# Formalizing Teamwork in Human-Robot Interaction

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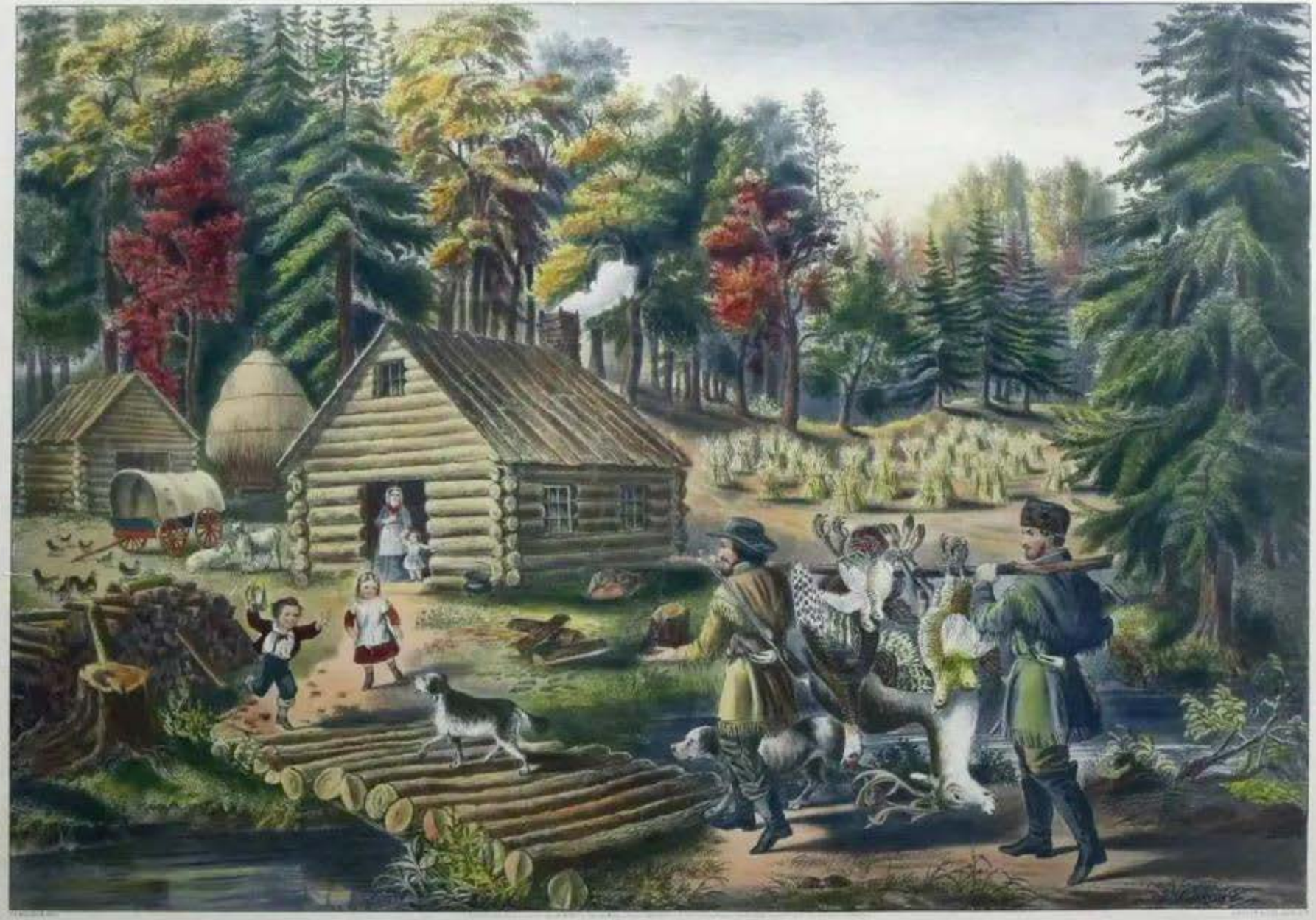
Cornell University

