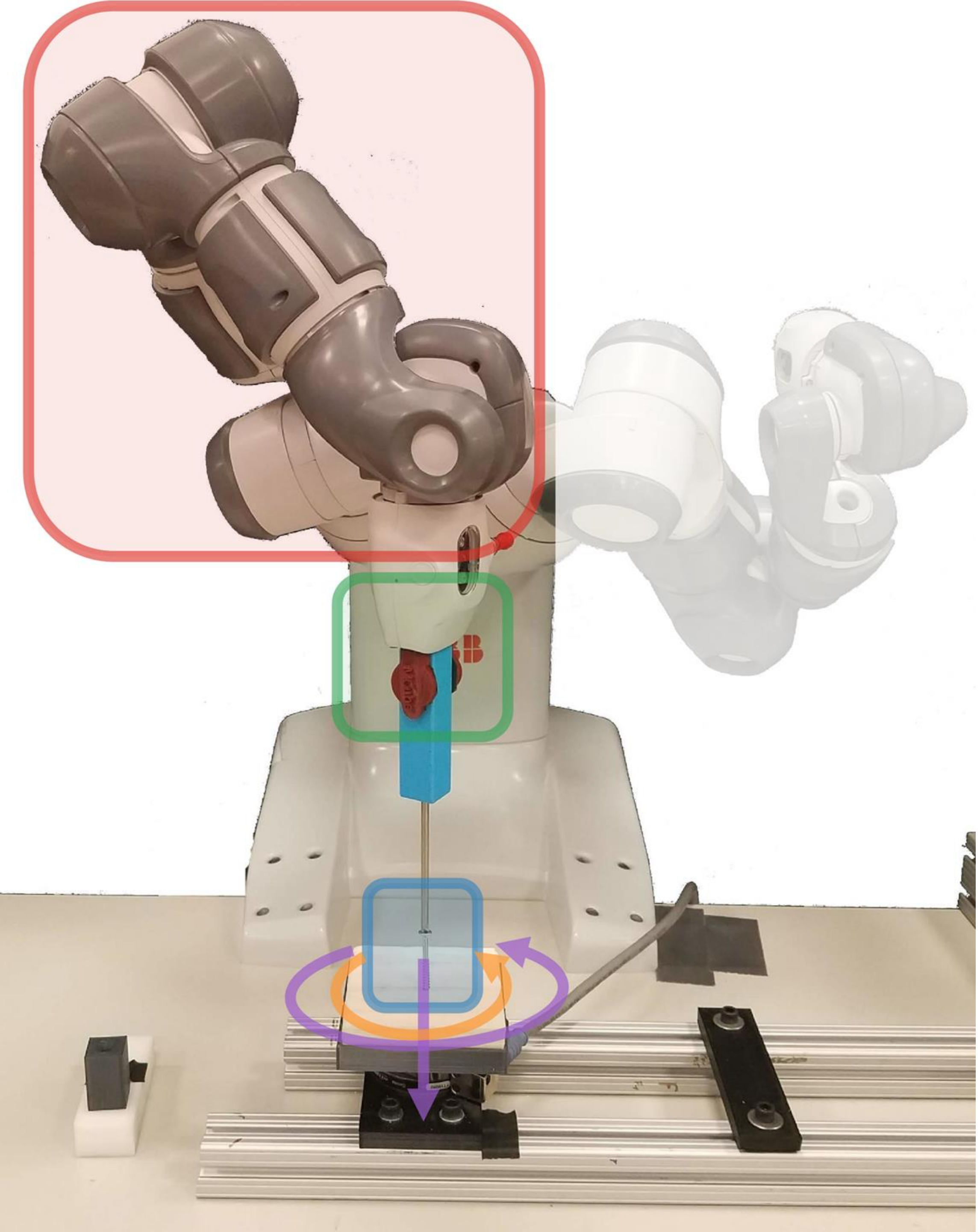


Force-and-Motion Constrained Planning for Tool Use

Rachel Holladay

Research Qualifying Exam
December 2019


123RF


3/4

Forceful Manipulation

Forceful Manipulation with Hand Tools

Animal Tool Use

B. B. Beck, Animal tool behavior. Garland STPM Pub., 1980.

Animal Tool Use

1. Extending reach

B. B. Beck, Animal tool behavior. Garland STPM Pub., 1980.

Animal Tool Use

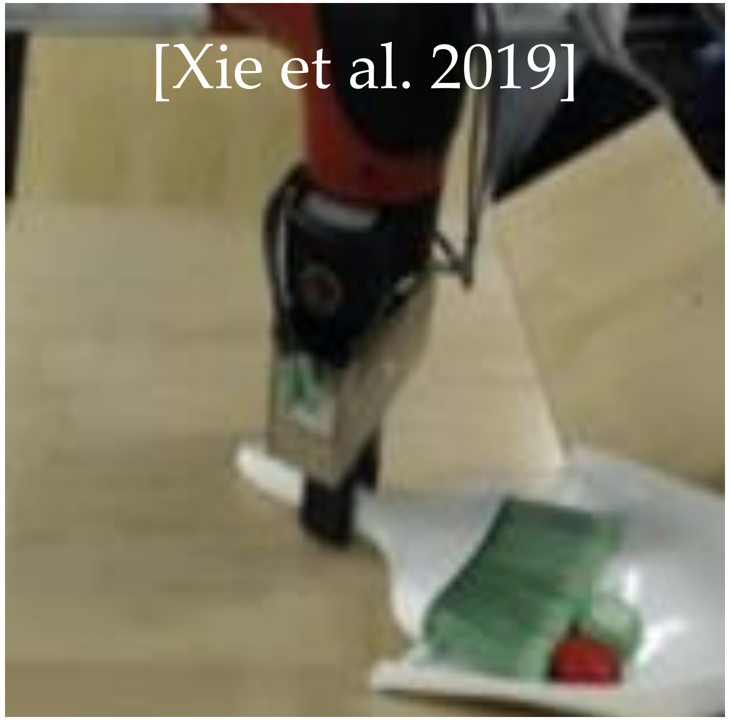
1. Extending reach

Sinapov et al. `08, Tikhanoff et al. `13, Jain et al. `14, Elliott et al. `16, Xie et al. `19

B. B. Beck, Animal tool behavior. Garland STPM Pub., 1980.

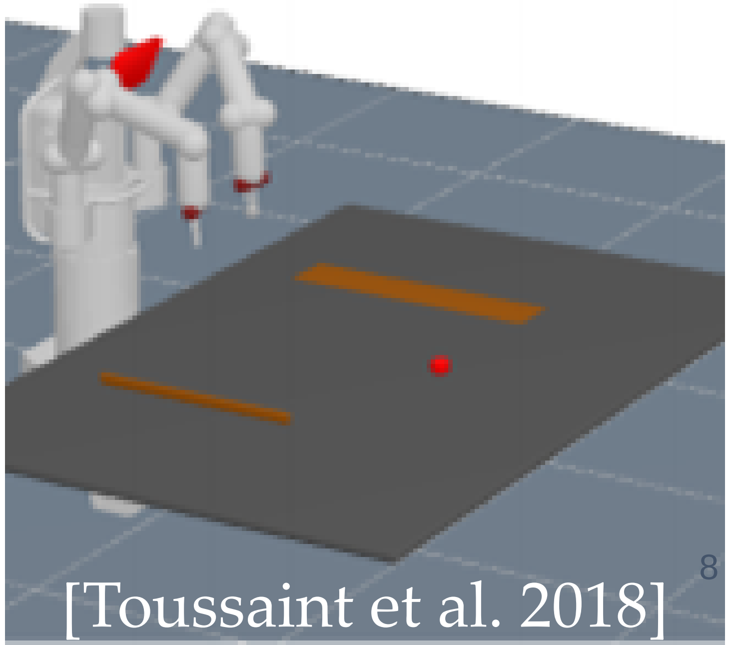

[Sinapov, Stoytchev 2008]


[Elliott et al. 2016]


[Xie et al. 2019]


[Antunes et al. 2015]


Goal
[Jain, Inamura 2014]


[Toussaint et al. 2018]

Animal Tool Use

1. Extending reach
2. Amplifying mechanical force

Sinapov et al. `08, Tikhanoff et al. `13, Jain et al. `14, Elliott et al. `16, Xie et al. `19

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Animal Tool Use

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4. Enhance effectiveness of antagonistic displays

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What does it mean to use a tool?

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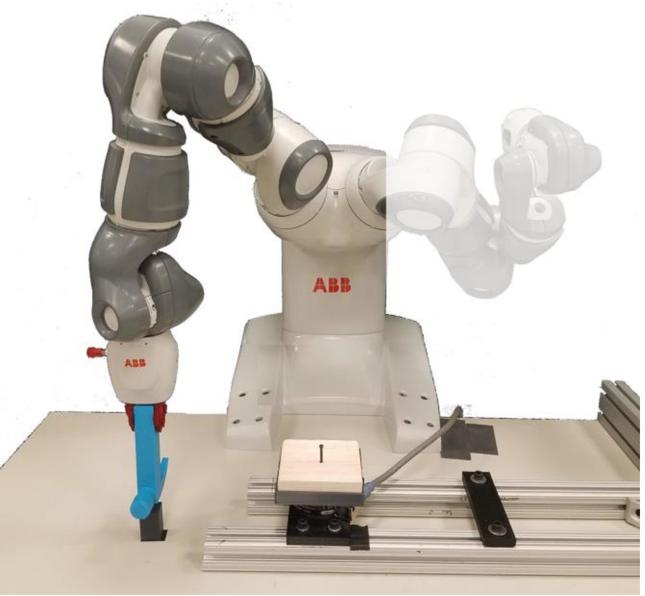
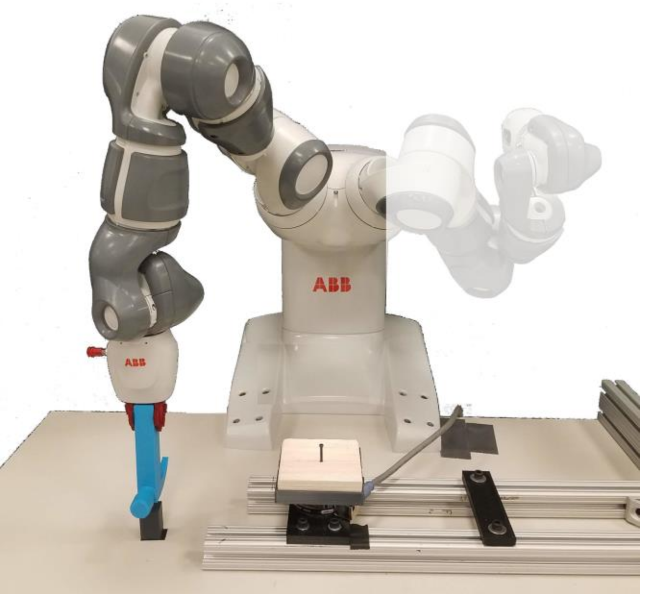
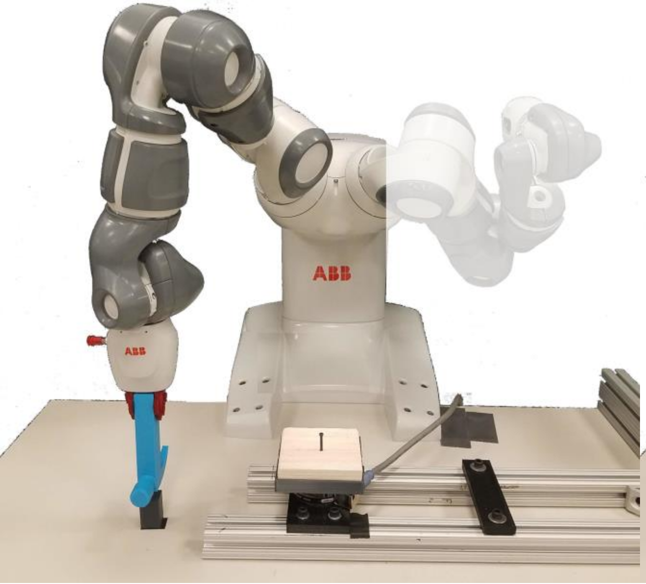


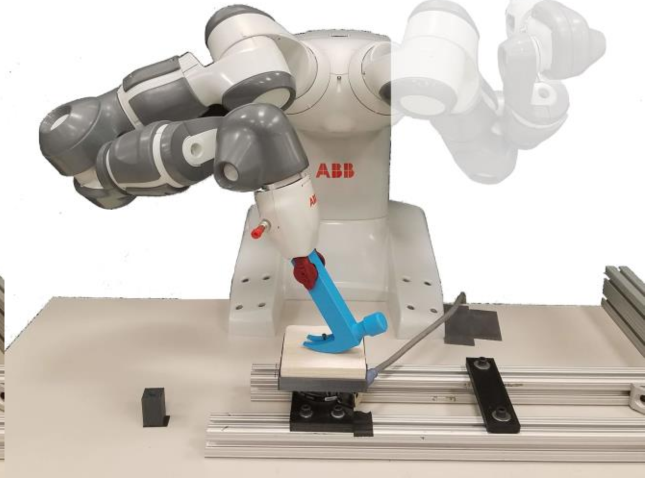
What does it mean to use a tool?



Grasp

What does it mean to use a tool?

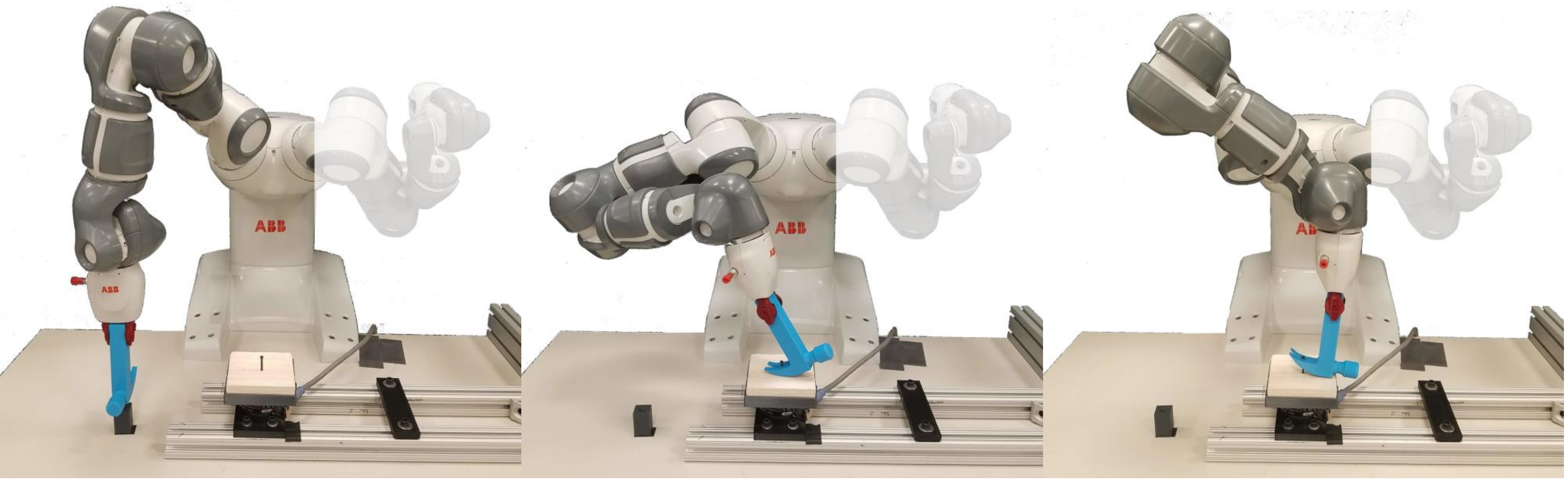




Grasp

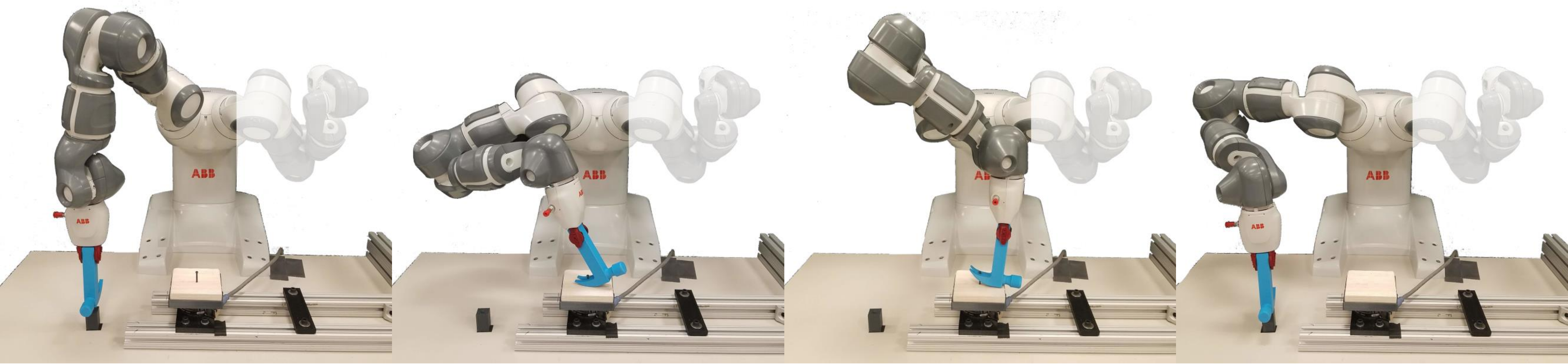
Engage

What does it mean to use a tool?



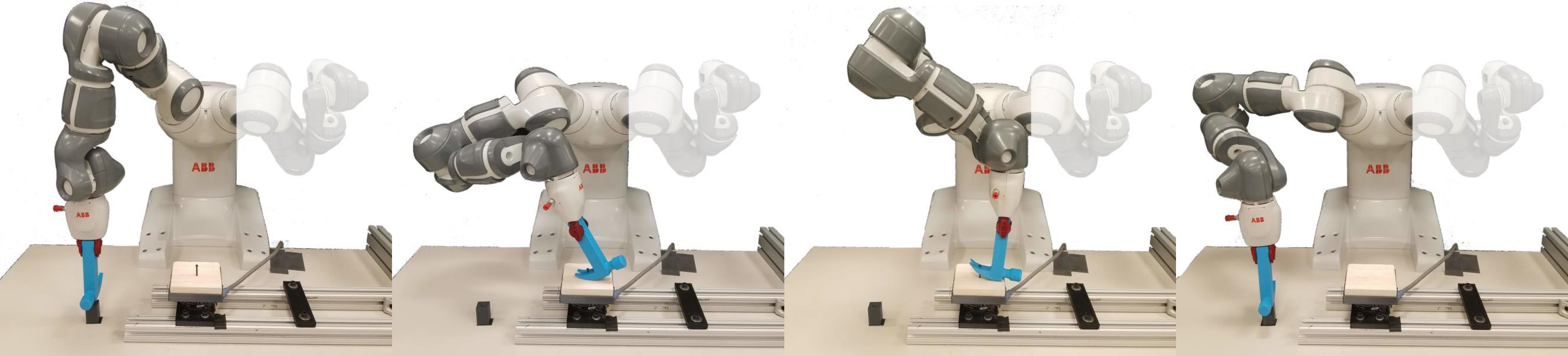
Grasp Engage Actuate

What does it mean to use a tool?



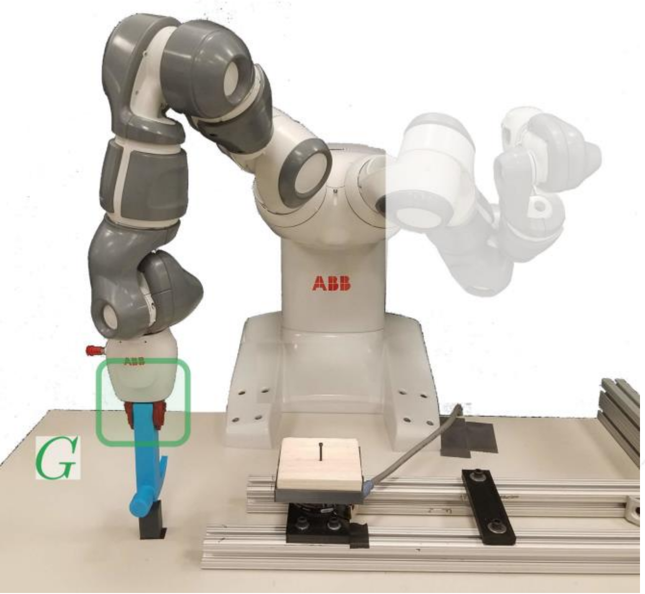
Grasp Engage Actuate Place

Existing Methods?



Grasp Engage Actuate Place

Existing Methods



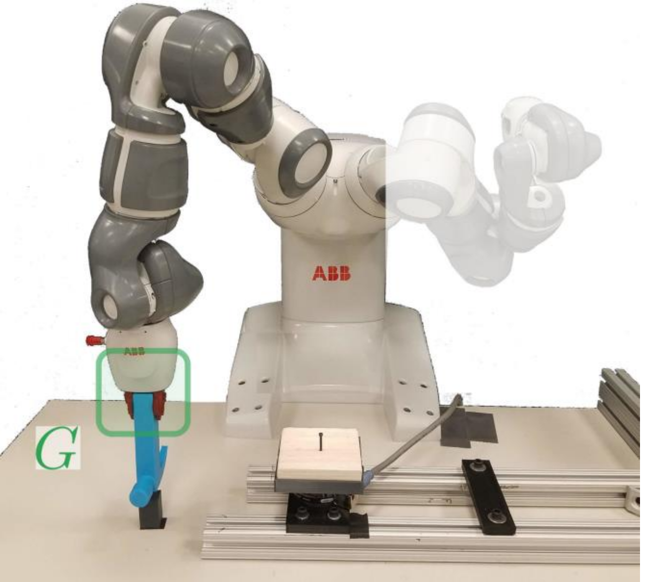
Grasp

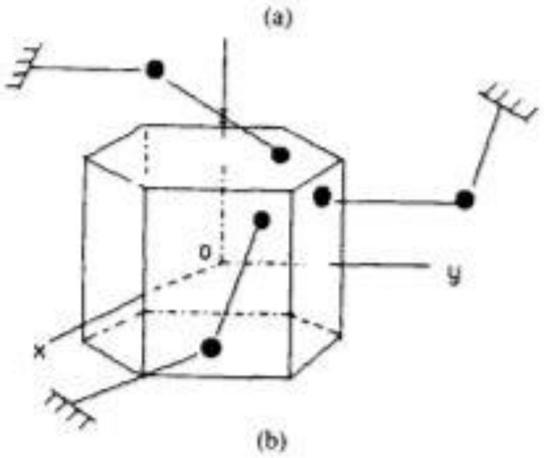
Engage

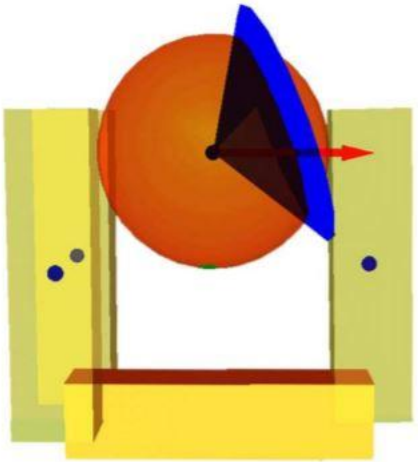
Actuate

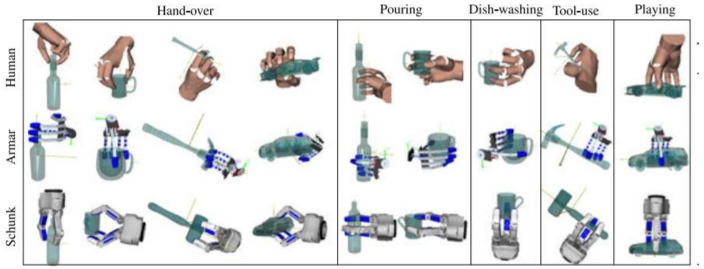
Place

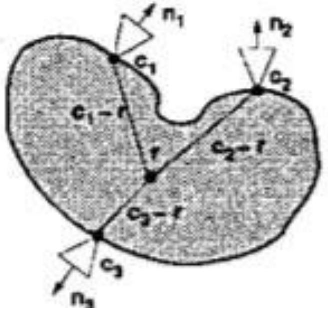
Task-Oriented Grasping

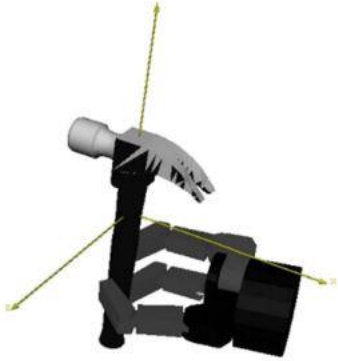


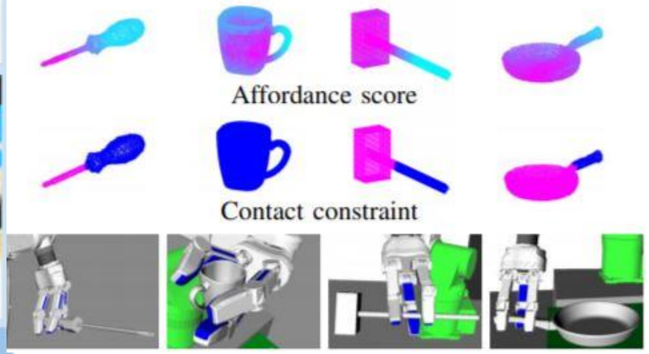






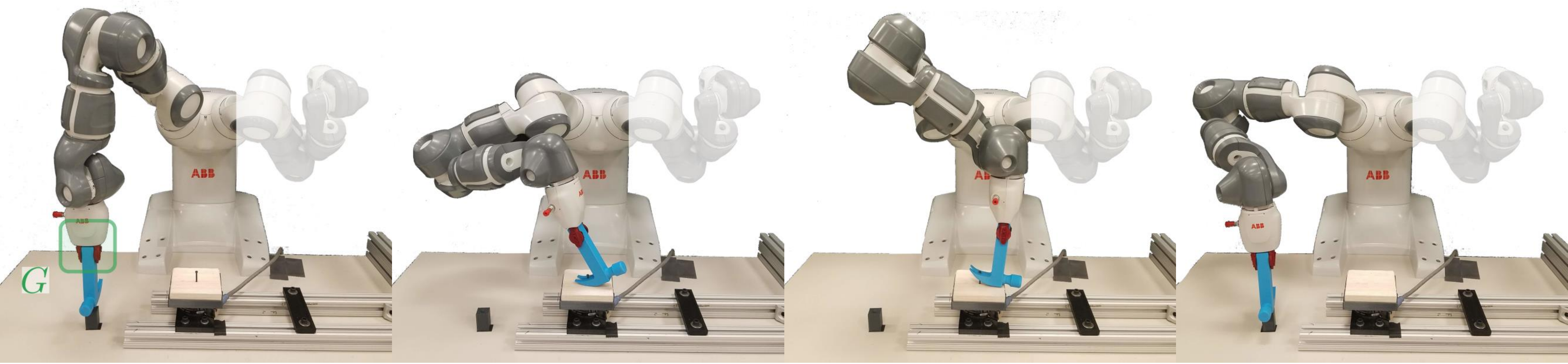






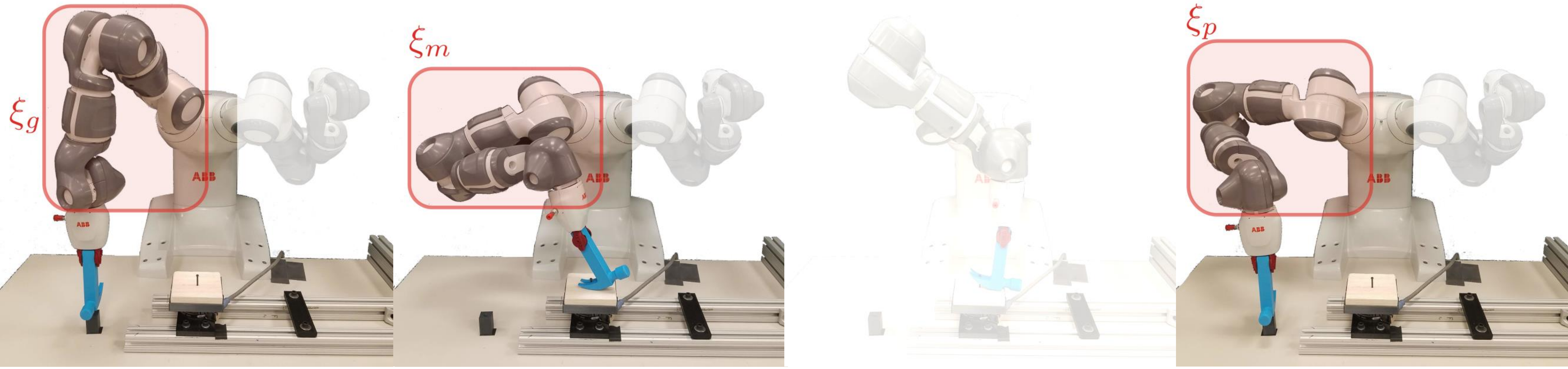
Li and Sastry 1988. Borst et al 2004. Haschke et al 2005. Song et al 2015. Nikandrova and Kyrki 2015. Lin and Sun 2015. Kokic et al 2017. Fang et al 2018.

Existing Methods



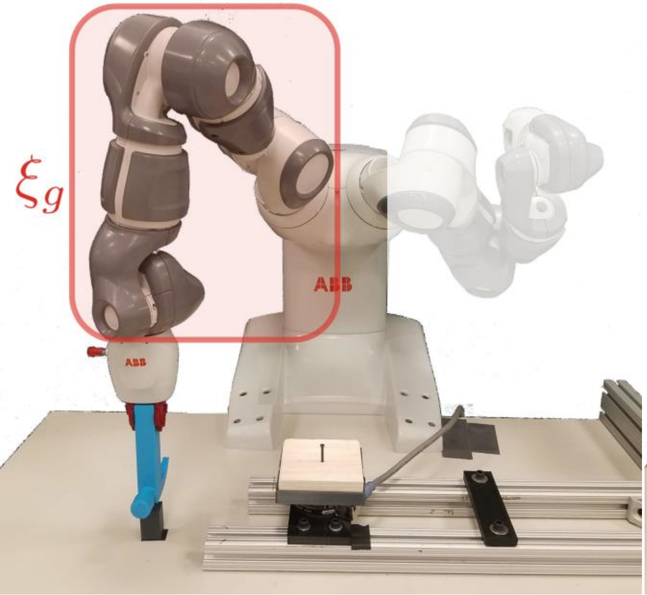
Grasp Engage Actuate Place

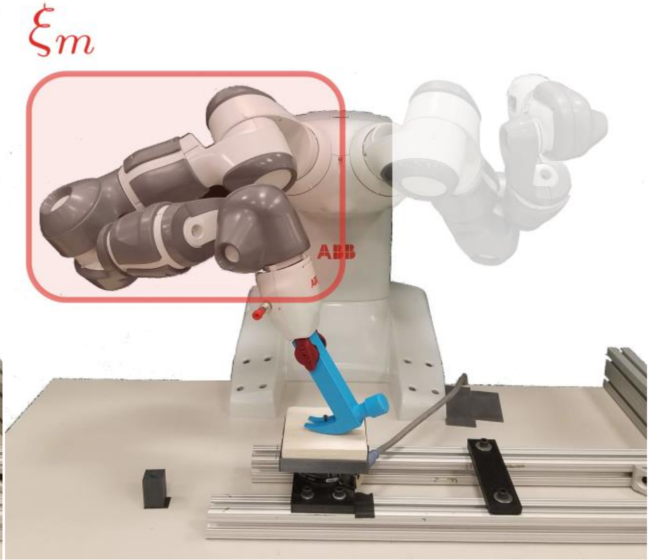
Existing Methods

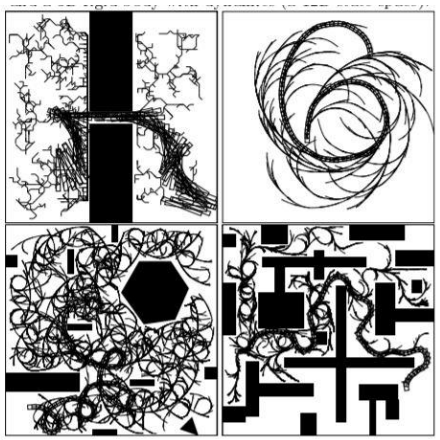


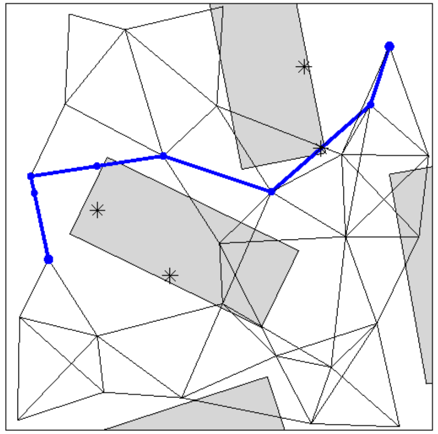
Grasp Engage Actuate Place

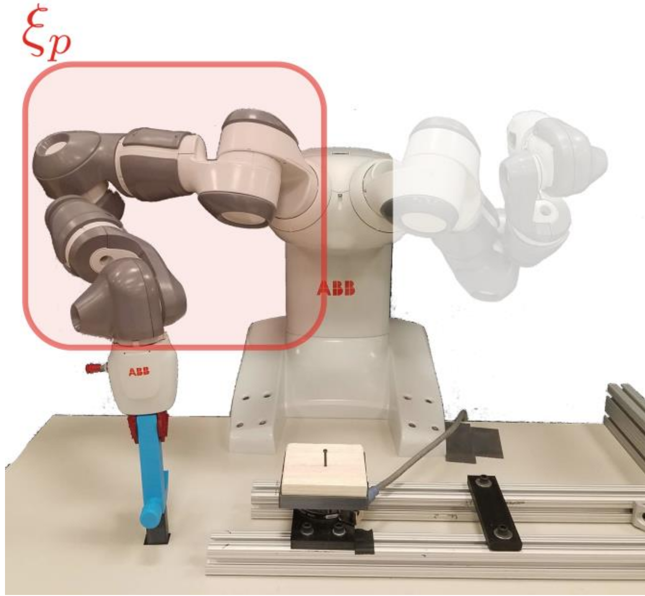
Collision-Free Planning

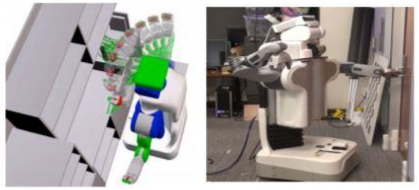


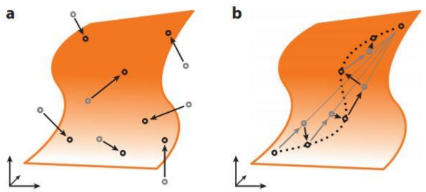


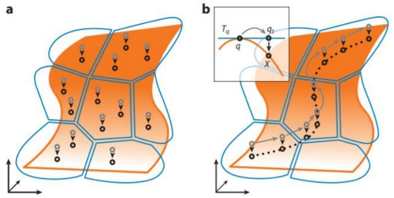


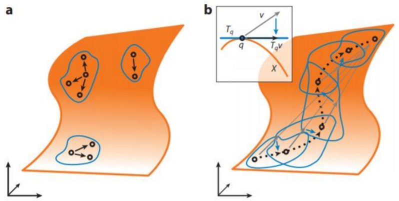






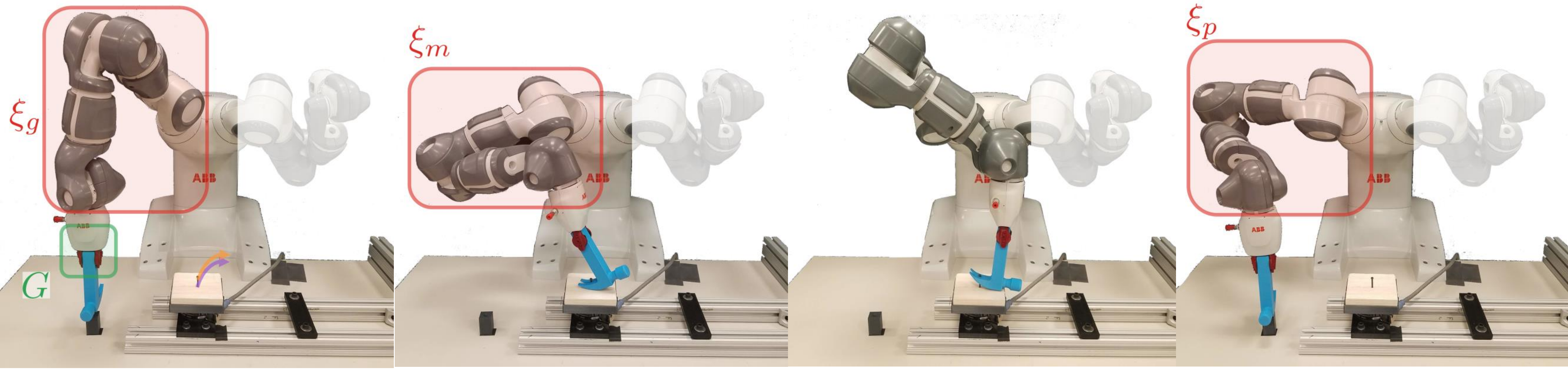






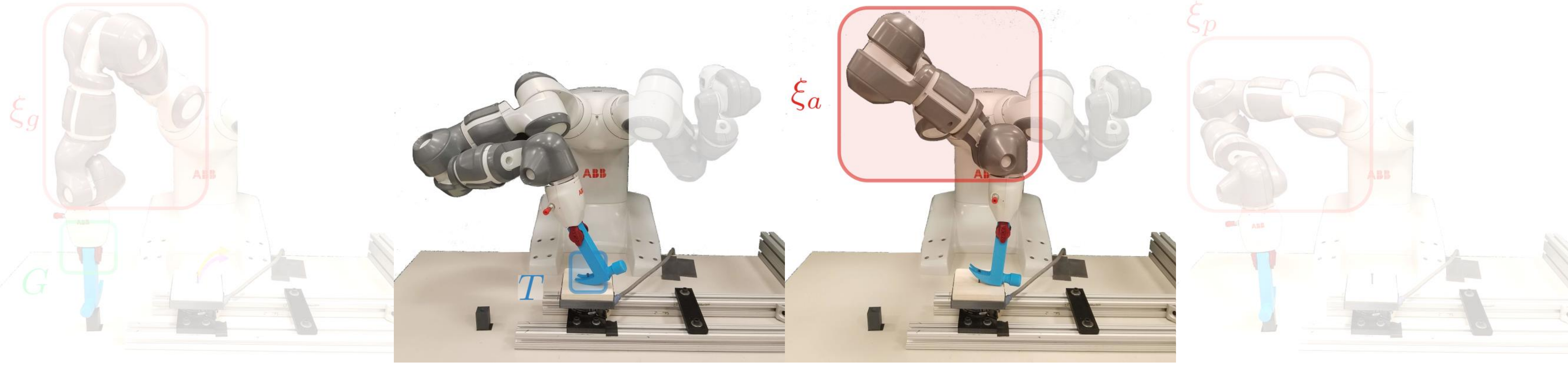
Lavalle 1996. Kingston 2018. Siciliano and Khatib 2016. Schulman et al 2013. etc., etc.

Existing Methods



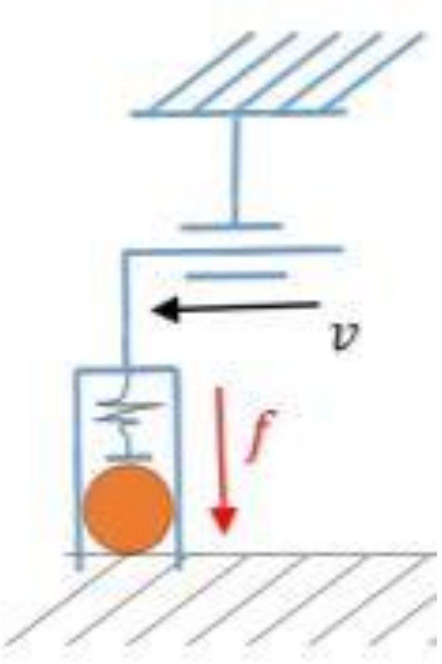
Grasp Engage Actuate Place

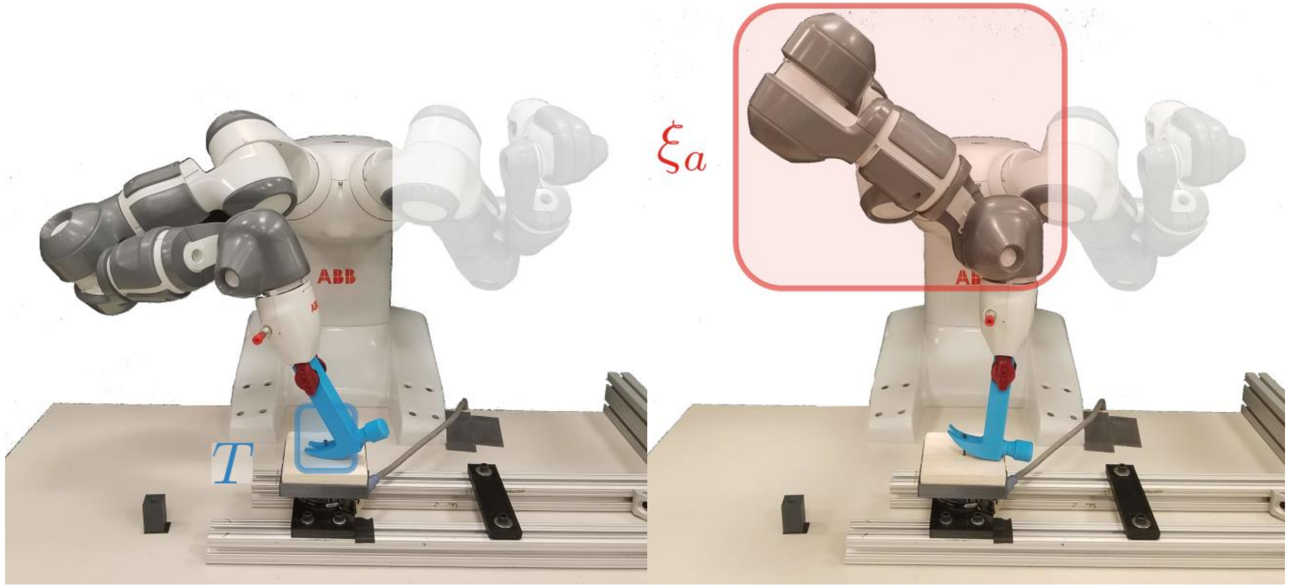
Existing Methods



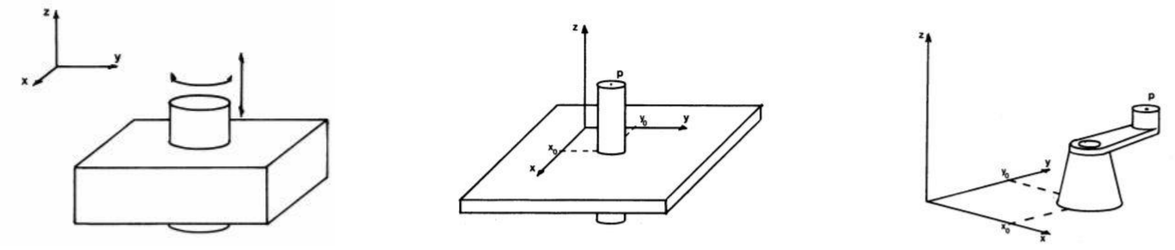
Grasp Engage Actuate Place

Hybrid Position-Force Control

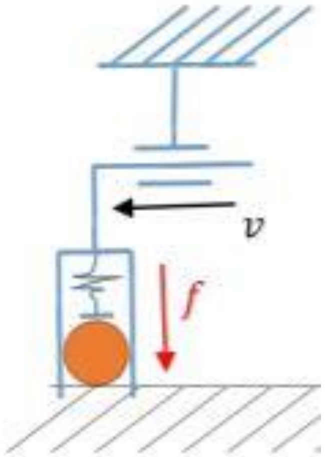


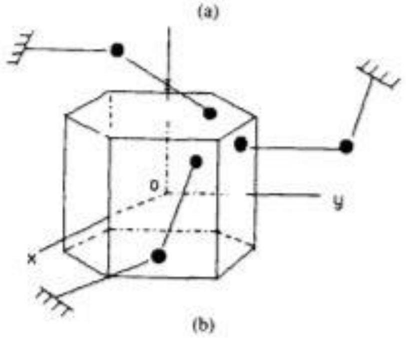


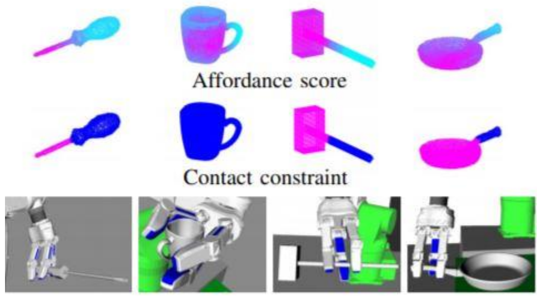
Move compliantly
with task frame
defined fixed to the end-effector,
at the tip of the screwdriver
with task-frame directions:
x_t: force: 0 N
y_t: velocity: 0 mm/s
z_t: force: $-F$ N
α_{xt}: force: 0 N mm
α_{yt}: force: 0 N mm
α_{zt}: velocity: $-\omega$ rad/s
with feedforward velocity frame equal to end-effector frame
and feedforward velocity (0,0,-pitch*ω/2π,0,0,0)
until z_{ee} exceeds s mm
and α_{zt} force equals T N mm.

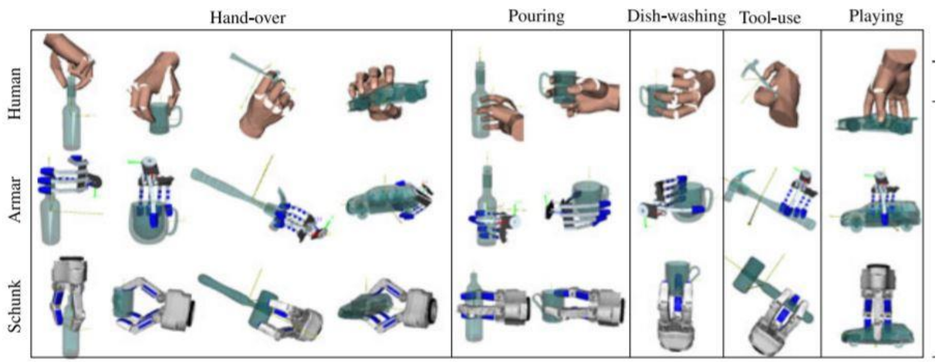


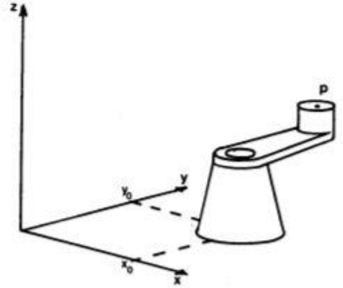
Mason, 1981. De Schetter and Van Brussel 1988. Hou and Mason 2019.

