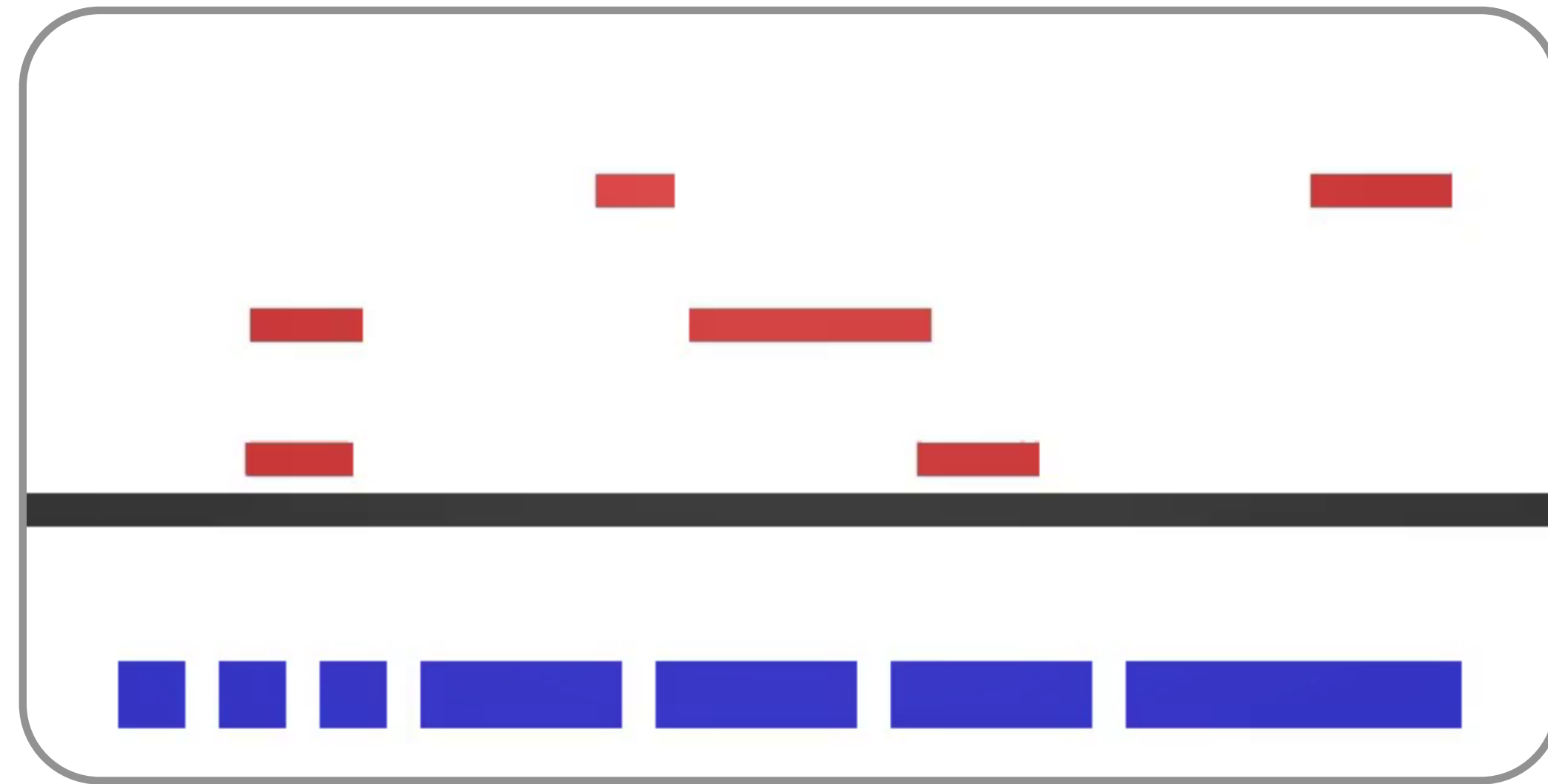
Contributions

1. A suite of challenging physical **construction tasks**
2. A new type of **structured agent** that uses:

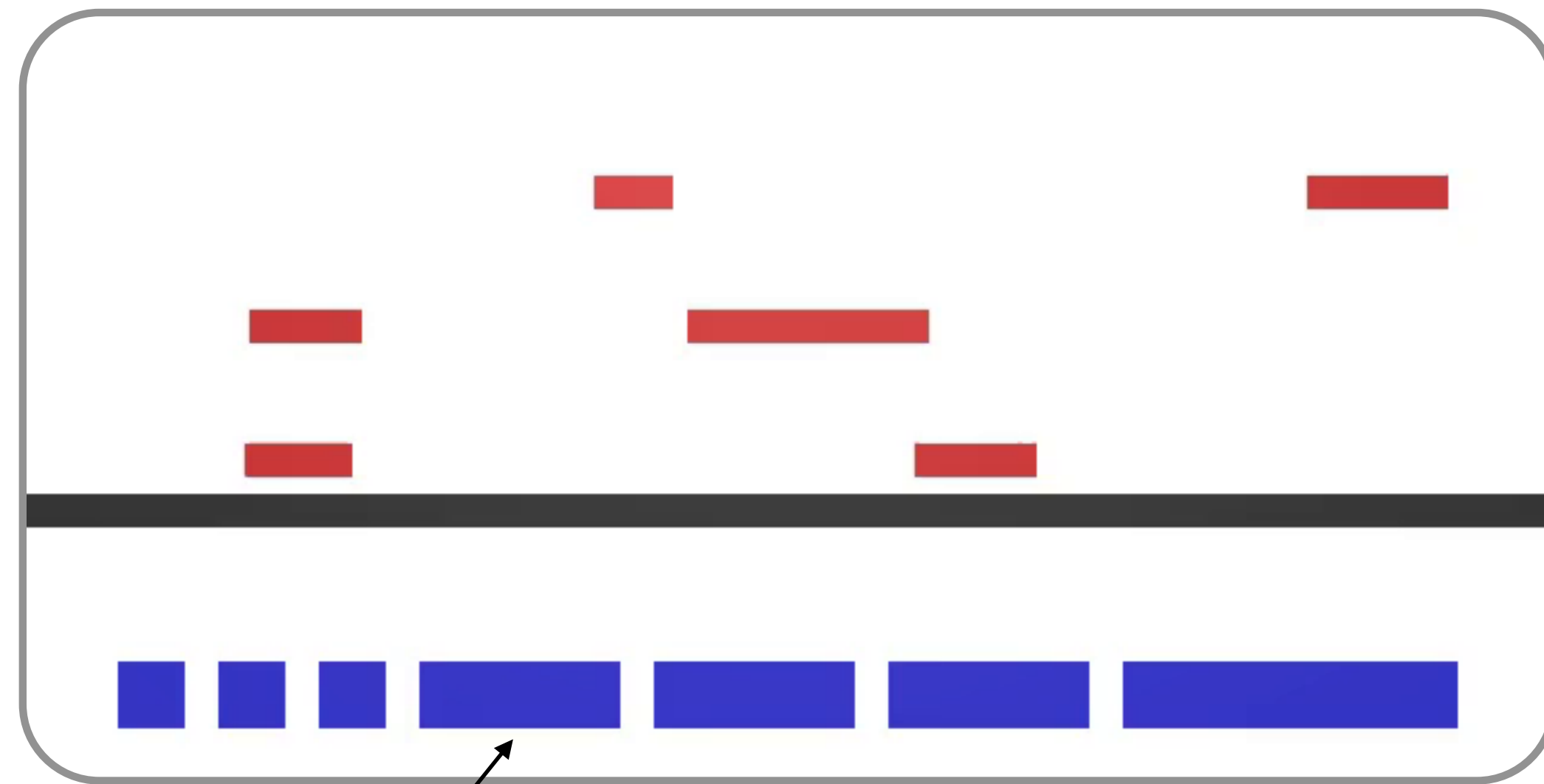
Contributions

1. A suite of challenging physical **construction tasks**
2. A new type of **structured agent** that uses:
 - structured representations
 - object-centric relative actions
 - combination of model-free and model-based

Construction Tasks



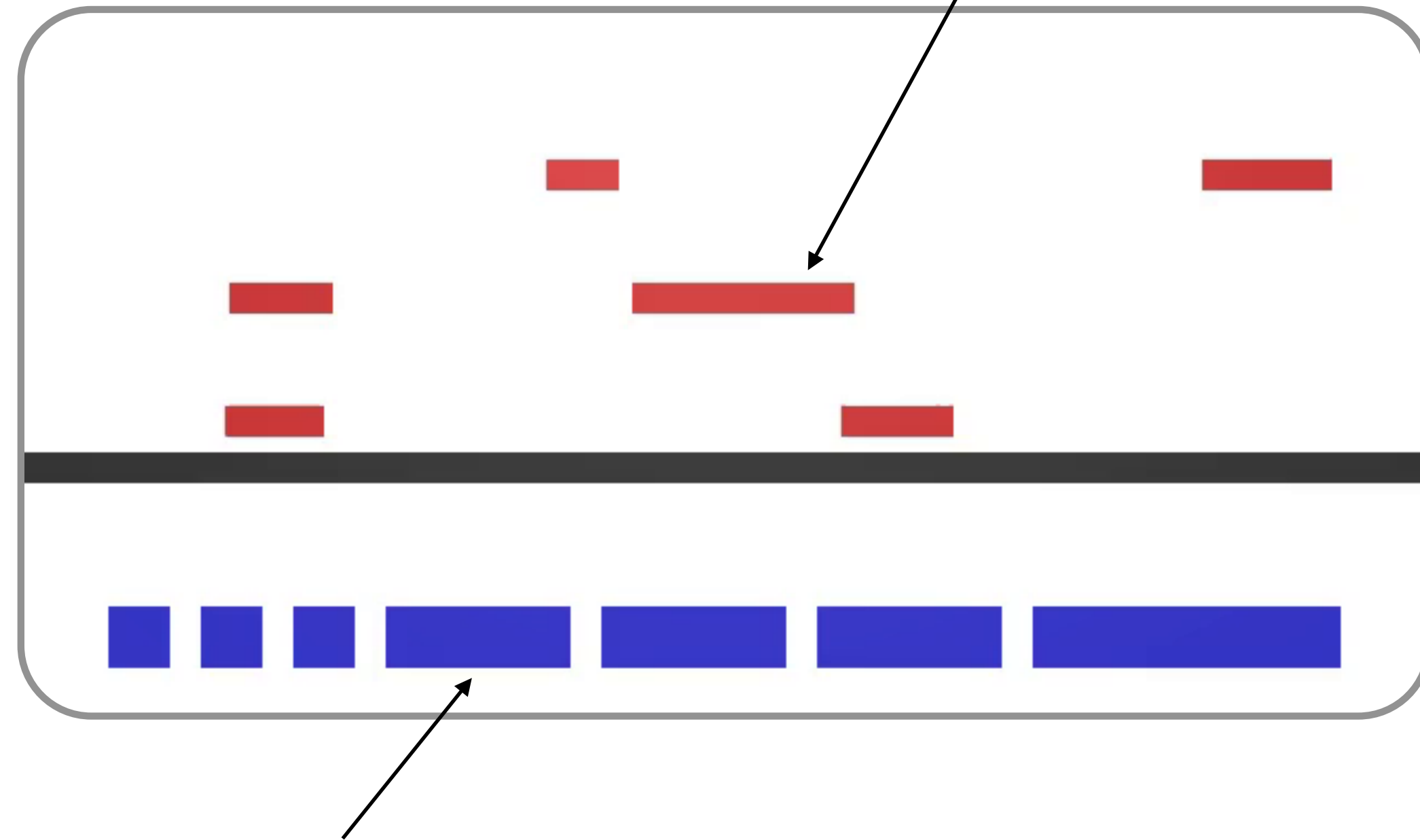
Construction Tasks



Pick up **blocks** and place them in the scene
(and optionally make them **sticky**)

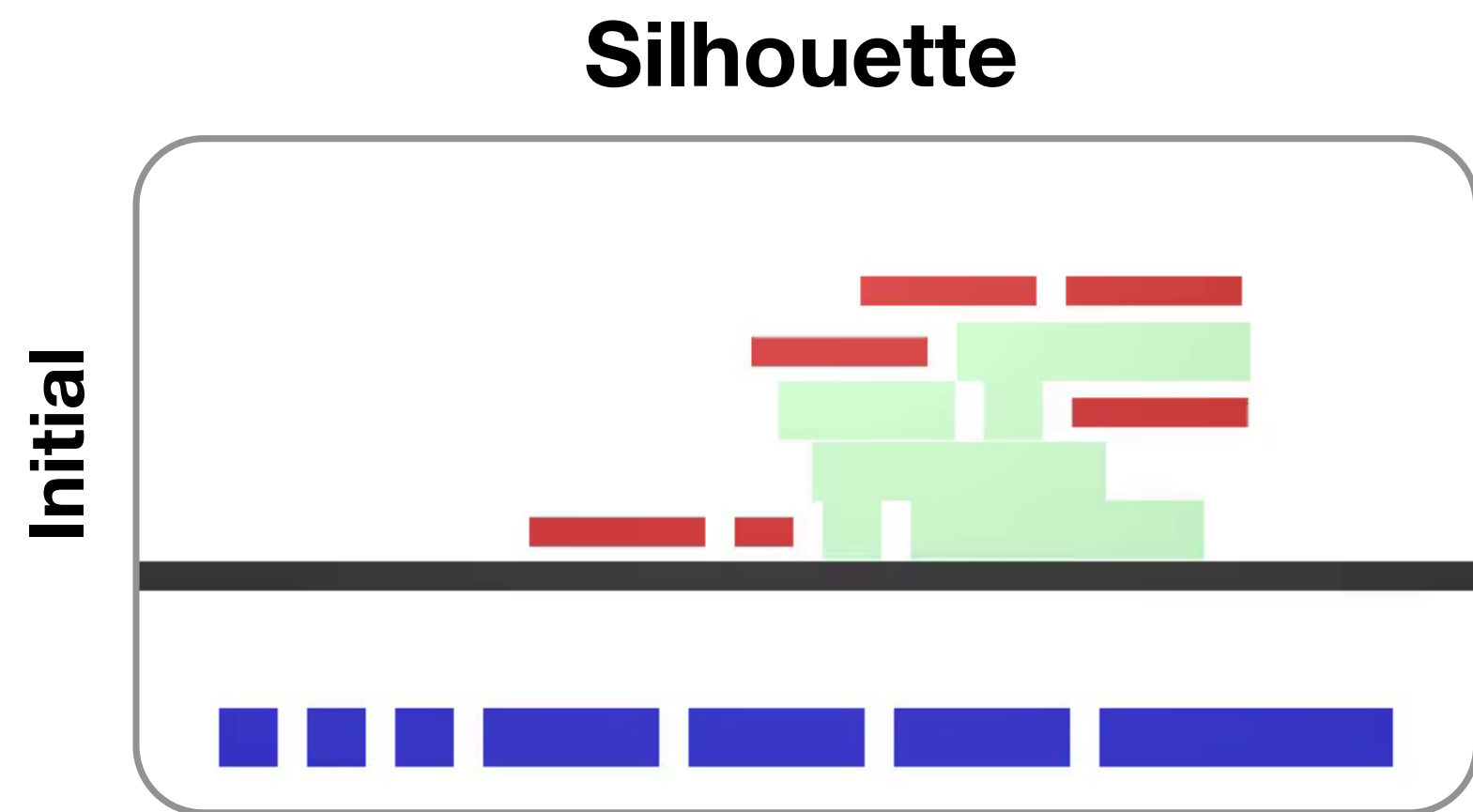
Construction Tasks

Avoid touching **obstacles**

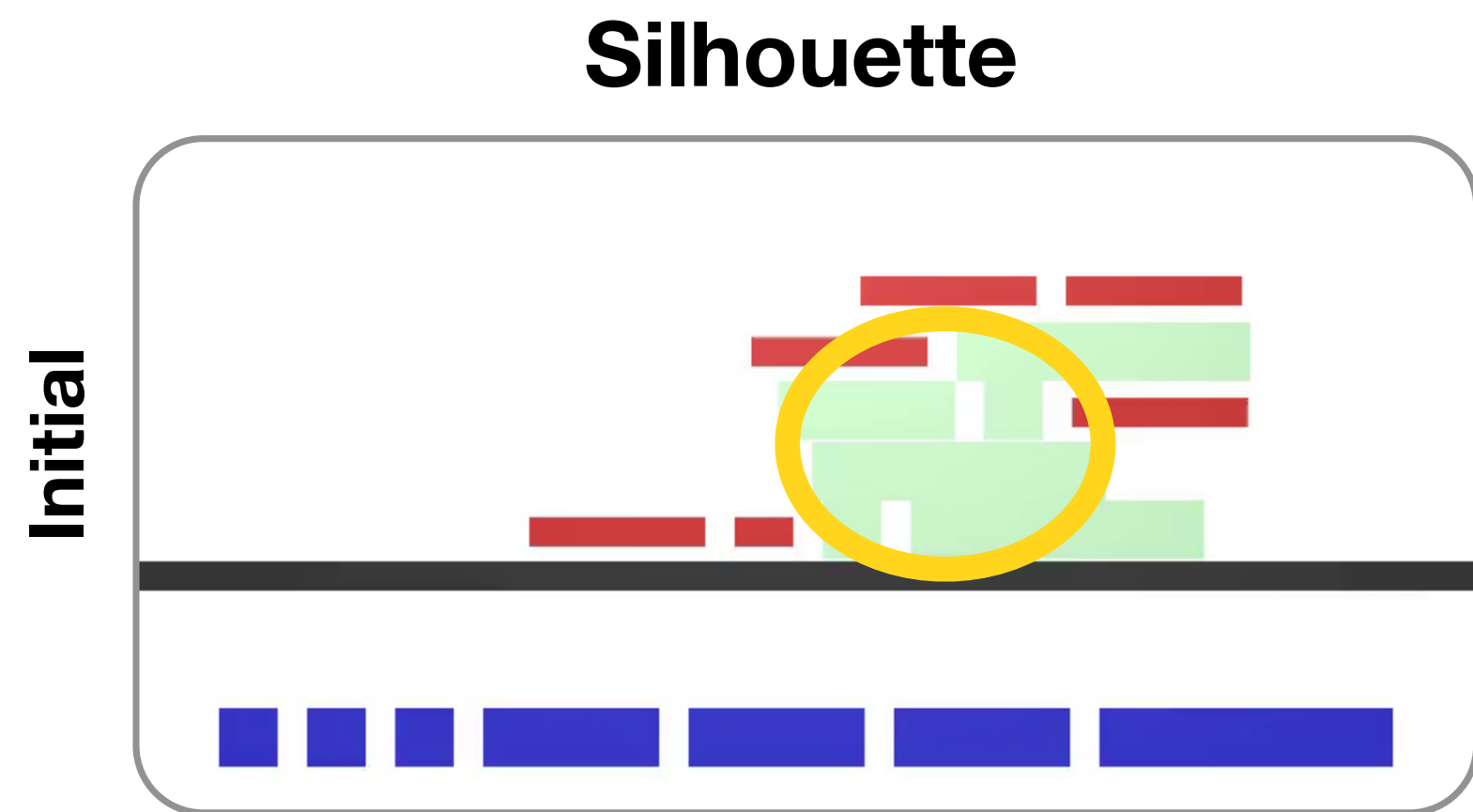


Pick up **blocks** and place them in the scene
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Construction Tasks

