Carnegie Mellon
THE ROBOTICS INSTITUTE

Legible Robot Pointing

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Anca Dragan
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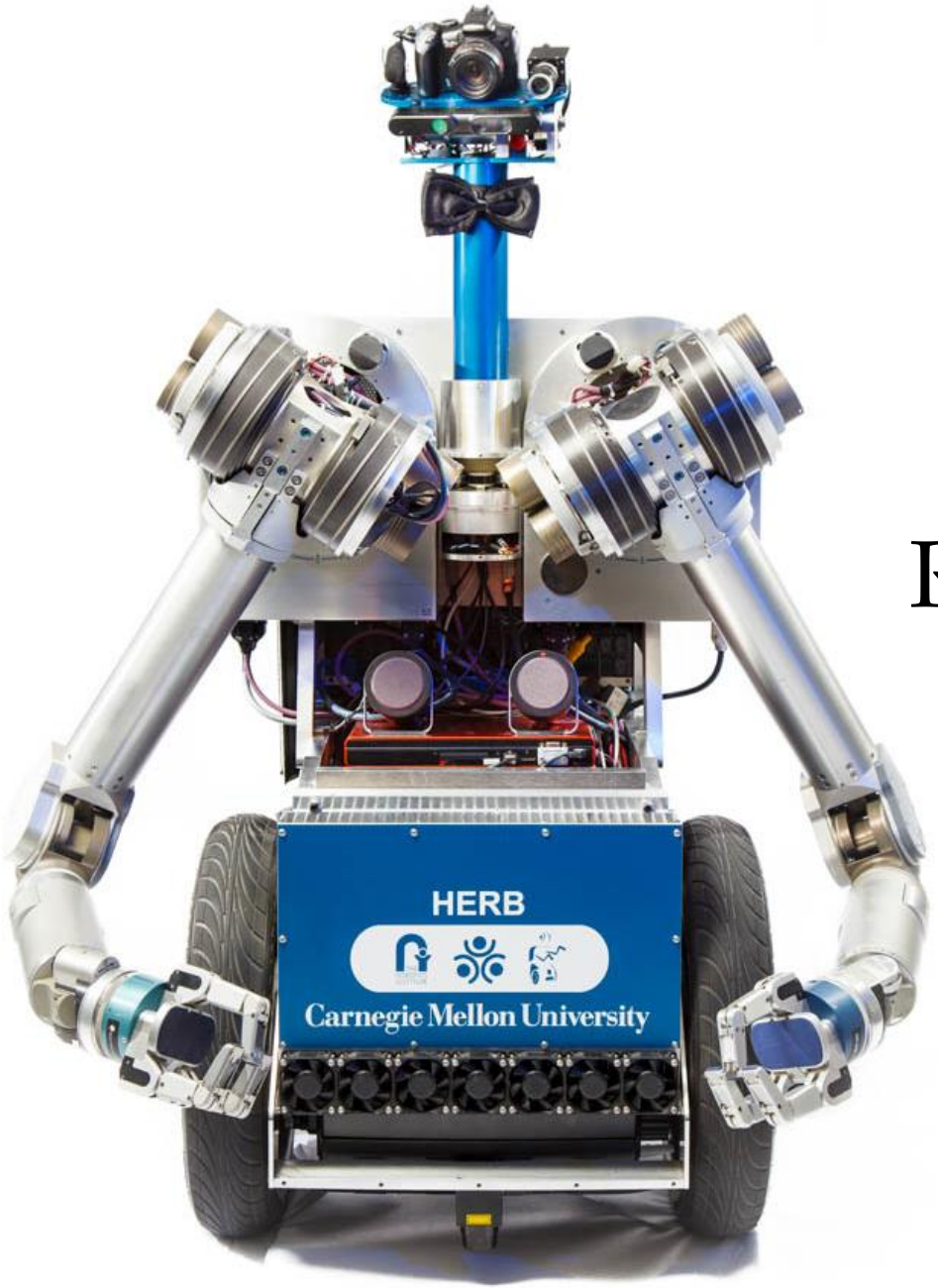

Personal Robotics Laboratory


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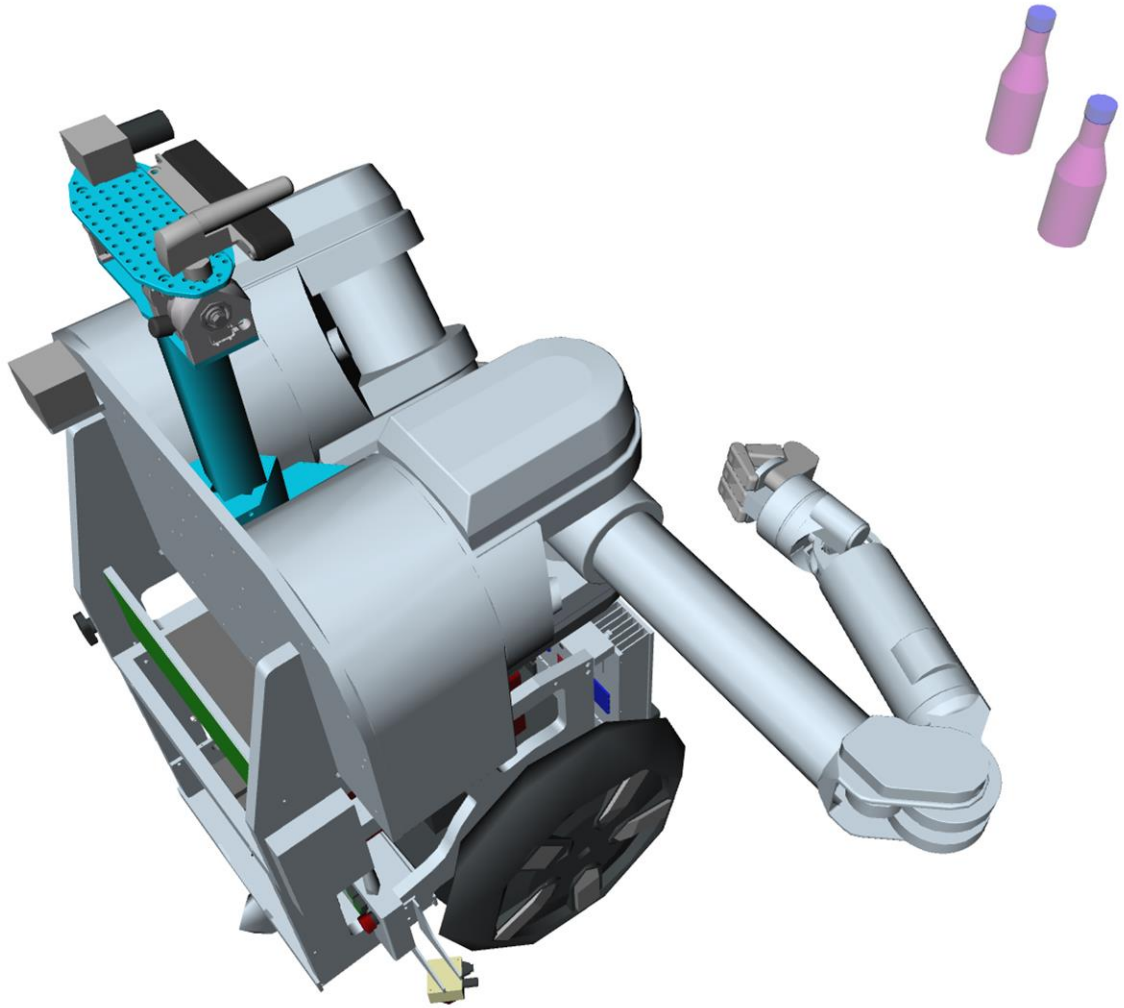
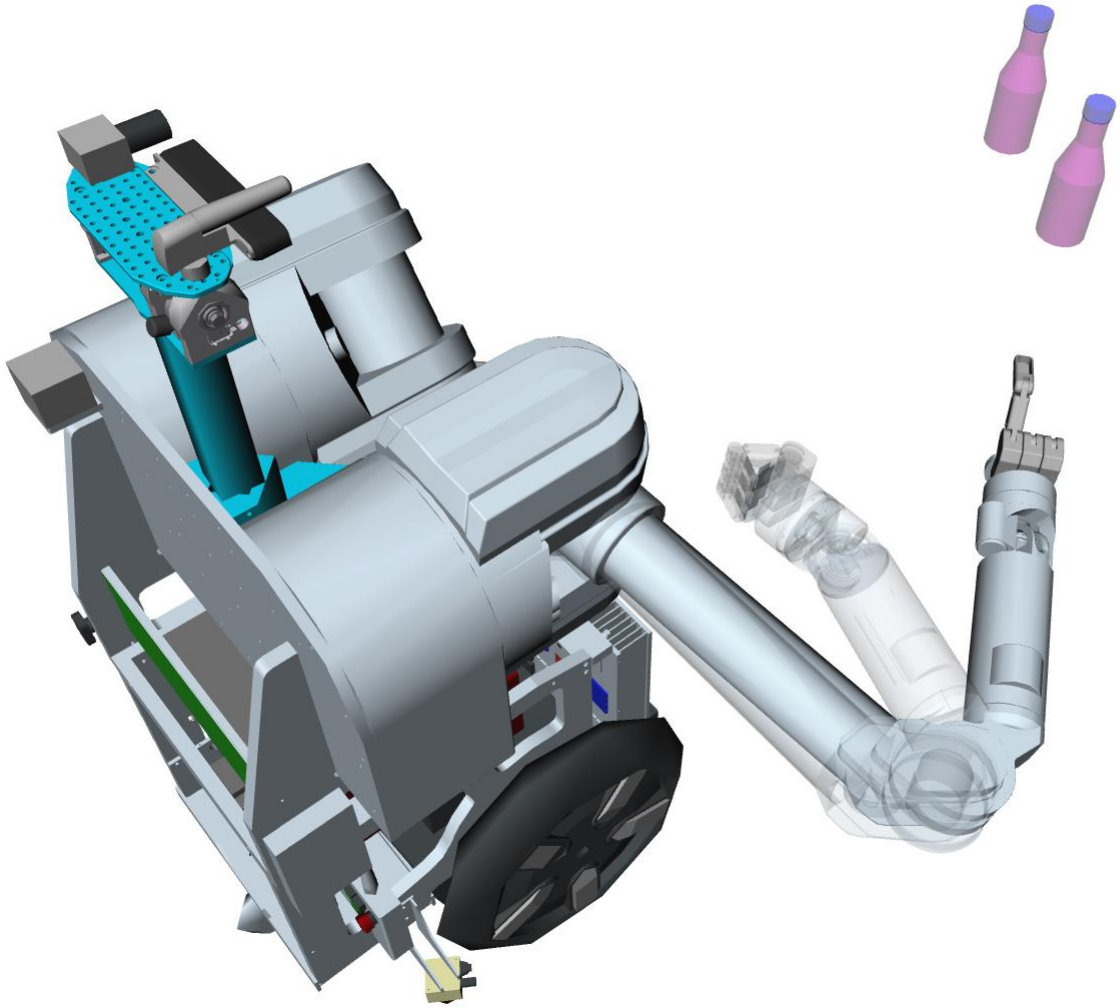
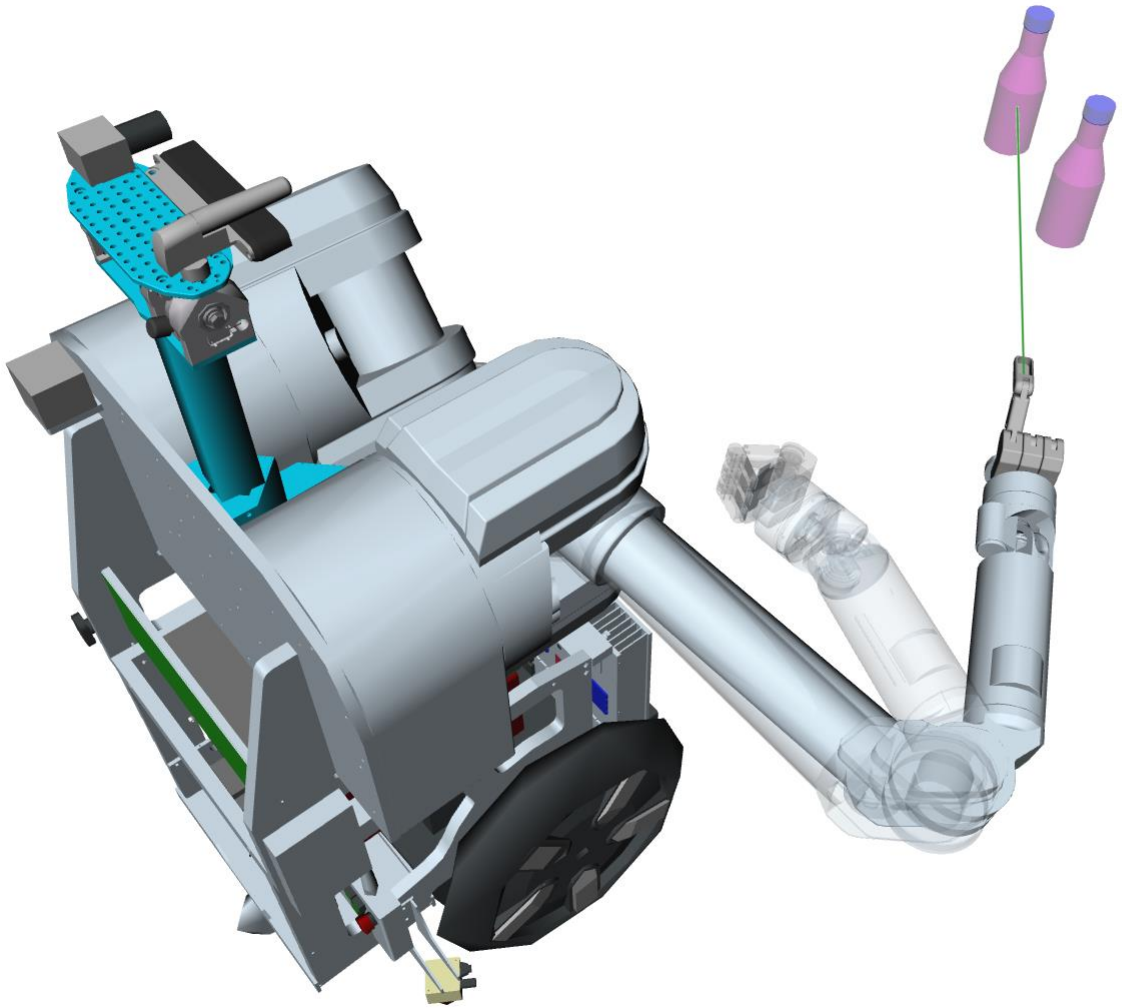
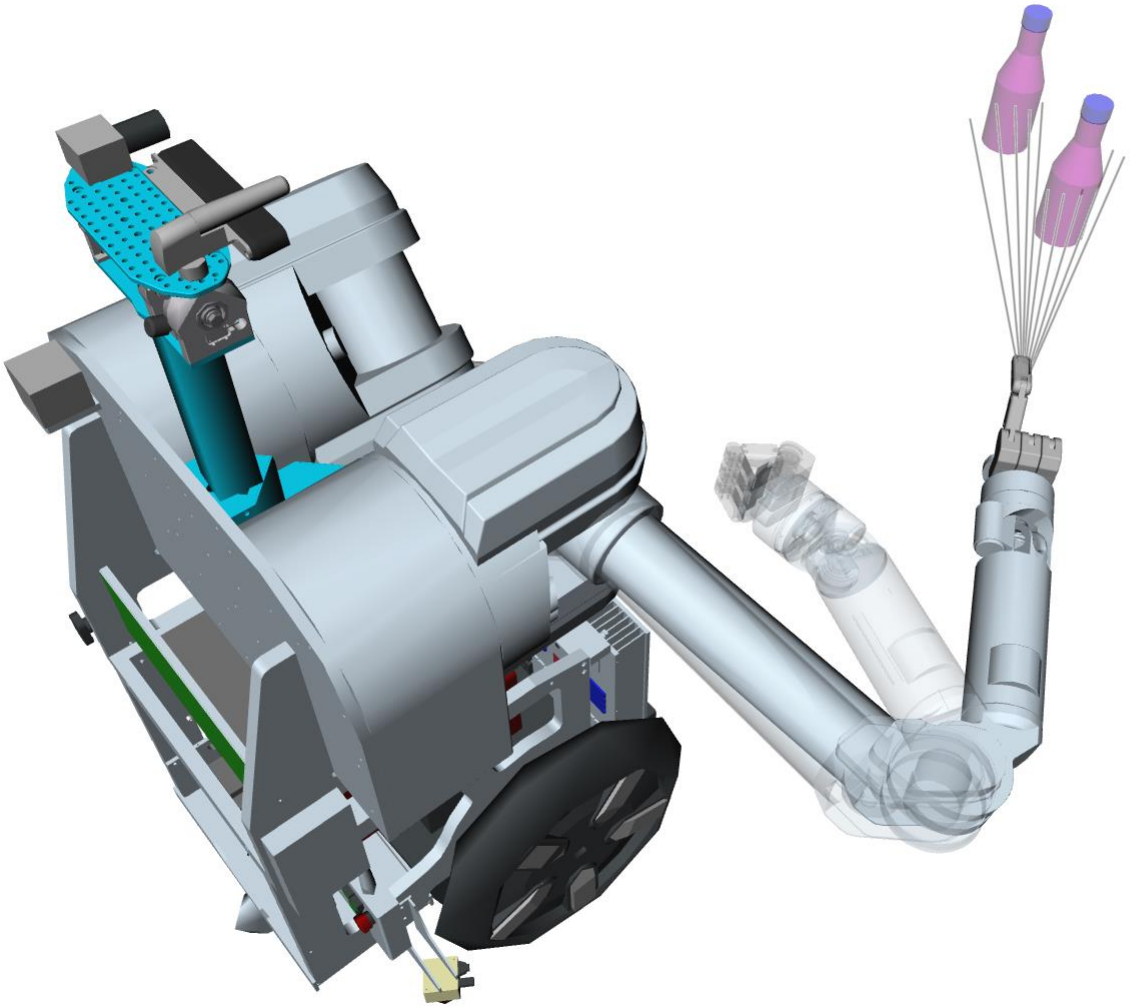
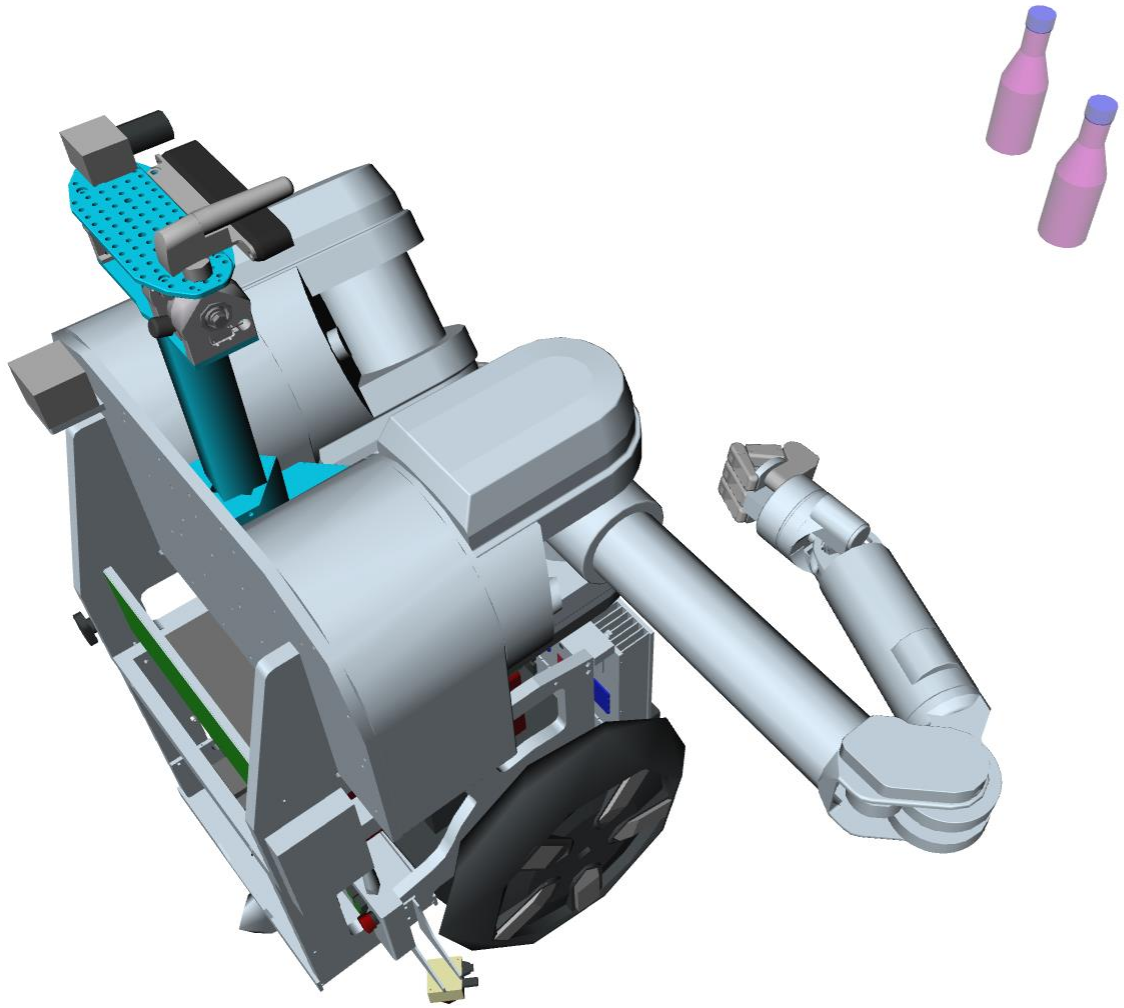