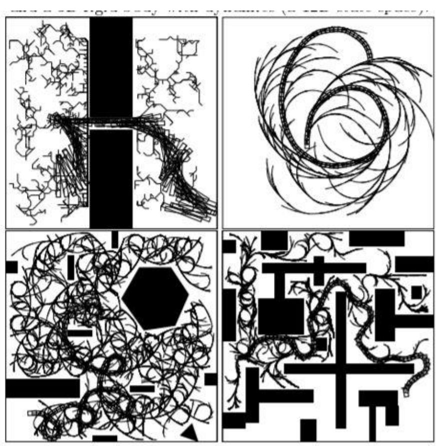


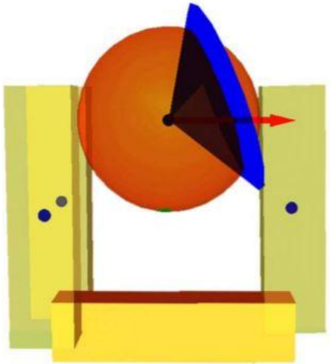


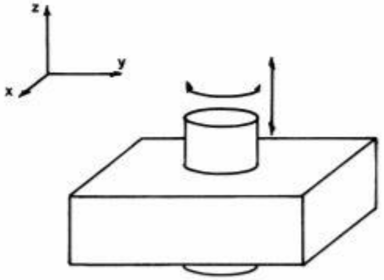












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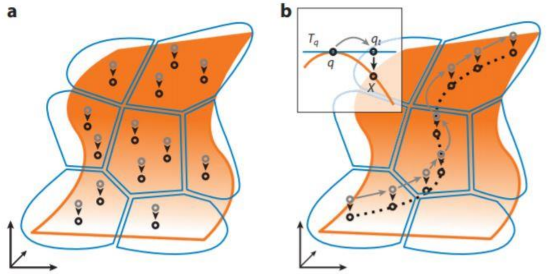
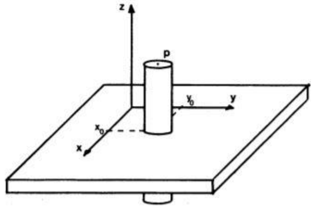
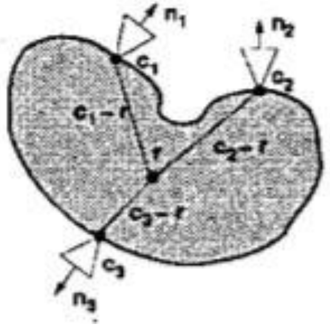
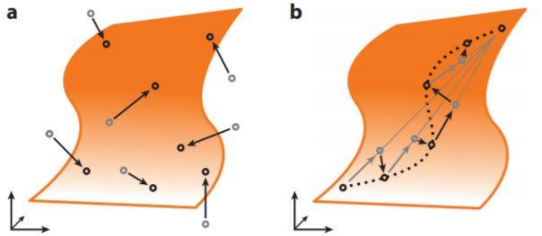
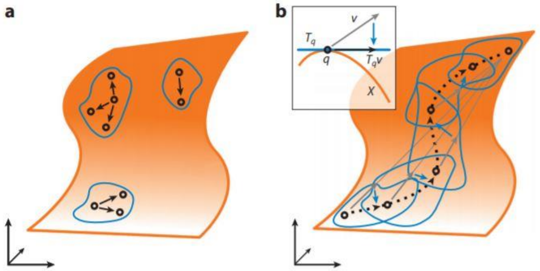
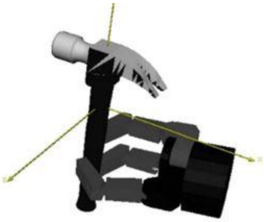




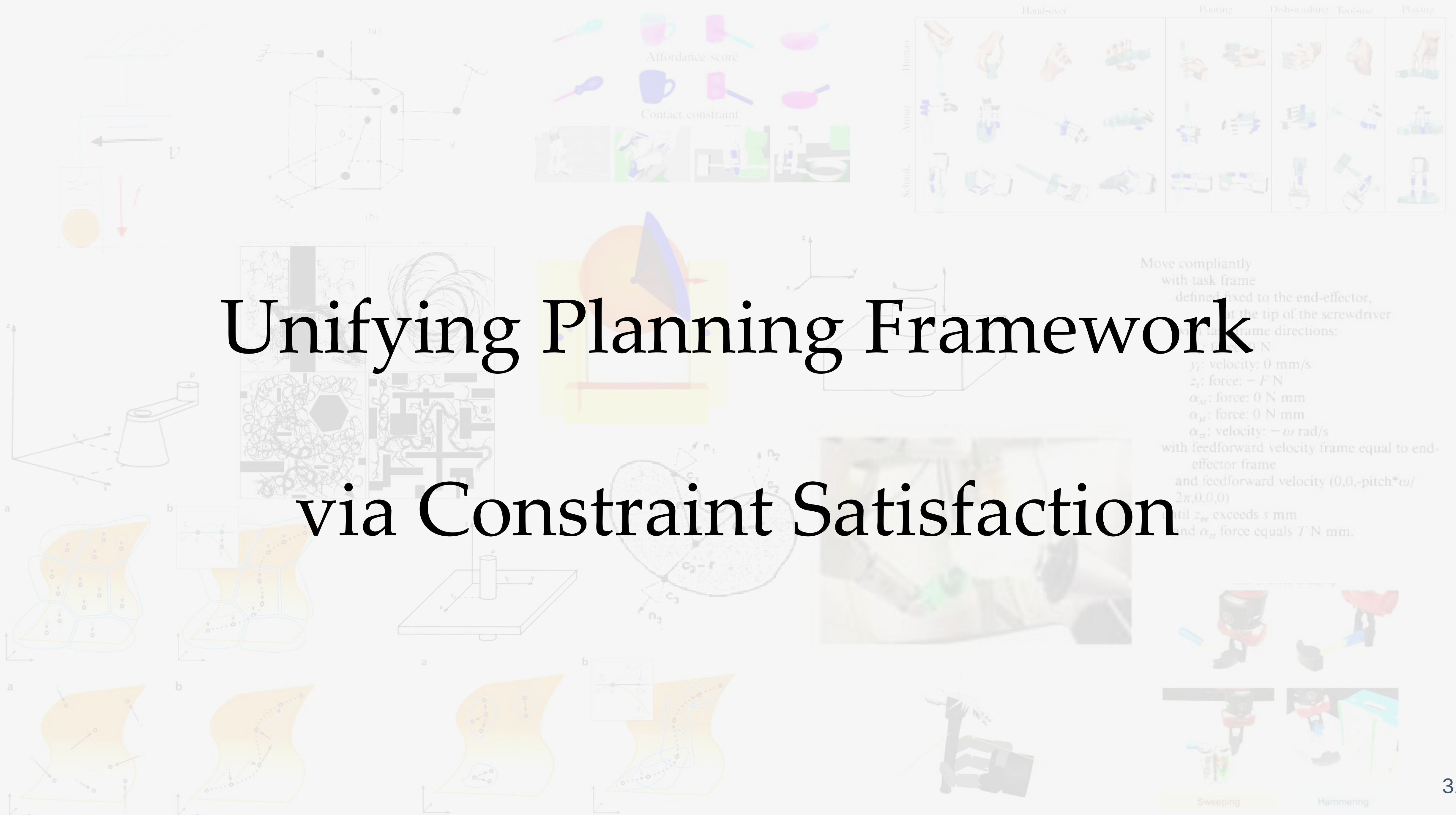




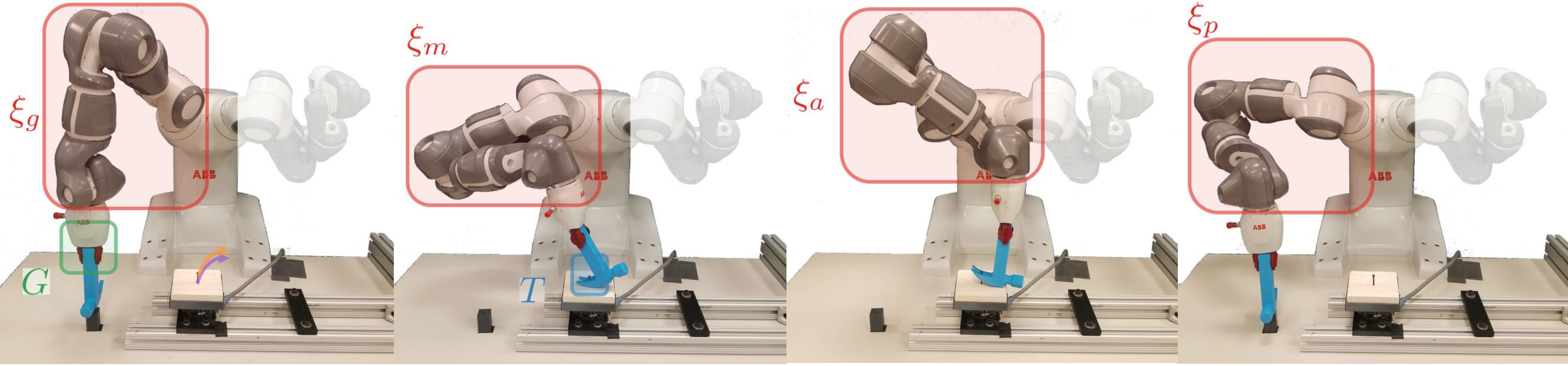




Unifying Planning Framework



Unifying Planning Framework via Constraint Satisfaction


ξ_g
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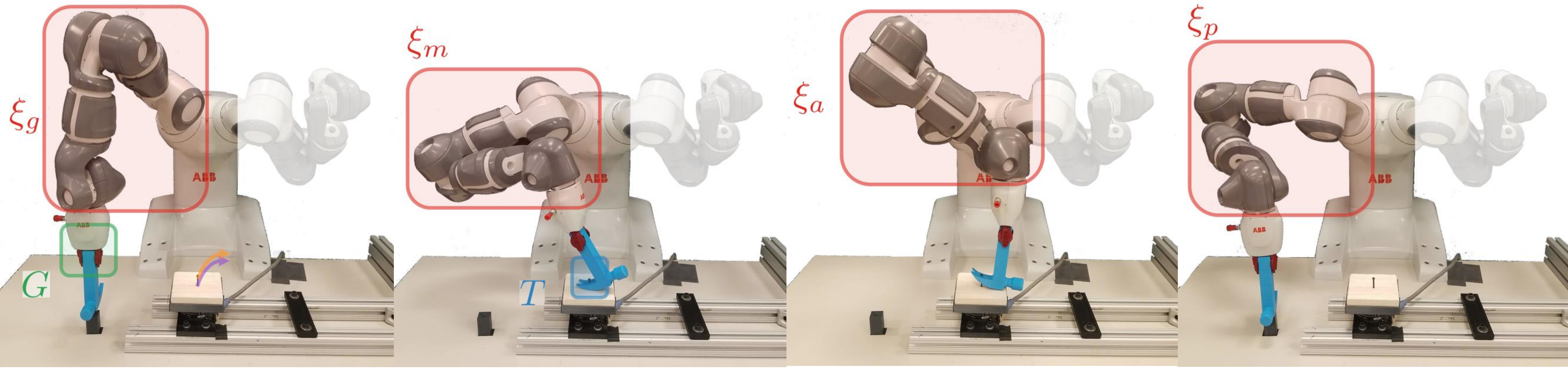
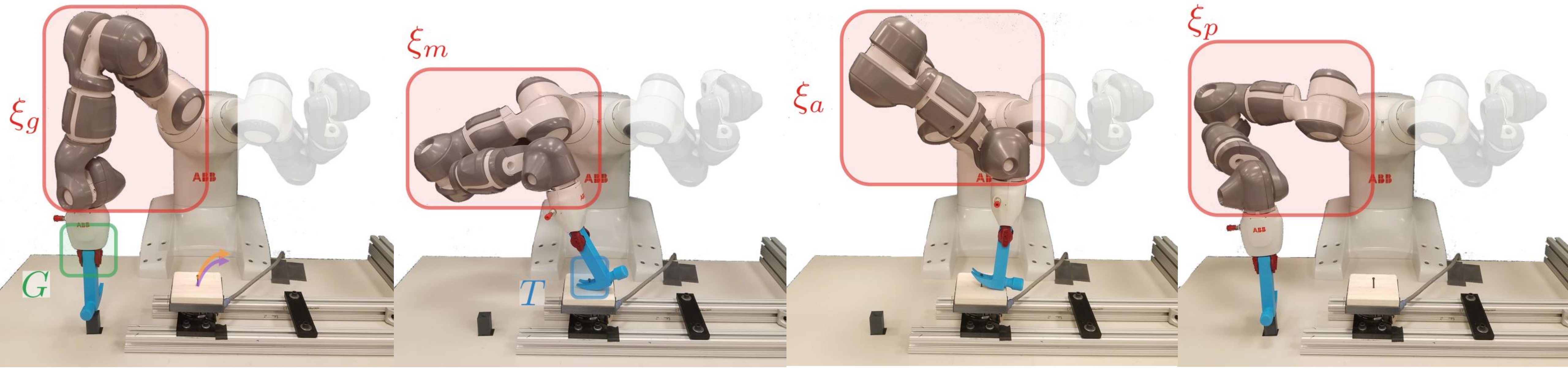


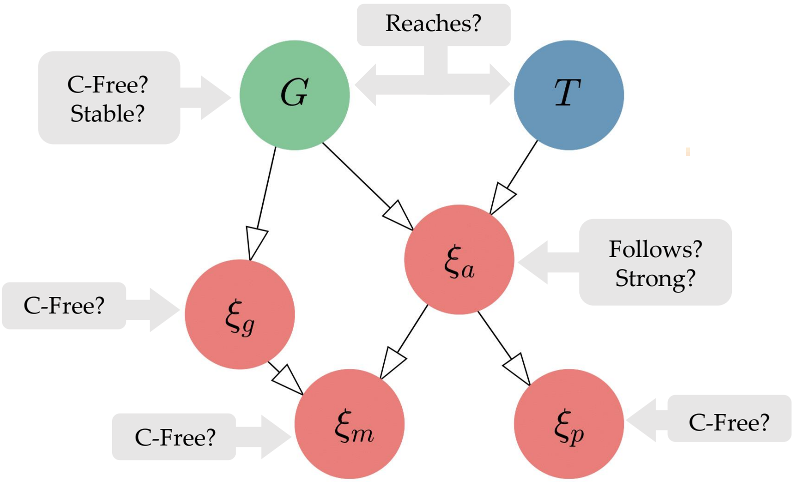
high-dimensional continuous decision variables



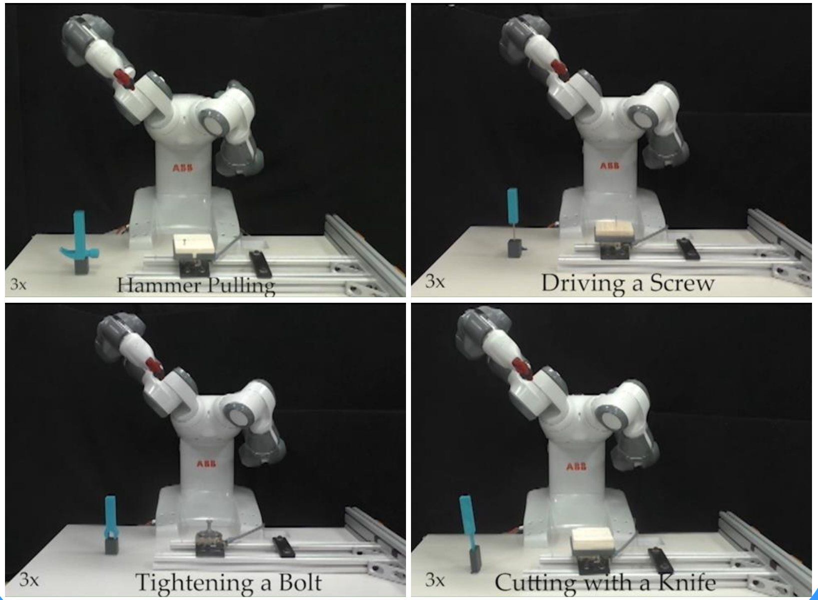
high-dimensional continuous decision variables

with constraints and dependencies

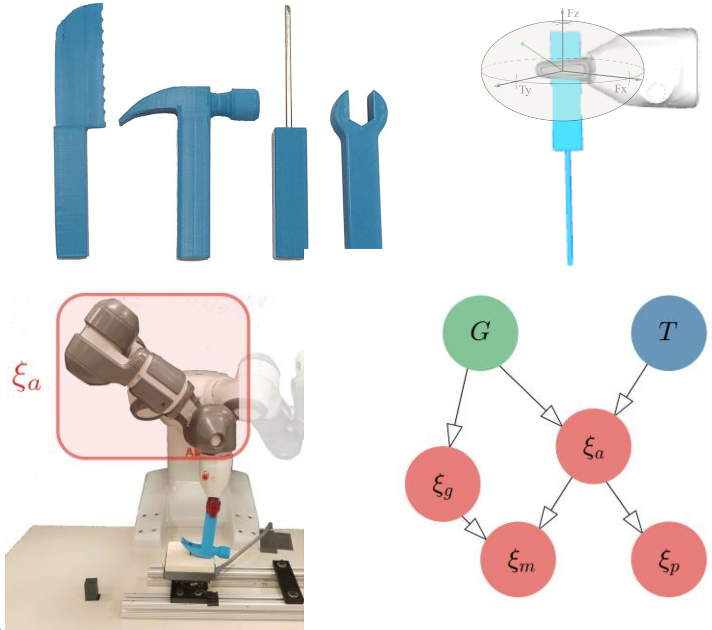
Constraints



Experiments



Assumptions



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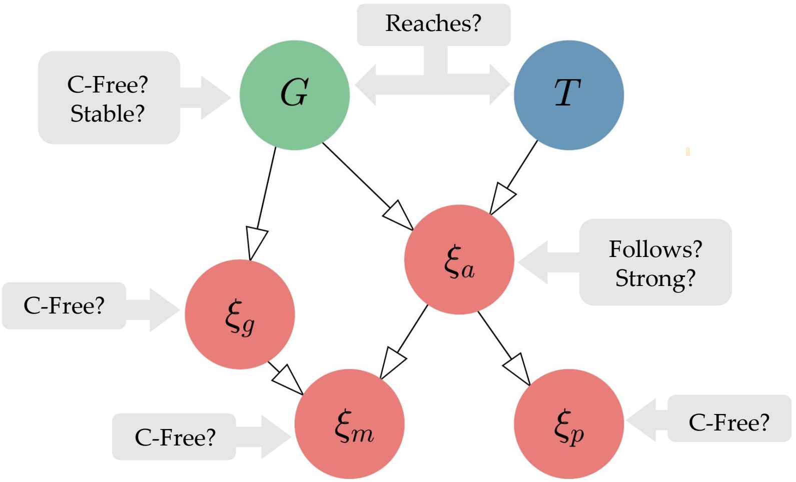
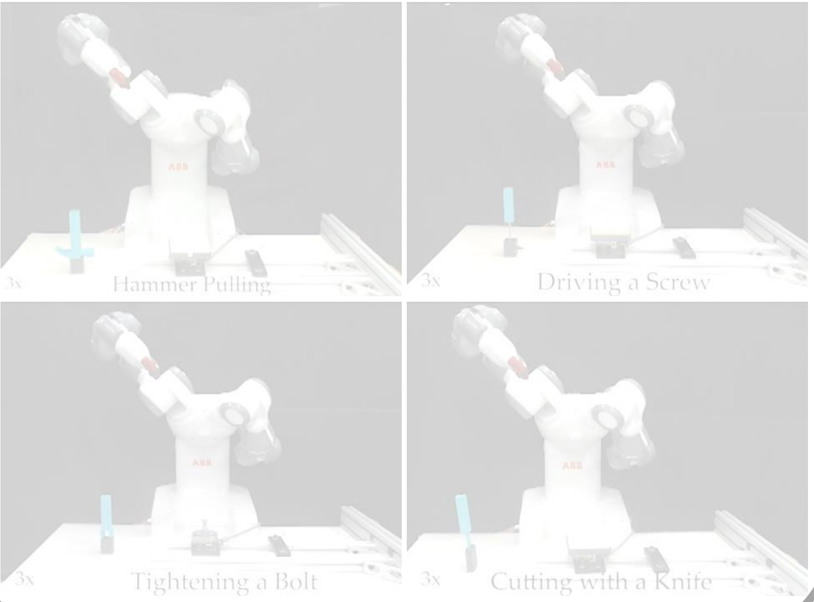
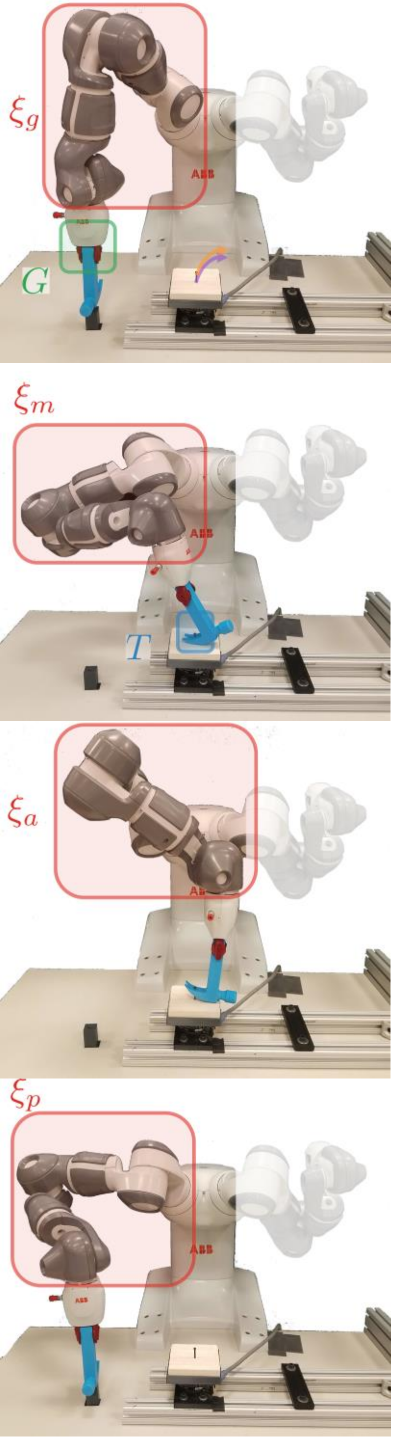


Experiments



Assumptions



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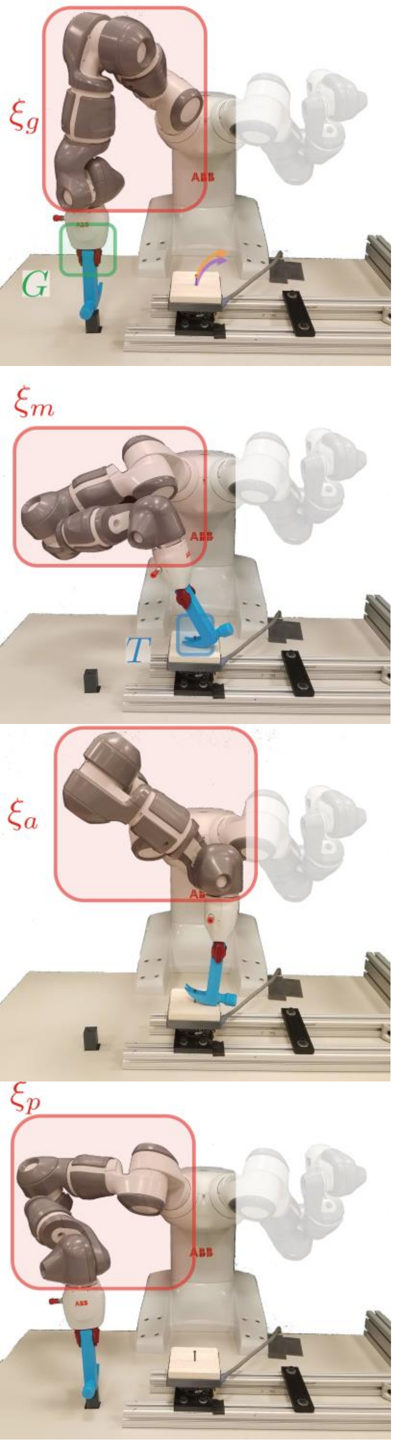
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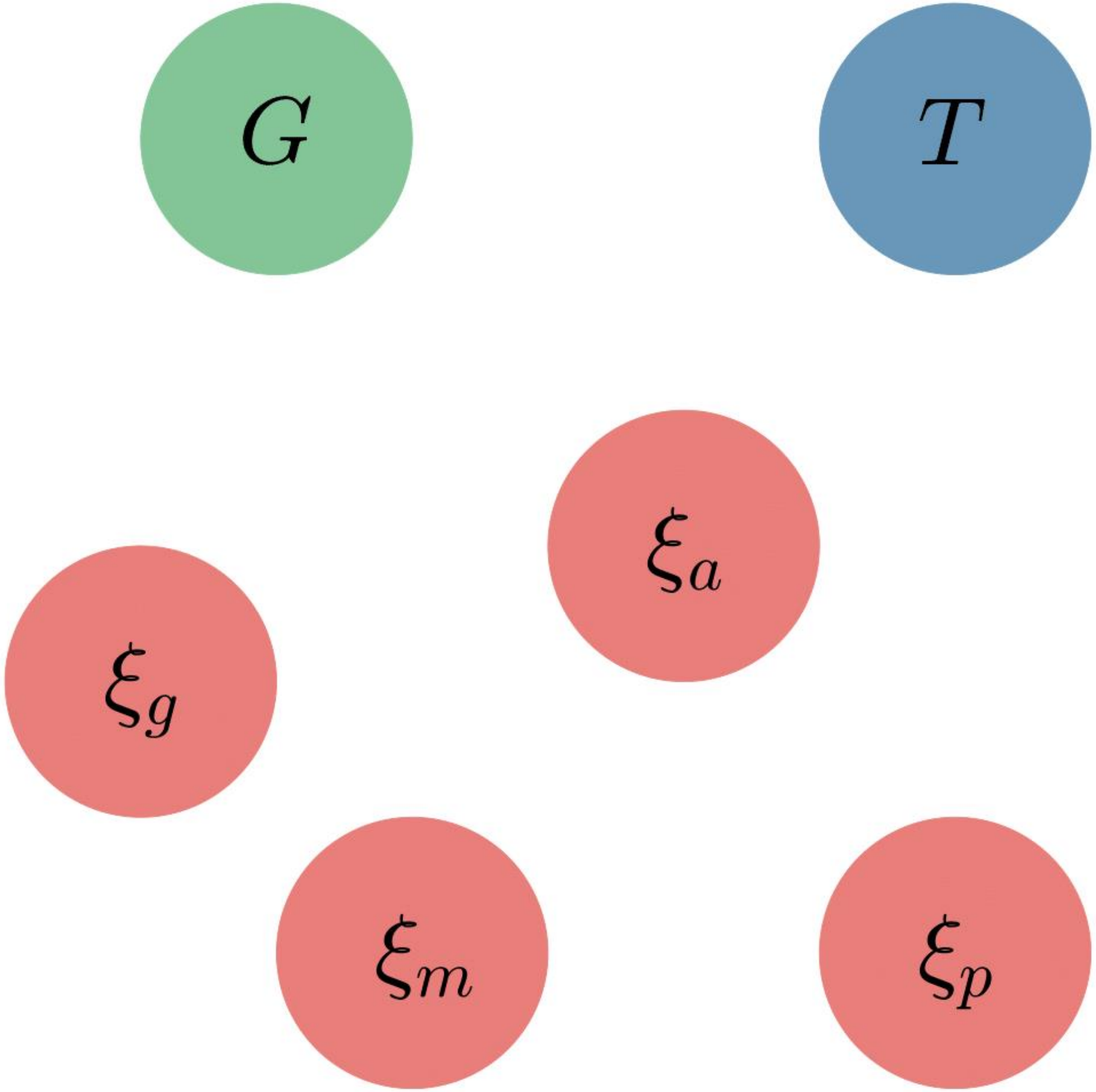
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ξ_a
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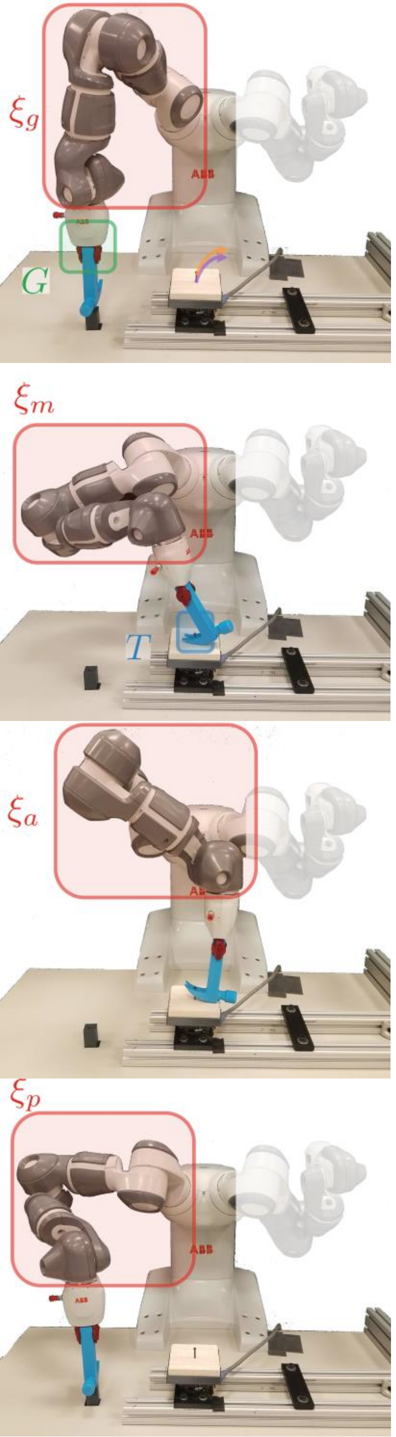
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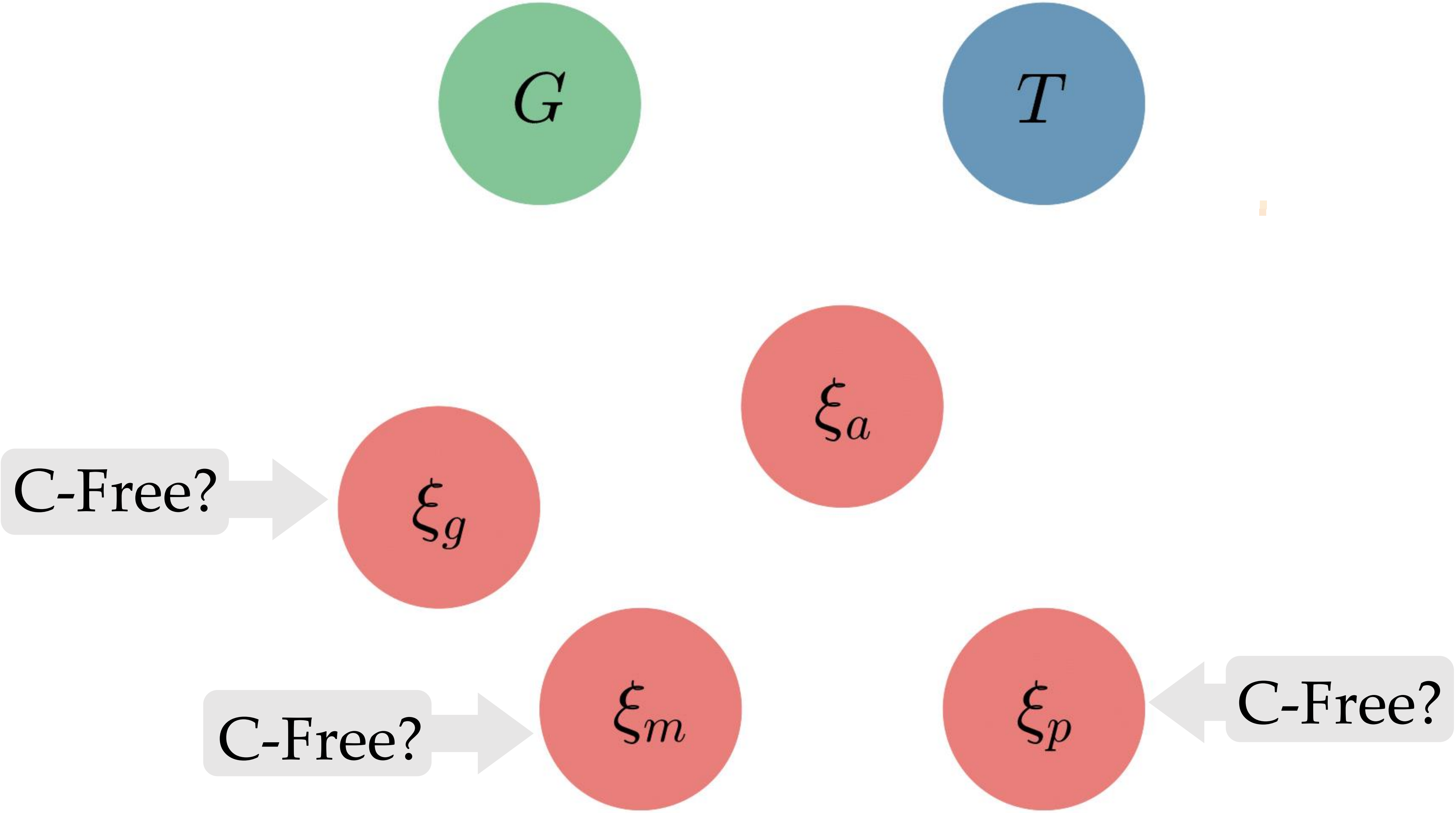
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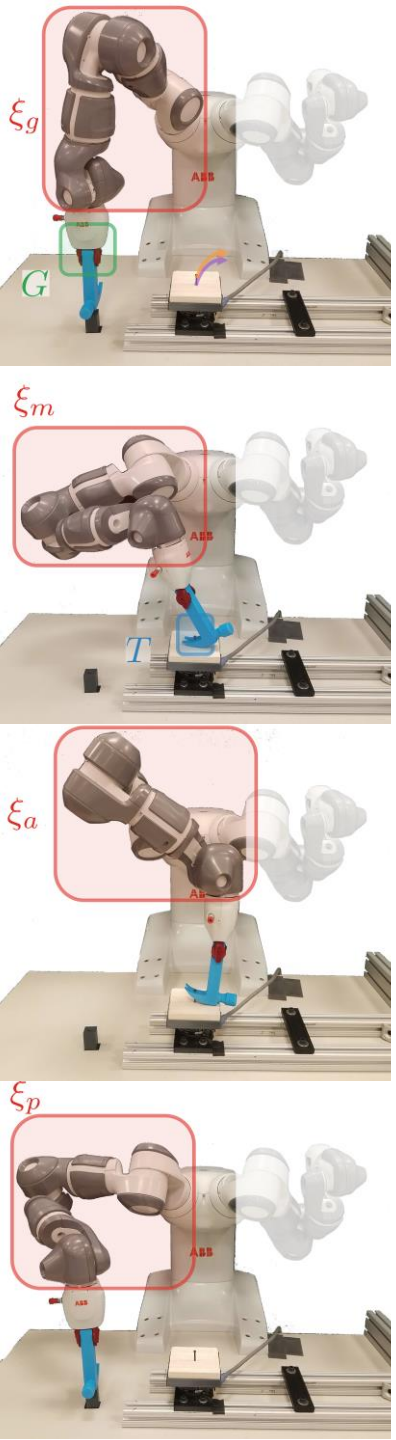
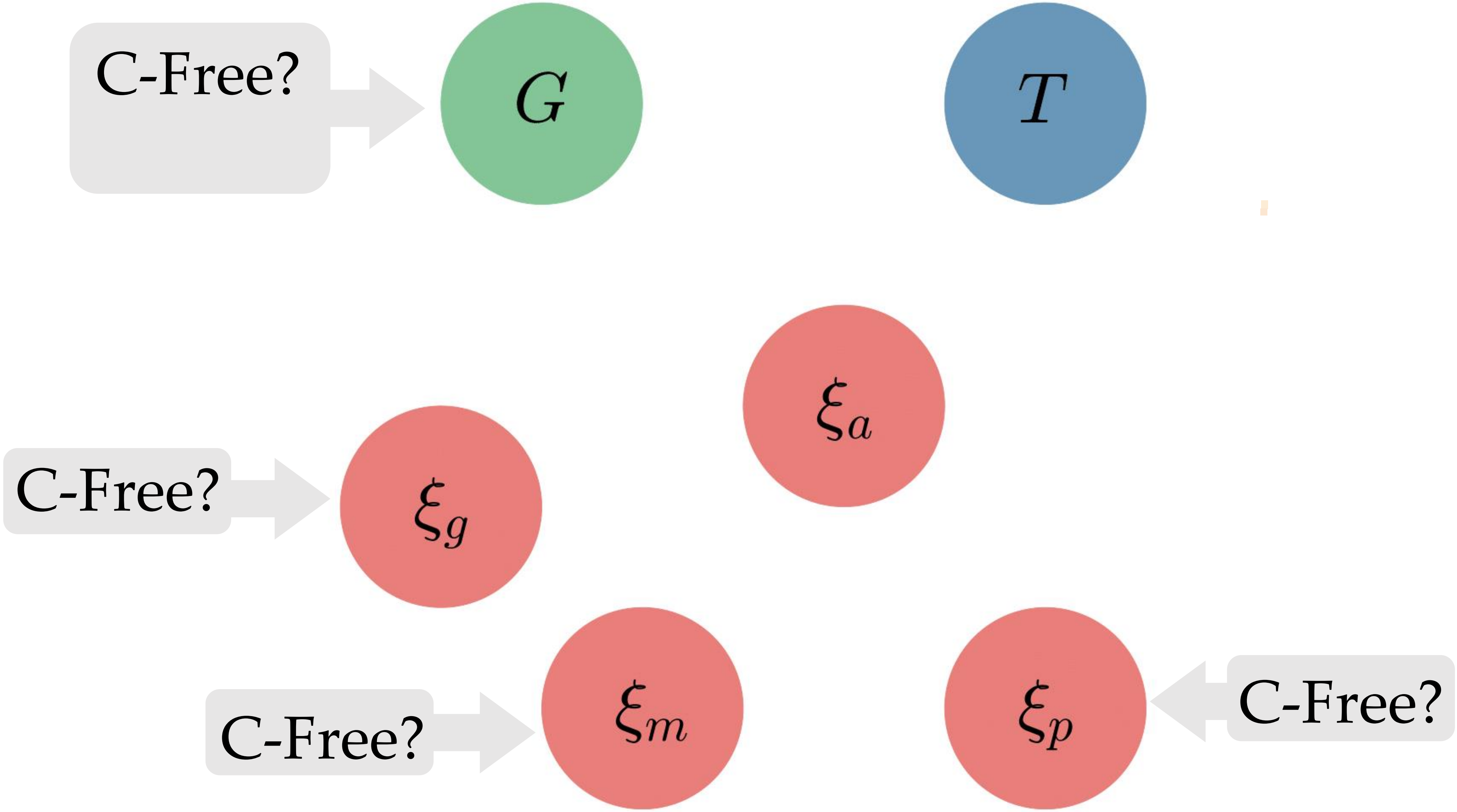
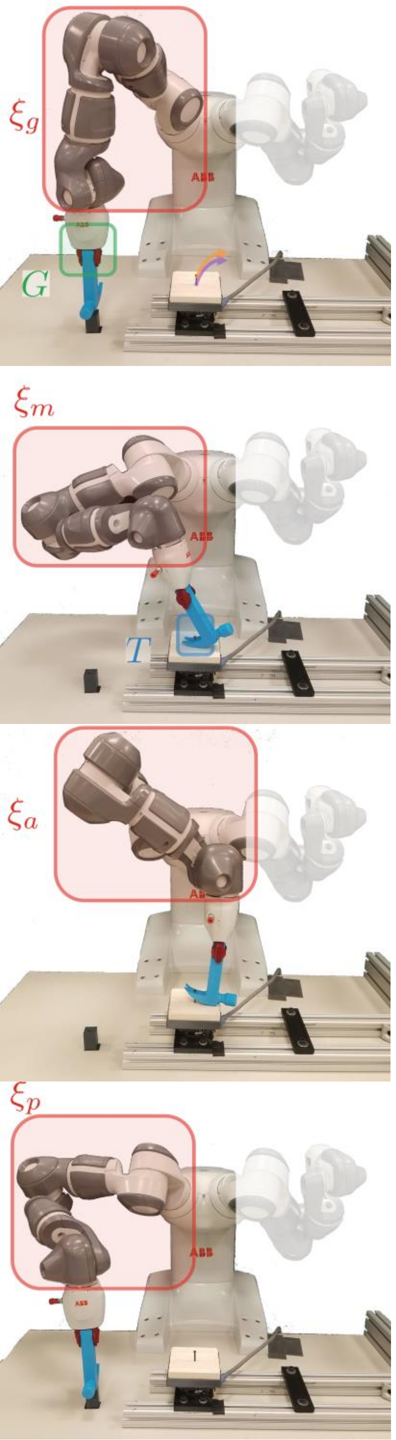
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?

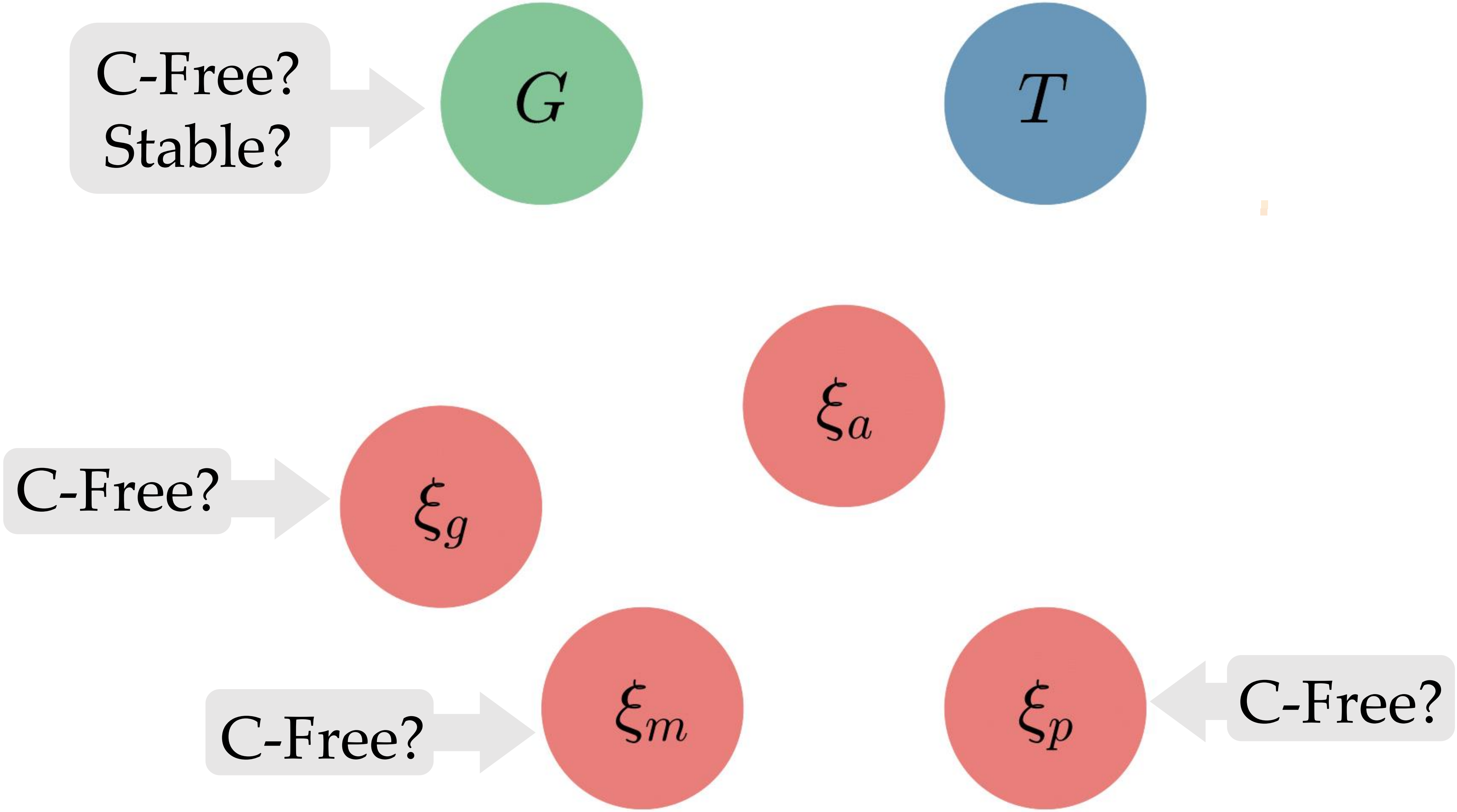


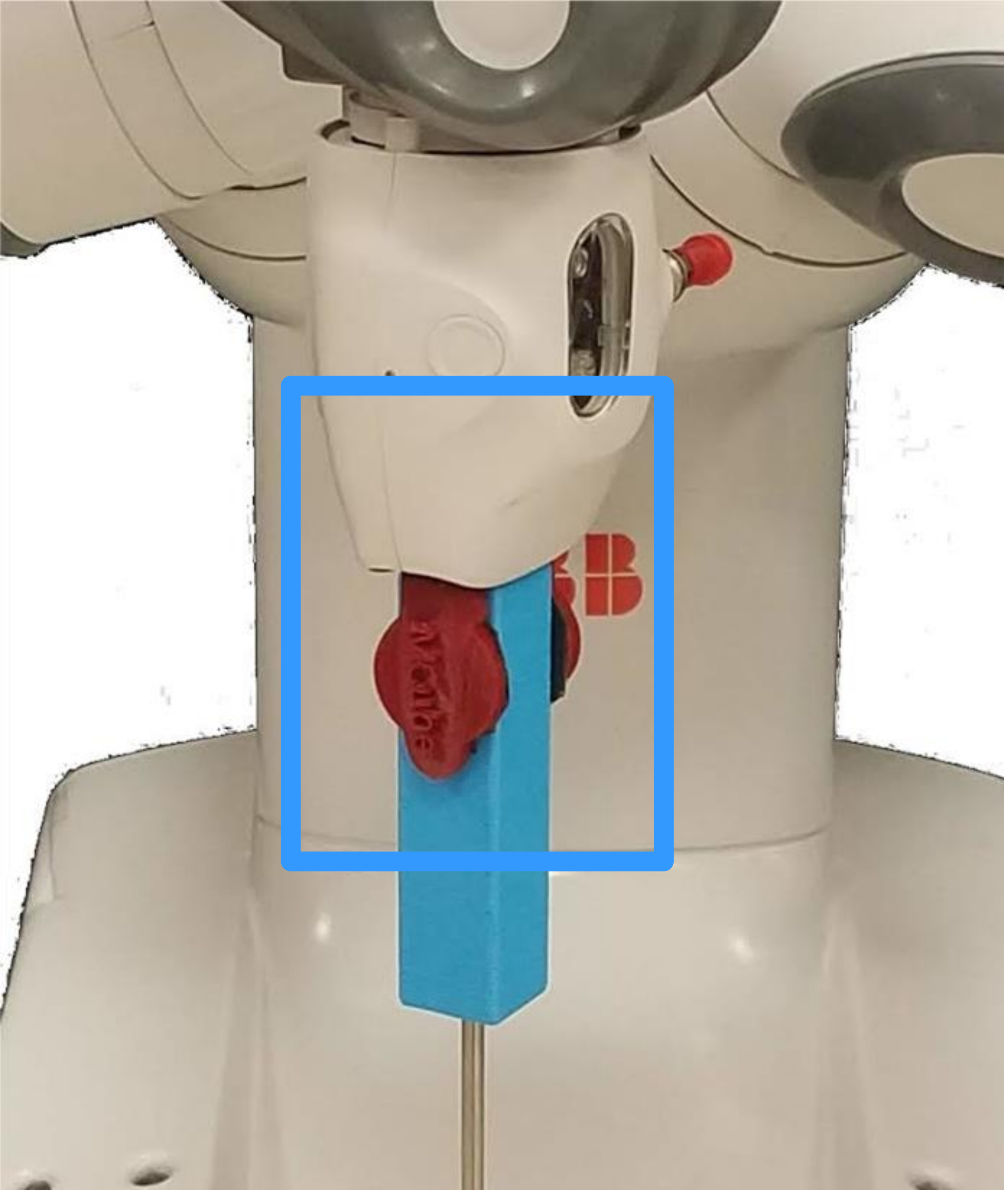
ξ_g
G
ξ_m
T
ξ_a
ξ_p



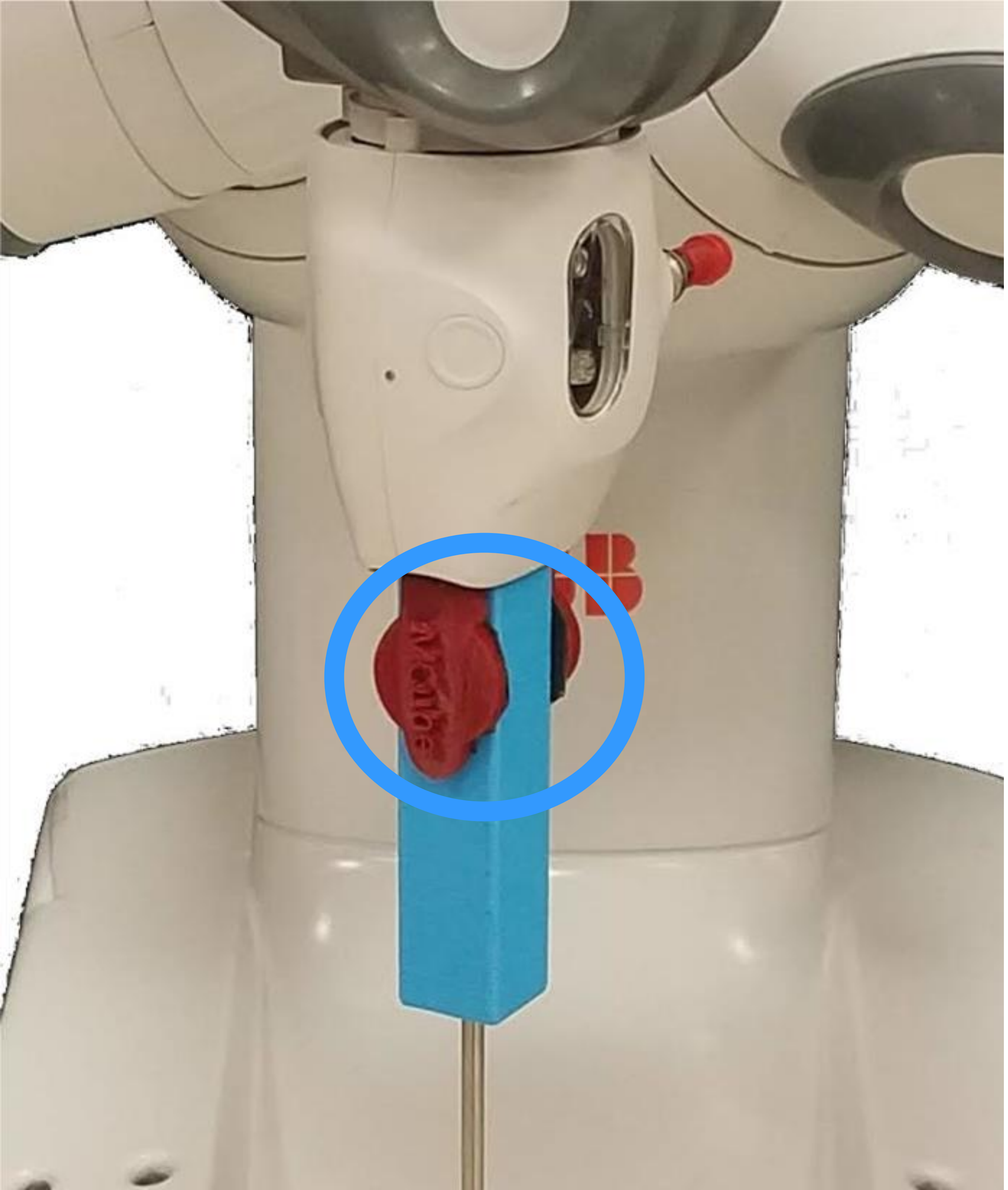
C-Free?
G
T
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?


ξ_g
G
ξ_m
T
ξ_a
ξ_p

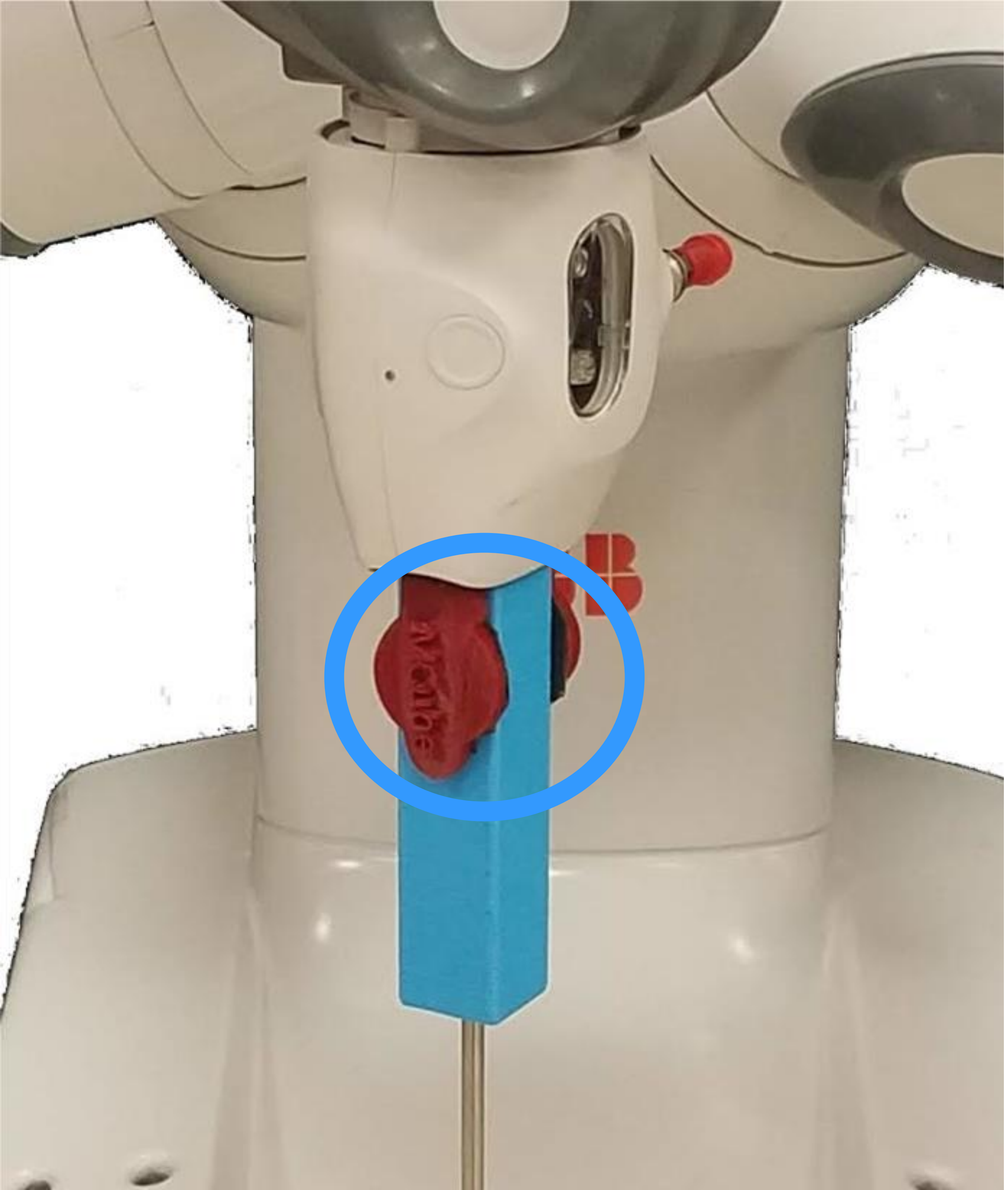

C-Free?
Stable?
G
T
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?