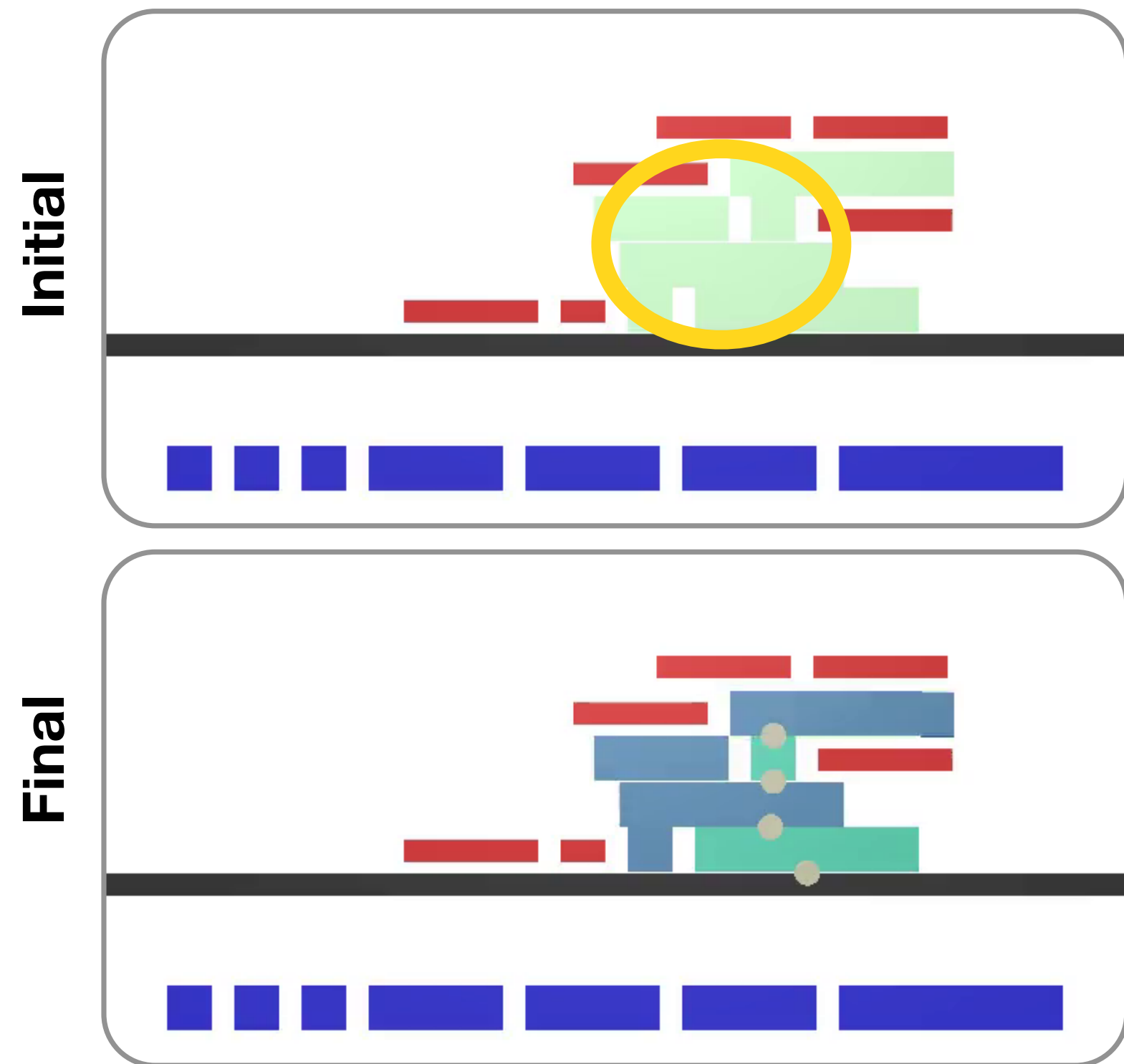


Construction Tasks



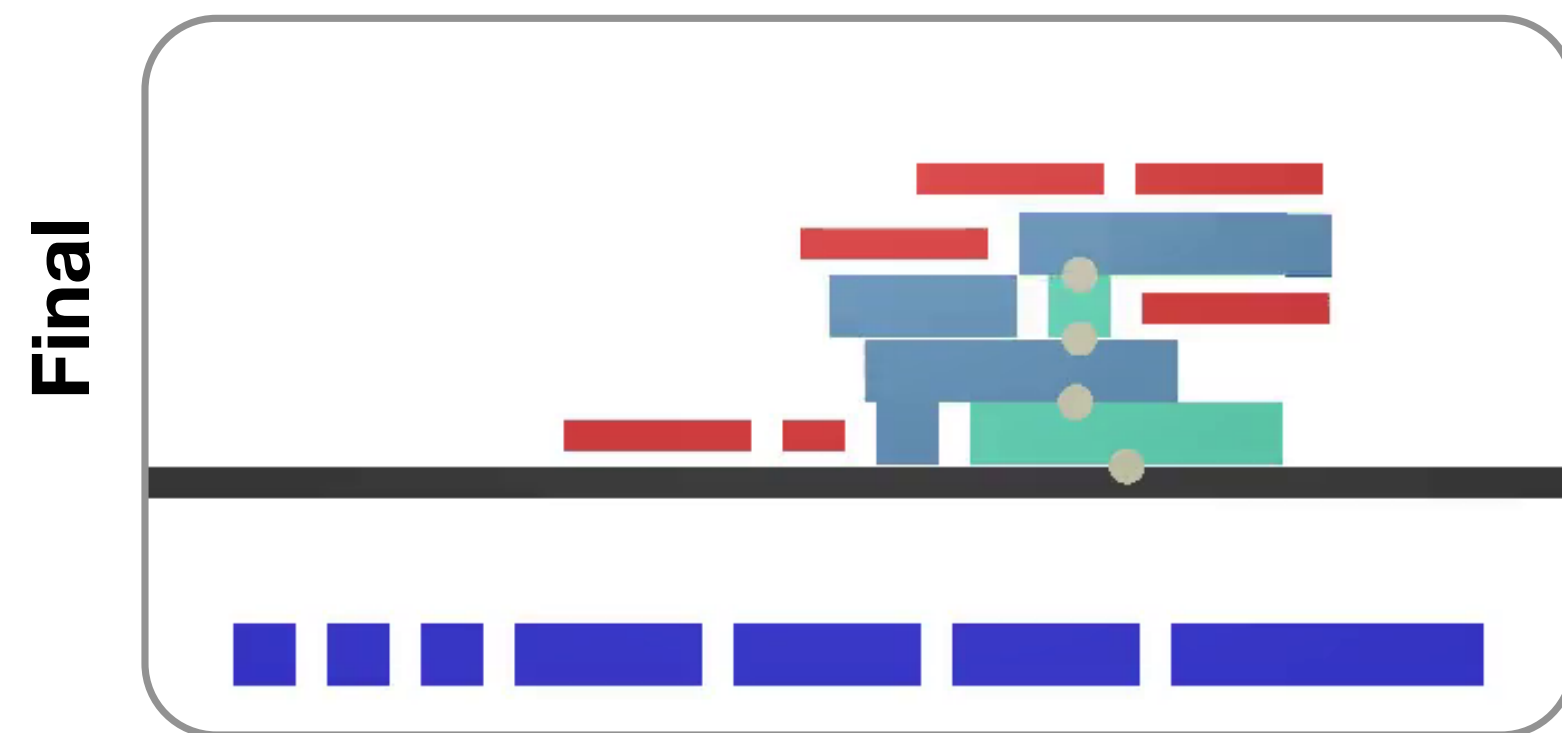
Construction Tasks

Silhouette



Construction Tasks

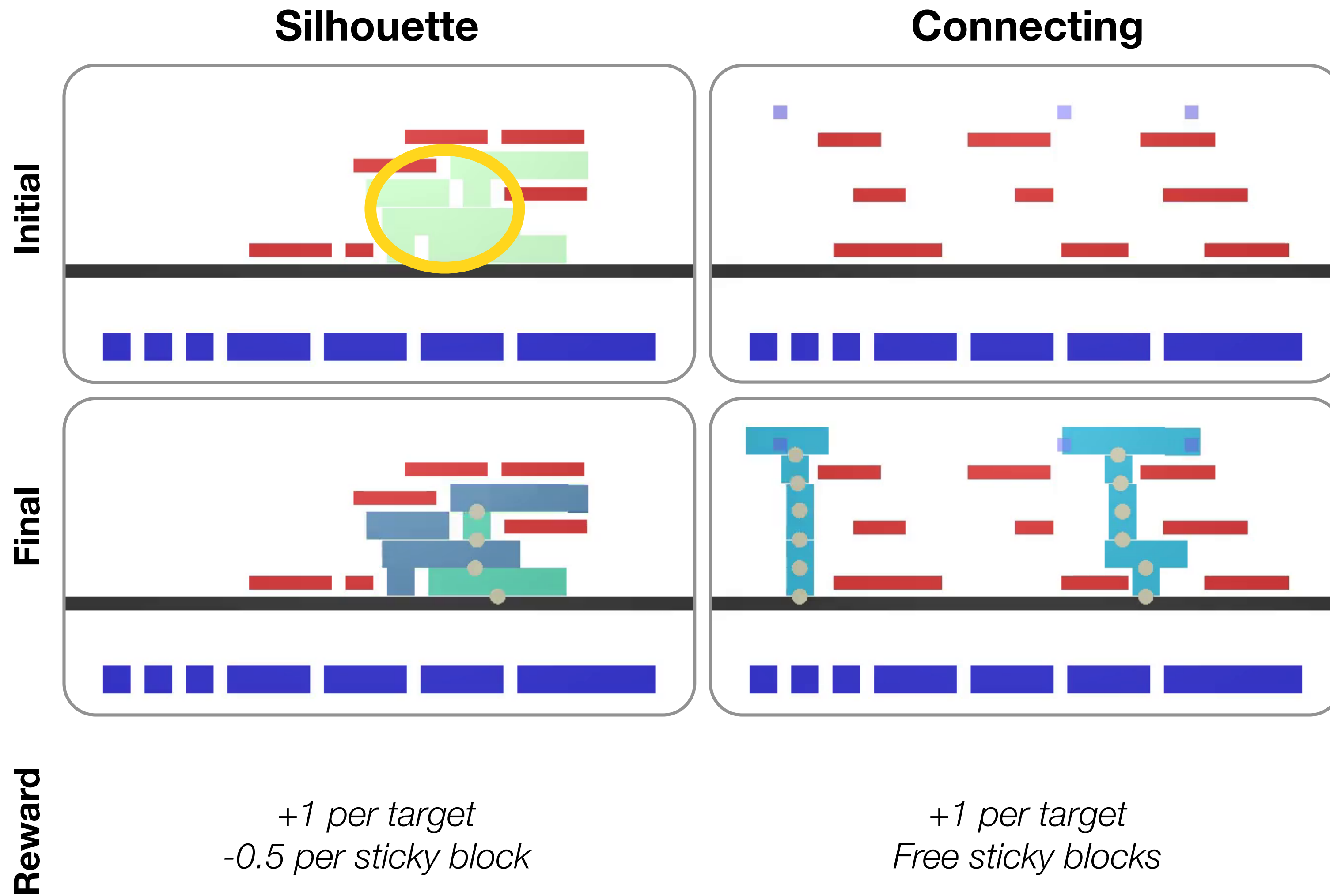
Silhouette



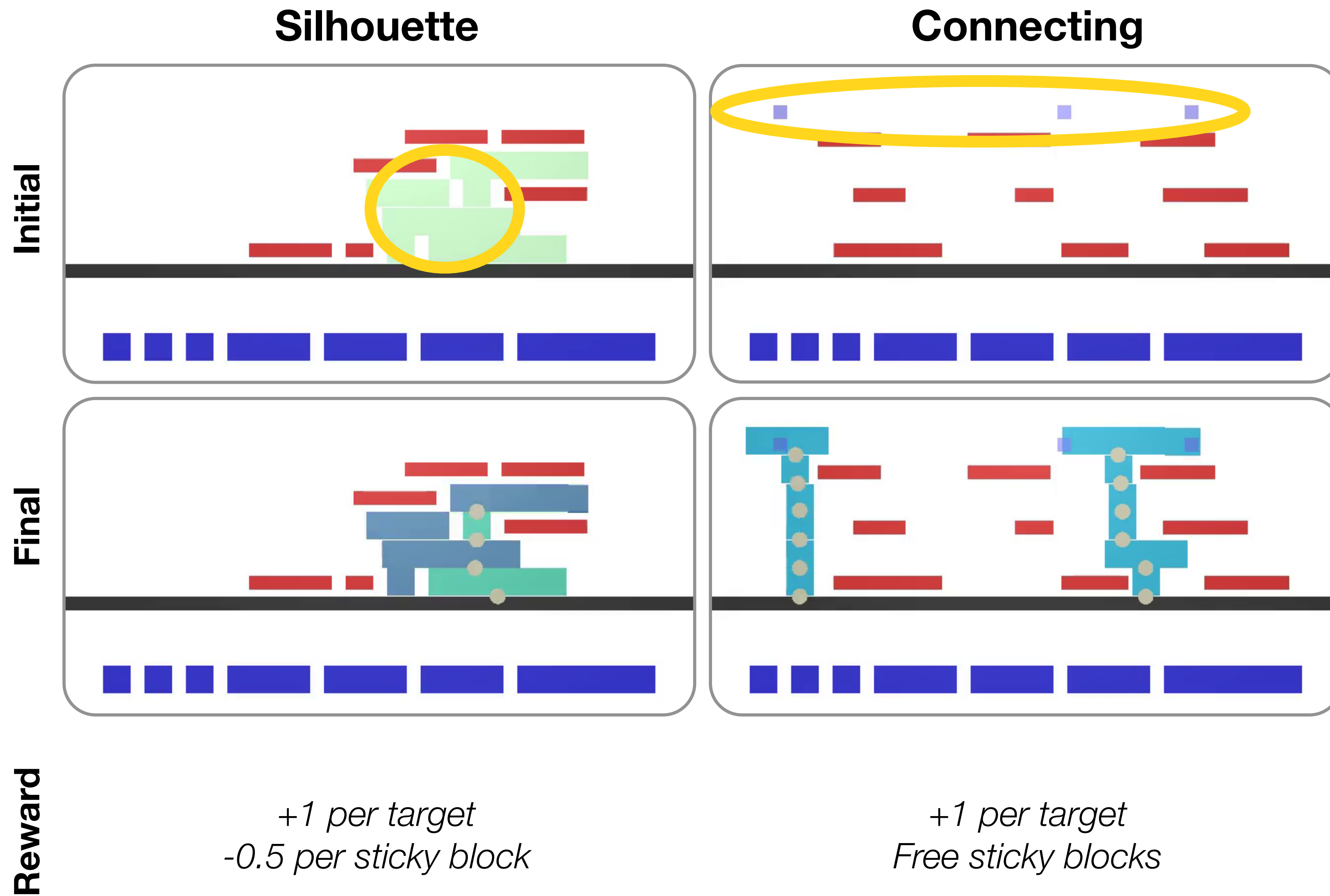
Reward

+1 per target
-0.5 per sticky block

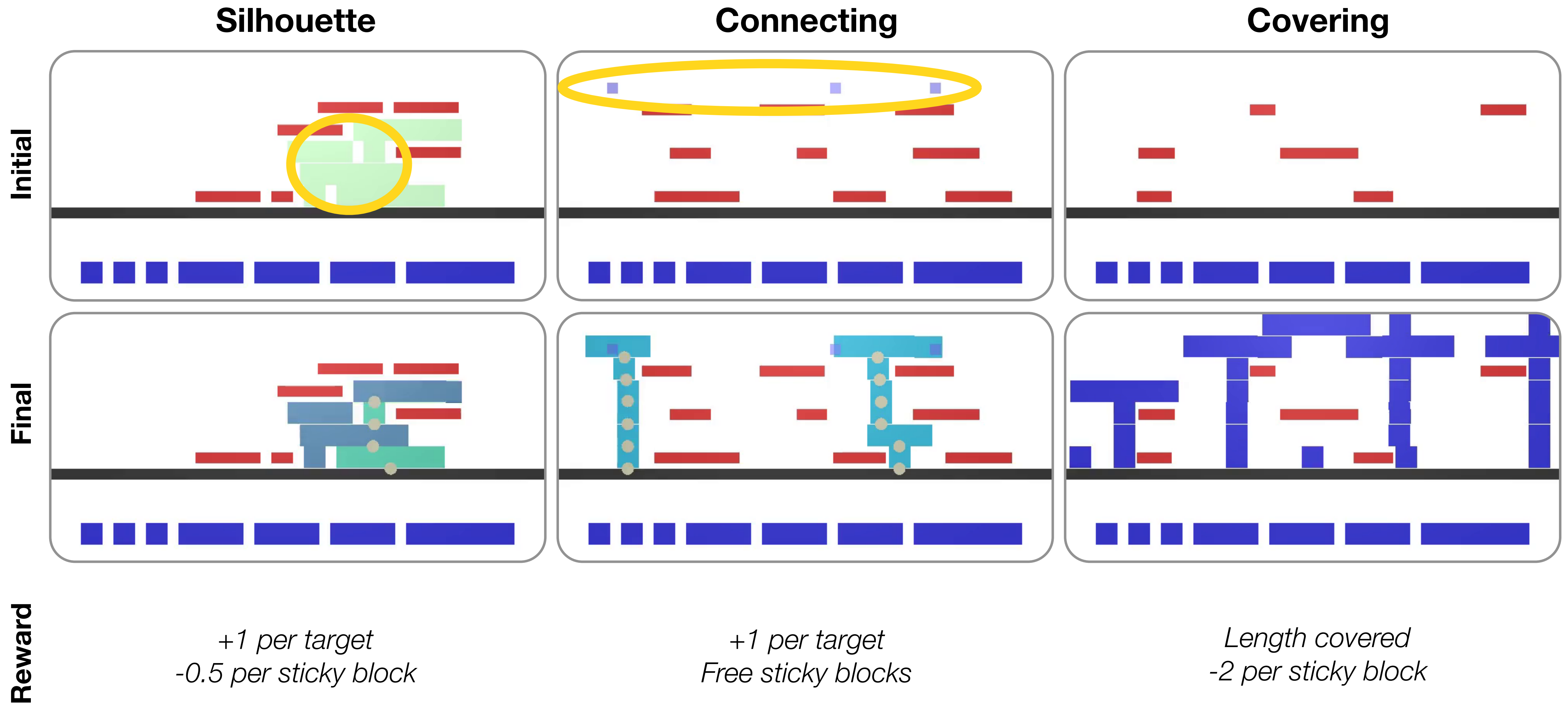
Construction Tasks



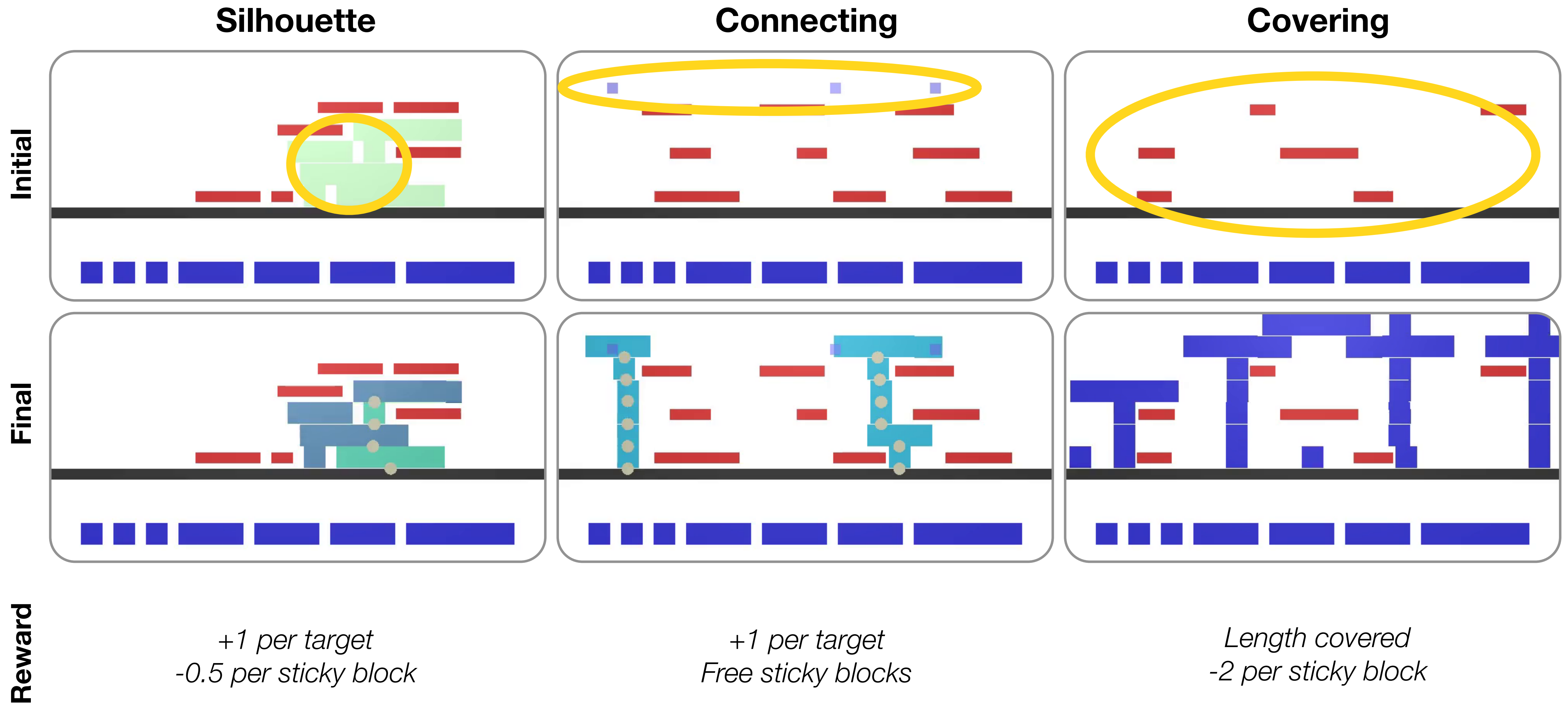
Construction Tasks



Construction Tasks



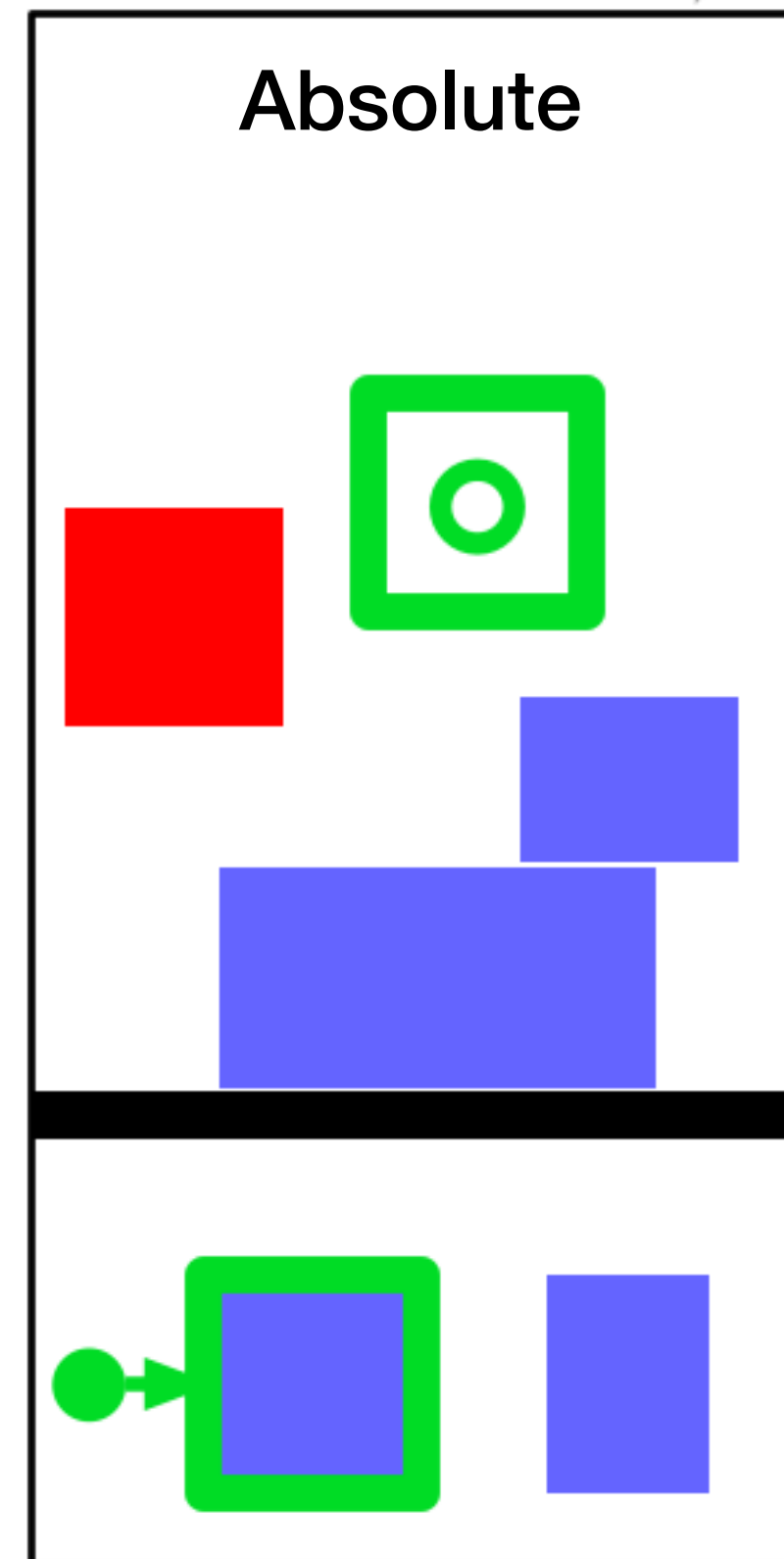
Construction Tasks



Action Format: Absolute vs. Relative

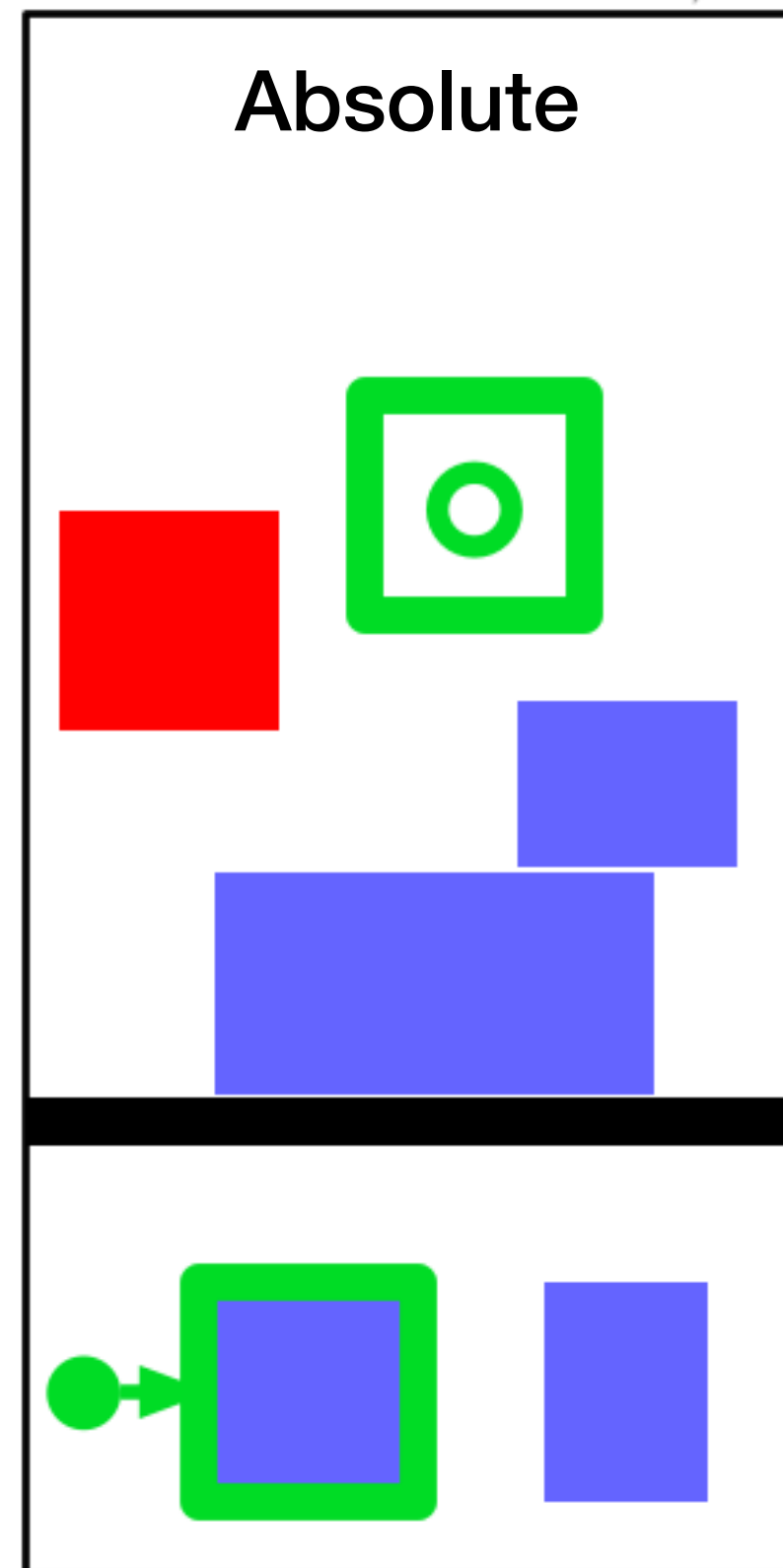
Action Format: Absolute vs. Relative

“Place block D at position (7.2, 8.5)”



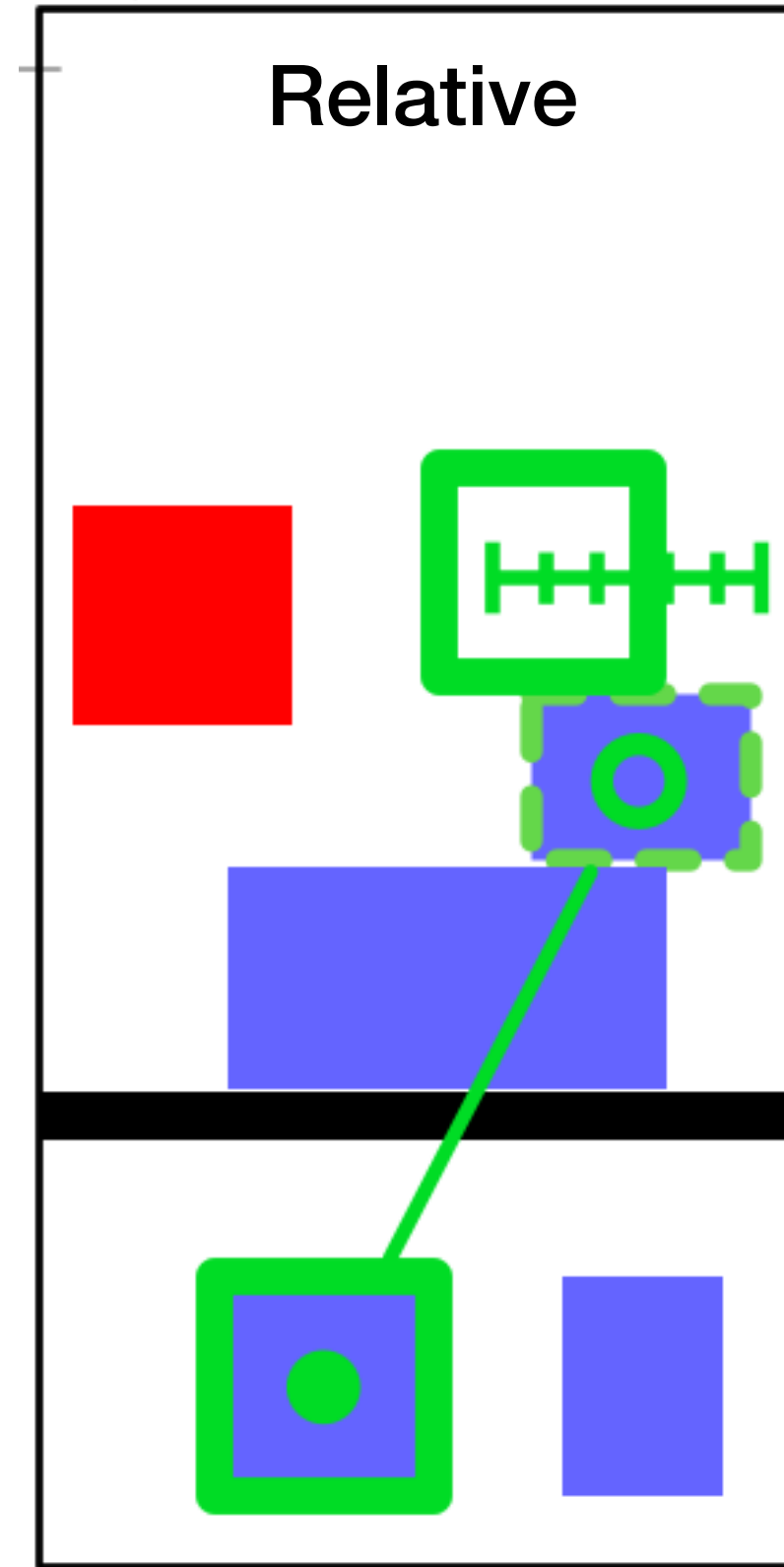
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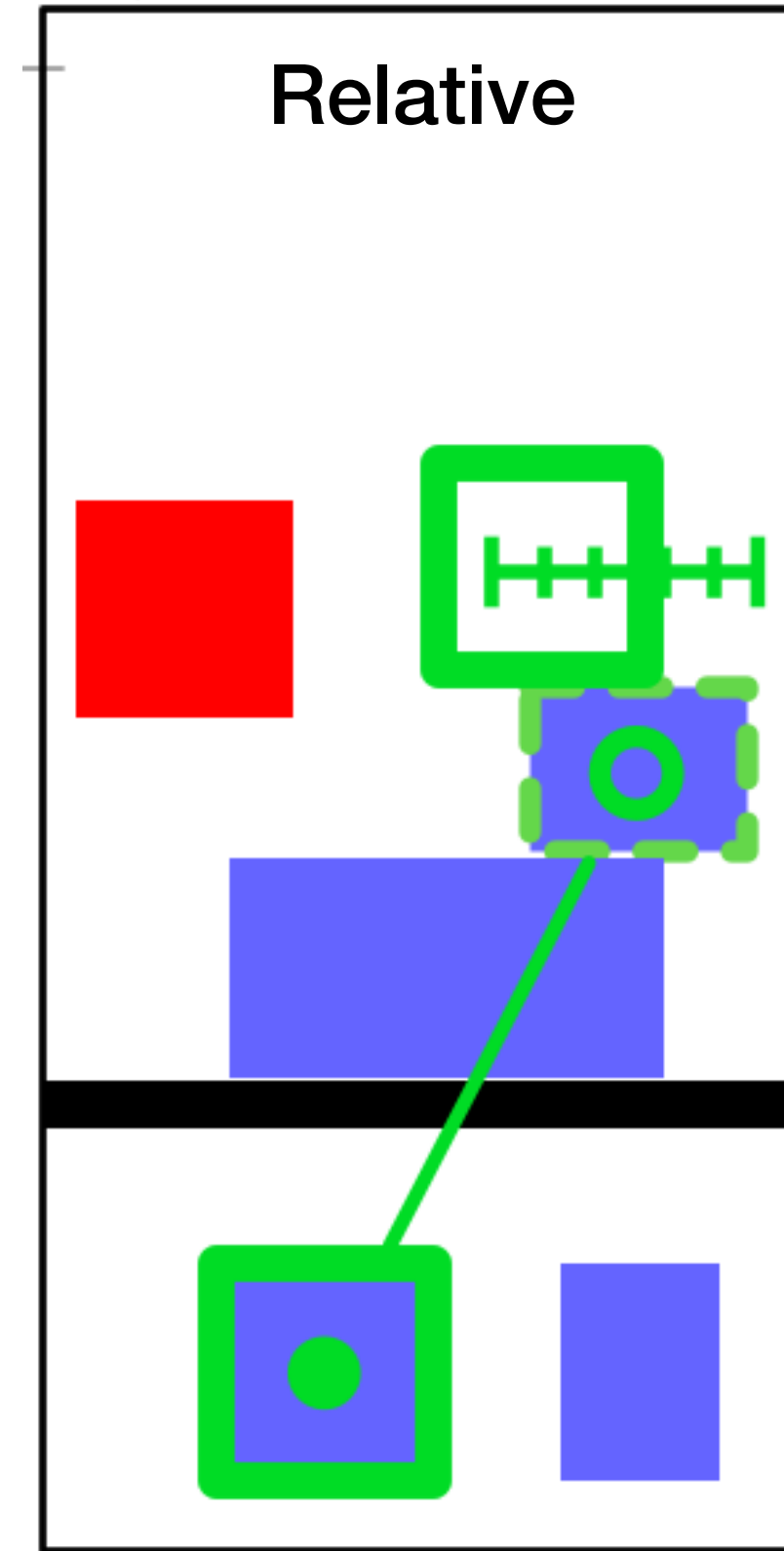
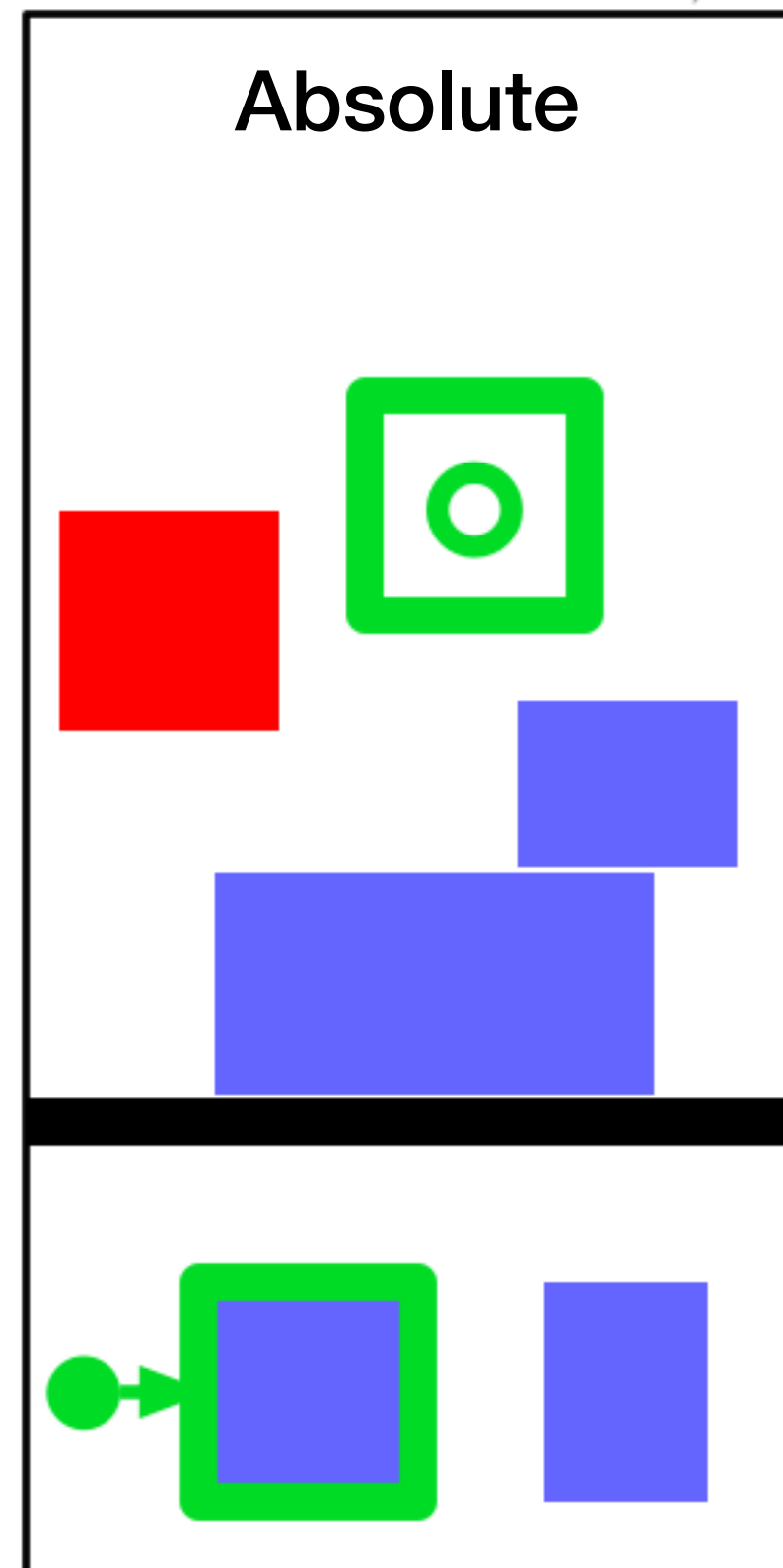
Relative

“Place block D on the top left of block B”

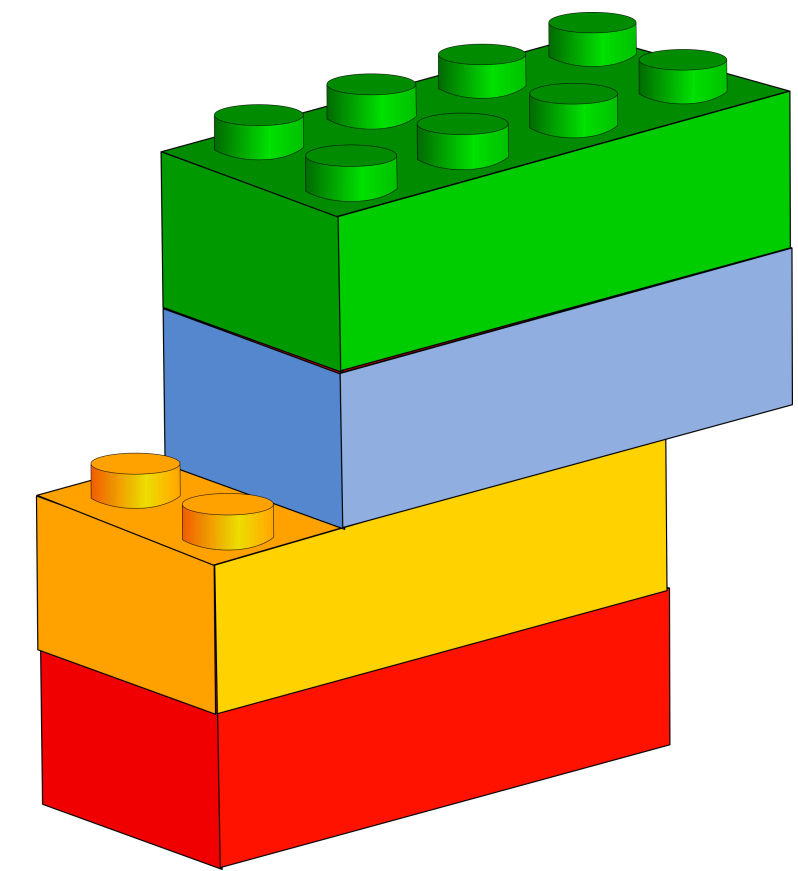


Action Format: Absolute vs. Relative

“Place block D at position (7.2, 8.5)”

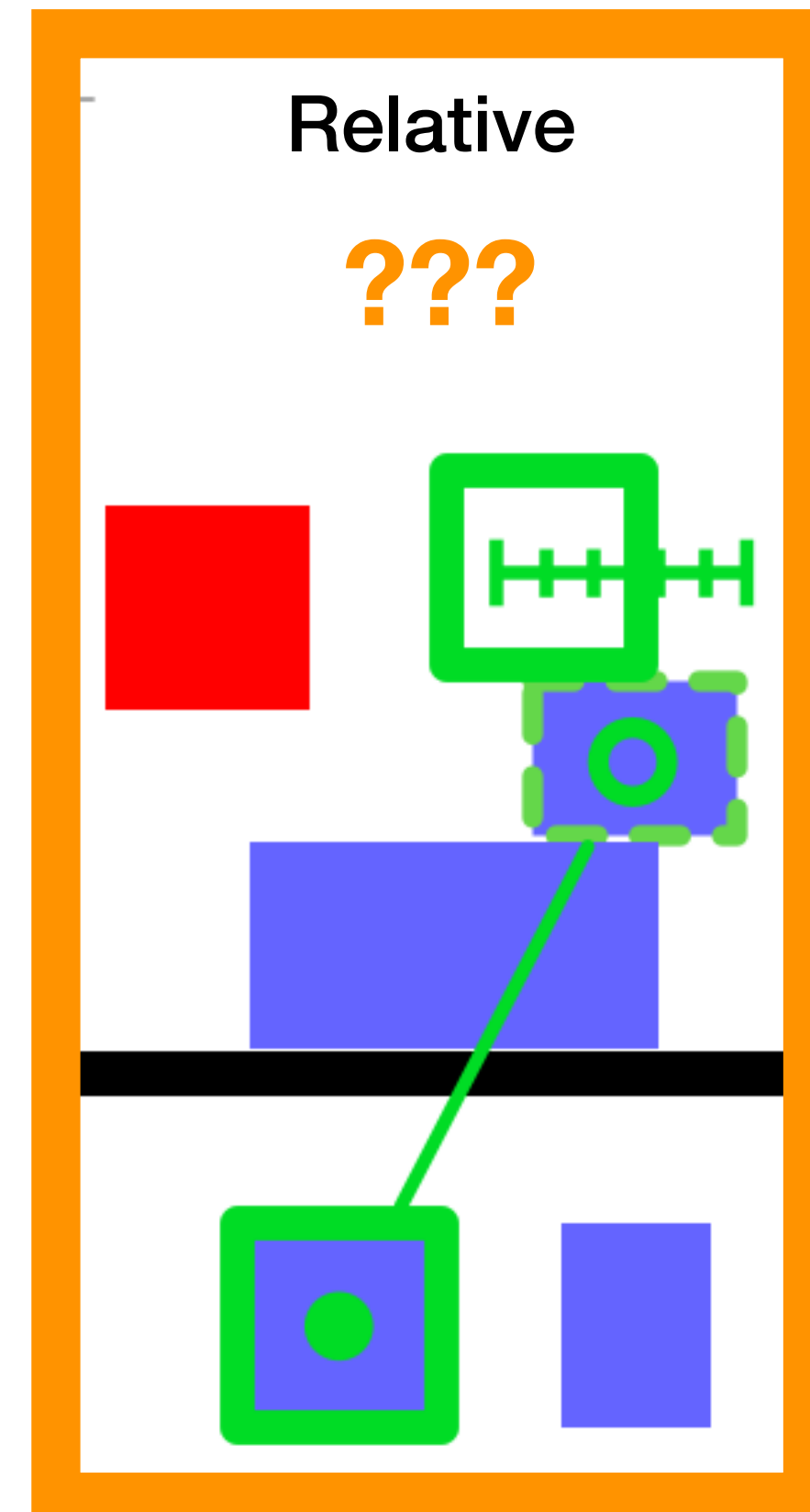
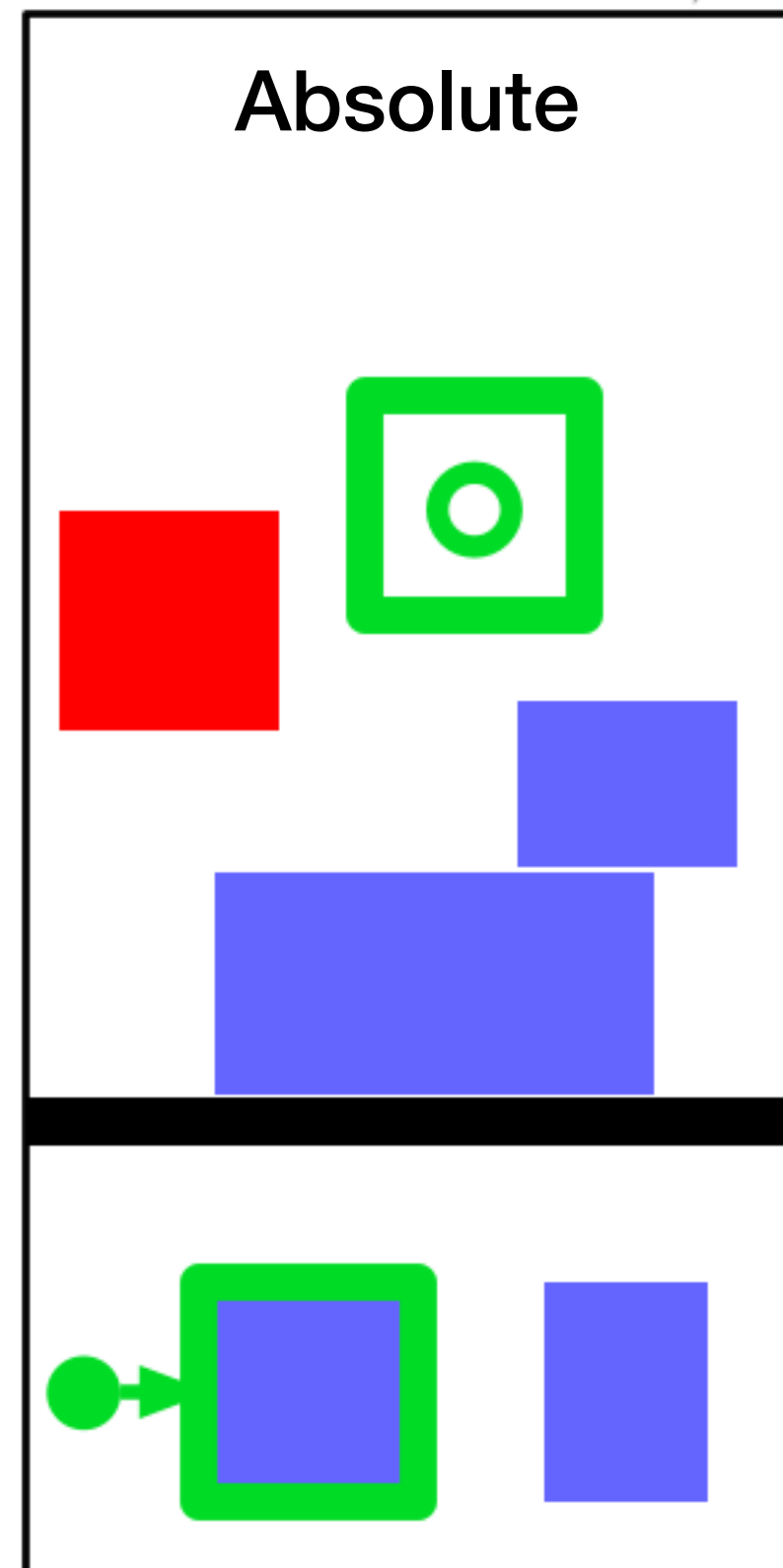