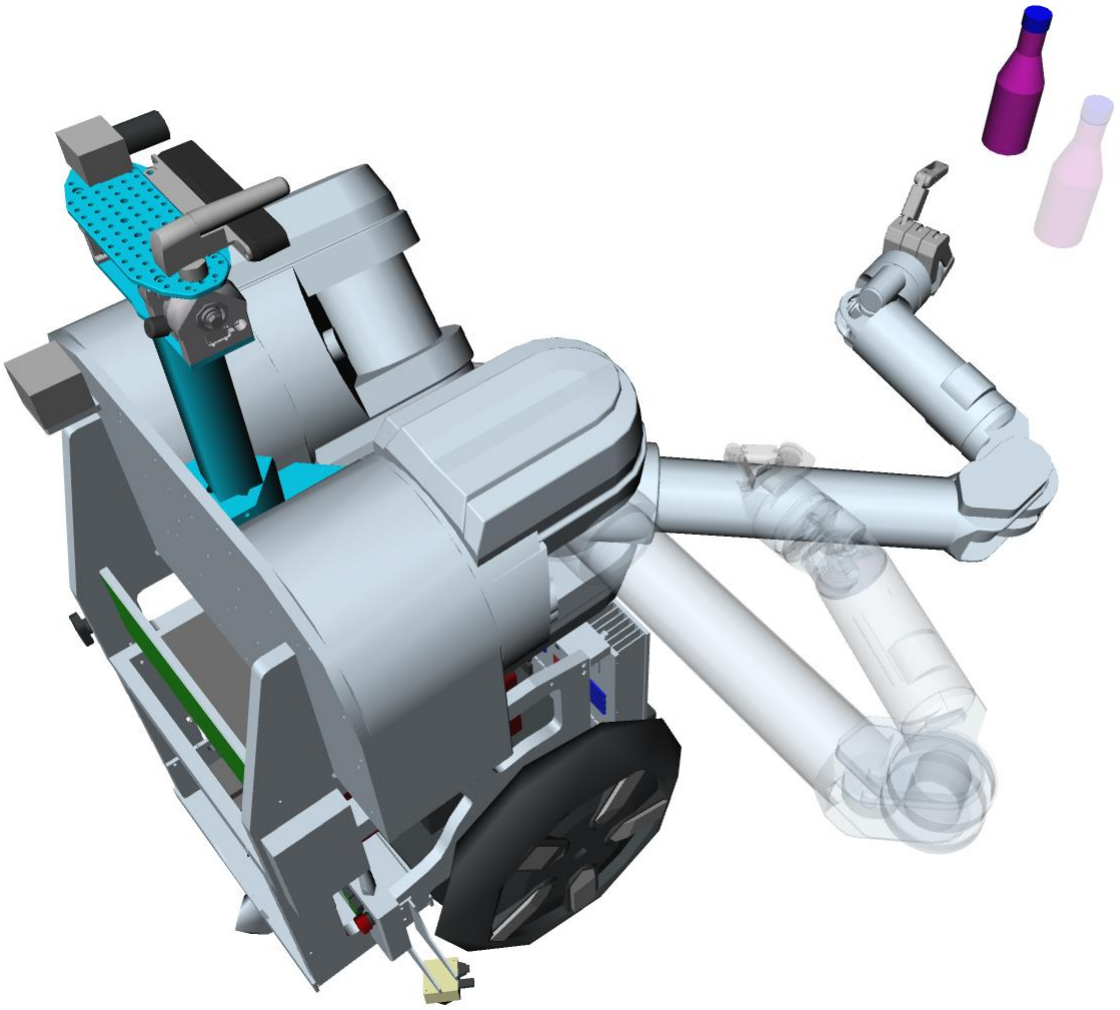






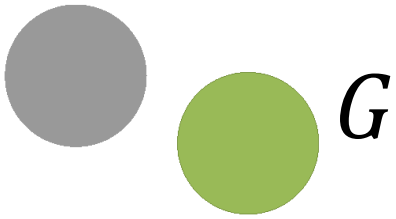


Legible



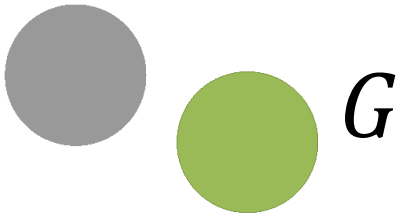
How can a robot autonomously generate legible pointing configurations?

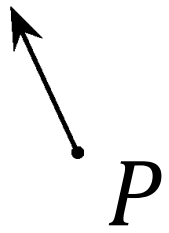
Ray Model for Pointing



P

Ray Model for Pointing





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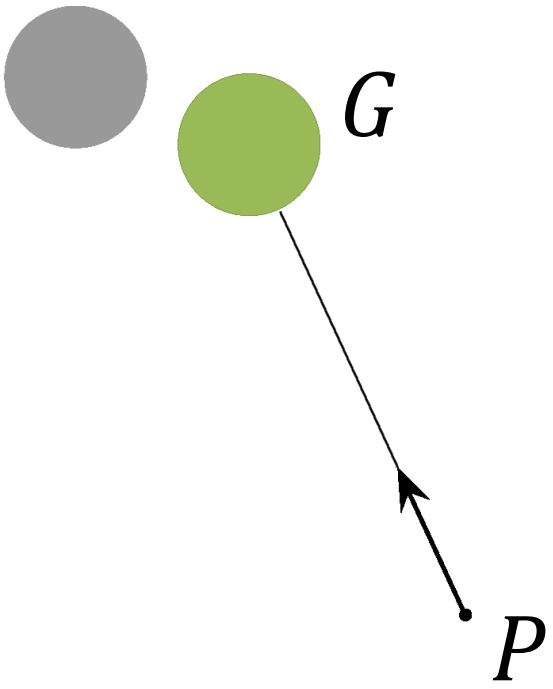

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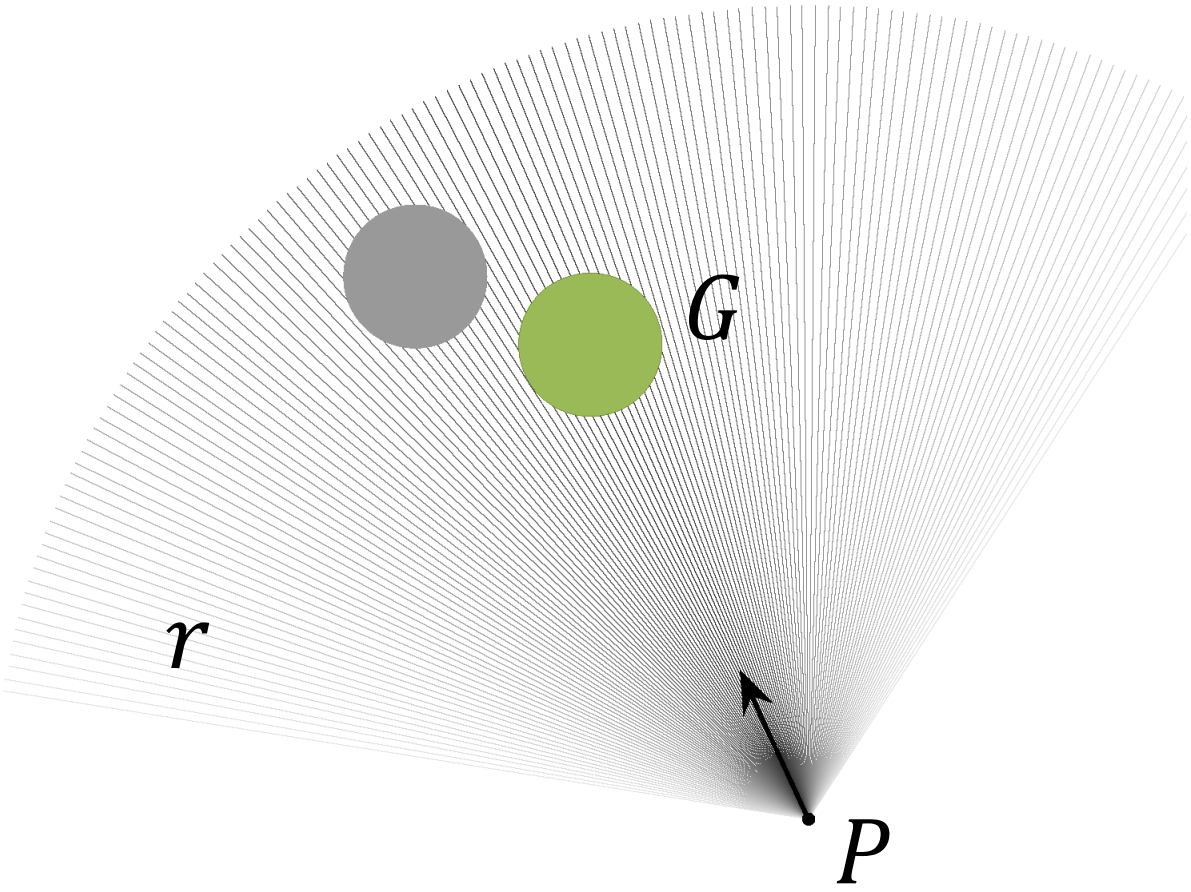
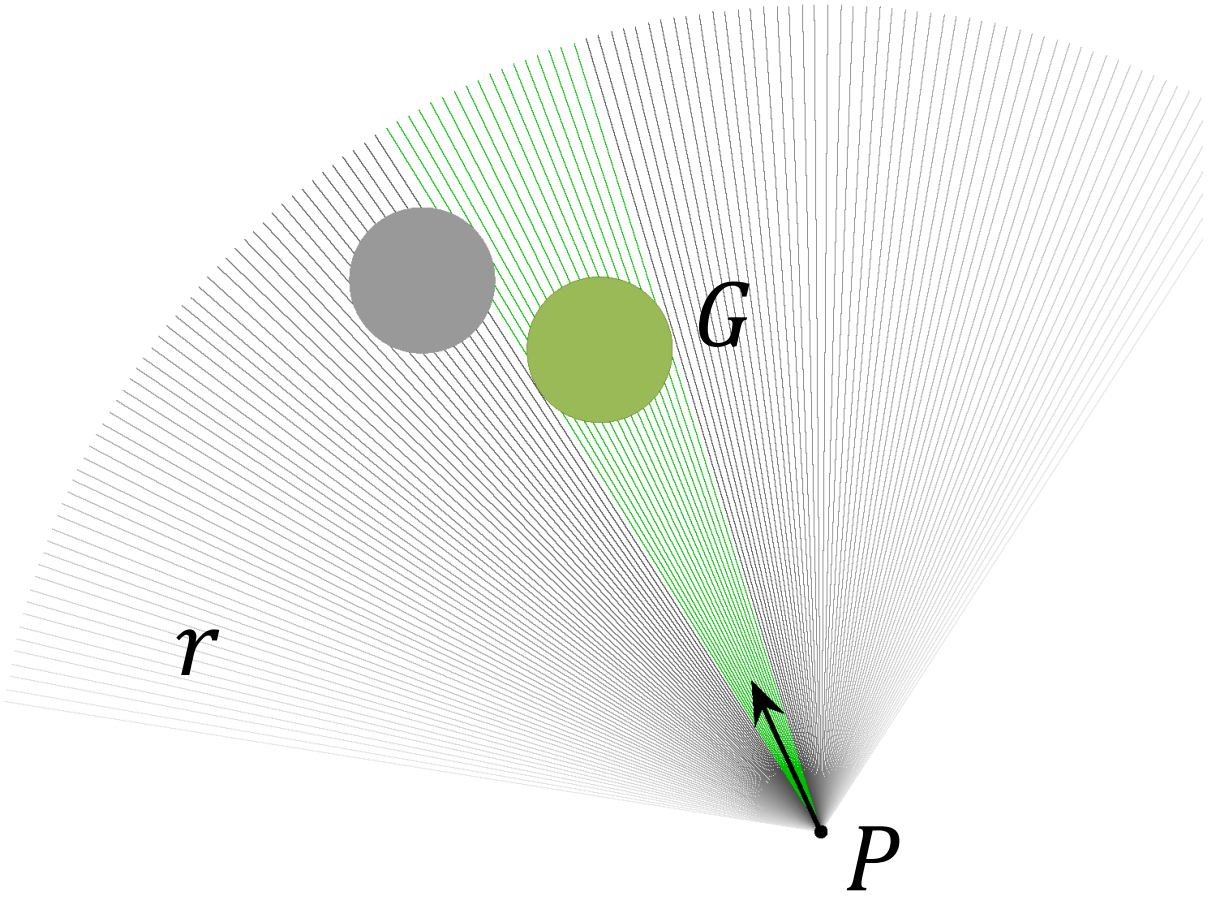
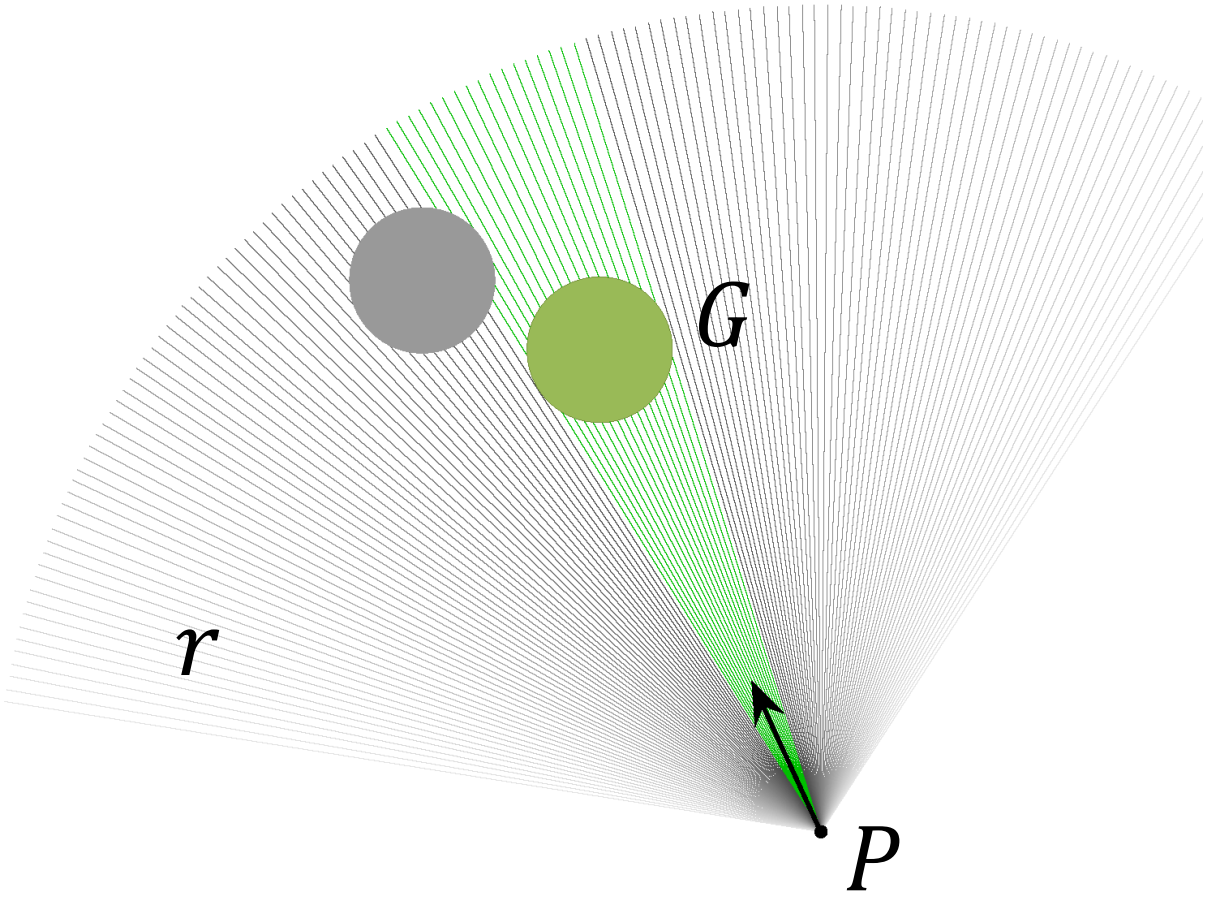