Frictional Joint

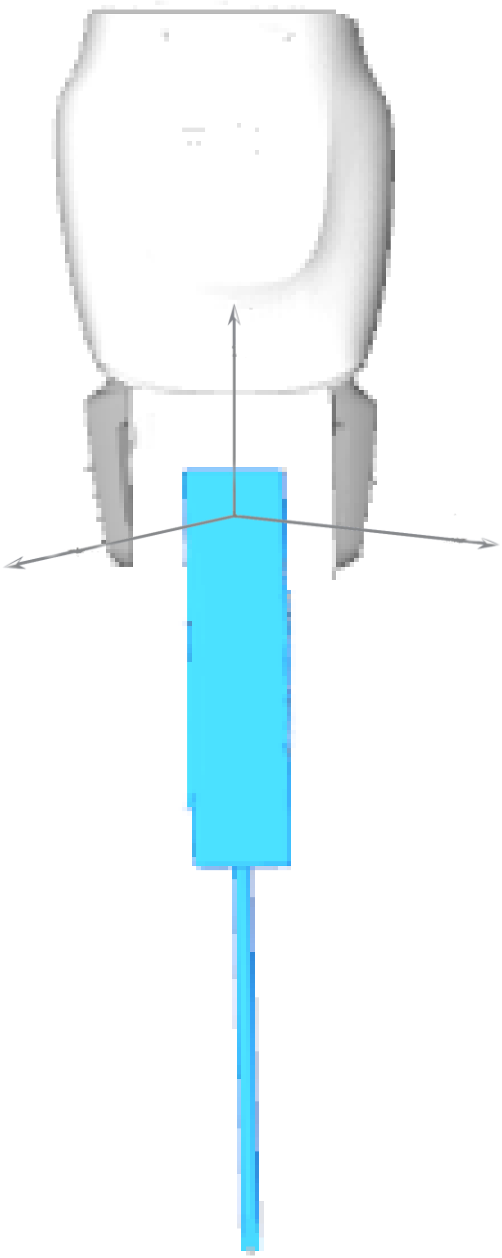


Planar Patch Contacts

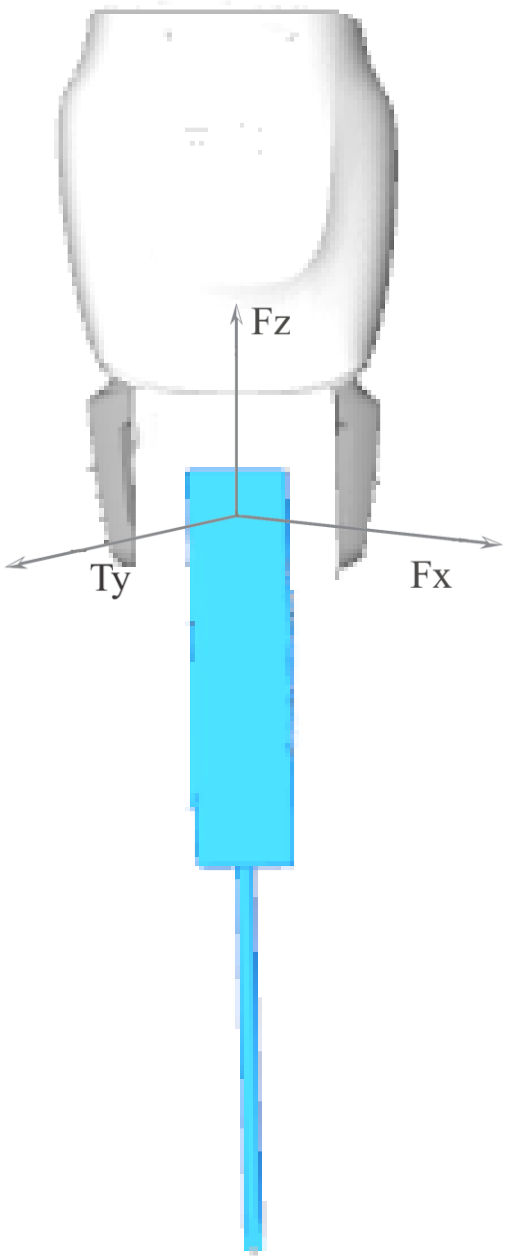


Planar Patch Contacts

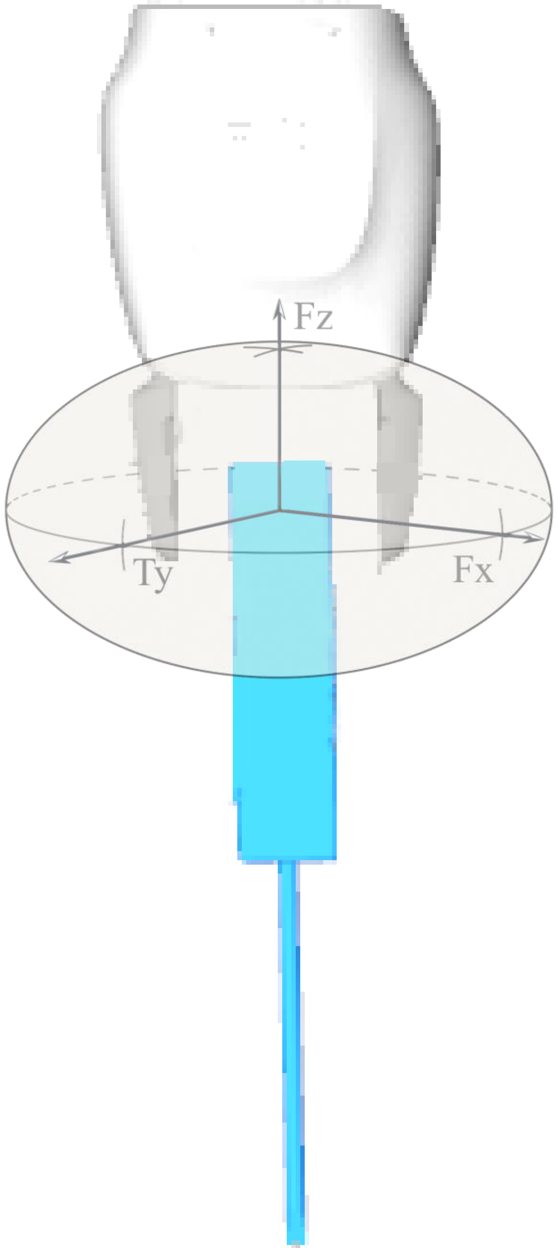
Planar Patch Contacts



Contact Frame

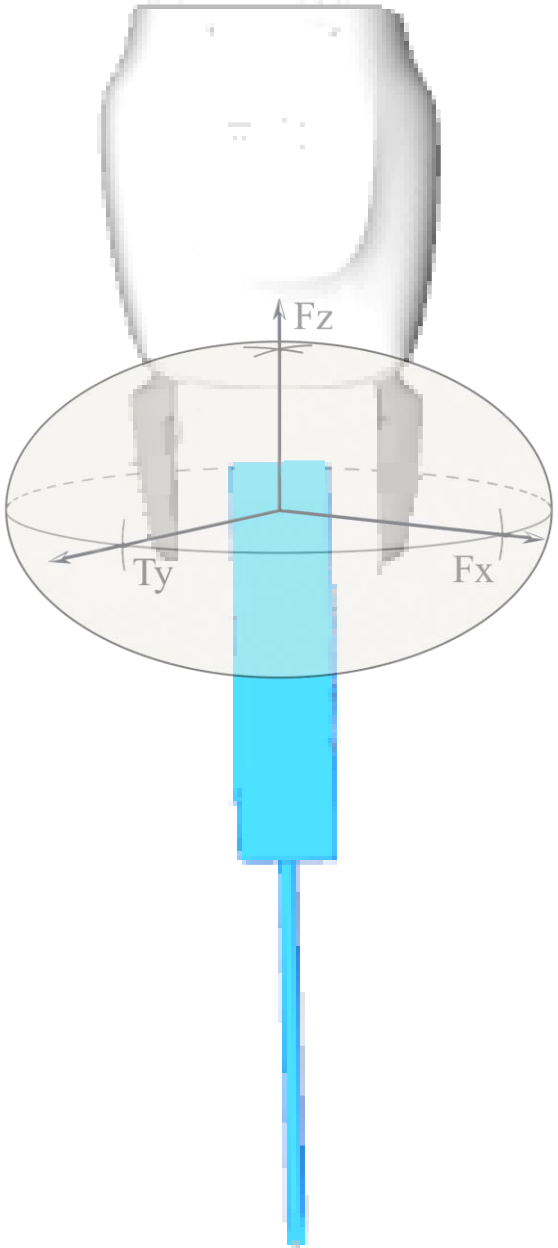


What friction does the grasp offer?



Limit Surface

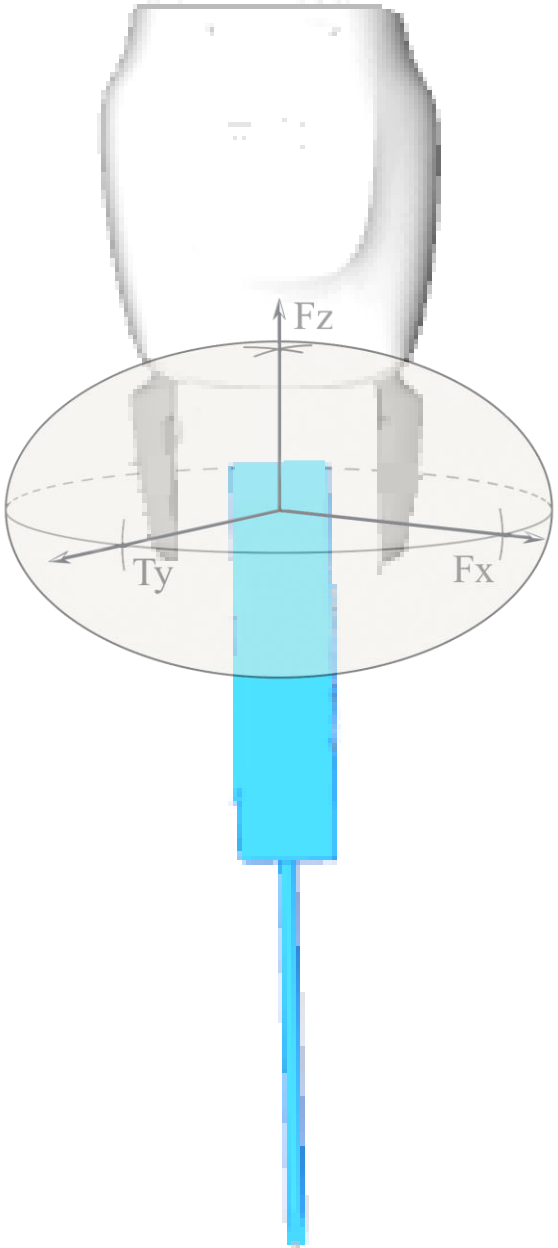
S. Goyal, A. Ruina, and J. Papadopoulos, "Planar sliding with dry friction part 1. limit surface and moment function," Wear, 1991
N. Xydas and I. Kao, "Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results," IJRR, 1999.



Limit Surface

$$w = (f_x, f_z, t_y)$$

S. Goyal, A. Ruina, and J. Papadopoulos, "Planar sliding with dry friction part 1. limit surface and moment function," Wear, 1991
N. Xydas and I. Kao, "Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results," IJRR, 1999.

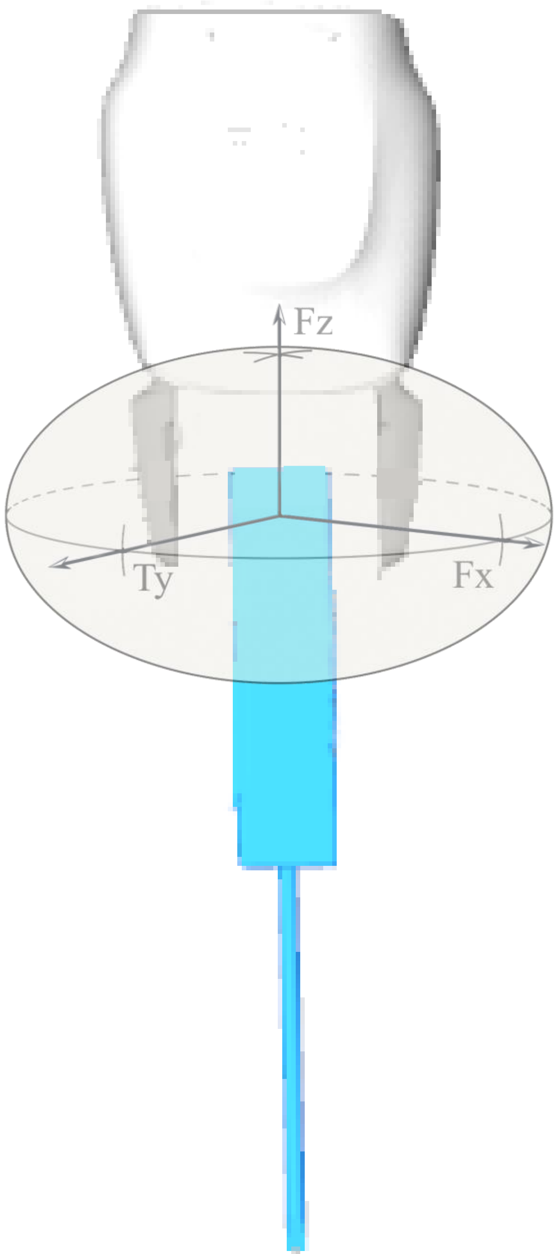


Limit Surface

$$w = (f_x, f_z, t_y)$$

$$w^T A w = 1$$

S. Goyal, A. Ruina, and J. Papadopoulos, "Planar sliding with dry friction part 1. limit surface and moment function," Wear, 1991
N. Xydas and I. Kao, "Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results," IJRR, 1999.



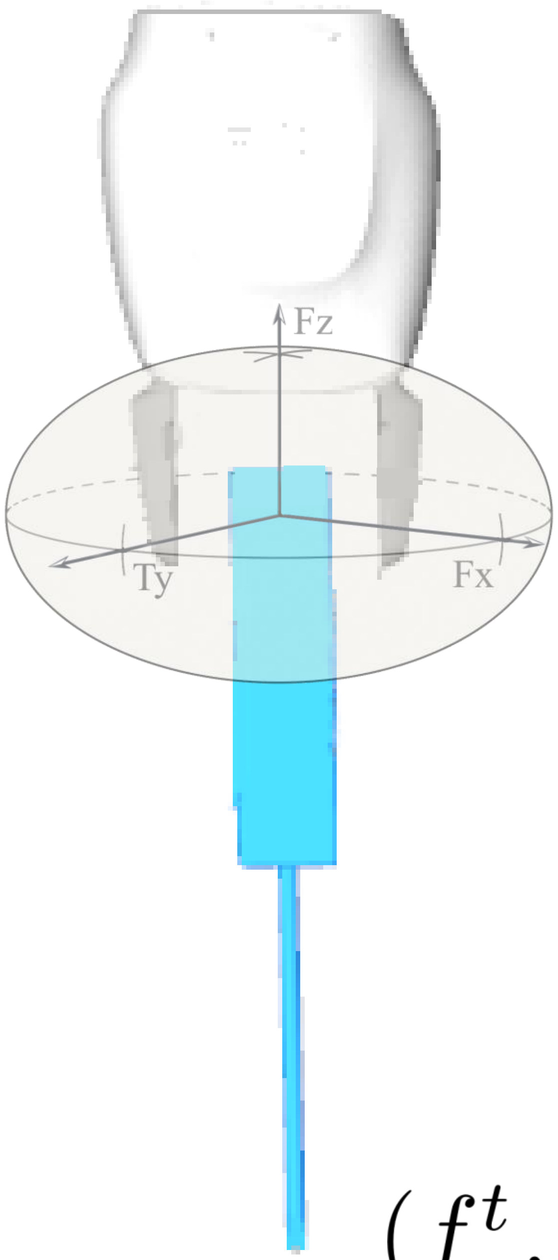
Limit Surface

$$w = (f_x, f_z, t_y)$$

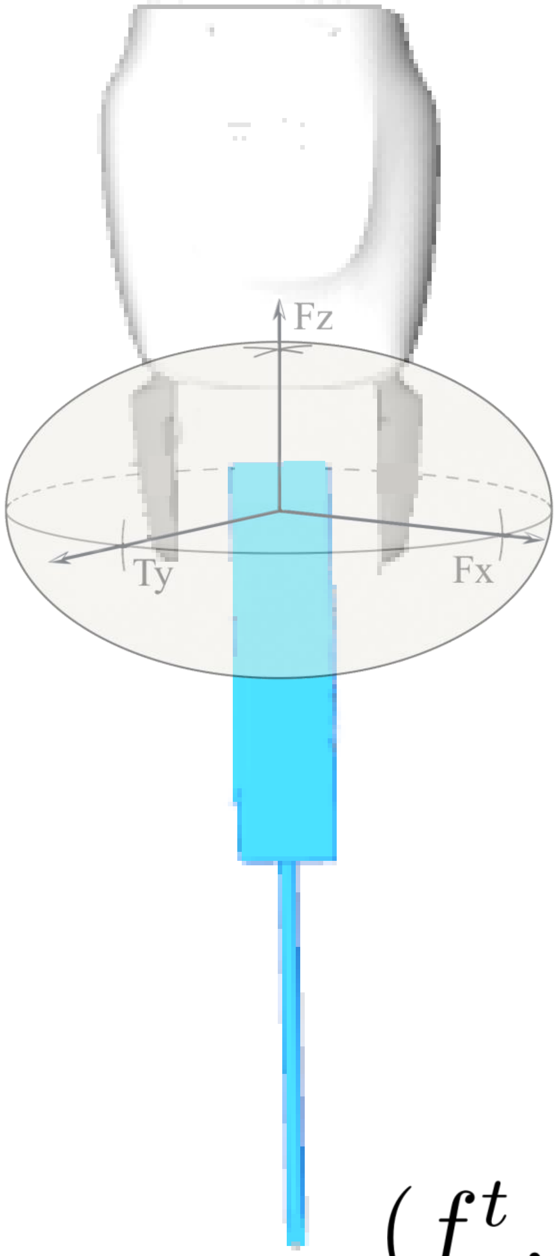
$$w^T A w = 1$$

$$A = \begin{bmatrix} \frac{1}{(N\mu)^2} & & 0 \\ & \frac{1}{(N\mu)^2} & \\ 0 & & \frac{1}{(N\mu)^2(rc)^2} \end{bmatrix}$$

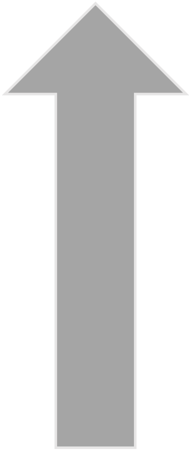
S. Goyal, A. Ruina, and J. Papadopoulos, “Planar sliding with dry friction part 1. limit surface and moment function,” Wear, 1991
N. Xydas and I. Kao, “Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results,” IJRR, 1999.



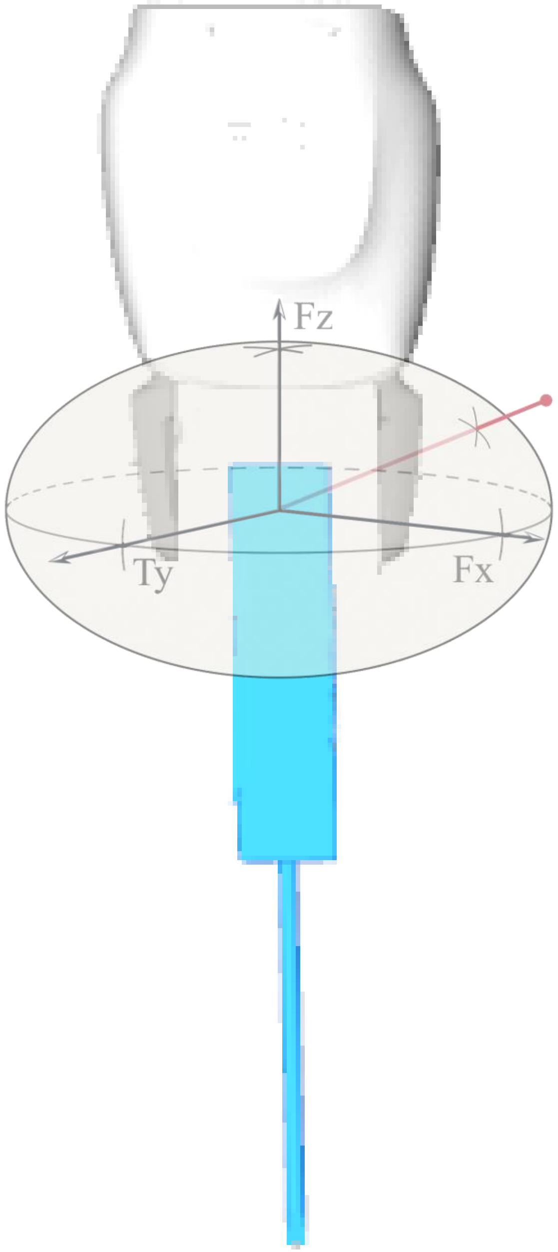
$$(f_x^t, f_y^t, f_z^t, t_x^t, t_y^t, t_z^t)$$



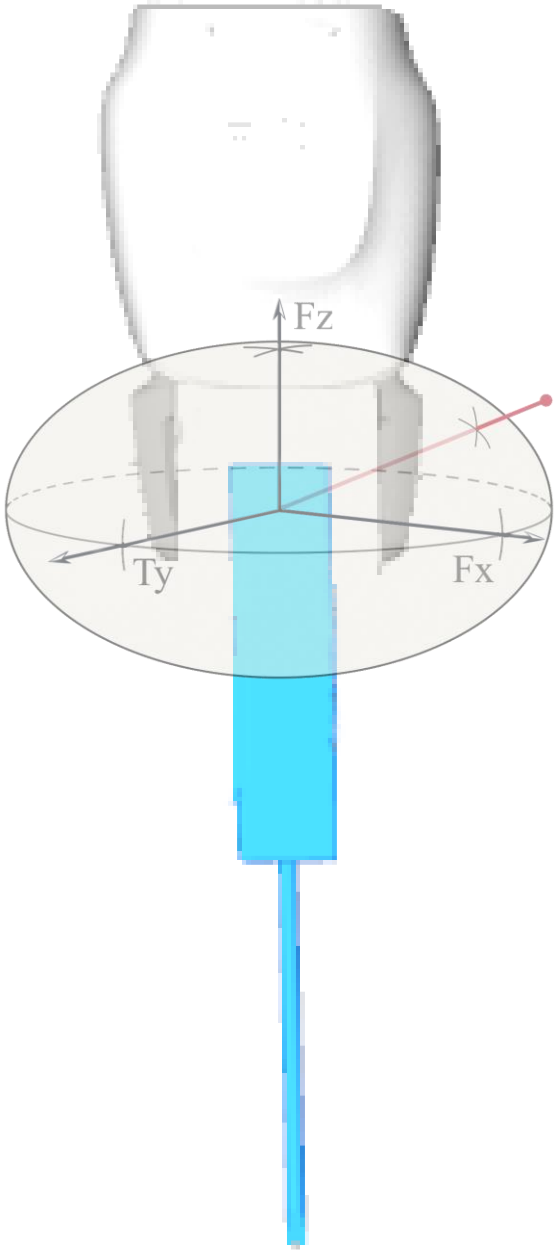
$$(f_x^c, f_y^c, f_z^c, t_x^c, t_y^c, t_z^c)$$



$$(f_x^t, f_y^t, f_z^t, t_x^t, t_y^t, t_z^t)$$

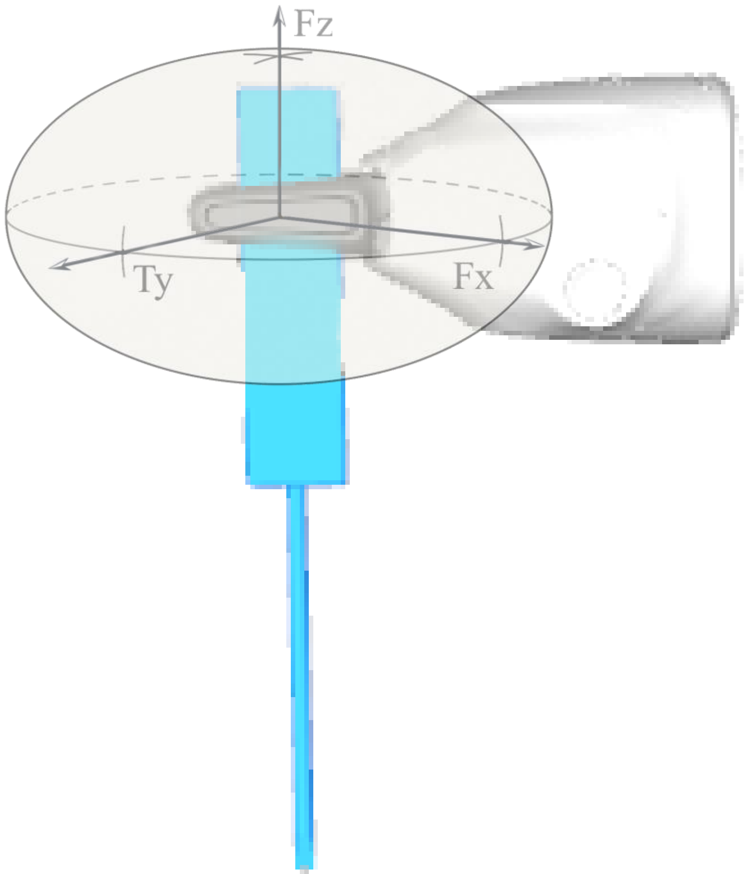


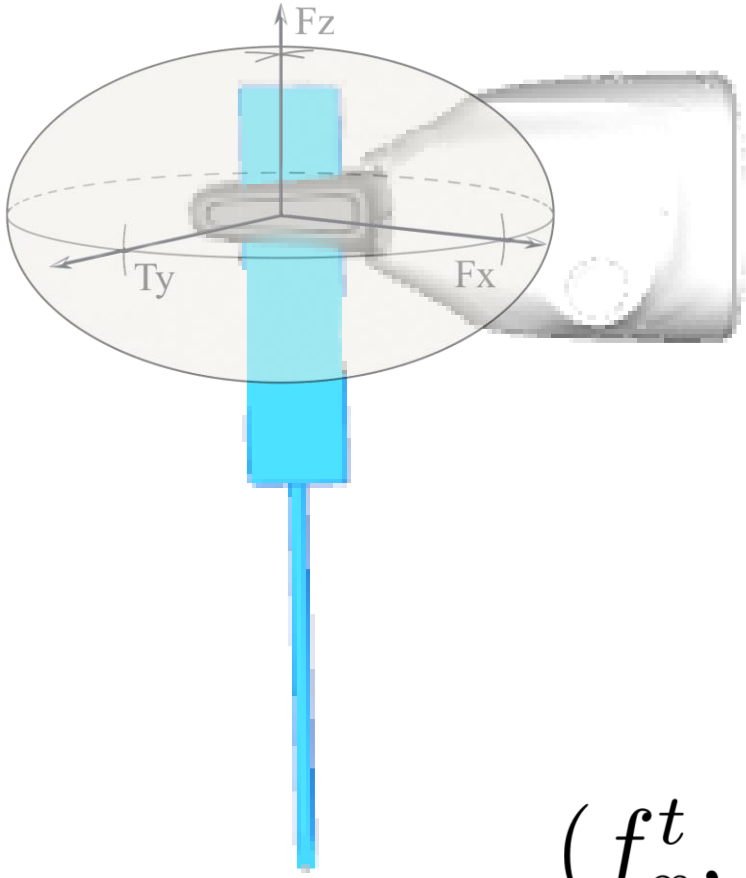
$$(f_x^c, f_z^c, t_y^c)$$



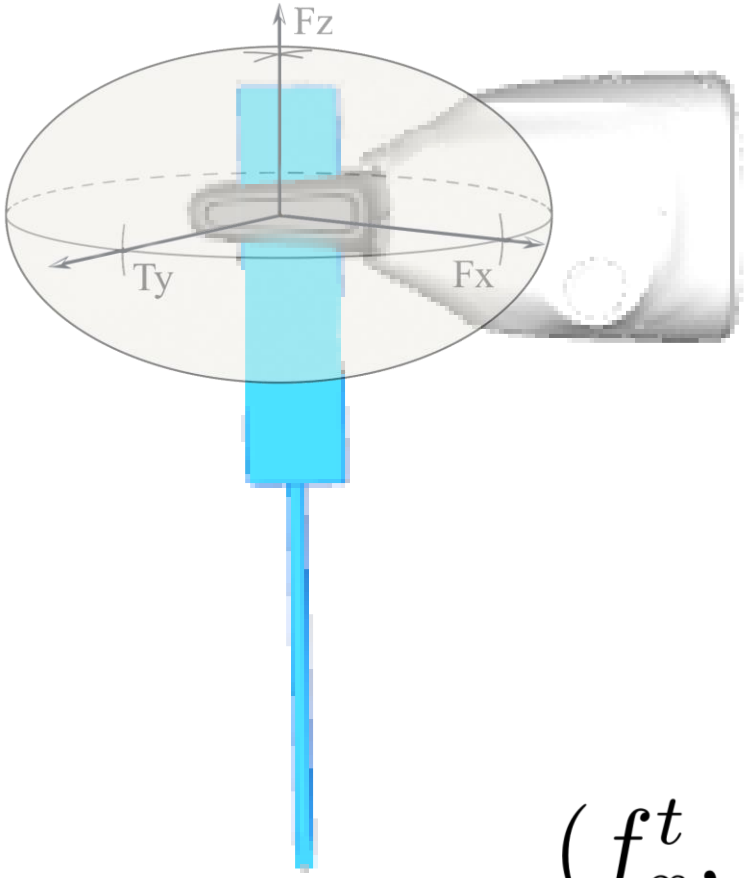
$$\frac{f_x^c}{(N\mu)^2} + \frac{f_z^c}{(N\mu)^2} + \frac{t_y^c}{(N\mu)^2(rc)^2} > 1$$

Bad Grasp!

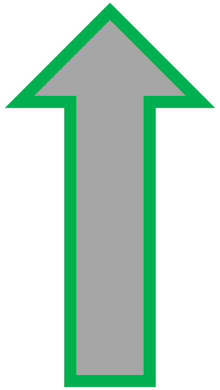

Fz
Ty
Fx



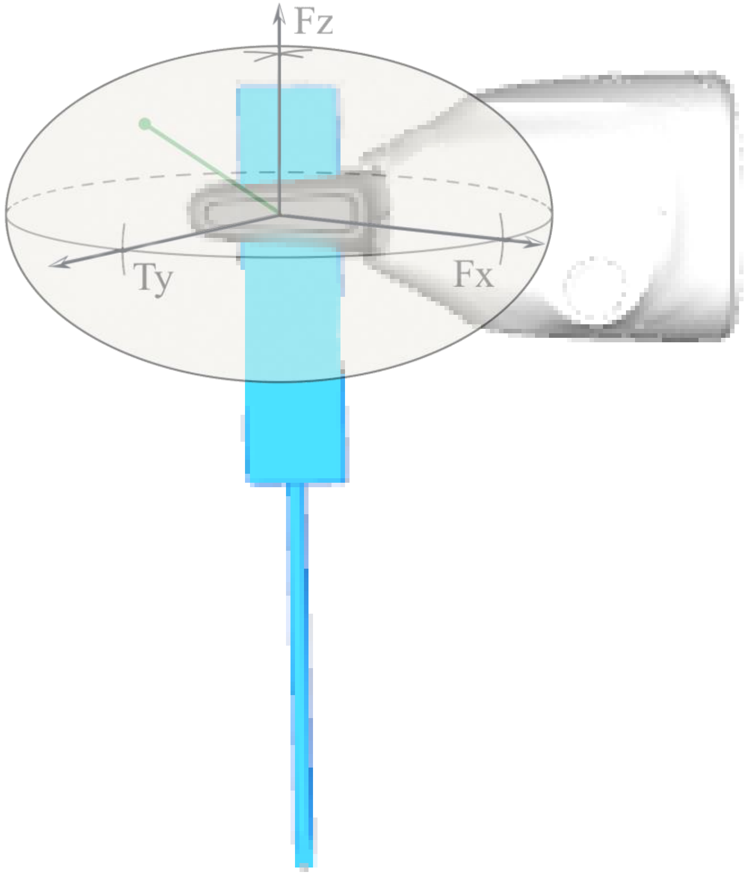
$$(f_x^t, f_y^t, f_z^t, t_x^t, t_y^t, t_z^t)$$



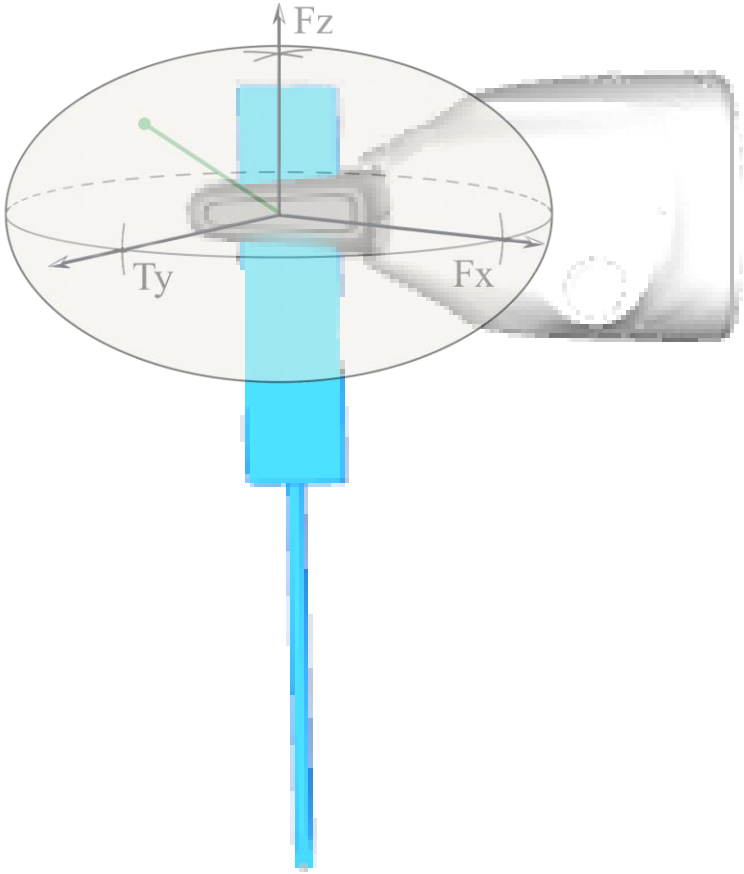
$$(f_x^c, f_y^c, f_z^c, t_x^c, t_y^c, t_z^c)$$



$$(f_x^t, f_y^t, f_z^t, t_x^t, t_y^t, t_z^t)$$

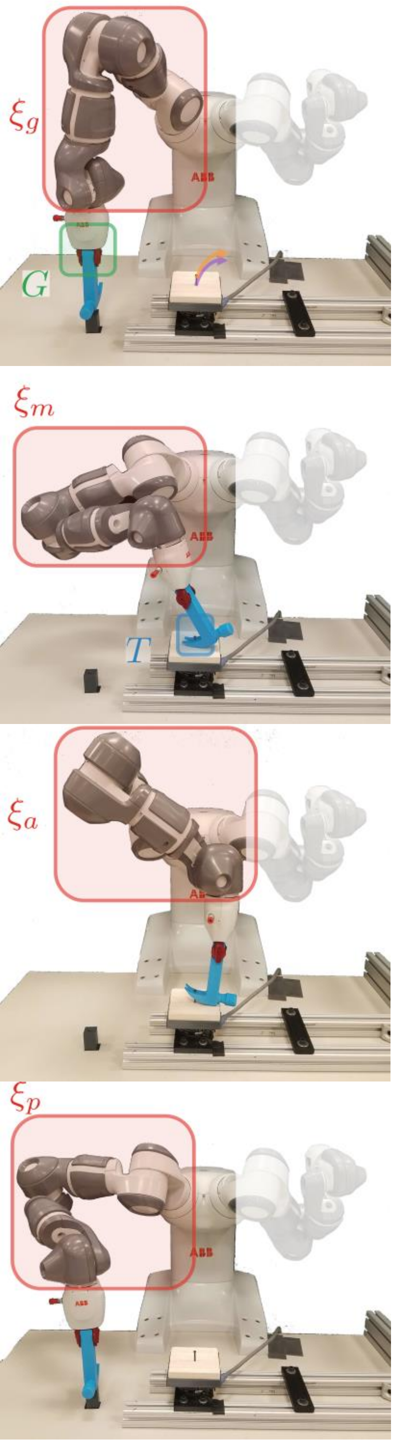


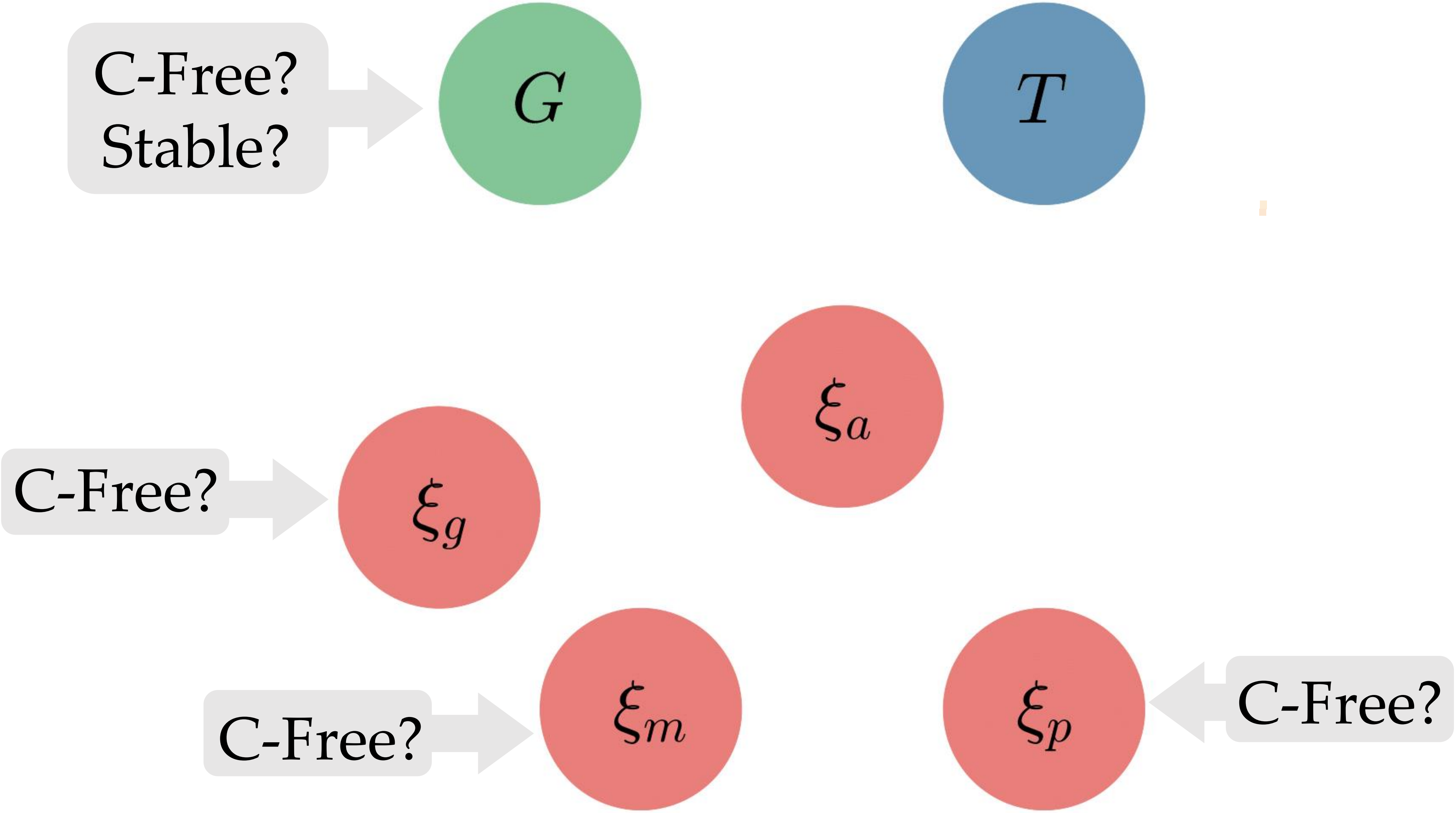
$$(f_x^c, f_z^c, t_y^c)$$

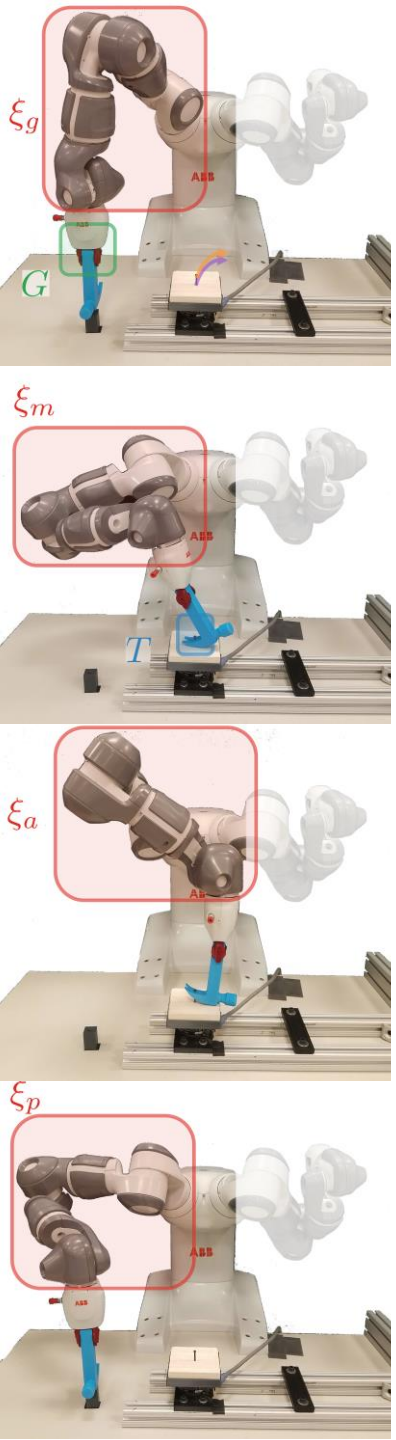


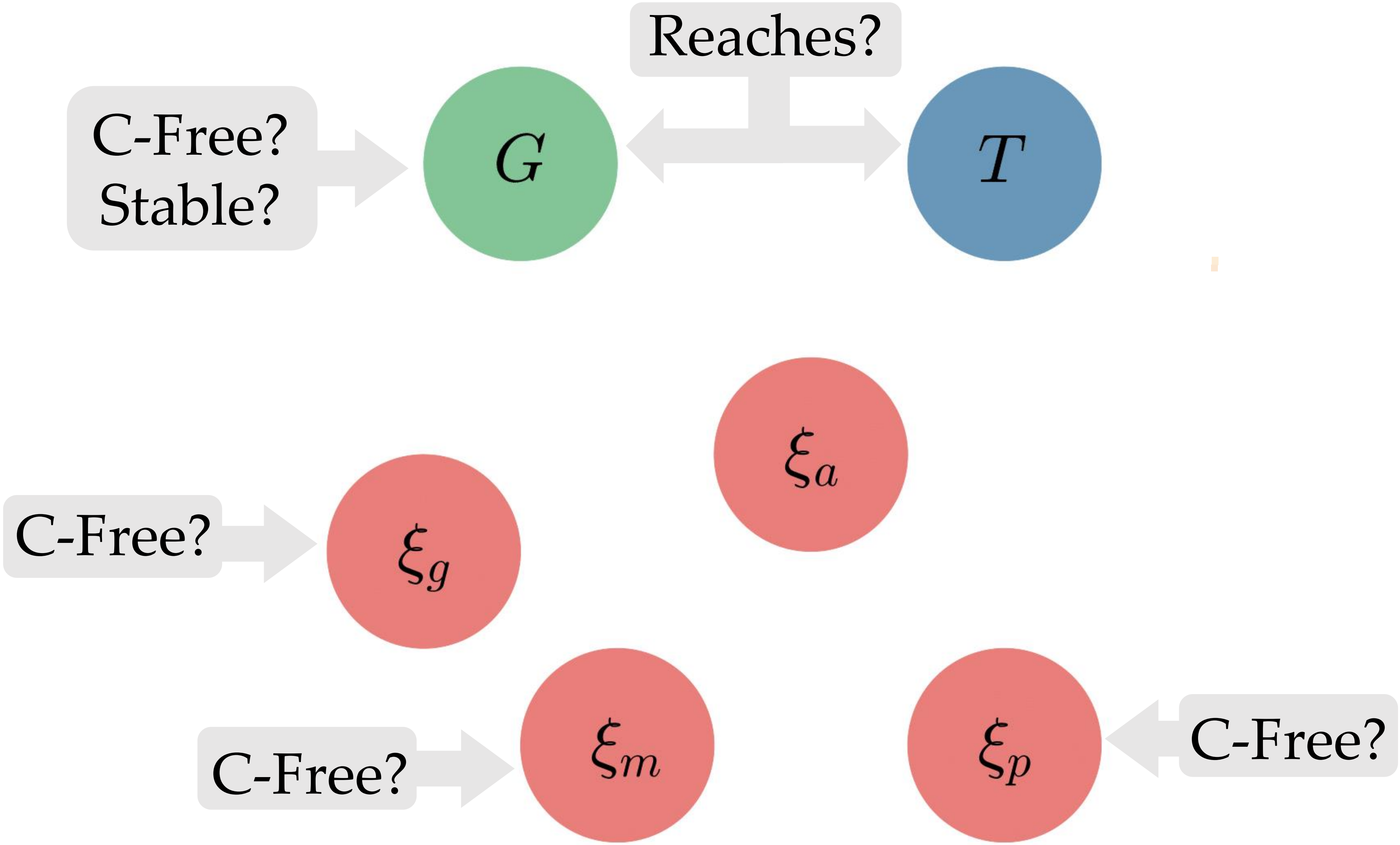
$$\frac{f_x^c}{(N\mu)^2} + \frac{f_z^c}{(N\mu)^2} + \frac{t_y^c}{(N\mu)^2(rc)^2} < 1$$

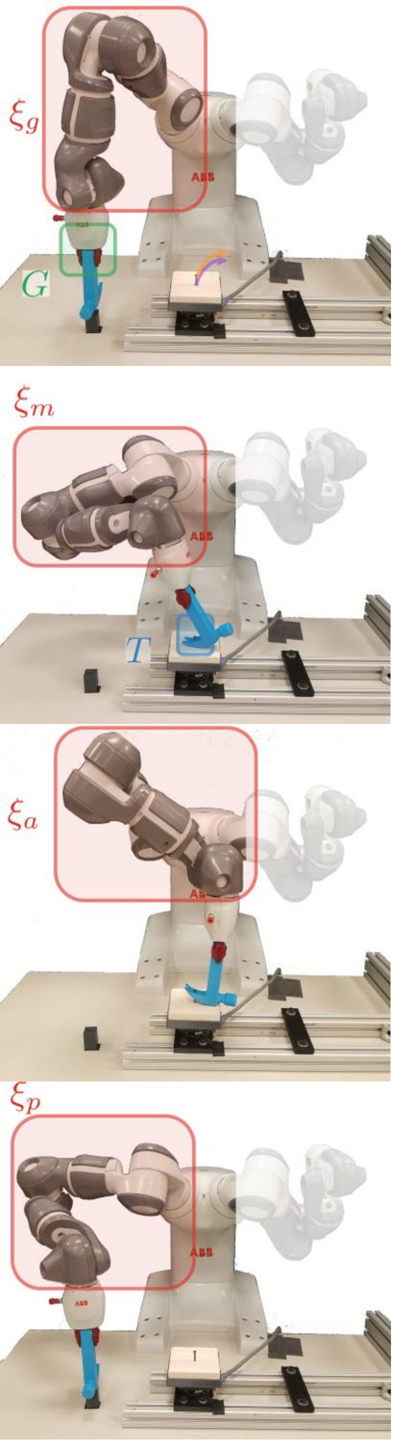
Valid Grasp!

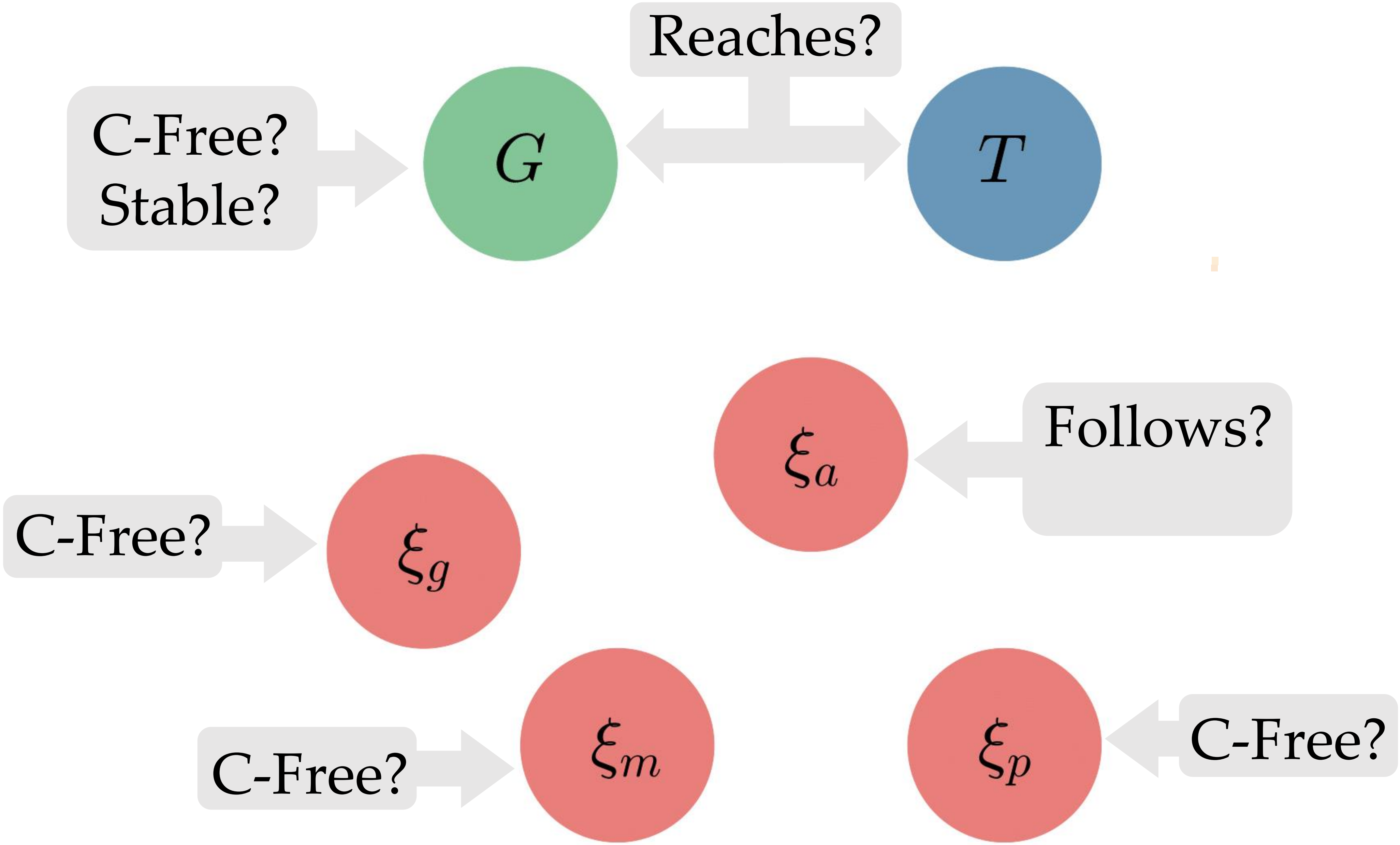

ξ_g
G
ξ_m
T
ξ_a
ξ_p

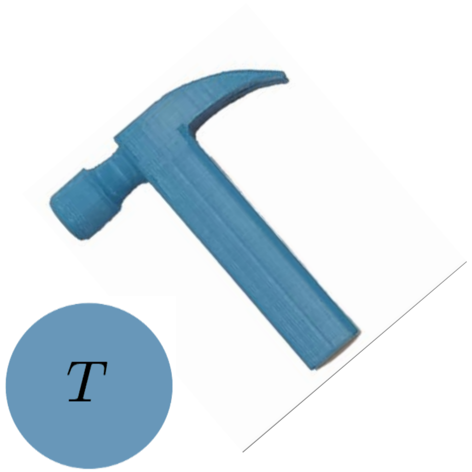

C-Free?
Stable?
G
T
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?