John Gash
*American Progress*




Currier and Ives
*The Pioneer's Home*


Currier and Ives
*Across the Continent*

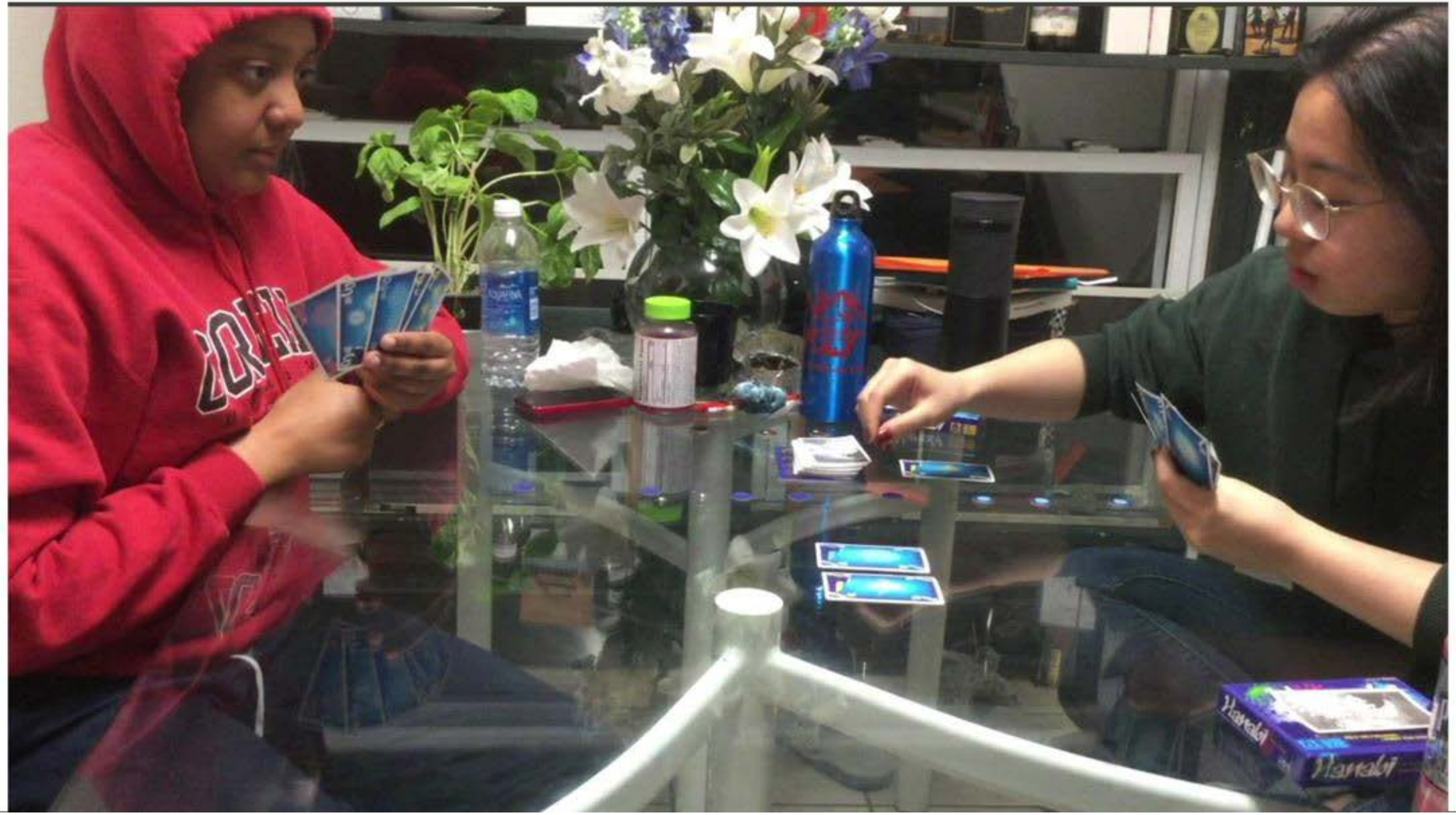

British North America
Washington
1889
Astoria
Portland
Fort Vancouver
Oregon
1859
Idaho
1890
Montana
1889
North Dakota
1889
Minnesota
1858
South Dakota
1889
Wyoming
1840
Wounded Knee 1890
Nebraska
1867
Iowa
1846
Omaha
Ogallala
Fort Bridger
Salt Lake City
Nevada
1864
San Francisco
California
1850
Utah Territory
Colorado
1876
Kansas
Abilene
Kansas City
Independence
Nauvoo
Tipton
Missouri
1821
Fort Atkinson
Dodge City
Los Angeles
Taos
Santa Fe
Indian Territory
Arizona Territory
New Mexico Territory
San Diego
Arkansas
1836
U N I T E D S T A T E S
Texas
1845
1861 seceded
1870 readmitted
El Paso
Louisiana
1812
San Antonio
M E X I C O
Gulf of Mexico
1 Central Pacific RR–Union Pacific RR, 1869
2 Northern Pacific RR,1883
3 Atchison, Topeka, and Santa Fe RR, 1883
4 Southern Pacific RR, 1883
5 Great Northern RR, 1893
Closing the Frontier 1890
European settlement, by 1890
Date of statehood, to 1890
Western railroad constructed, 1869–97
Railroad land grant
Indian Reservation, by 1930
Area of Ghost Dance religion
Indian battle
0 200 km
0 200 miles