Ray Model for Pointing



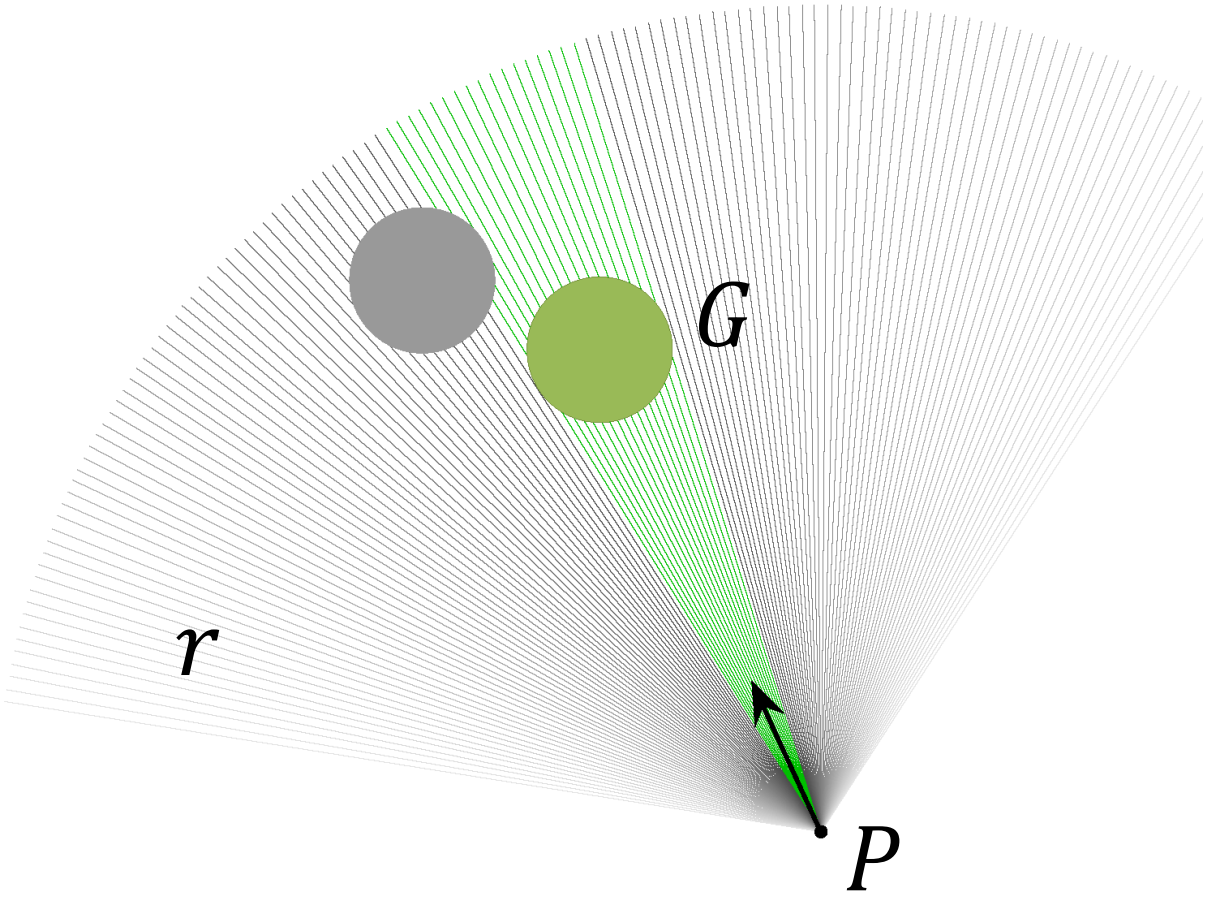
Ray Model for Pointing

$$R_G(P) = \int dr$$



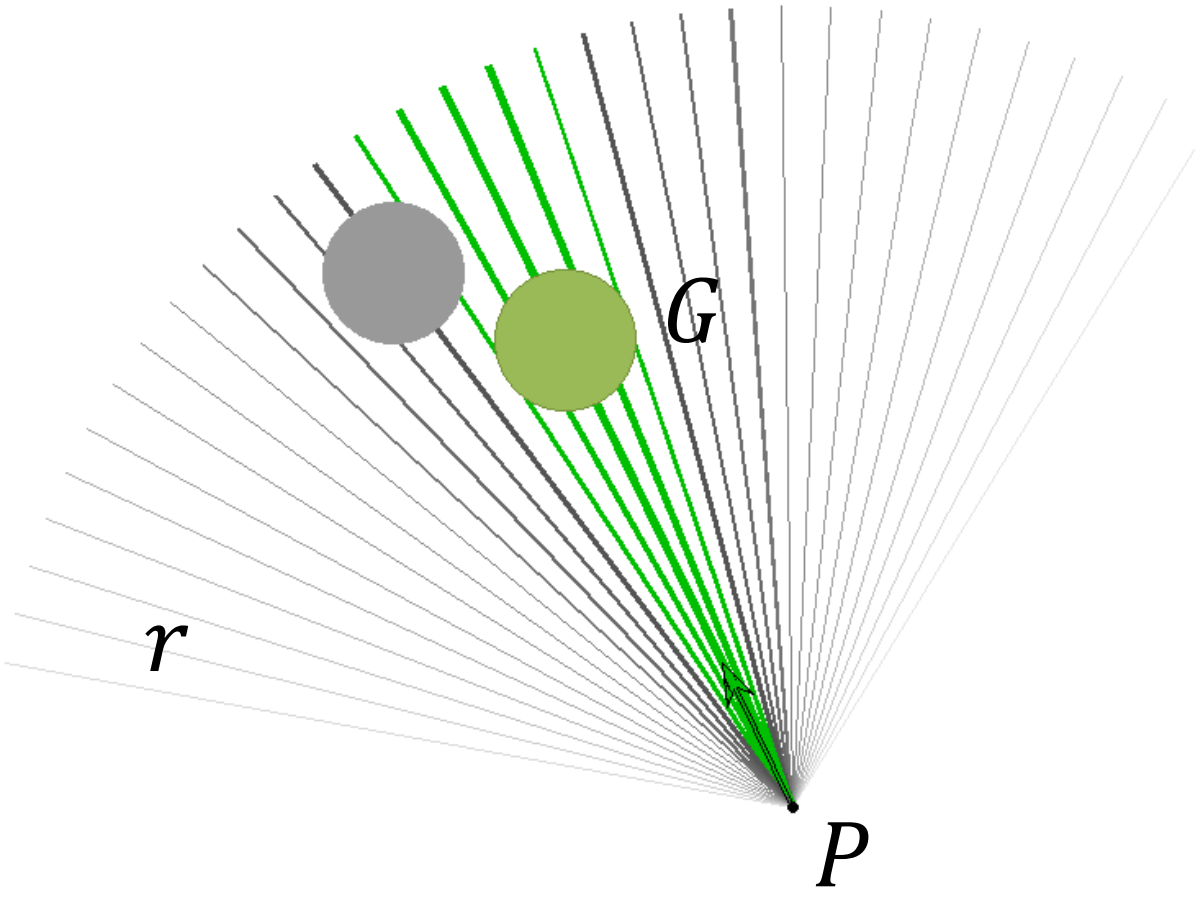
Ray Model for Pointing

$$R_G(P) = \int \delta(P, r, G)\, dr$$



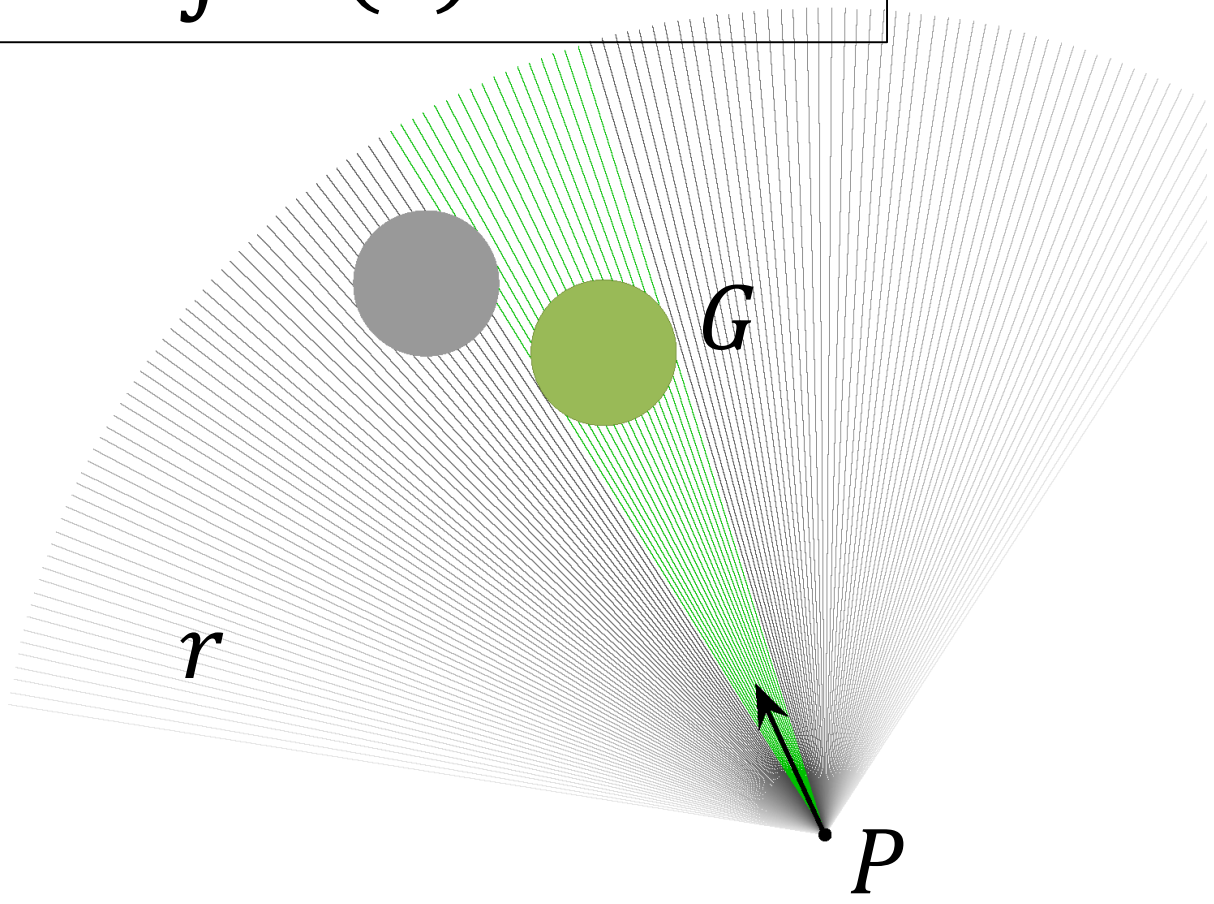
Ray Model for Pointing

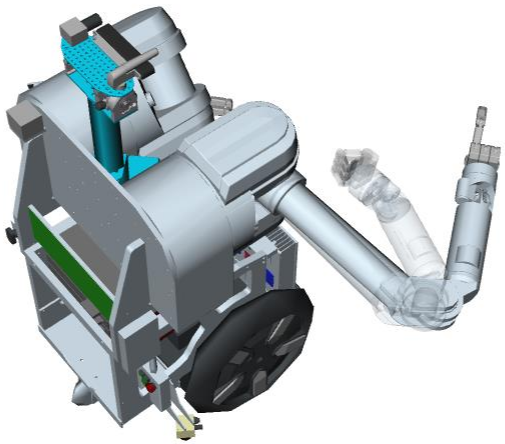
$$R_G(P) = \int \delta(P, r, G)\, w(r) dr$$

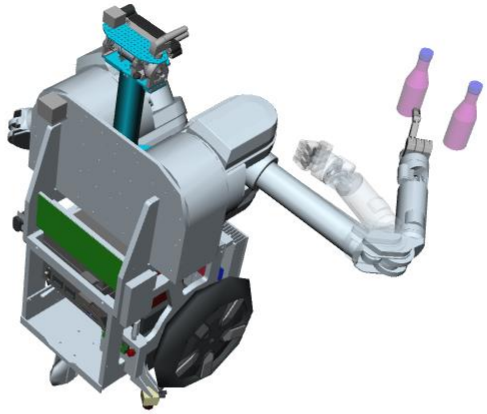


Ray Model for Pointing

$$R_G(P) = \frac{\int \delta(P, r, G)\, w(r)\, dr}{\int w(r)\, dr}$$

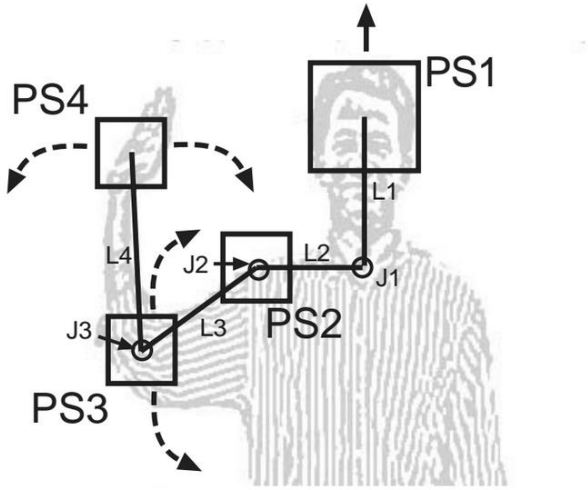




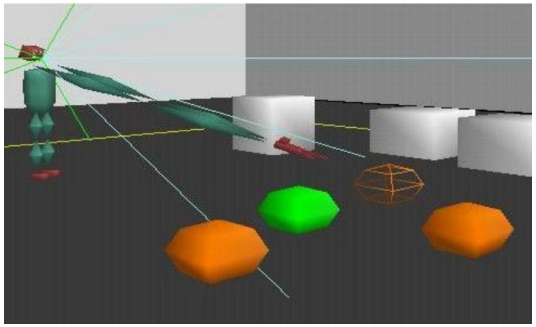


[Calinon 2007]

[Sauppe 2014]

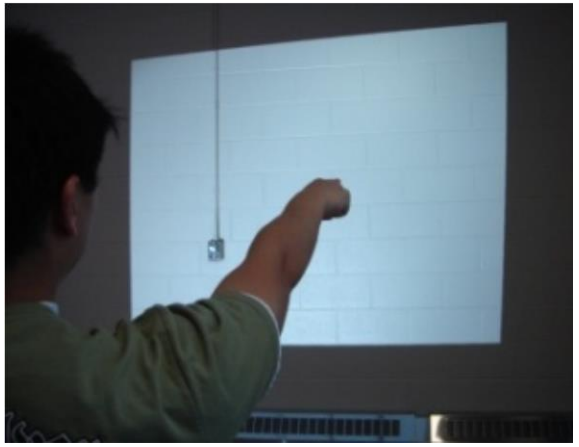


[Kortenkamp 1996]



[Frazer 1999]

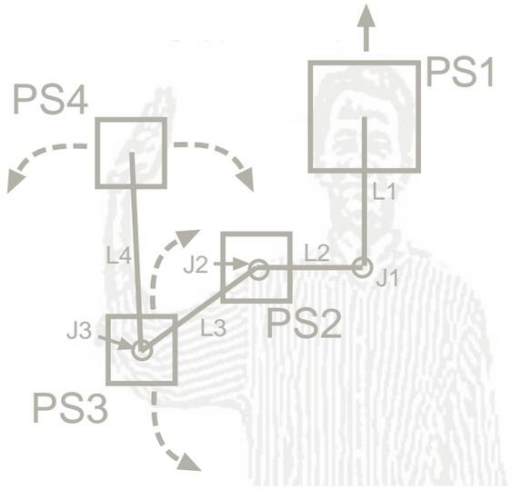
[Tolani 2000]



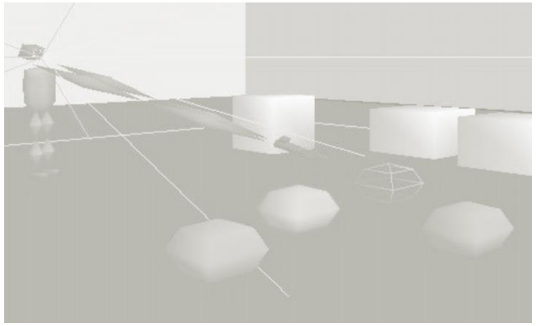
[Wong 2010]

[Calinon 2007]

[Sauppe 2014]



[Kortenkamp 1996]



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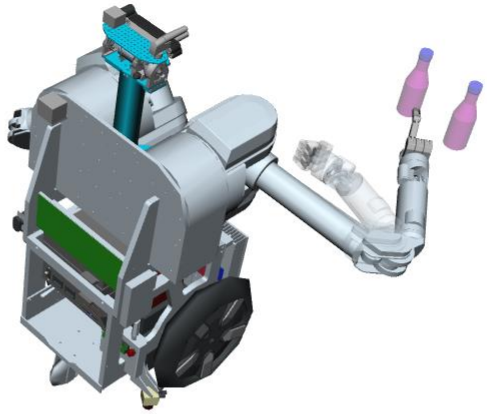
[Wong 2010]



The Cost of a Pointer

$C_G(P)$

The Cost of a Pointer

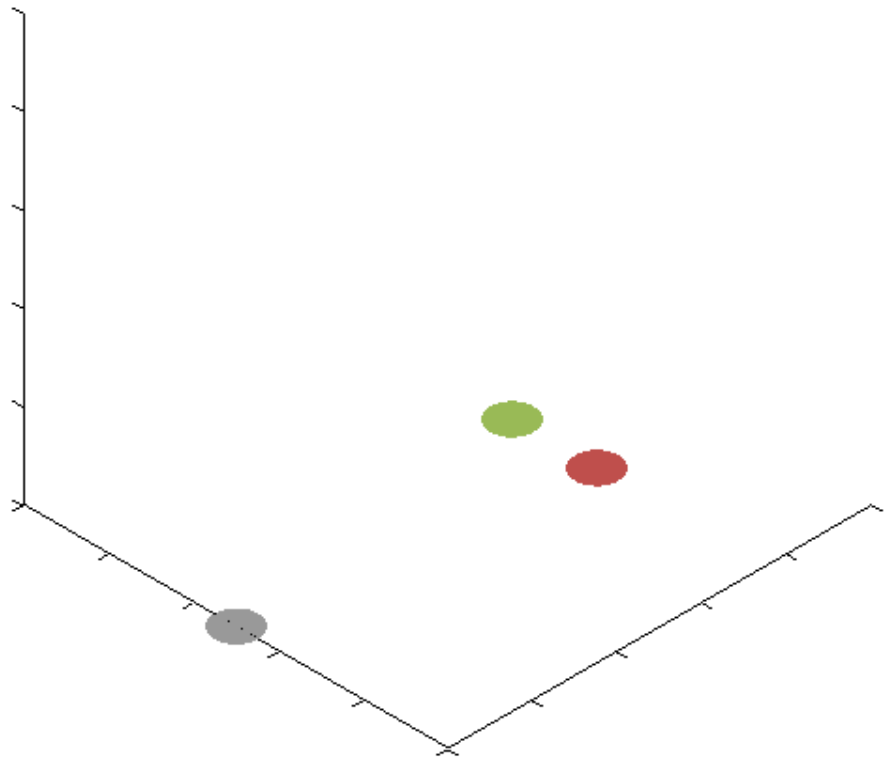
$$C_G(P) = \underbrace{\left(1 - R_G(P)\right)}_{\text{Maximize } R_G}$$

The Cost of a Pointer

$$C_G(P) = \underbrace{\left(1 - R_G(P)\right)}_{\text{Maximize } R_G} + \underbrace{\frac{\lambda}{M}||S - P||^2}_{\text{Minimize Distance}}$$

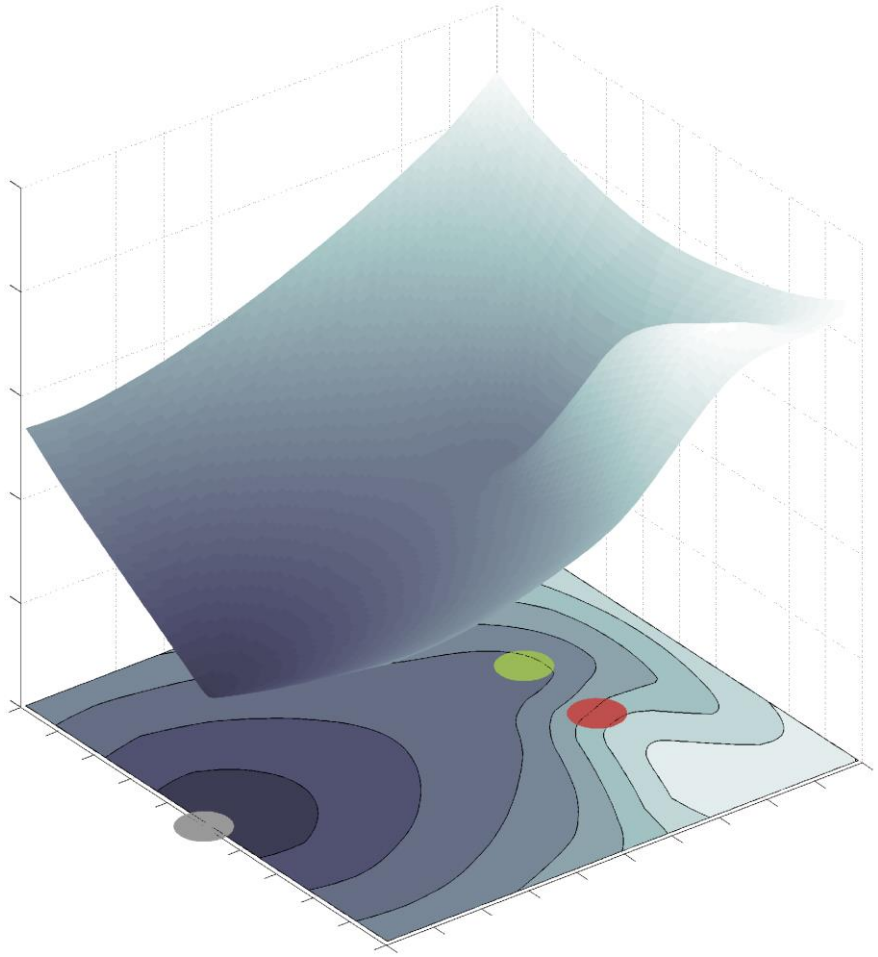
The Cost of a Pointer

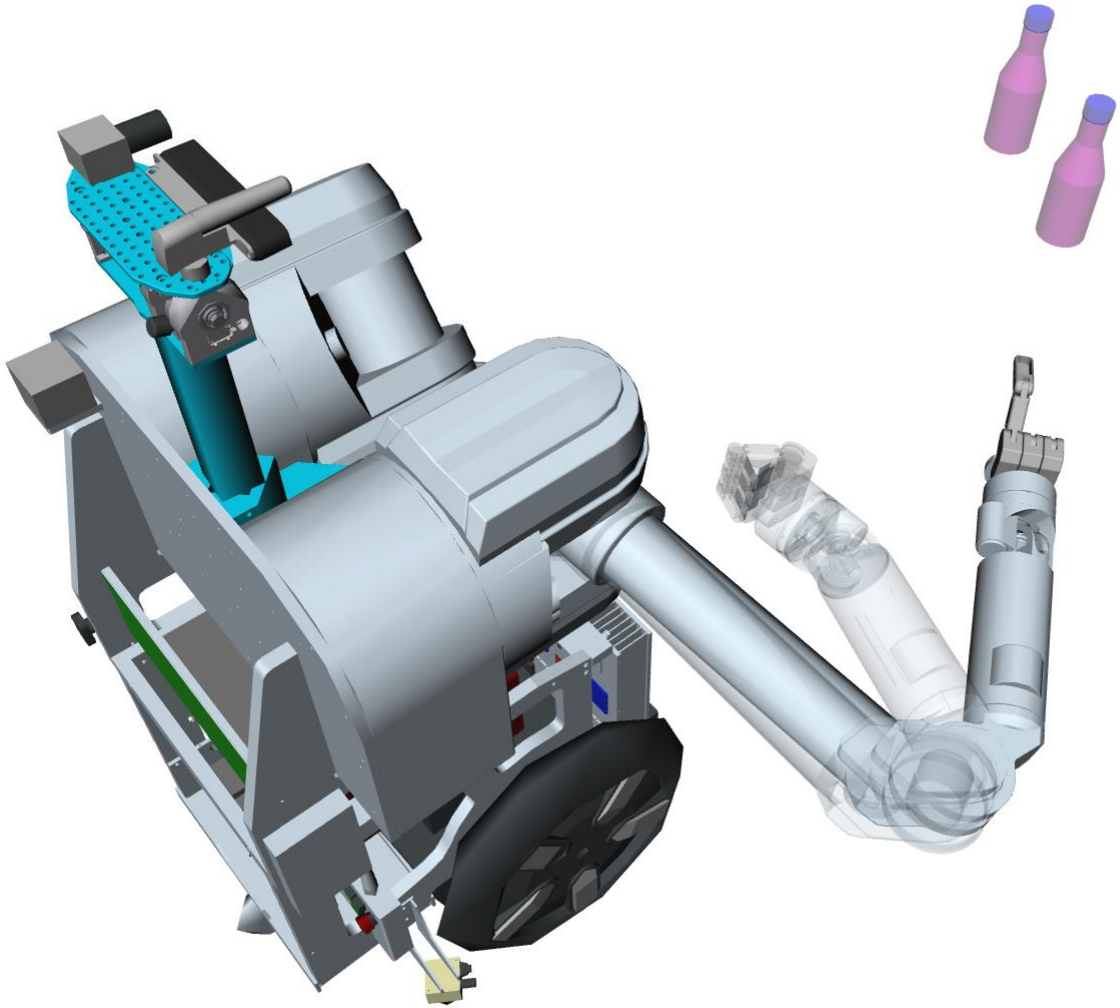
$$C_G(P) = \left(1 - R_G(P)\right) + \frac{\lambda}{M}||S - P||^2$$