“Place block D on the top left of block B”

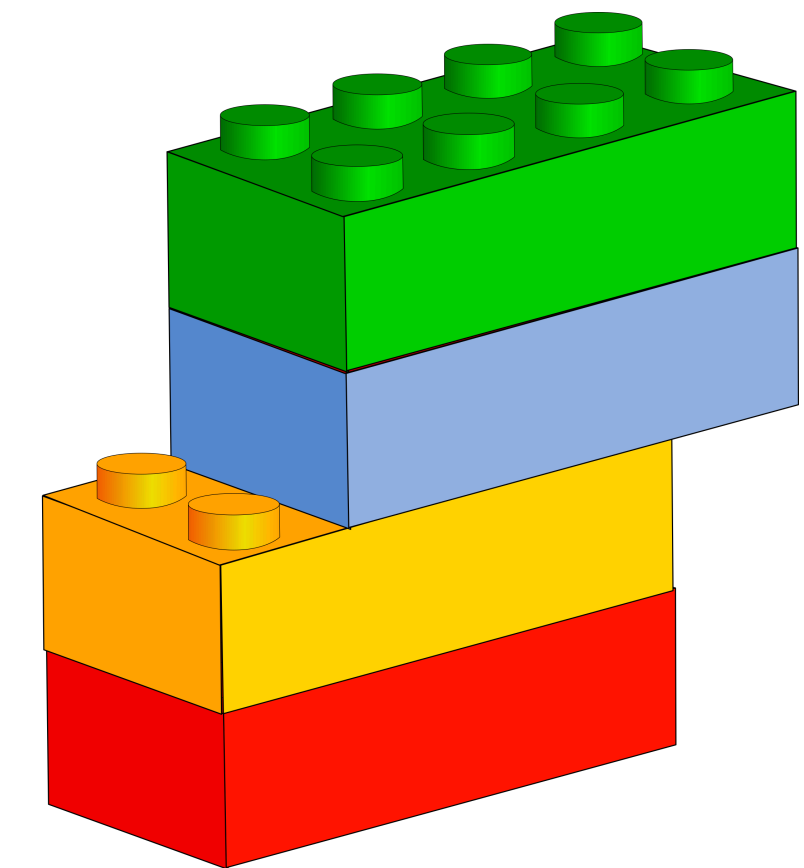


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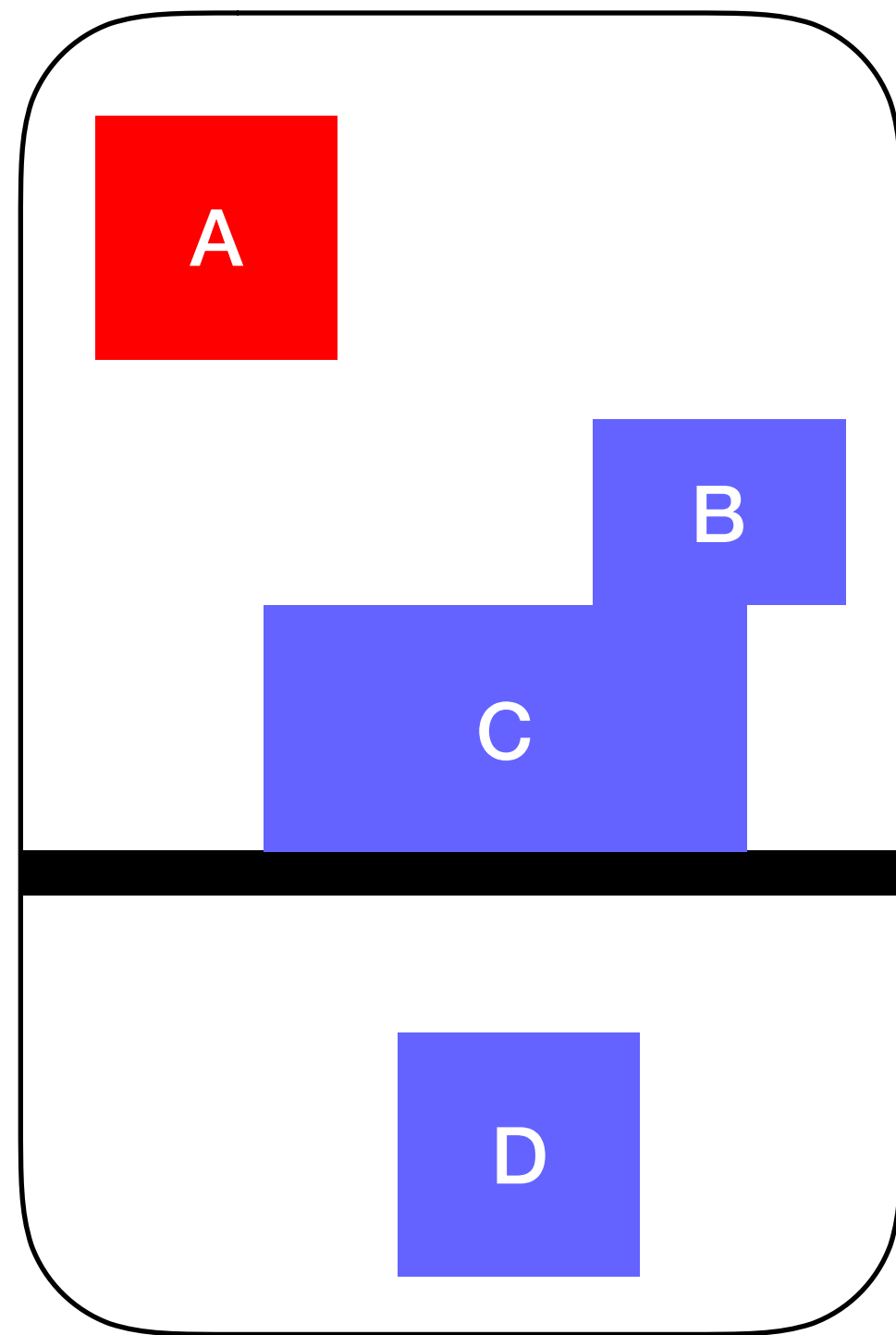


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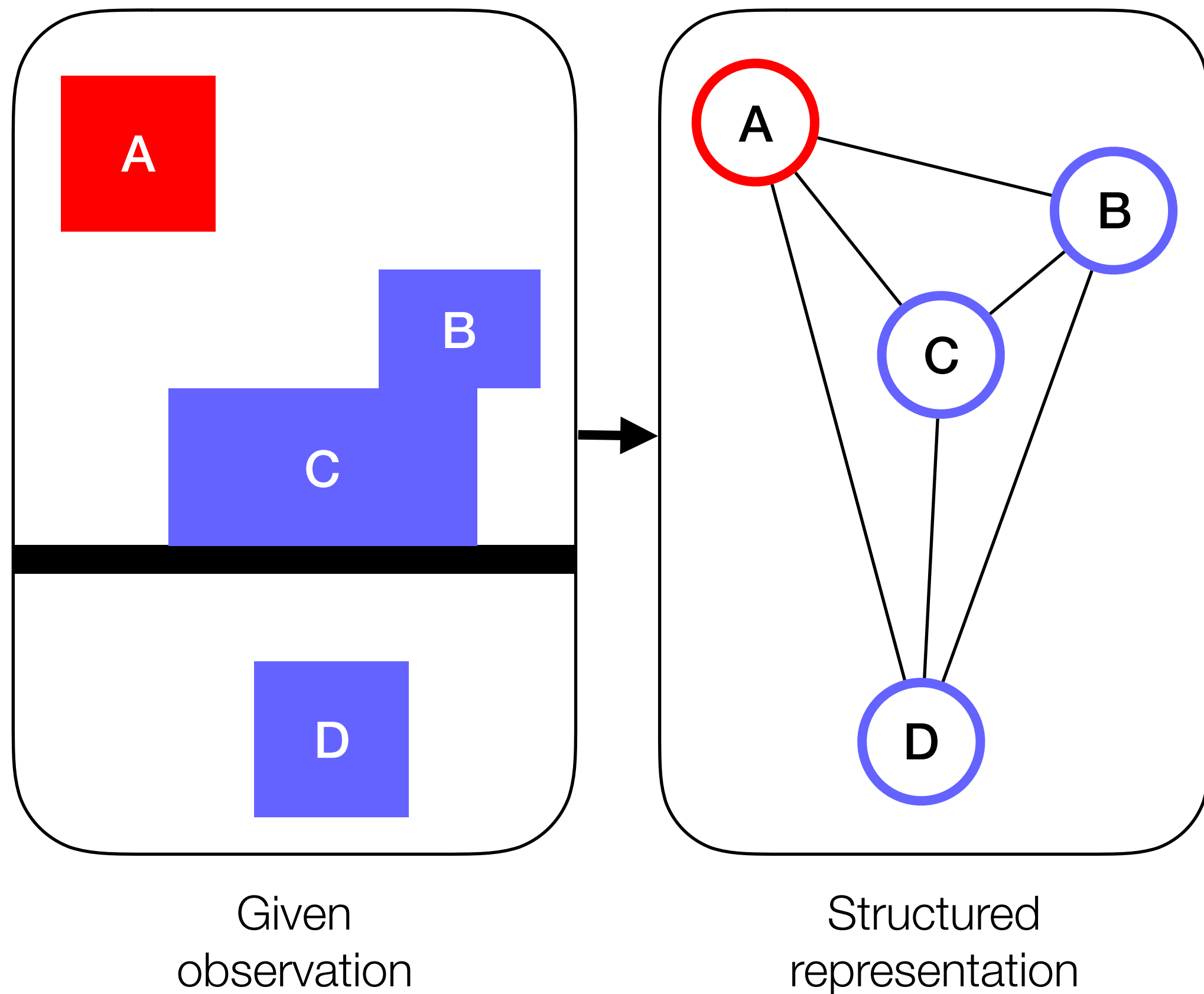
Graph Network Agent (GN-DQN)

Graph Network Agent (GN-DQN)



Given
observation

Graph Network Agent (GN-DQN)

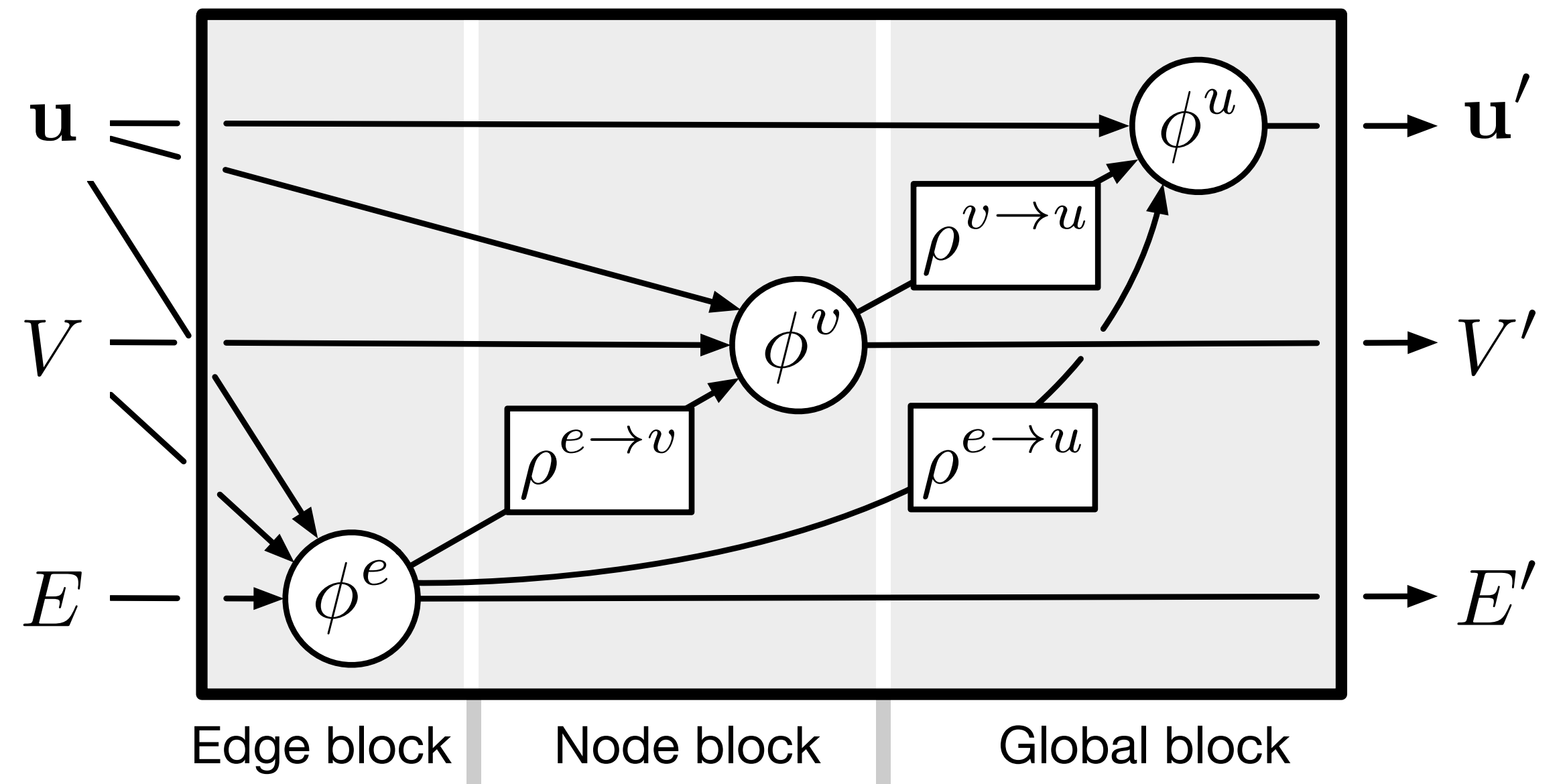


Background: Graph Networks

Graph neural networks: Gori et al. (2005), Scarselli et al. (2005, 2009), Li et al. (2015), Kipf & Welling (2016), Gilmer et al. (2017), many more!

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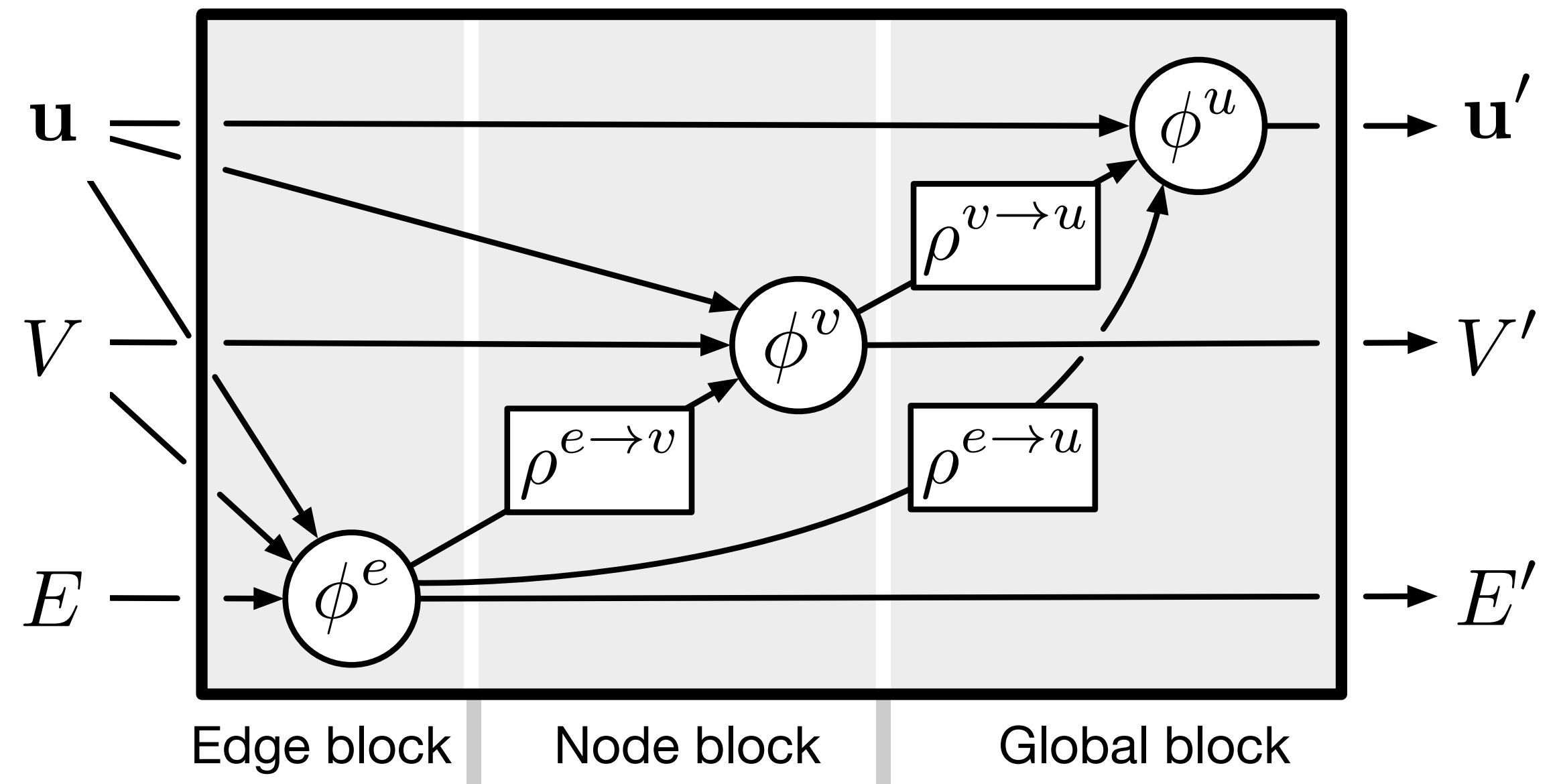


Battaglia, Hamrick, Bapst, Sanchez-Gonzalez, Zambaldi, et al. (*arXiv 2018*)

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1. Takes **graphs** as input, return graphs as output

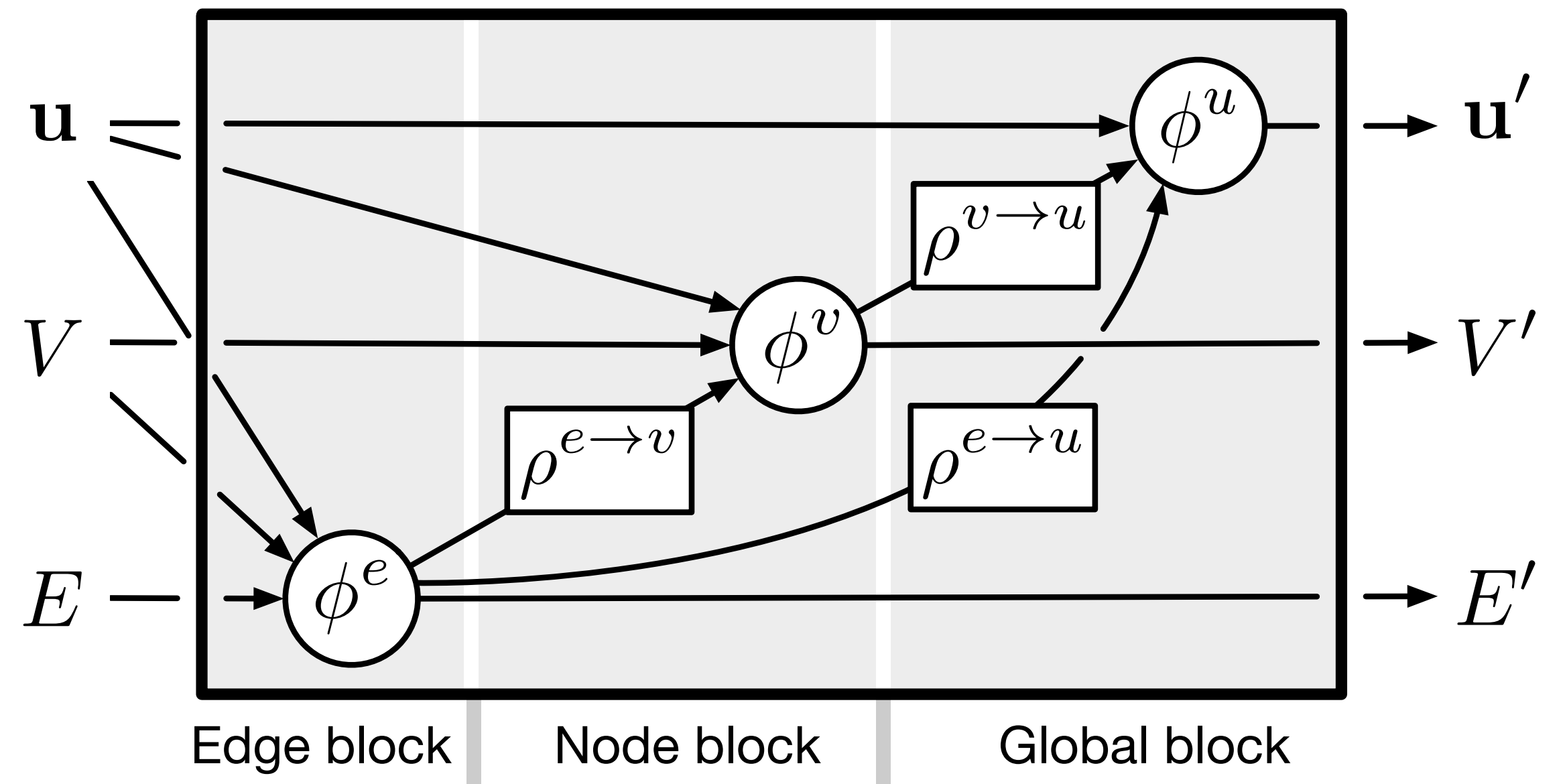


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1. Takes **graphs** as input, return graphs as output
2. Invariant to the **permutation** of the nodes and edges

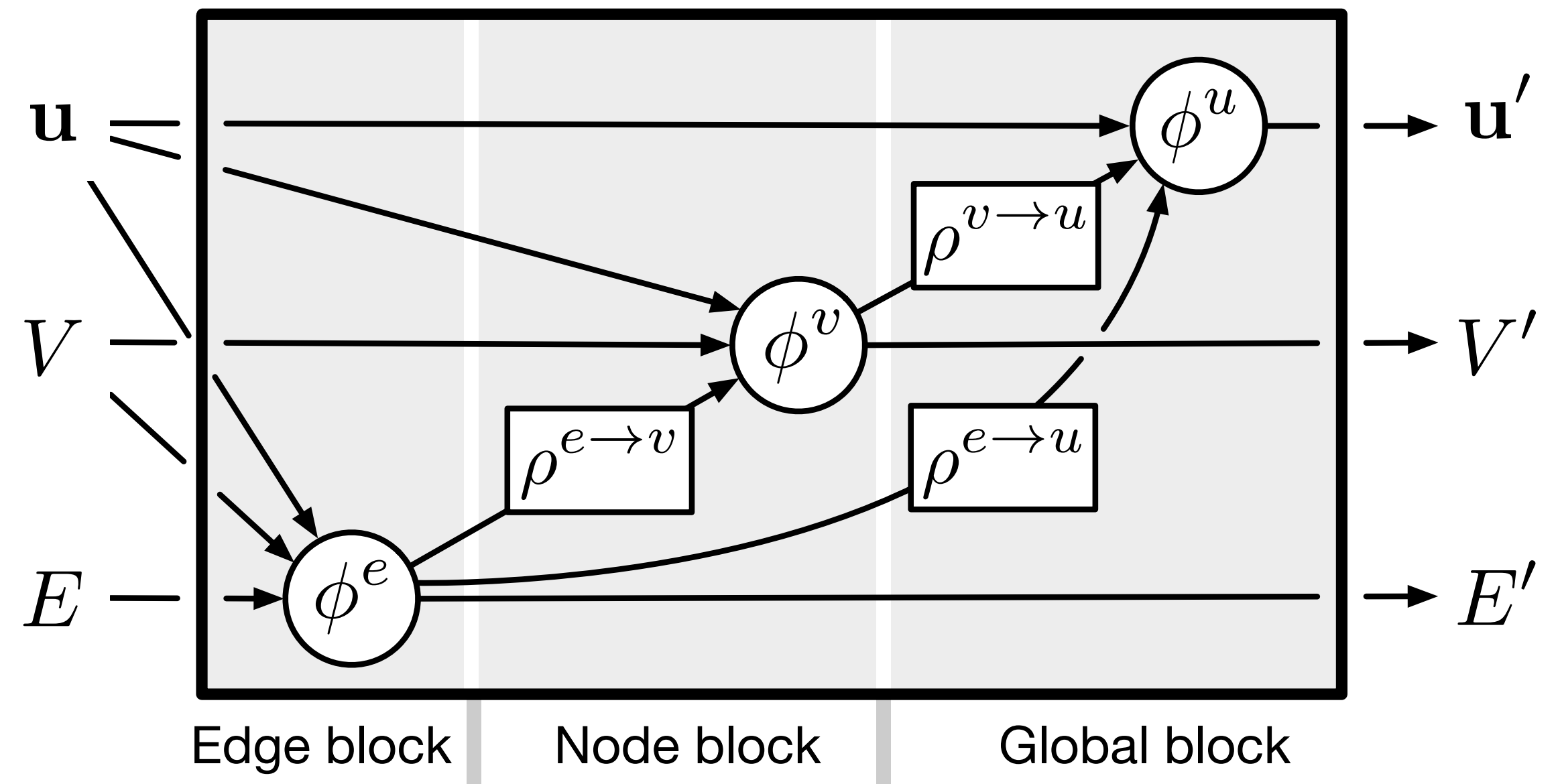


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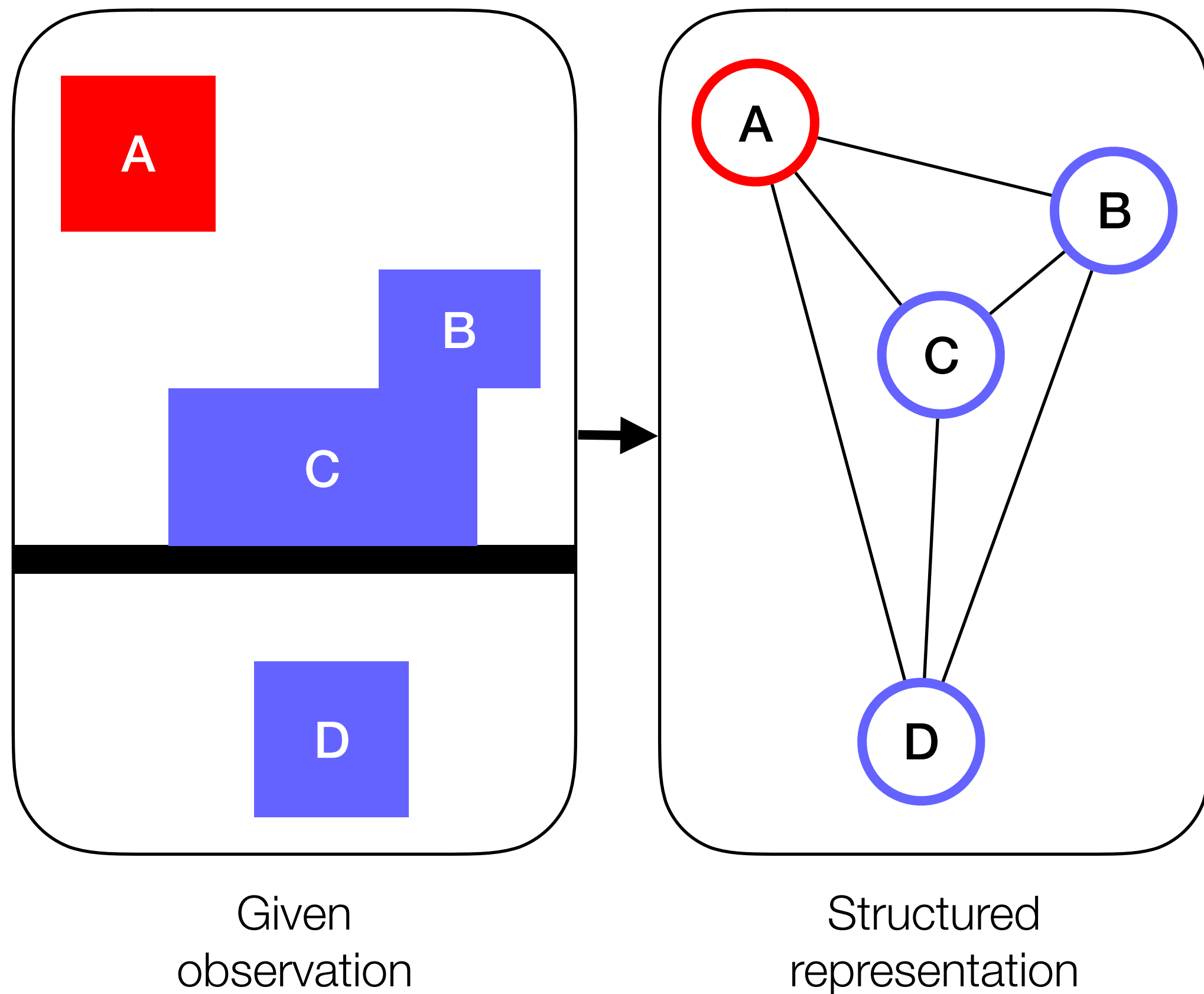
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1. Takes **graphs** as input, return graphs as output
2. Invariant to the **permutation** of the nodes and edges
3. Scales to different **numbers** of nodes and edges