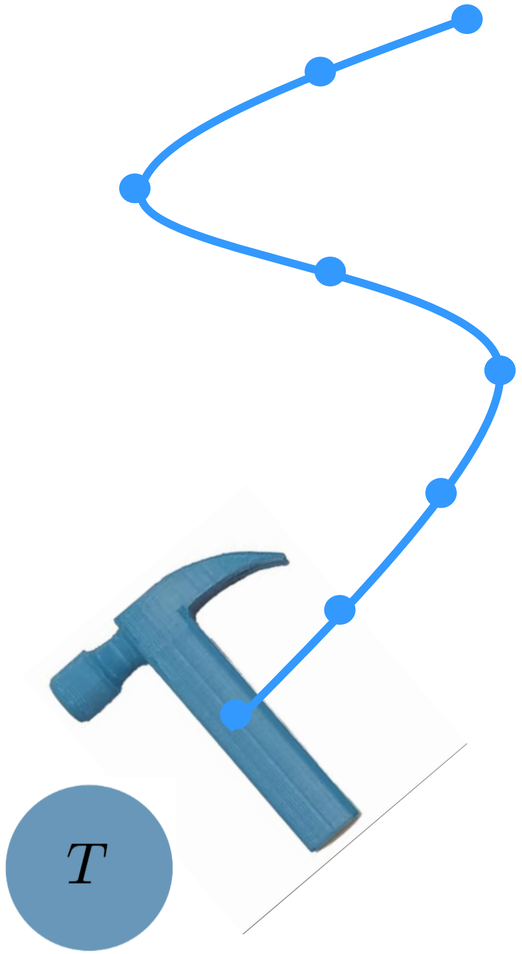

ξ_g
G
ξ_m
T
ξ_a
ξ_p


Reaches?
C-Free?
Stable?
G
T
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?


ξ_g
G
ξ_m
T
ξ_a
ξ_p

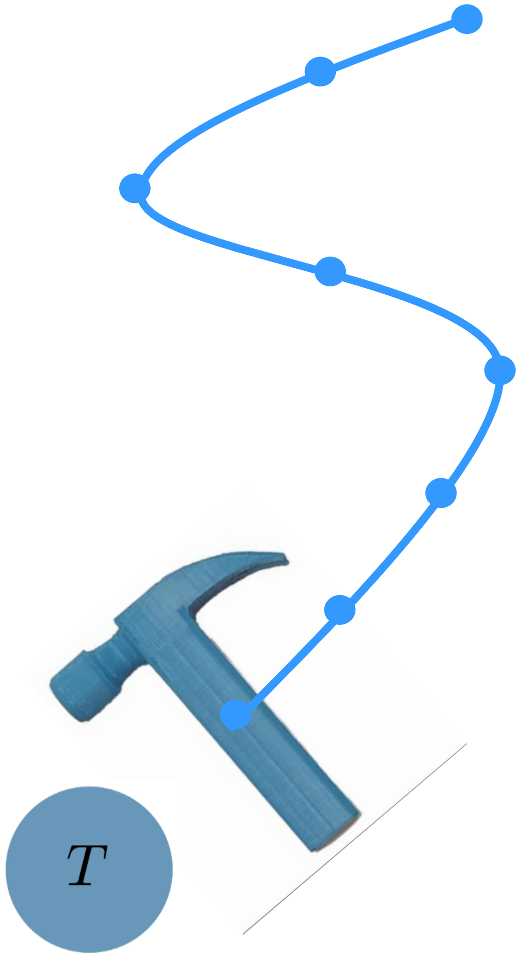

Reaches?
C-Free?
Stable?
G
T
ξ_a
Follows?
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?


T

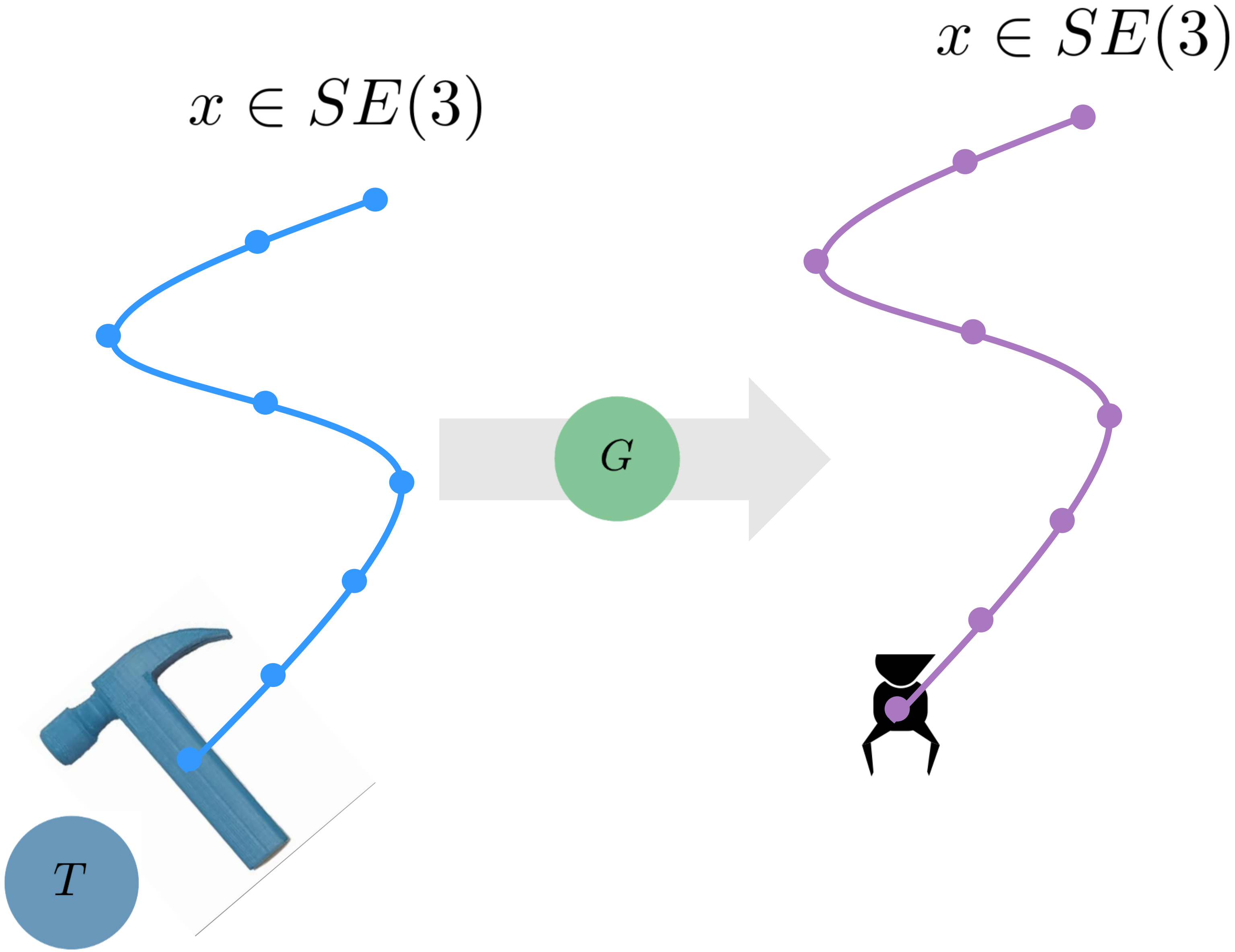

T

Task Space

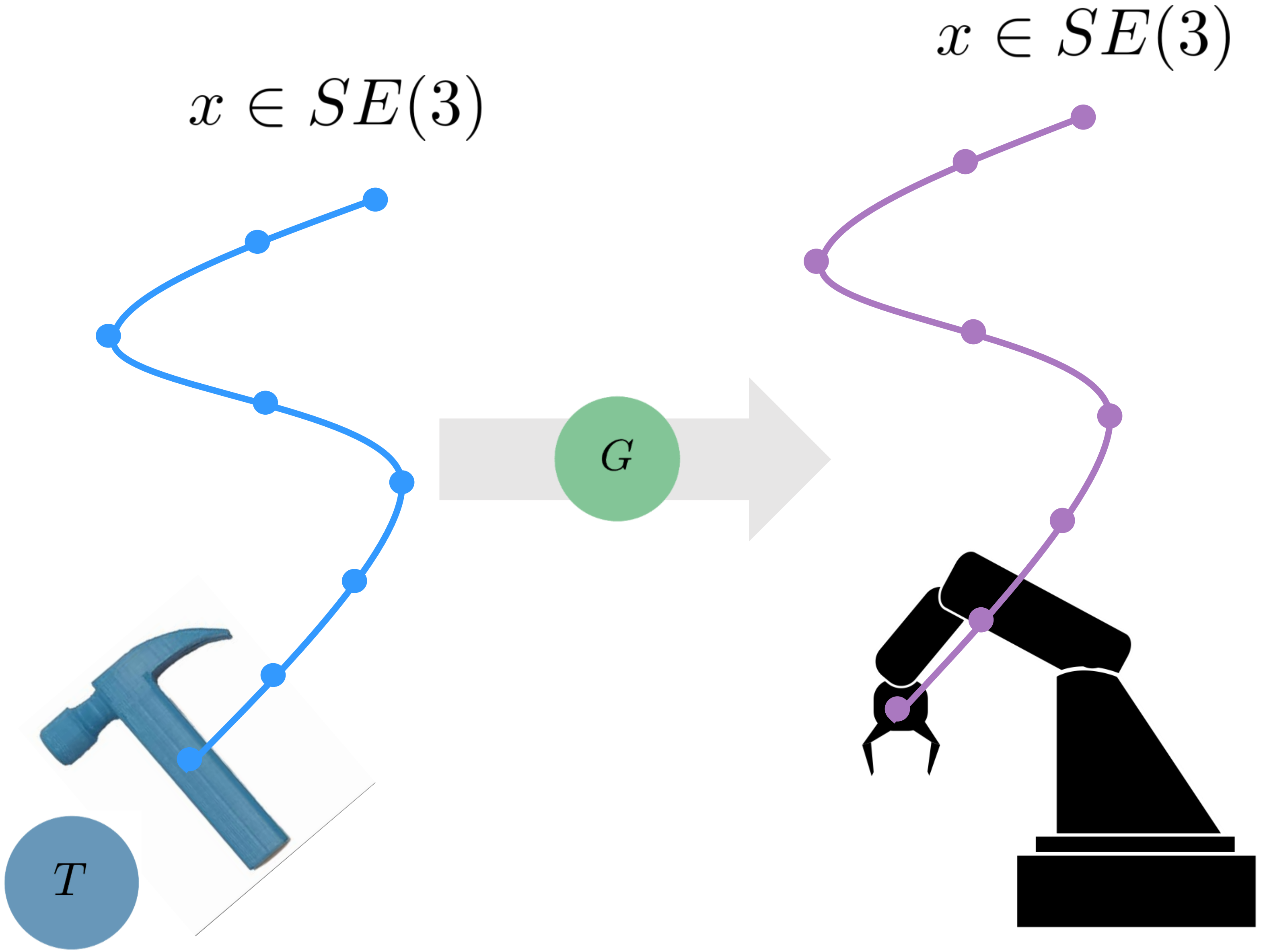
$$x \in SE(3)$$

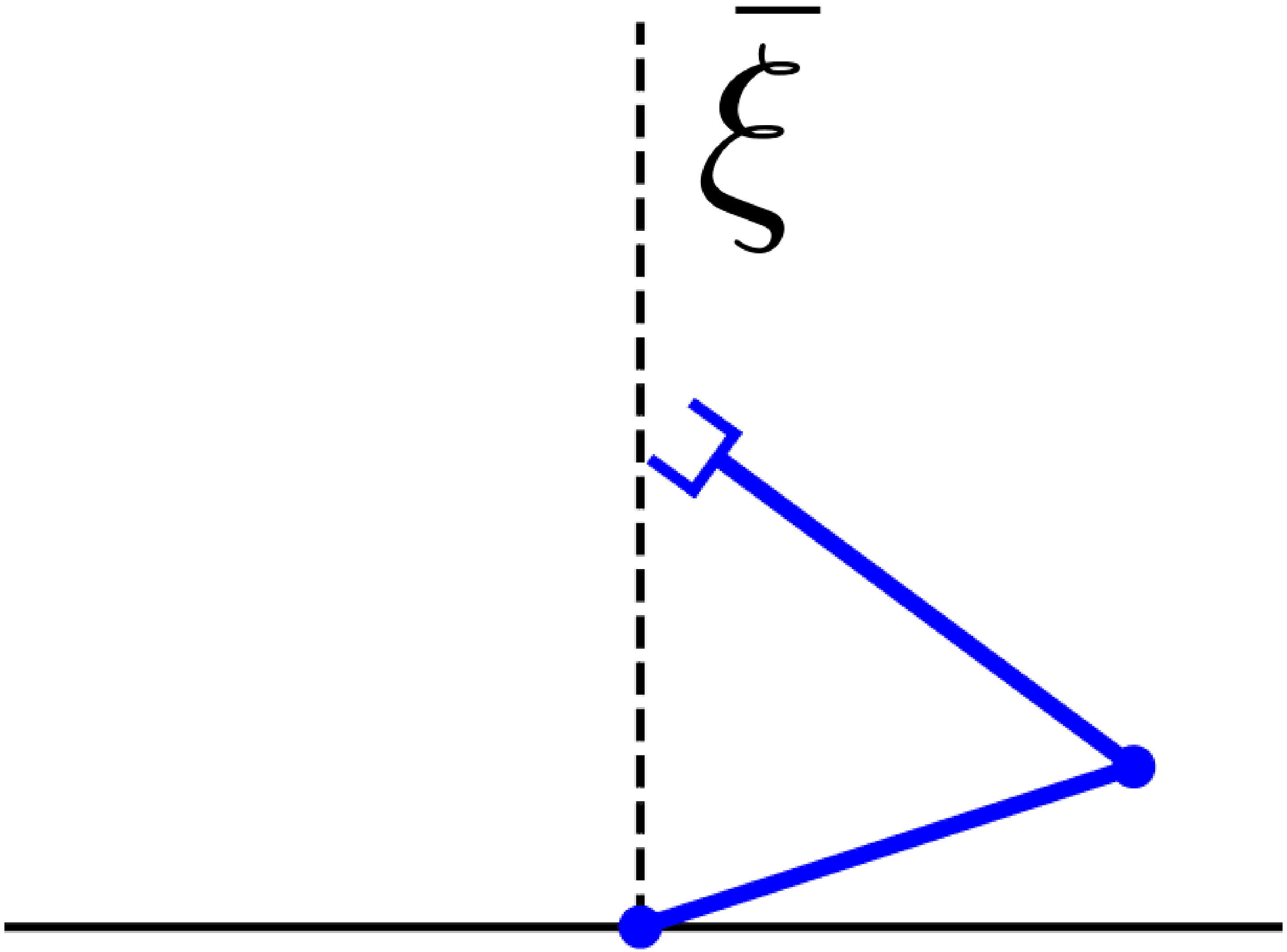


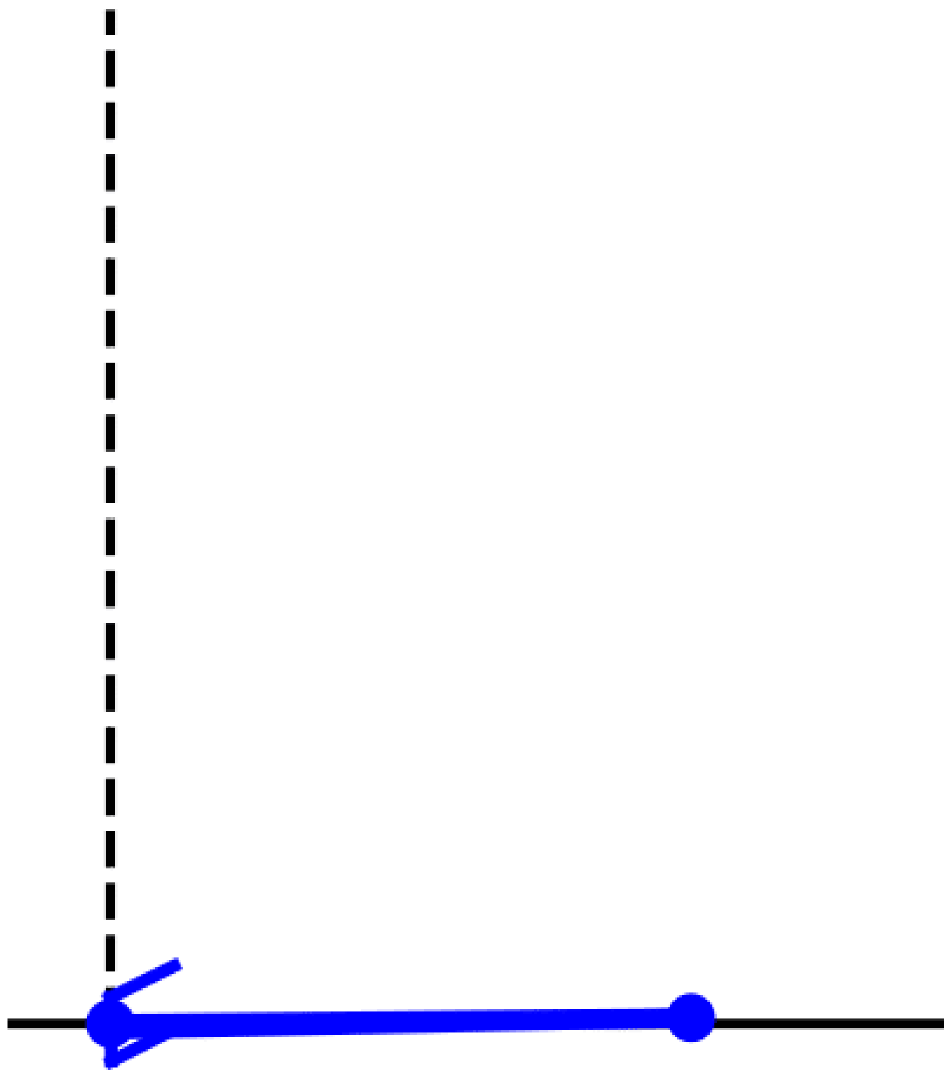
Task Space

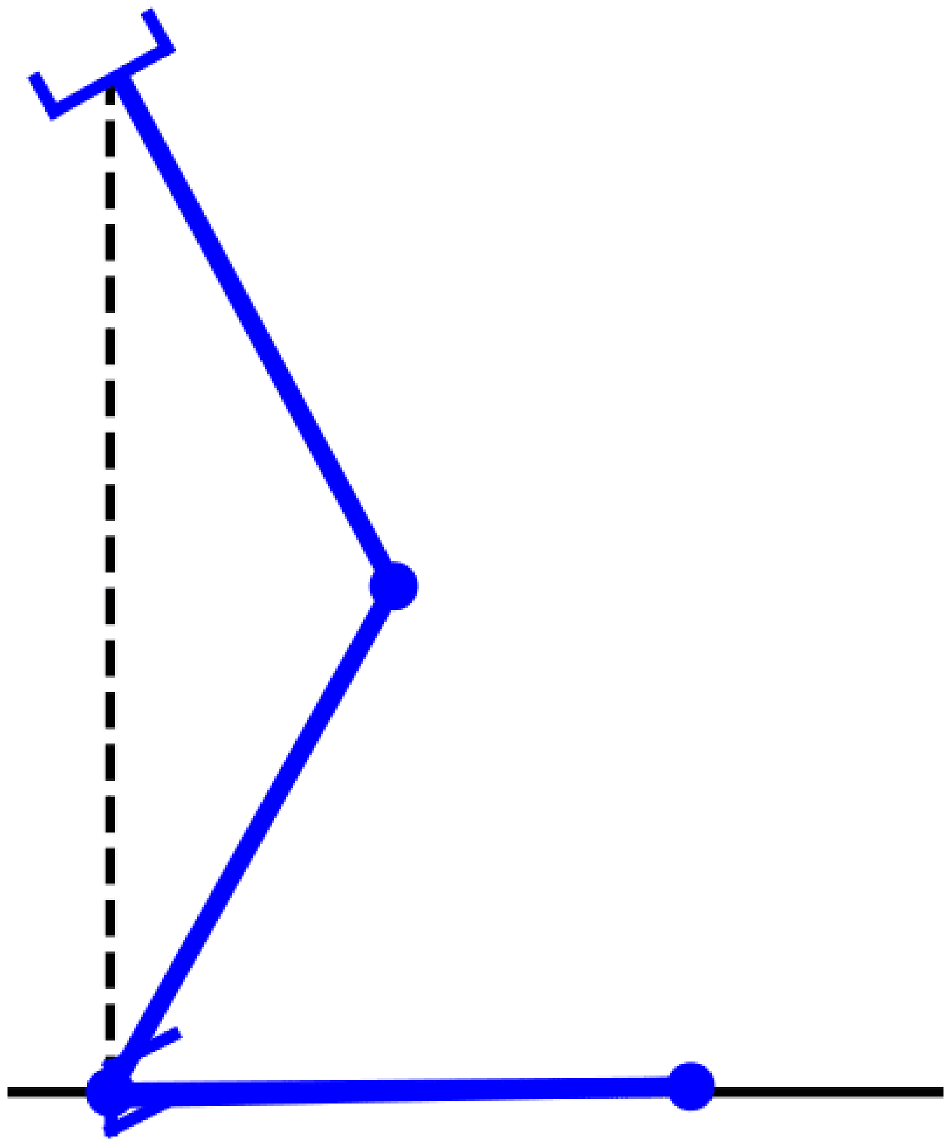


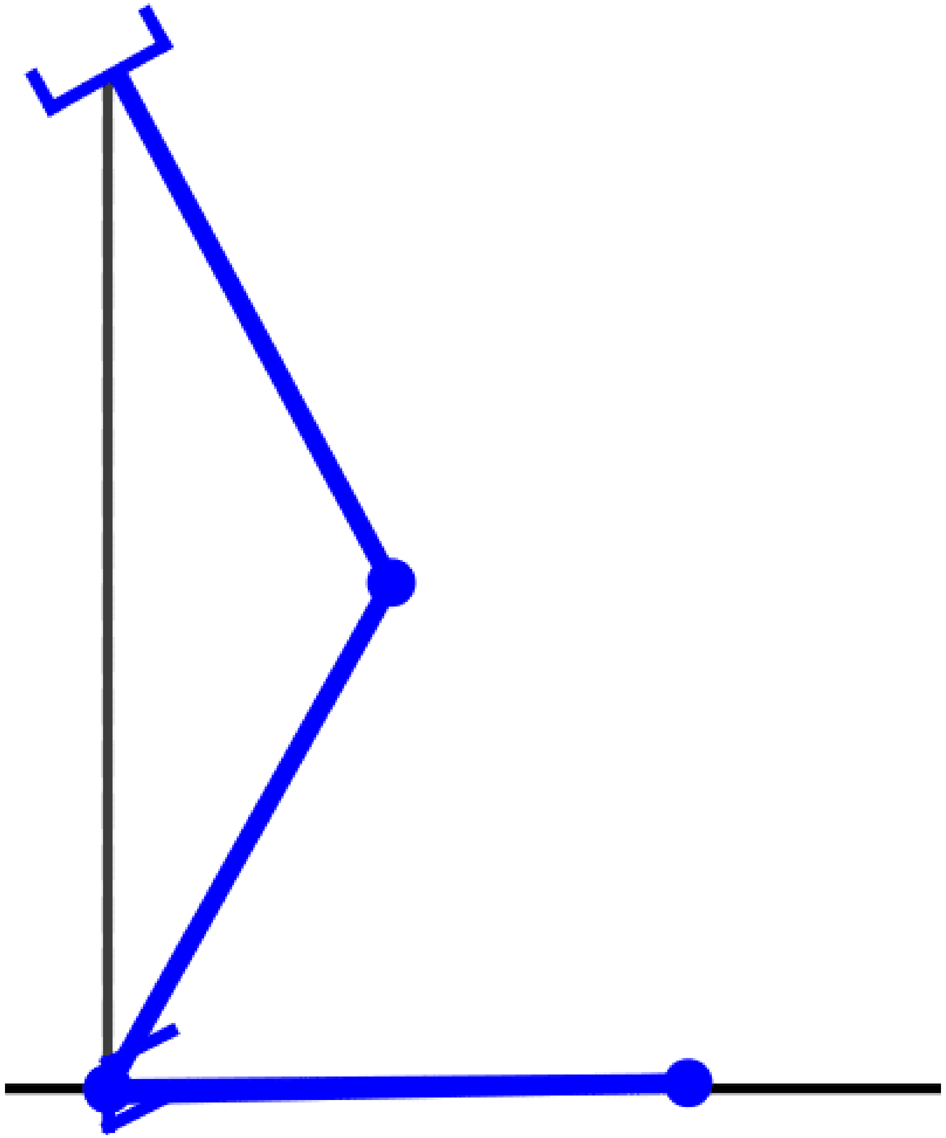
Task Space



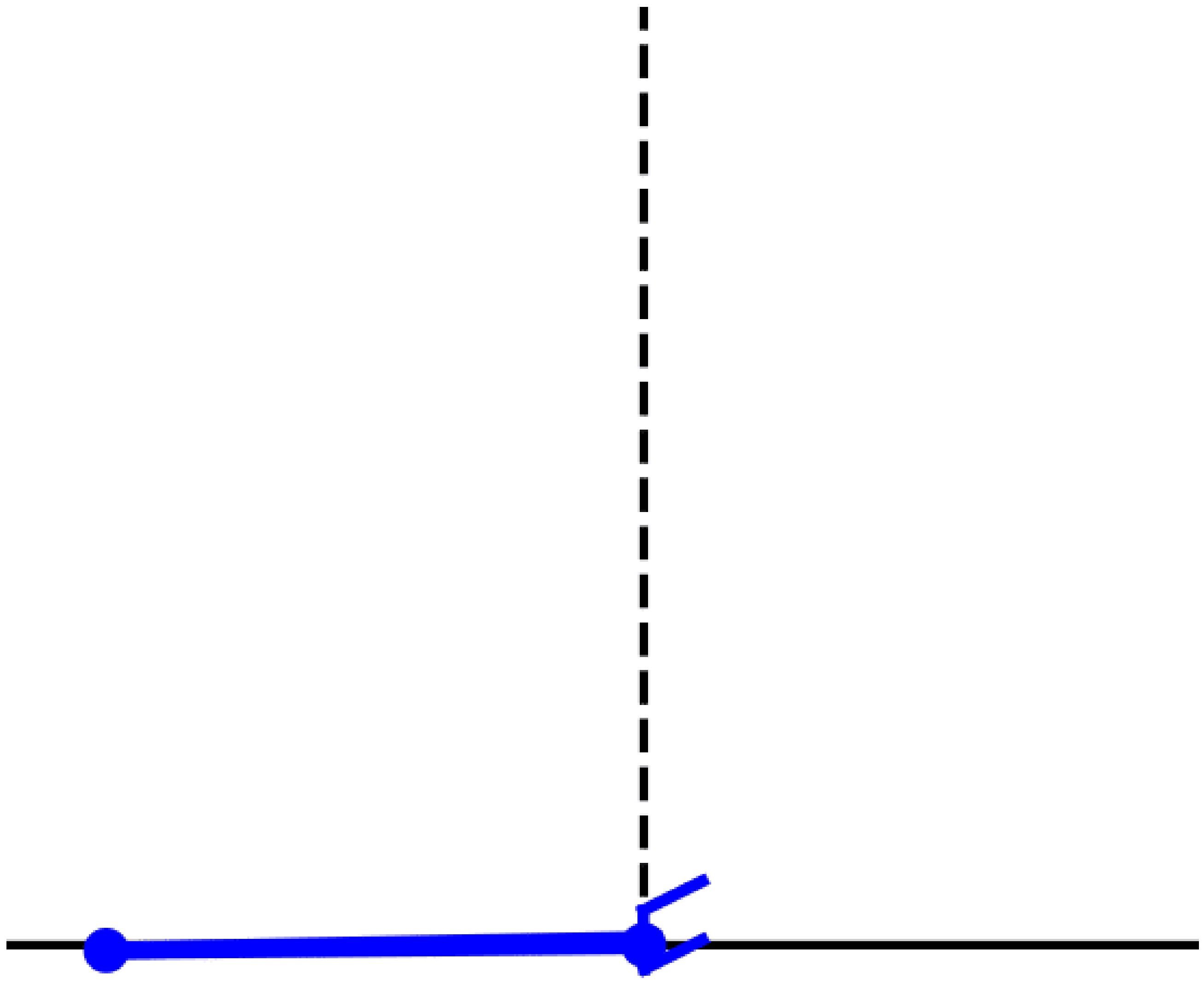

$\bar{\xi}$

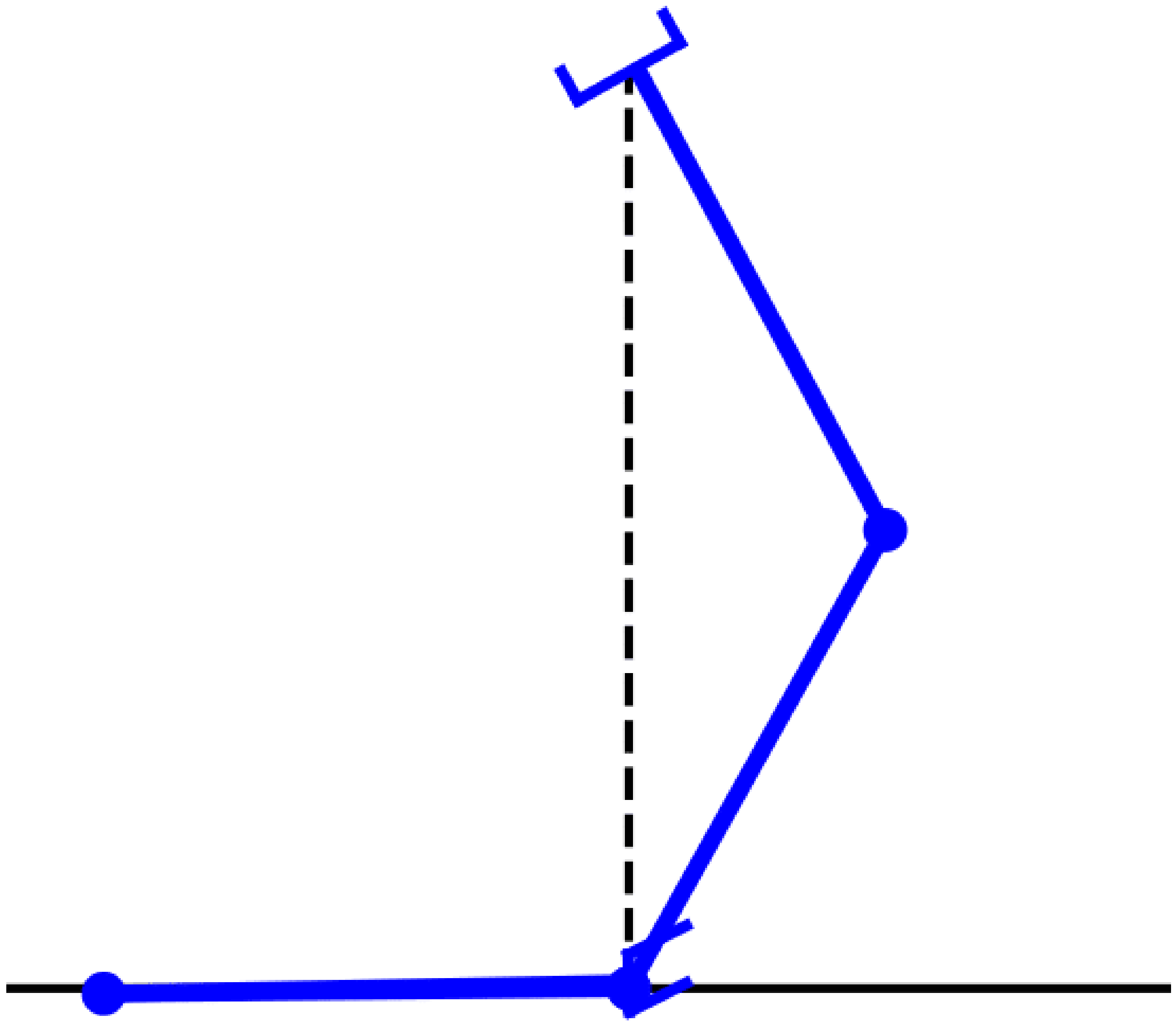


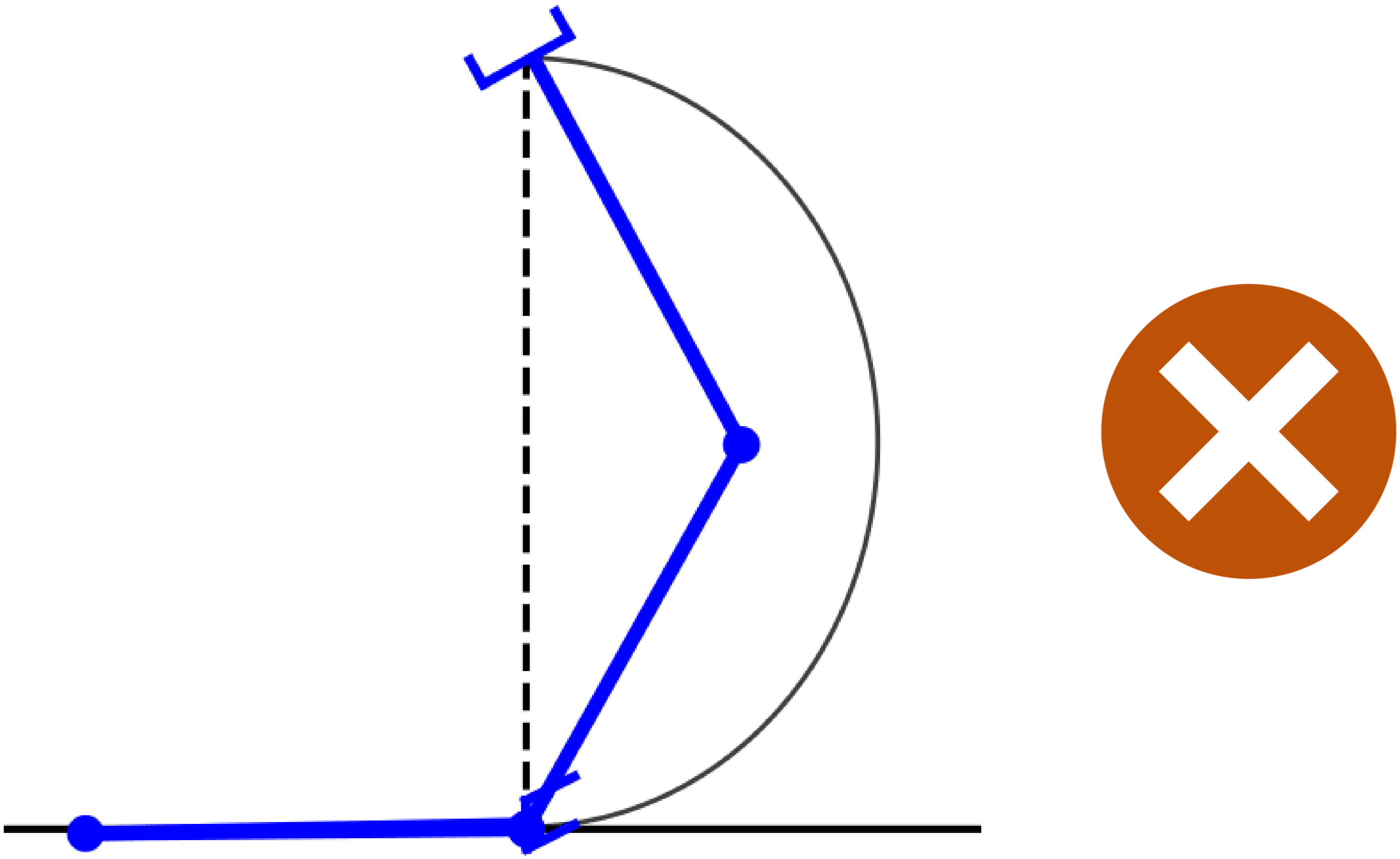




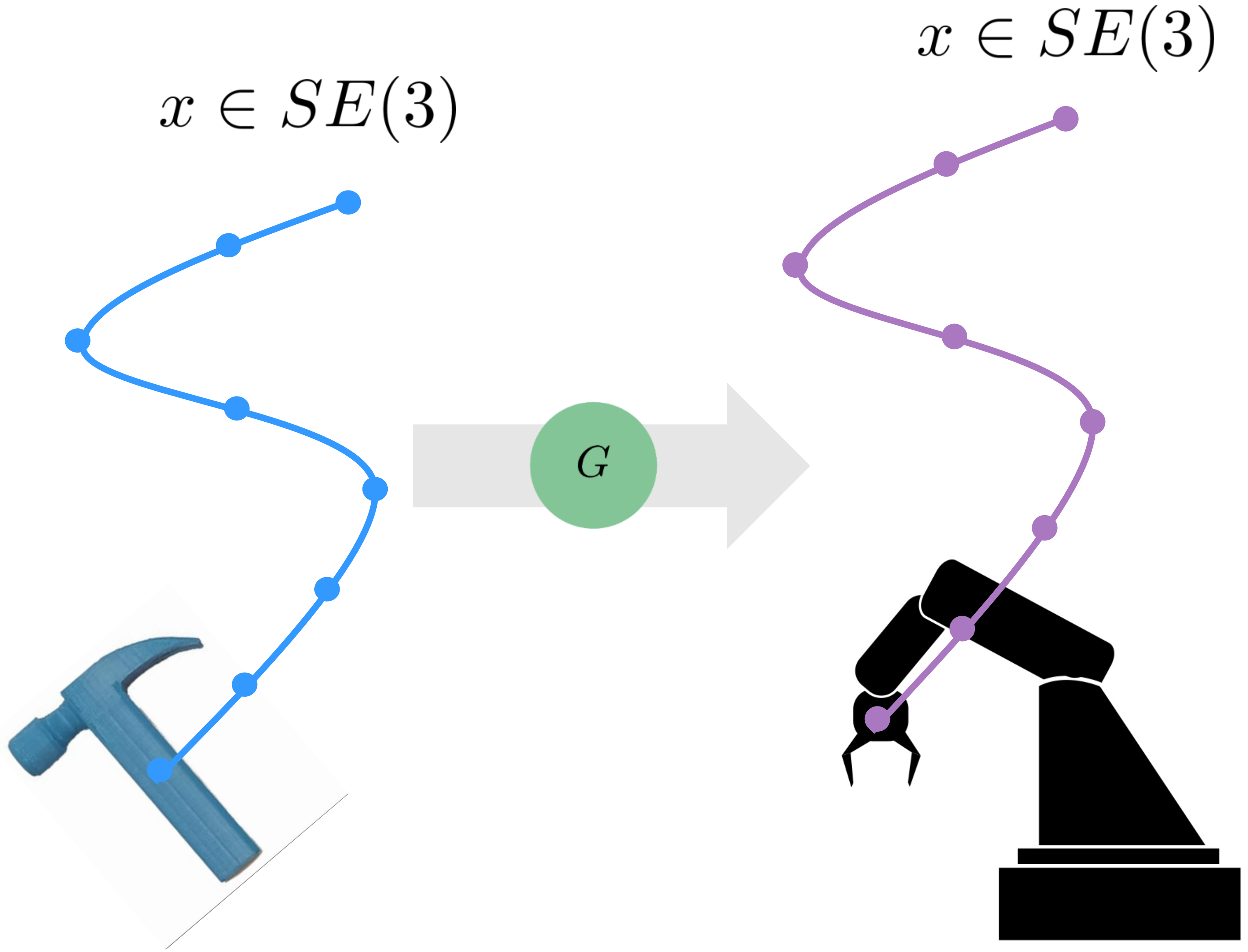
Distance Metrics and Algorithms for Task Space Path Optimization. Rachel Holladay and Siddhartha Srinivasa. IROS, 2016.