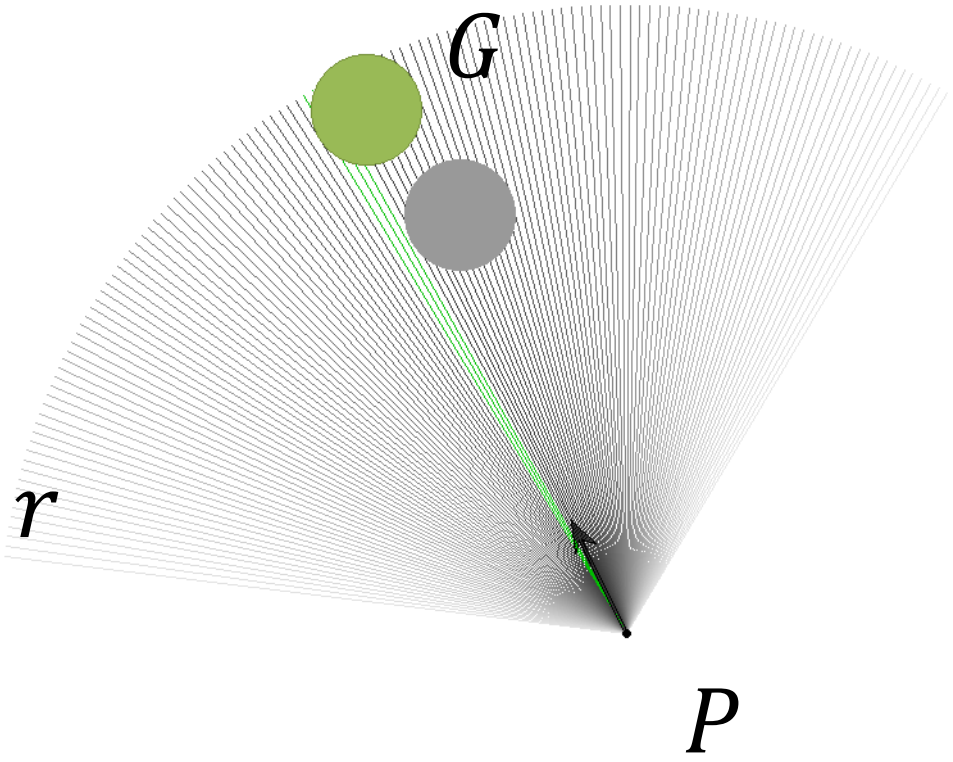


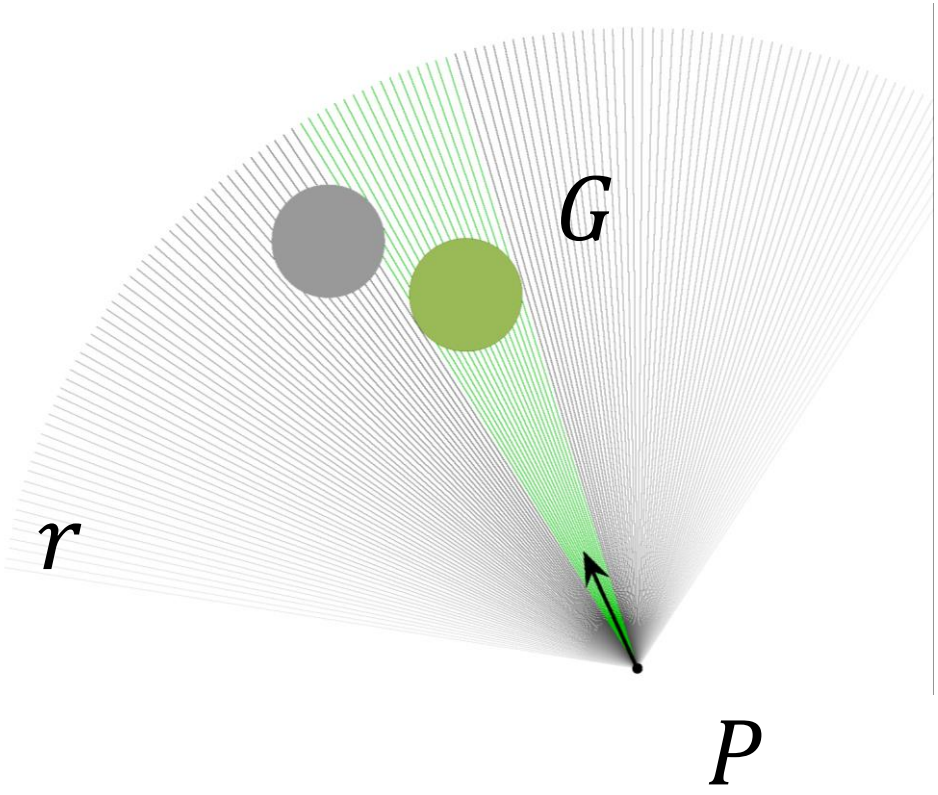
The Cost of a Pointer

$$C_G(P) = \left(1 - R_G(P)\right) + \frac{\lambda}{M}||S - P||^2$$






G
r
P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r
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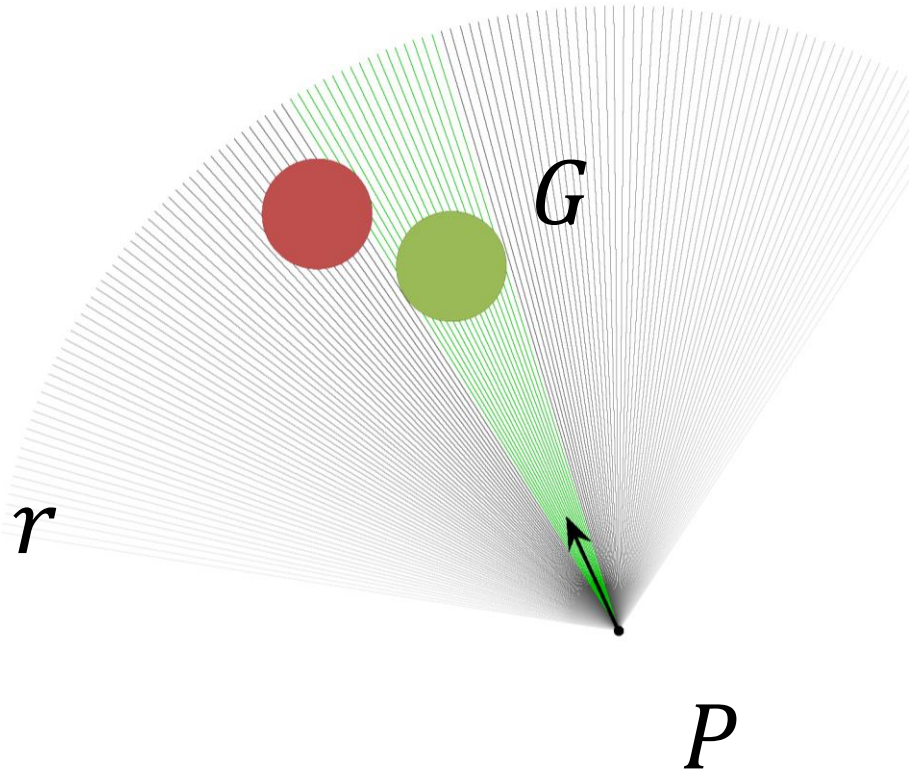
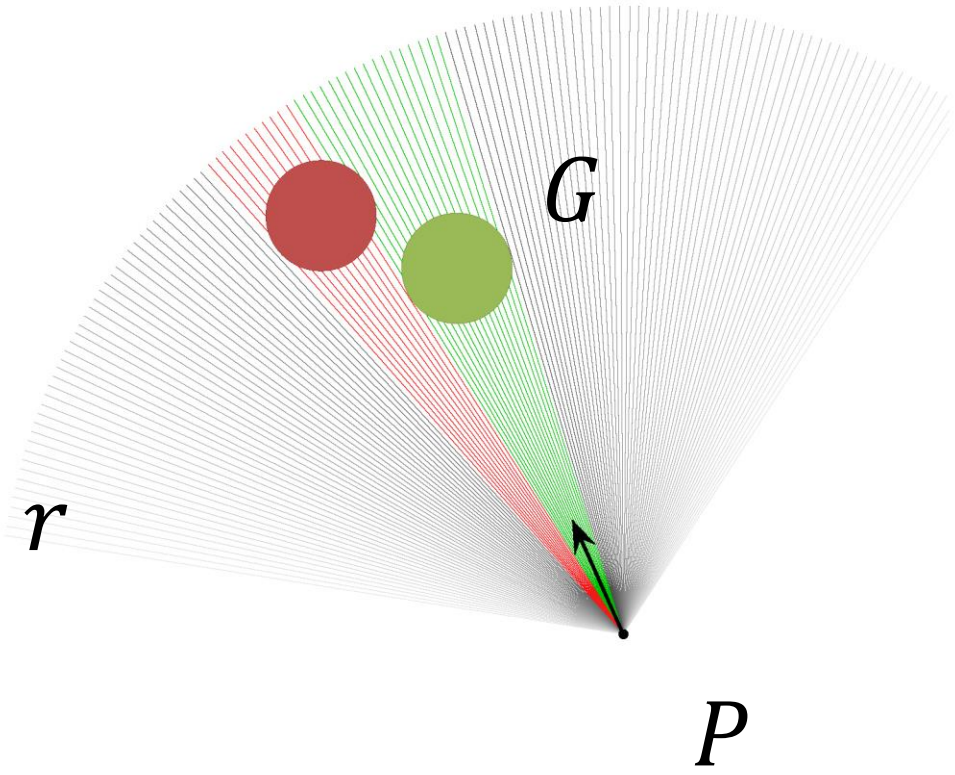
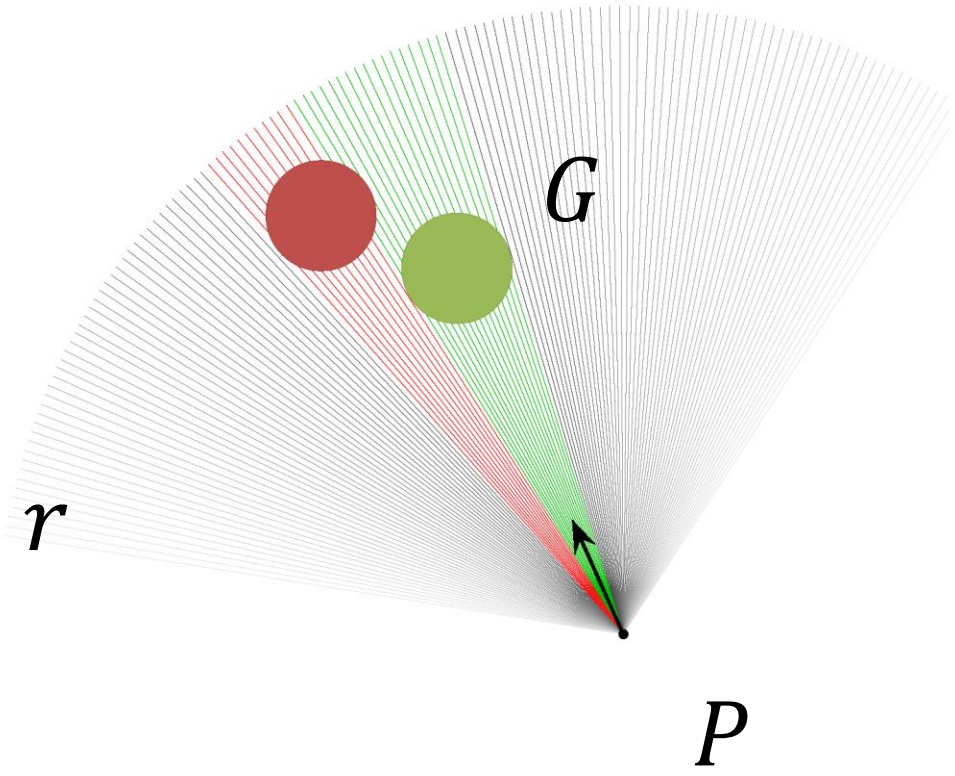

G
r
P

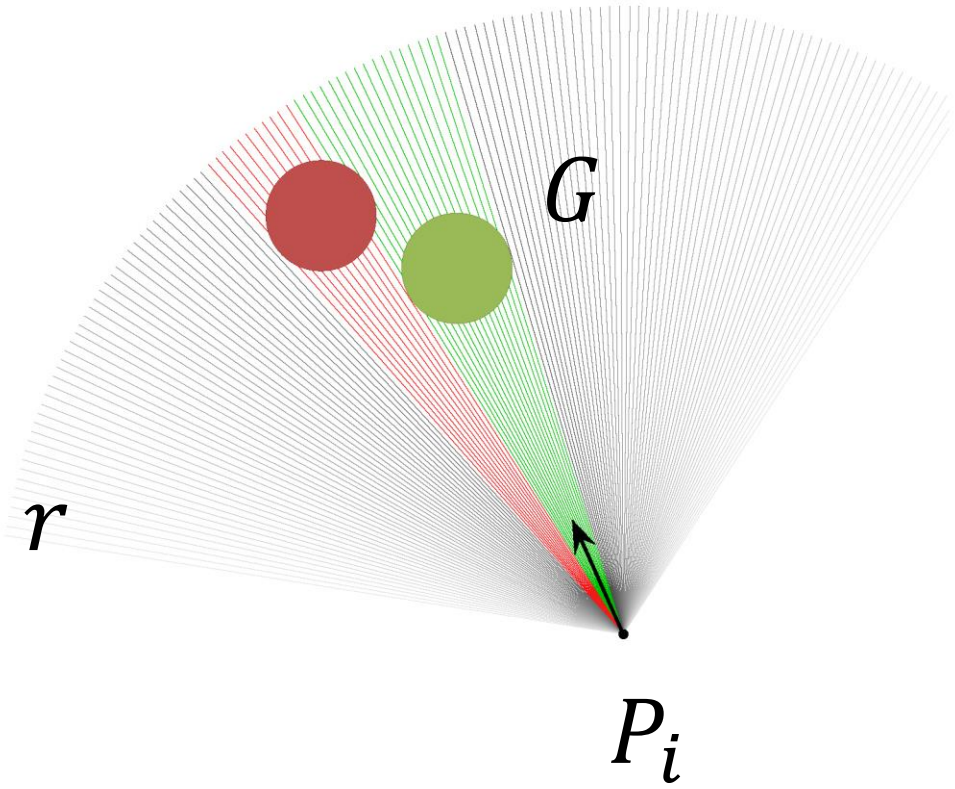

G
r
P

Key Insight:

Consider what you are pointing at and what you <u>aren't</u> pointing at.