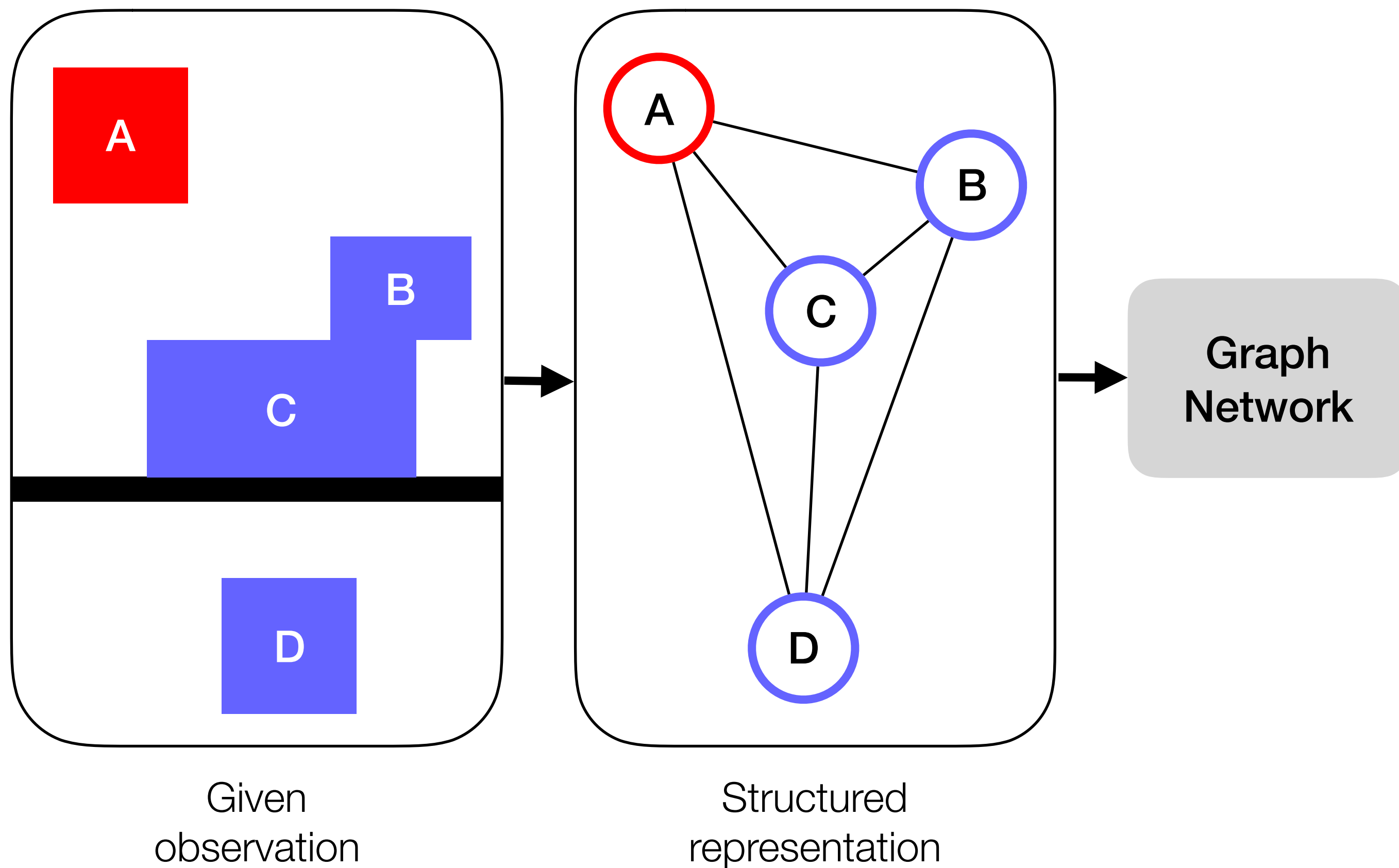


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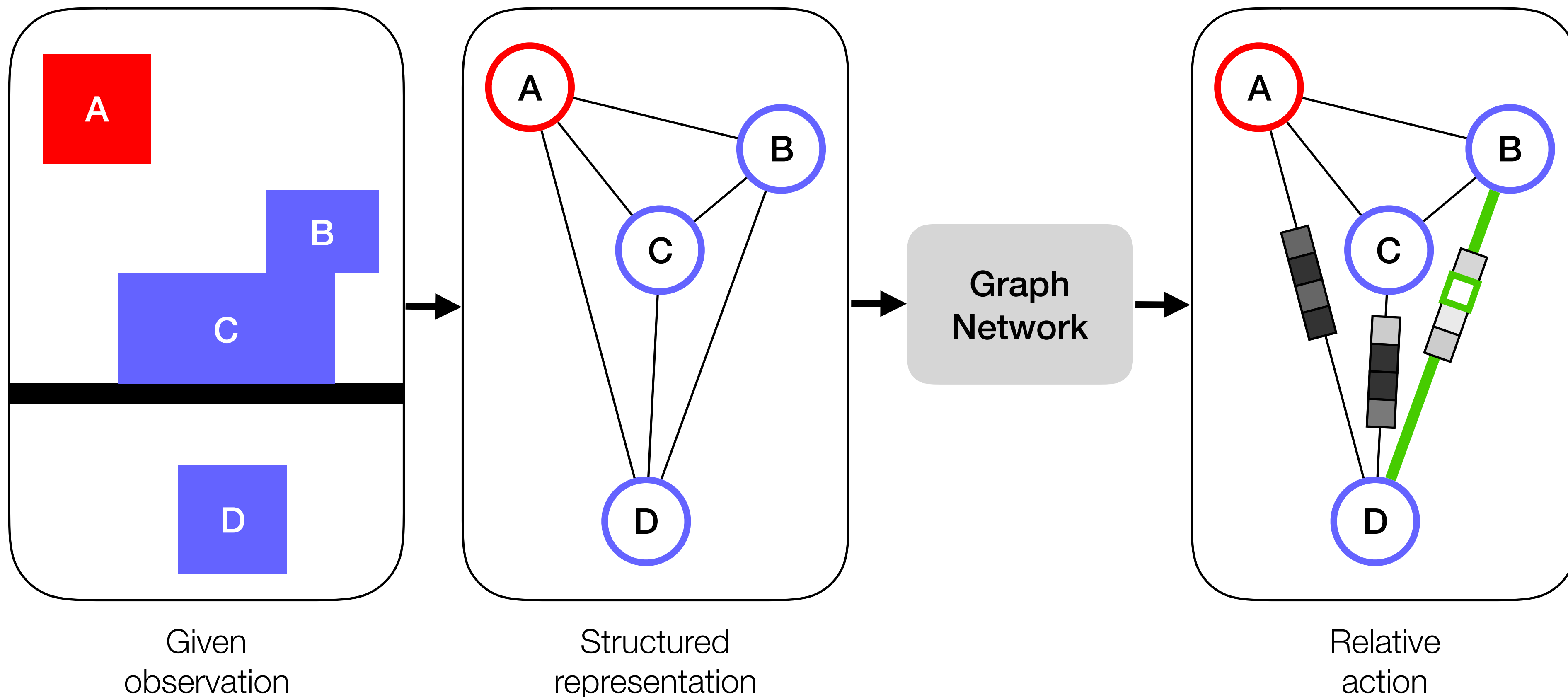
Graph Network Agent (GN-DQN)



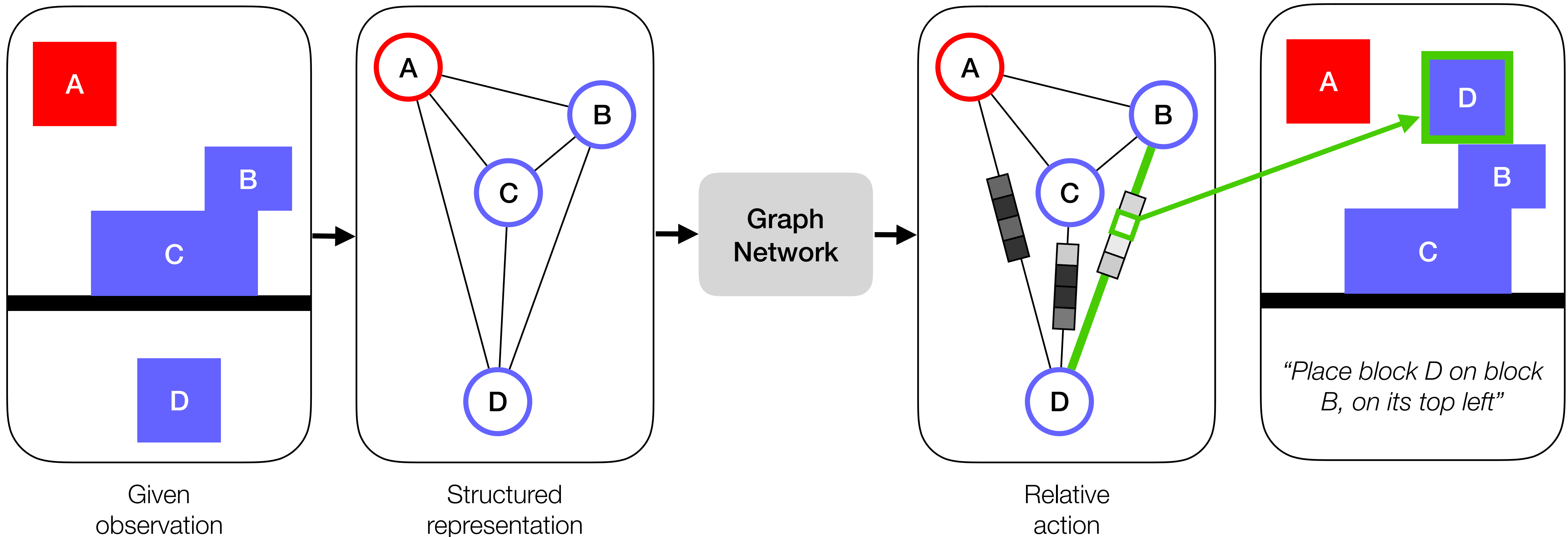
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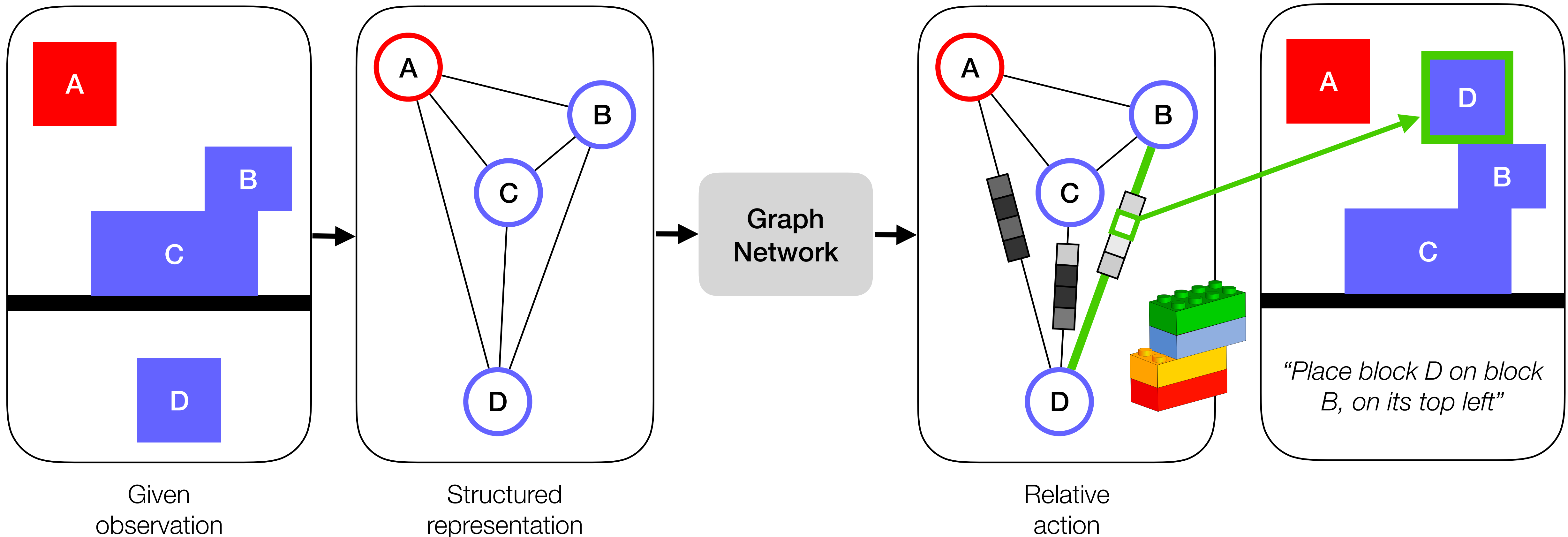
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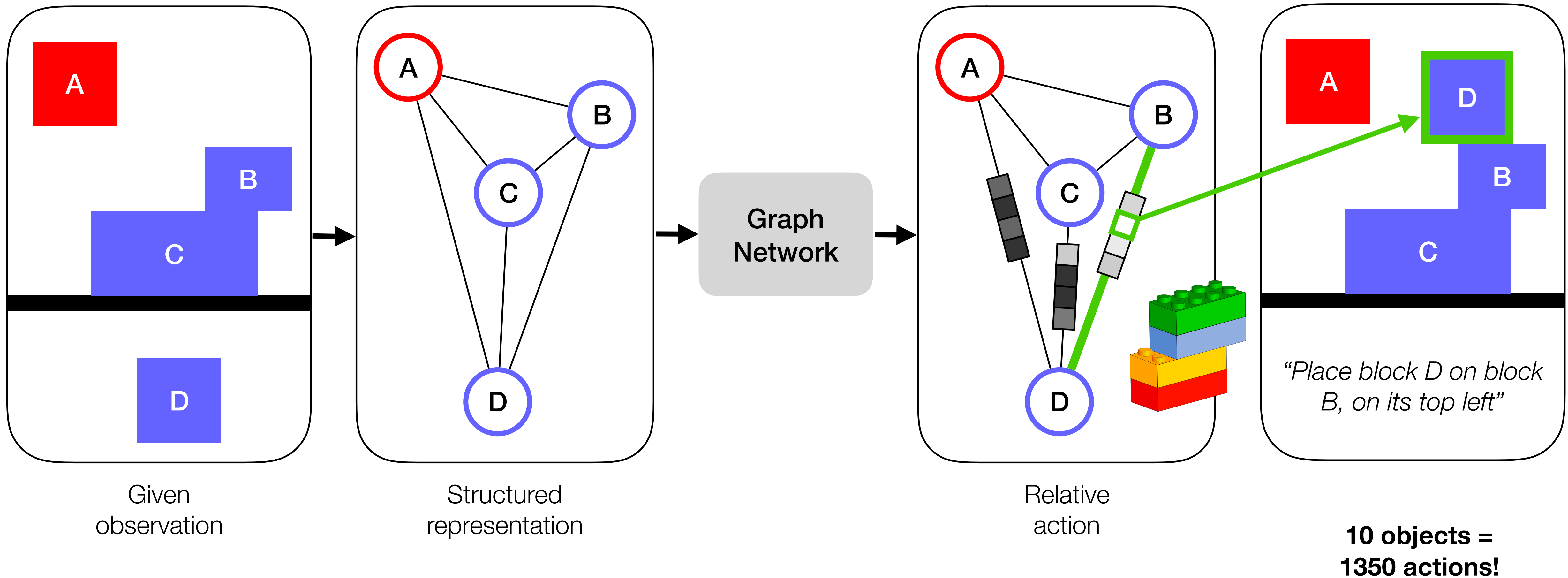
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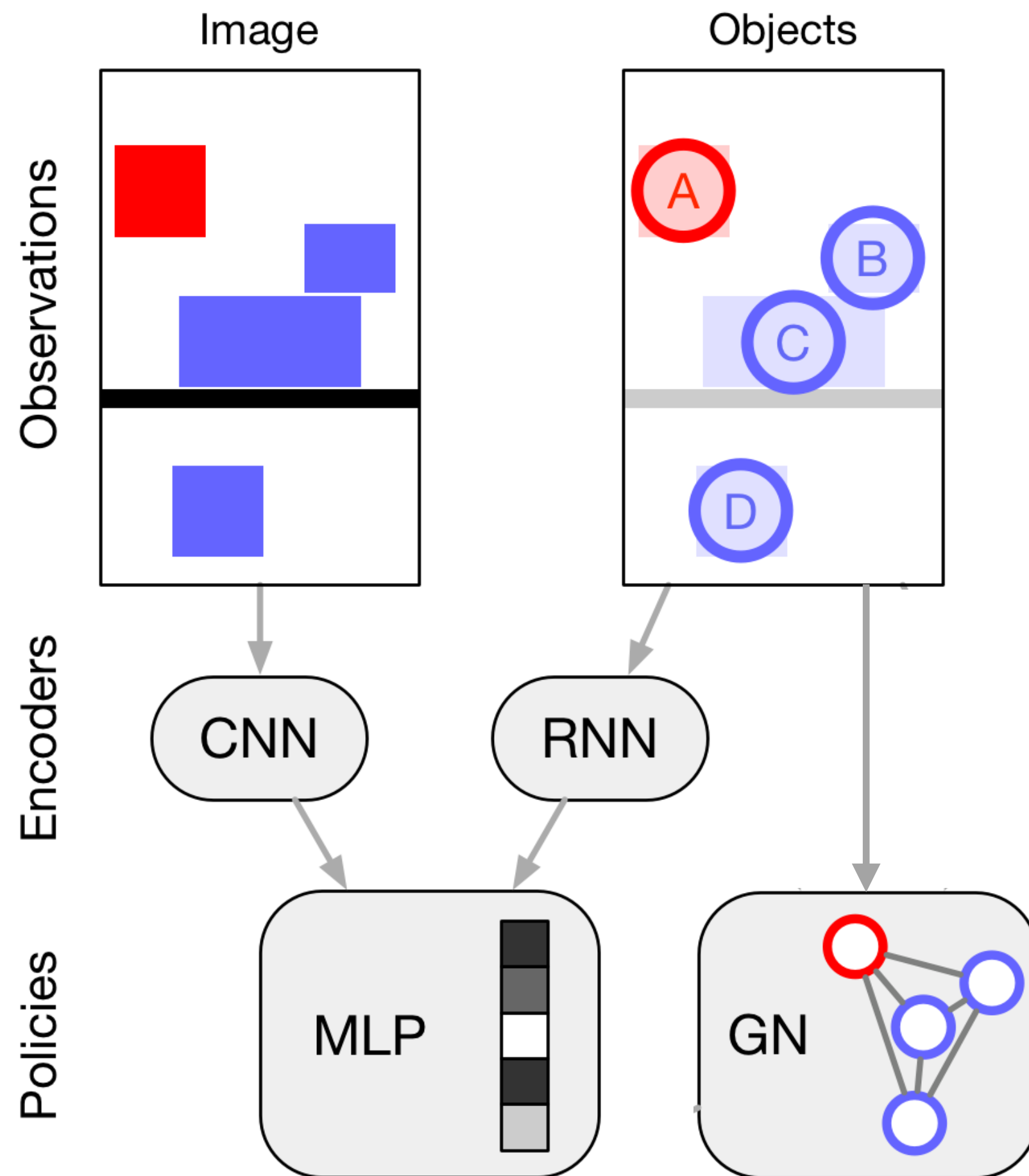
Graph Network Agent (GN-DQN)



Graph Network Agent (GN-DQN)



Baseline Architectures



Agent	Obs.	Encoder	Policy	Learning Algorithm	Actions
GN-DQN	Objects	-	GN	DQN	Discrete
GN-RS0	Objects	-	GN	RS0	Continuous
RNN-RS0	Objects	RNN	MLP	RS0	Continuous
CNN-RS0	Image	CNN	MLP	RS0	Continuous

Key Questions

Key Questions

1. What is the contribution of *relative* vs. absolute actions?

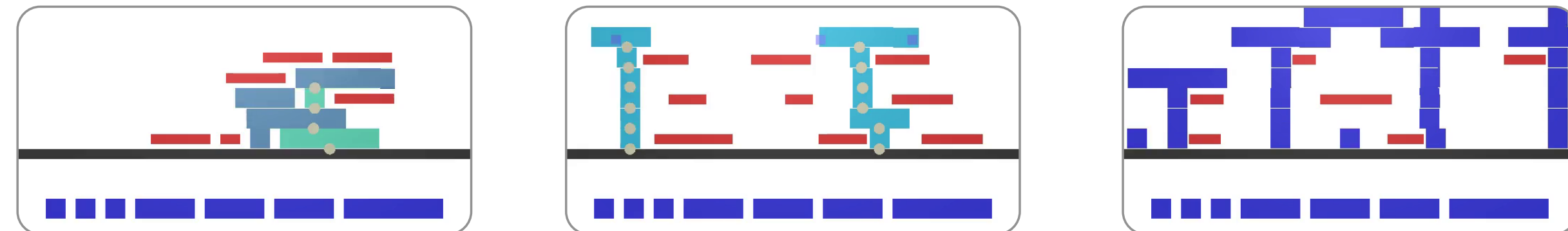
Key Questions

1. What is the contribution of *relative* vs. absolute actions?
2. What is the contribution of *structured* representations?

Key Questions

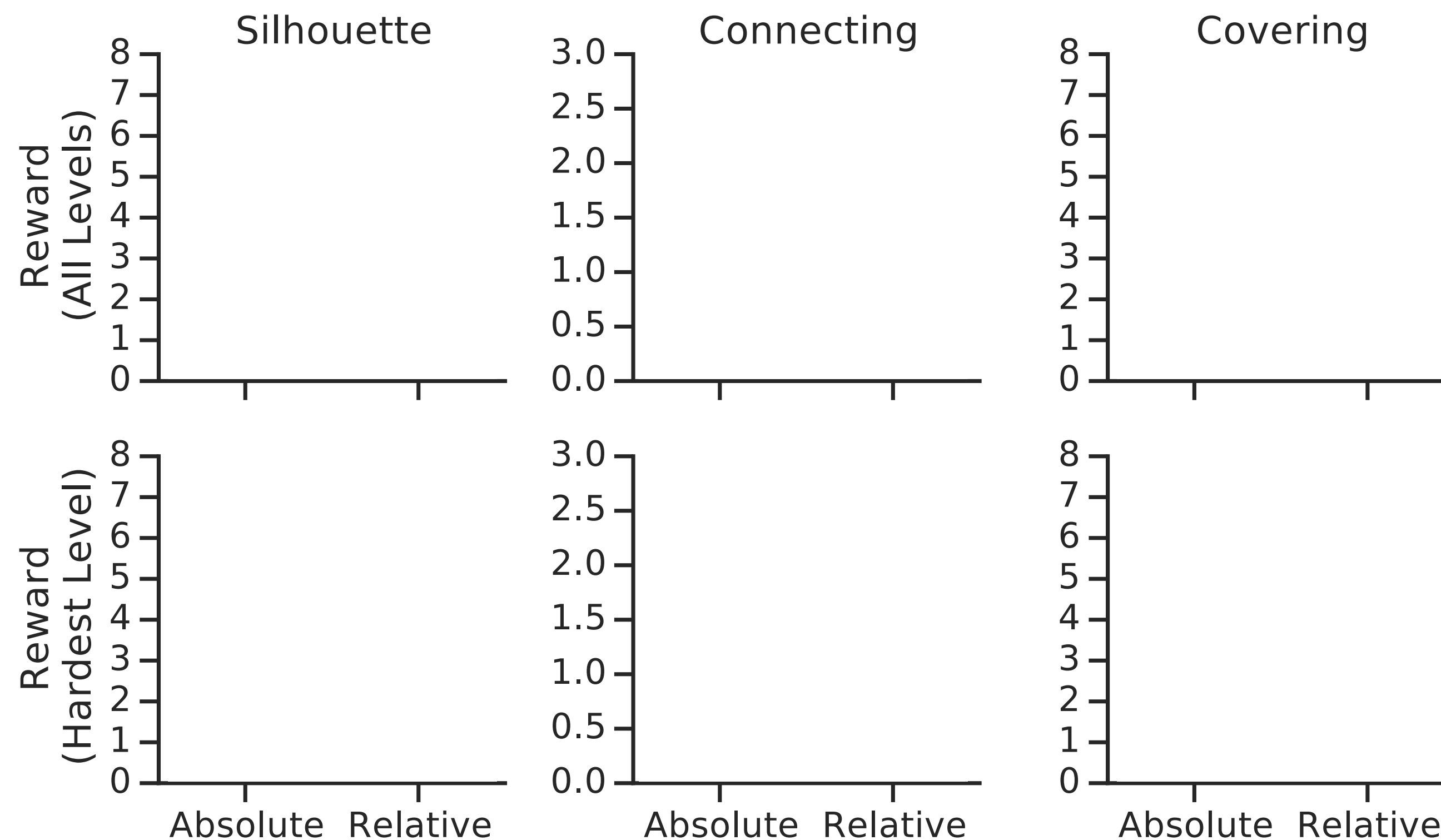
1. What is the contribution of *relative* vs. absolute actions?
2. What is the contribution of *structured* representations?
3. What is the contribution of *planning*?

What is the contribution of *relative* vs. absolute actions?

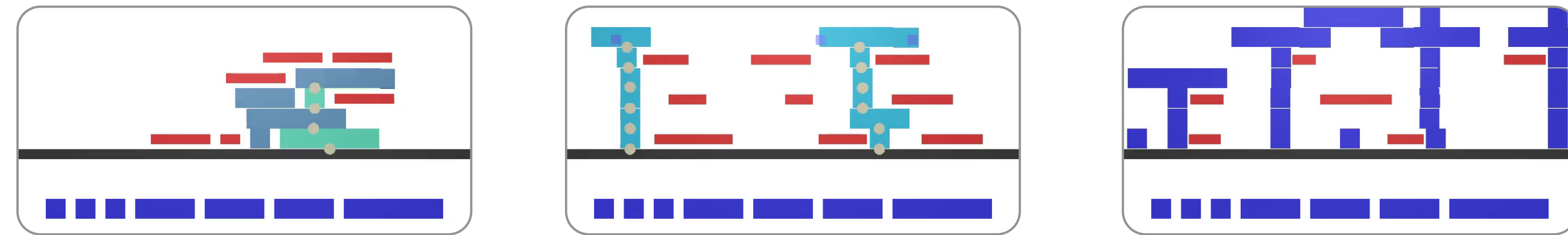


- Best absolute agent
- Relative agent (GN-DQN)

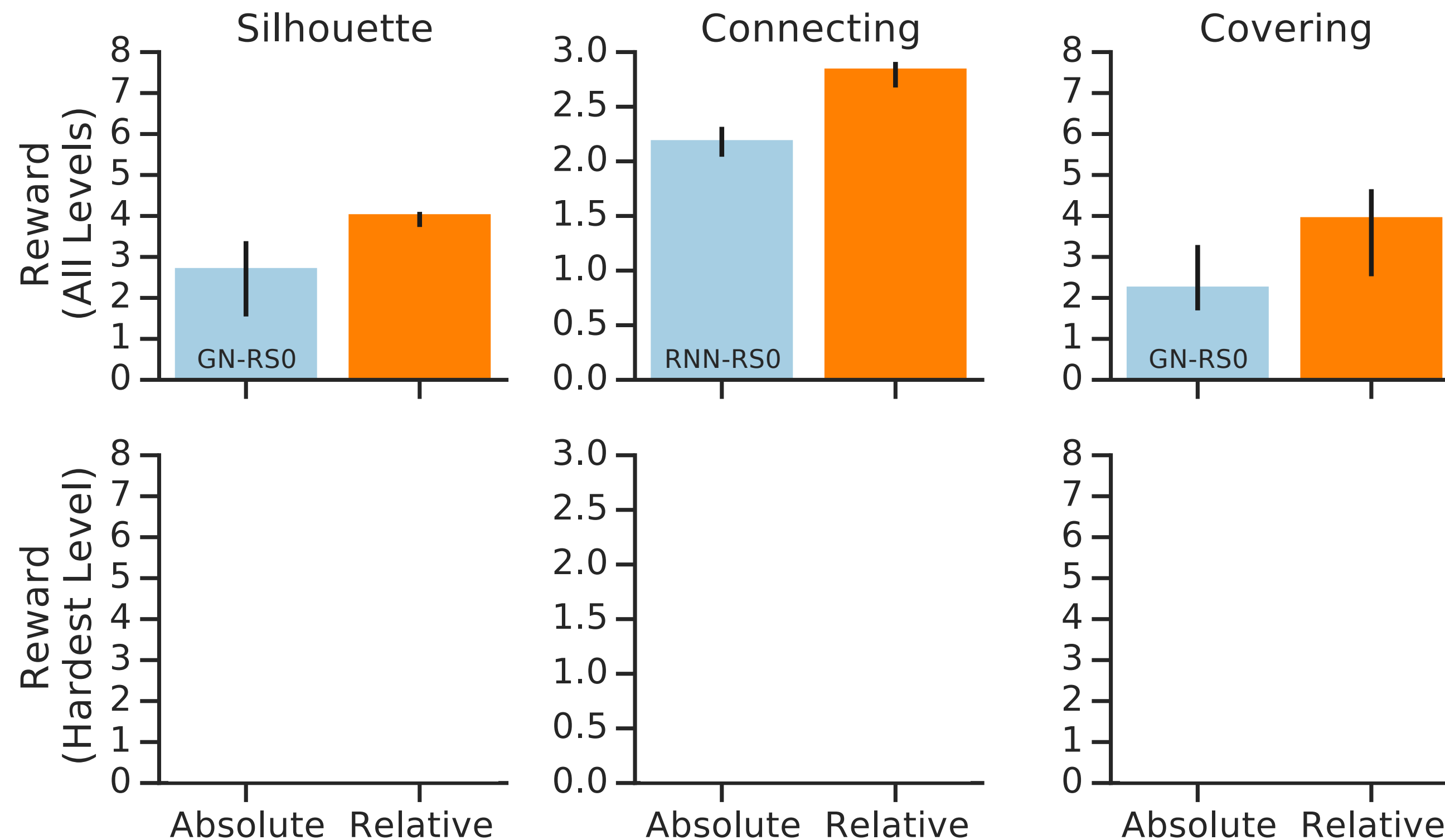
(Median across 10 seeds, with error bars for min/max seed)



What is the contribution of *relative* vs. absolute actions?

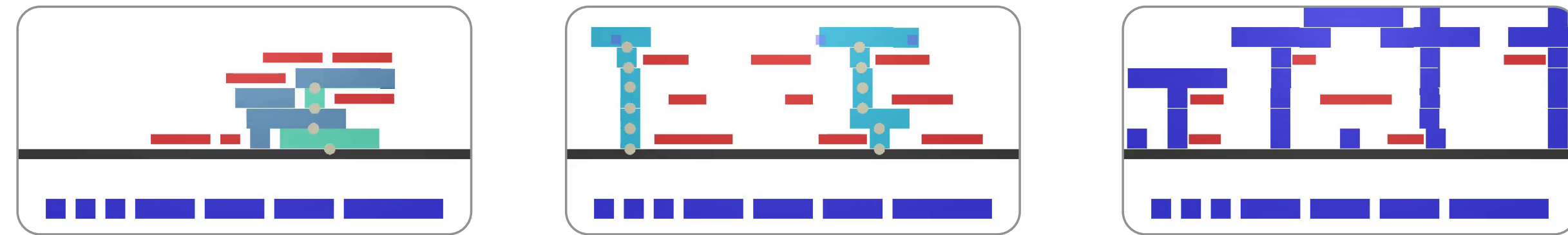


■ Best absolute agent
■ Relative agent (GN-DQN)

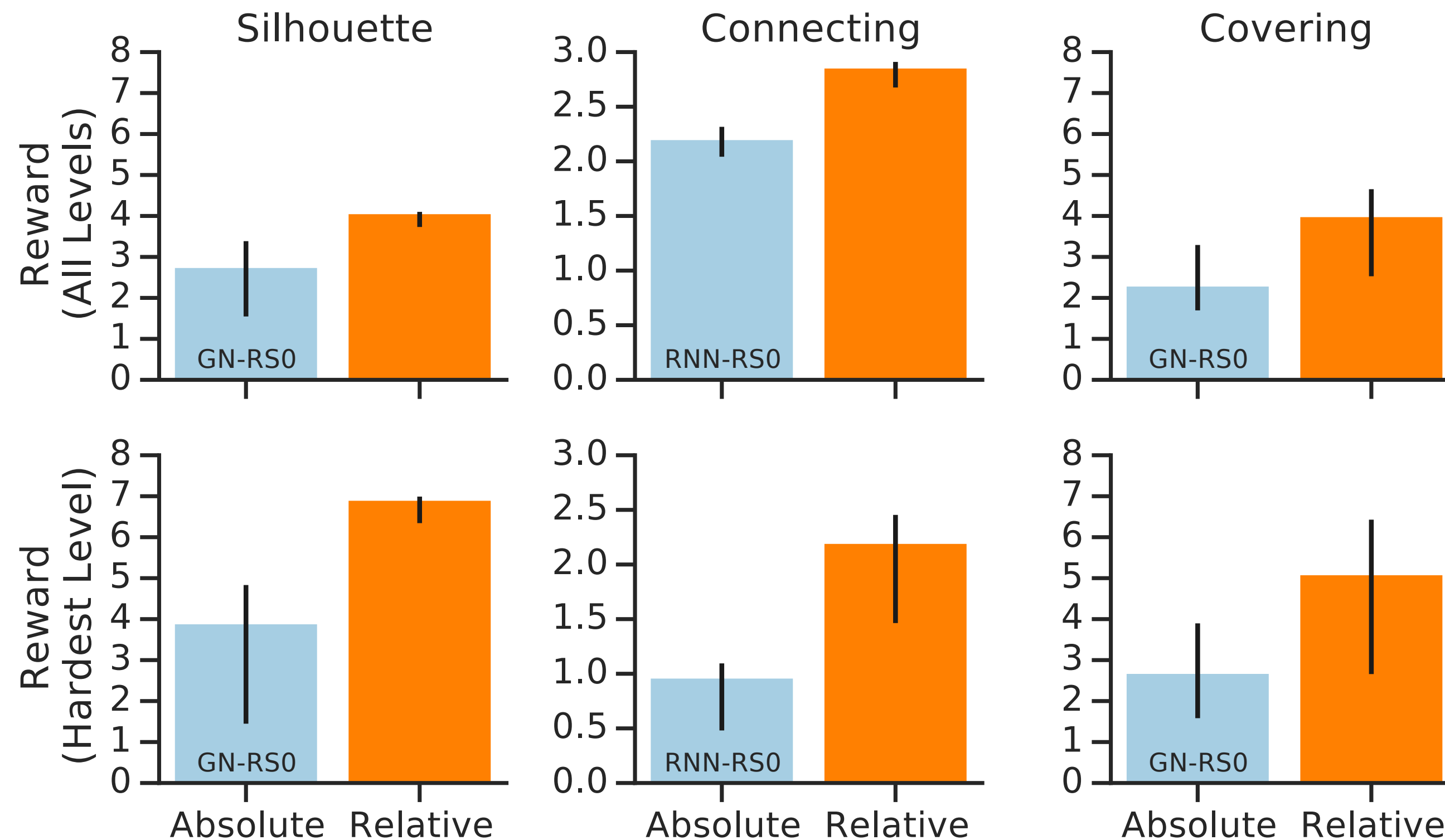


(Median across 10 seeds, with error bars for min/max seed)

What is the contribution of *relative* vs. absolute actions?