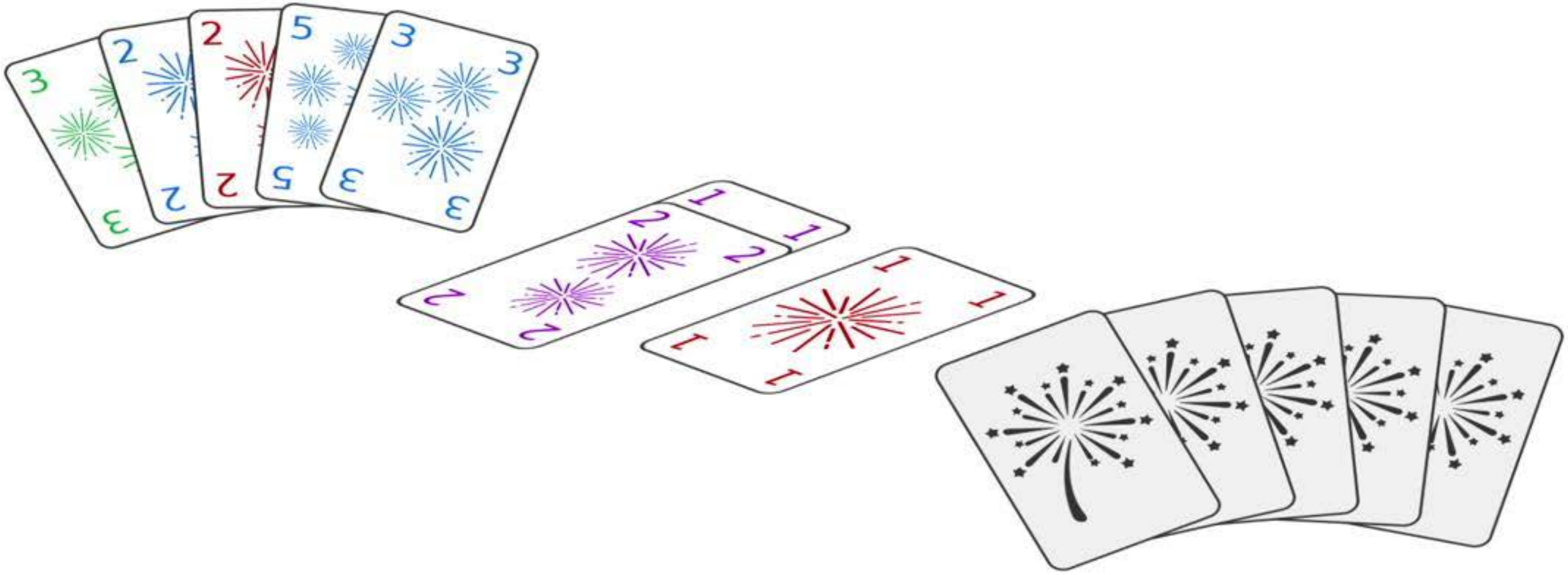
# Closing the Frontier

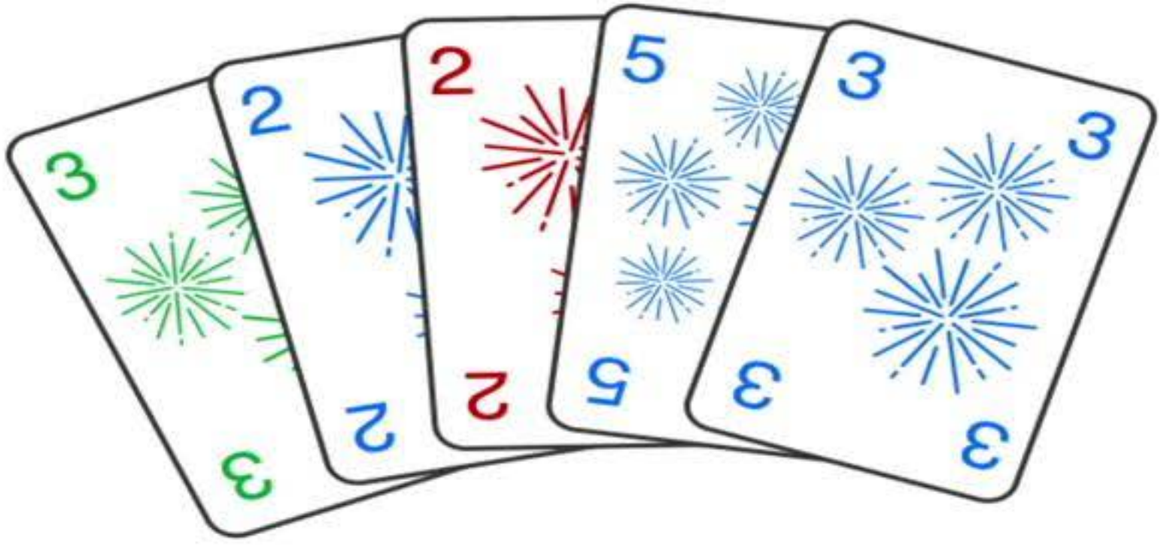
- Fewer, larger problems
- More replication of results
- More scientific, less engineering outlook
- More standardized metrics and benchmarks
  - without being beholden to them