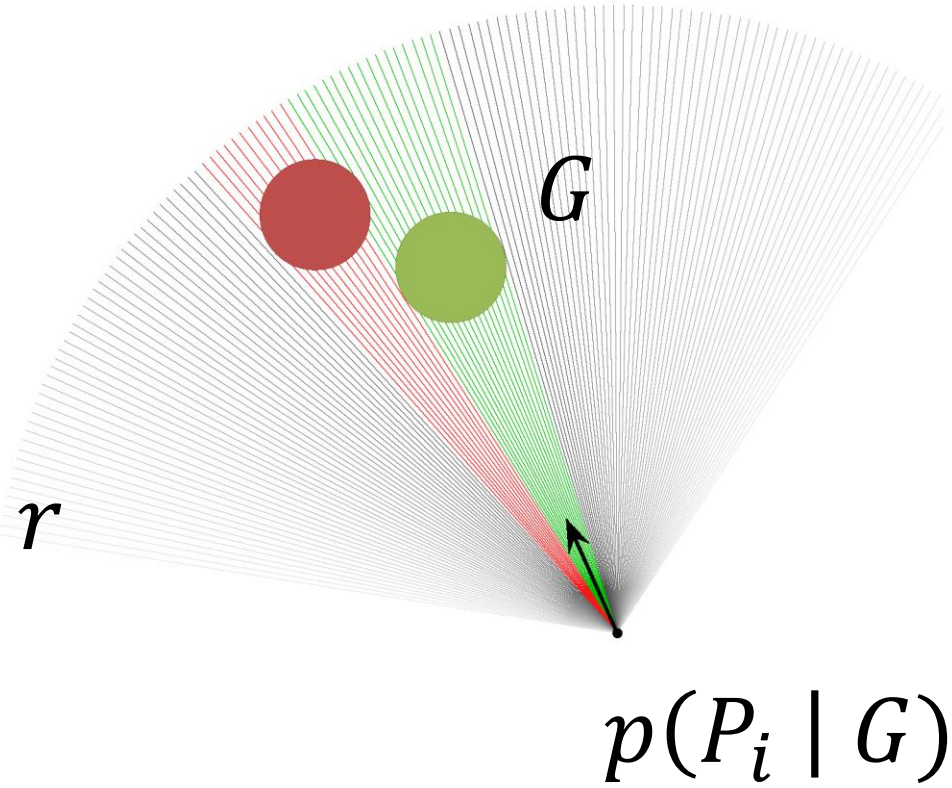


Model for Legible Pointing



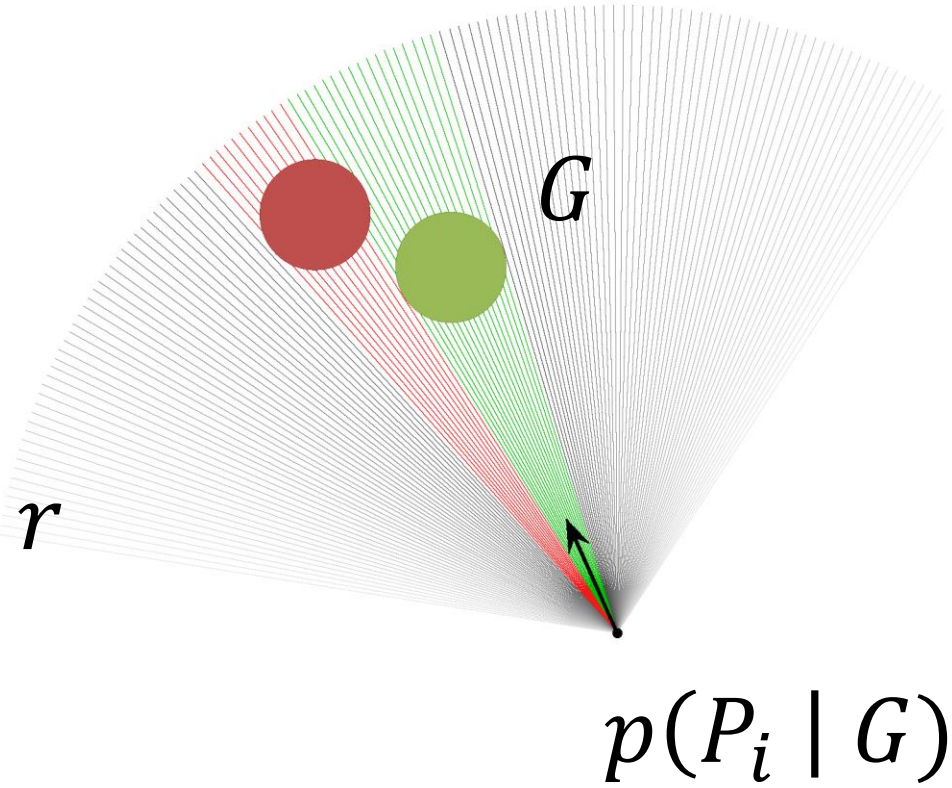
Model for Legible Pointing

$$p(P|G) \propto e^{-C_G(P)}$$

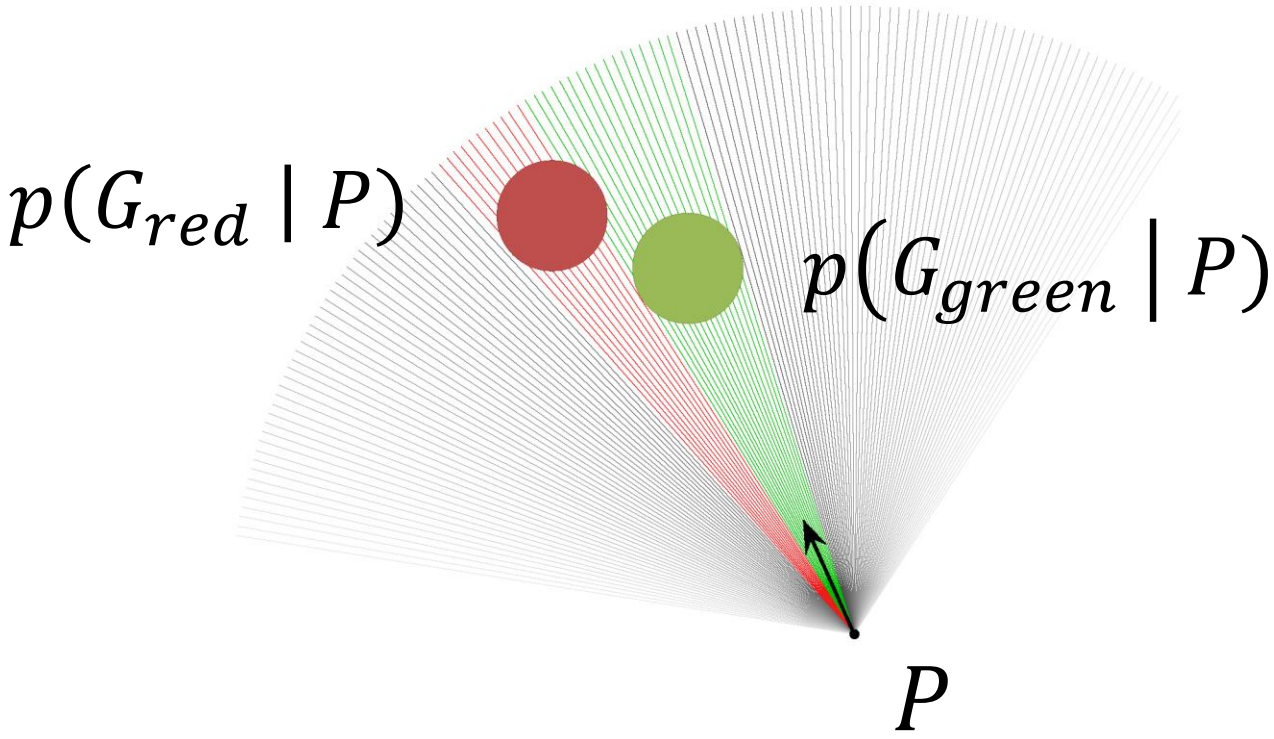


Model for Legible Pointing

$$p(P|G) \implies p(G|P)$$

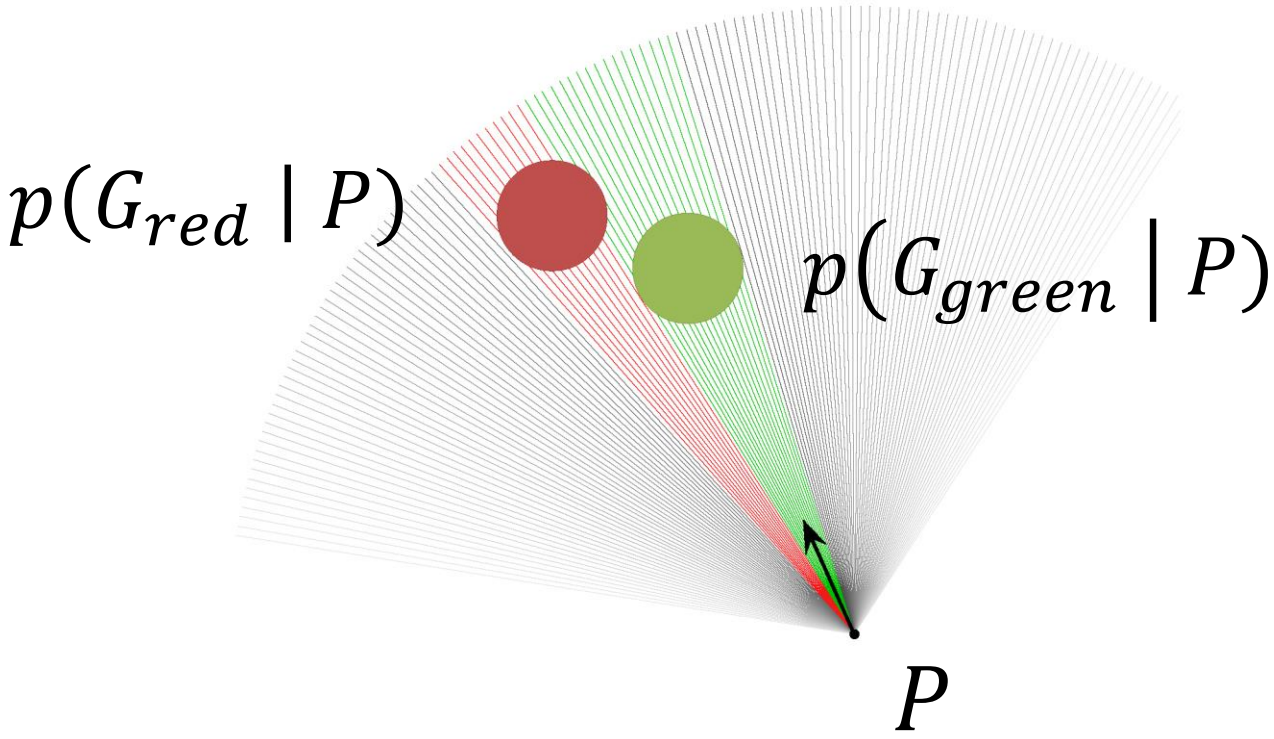


Model for Legible Pointing



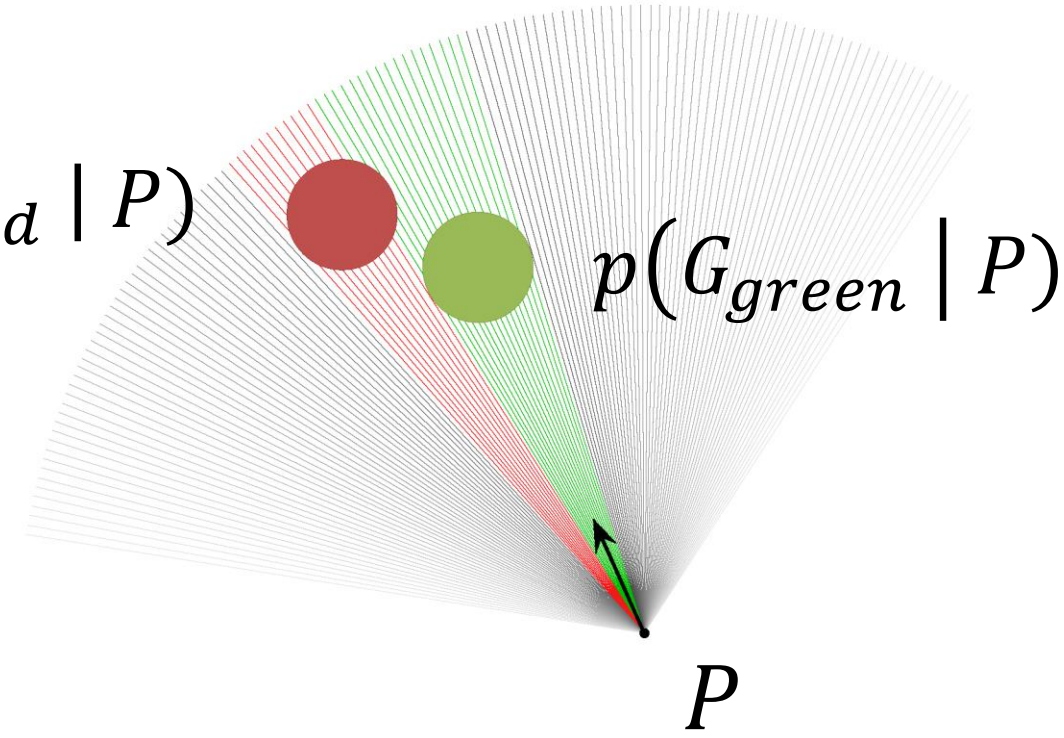
Model for Legible Pointing

$$L_G(P) = P(G|P)$$



Model for Legible Pointing

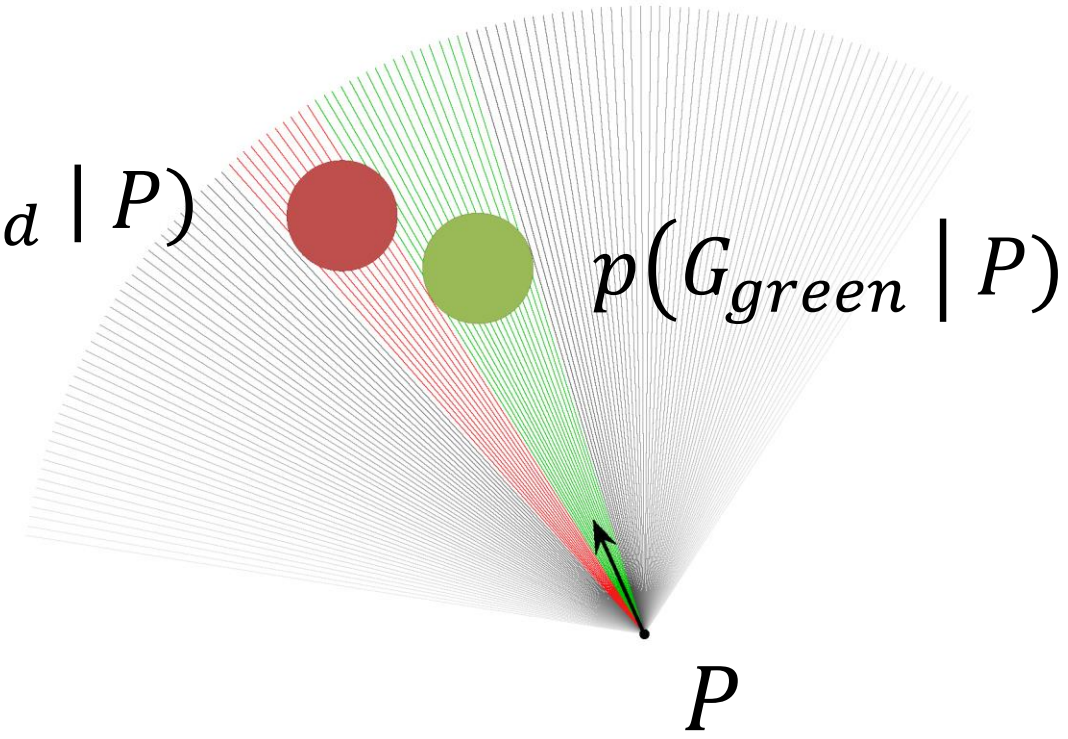
$$p^* = \max_{p \in P} L_G(p)$$



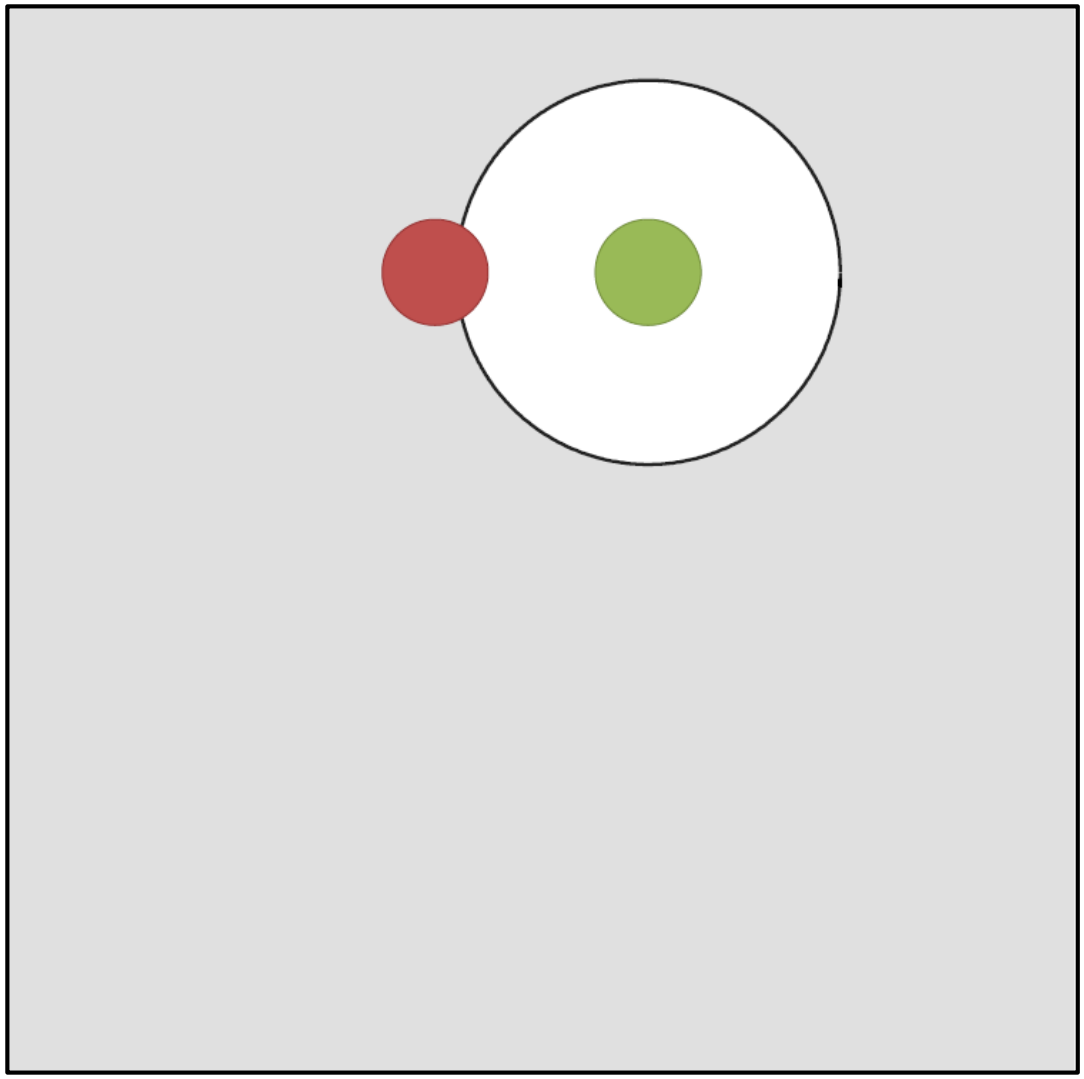
Model for Legible Pointing

$$p^* = \max_{p \in P} L_G(p)$$

$$p \leftarrow p + \alpha \nabla L_G$$



Legible Pointing :
$C_G \neq L_G$



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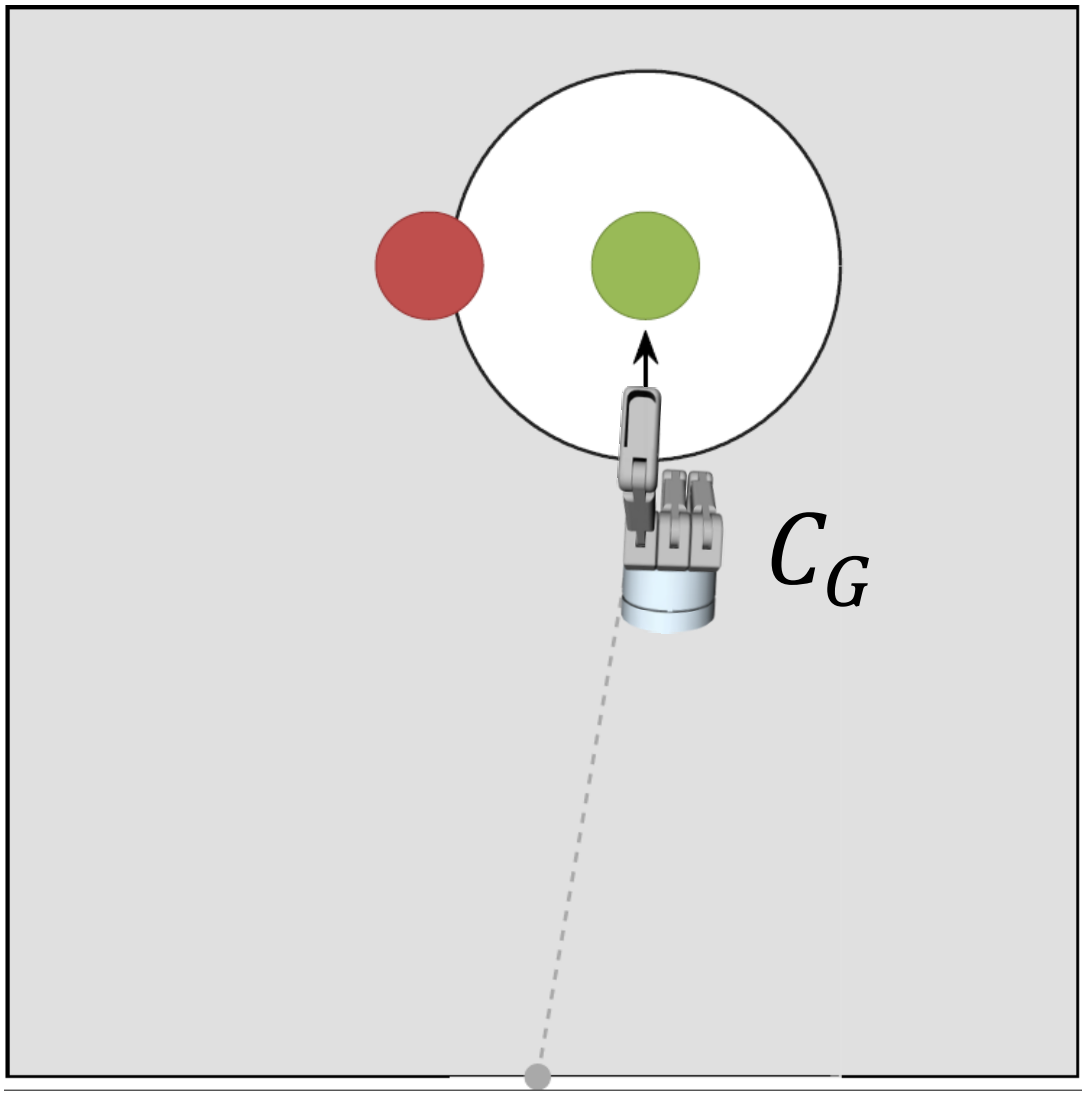

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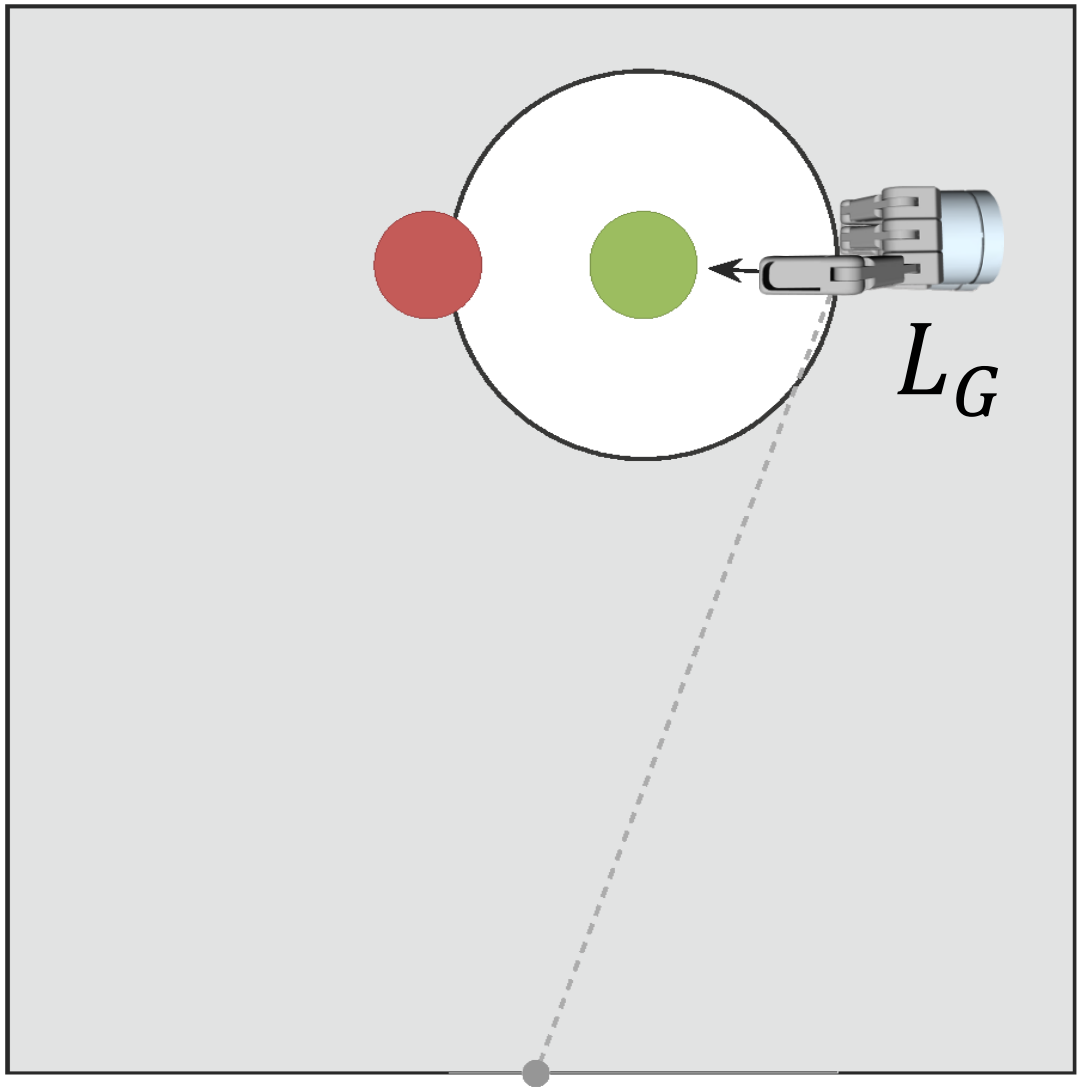