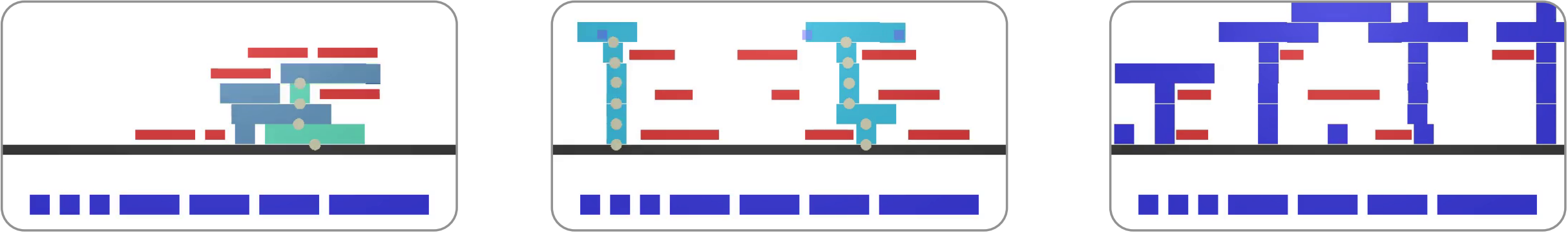


■ Best absolute agent
■ Relative agent (GN-DQN)



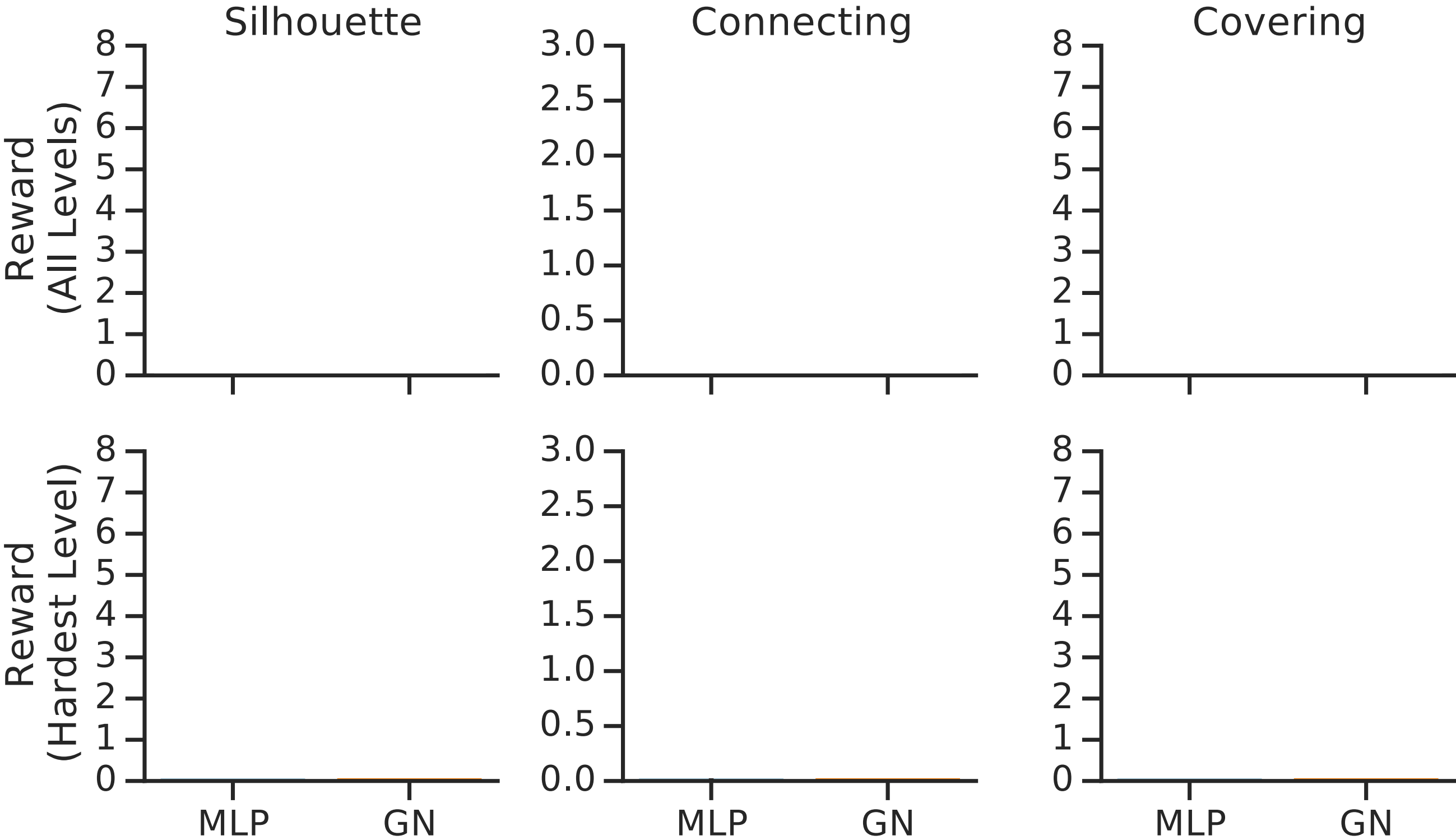
(Median across 10 seeds, with error bars for min/max seed)

What is the contribution of *structured* representations?

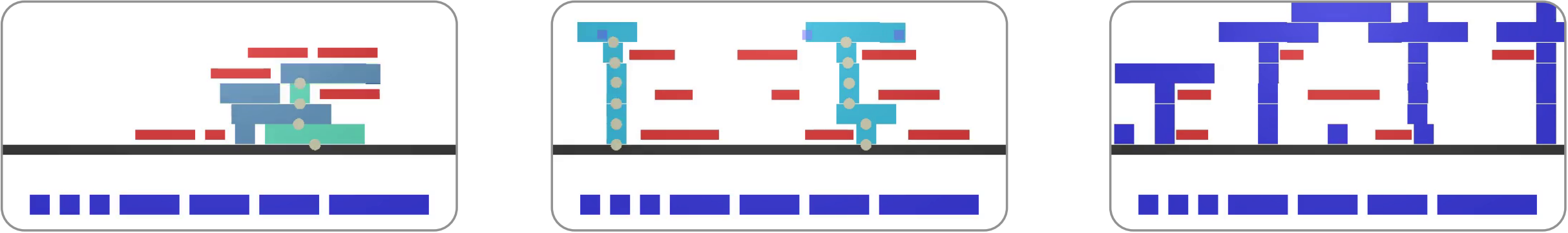


■ Best unstructured agent
■ Structured agent (GN-DQN)
 (Both with relative actions)

(Median across 10 seeds, with error bars for min/max seed)



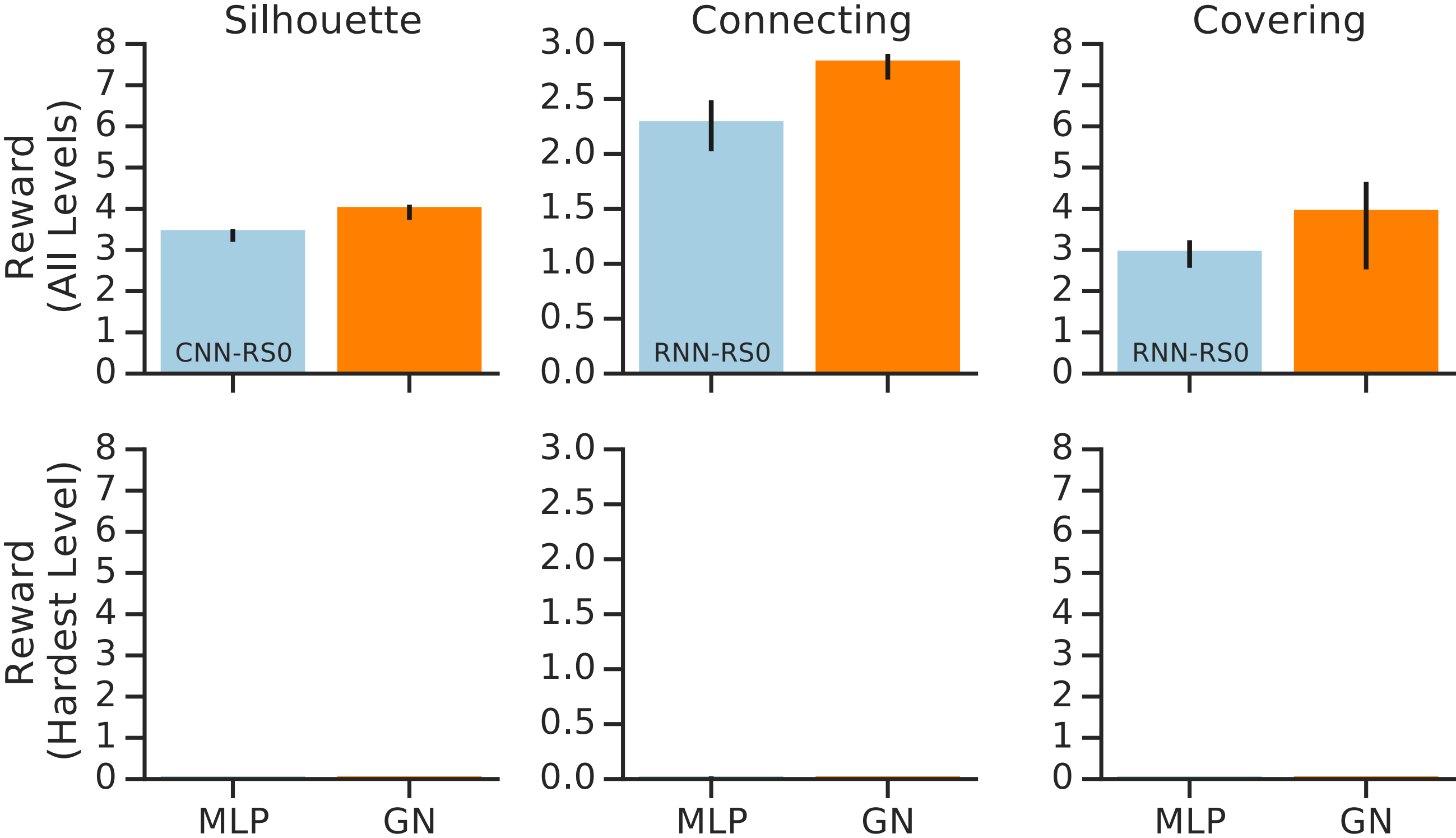
What is the contribution of *structured* representations?



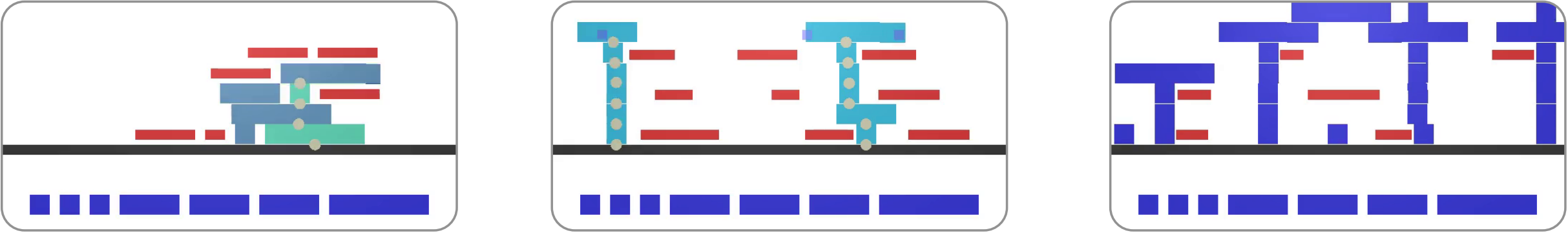
■ Best unstructured agent
■ Structured agent (GN-DQN)

(Both with relative actions)

(Median across 10 seeds, with error bars for min/max seed)



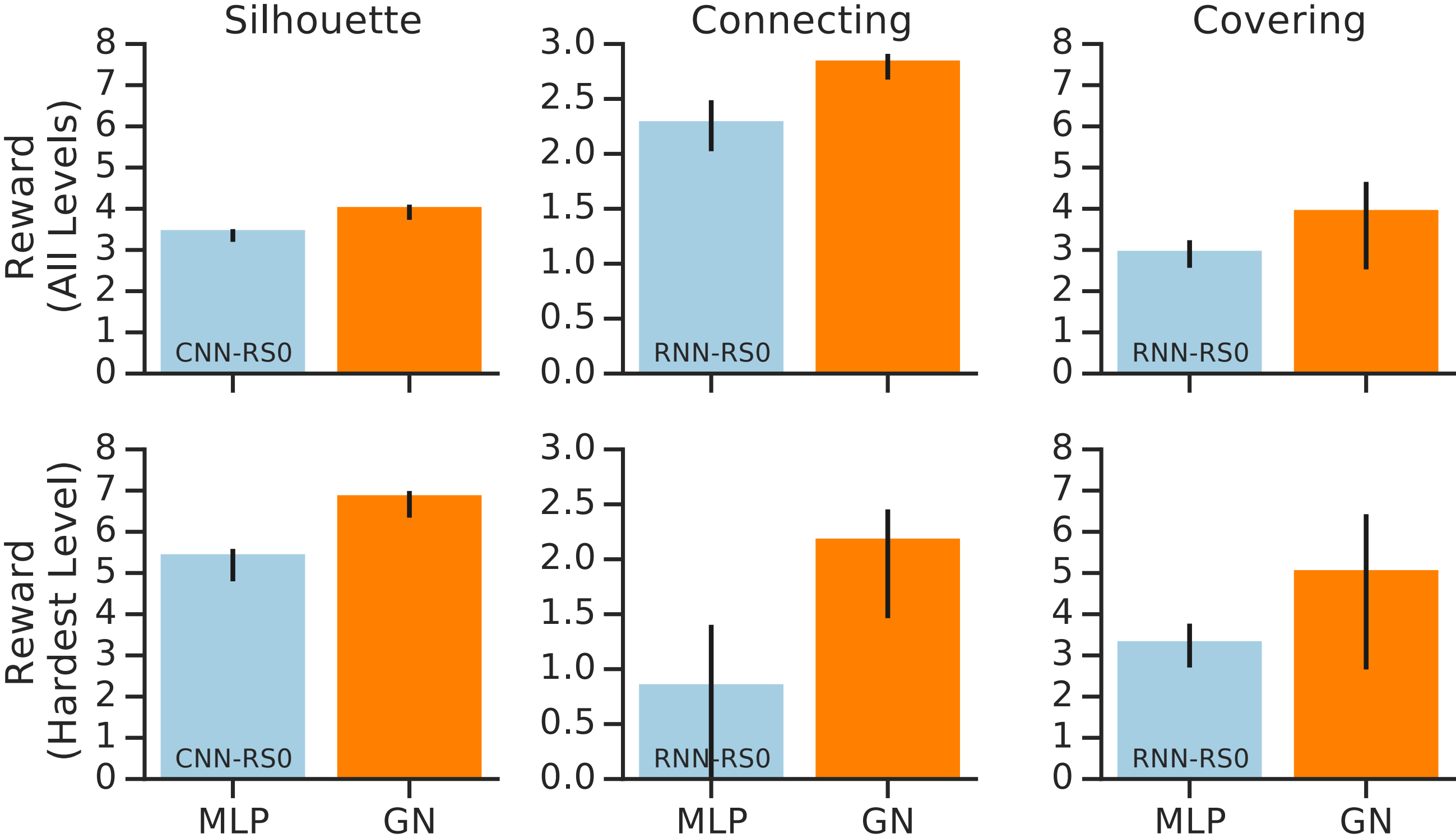
What is the contribution of *structured* representations?



■ Best unstructured agent
■ Structured agent (GN-DQN)

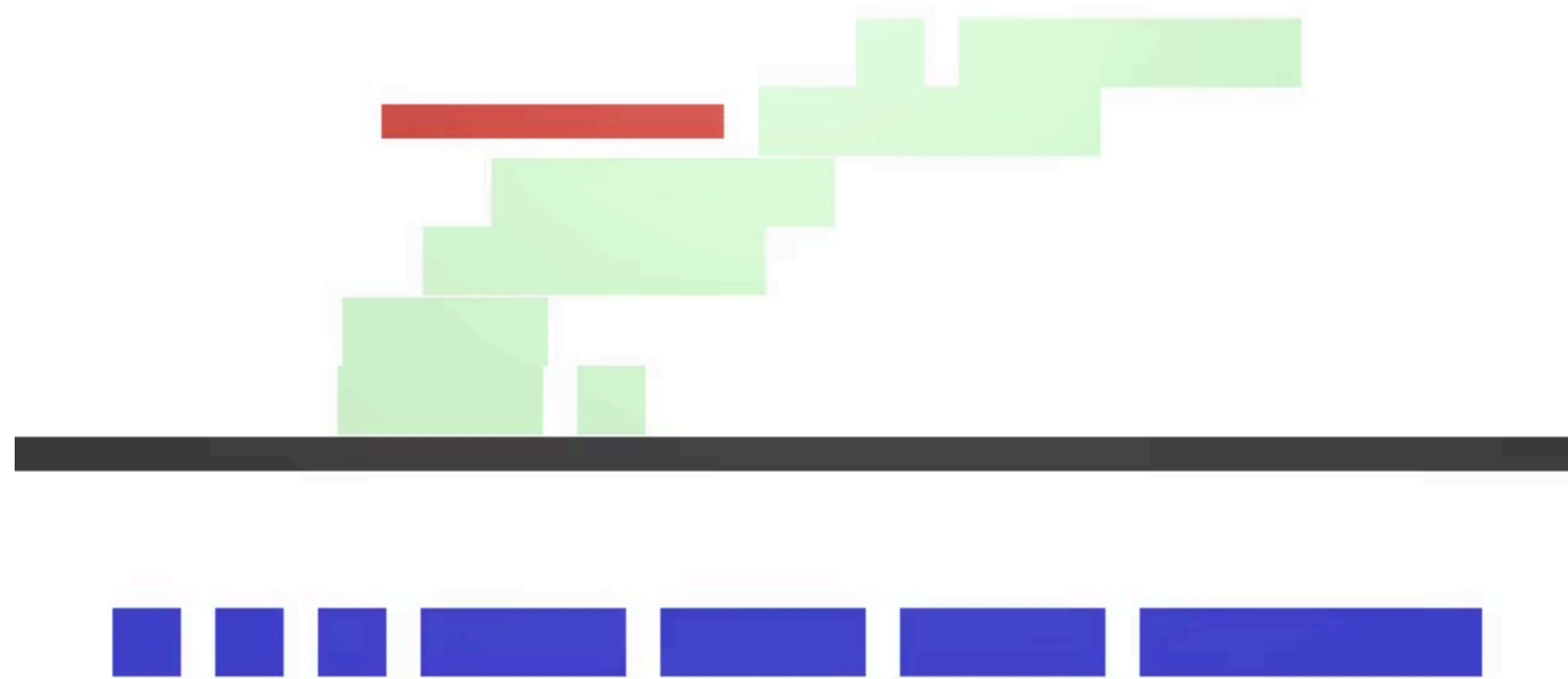
(Both with relative actions)

(Median across 10 seeds, with error bars for min/max seed)

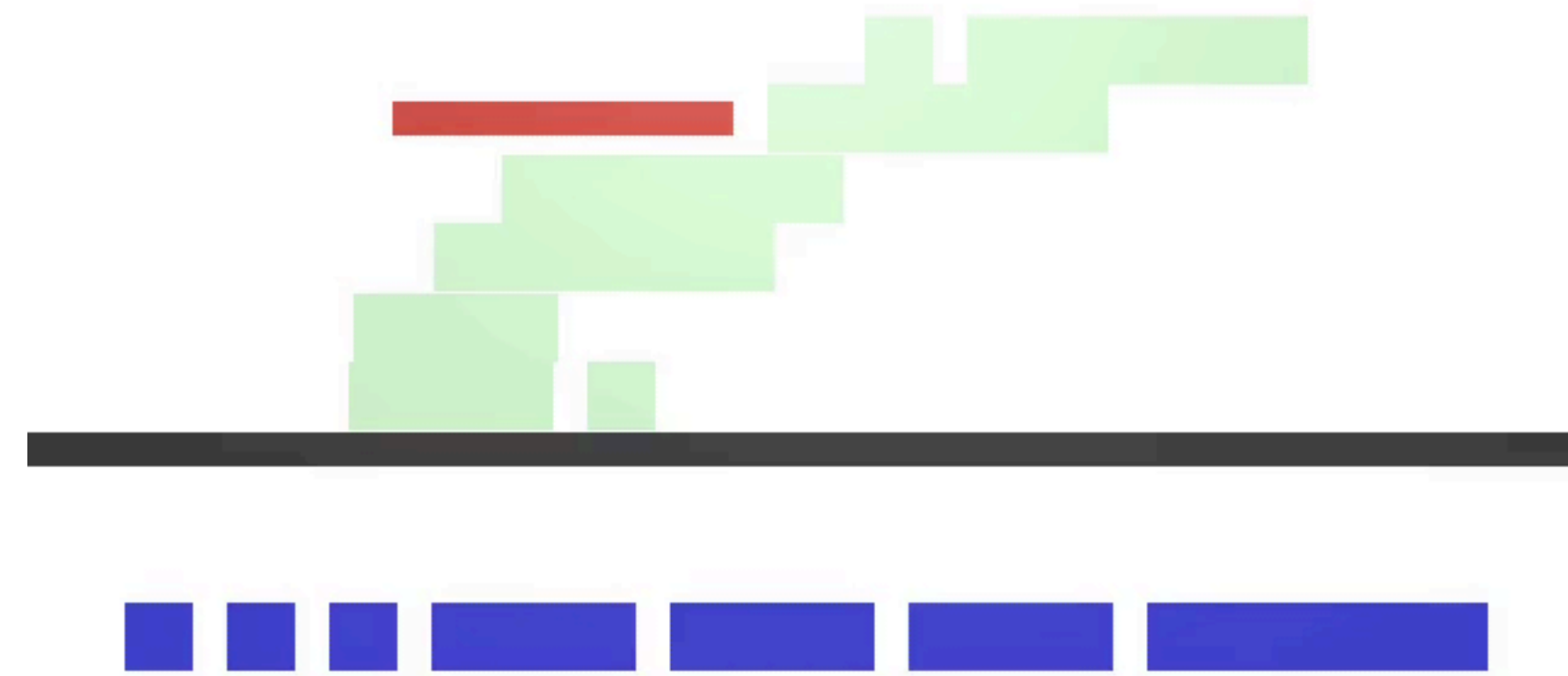


Silhouette

Absolute Actions (GN-RS0)
(Average reward: 4.83)



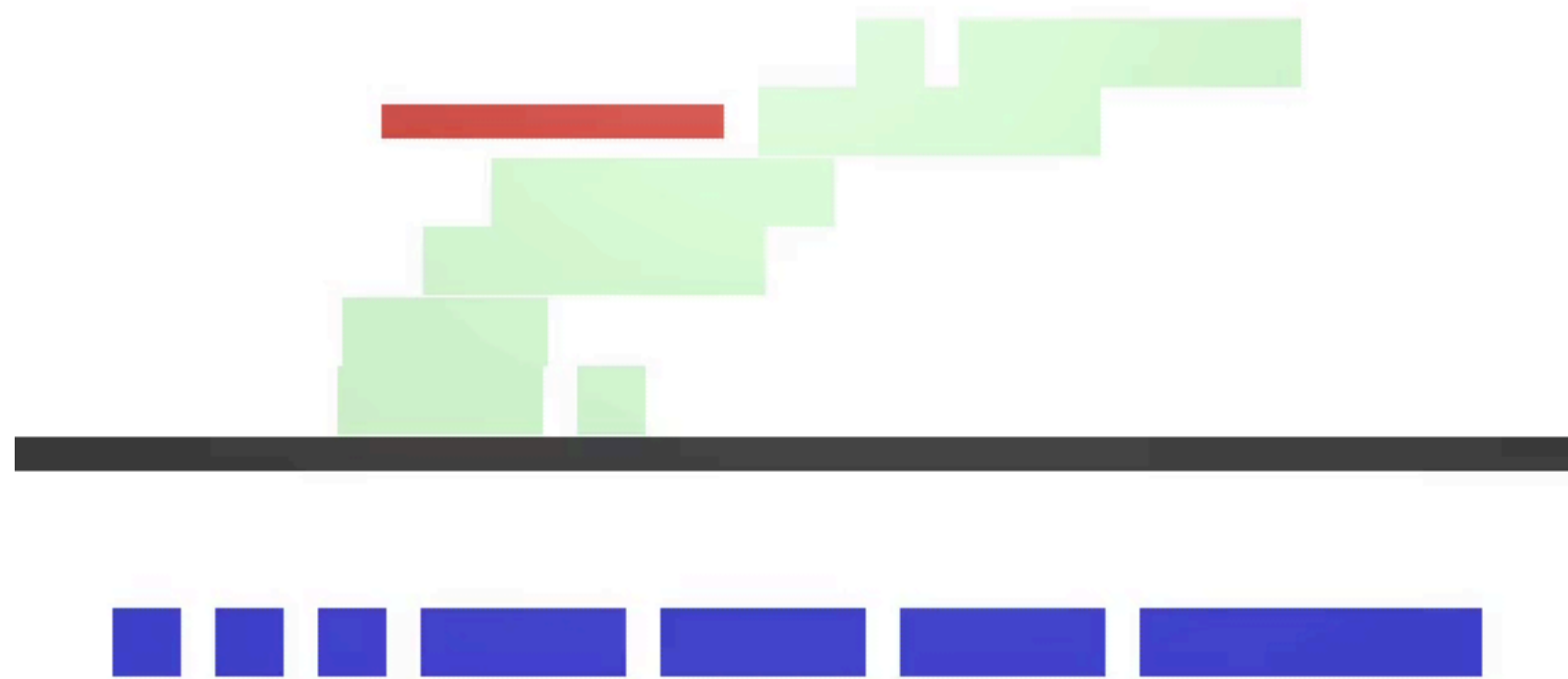
Relative Actions (GN-DQN)
(Average reward: 6.99)



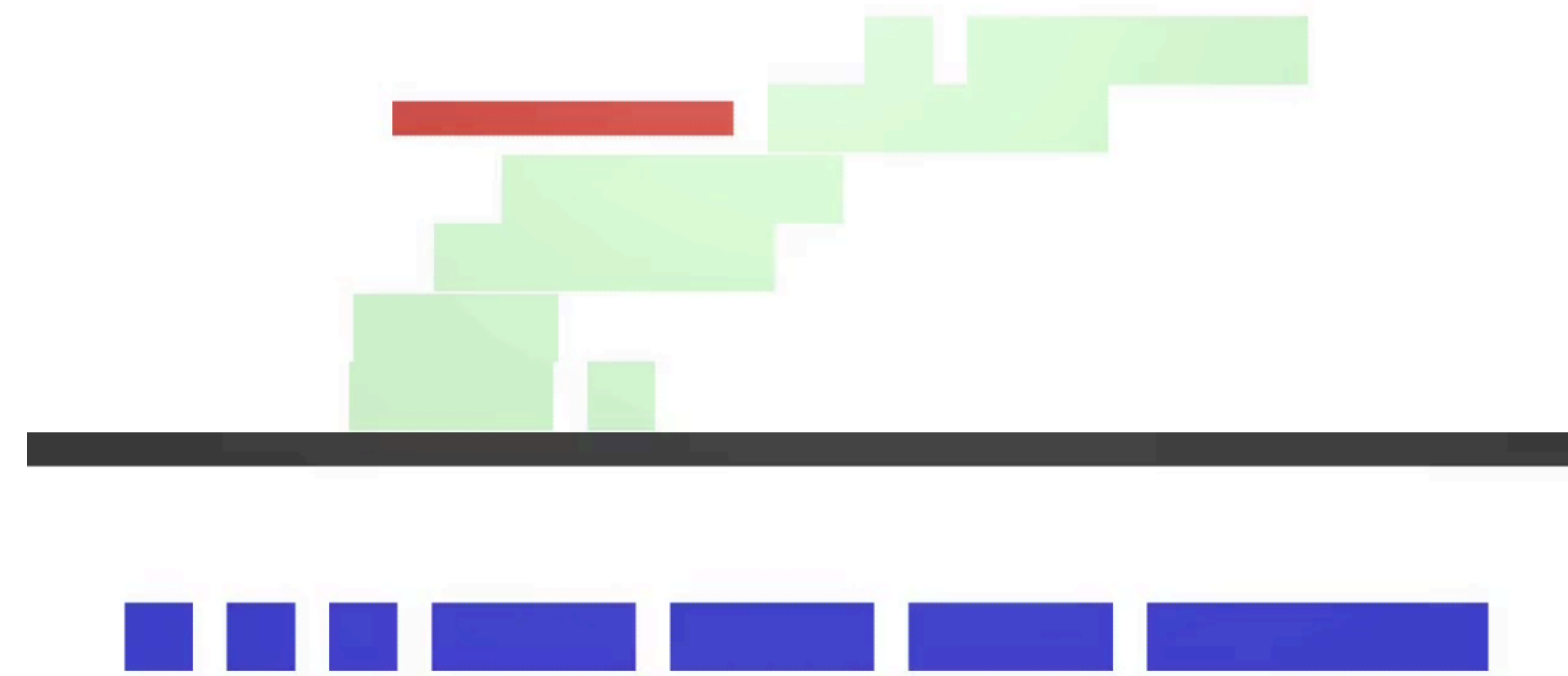
Reward: +1 per target, -0.5 per sticky block

Silhouette

Absolute Actions (GN-RS0)
(Average reward: 4.83)



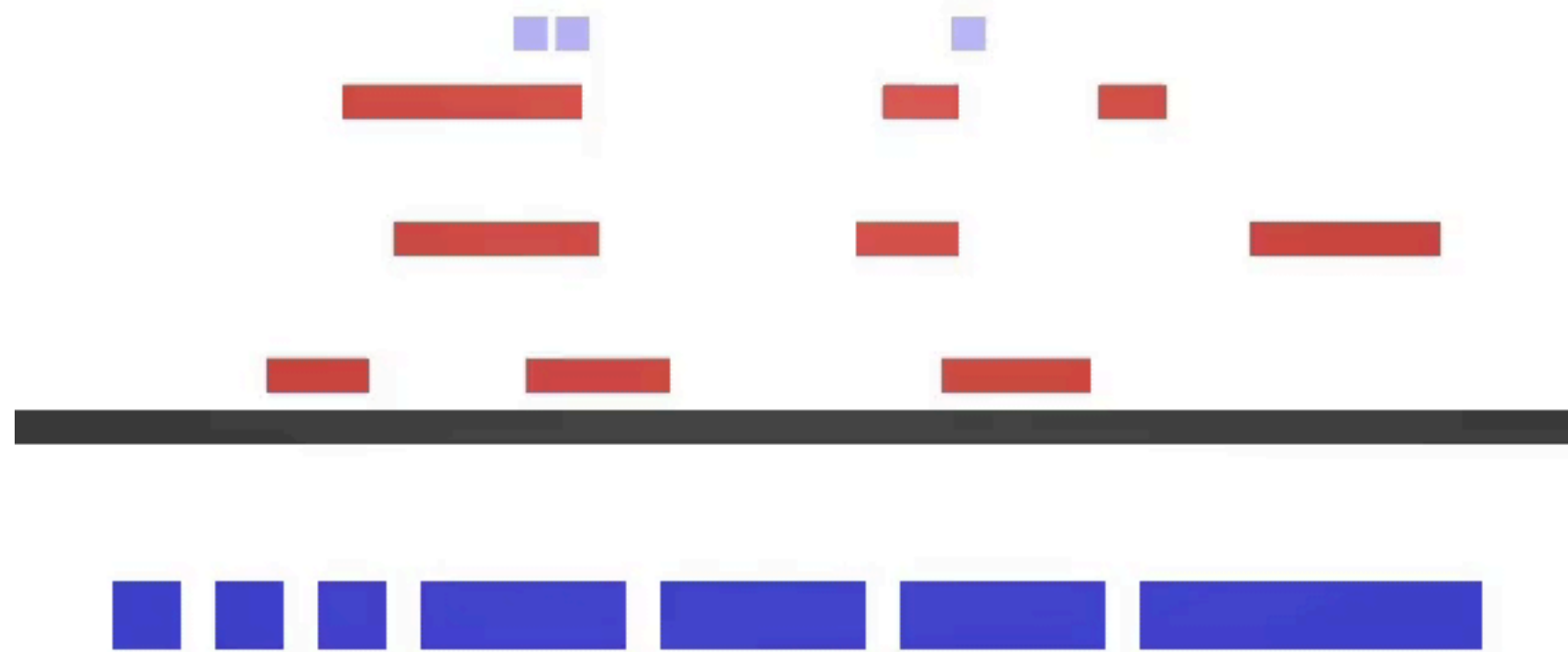
Relative Actions (GN-DQN)
(Average reward: 6.99)