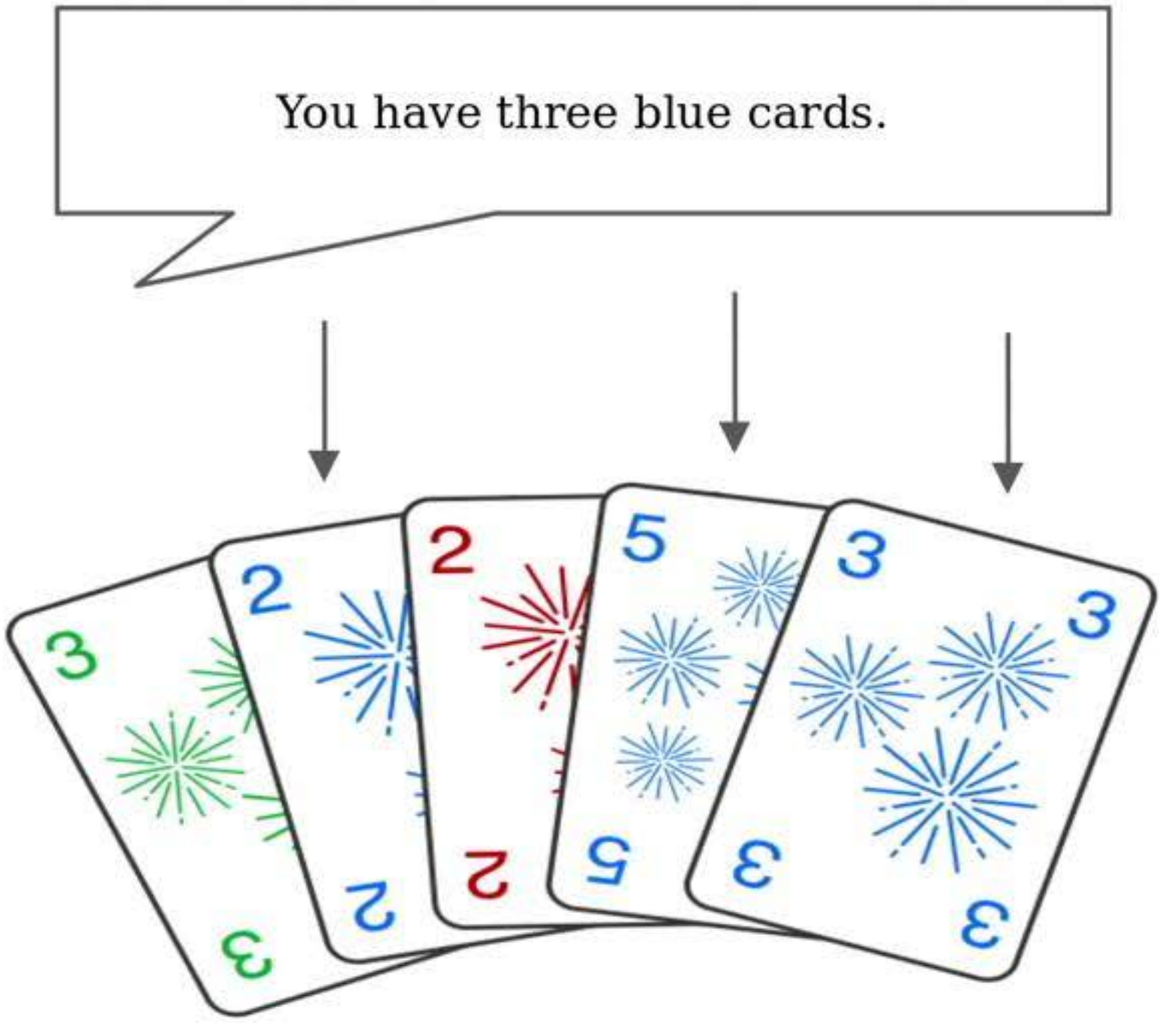
# Waymo Finds Merging Hard

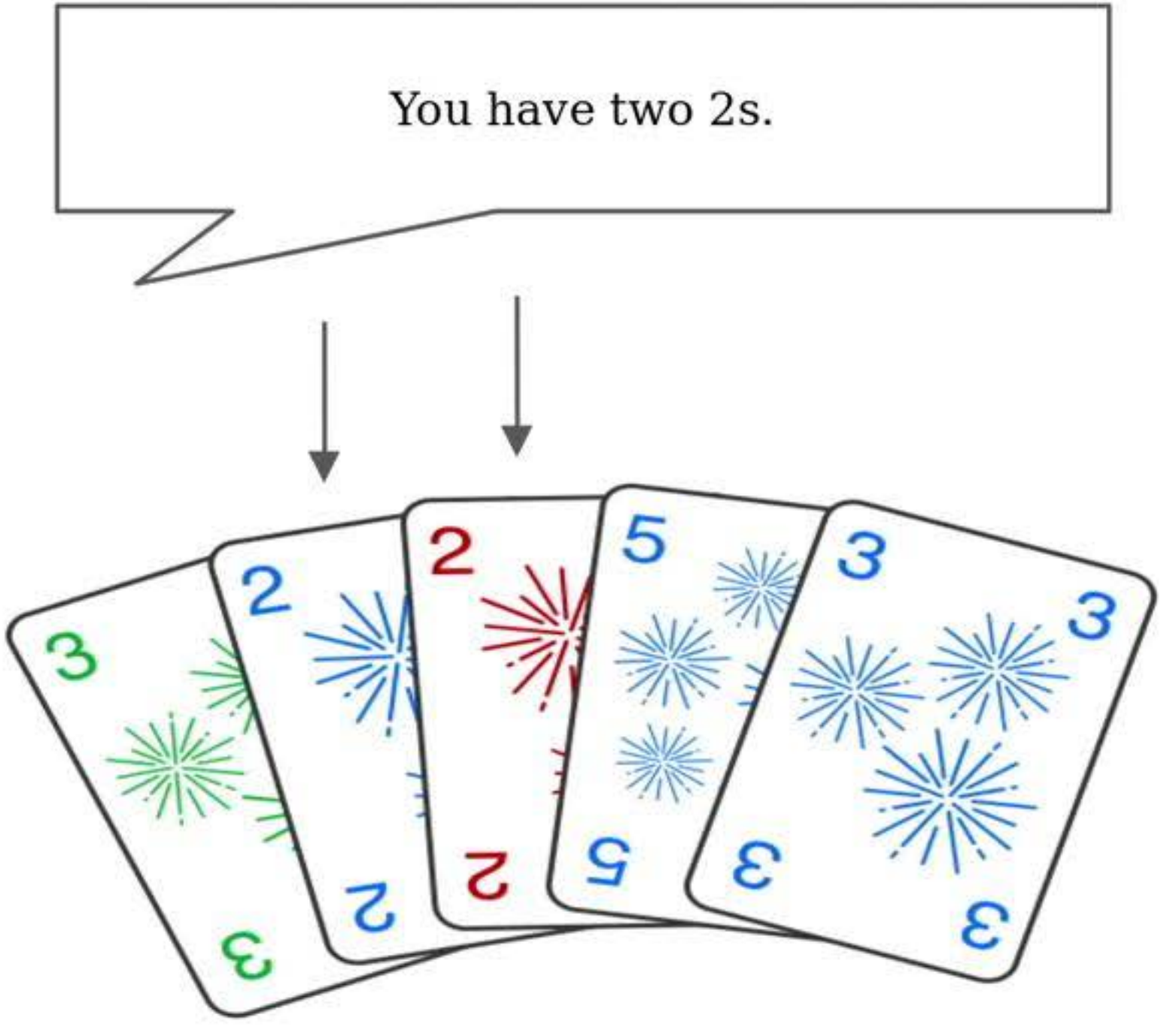
# DeepMind Finds “Hanabi” Hard