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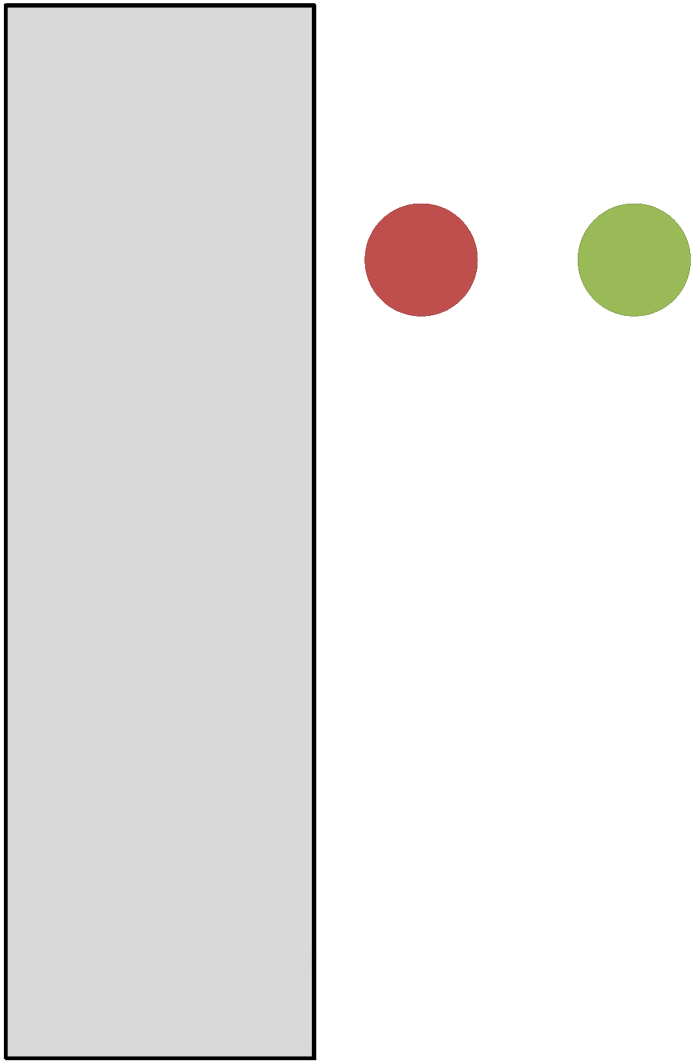

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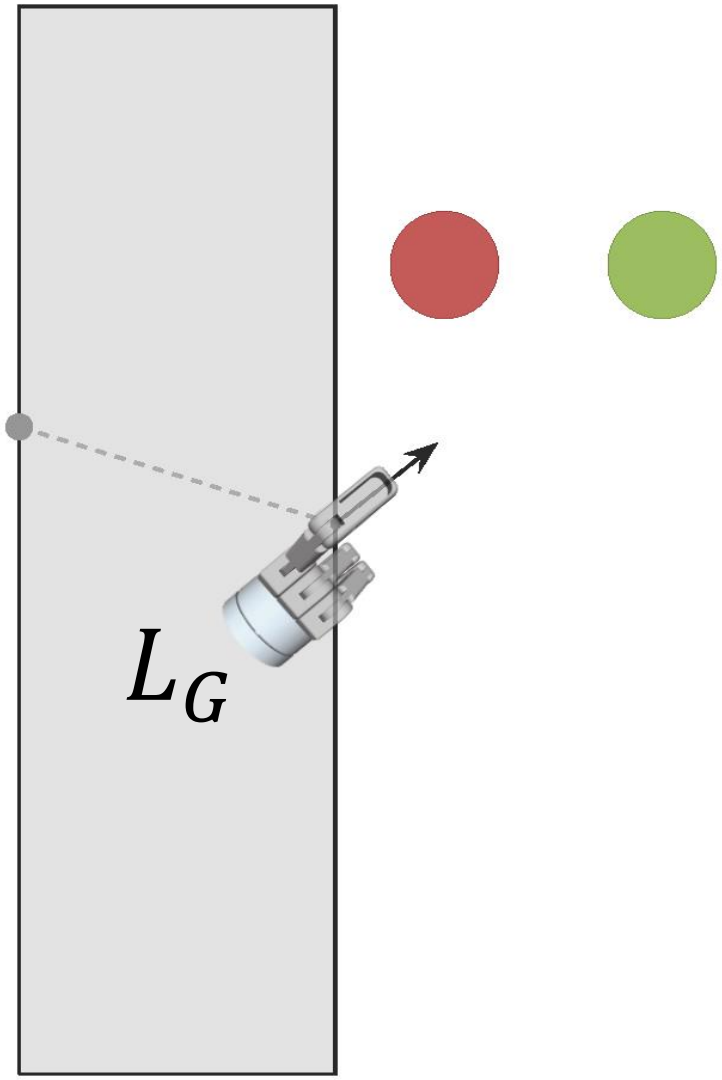

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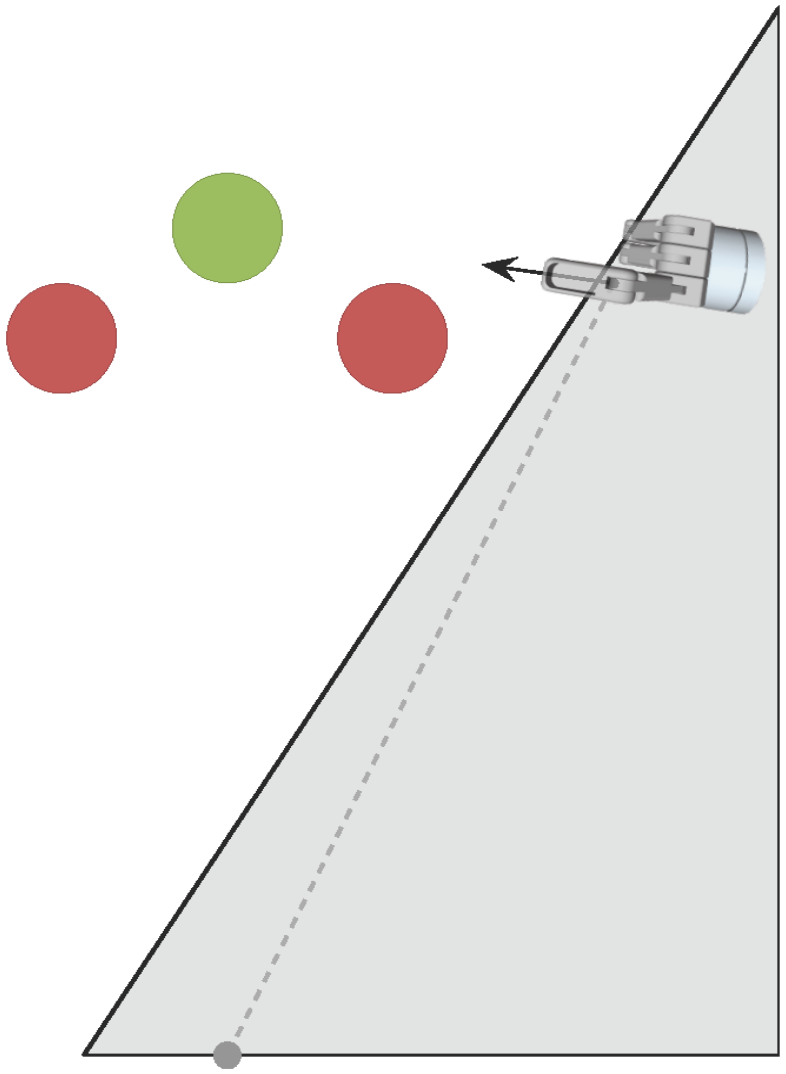

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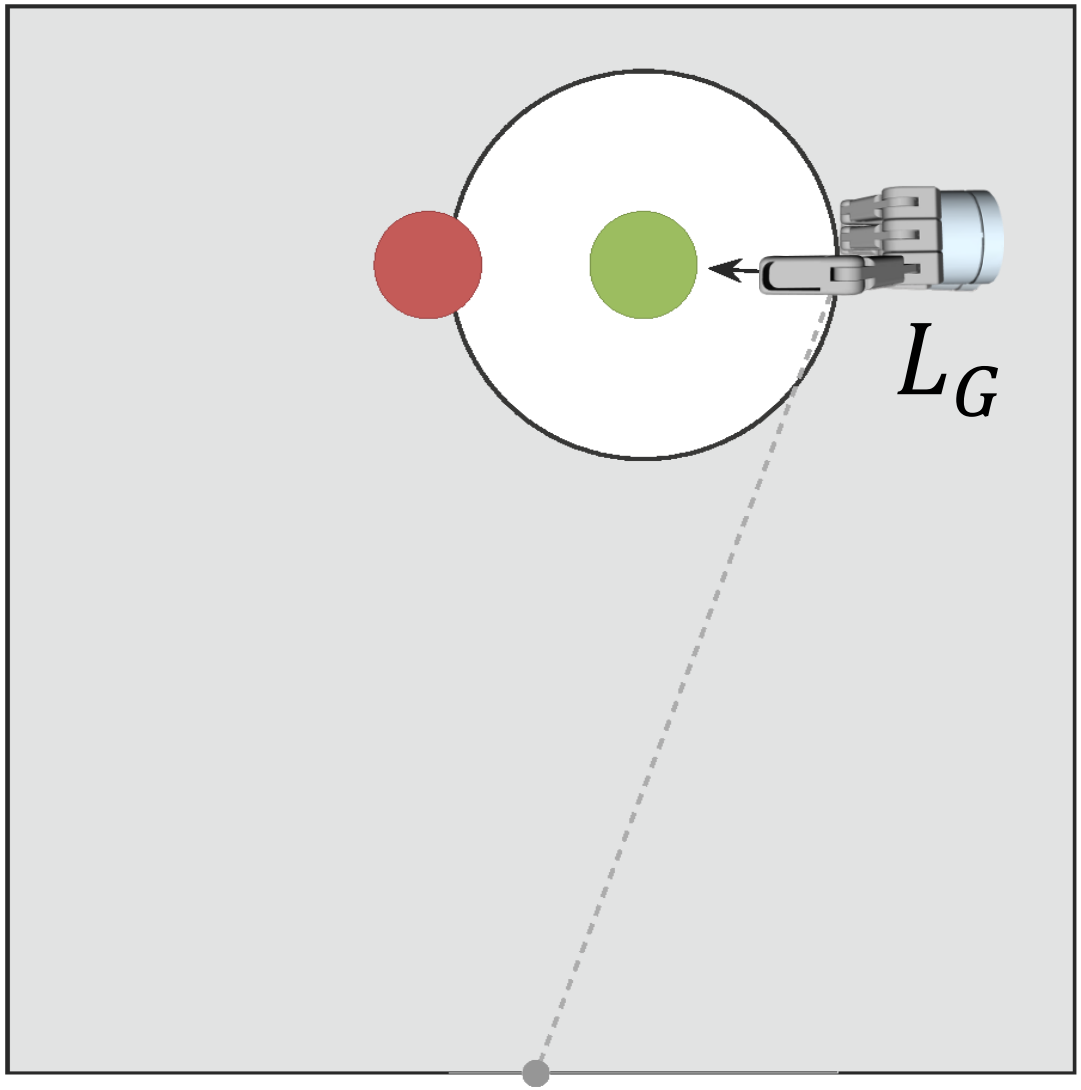
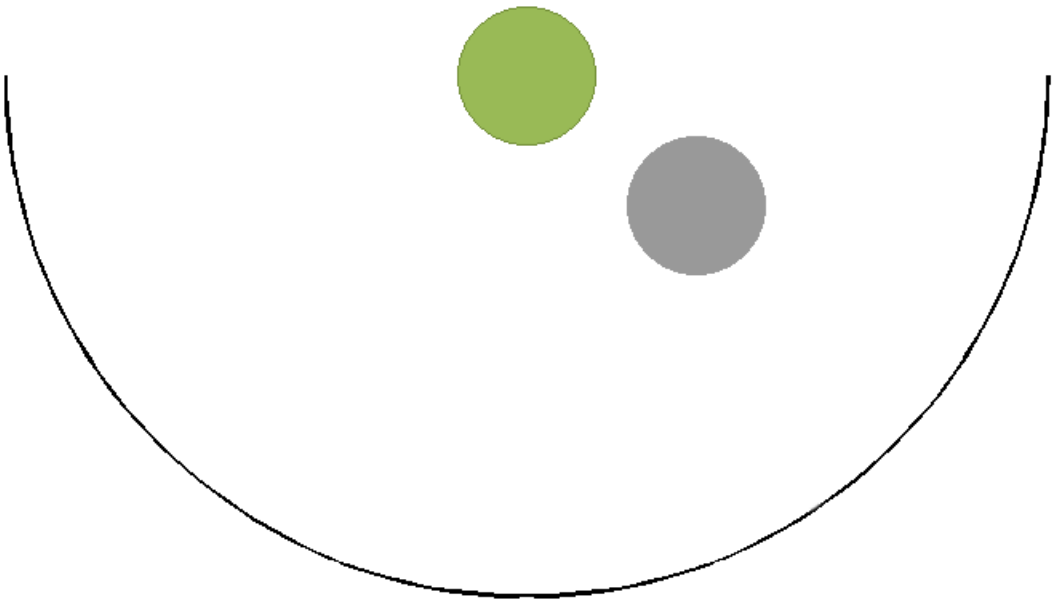
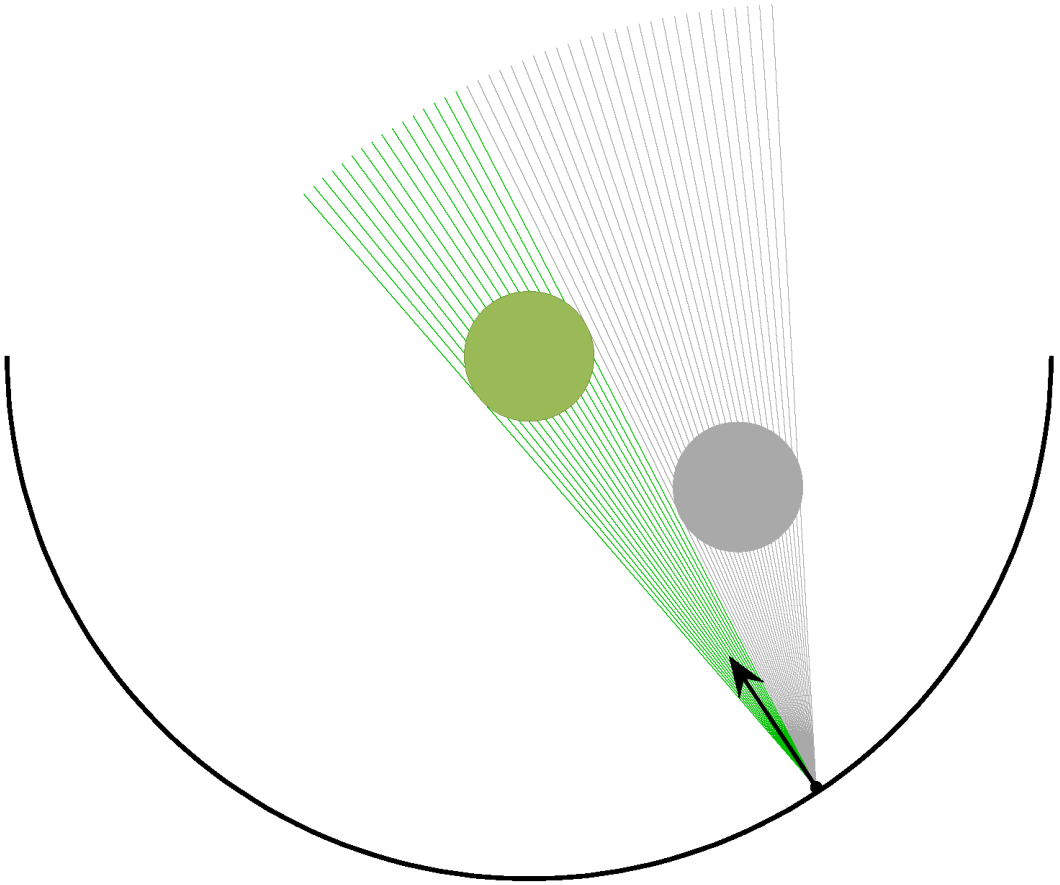


Legible Pointing :
$R_G \neq L_G$

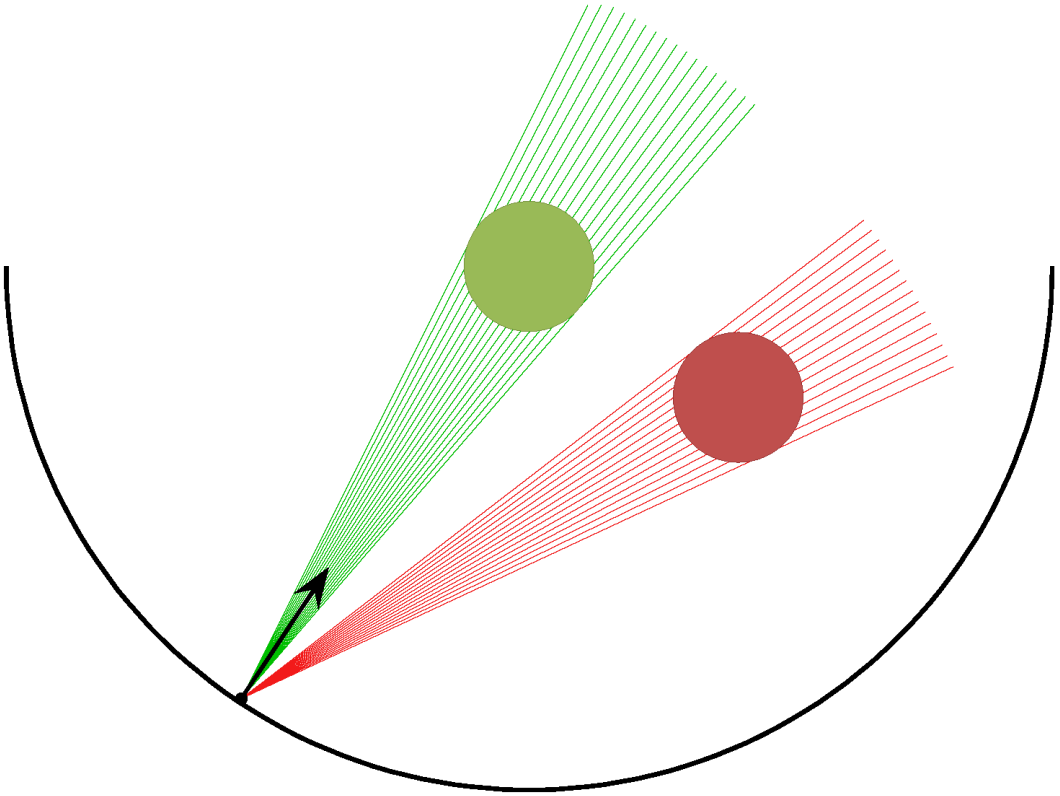
Legible Pointing :
$R_G \neq L_G$



Legible Pointing :
$R_G \neq L_G$



Legible Pointing :
$R_G \neq L_G$



Legible Pointing : Orientation

Legible Pointing : Orientation

Legible Pointing : Orientation

Exaggerate
to increase legibility

Does is work?

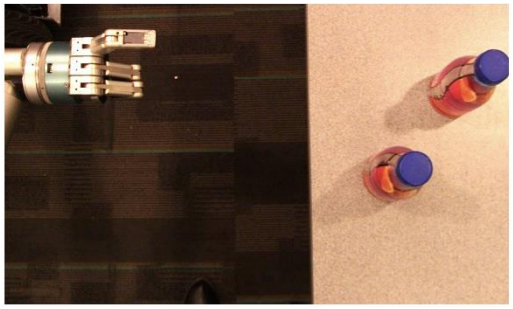
$C_G \neq L_G$

[Position]

Follow-Up #1:

$R_G \neq L_G$

[Position]



Follow-Up #2:

$C_G \neq L_G$

[Orientation]

Does is work?

$C_G \neq L_G$

[Position]

Follow-Up #1:

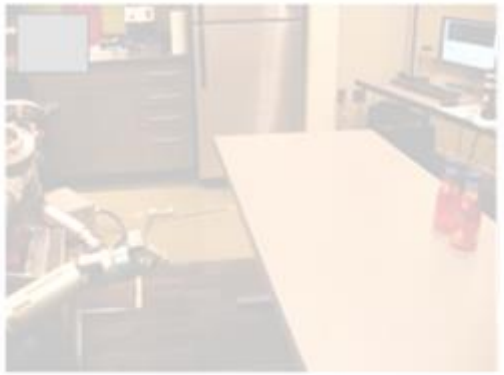
$R_G \neq L_G$

[Position]

Follow-Up #2:

$C_G \neq L_G$

[Orientation]



Theoretical L_G affects legibility in practice.