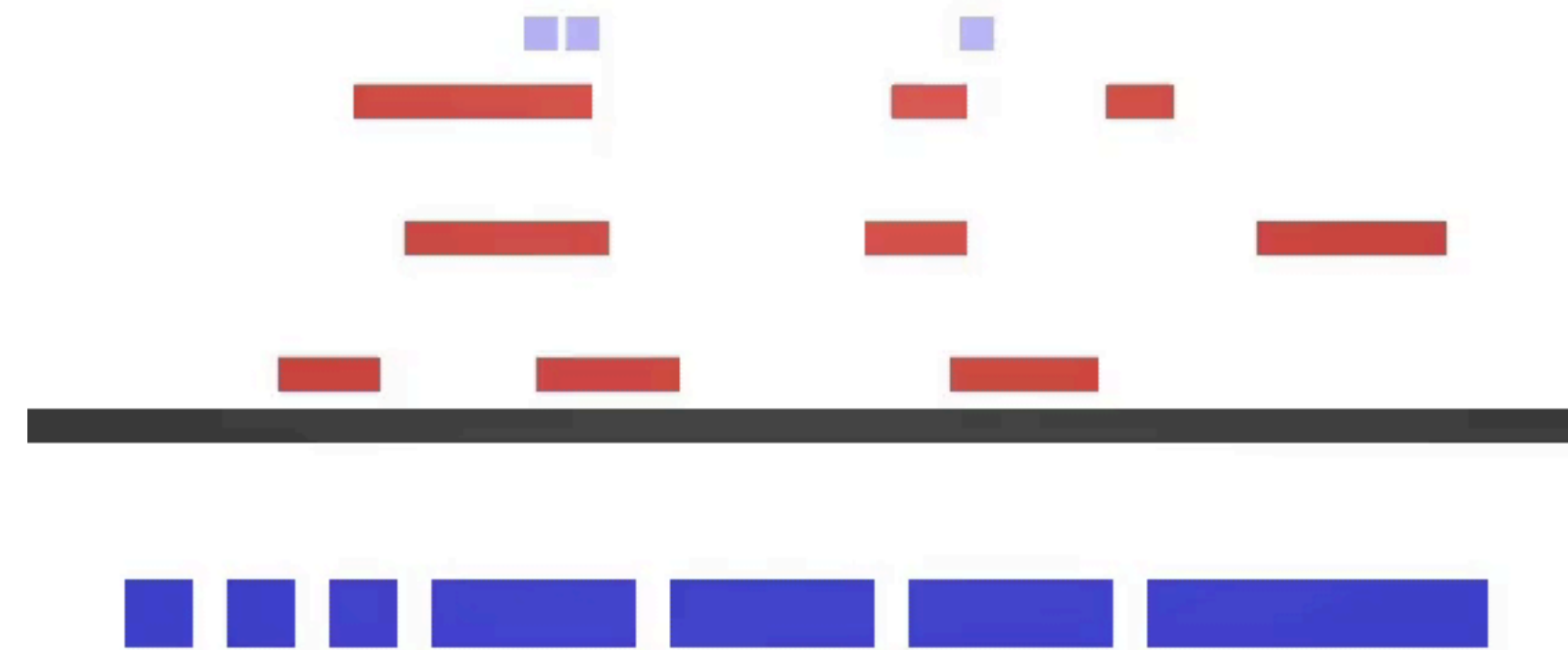
Reward: +1 per target, -0.5 per sticky block

Connecting

Absolute Actions (RNN-RS0)
(Average reward: 1.09)



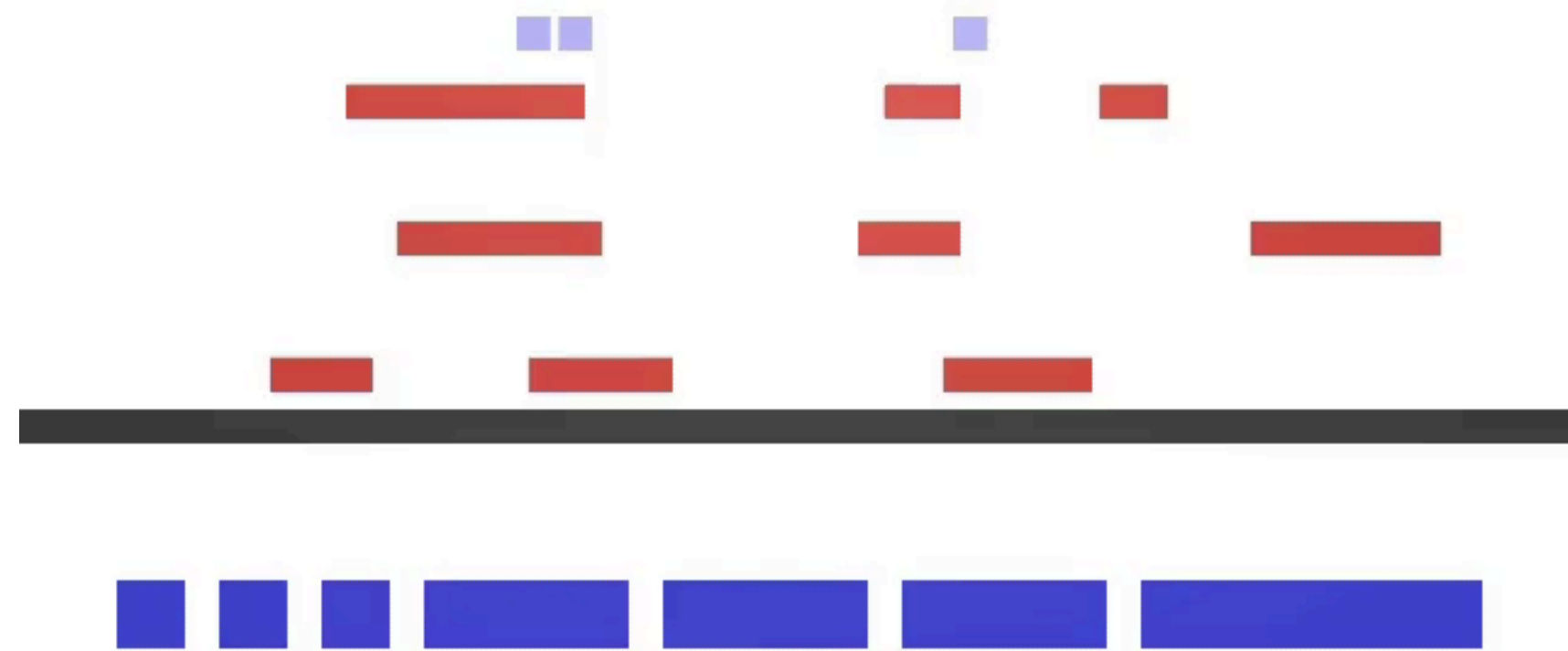
Relative Actions (GN-DQN)
(Average reward: 2.45)



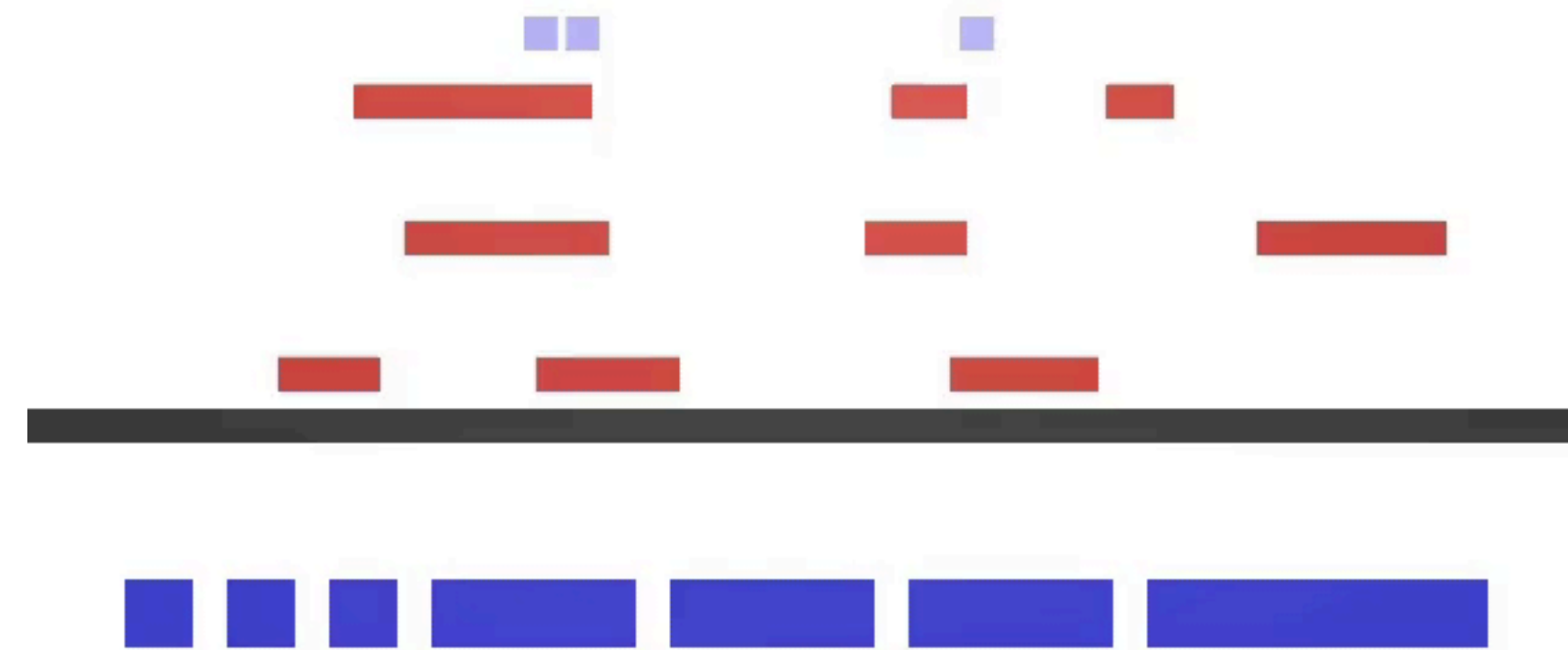
Reward: +1 per target, free sticky blocks

Connecting

Absolute Actions (RNN-RS0)
(Average reward: 1.09)



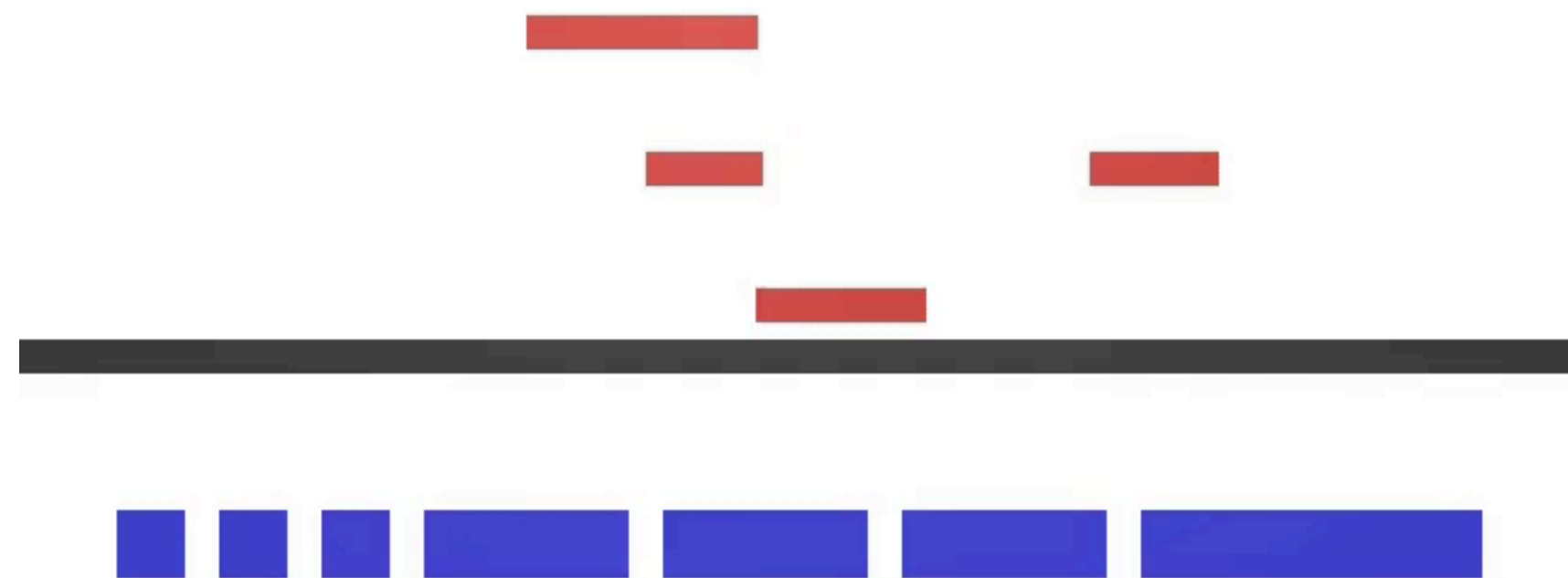
Relative Actions (GN-DQN)
(Average reward: 2.45)



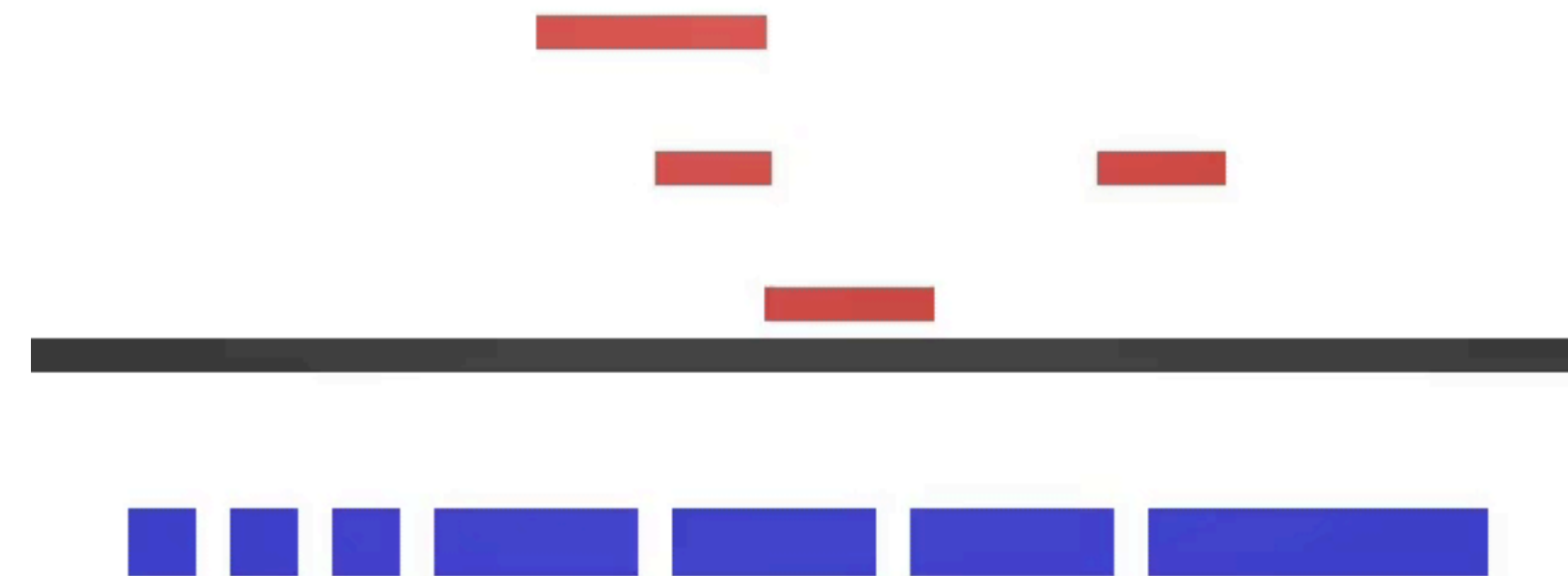
Reward: +1 per target, free sticky blocks

Covering

Absolute Actions (GN-RS0)
(Average reward: 3.90)



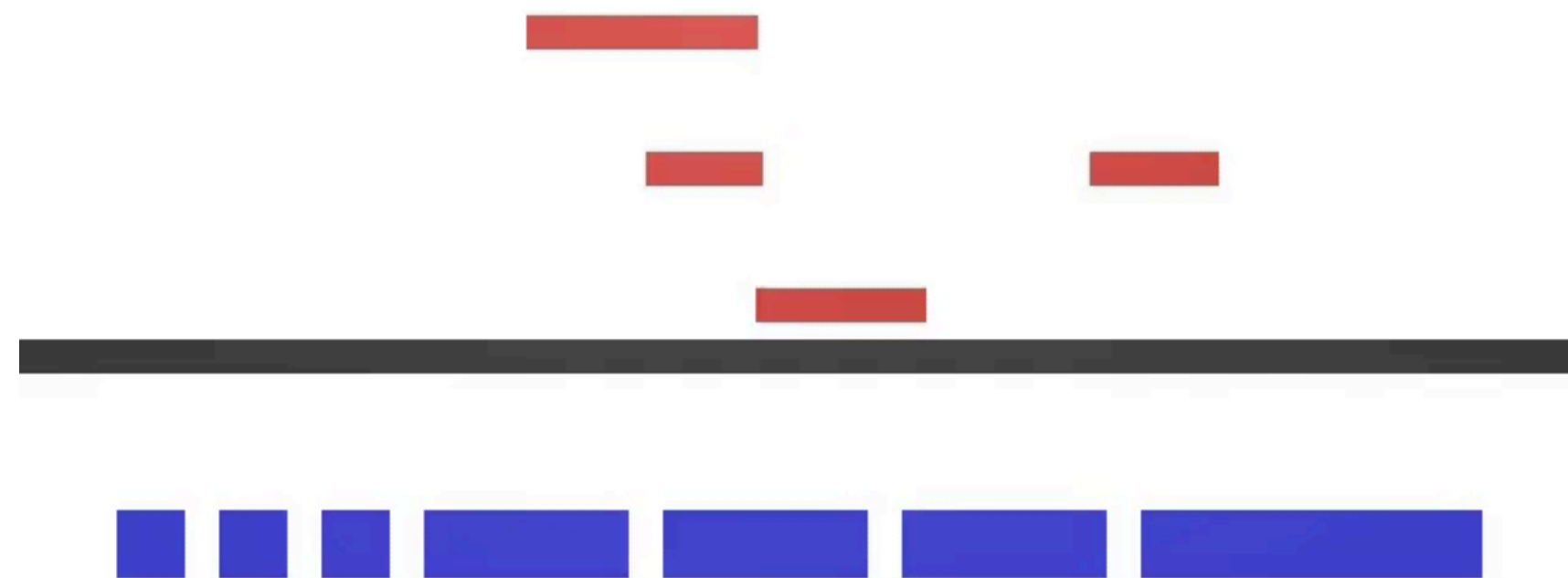
Relative Actions (GN-DQN)
(Average reward: 6.43)



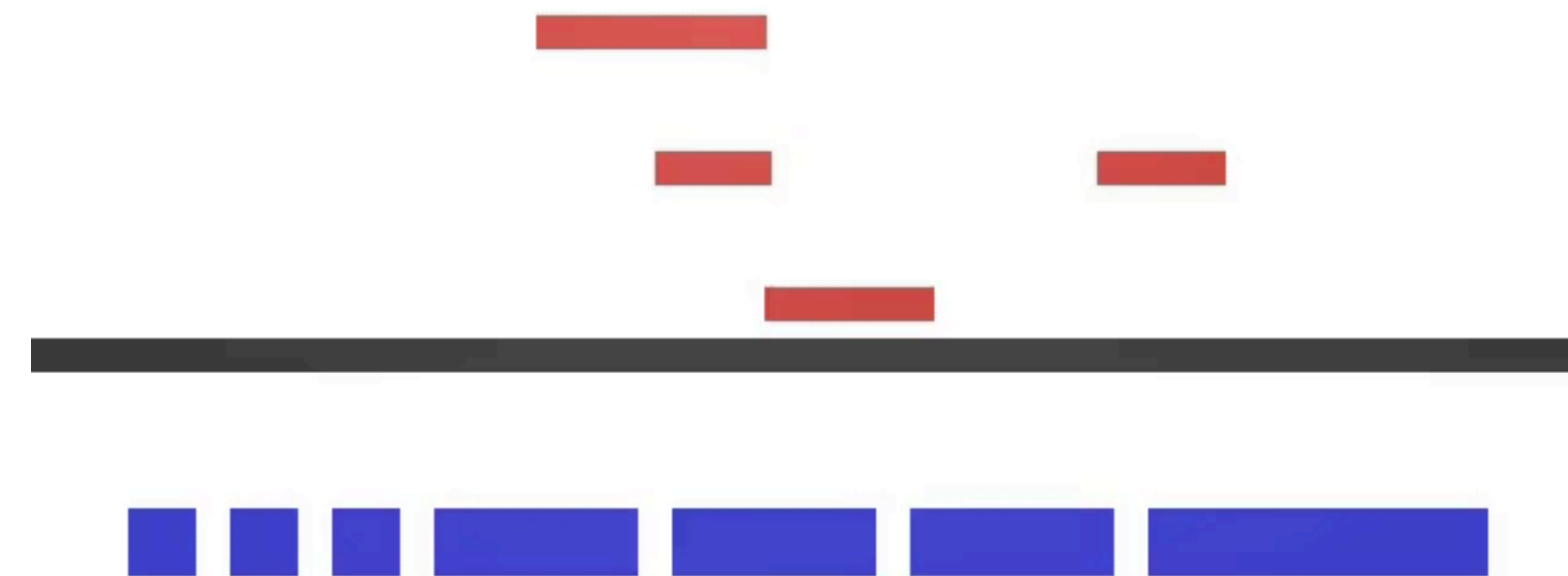
Reward: proportional to length covered, -2 per sticky block

Covering

Absolute Actions (GN-RS0)
(Average reward: 3.90)



Relative Actions (GN-DQN)
(Average reward: 6.43)

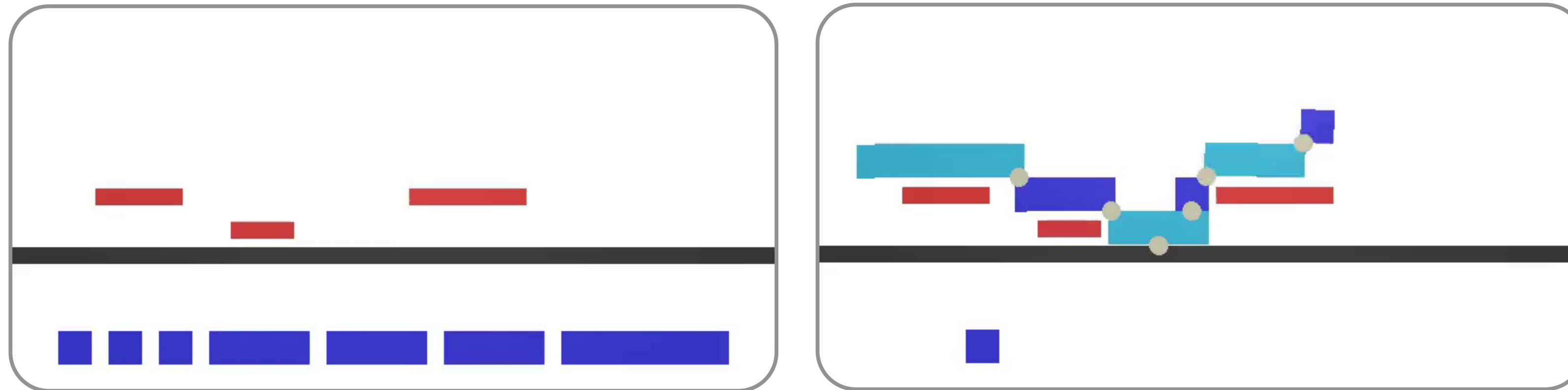


Reward: proportional to length covered, -2 per sticky block

What is the contribution of *planning*?

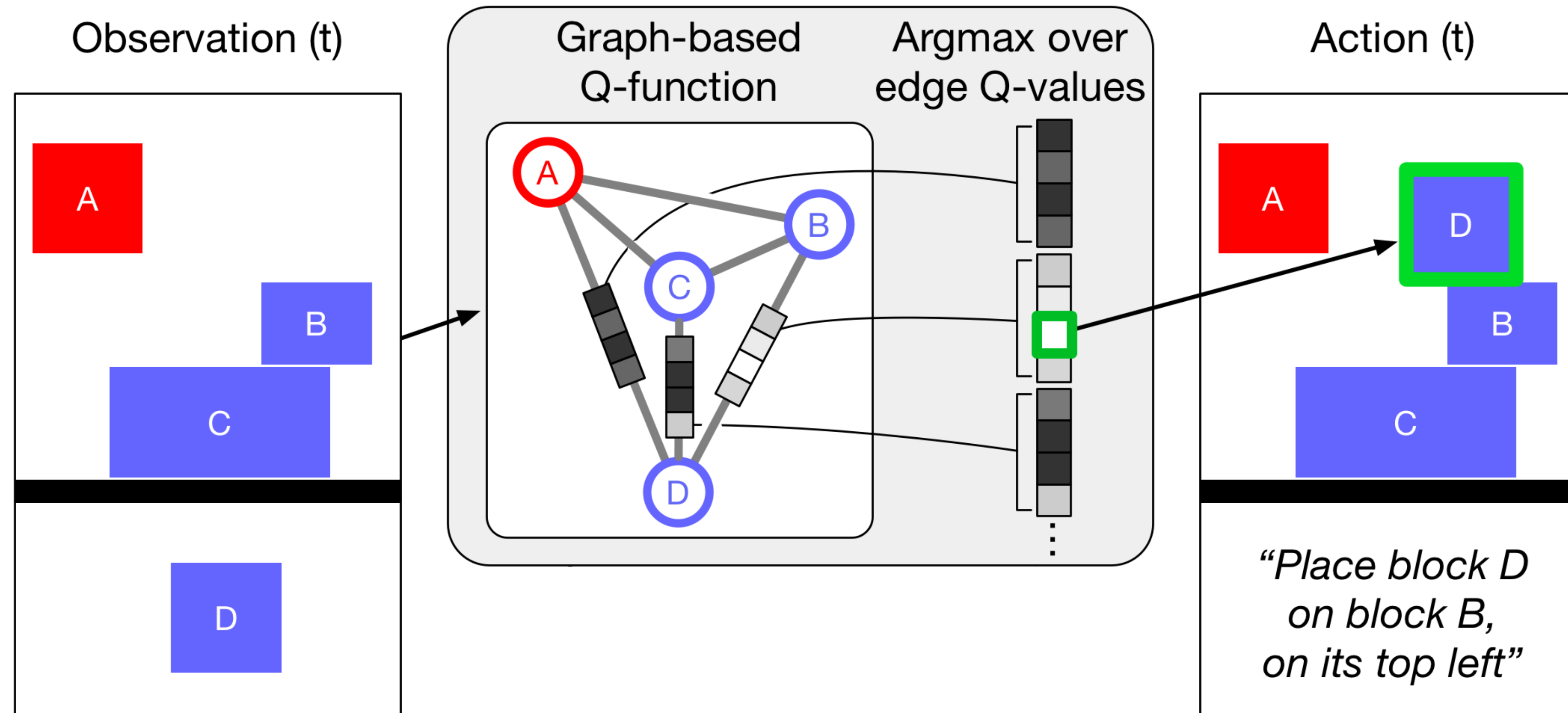
What is the contribution of *planning*?

Covering Hard

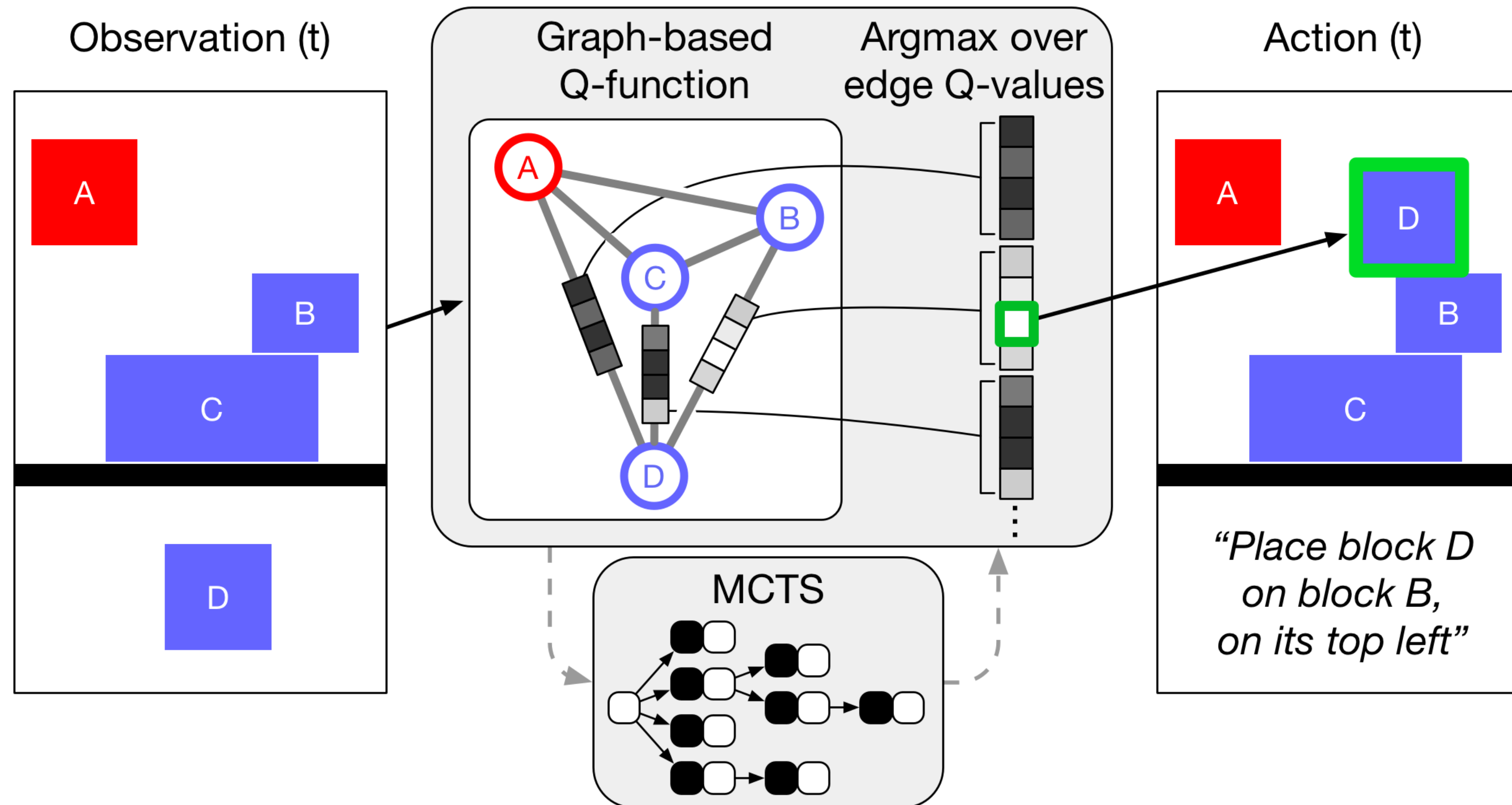


*Length covered
-0.5 per sticky block*

What is the contribution of *planning*?