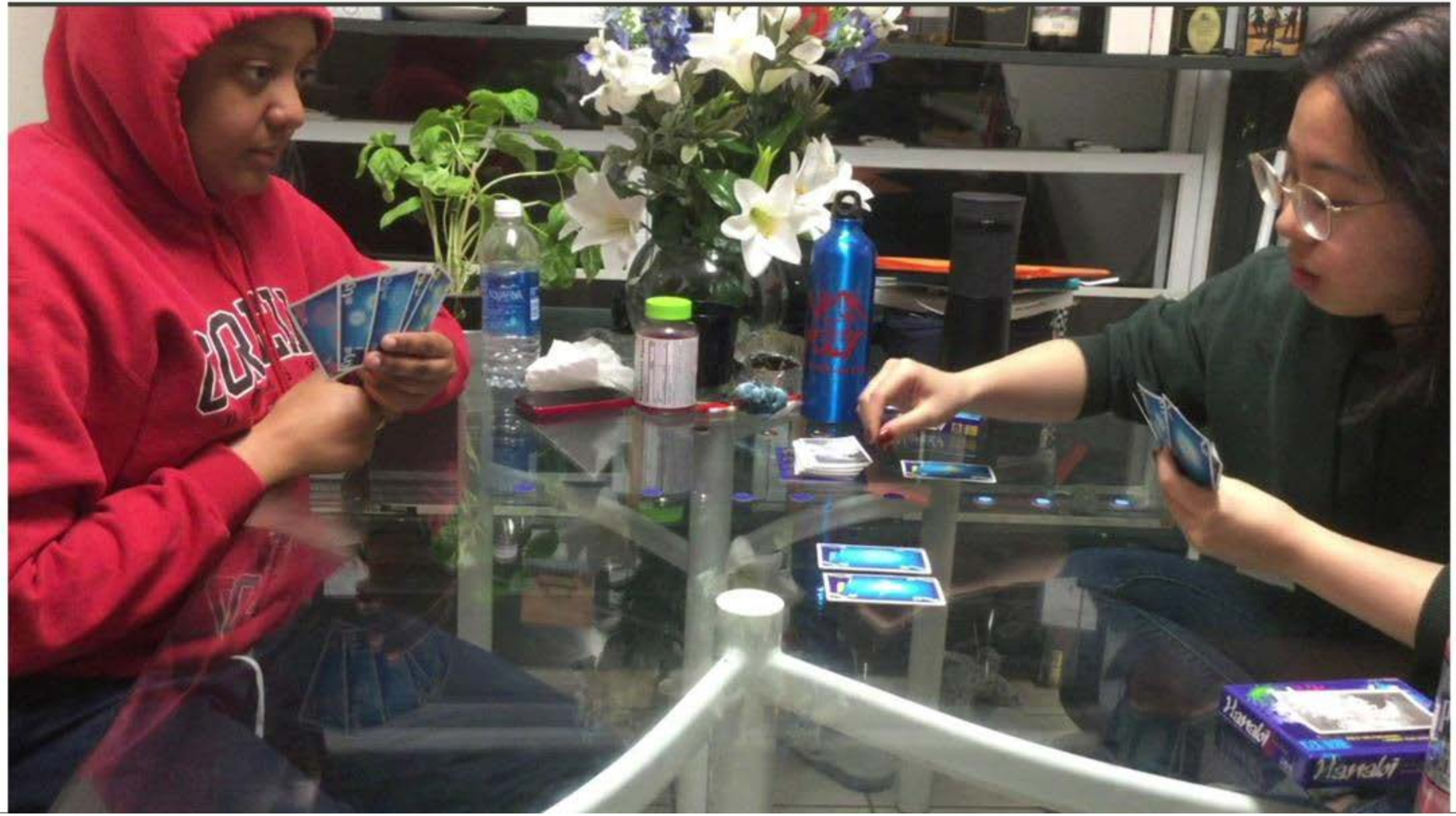




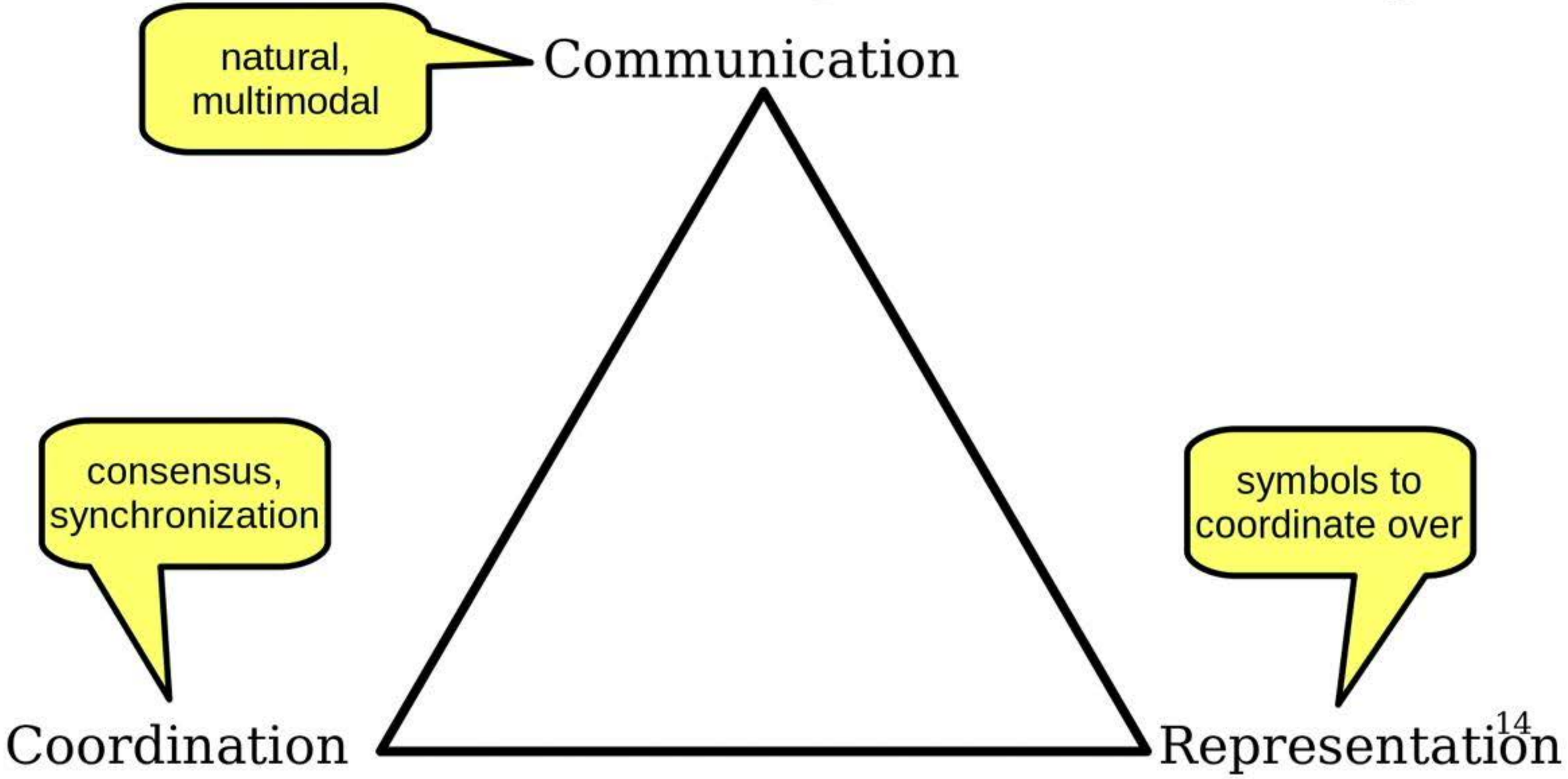

3
2
2
5
3


You have three blue cards.
3
2
2
5
3


You have two 2s.
3
2