Measuring Legibility

Objective Measure: accuracy

○ Left ○ Right

Subjective Measure: rating

confidence

○ ○ ○ ○ ○ ○ ○

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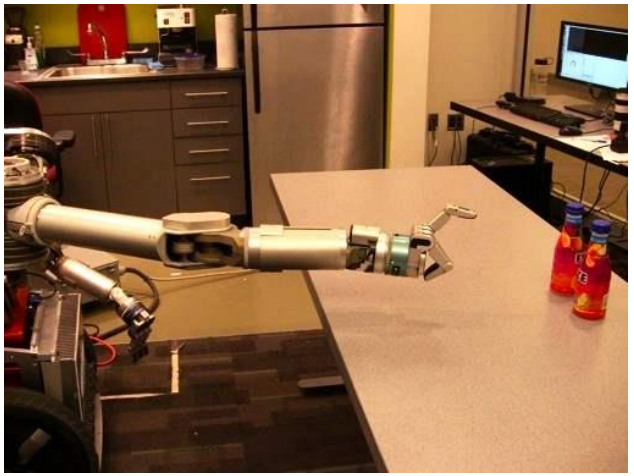


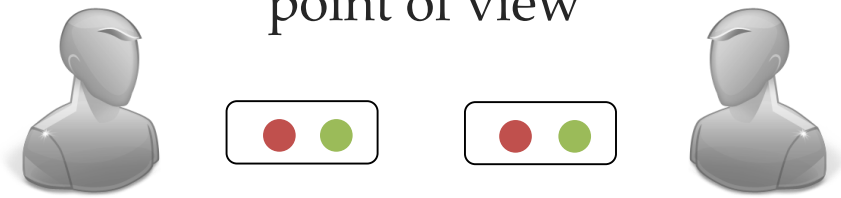
Between-Subjects Study (N=80)

Manipulate:

model

C_G L_G

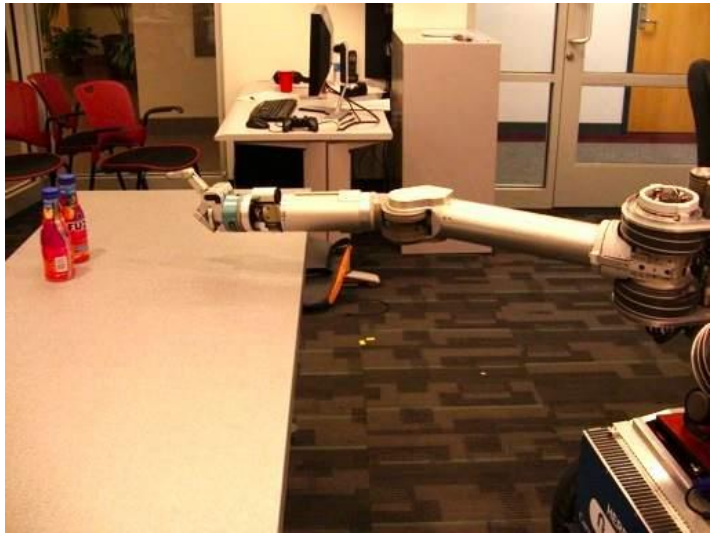
point of view

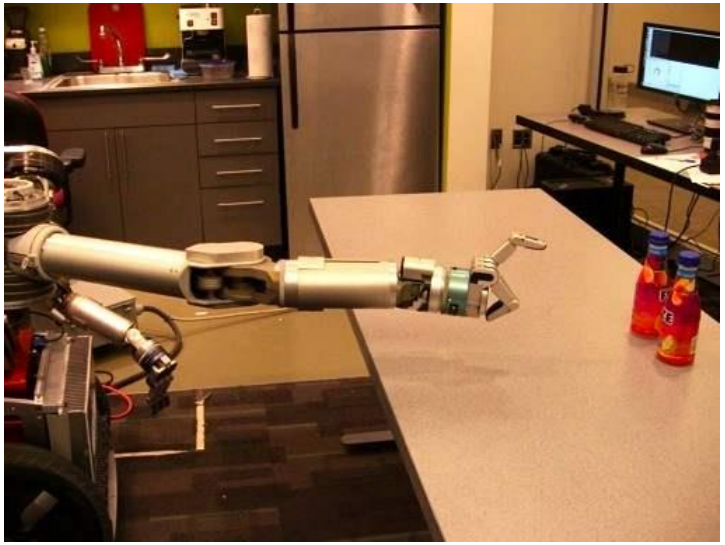


Measure:

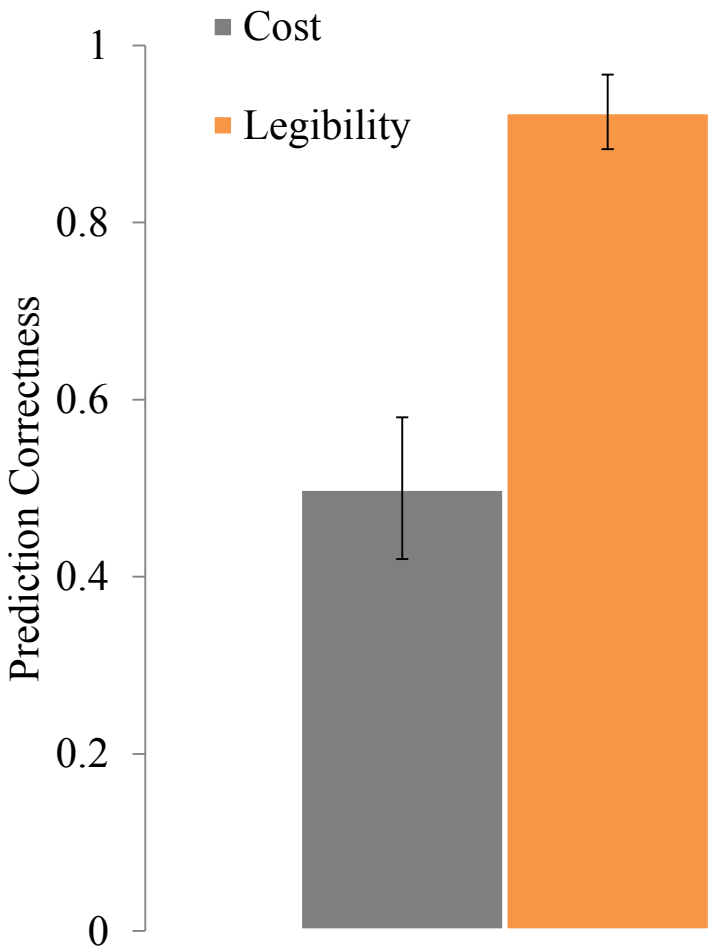
legibility: (accuracy + confidence)

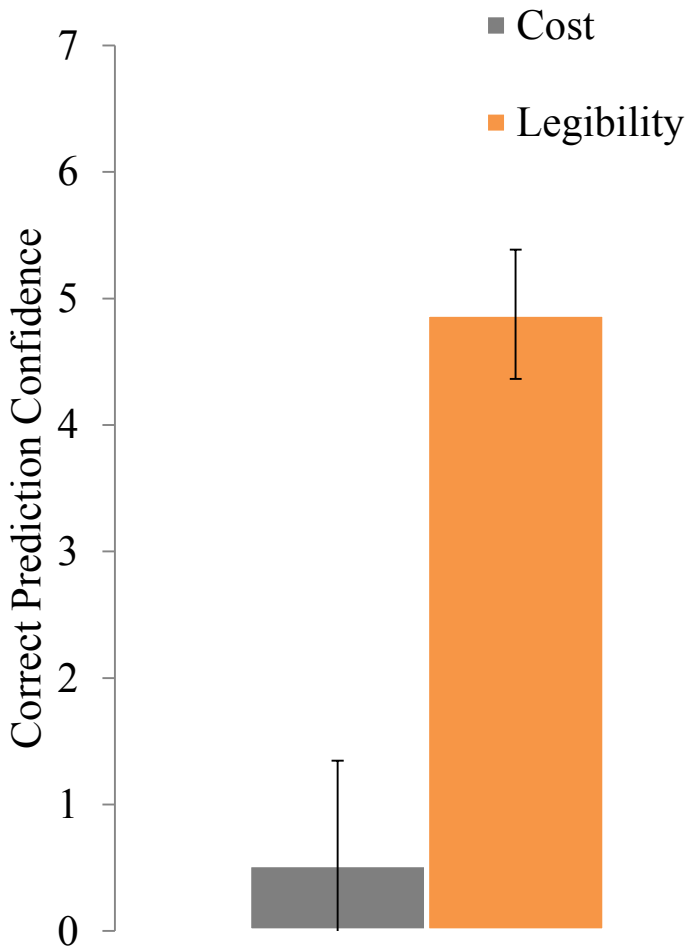
Between-Subjects Study (*N*=80)





Between-Subjects Study (*N*=80)

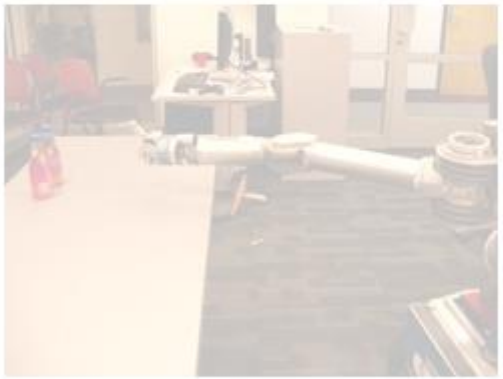




Does is work?

$C_G \neq L_G$

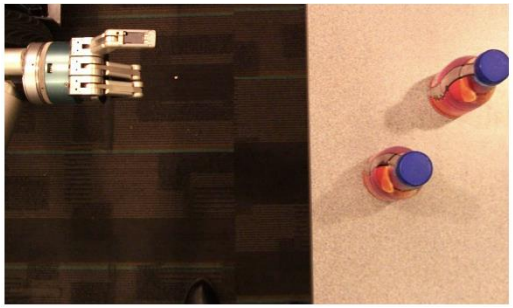
[Position]



Follow-Up #1:

$R_G \neq L_G$

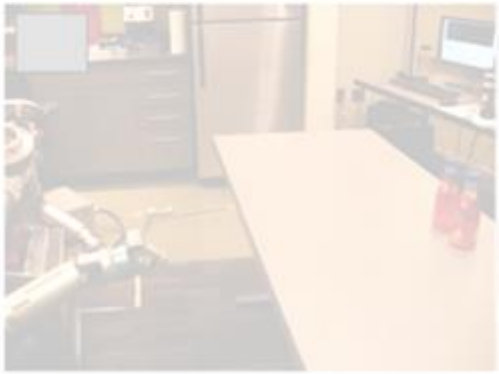
[Position]



Follow-Up #2:

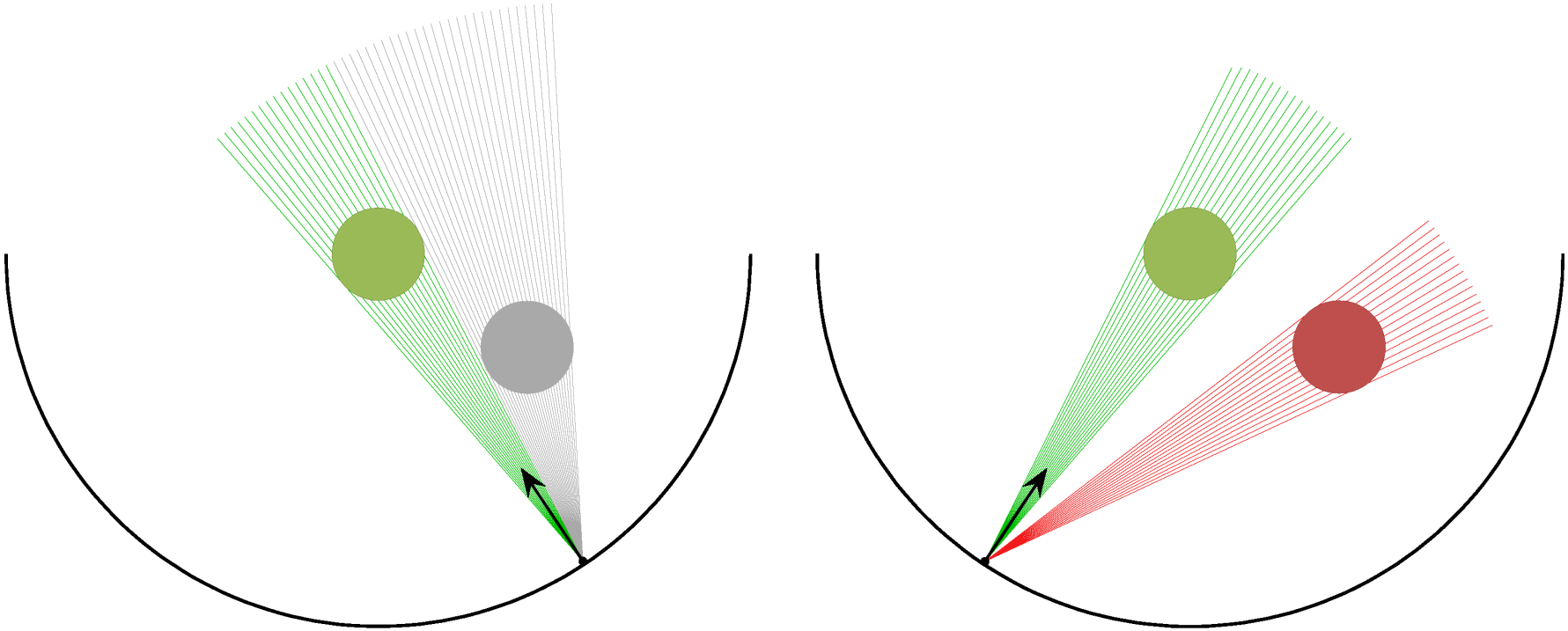
$C_G \neq L_G$

[Orientation]

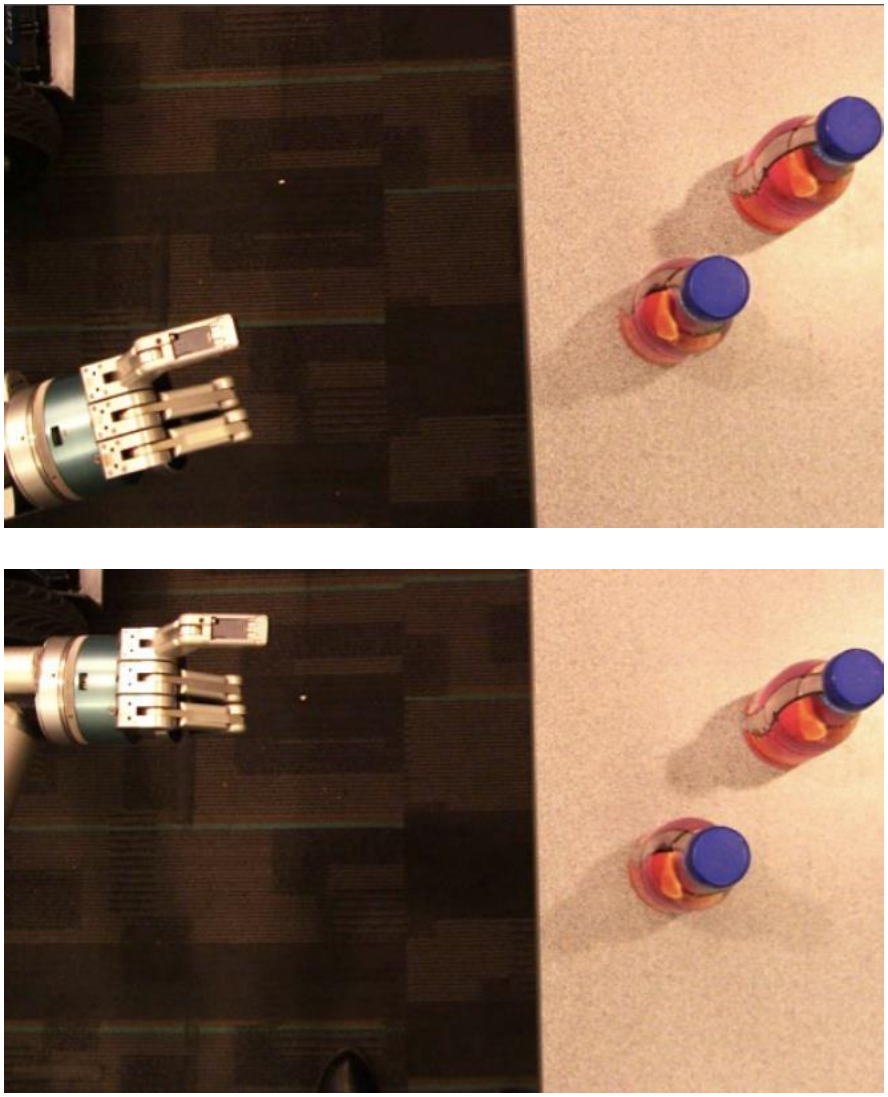


The ray model alone does not produce legible pointing.

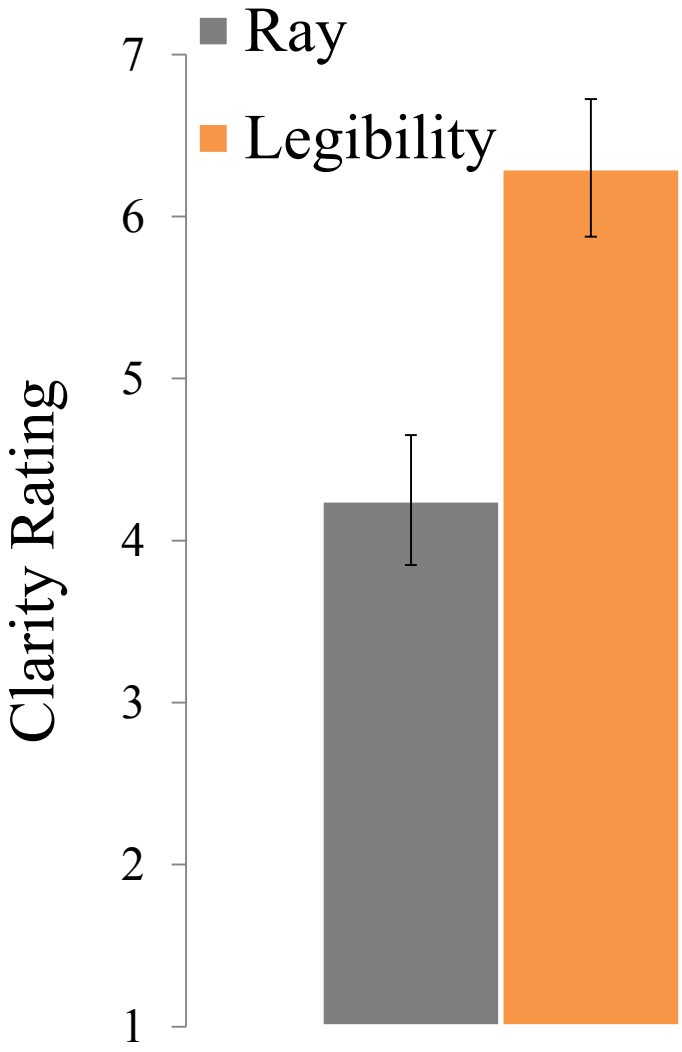
Legible Pointing :
Difference from the Ray Model



Within-Subjects Study *(N=20)*



Within-Subjects Study *(N=20)*

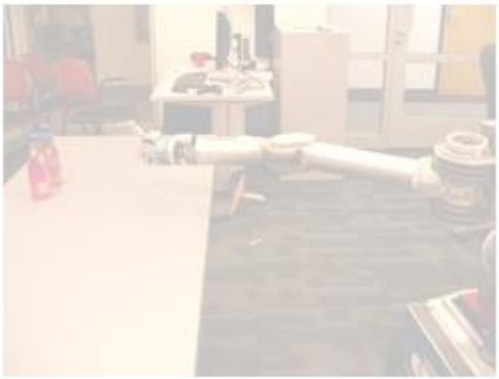


The ray model alone is <u>not sufficient</u> for legibility.

Does is work?

$C_G \neq L_G$

[Position]



Follow-Up #1:

$R_G \neq L_G$

[Position]

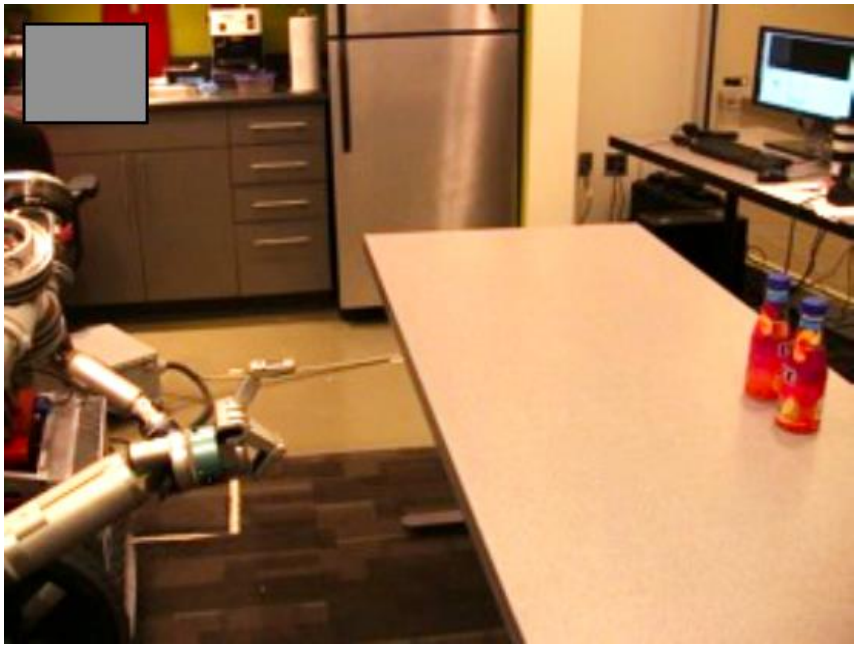
Follow-Up #2:

$C_G \neq L_G$

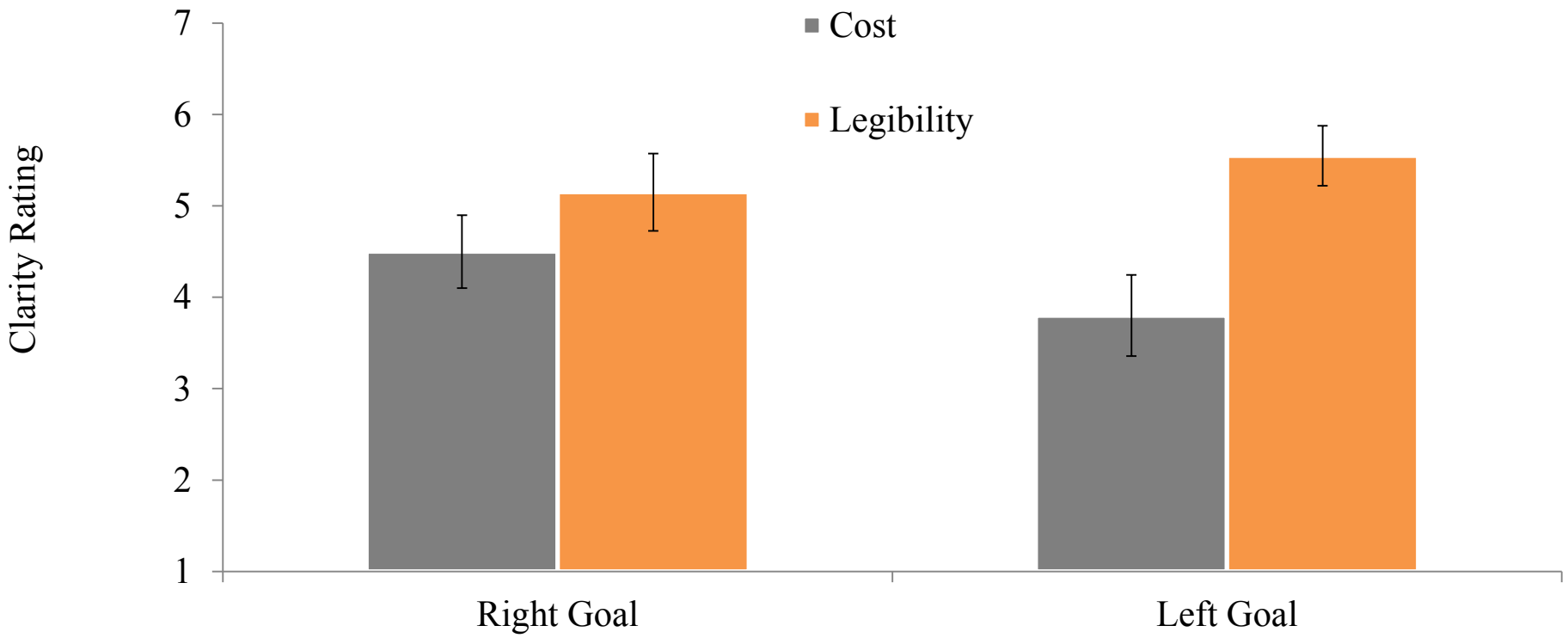
[Orientation]

Angle exaggeration increases legibility.