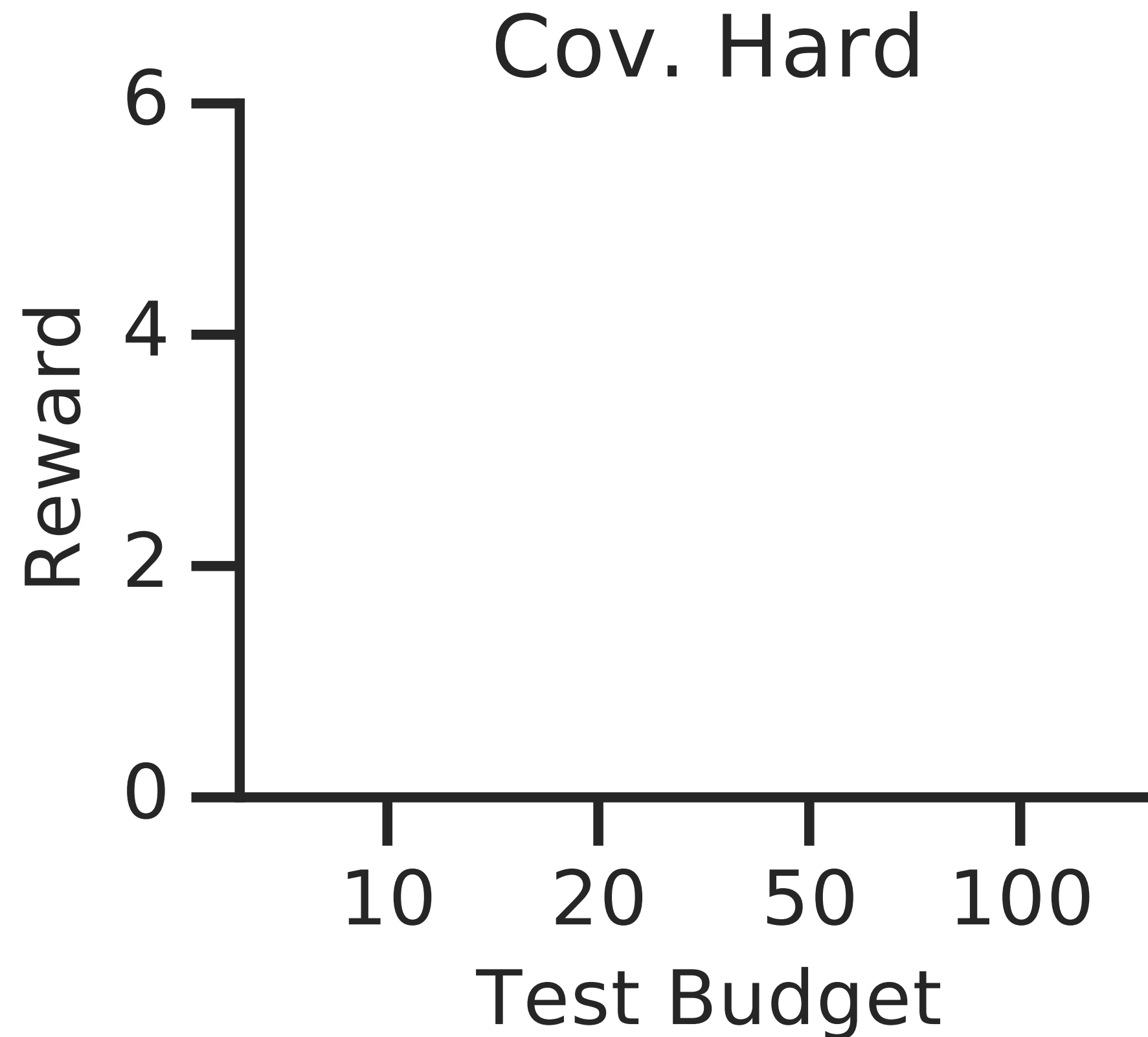
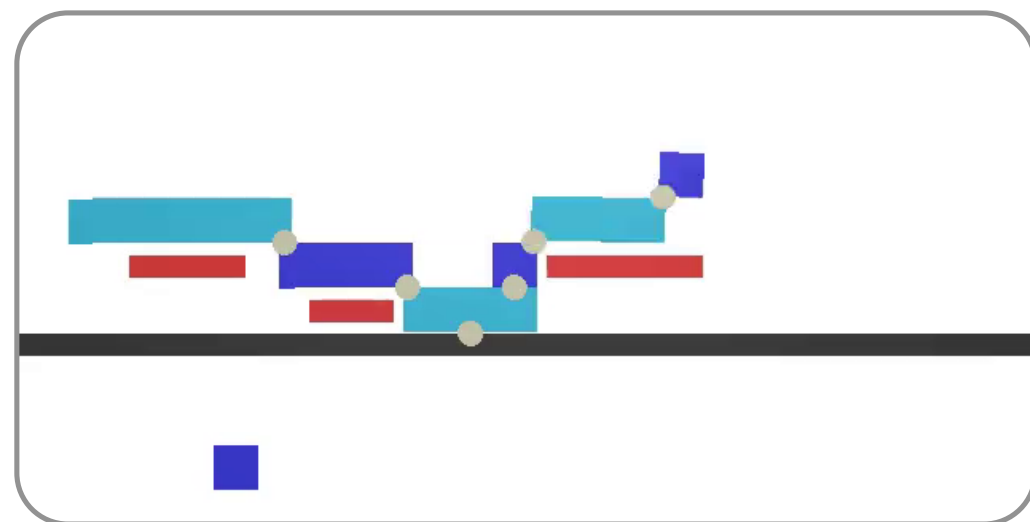


What is the contribution of *planning*?



What is the contribution of *planning*?

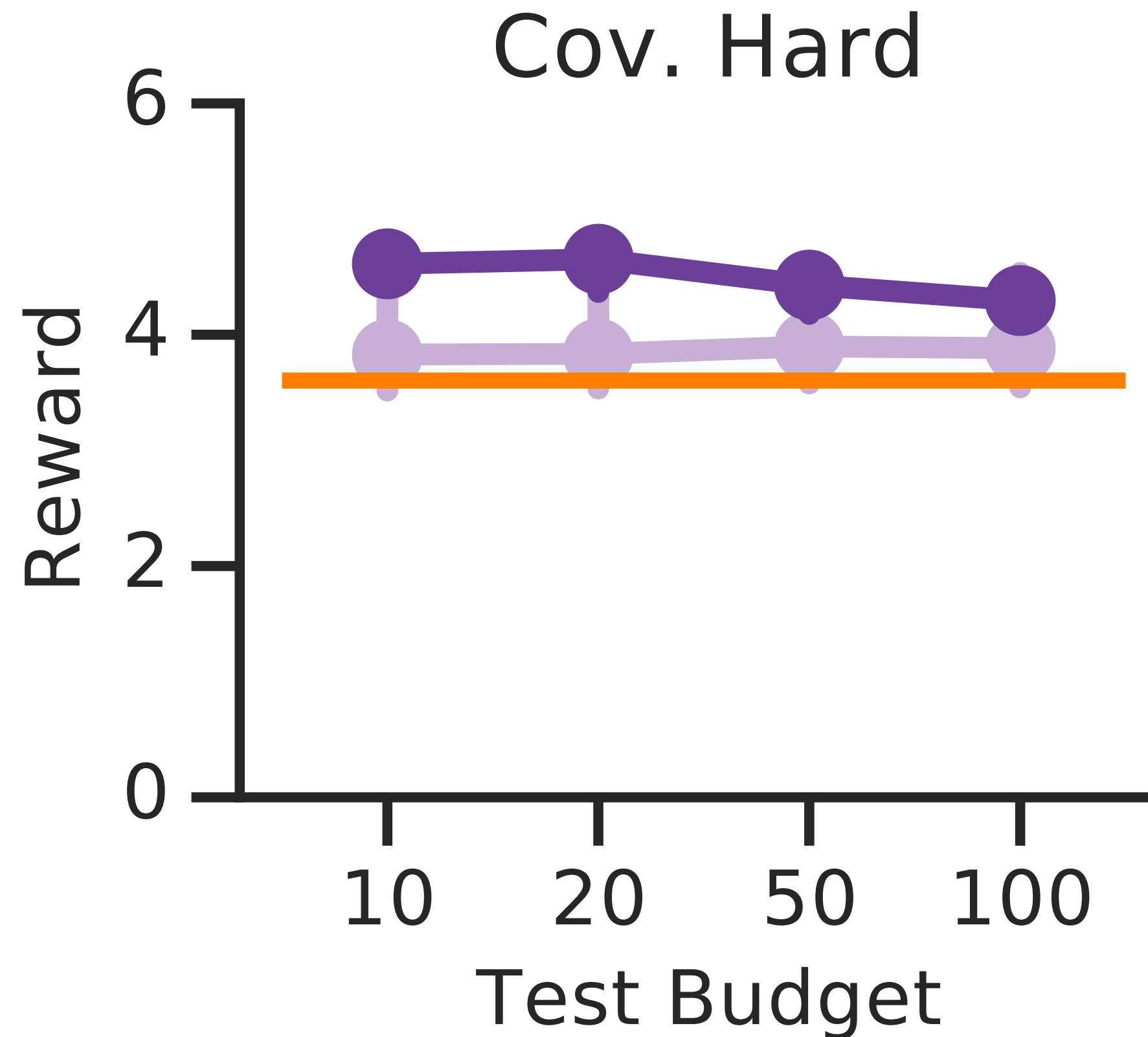
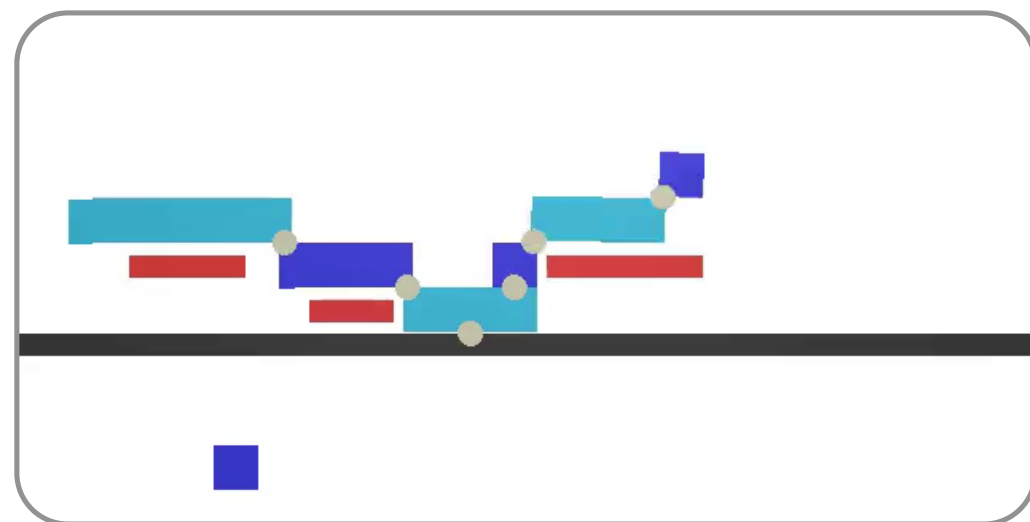
- Model-free
- MCTS @ test time only
- MCTS @ train (10) and test



(Median across 10 seeds, with error bars for min/max seed)

What is the contribution of *planning*?

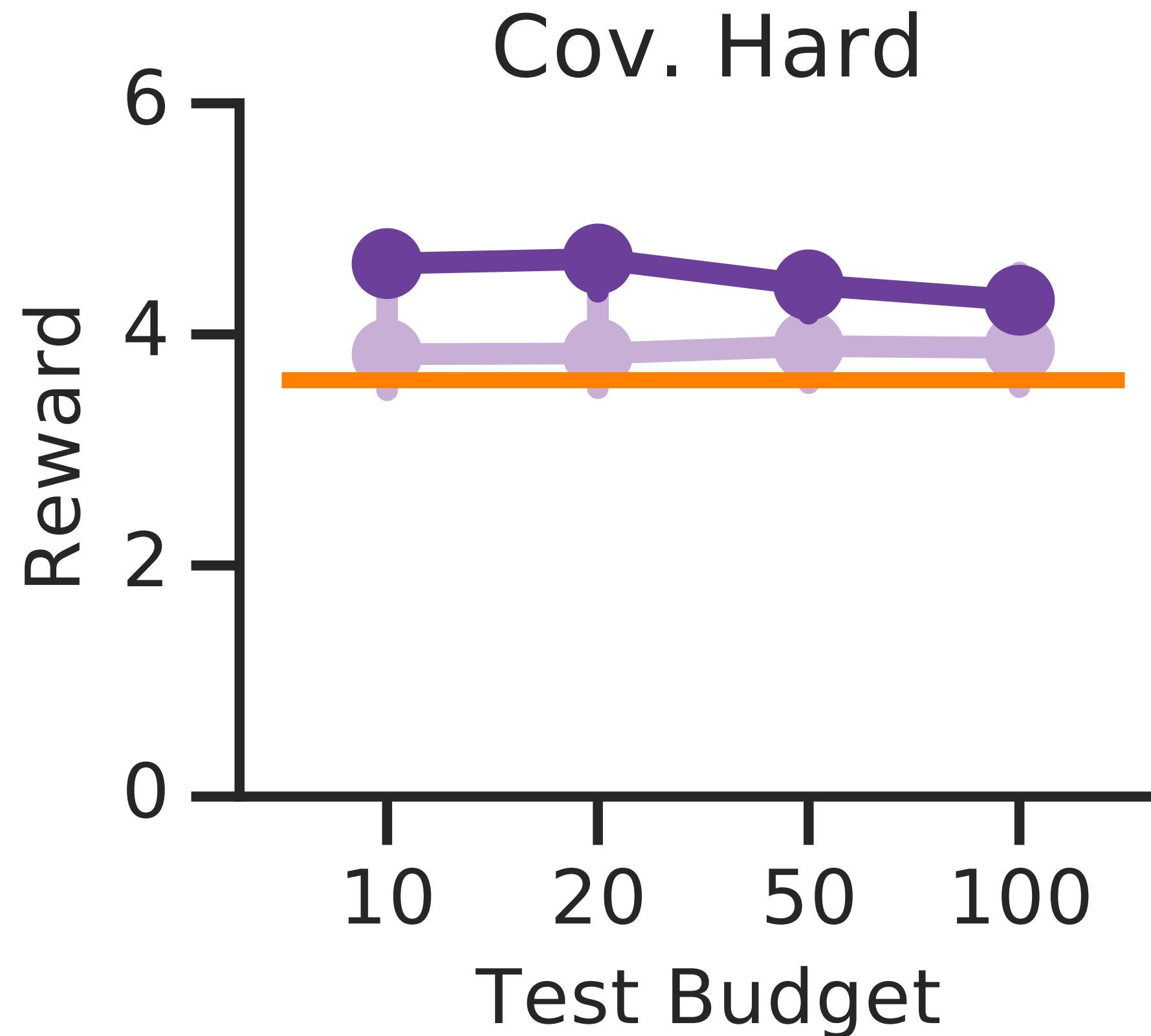
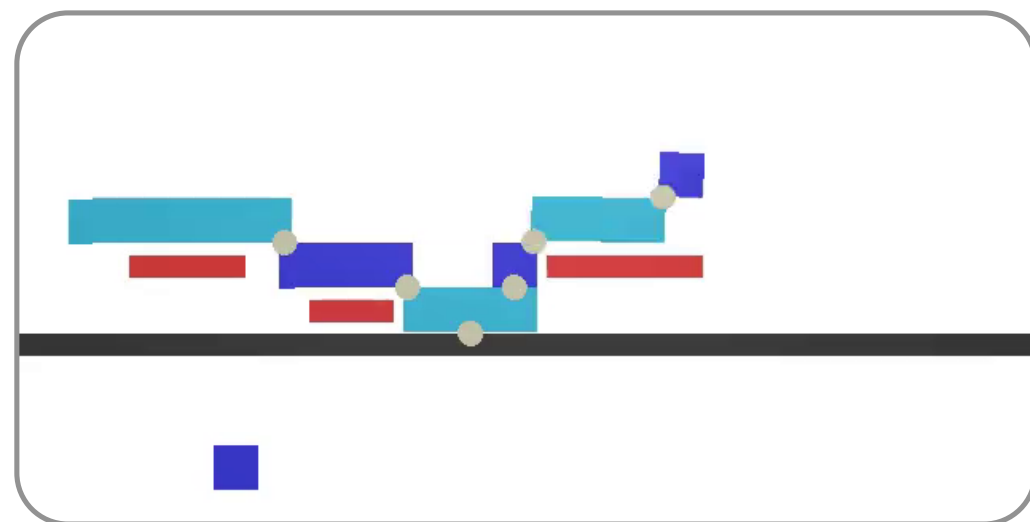
- Model-free
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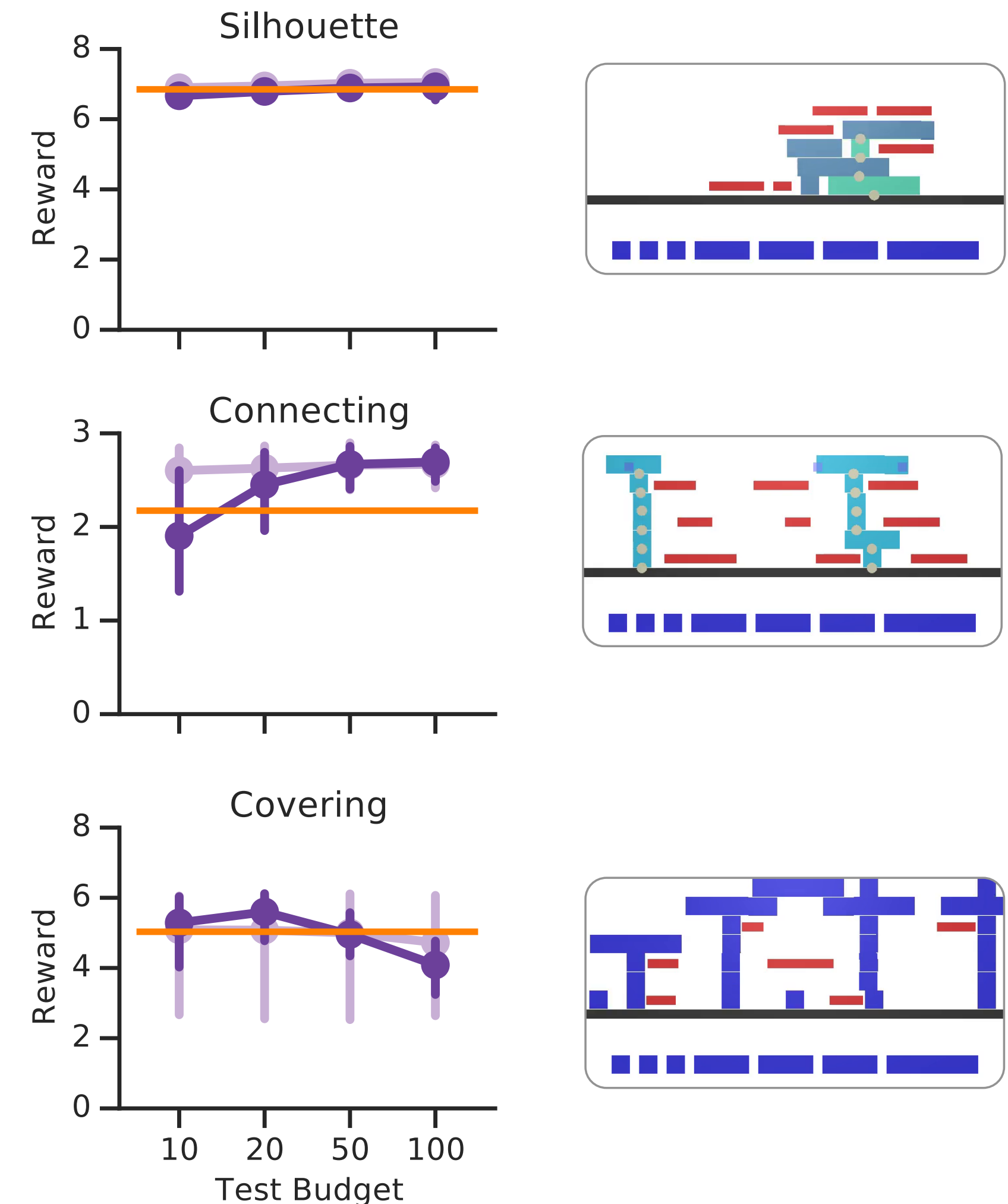
(Median across 10 seeds, with error bars for min/max seed)

What is the contribution of *planning*?

- Model-free
- MCTS @ test time only
- MCTS @ train (10) and test

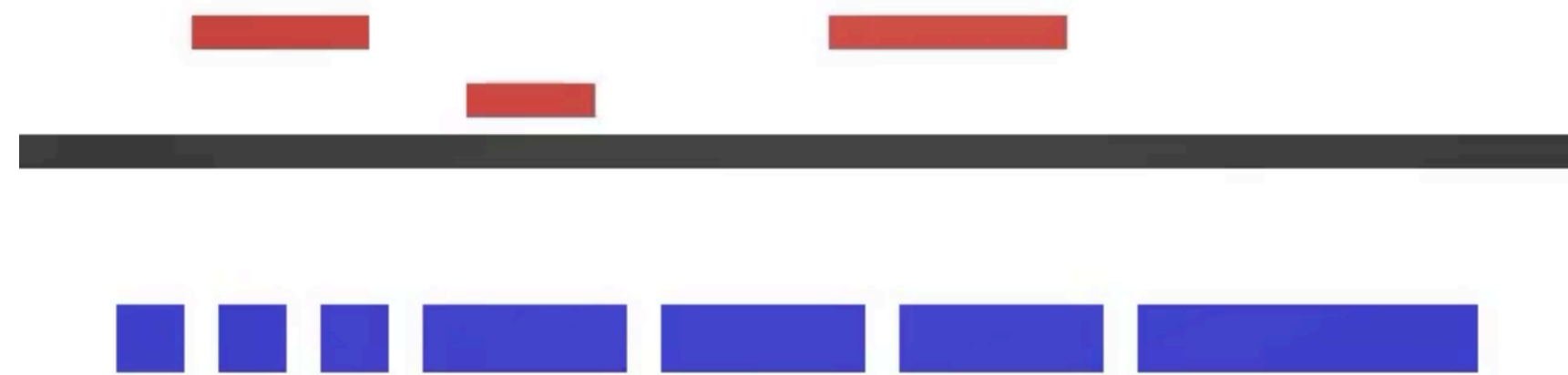


(Median across 10 seeds, with error bars for min/max seed)

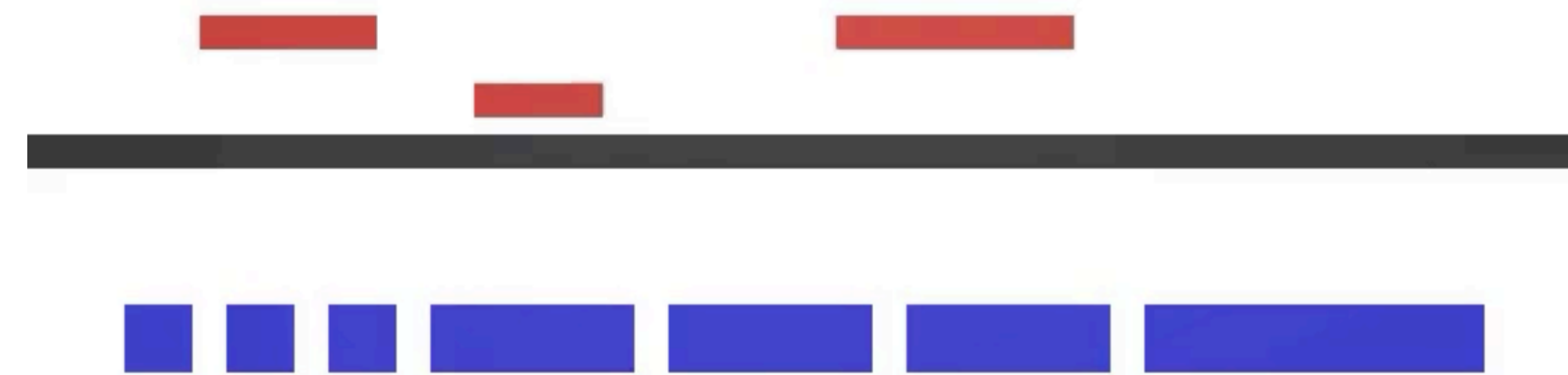


Covering Hard

Model-Free (GN-DQN)
Reward: 3.1



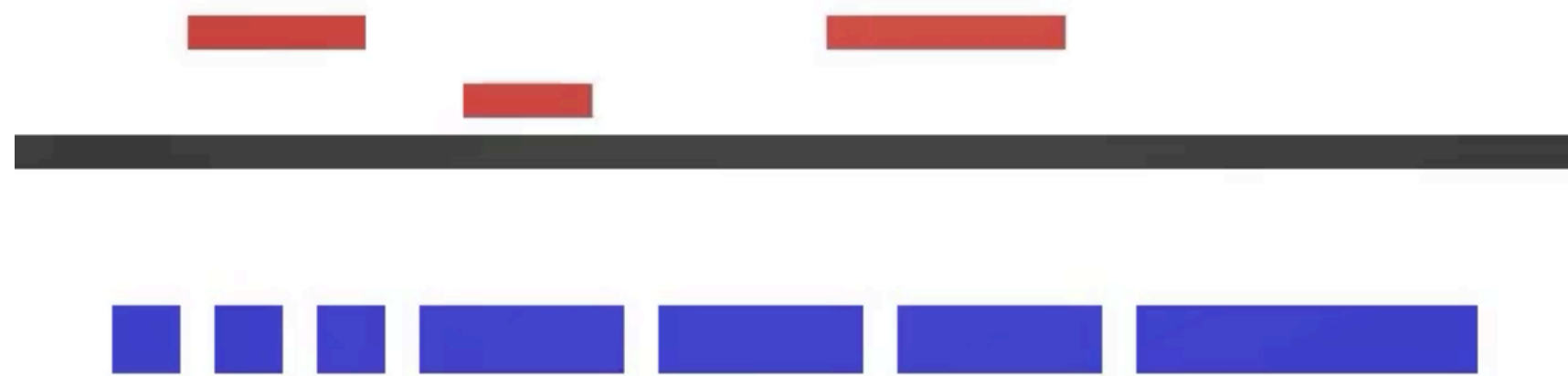
Model-Based (GN-DQN-MCTS)
Reward: 4.1



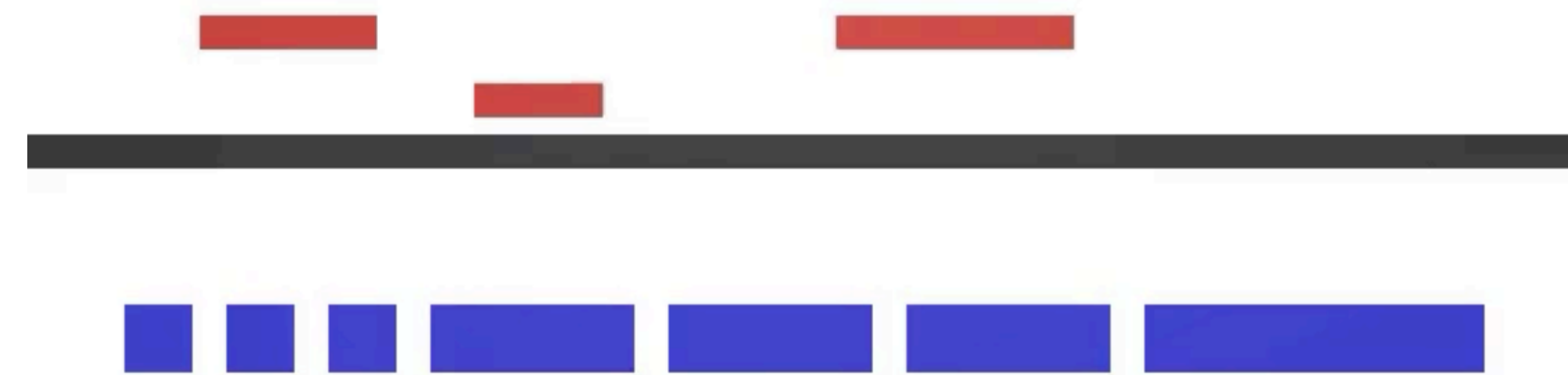
Reward: proportional to length covered, -0.5 per sticky block

Covering Hard

Model-Free (GN-DQN)
Reward: 3.1

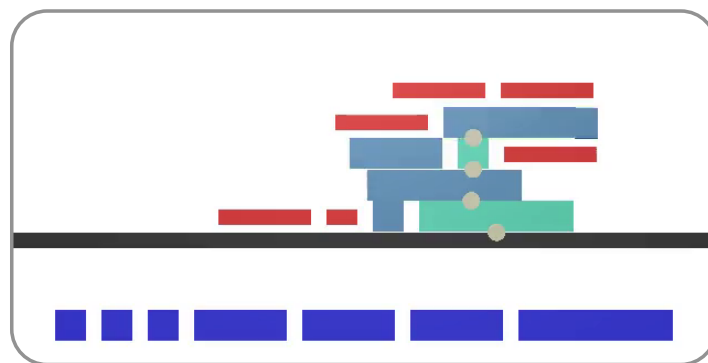


Model-Based (GN-DQN-MCTS)
Reward: 4.1

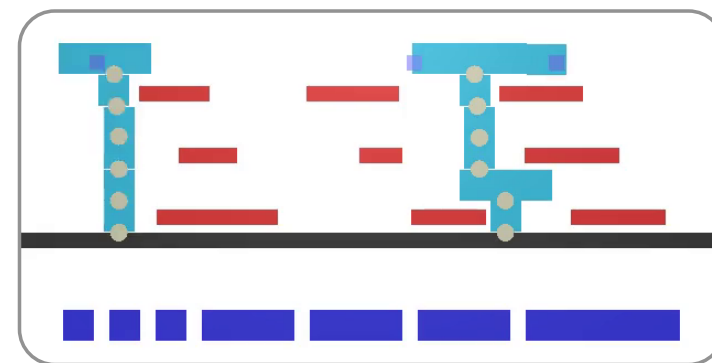


Reward: proportional to length covered, -0.5 per sticky block

Additional Results: Generalization

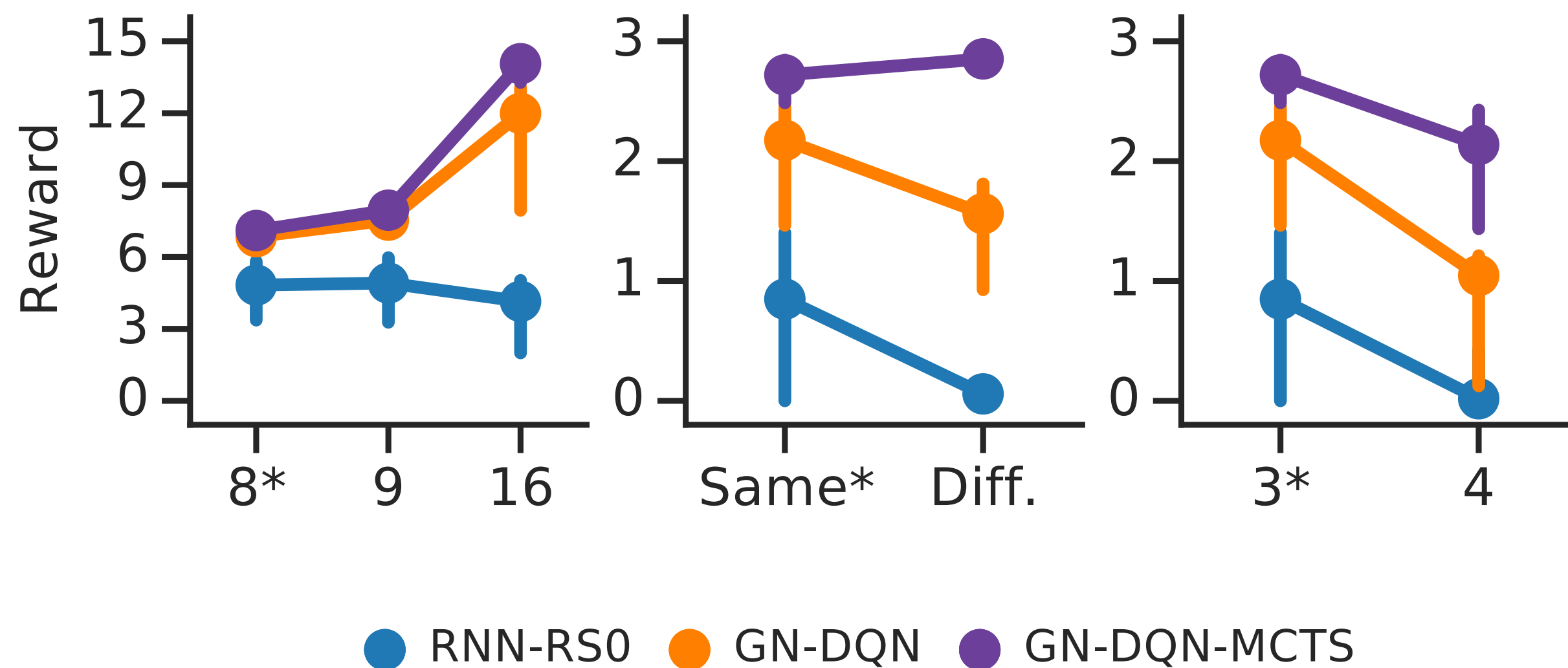


(a) Silhouette
Targets

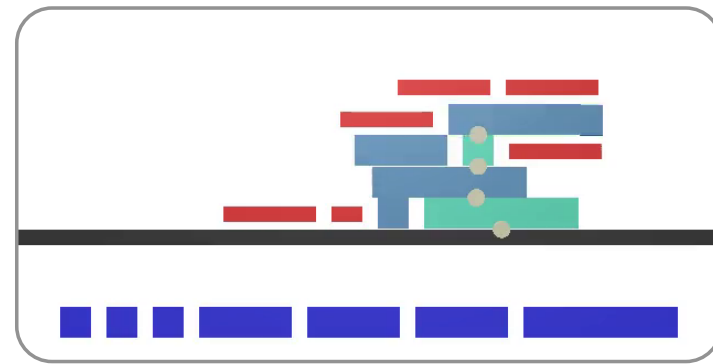


(b) Connecting
Target Locs.