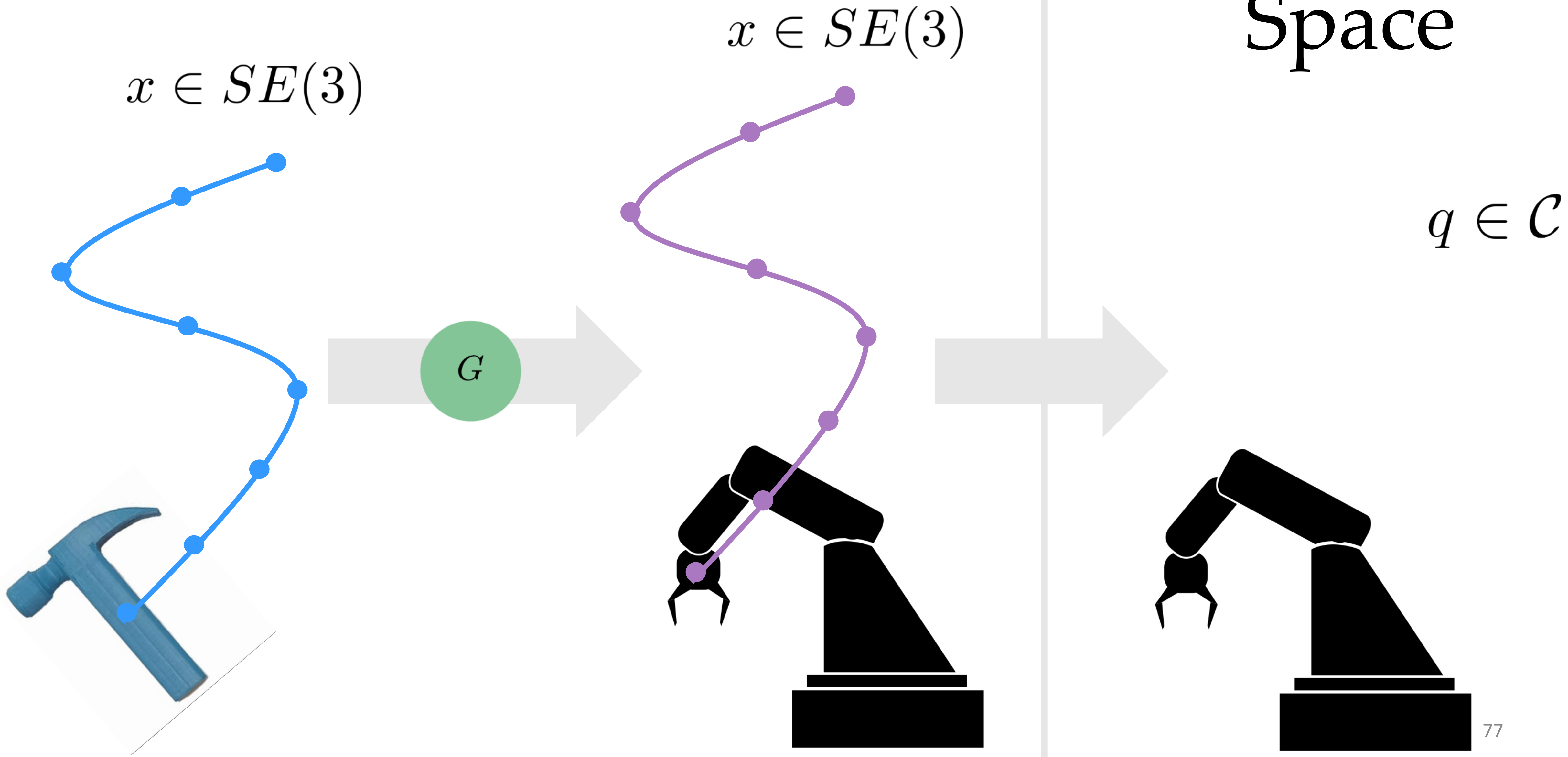


Task Space



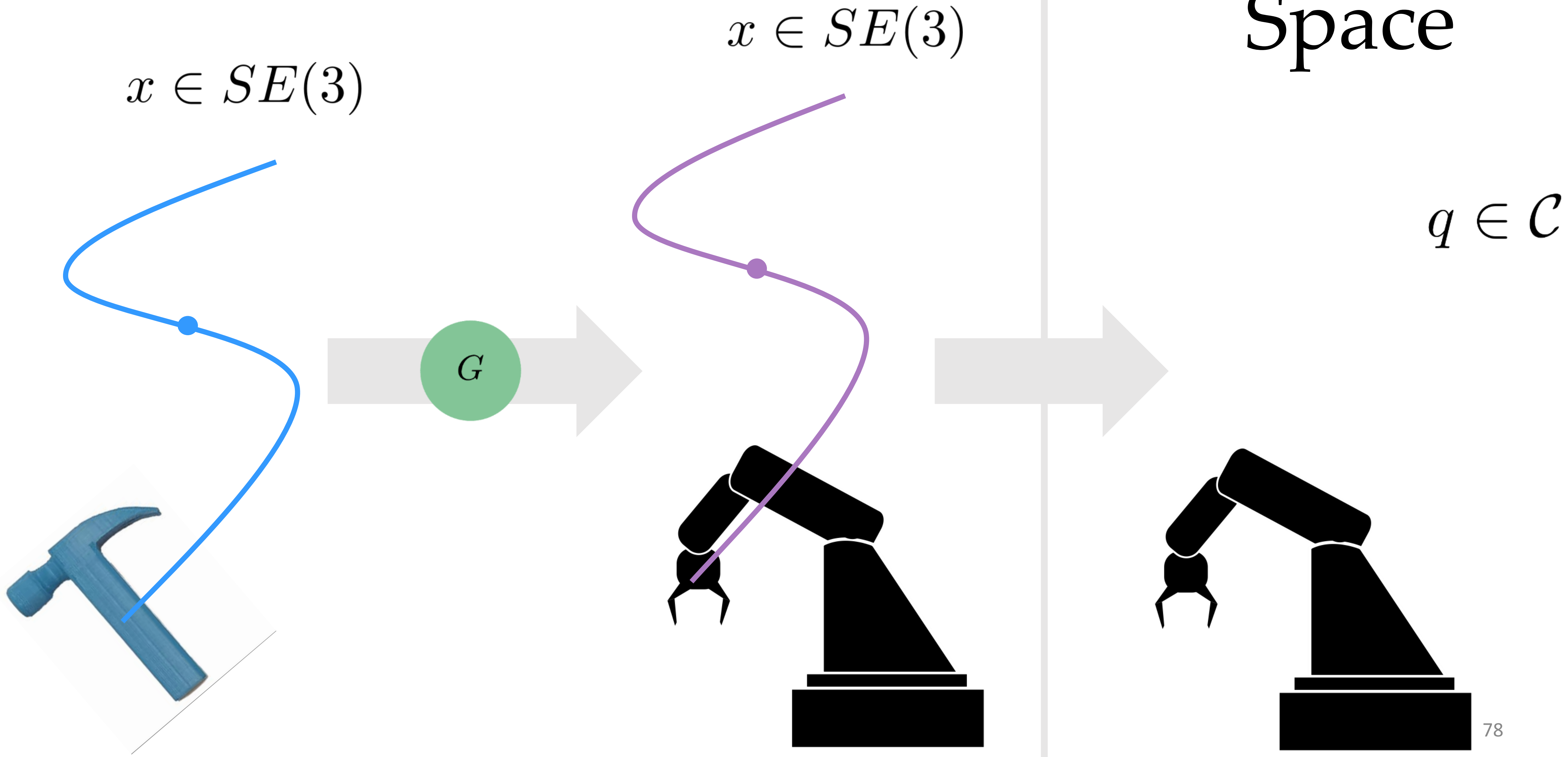
Task Space

Configuration Space



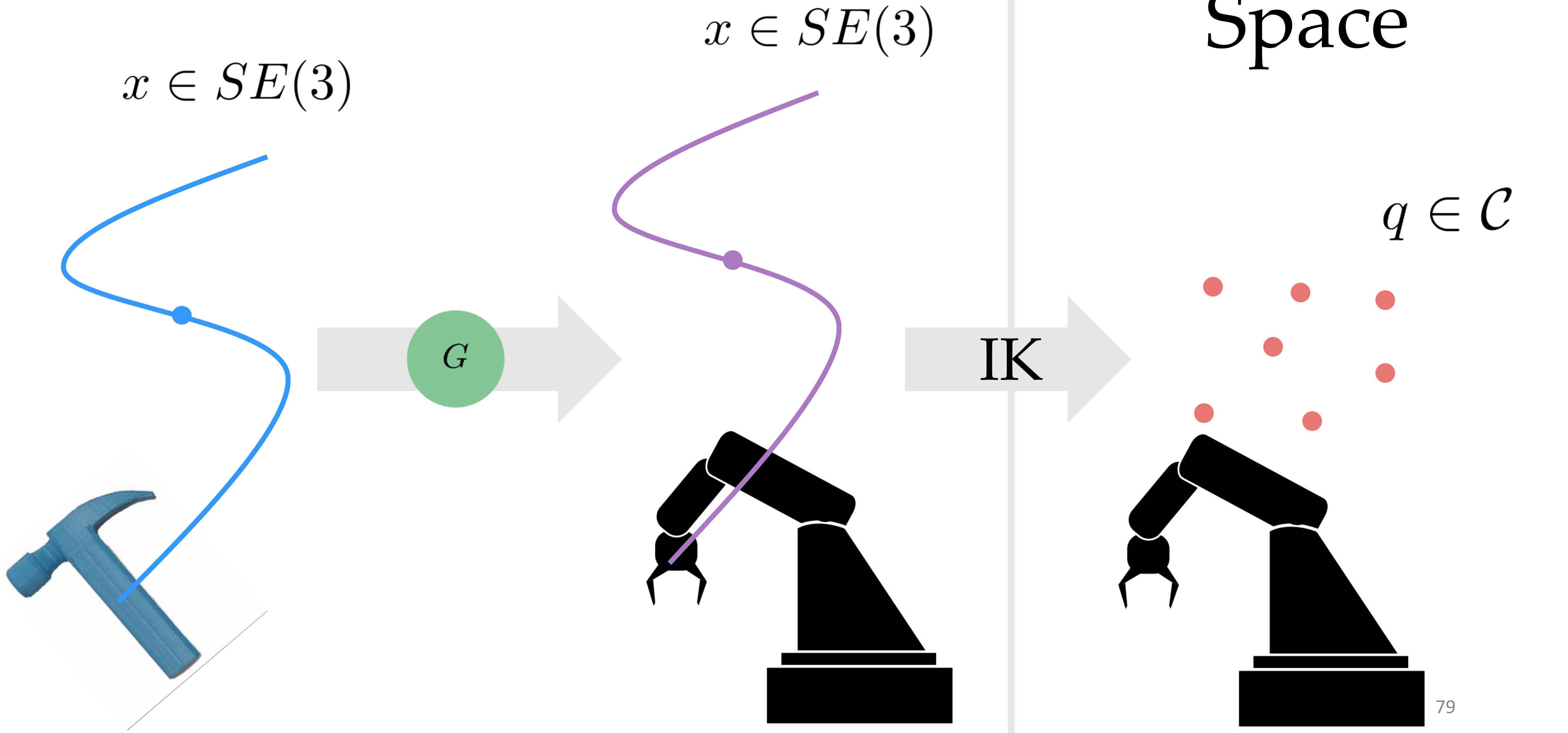
Task Space

Configuration Space

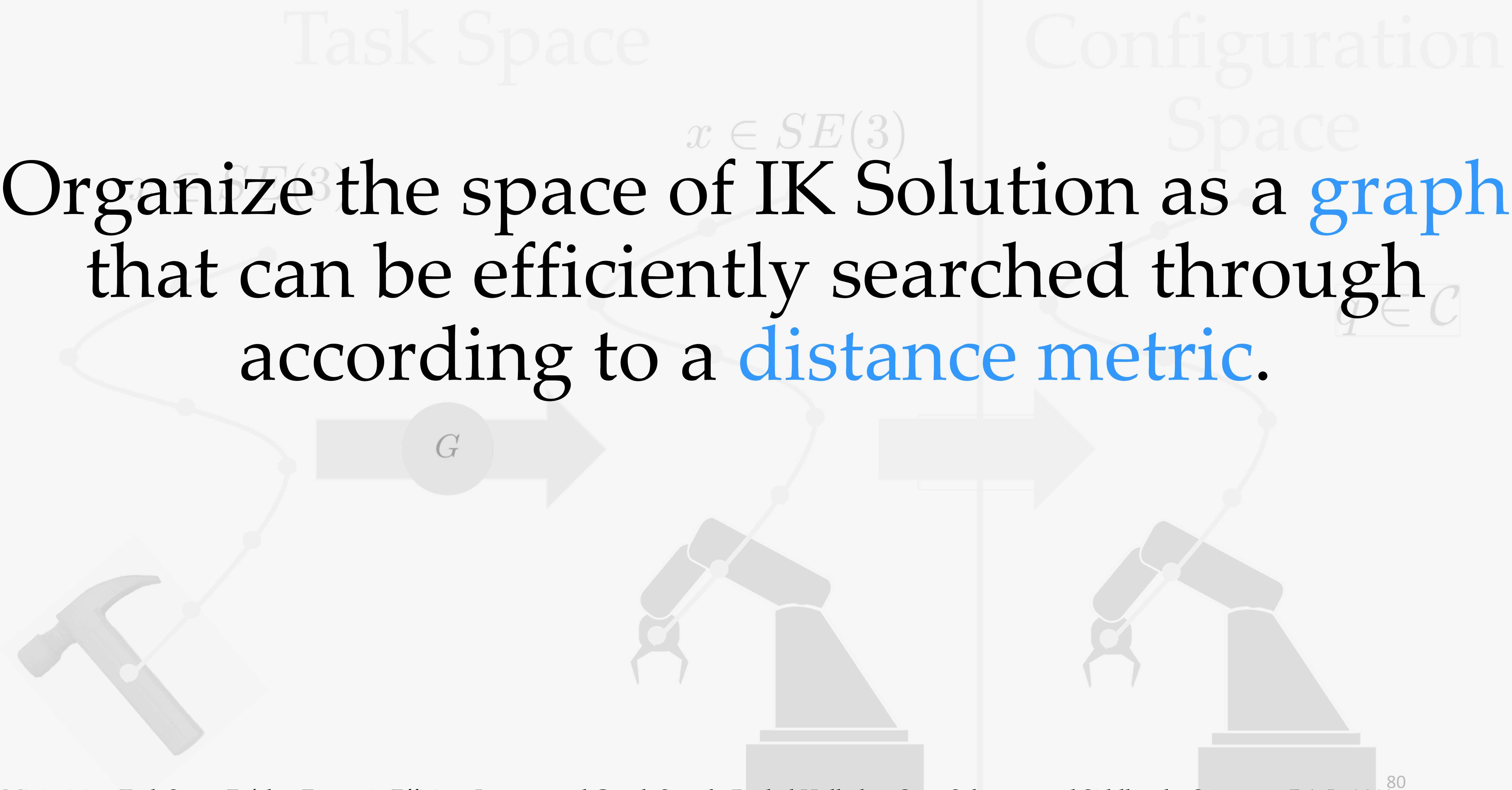


Task Space

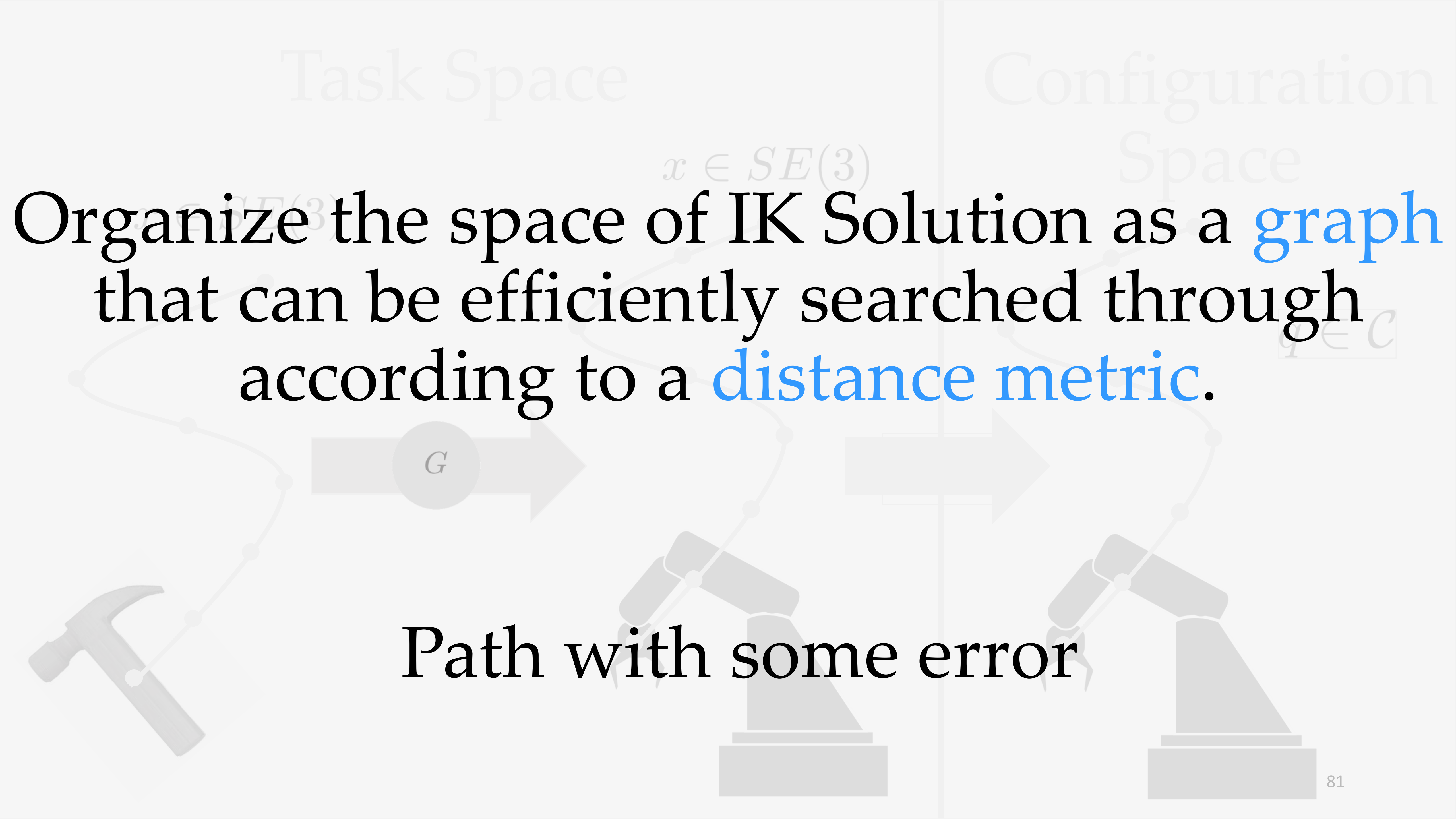
Configuration Space



Organize the space of IK Solution as a graph that can be efficiently searched through according to a distance metric.

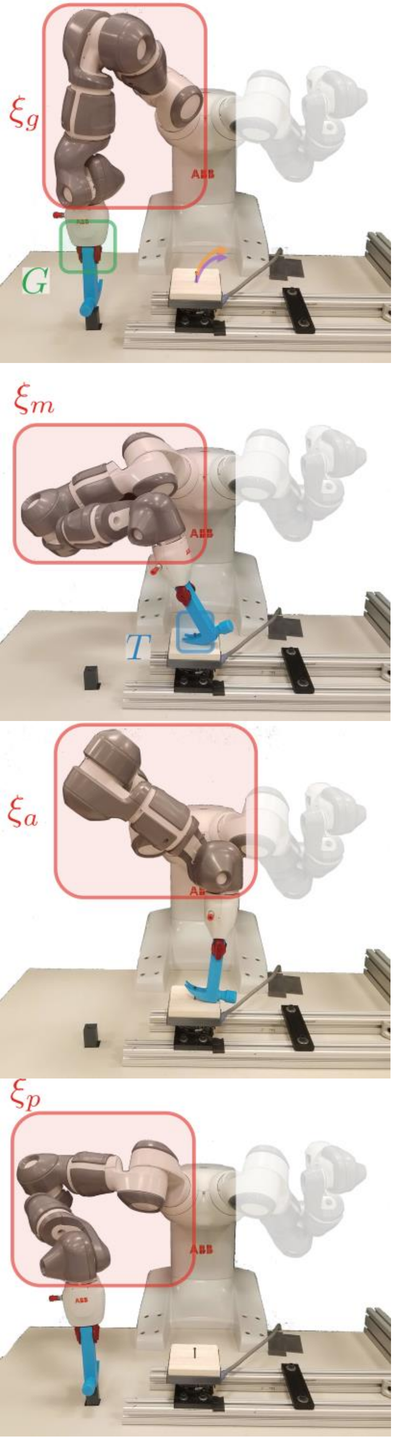


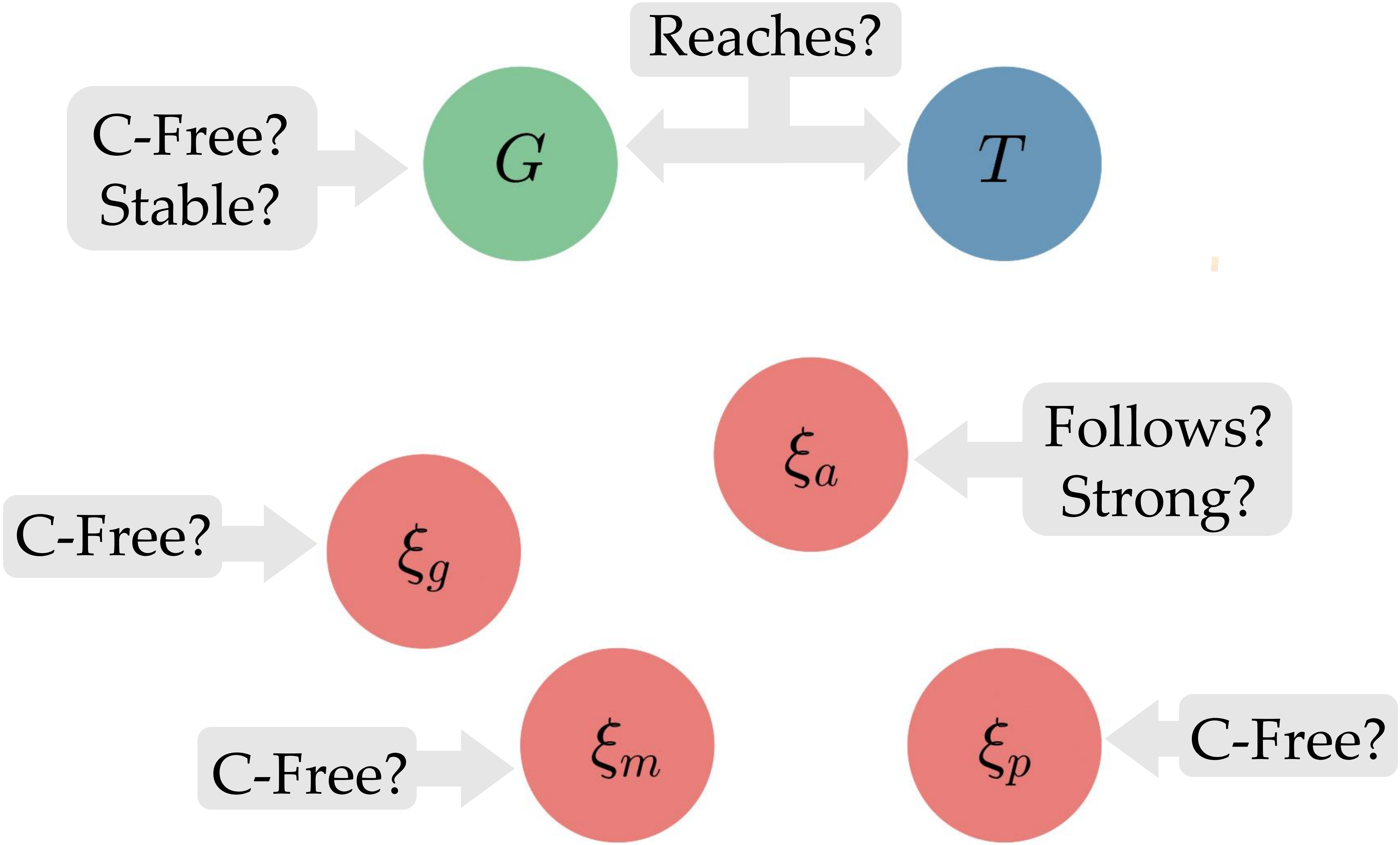
Minimizing Task Space Fréchet Error via Efficient Incremental Graph Search. Rachel Holladay, Oren Salzman, and Siddhartha Srinivasa. RA-L, 2019.



Organize the space of IK Solution as a graph that can be efficiently searched through according to a distance metric.

Path with some error

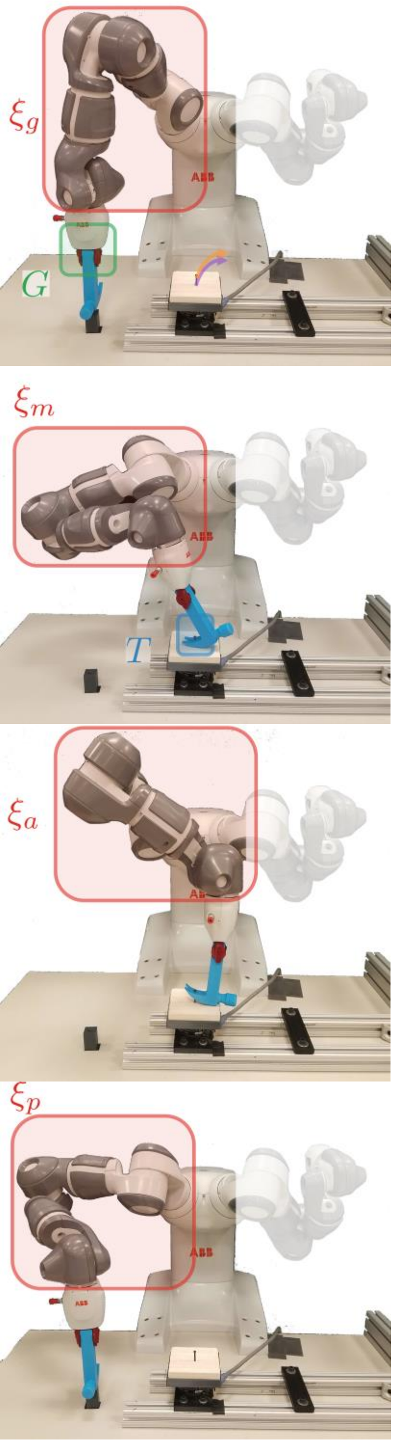

ξ_g
G
ξ_m
T
ξ_a
ξ_p

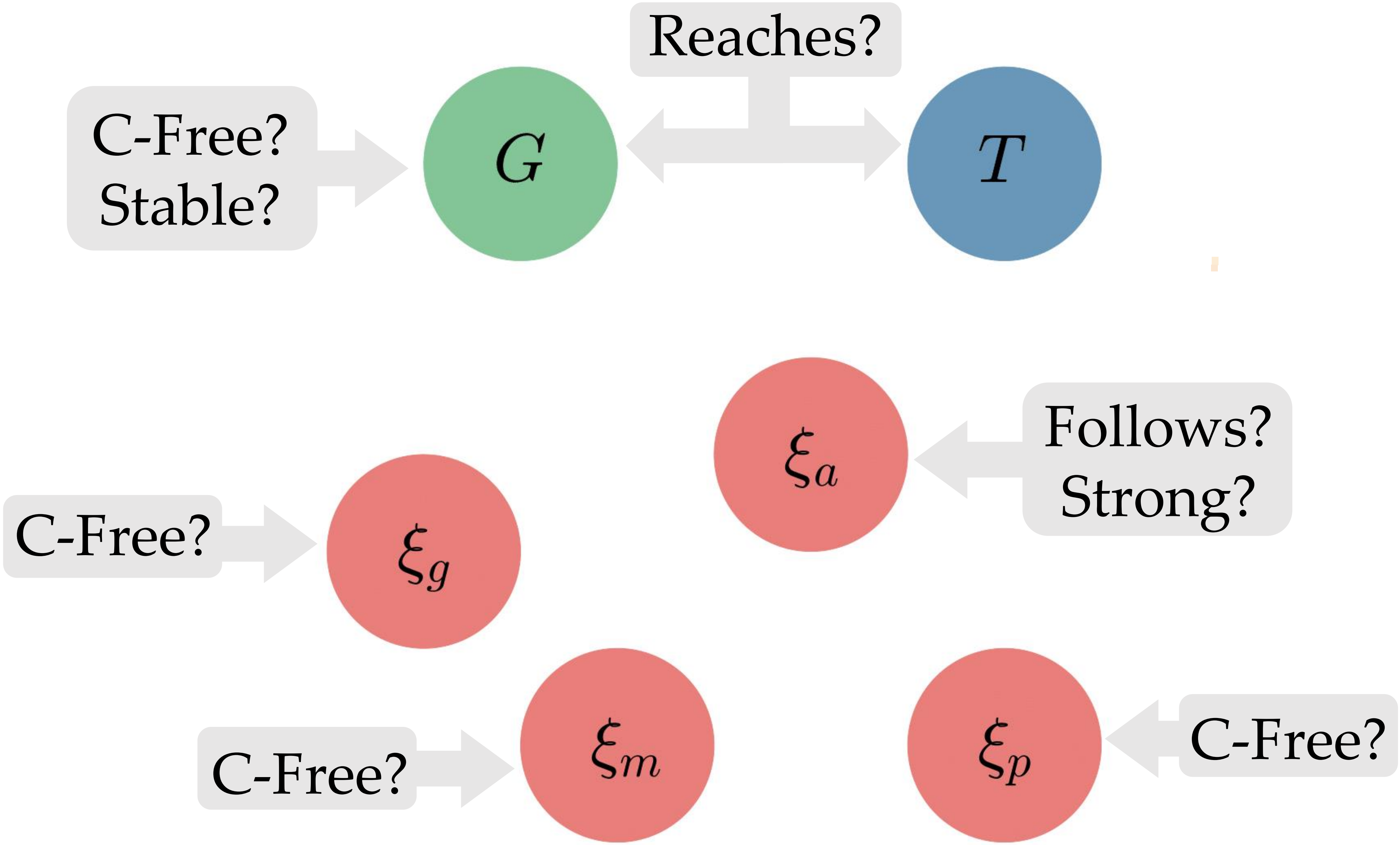

Reaches?
C-Free?
Stable?
G
T
ξ_a
Follows?
Strong?
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?

$$\tau_{ext} = J^T(q) f_{ext}$$

$$\tau_{lim} > \tau_{ext} = J^T(q) f_{ext}$$

Dmitry Berenson. “Constrained Manipulation Planning,” Carnegie Mellon University, 2011.
Chen, Lipeng, Luis FC Figueredo, and Mehmet Dogar. "Manipulation planning under changing external forces." *IROS*. IEEE, 2018.


ξ_g
G
ξ_m
T
ξ_a
ξ_p


Reaches?
C-Free?
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ξ_a
Follows?
Strong?
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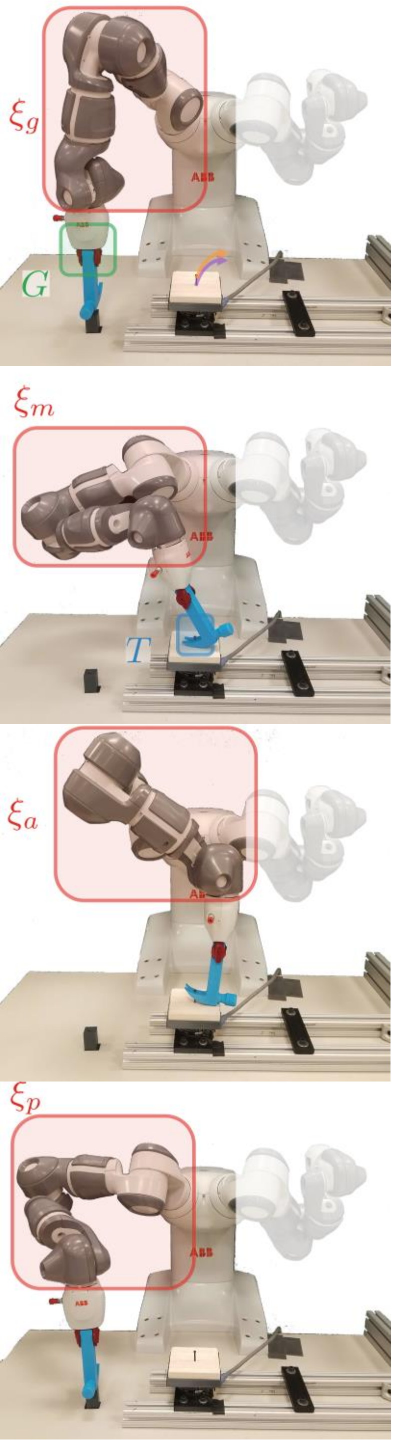
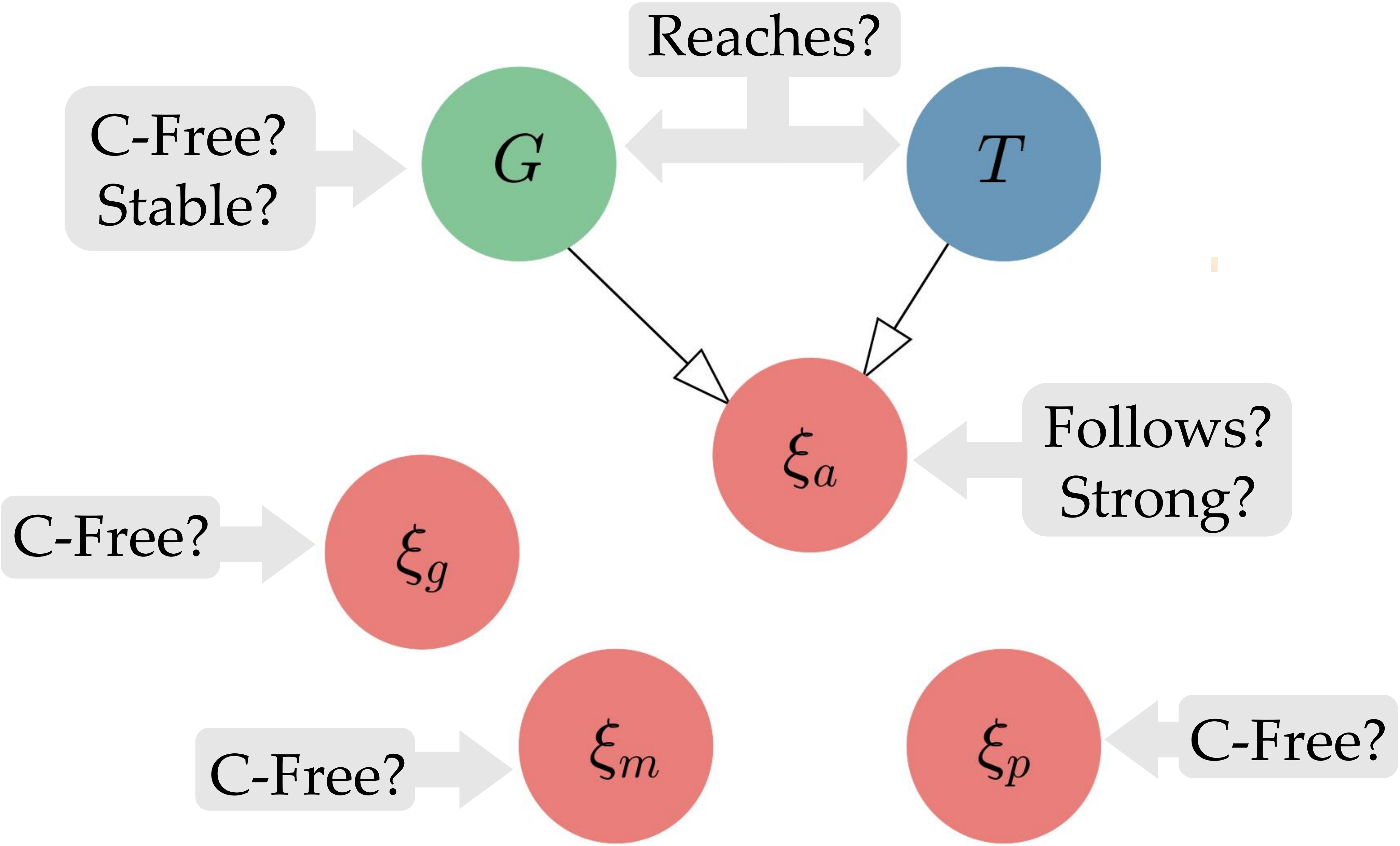
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?



ξ_g
G
ξ_m
T
ξ_a
ξ_p



Reaches?
C-Free?
Stable?
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Follows?
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ξ_g
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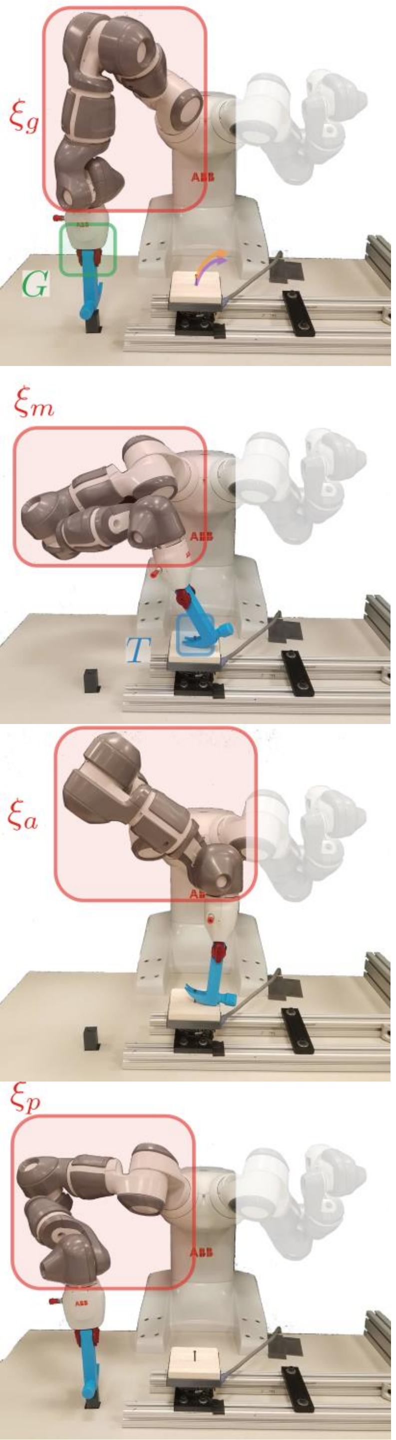
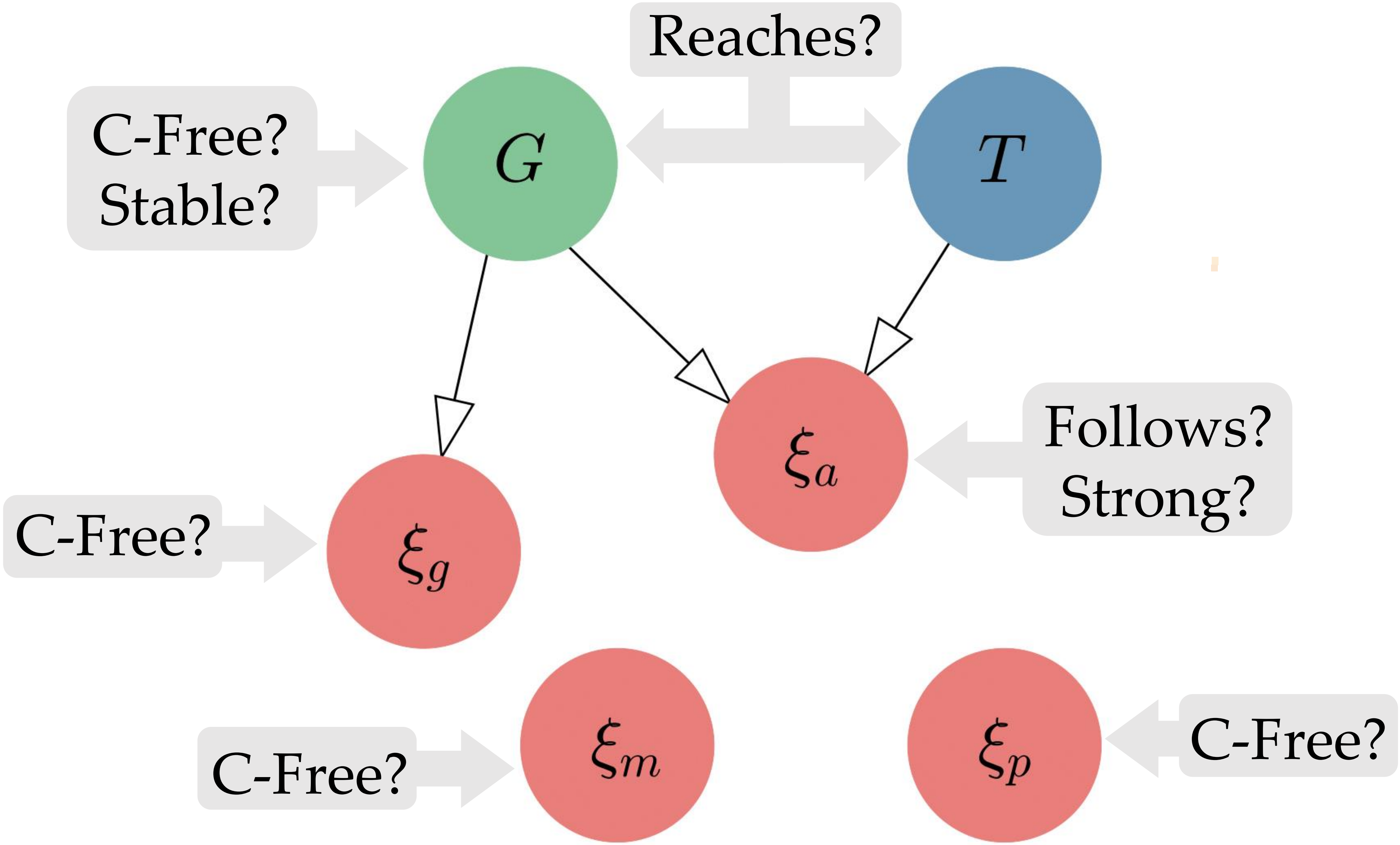
ξ_m
ξ_p
C-Free?



ξ_g
G
ξ_m
T
ξ_a
ξ_p



Reaches?
C-Free?
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T
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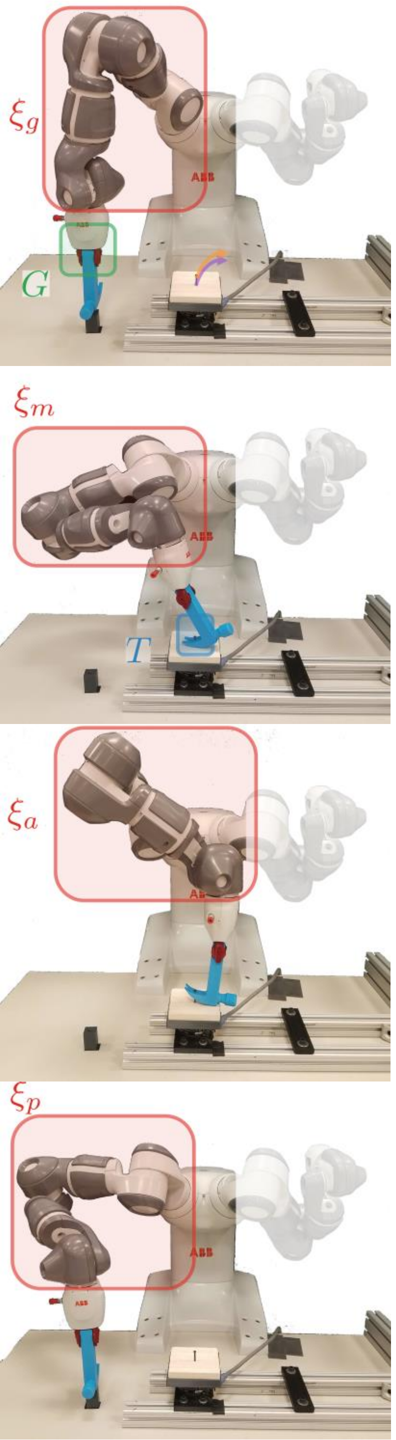
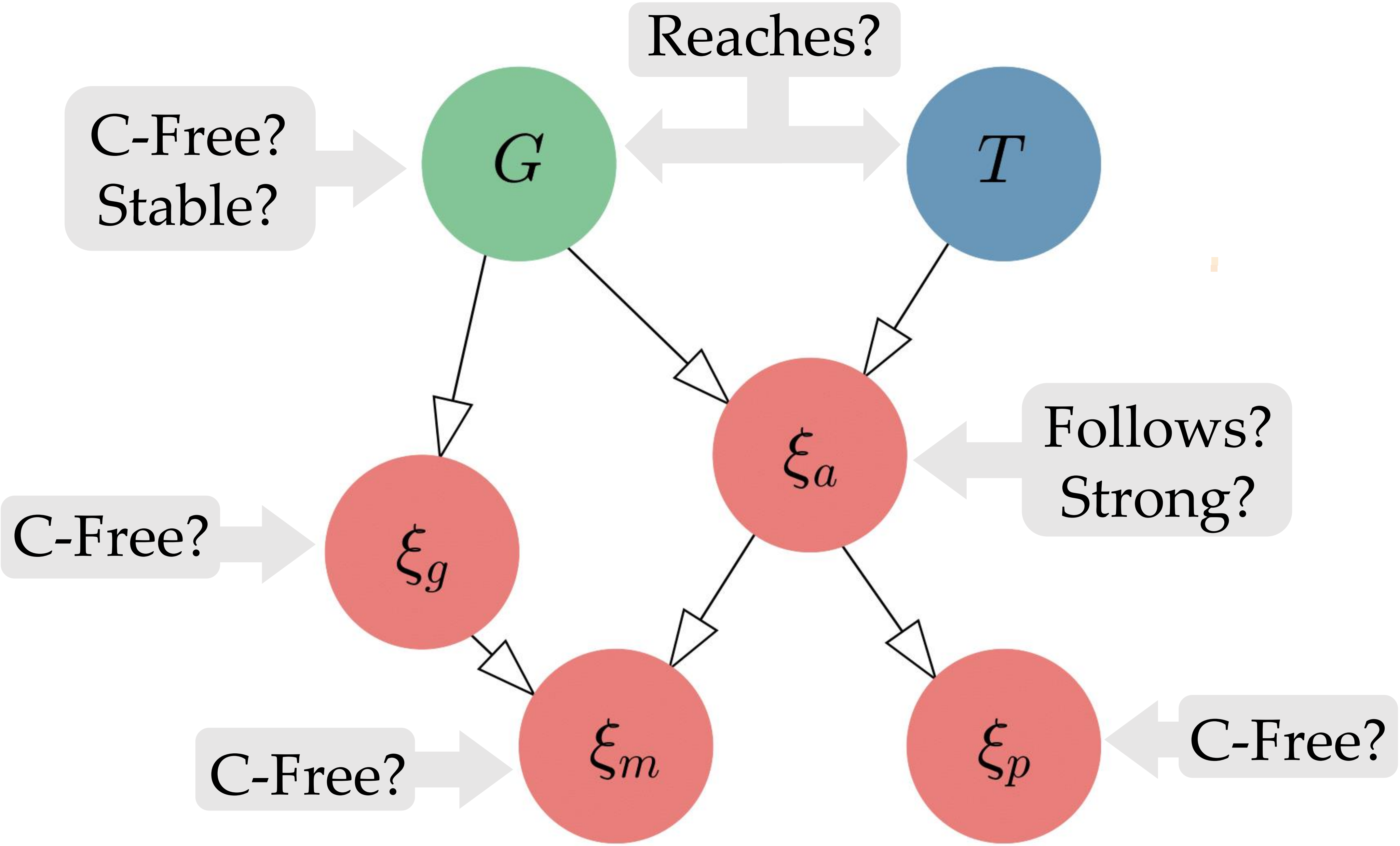
C-Free?
ξ_g
ξ_a
C-Free?
ξ_m
ξ_p
C-Free?

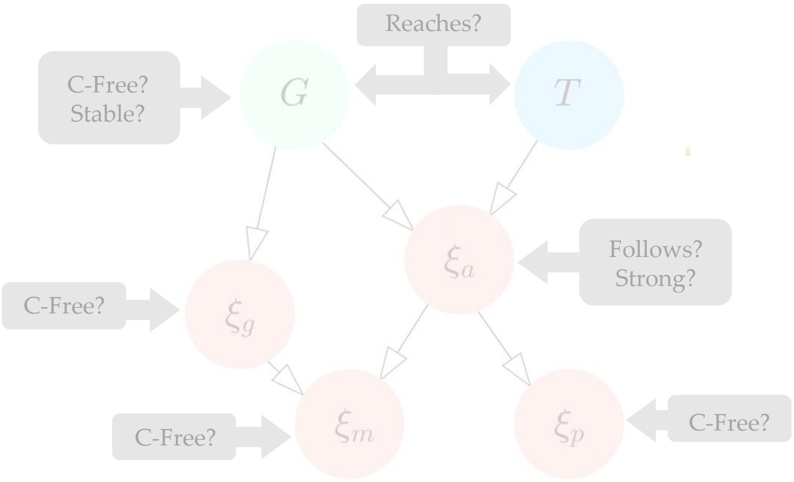


ξ_g
G
ξ_m
T
ξ_a
ξ_p

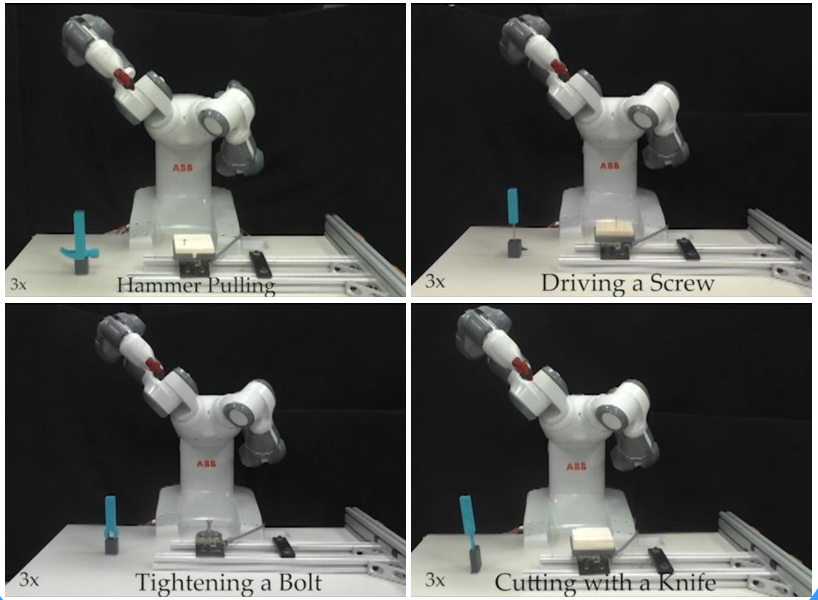


Reaches?
C-Free?
Stable?
G
T
Follows?
Strong?
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?

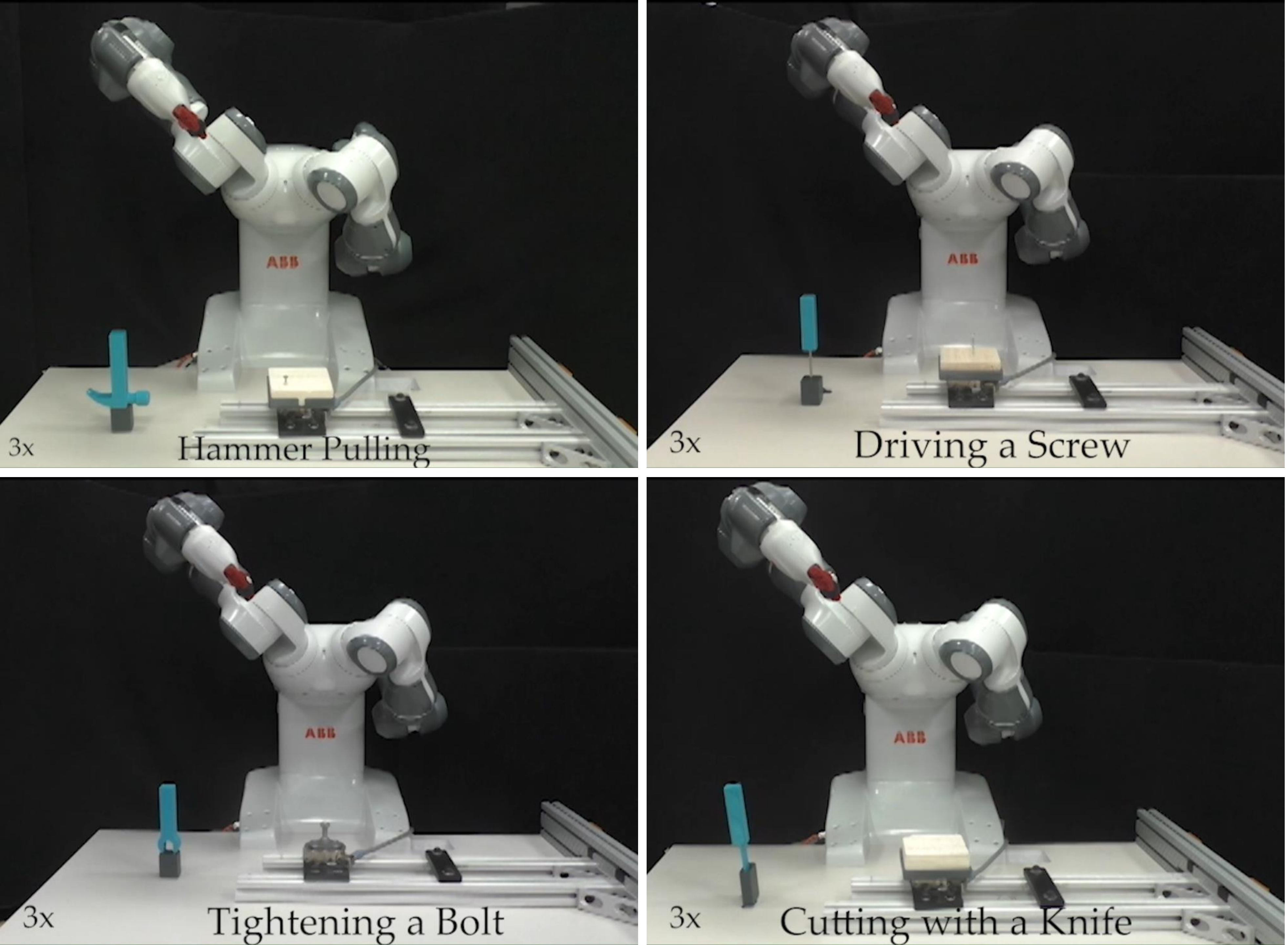
Constraints



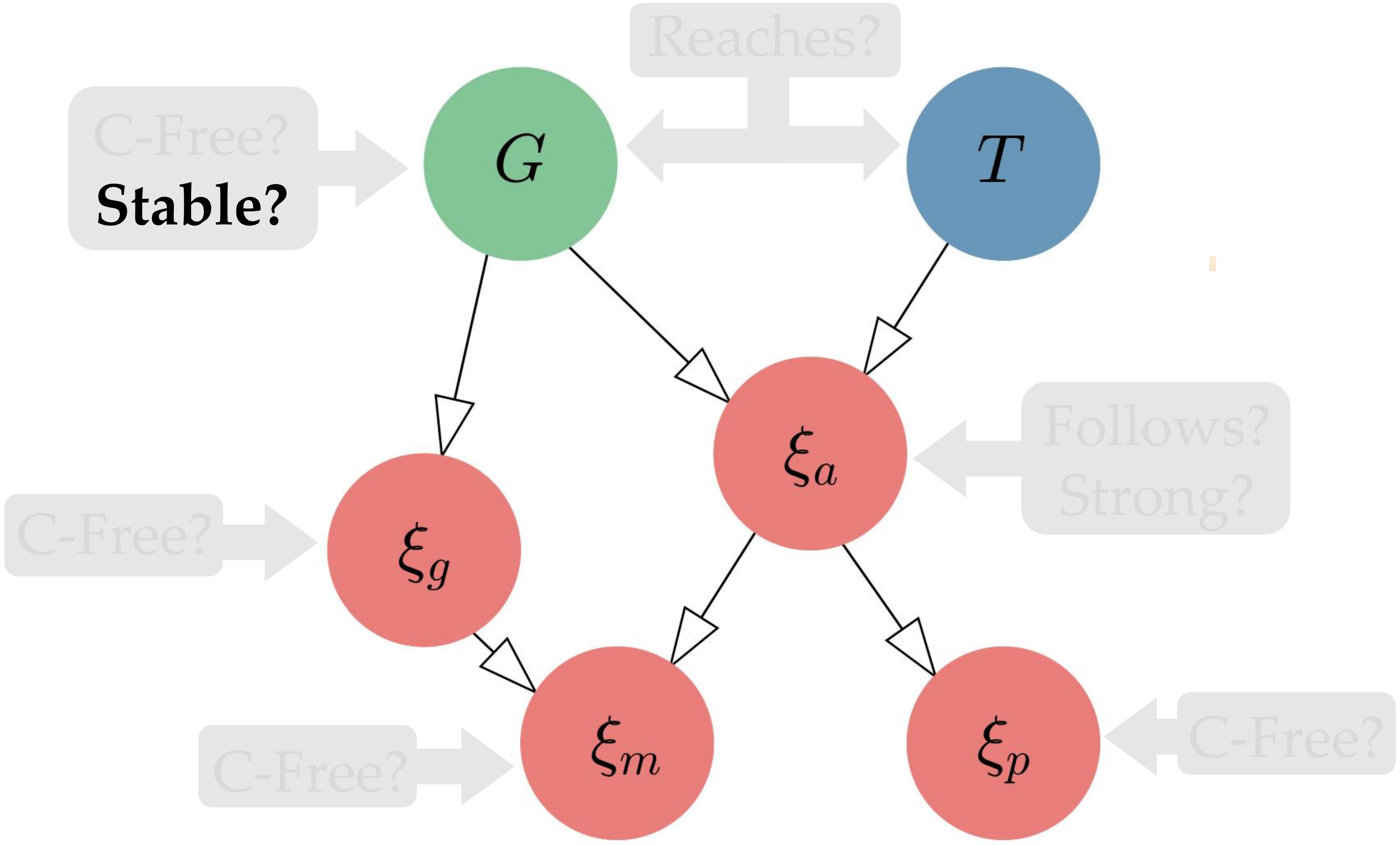
Experiments



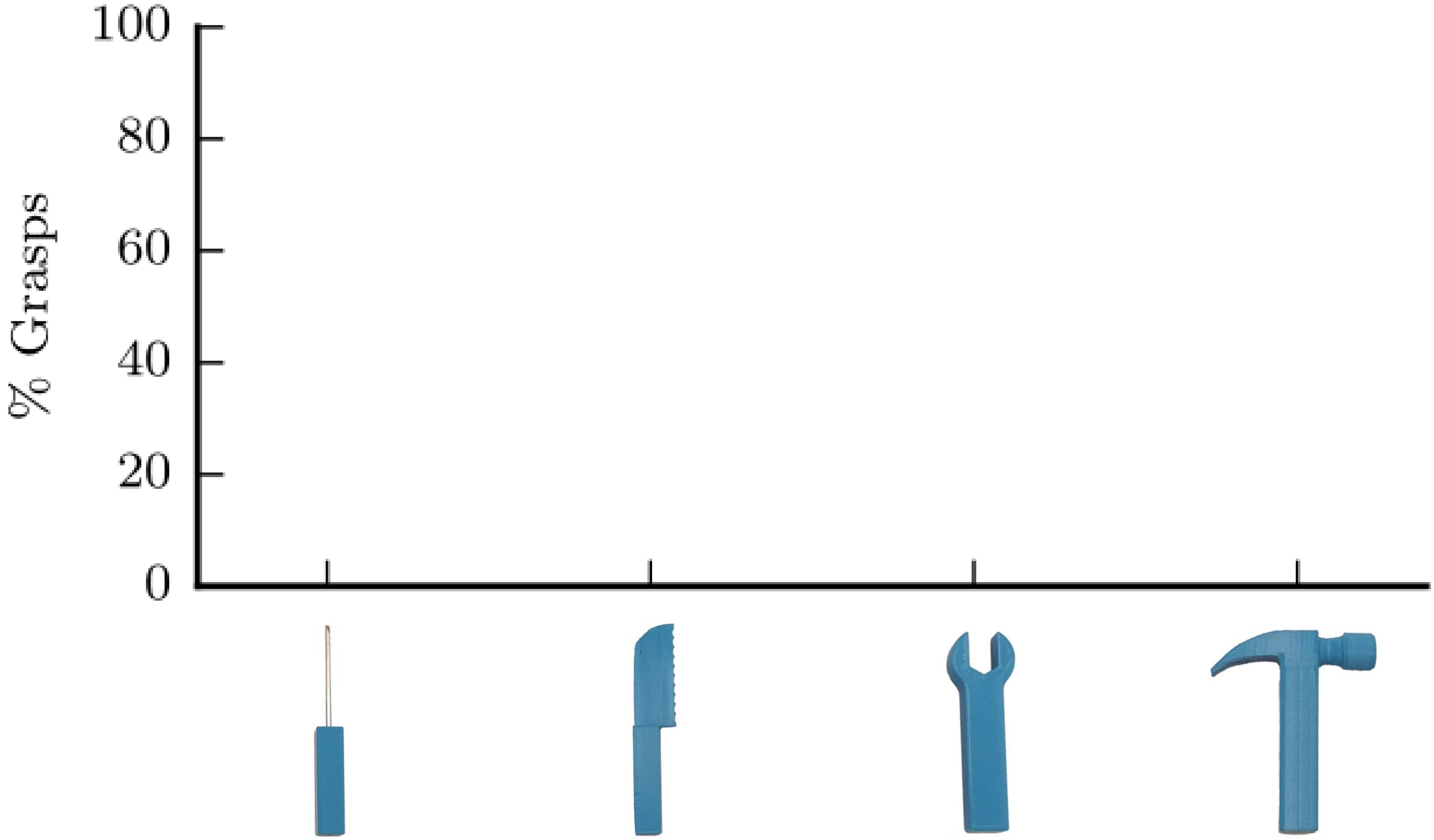
Assumptions



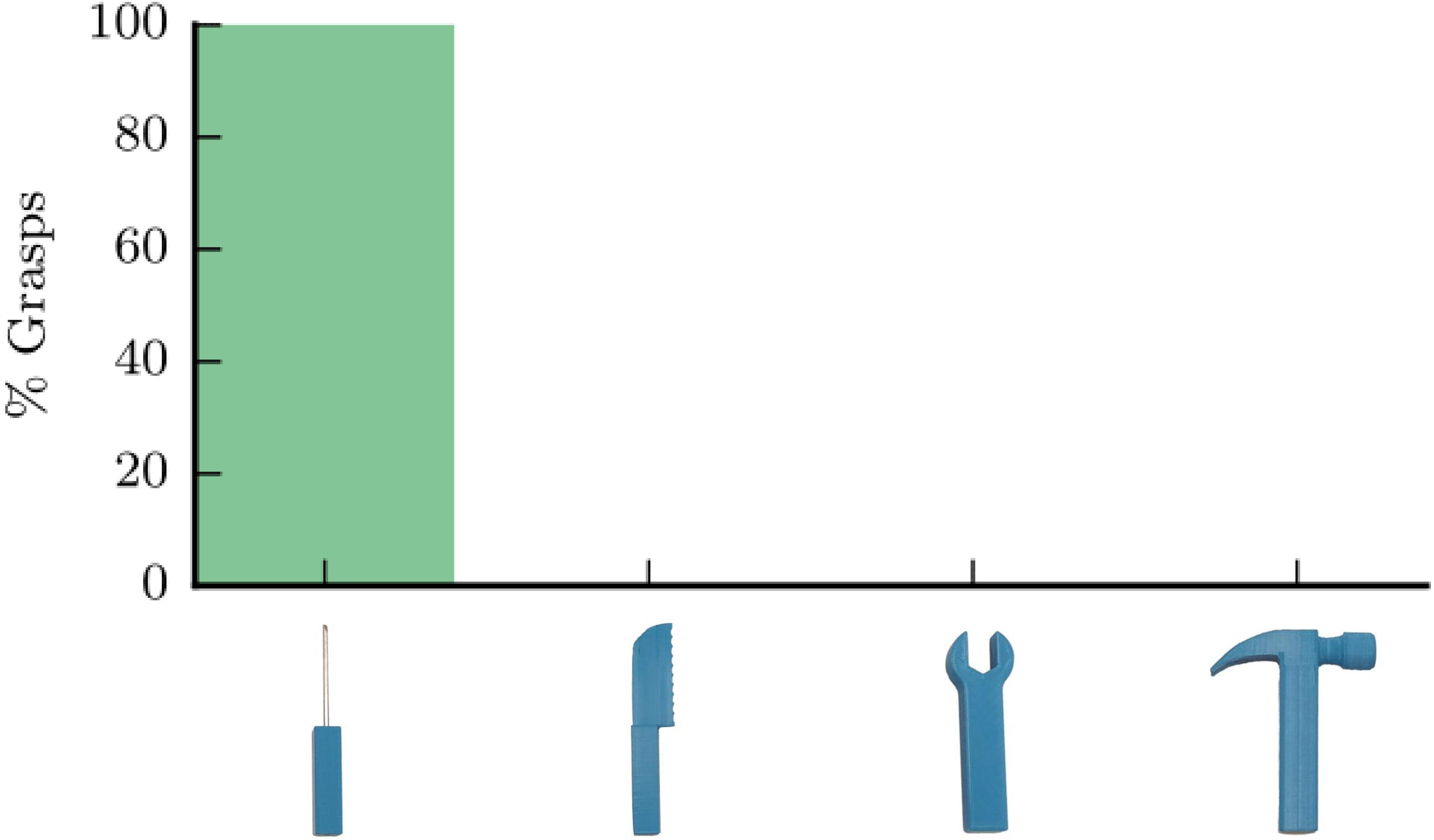
Applied to four tasks


Reaches?
C-Free?
Stable?
G
T
ξ_a
Follows?
Strong?
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?