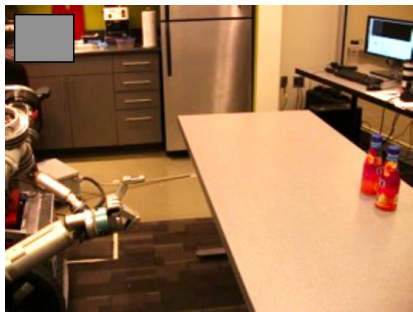
Within-Subjects Study *(N=20)*



Within-Subjects Study (*N*=20)



Exaggeration increases legibility



Creating a Legible Pointer

Does is work?

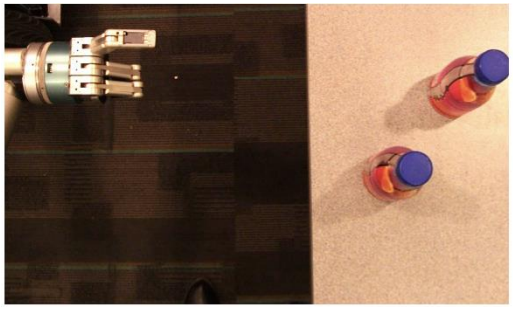
$C_G \neq L_G$

[Position]

Follow-Up #1:

$R_G \neq L_G$

[Position]



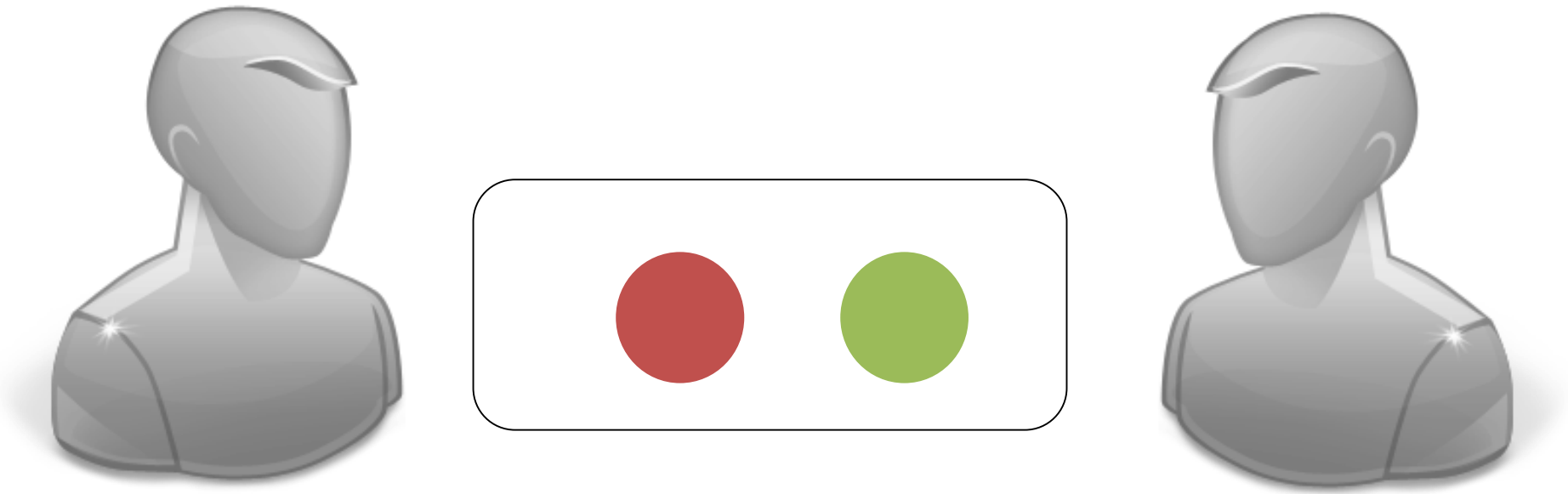
Follow-Up #2:

$C_G \neq L_G$

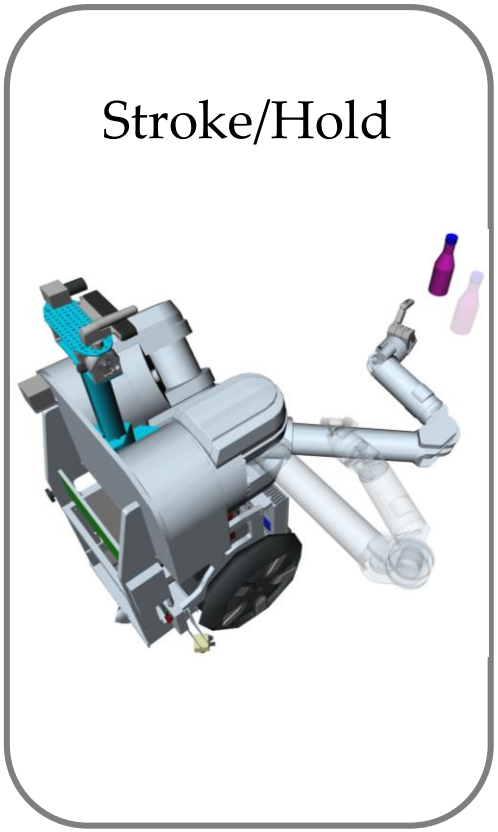
[Orientation]

What's next?

Point of View

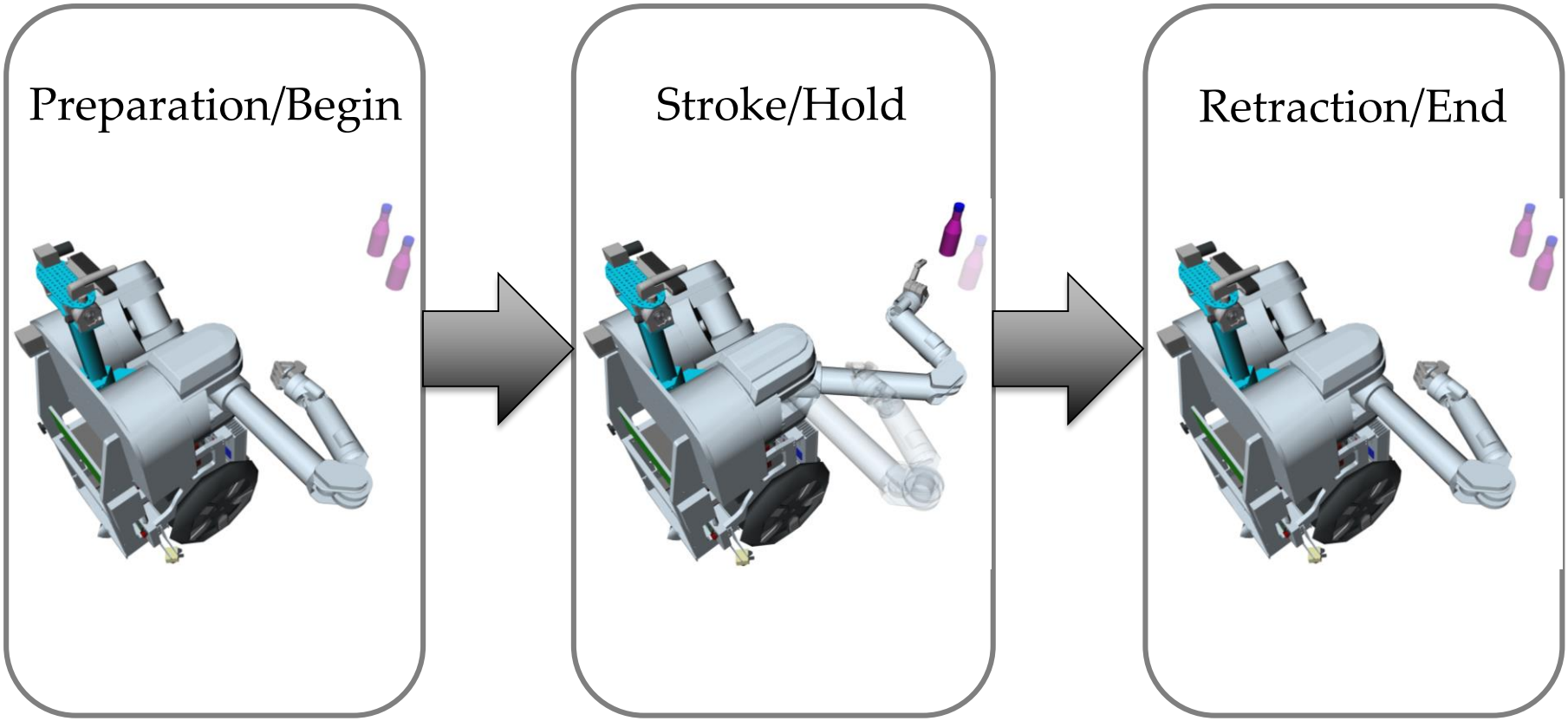


Gesture Sequence



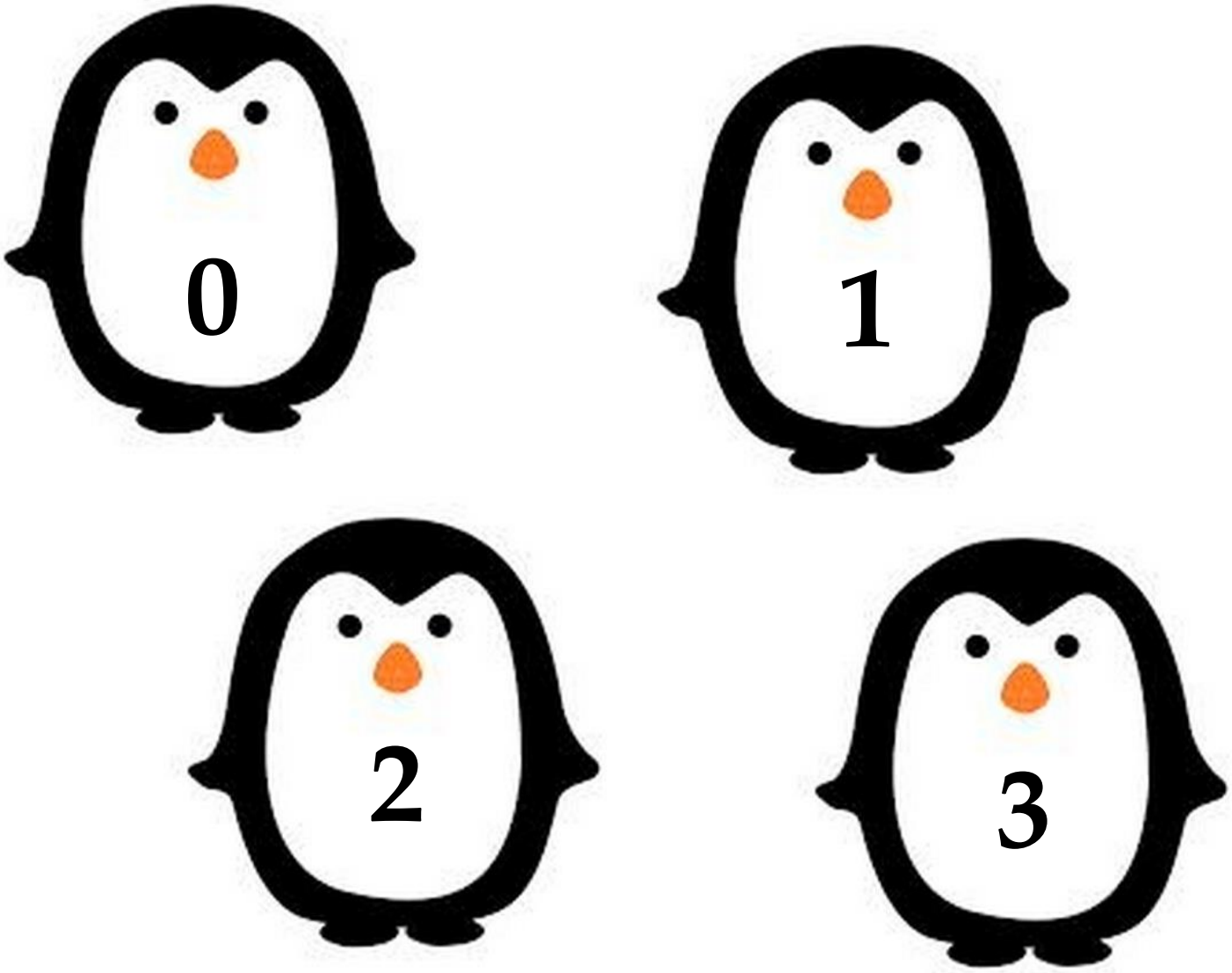
[Rick, et al 2010] / [Stiefelhagen 2004]

Gesture Sequence

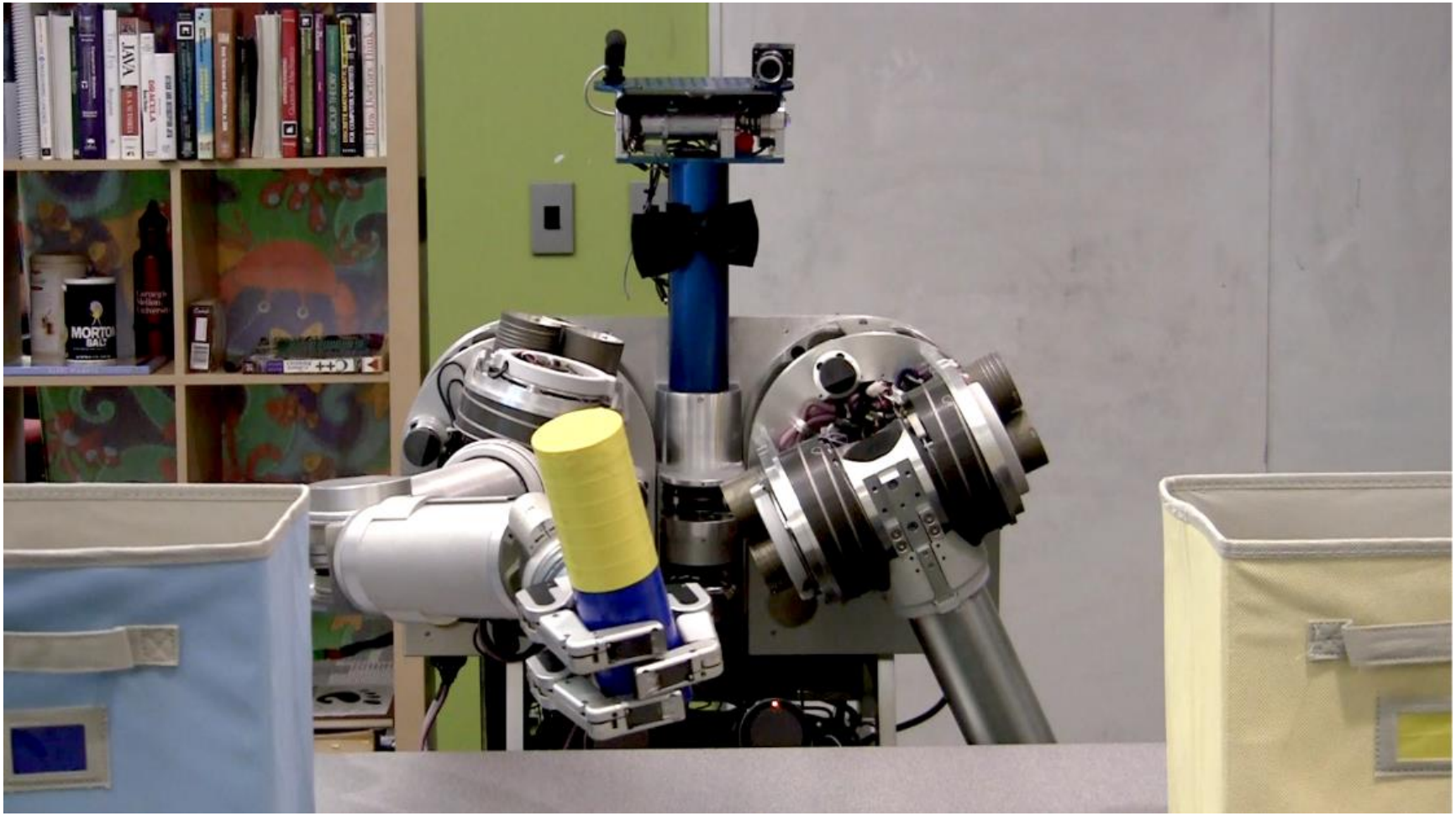


[Rick, et al 2010] / [Stiefelhagen 2004]

Multi-Object Planning

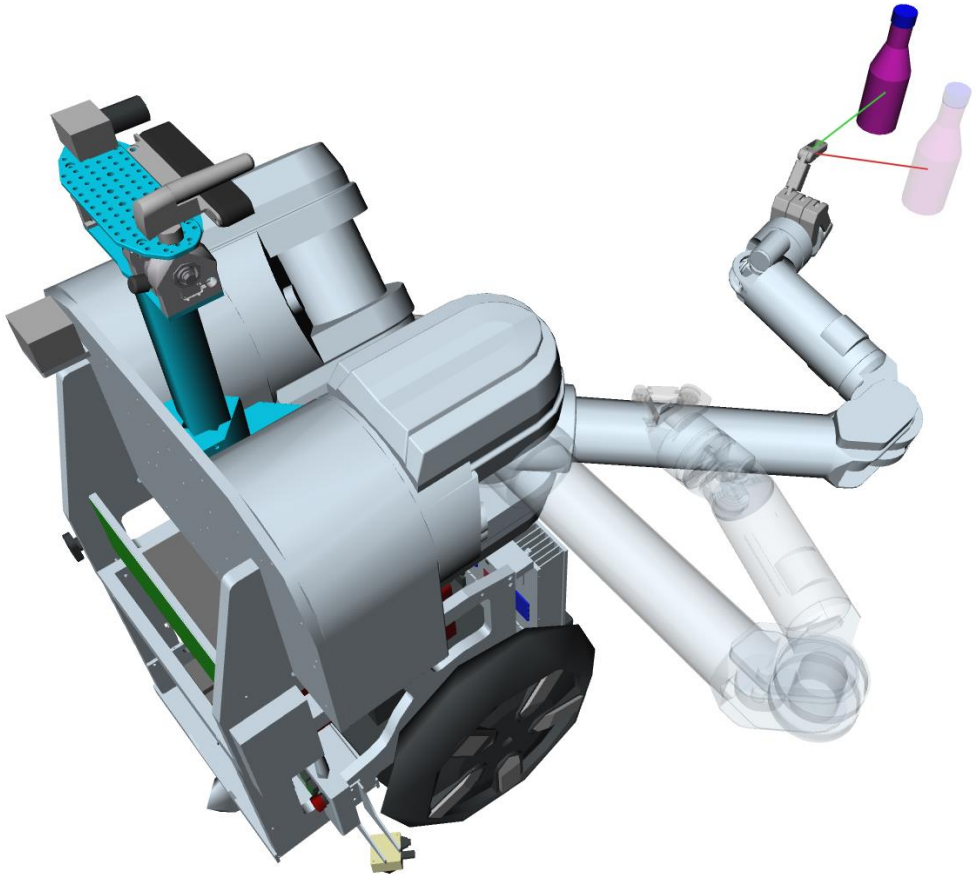


Gaze



[Admoni 2014]

Key Insight: Pointing is not just about pointing to the correct object, but also about NOT pointing at the other objects.



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Legible Robot Pointing

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