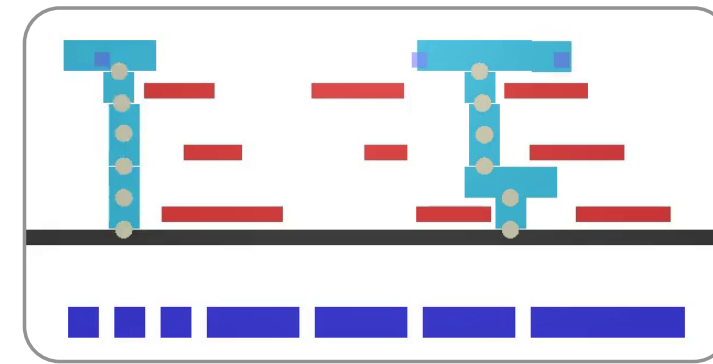
(c) Connecting
Layers



Additional Results: Generalization

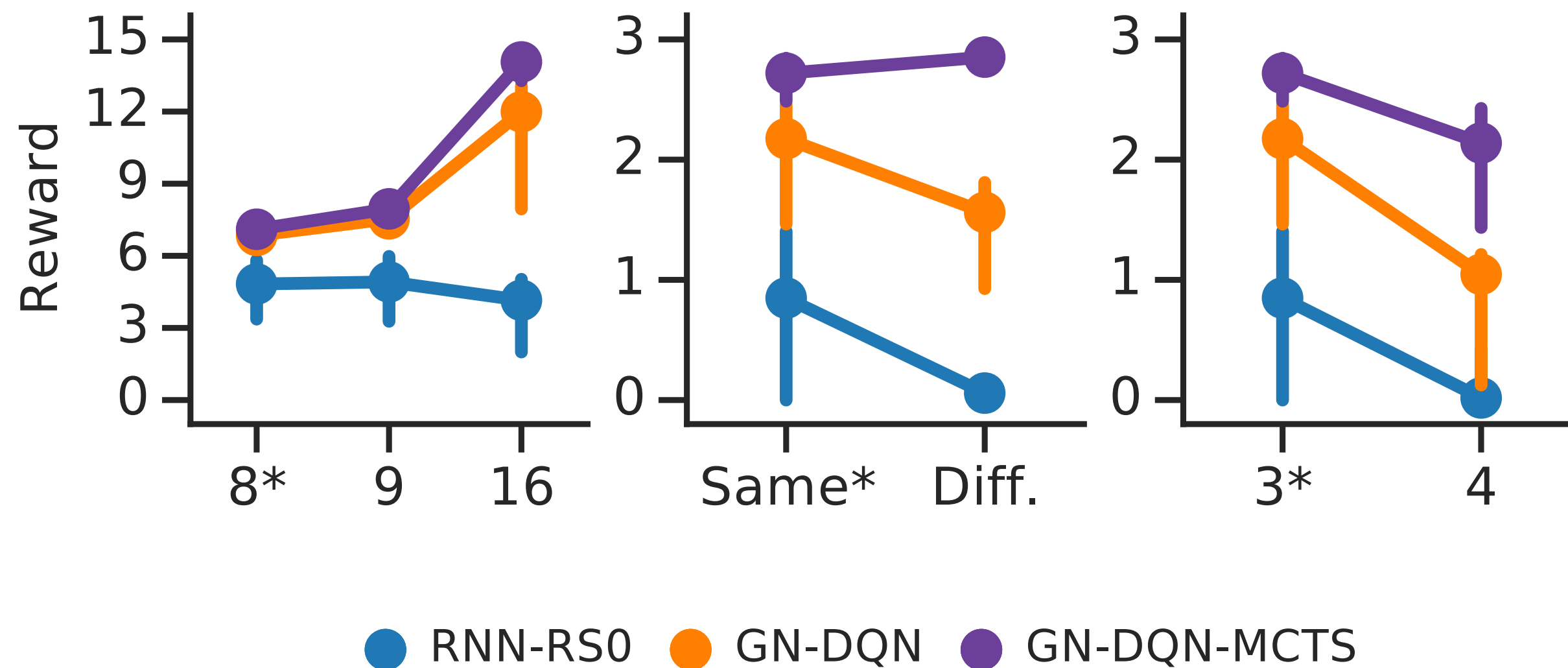


(a) Silhouette
Targets

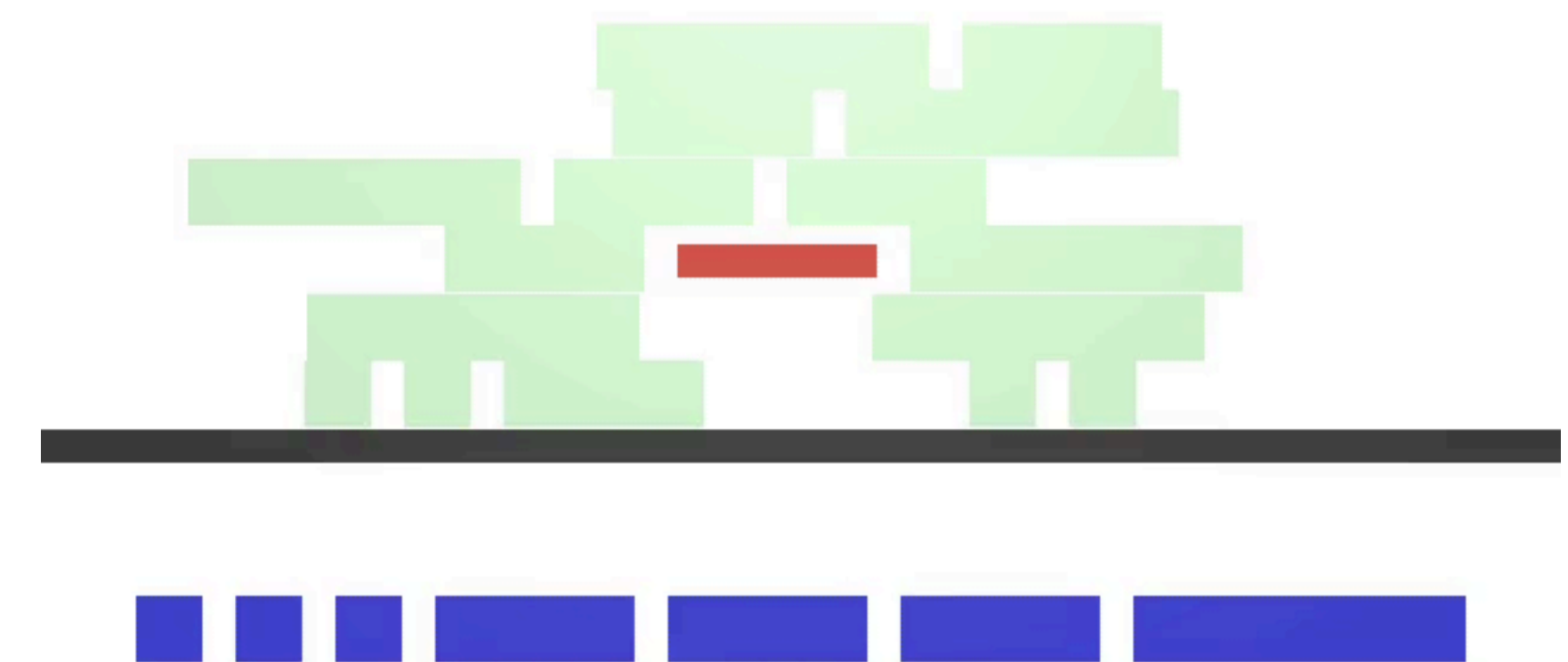


(b) Connecting
Target Locs.

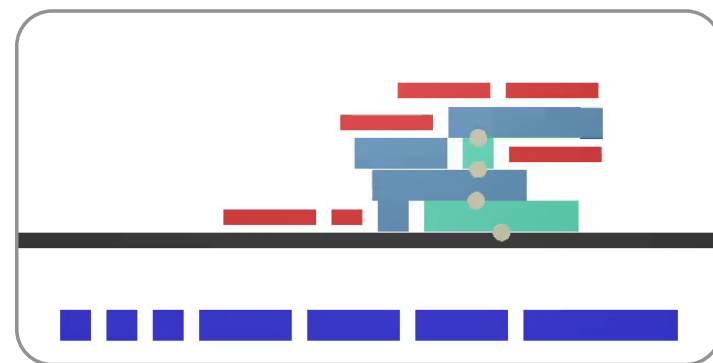
(c) Connecting
Layers



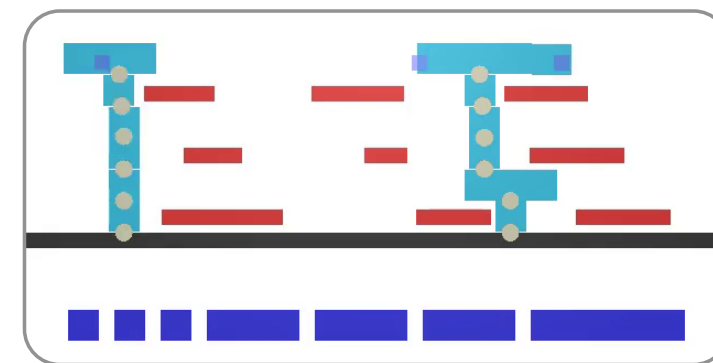
GN-DQN-MCTS
(Average reward: 14.25)



Additional Results: Generalization

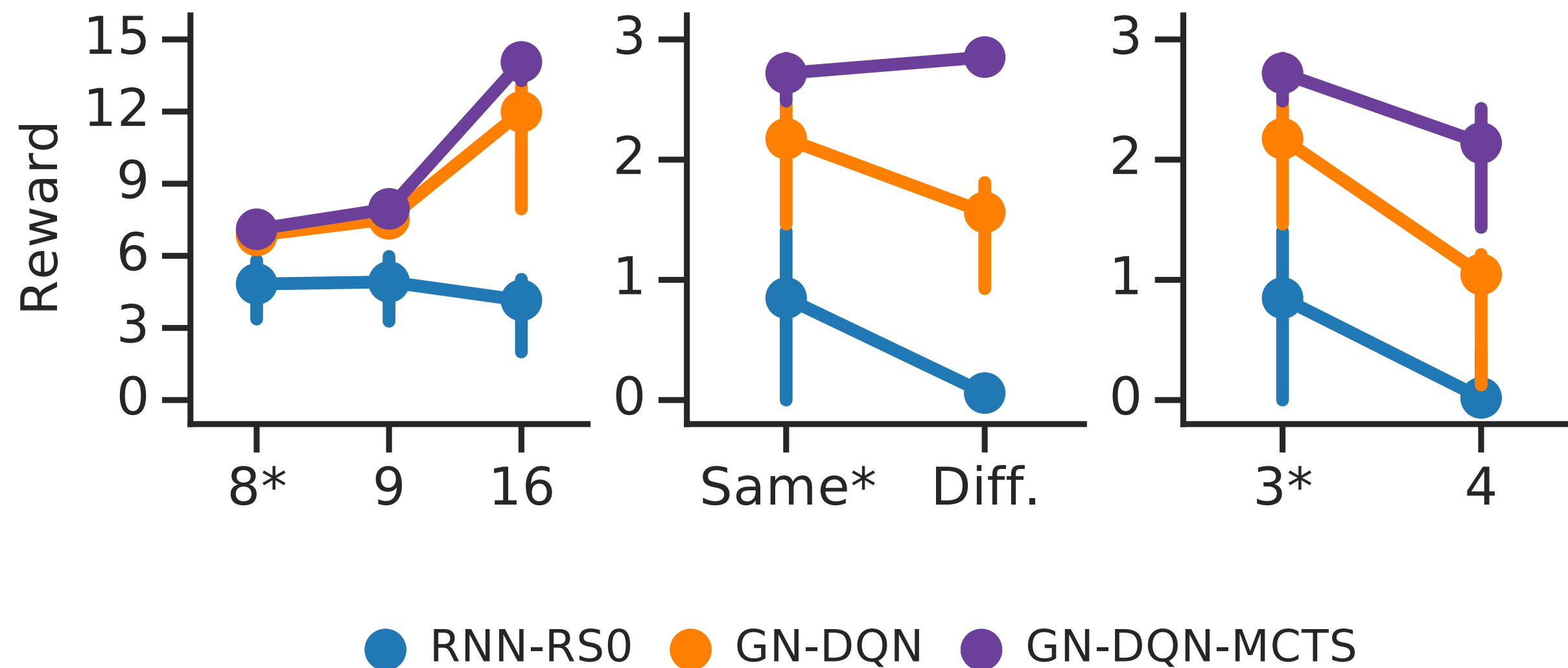


(a) Silhouette
Targets

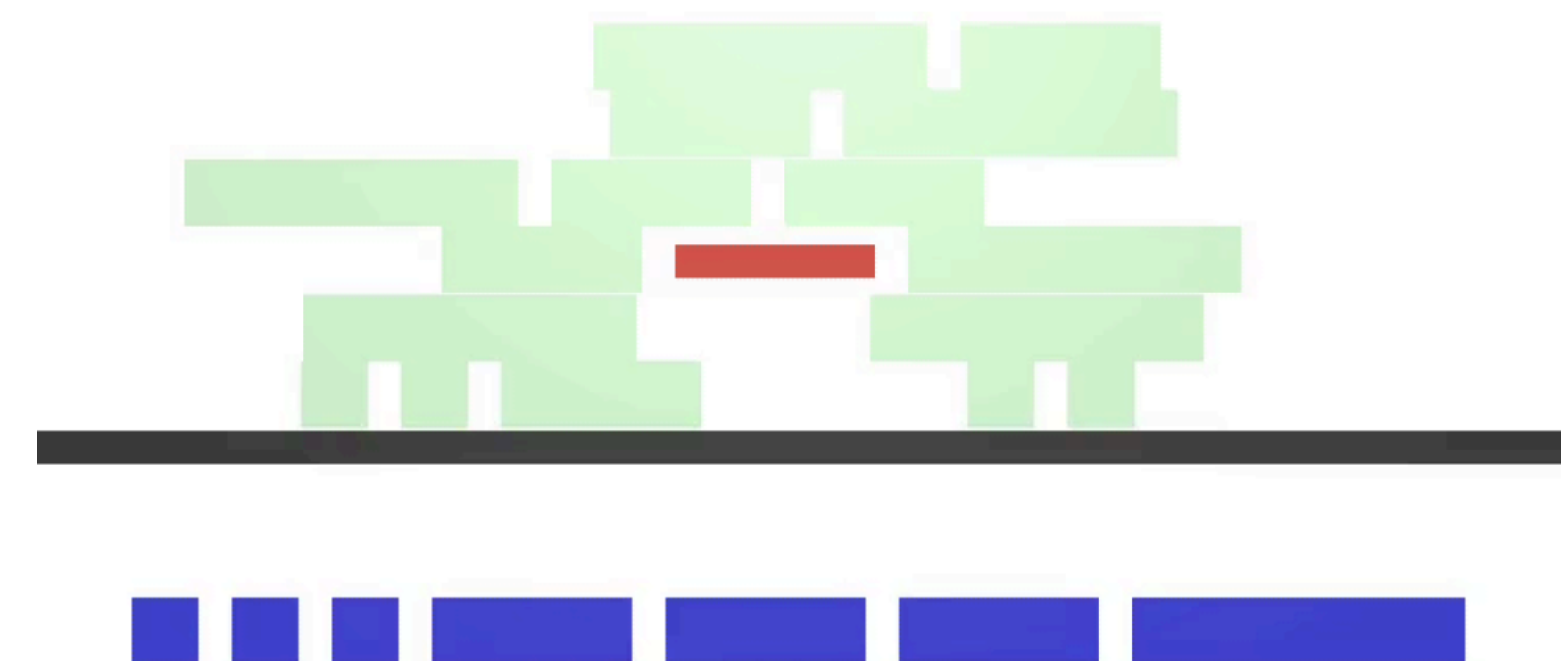


(b) Connecting
Target Locs.

(c) Connecting
Layers



GN-DQN-MCTS
(Average reward: 14.25)



Key Questions

1. What is the contribution of *relative* vs. absolute actions?
2. What is the contribution of *structured* representations?
3. What is the contribution of *planning*?

Key Questions

1. What is the contribution of **relative** vs. absolute actions?

80-130% *improvement*

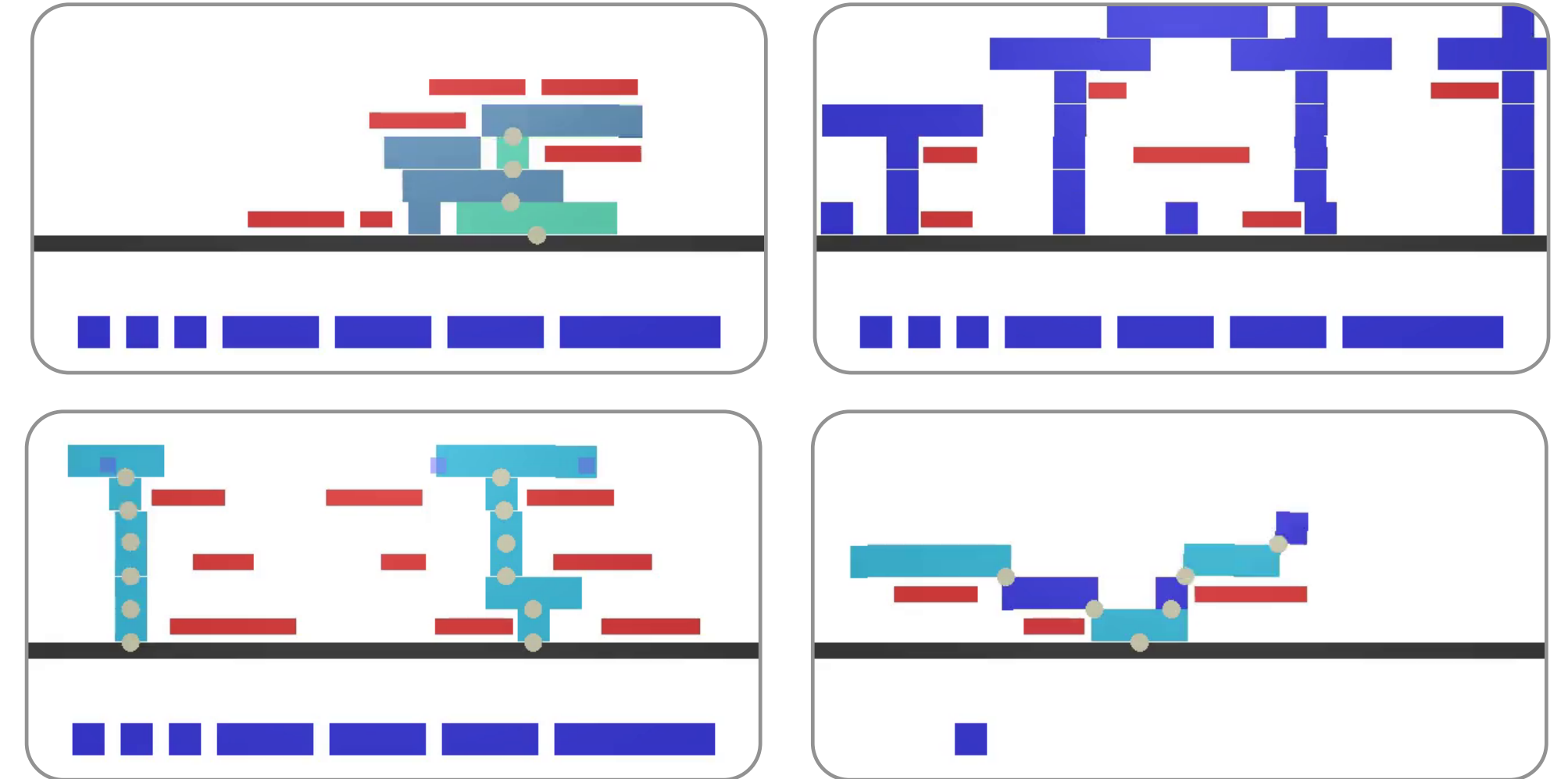
2. What is the contribution of **structured** representations?

25-155% *improvement*

3. What is the contribution of **planning**?

28% *improvement (Covering Hard)*

1. A suite of challenging **construction tasks**
2. A new type of **structured agent** that uses:
 - structured representations
 - object-centric relative actions
 - combination of model-free and model-based



Only the beginning! Next steps: bigger scenes, harder tasks, more interesting physics, connecting with perception and control, learning environment models, etc.

Come see the poster tonight: Pacific Ballroom #36

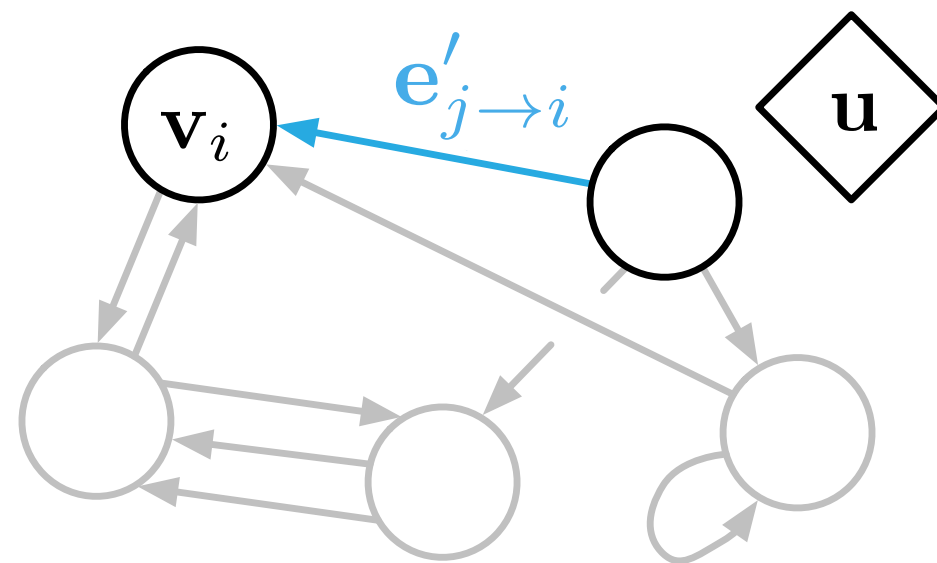
Extra slides

Graph Networks

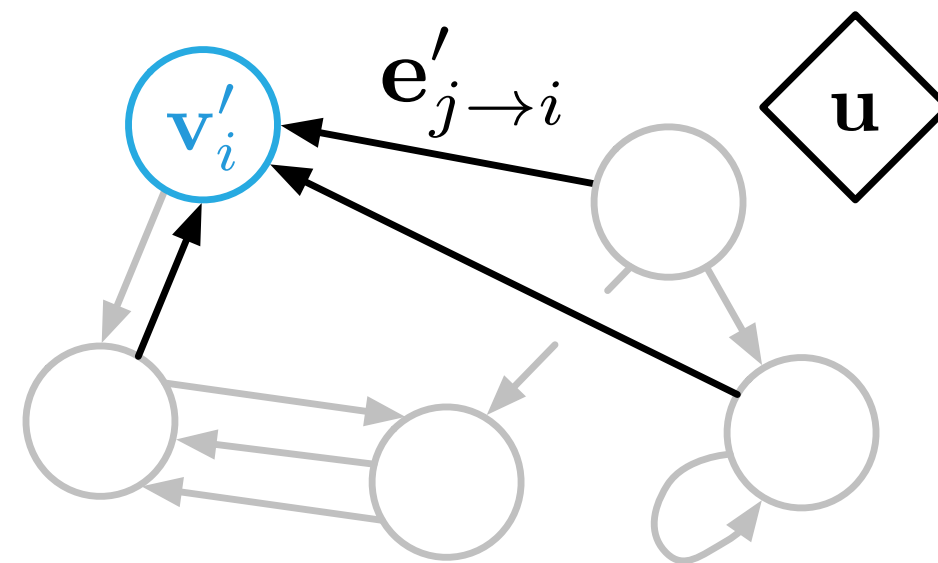
Battaglia, Hamrick, Bapst, Sanchez-Gonzalez, Zambaldi, et al. (*arXiv* 2018)

Edges	Nodes	Globals
E	V	\mathbf{u}

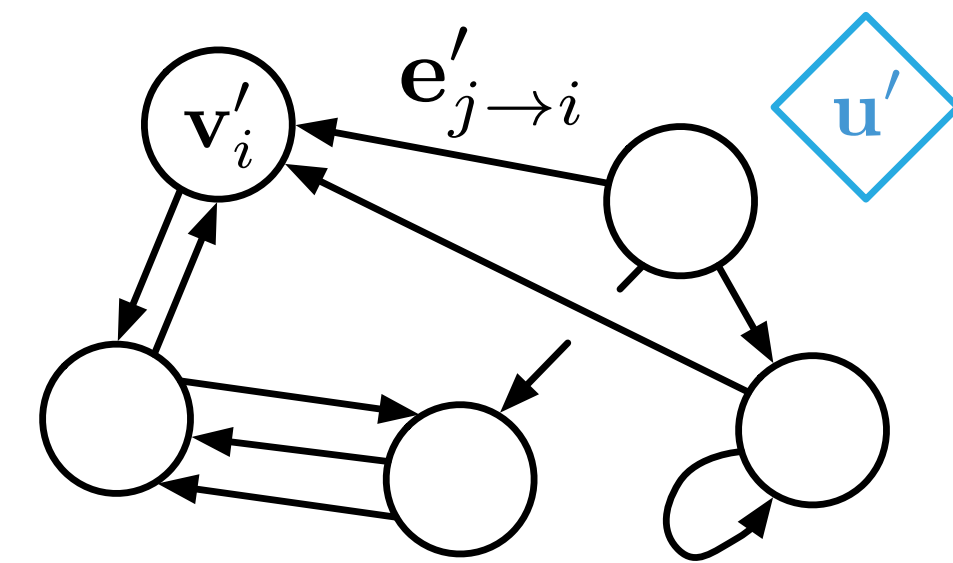
Edge update



Node update



Globals update

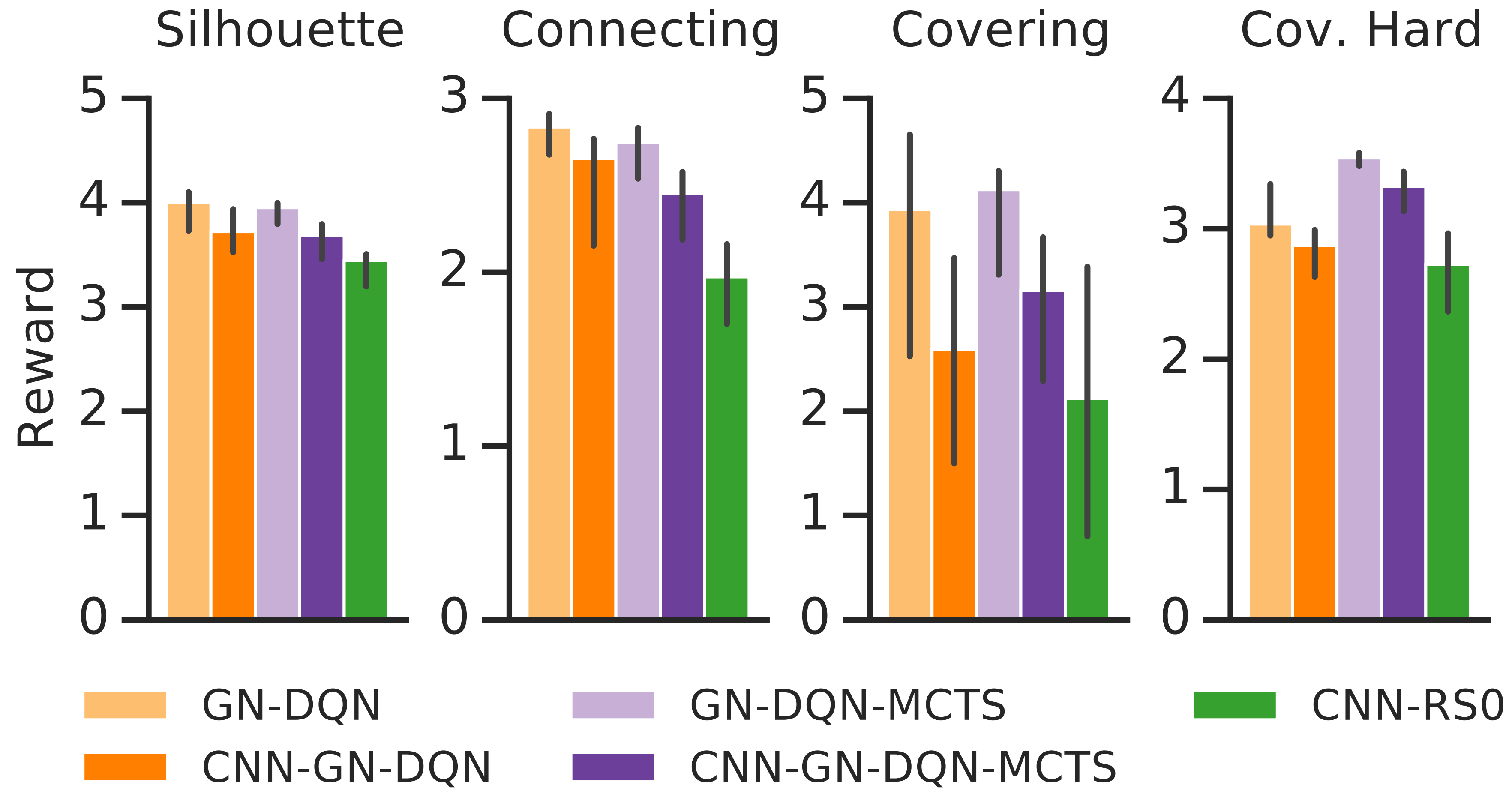


$$\mathbf{e}'_{i \rightarrow j} = \phi_e(\mathbf{v}_i, \mathbf{v}_j, \mathbf{e}_{i \rightarrow j}, \mathbf{u})$$

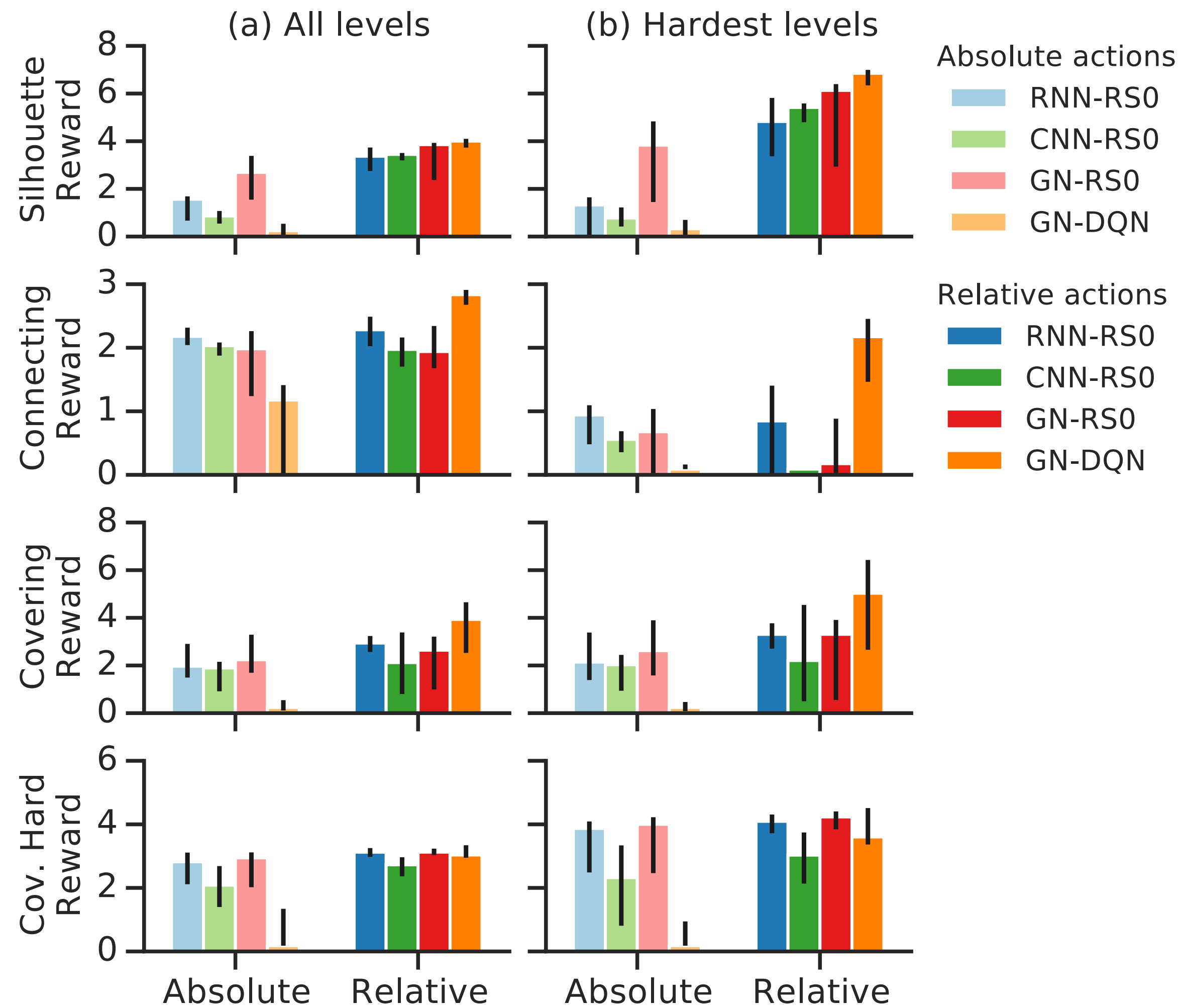
$$\mathbf{v}'_i = \phi_v(\mathbf{v}_i, \sum_j \mathbf{e}'_{j \rightarrow i}, \mathbf{u})$$

$$\mathbf{u}' = \phi_u(\sum_i \mathbf{v}'_i, \sum_{i,j} \mathbf{e}'_{i \rightarrow j}, \mathbf{u})$$

CNN comparison



Full Comparison



More Comparisons