100
80
60
40
20
0
% Grasps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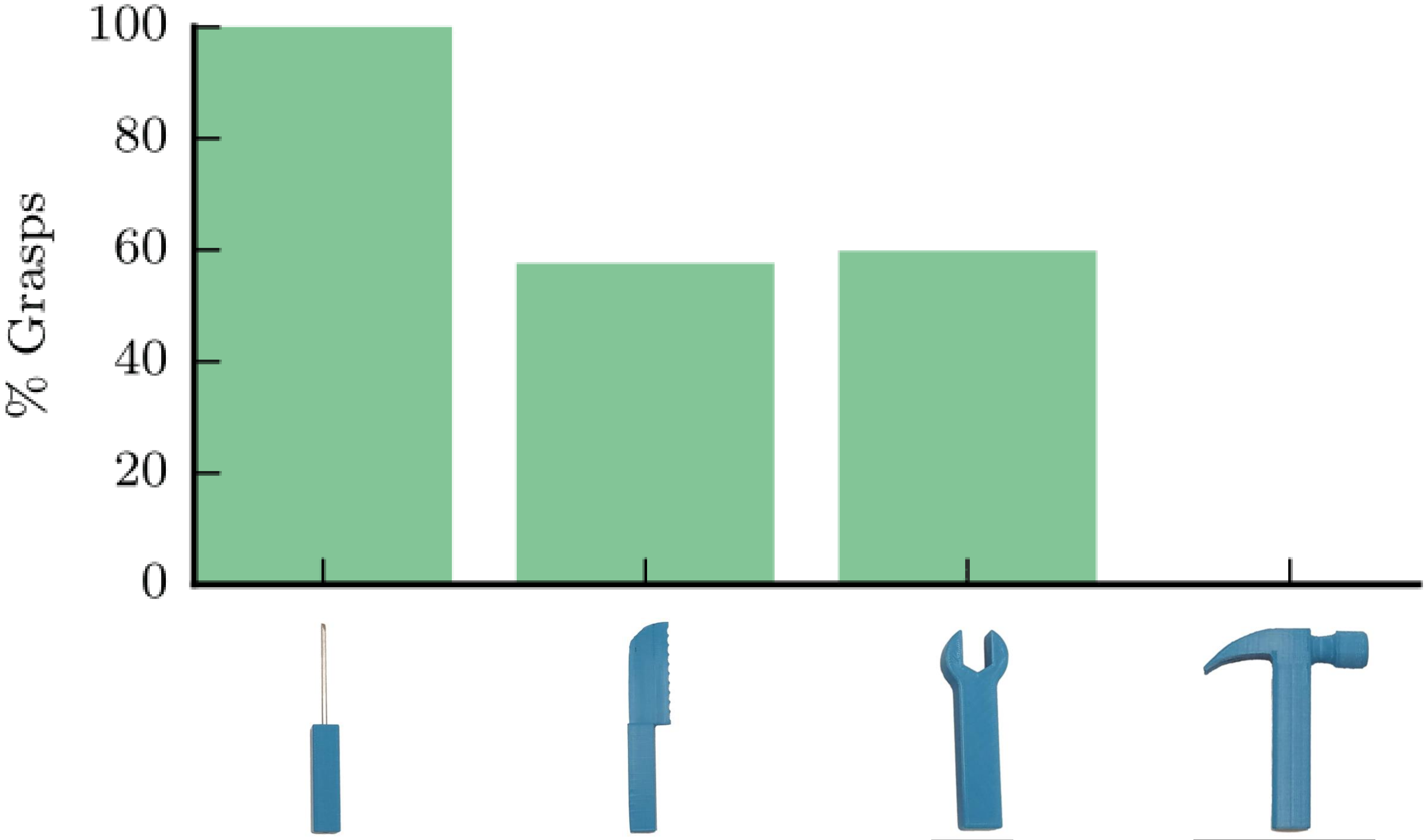
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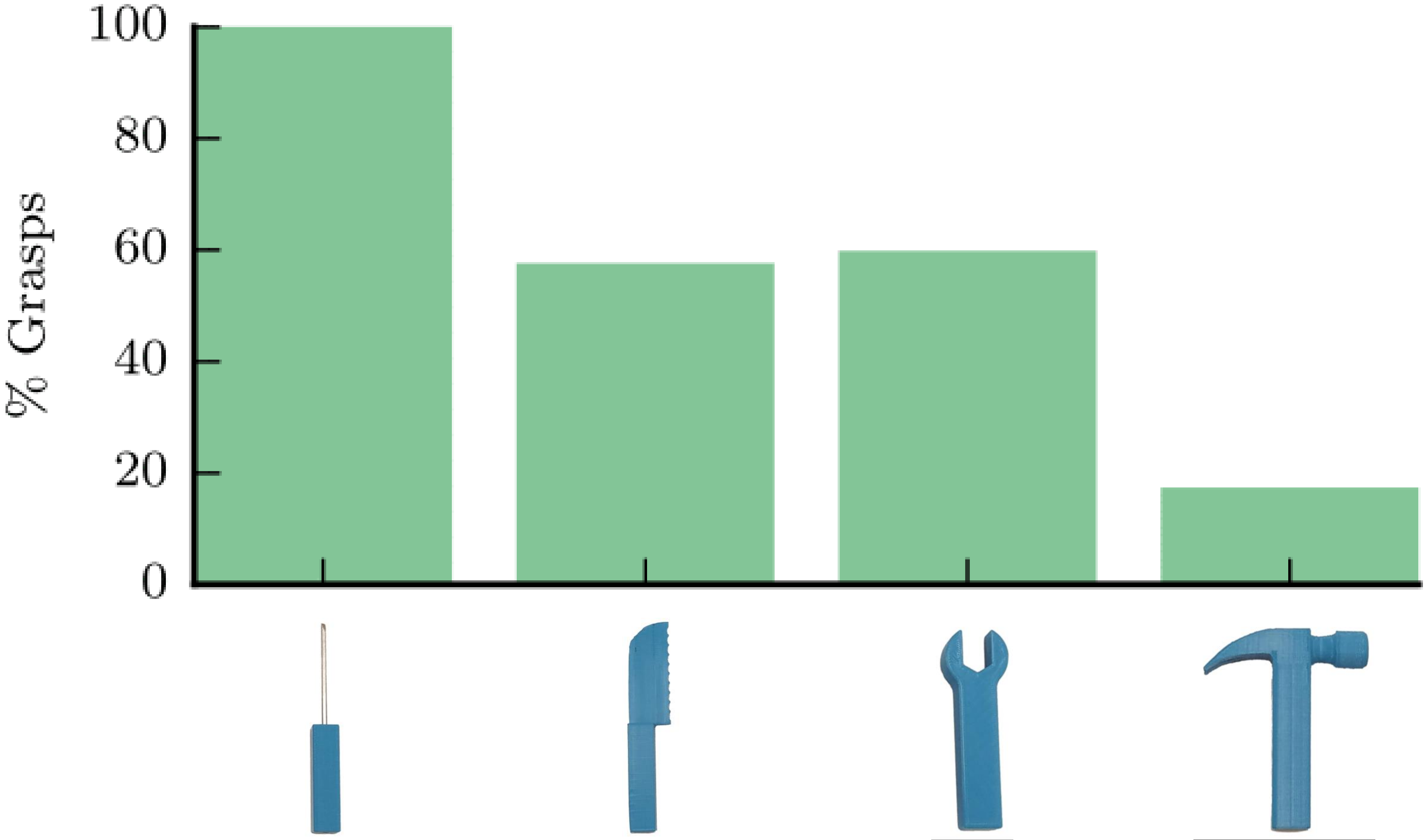
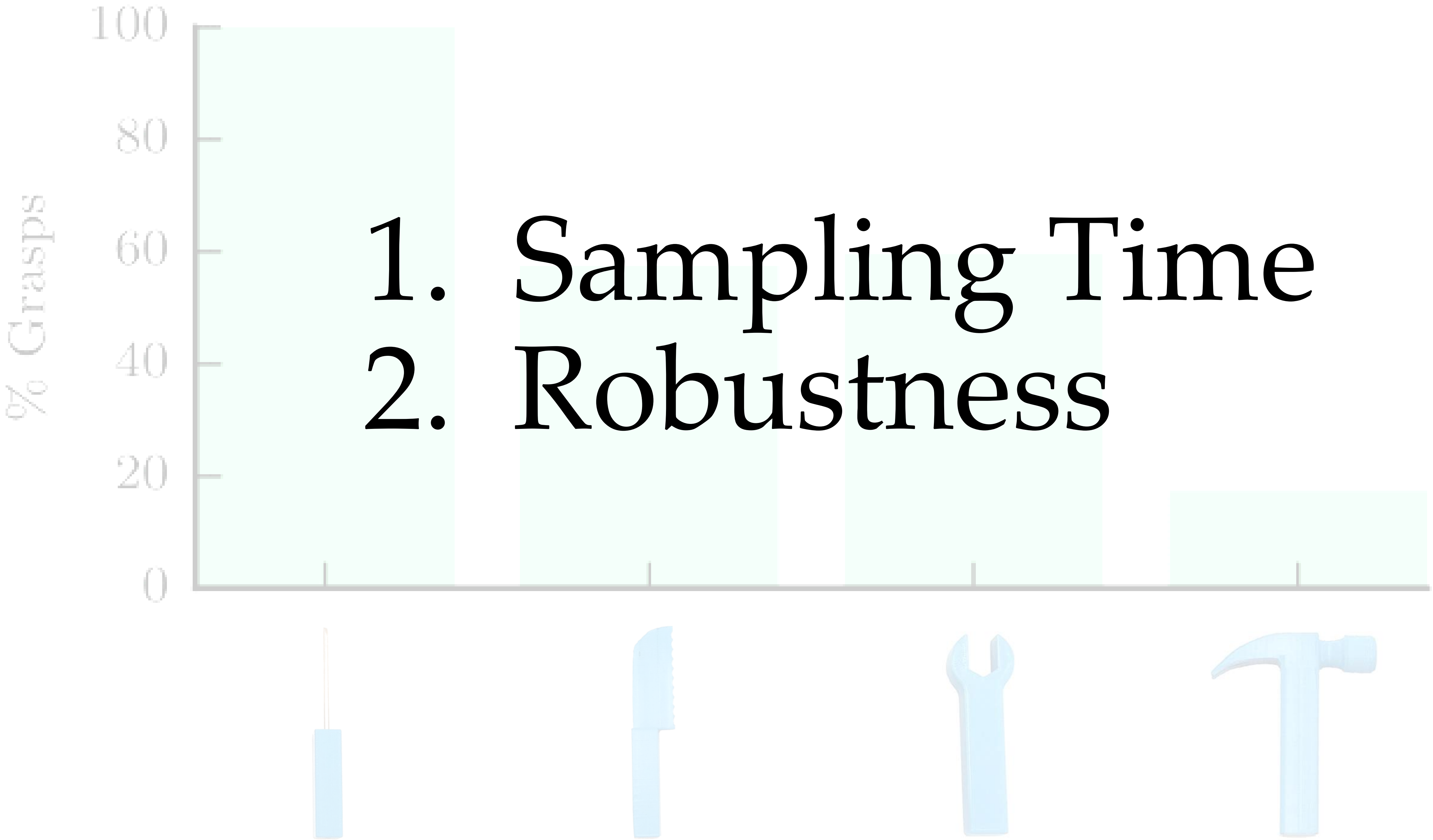
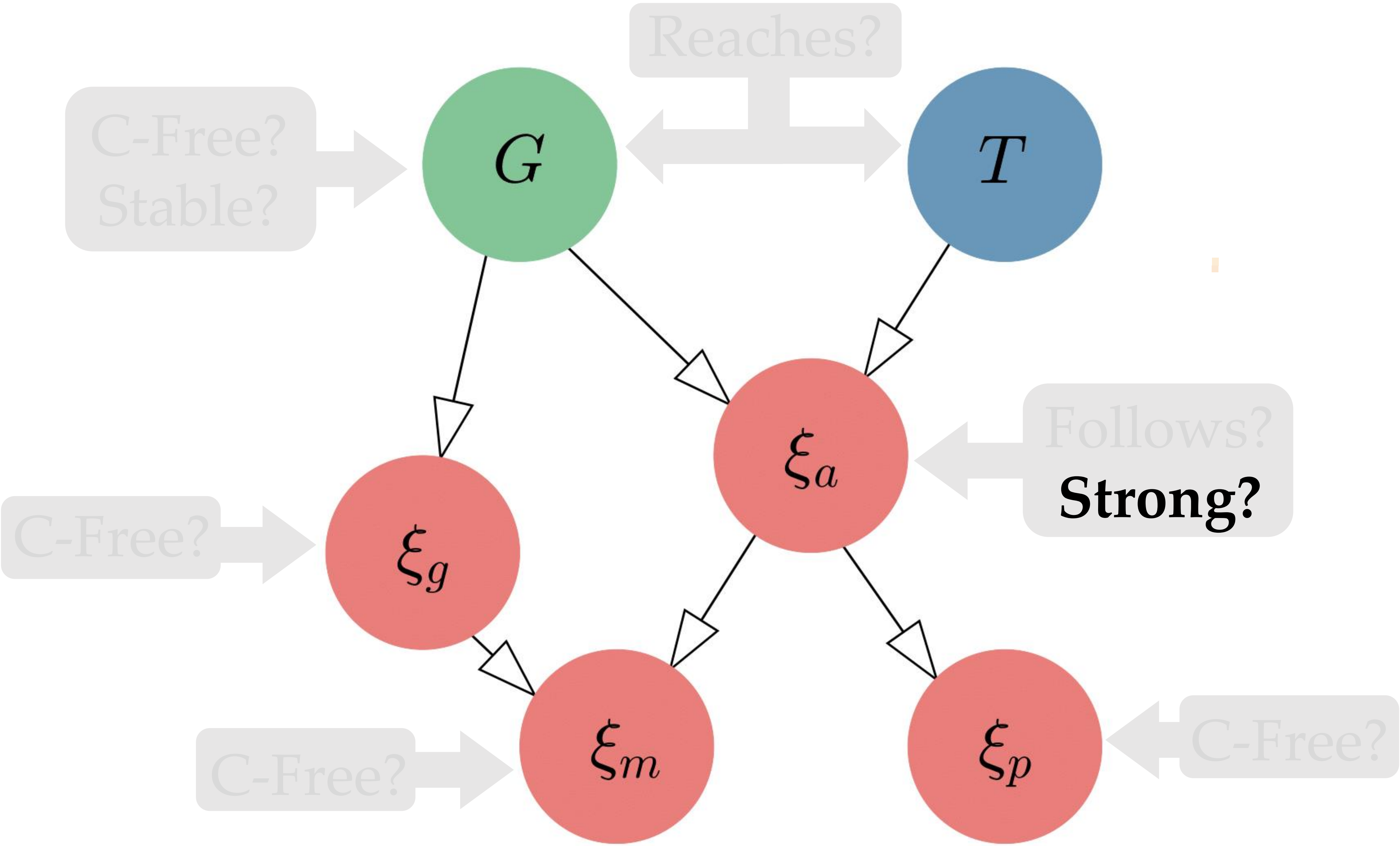
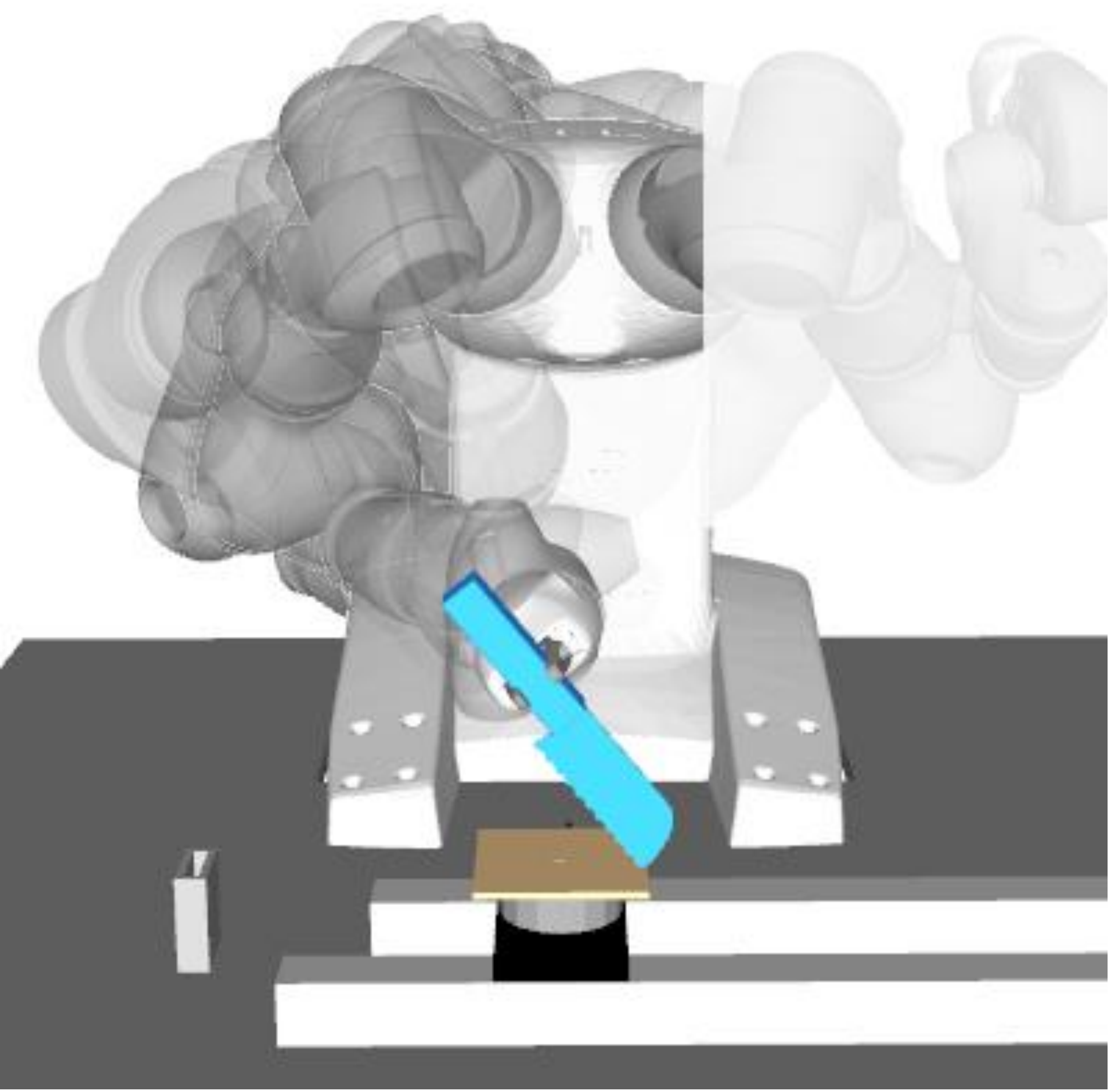
0
% Grasps

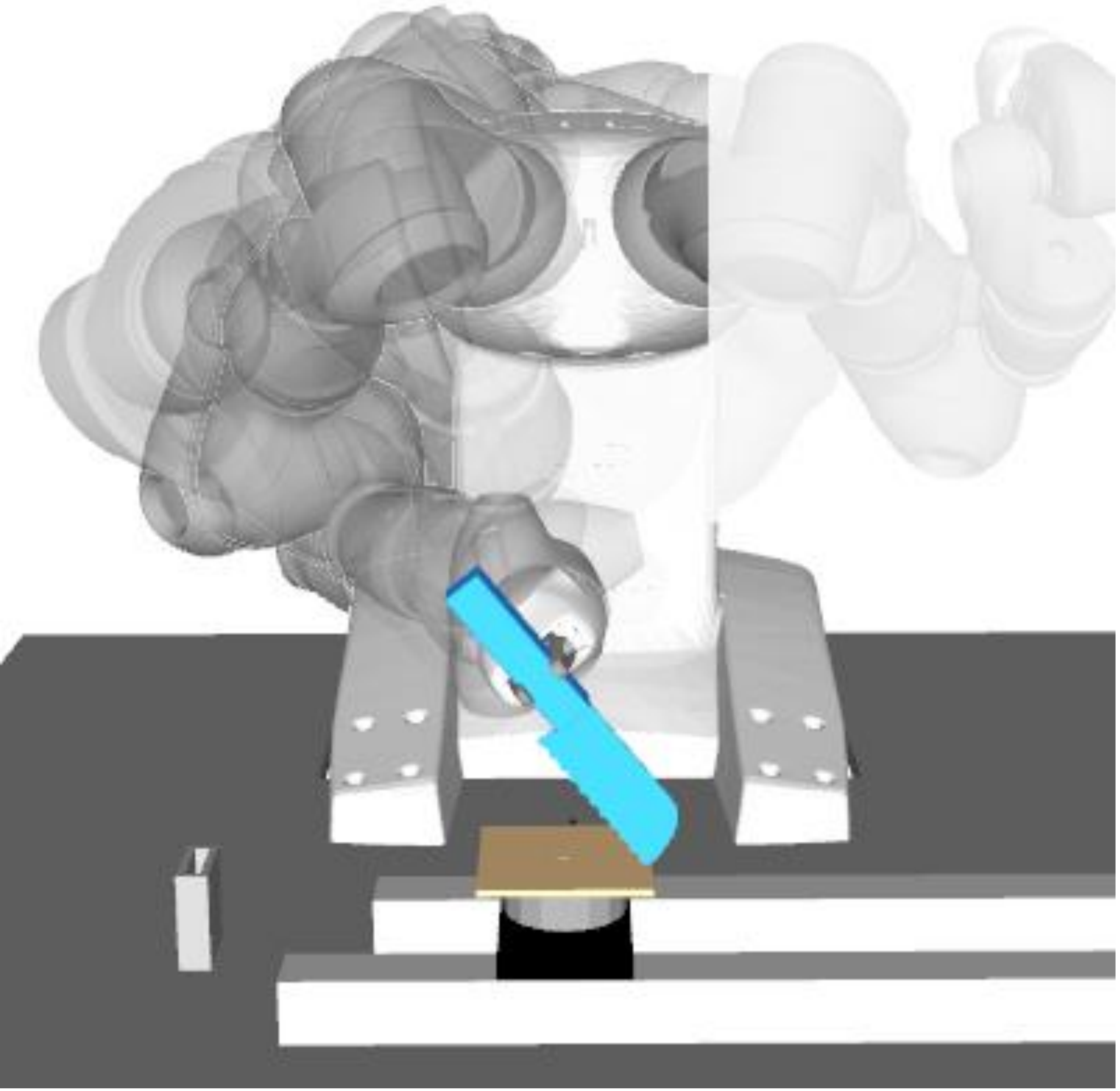

% Grasps
100
80
60
40
20
0

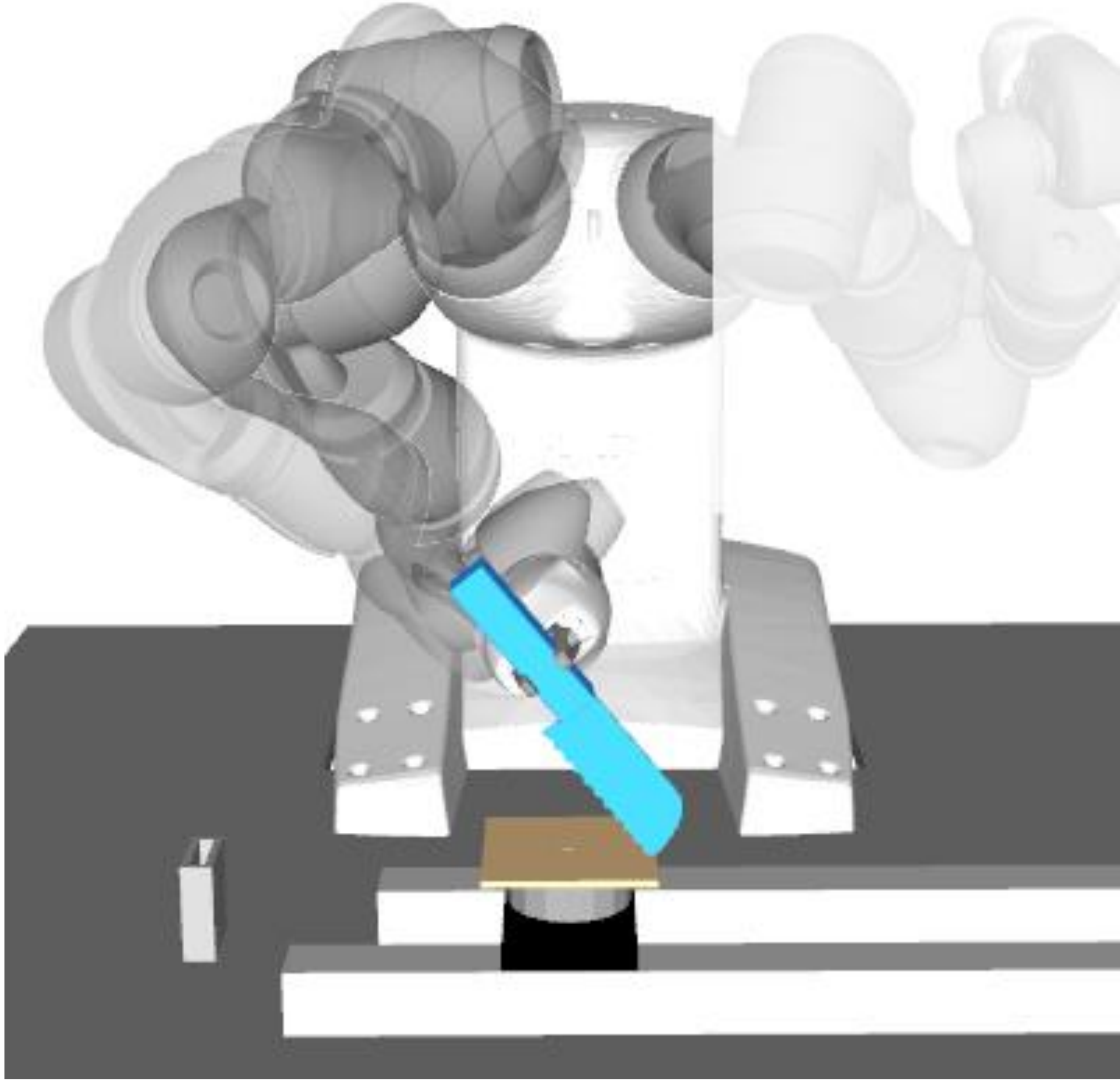


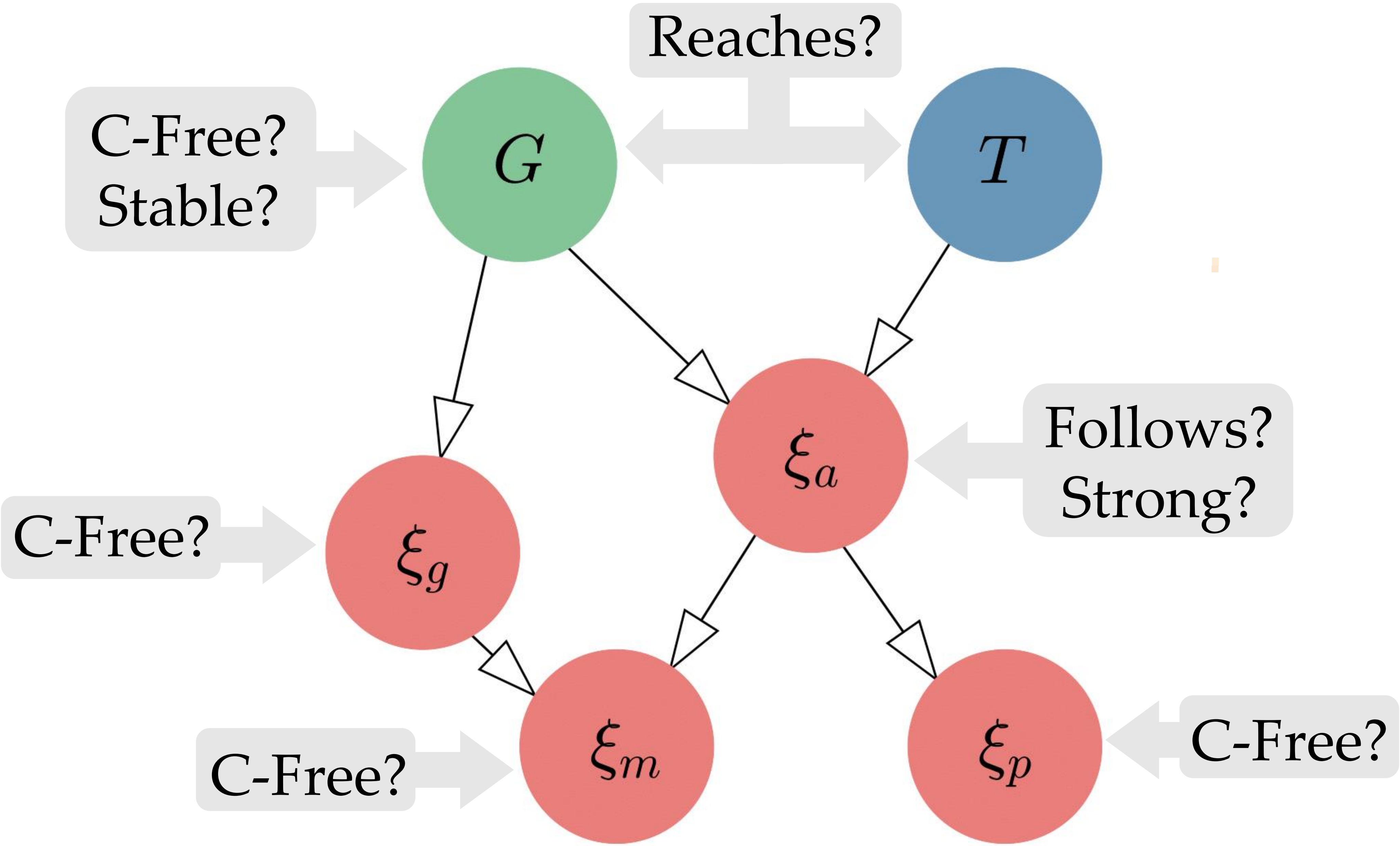
1. Sampling Time
2. Robustness


Reaches?
C-Free?
Stable?
G
T
ξ_a
Follows?
Strong?
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?



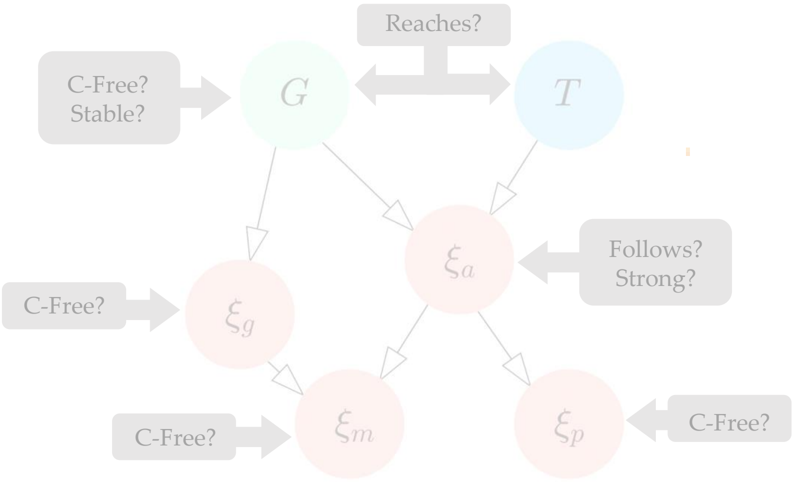




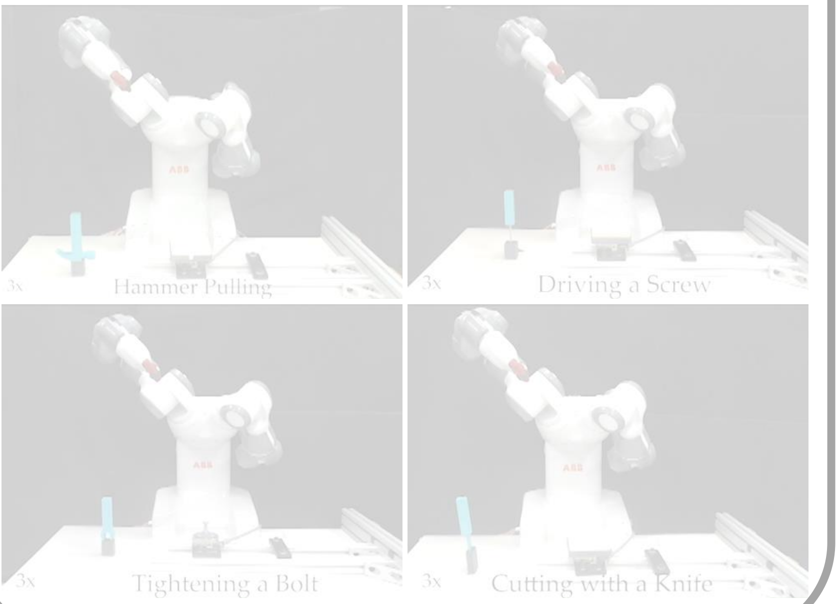


Reaches?
C-Free?
Stable?
G
T
Follows?
Strong?
ξ_a
C-Free?
ξ_g
C-Free?
ξ_m
ξ_p
C-Free?

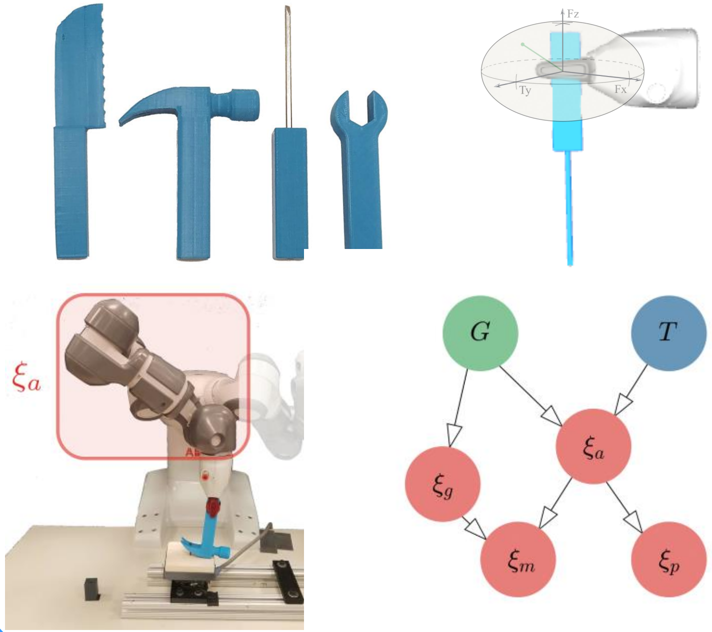
Constraints



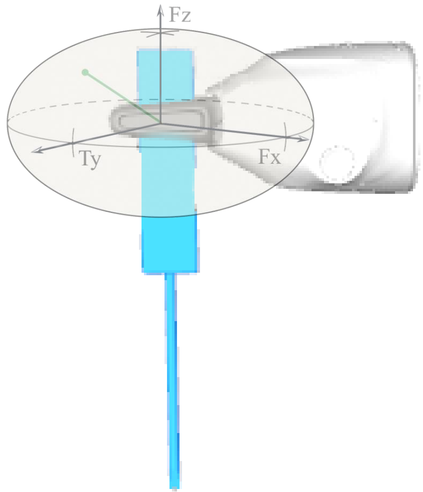
Experiments

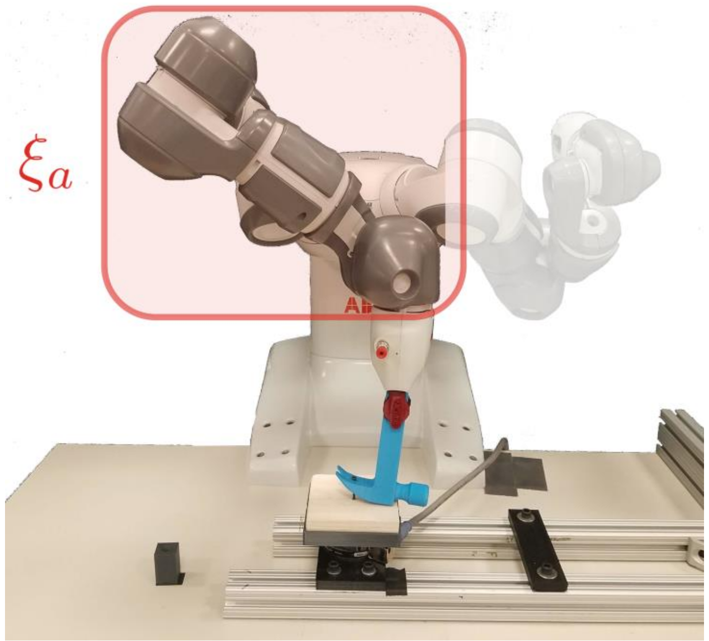


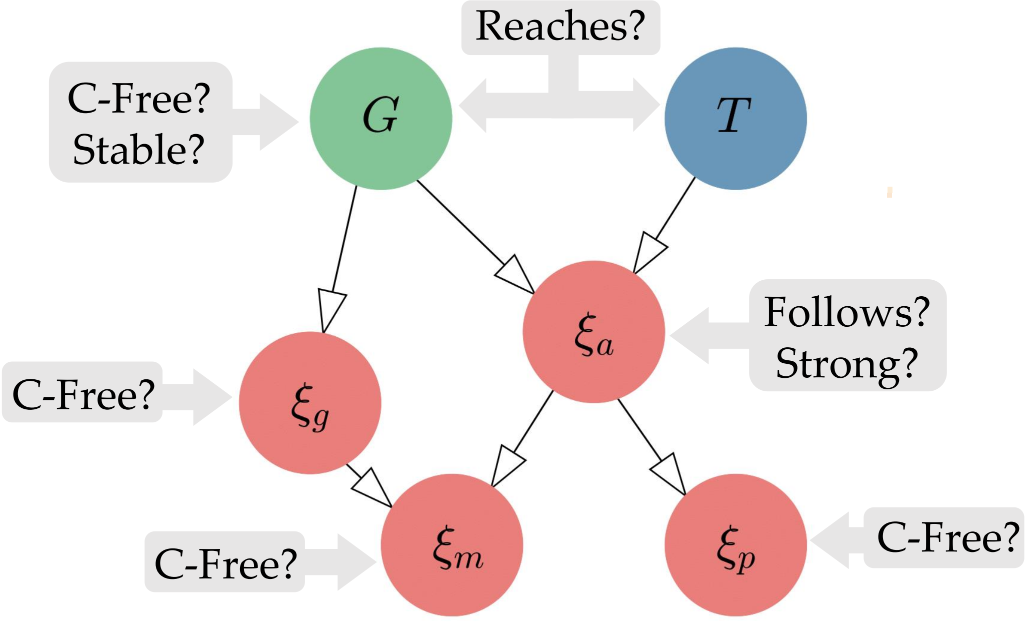
Assumptions



Assumptions







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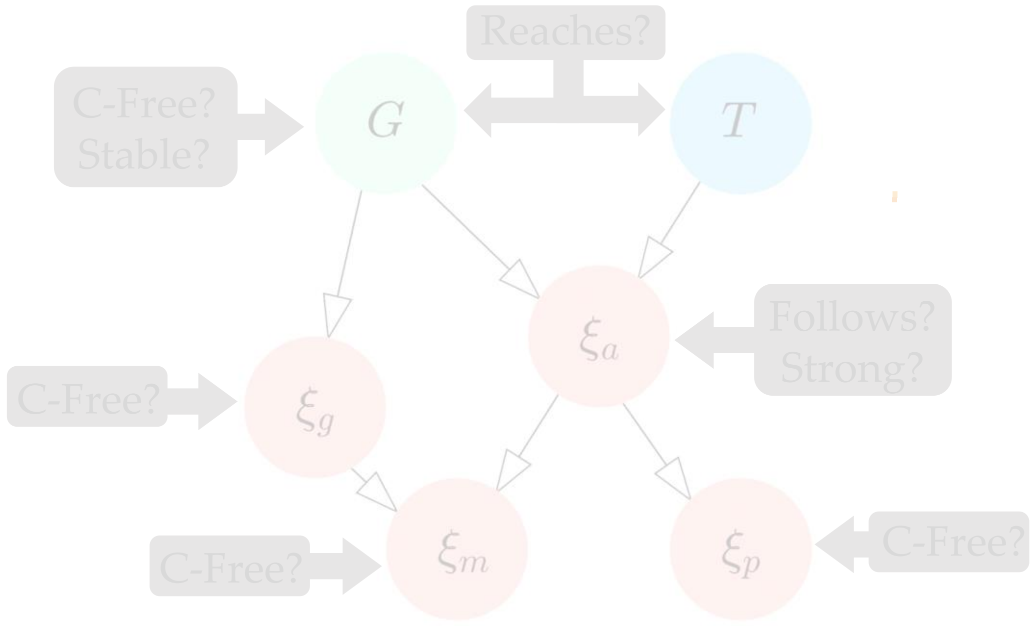

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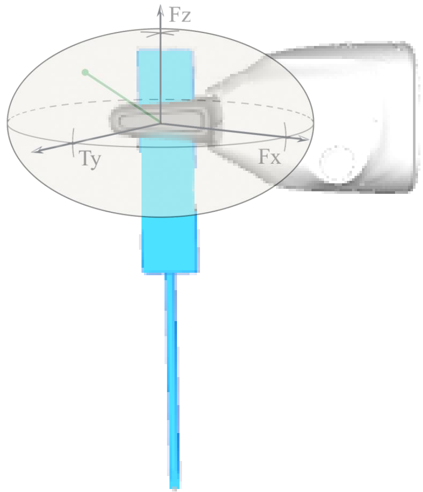

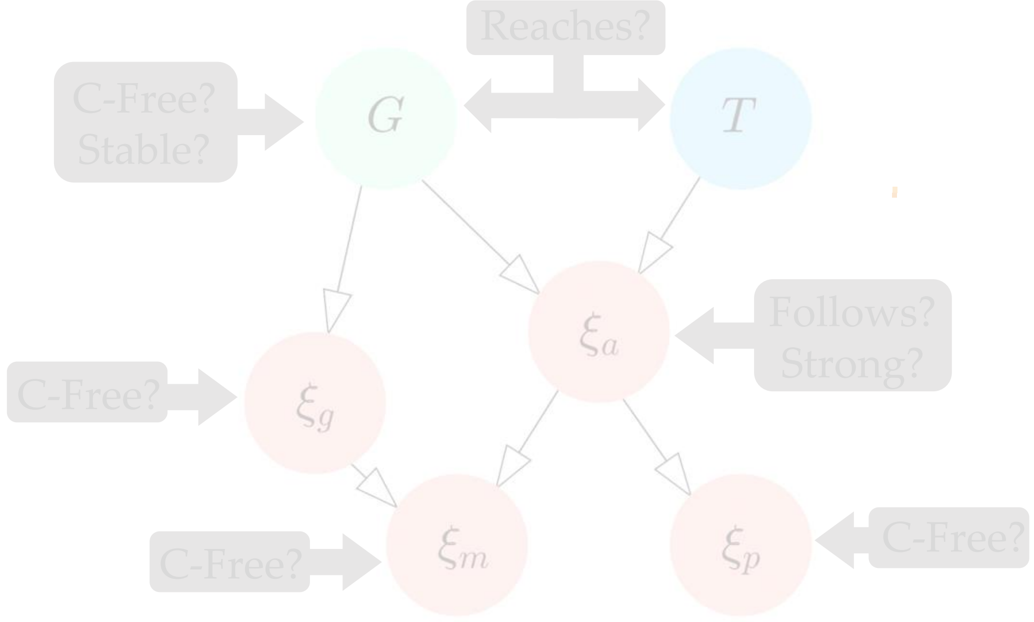

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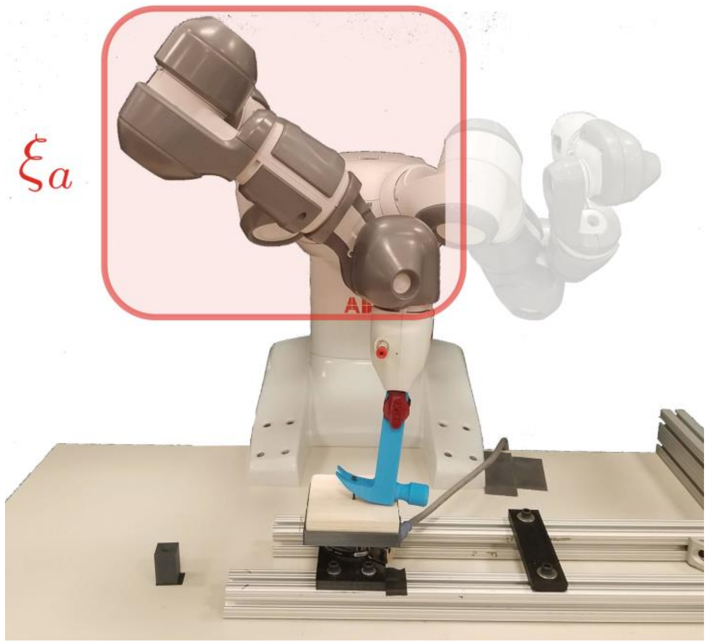