2
5
3


Marvel
Marvel

# Teamwork in a Joint Activity



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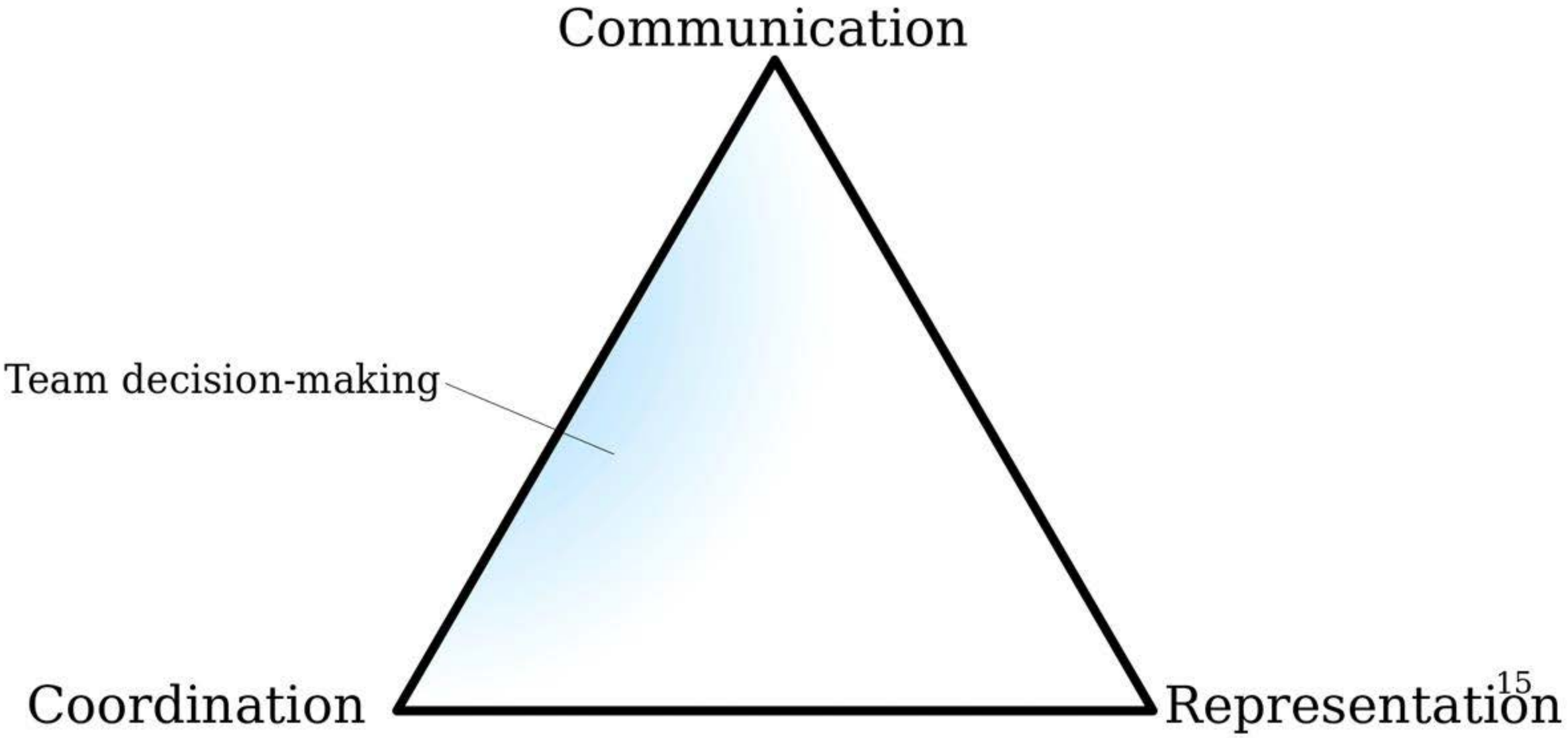

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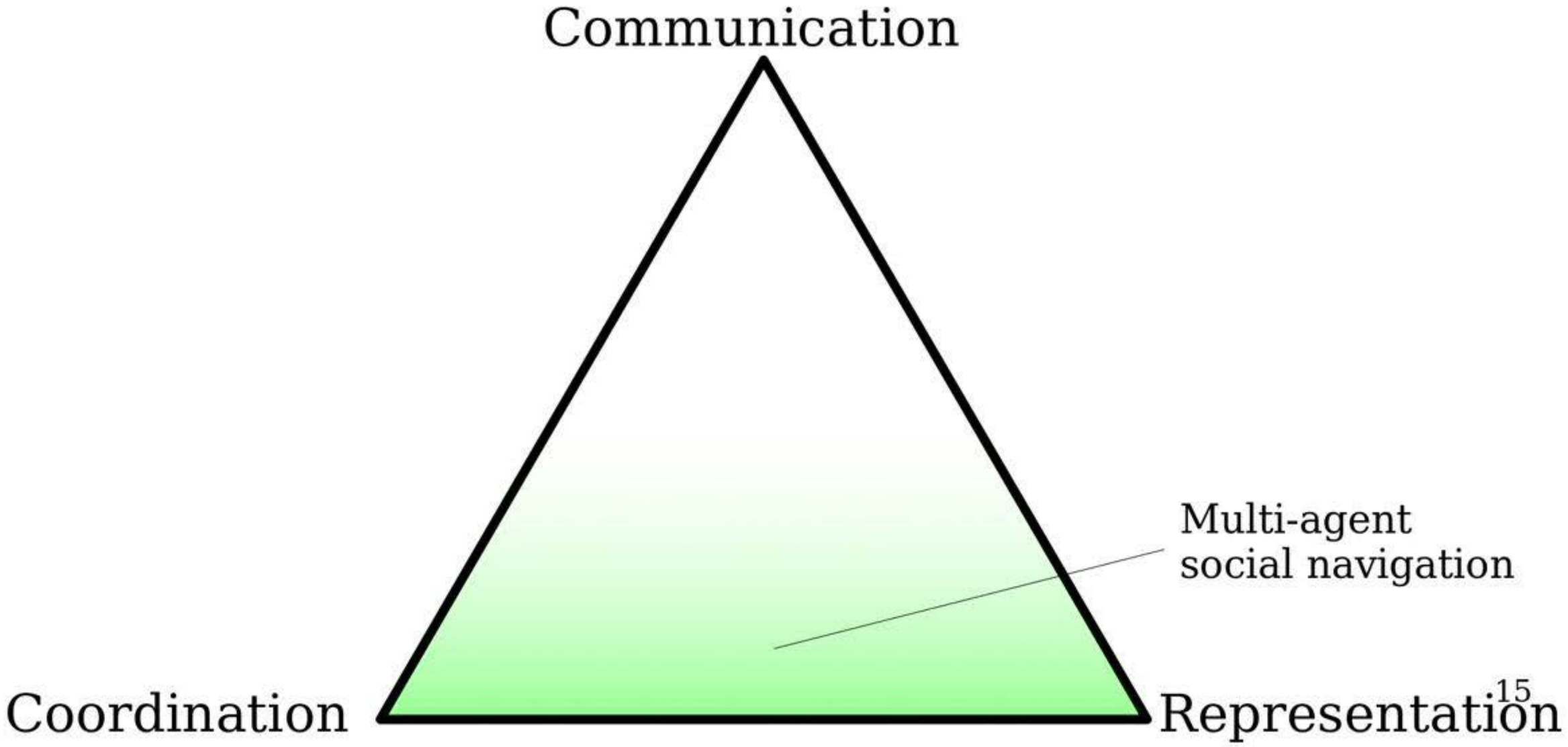