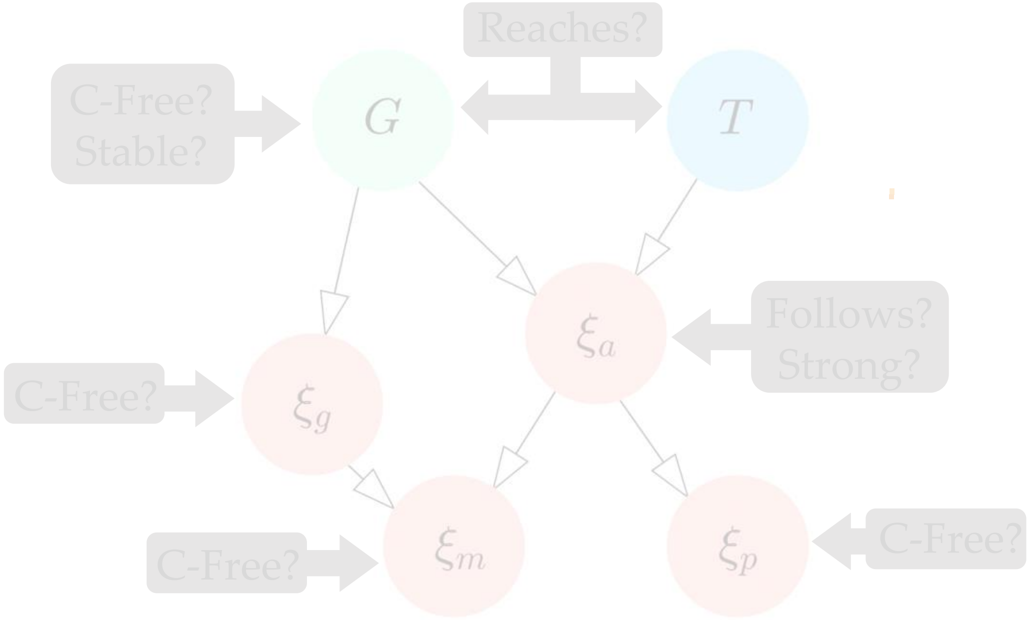

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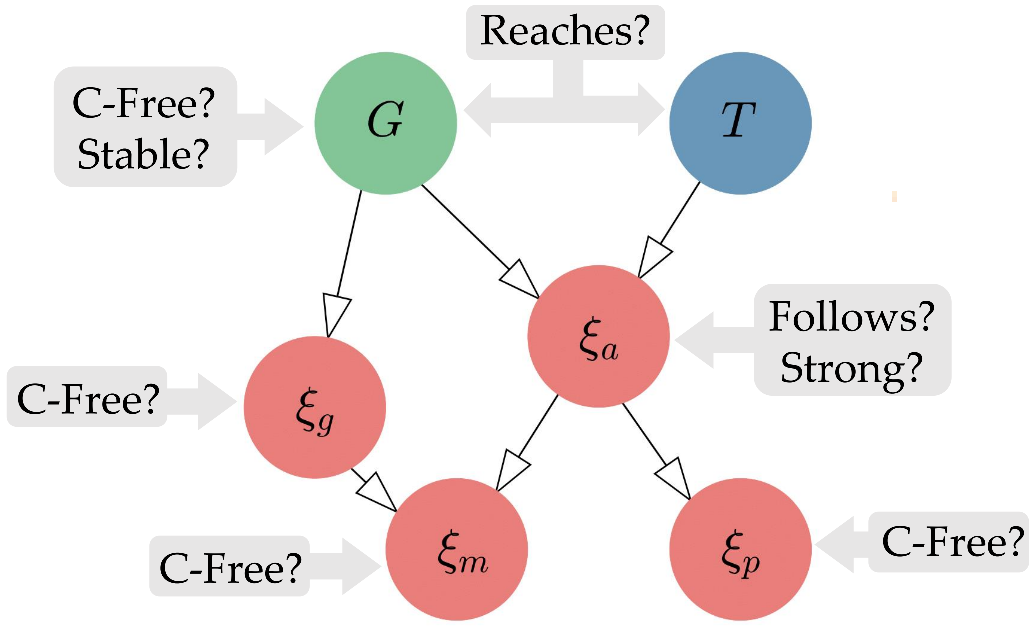

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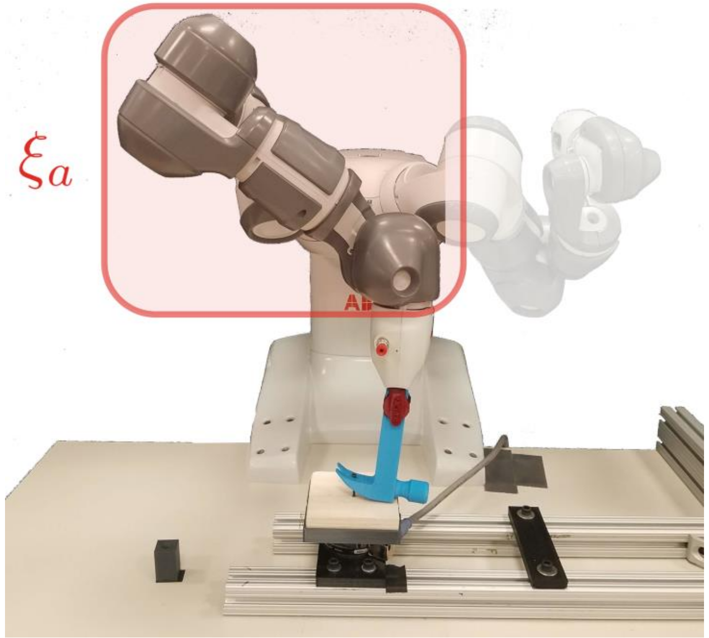
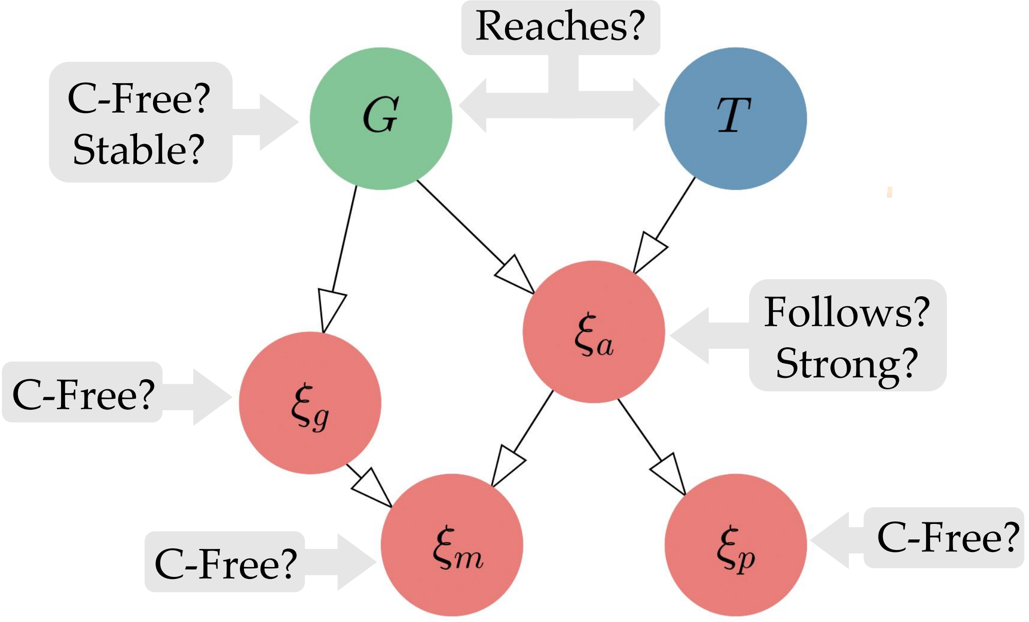
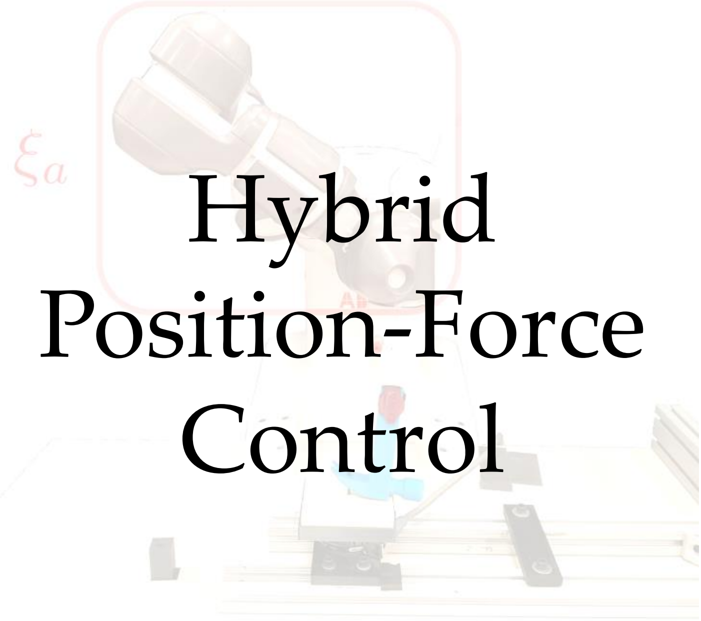
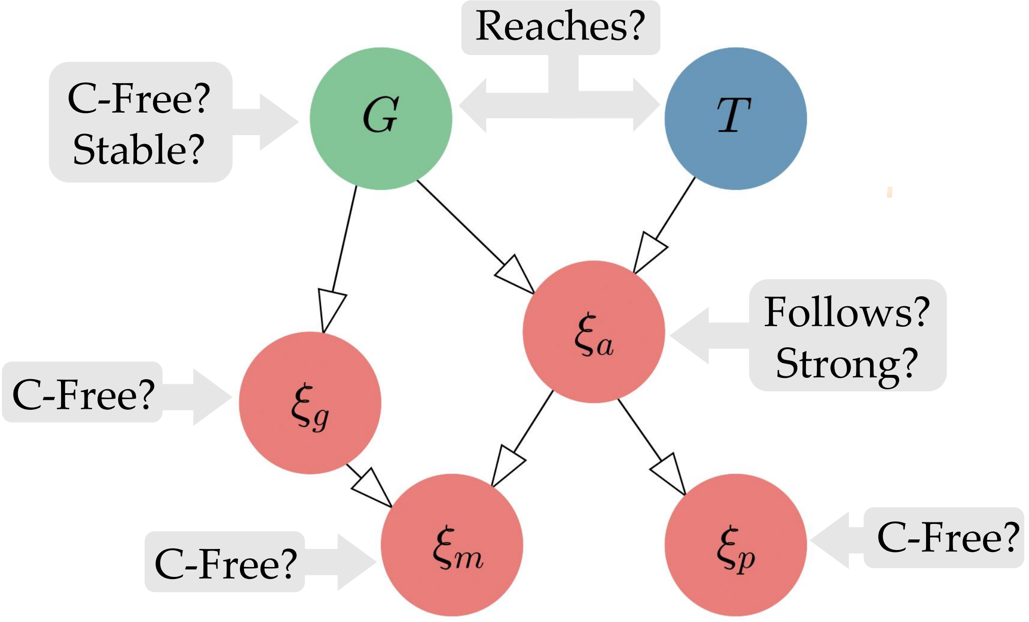




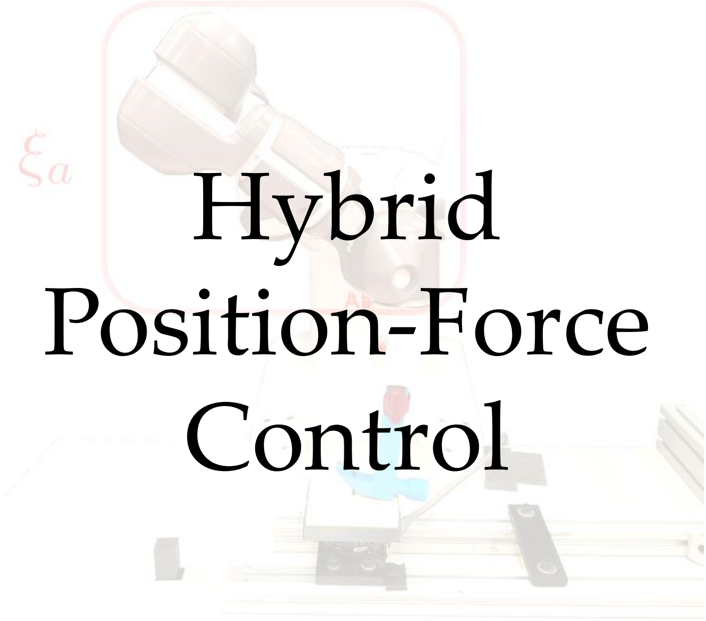
On-Going Work



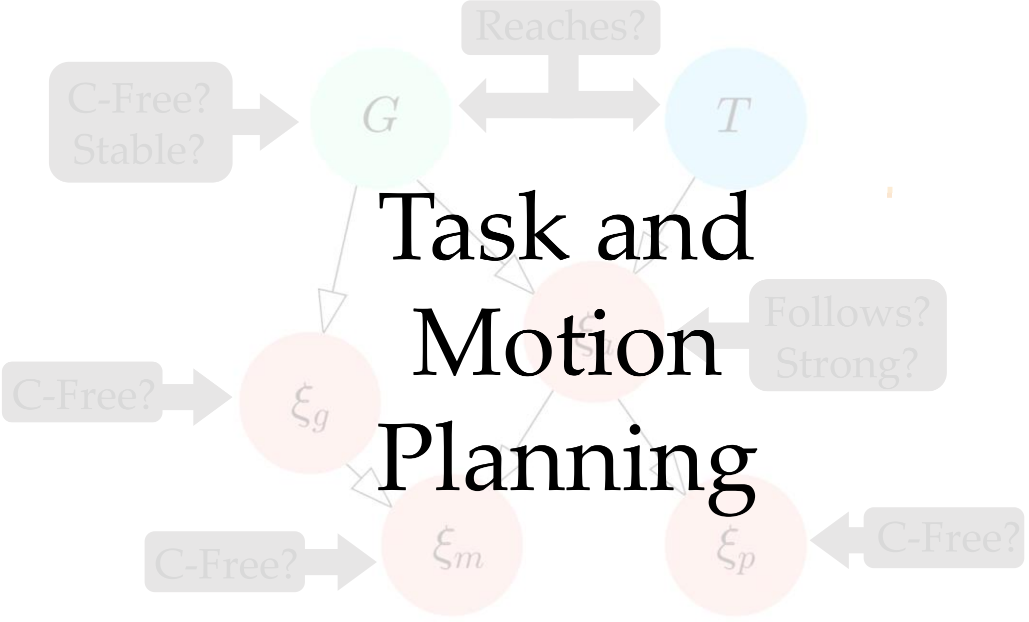
Hybrid Position-Force Control



On-Going Work



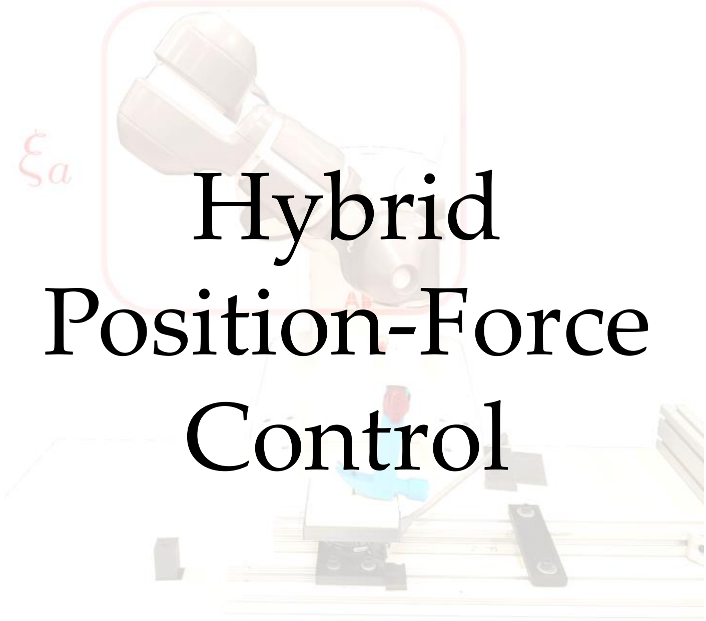
Hybrid
Position-Force
Control



Task and
Motion
Planning

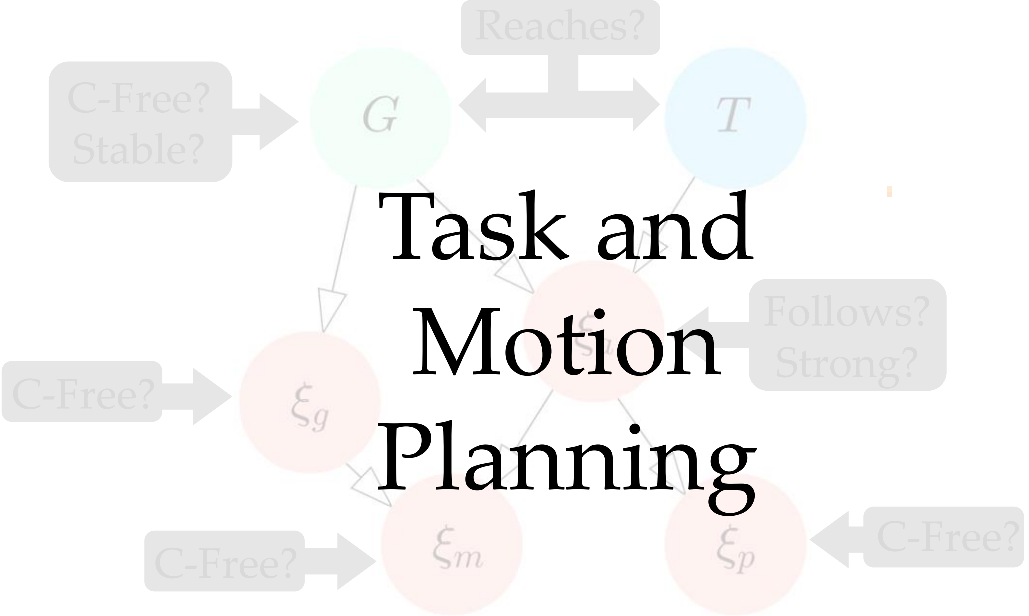
On-Going Work

Force-and-Motion Constraints

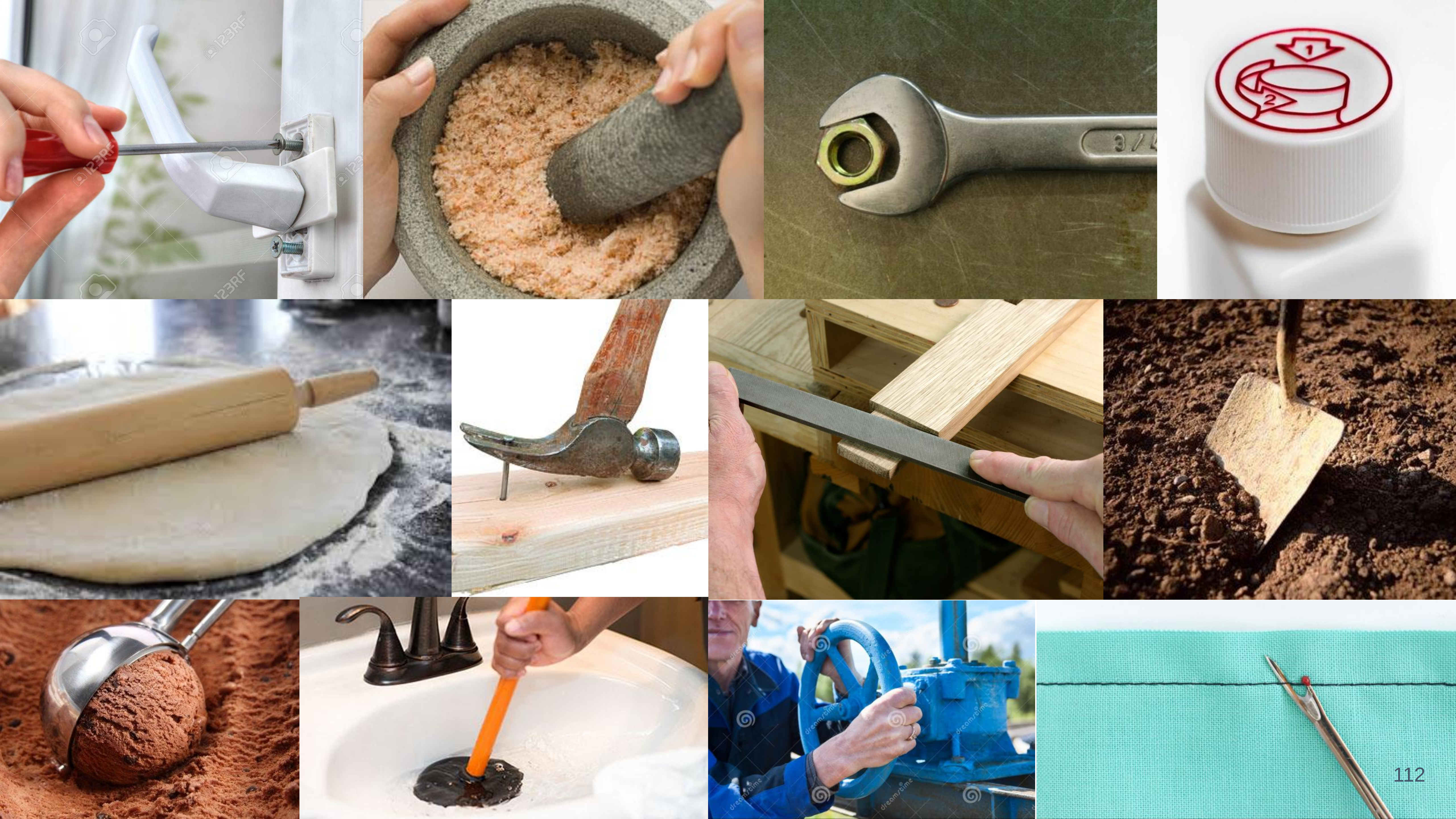


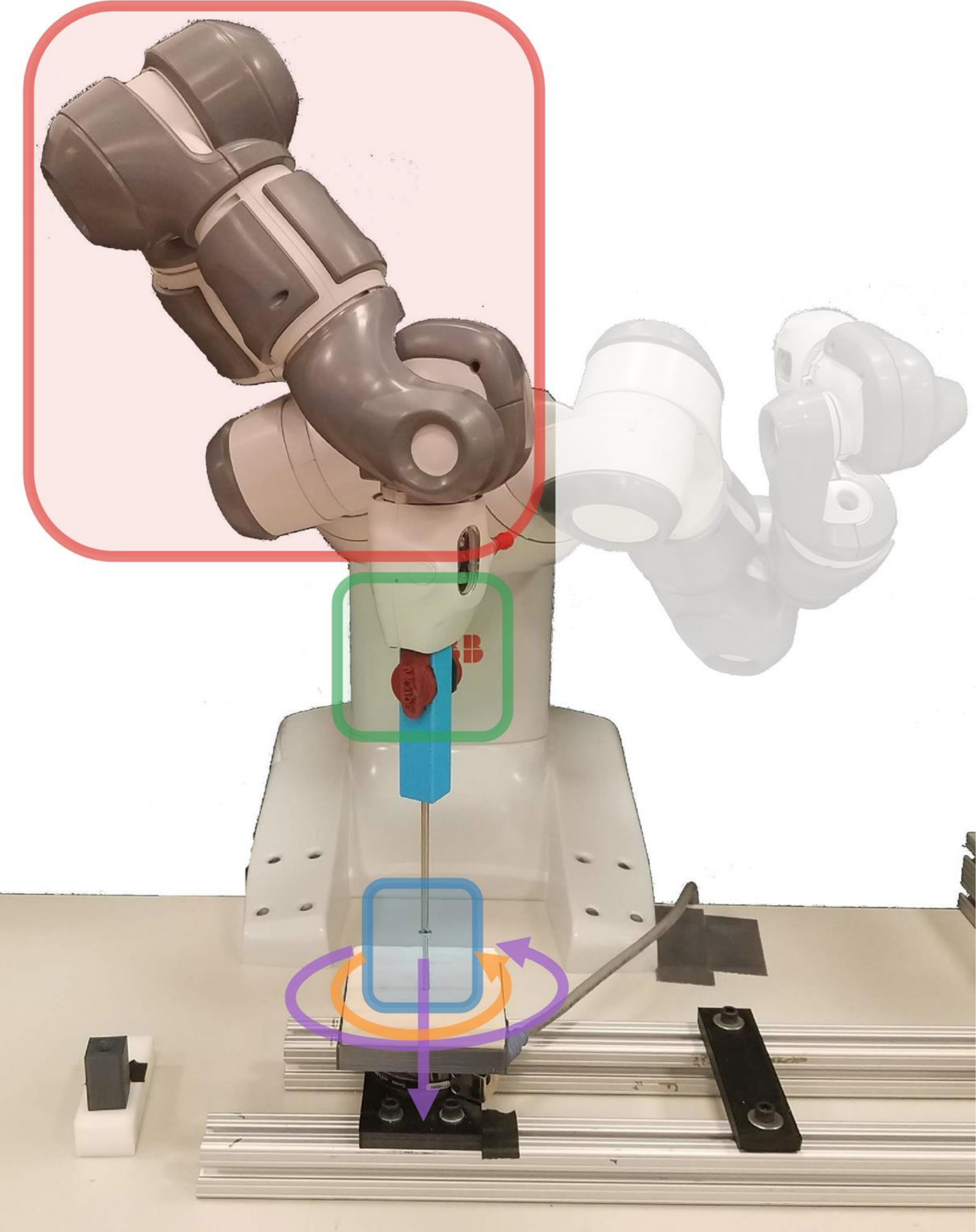
Hybrid Position-Force Control

+



Task and Motion Planning



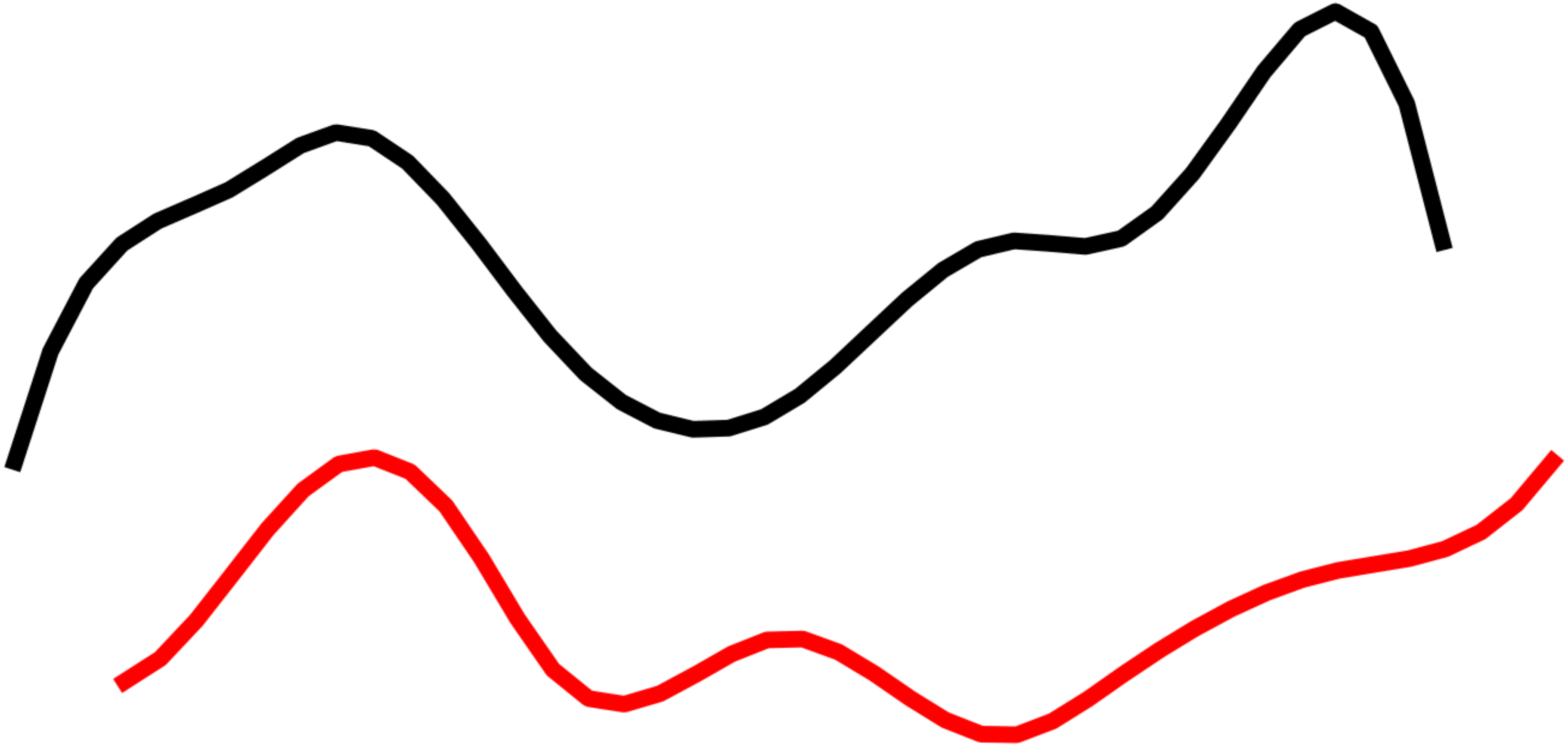


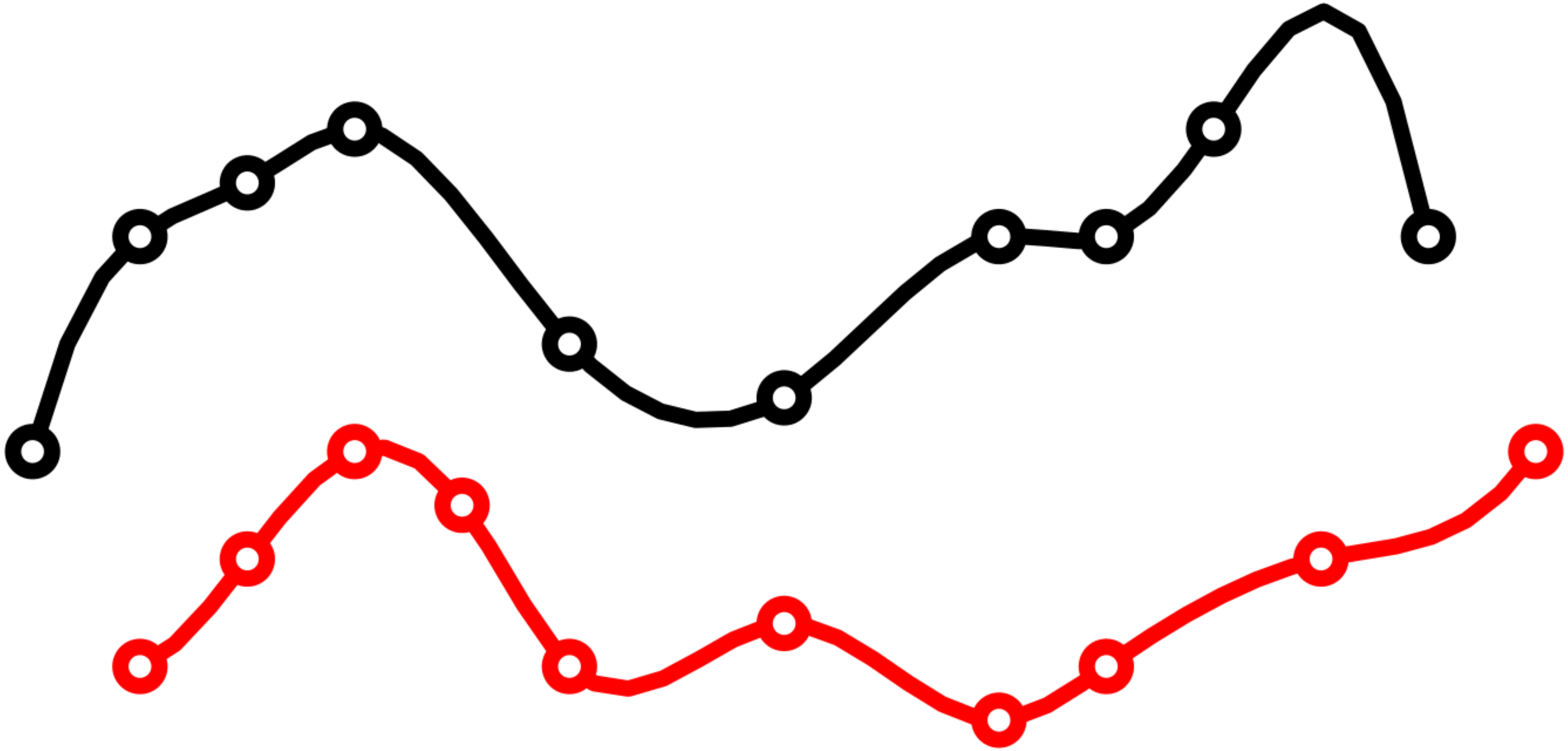
Force-and-Motion Constrained Planning for Tool Use

Rachel Holladay

Research Qualifying Exam
December 2019

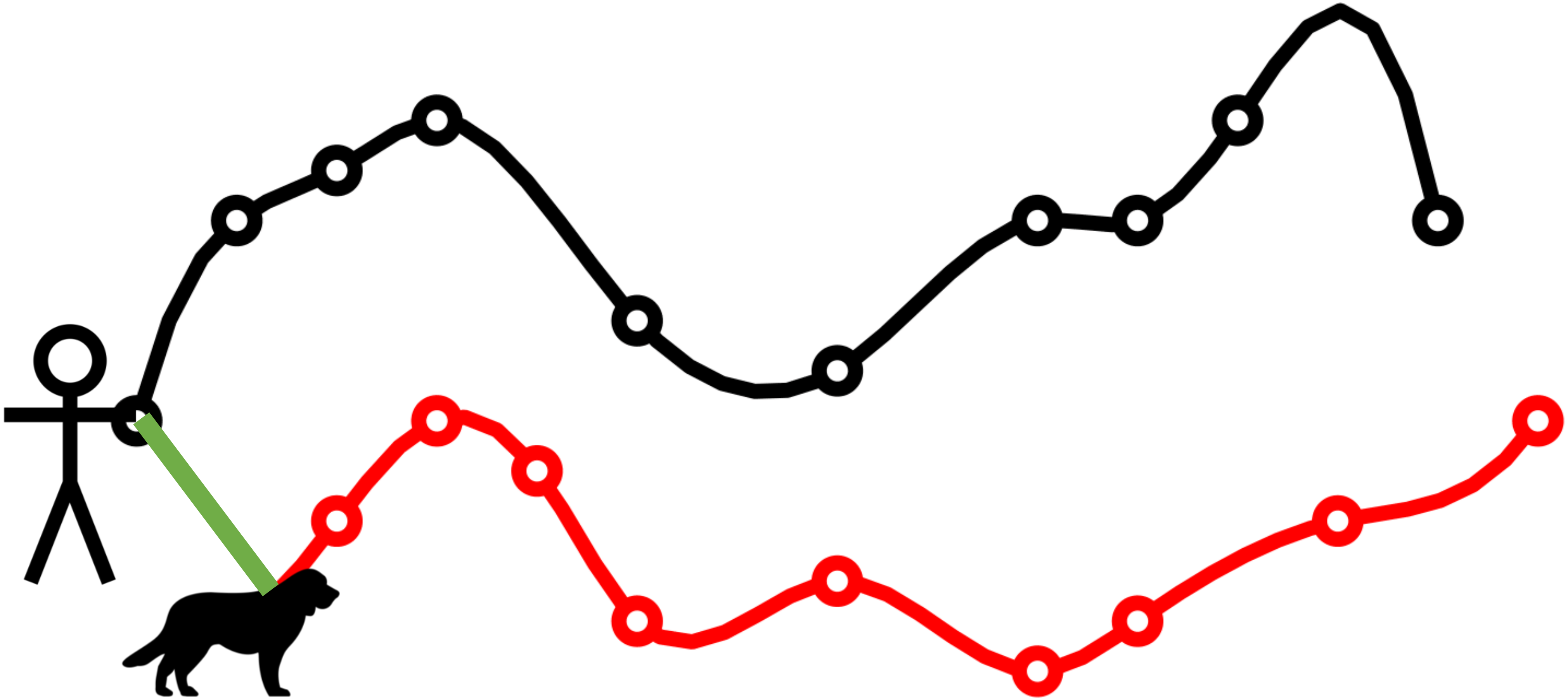
Back-Up Slides: Fréchet Distance



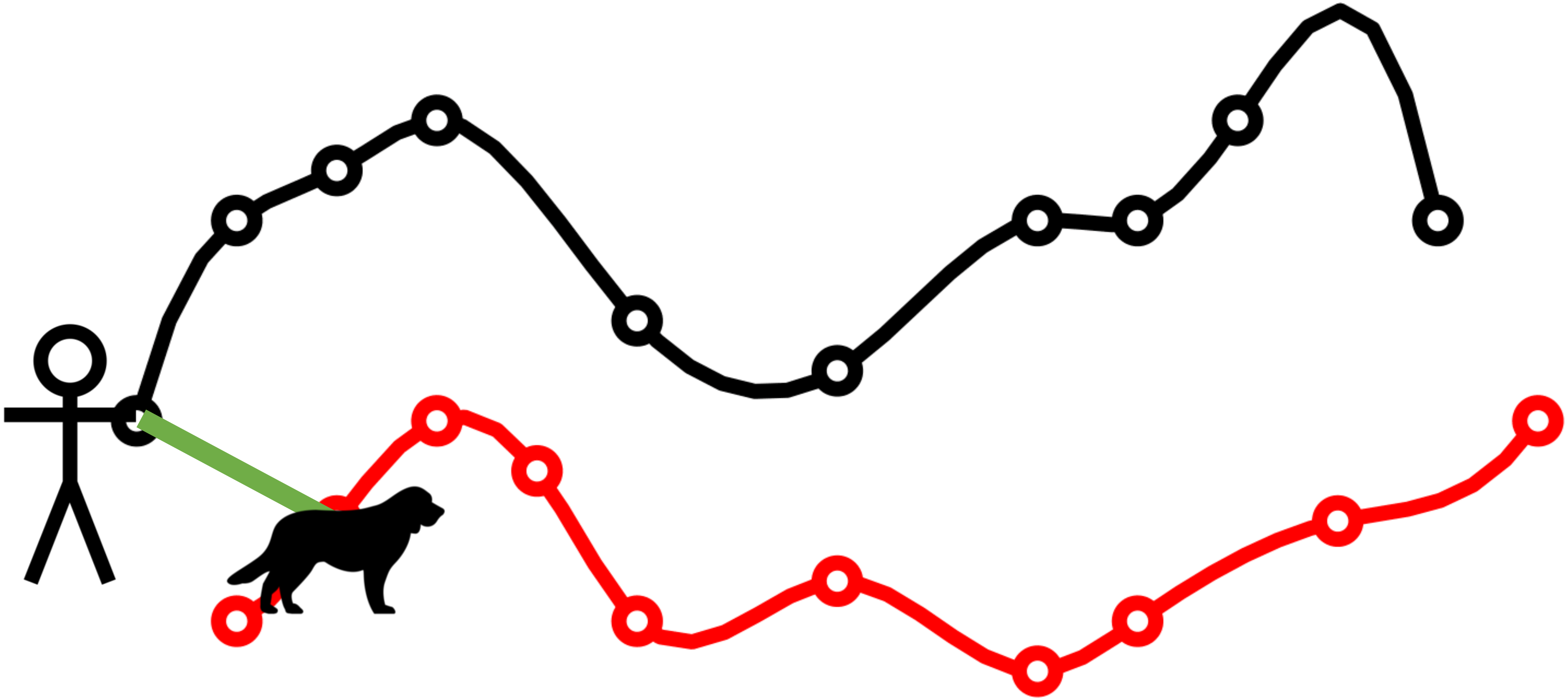


Fréchet Distance

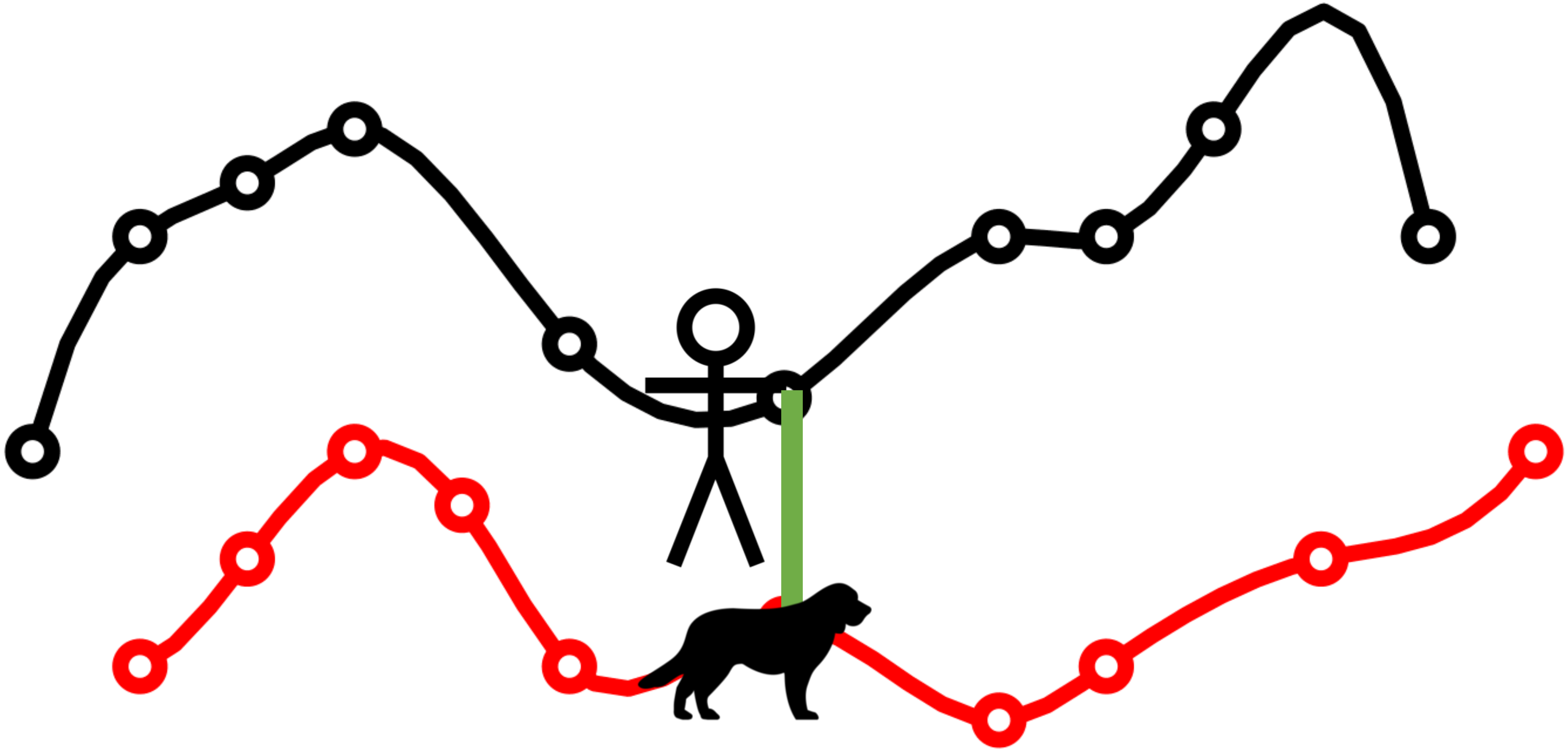
Fréchet Distance



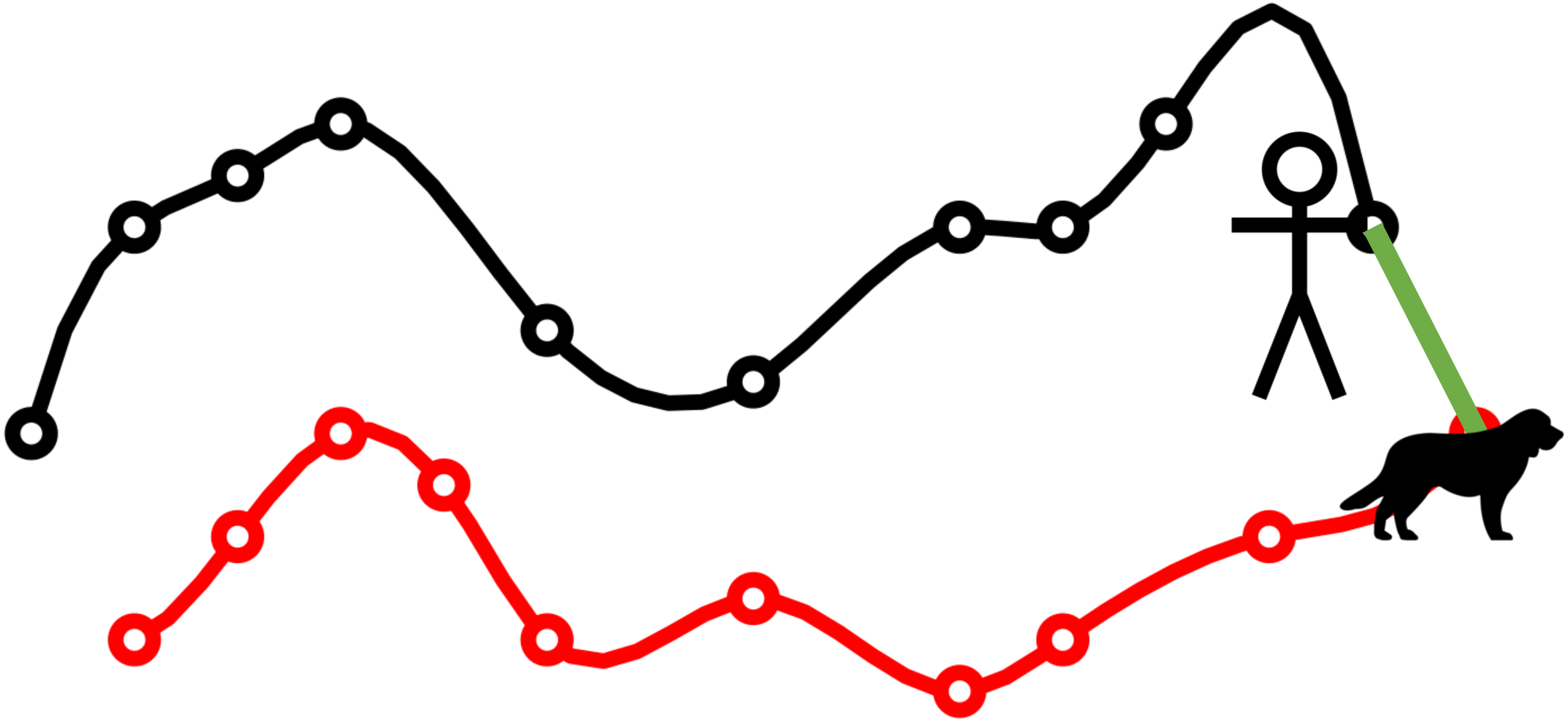
Fréchet Distance



Fréchet Distance

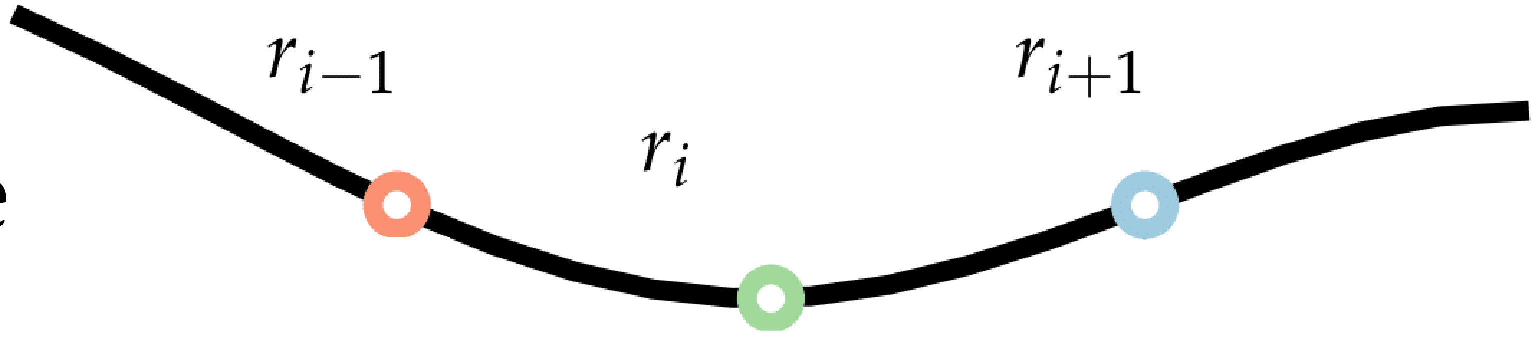


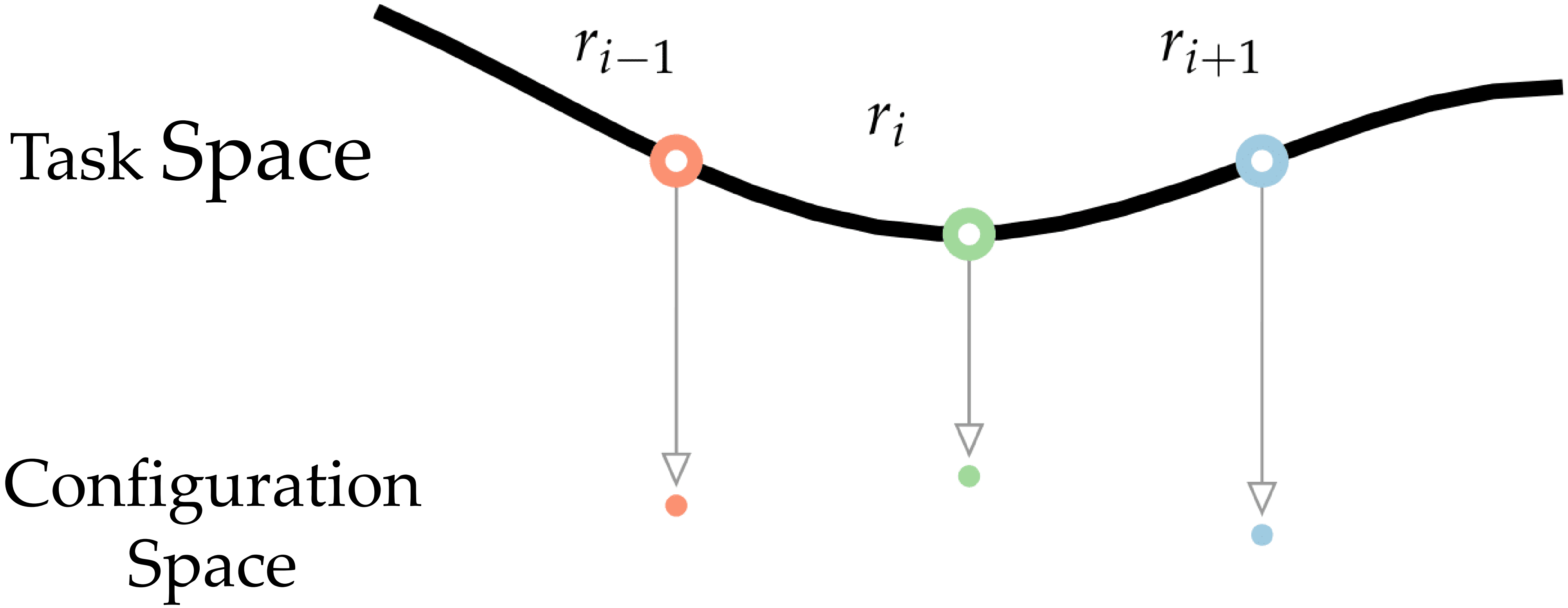
Fréchet Distance



Back-Up Slides: Layered Graph

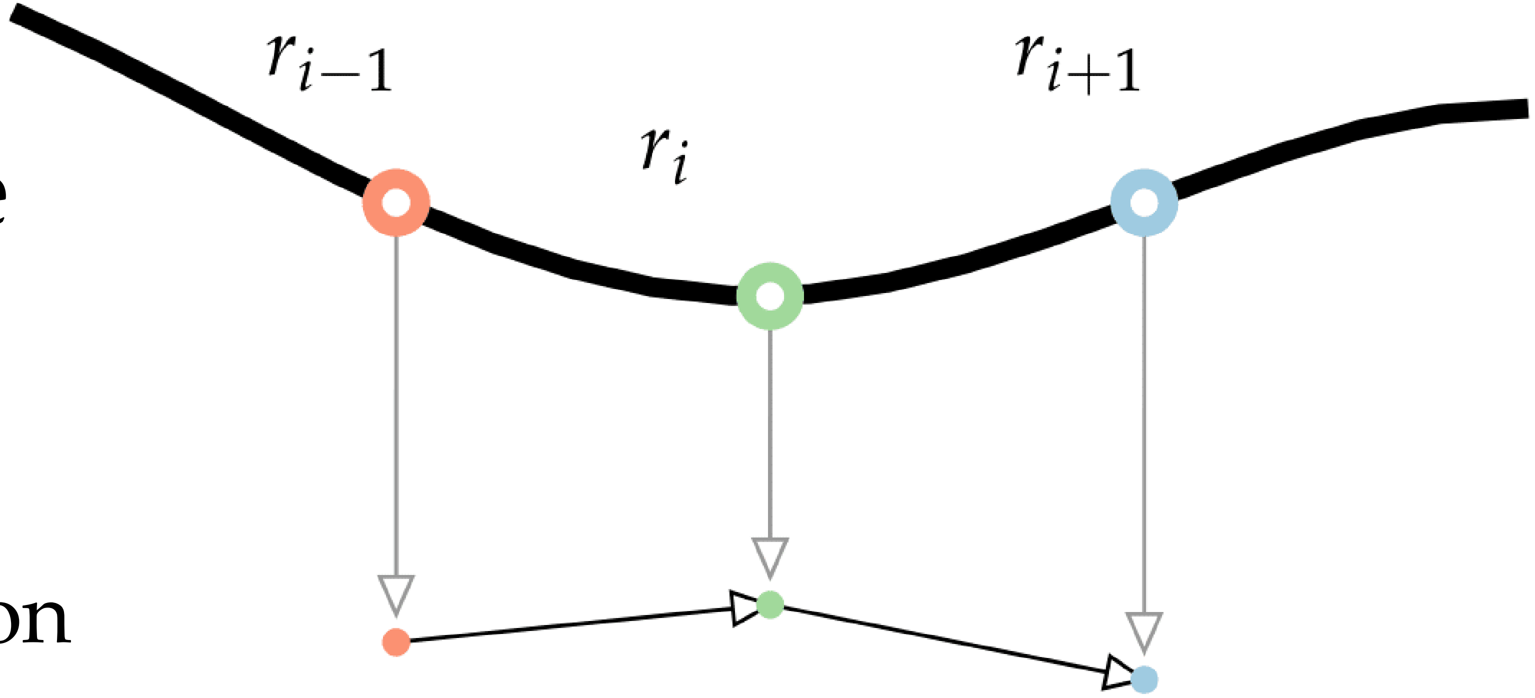
Task Space

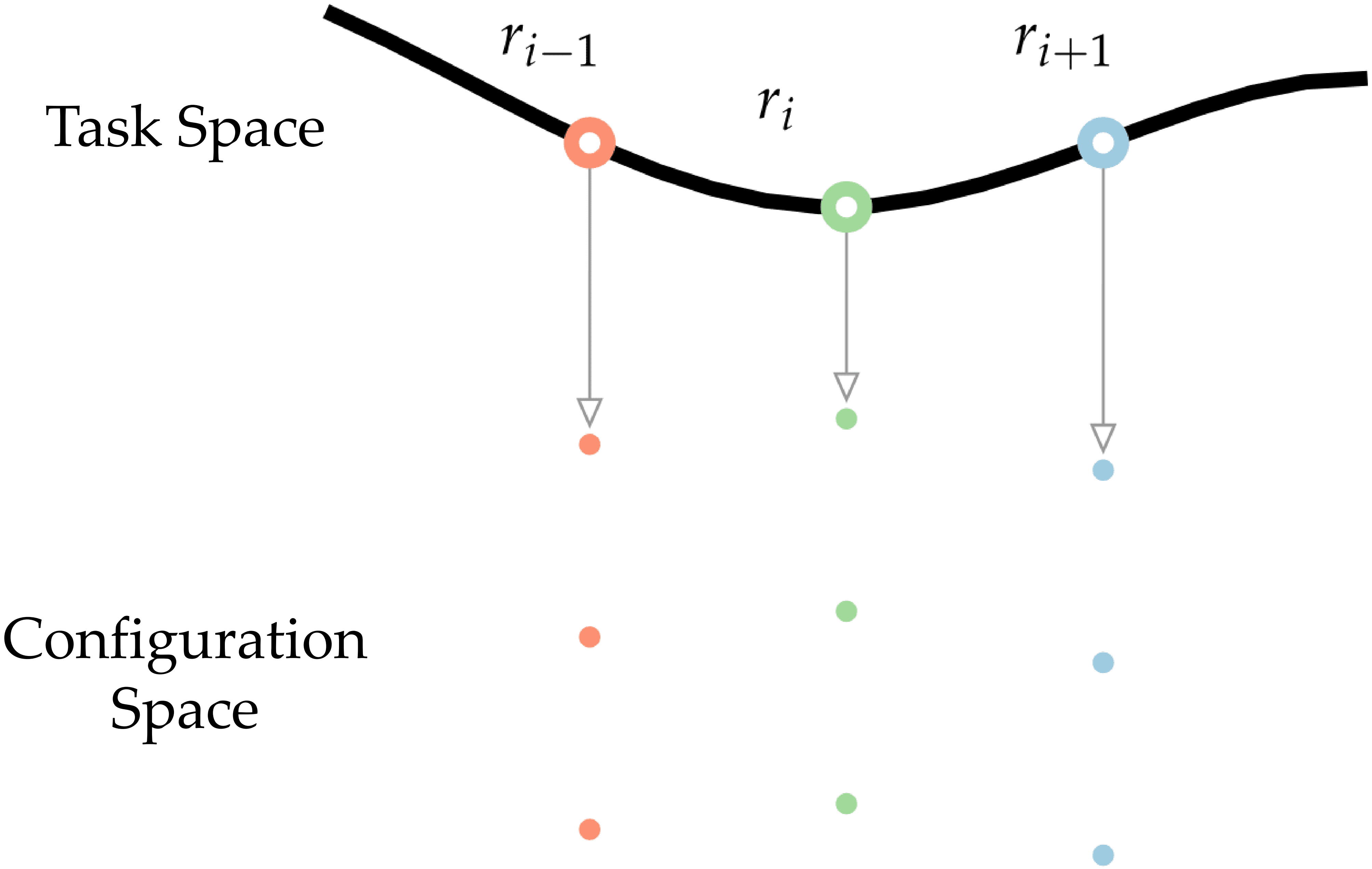



Task Space
Configuration Space
r_{i-1}
r_i
r_{i+1}

Task Space

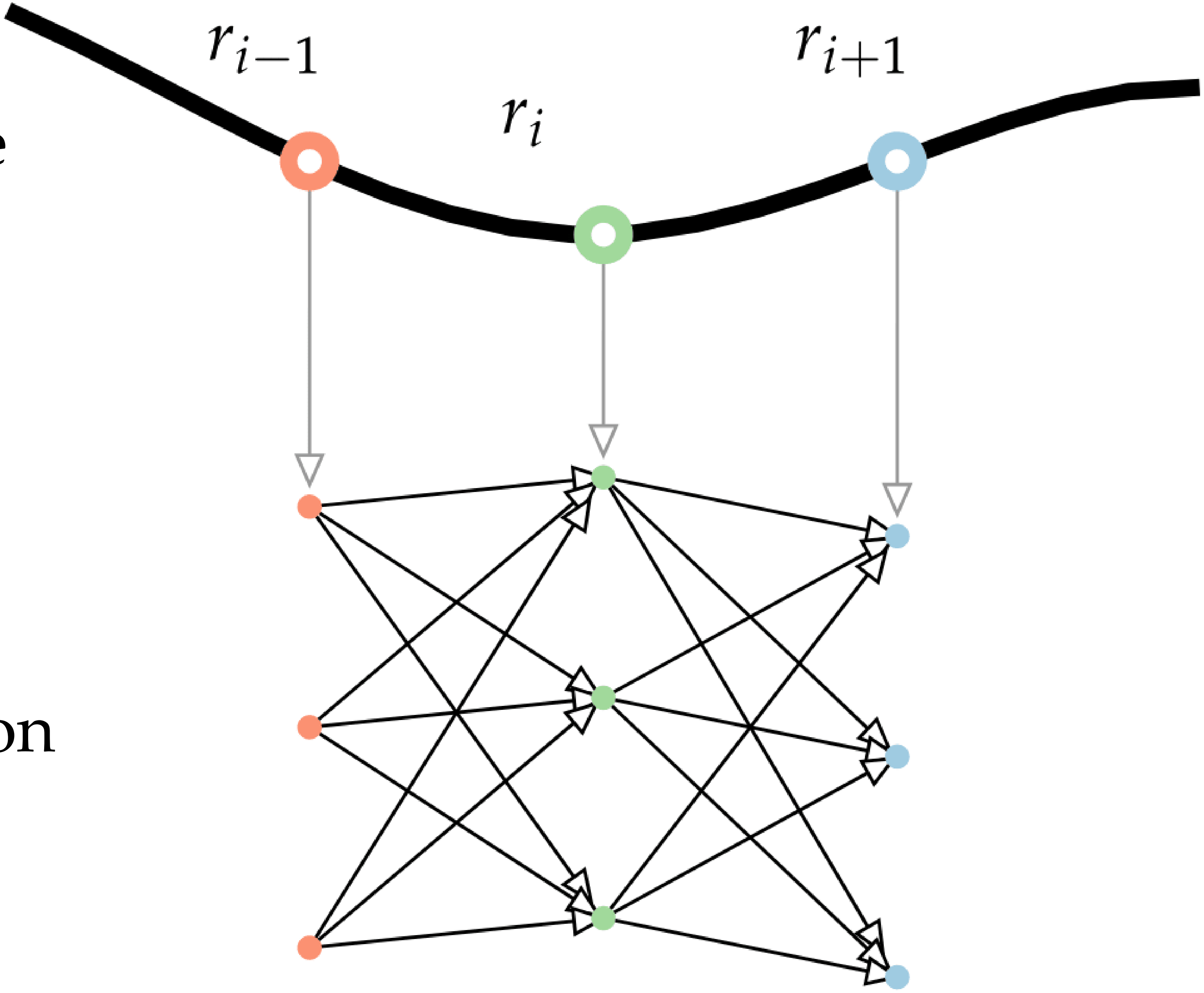
Configuration Space

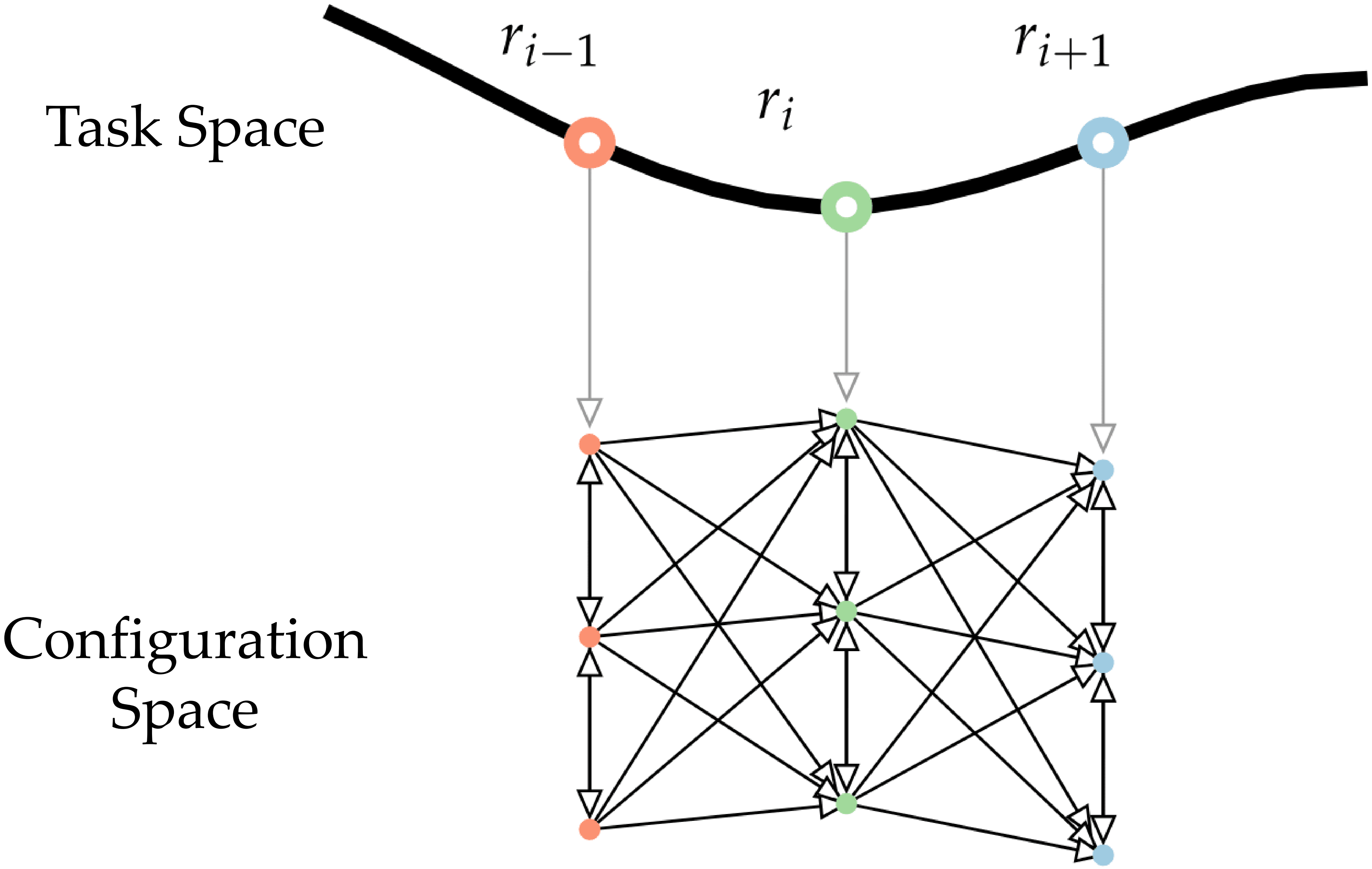


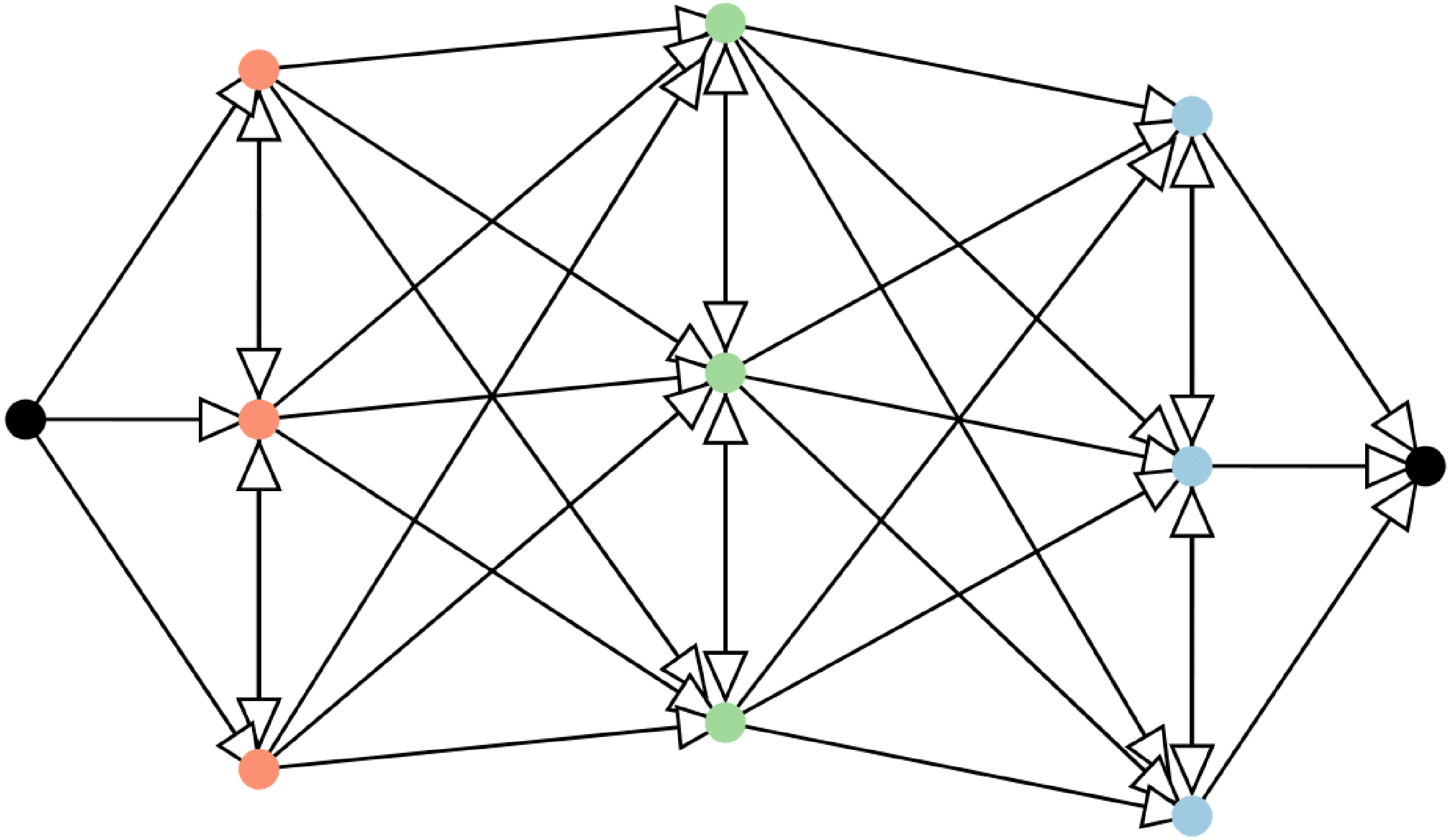

r_{i-1}
r_i
r_{i+1}
Task Space
Configuration Space

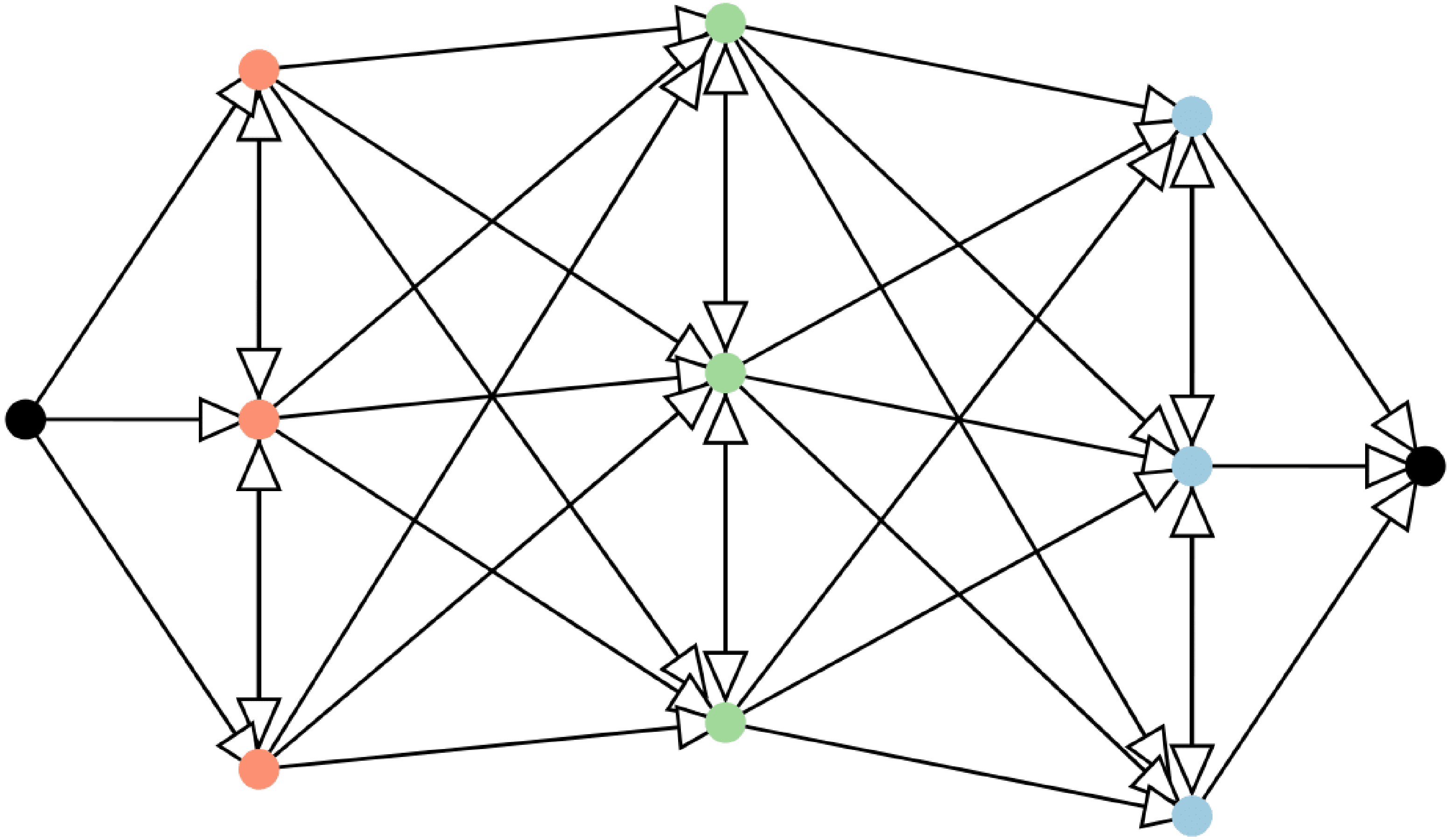
Task Space

Configuration Space

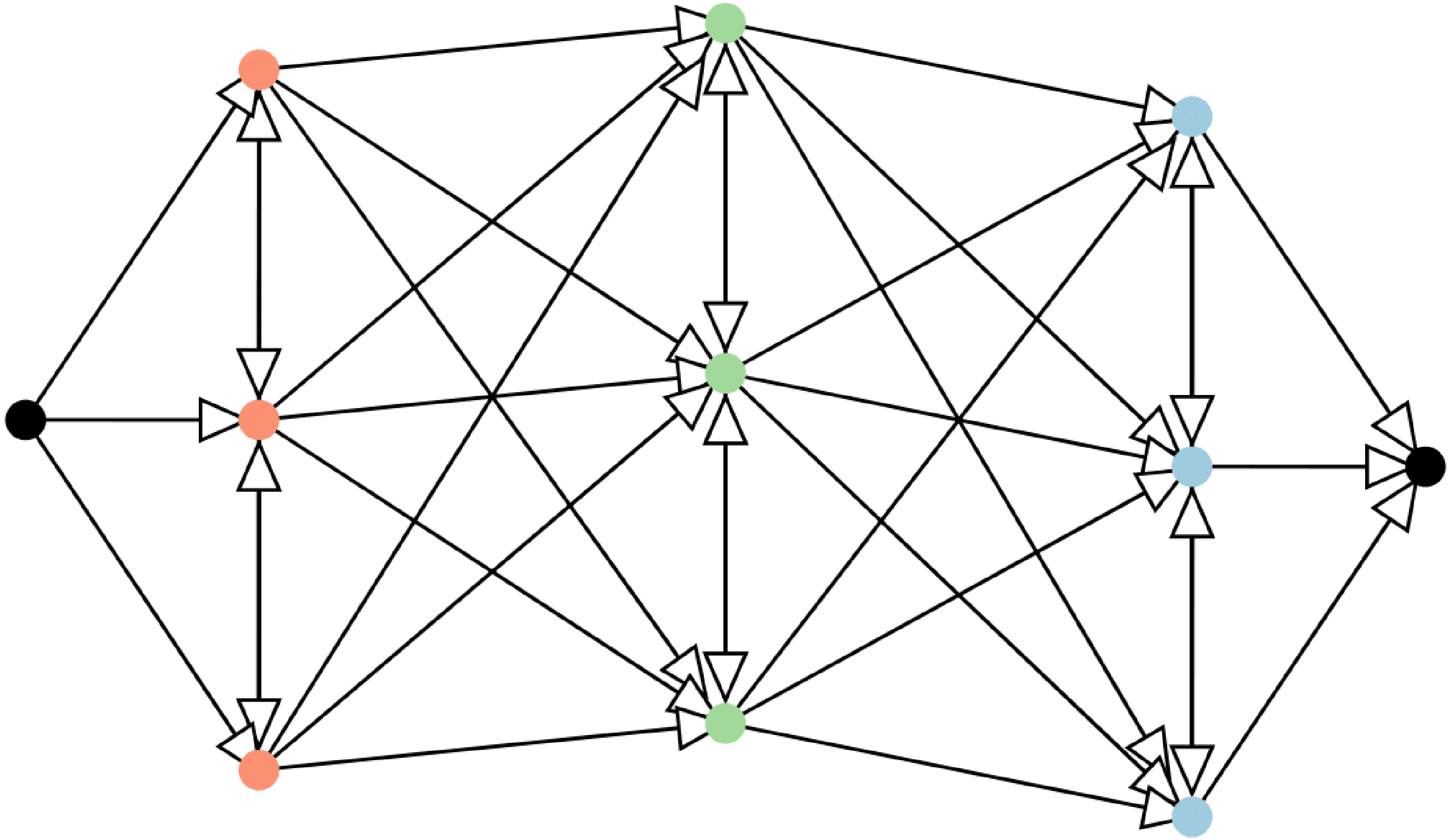



r_{i-1}
r_i
r_{i+1}
Task Space
Configuration Space



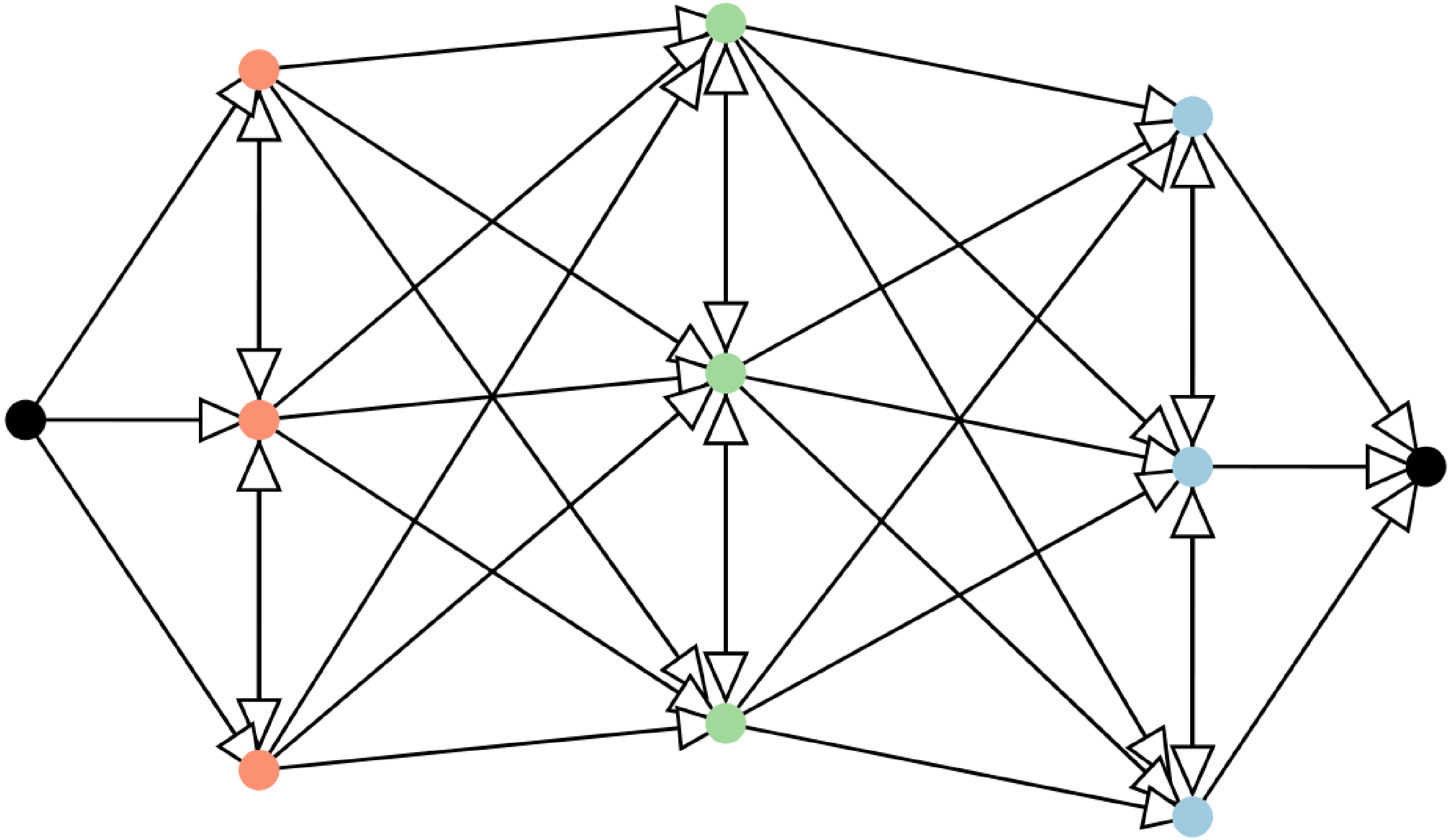


$$\xi^* = \arg\min_{p \in L} Frechet(FK(p), \bar{\xi})$$



$$\xi^* = \arg\min_{p \in L} Frechet(FK(p), \bar{\xi})$$

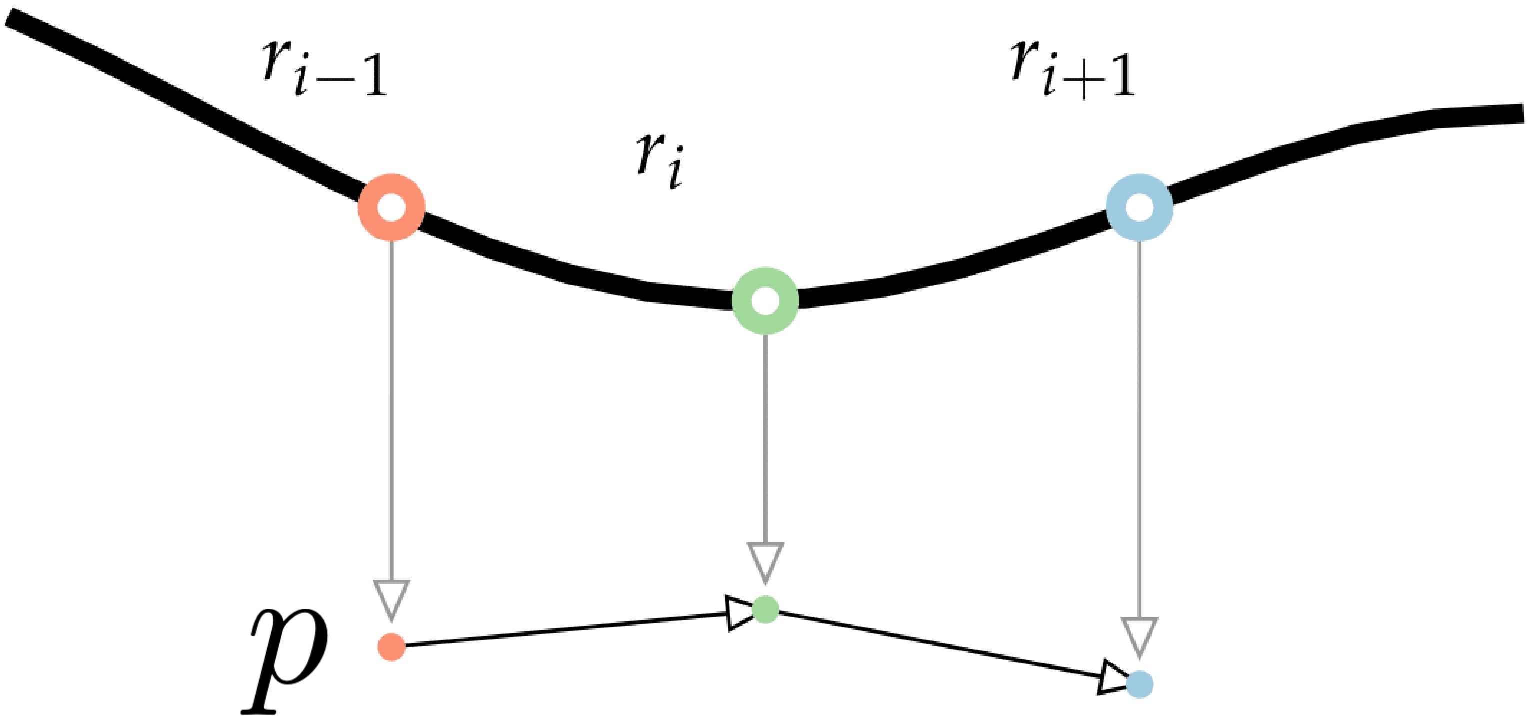
$$|p \in L|$$



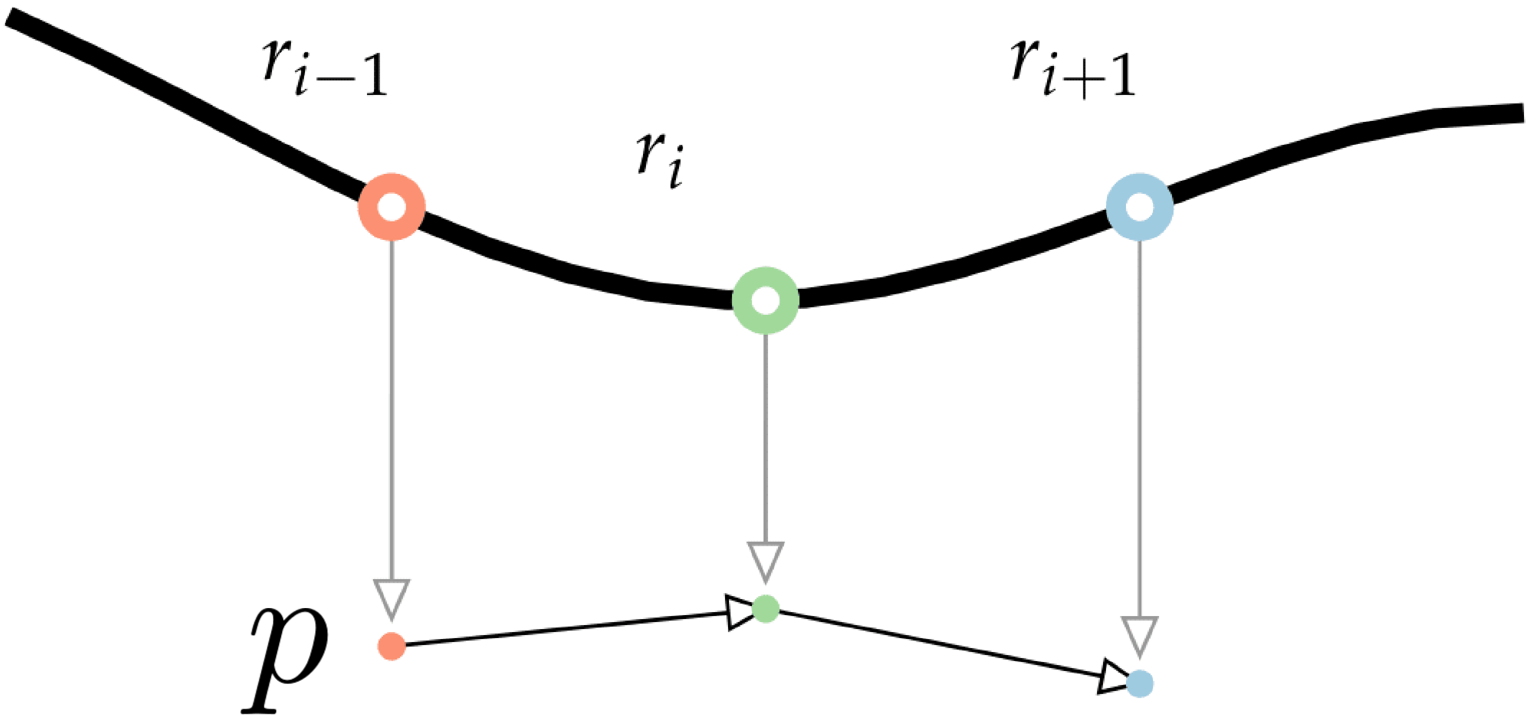
$$\xi^* = \arg\min_{p \in L} Frechet(FK(p), \bar{\xi})$$

$$|p \in L| \in \mathcal{O}(n^k)$$

Can we be more intelligent in our search?



r_{i-1}
r_i
r_{i+1}
p



$$Frechet(FK(p), \bar{\xi})$$

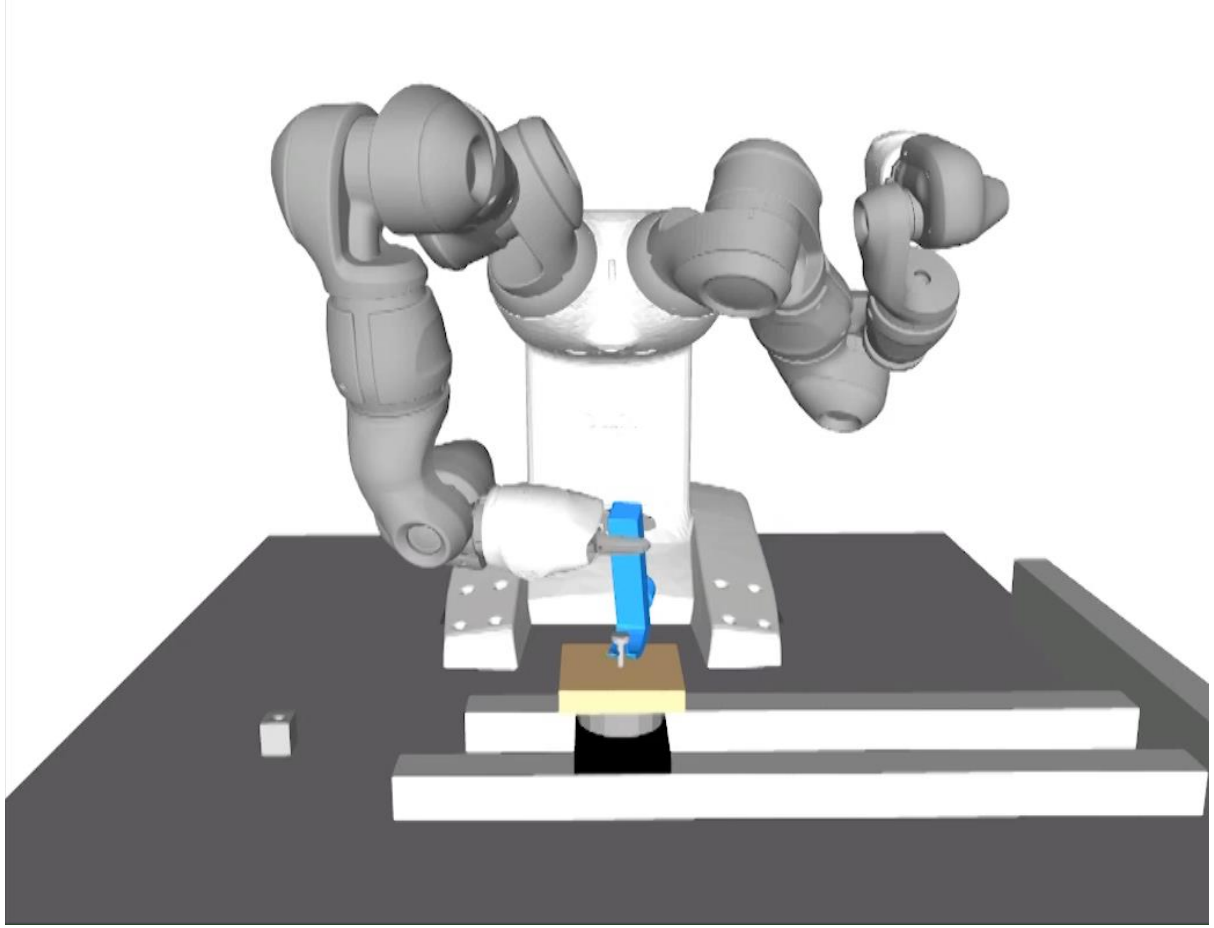
Search the Cross Product Space of
the two paths
to find the Minimum Leash.

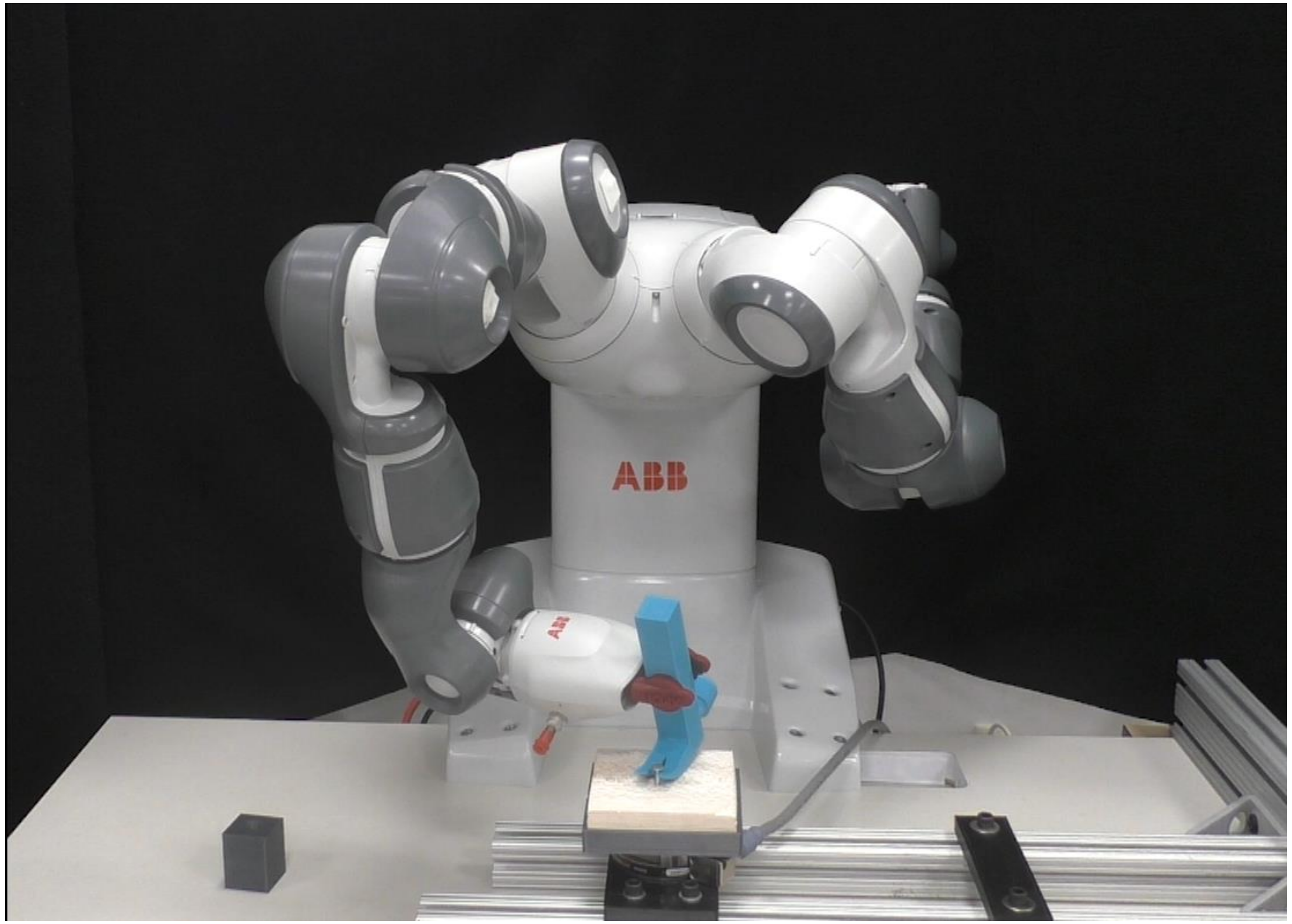
Search the Cross Product Space of
the reference path and the graph
to find the Minimum Leash.

Search the Cross Product Space of *the reference path and the graph* to find the *Bottleneck Shortest Path*.

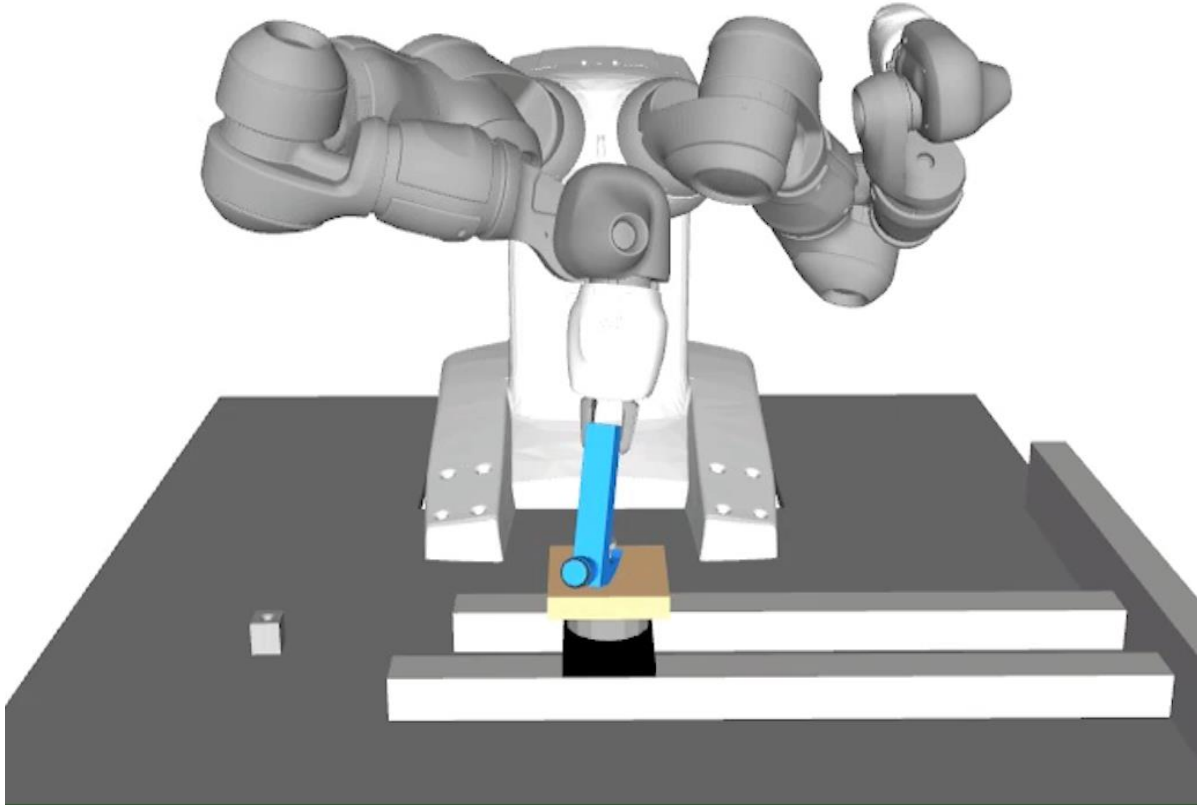
Back-Up Slides: Impact of Torque Constraint

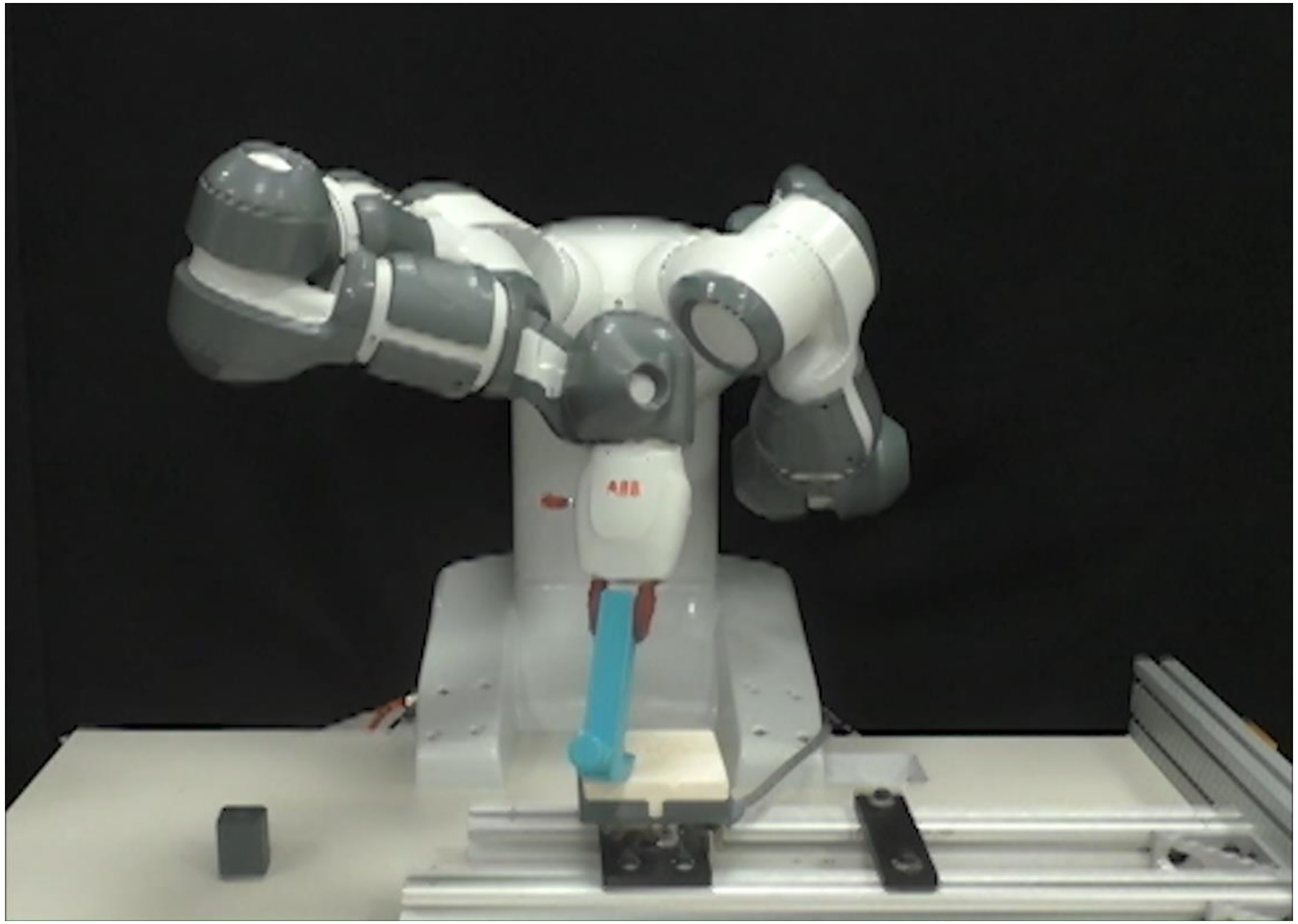
What if we violate these constraints?





Torque Fault!





Success!