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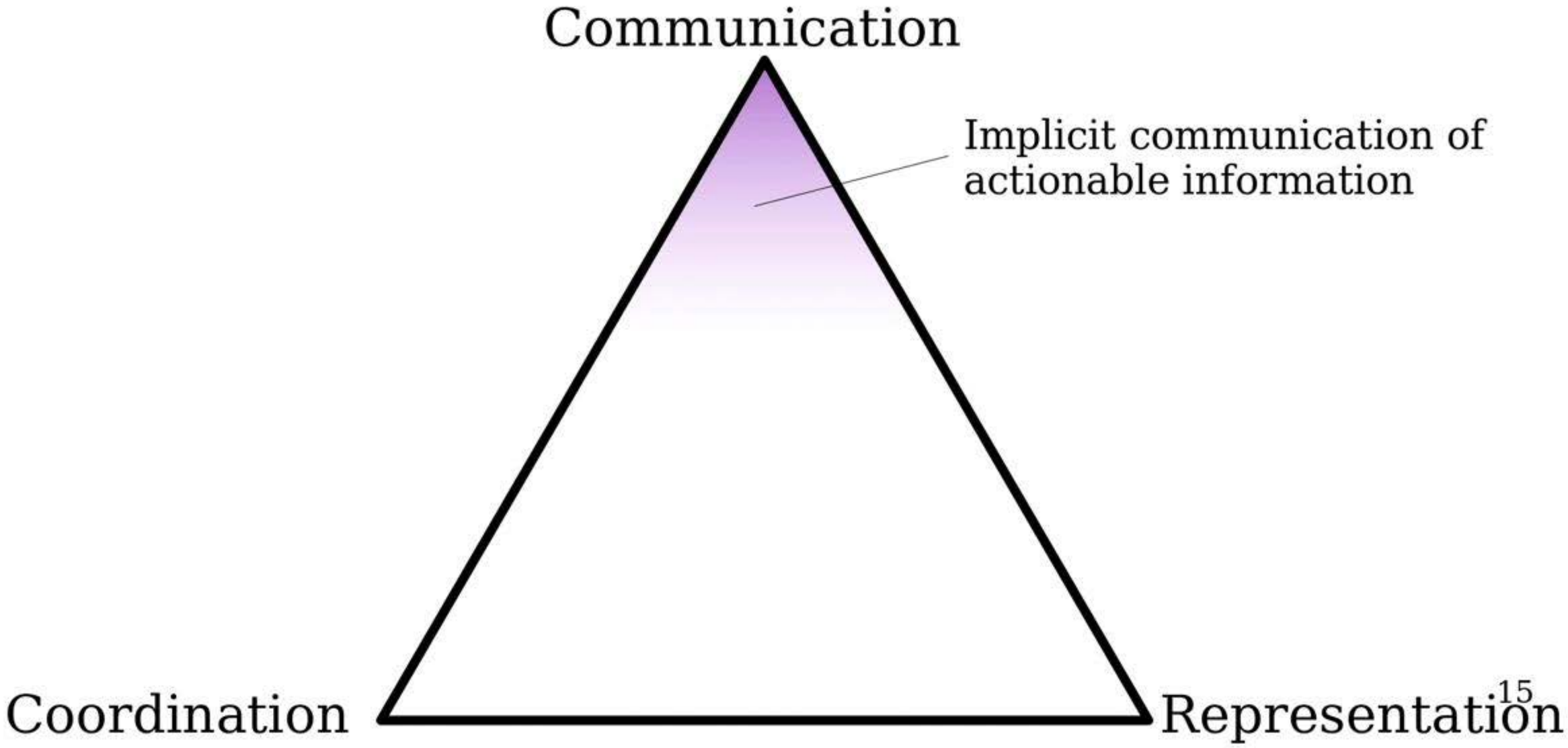

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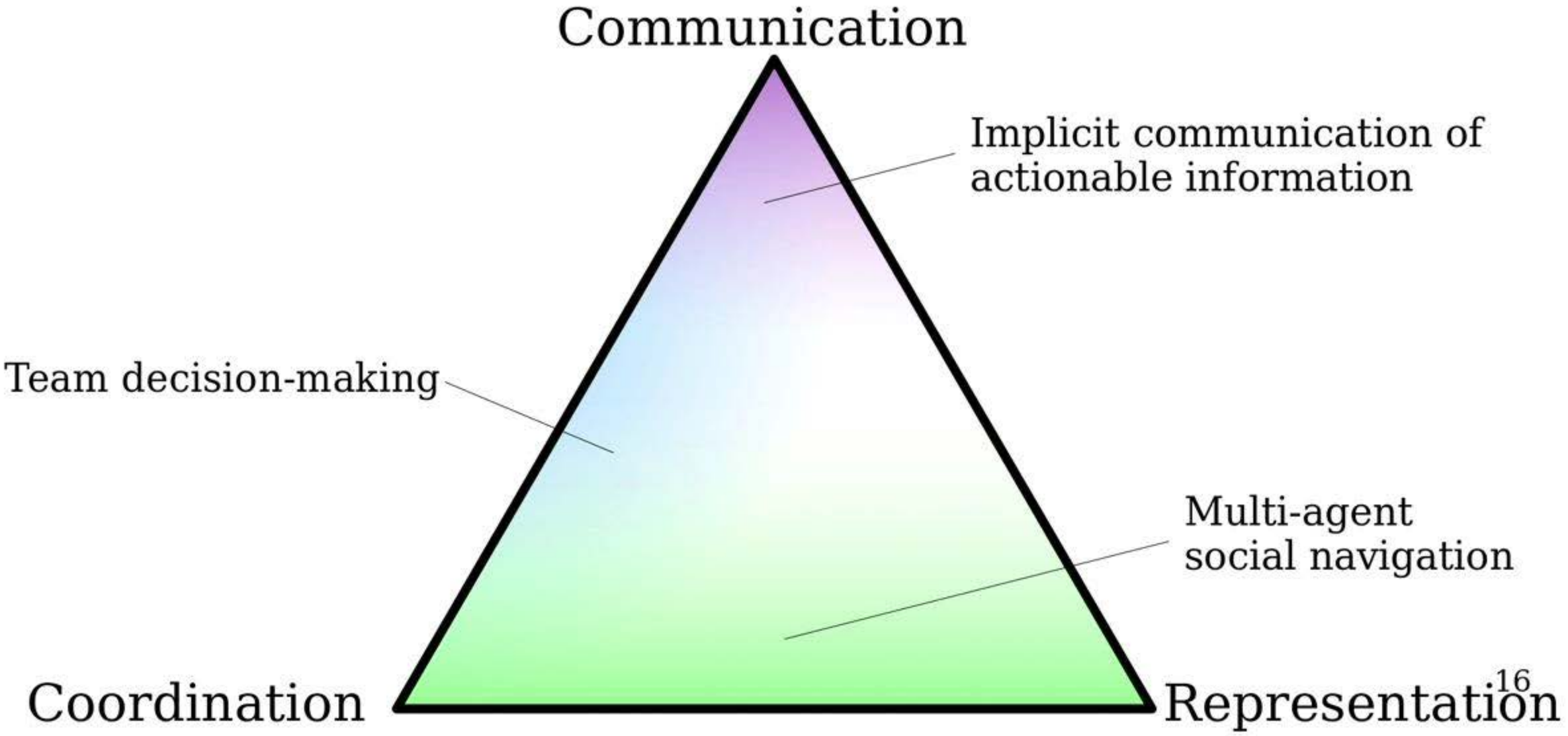
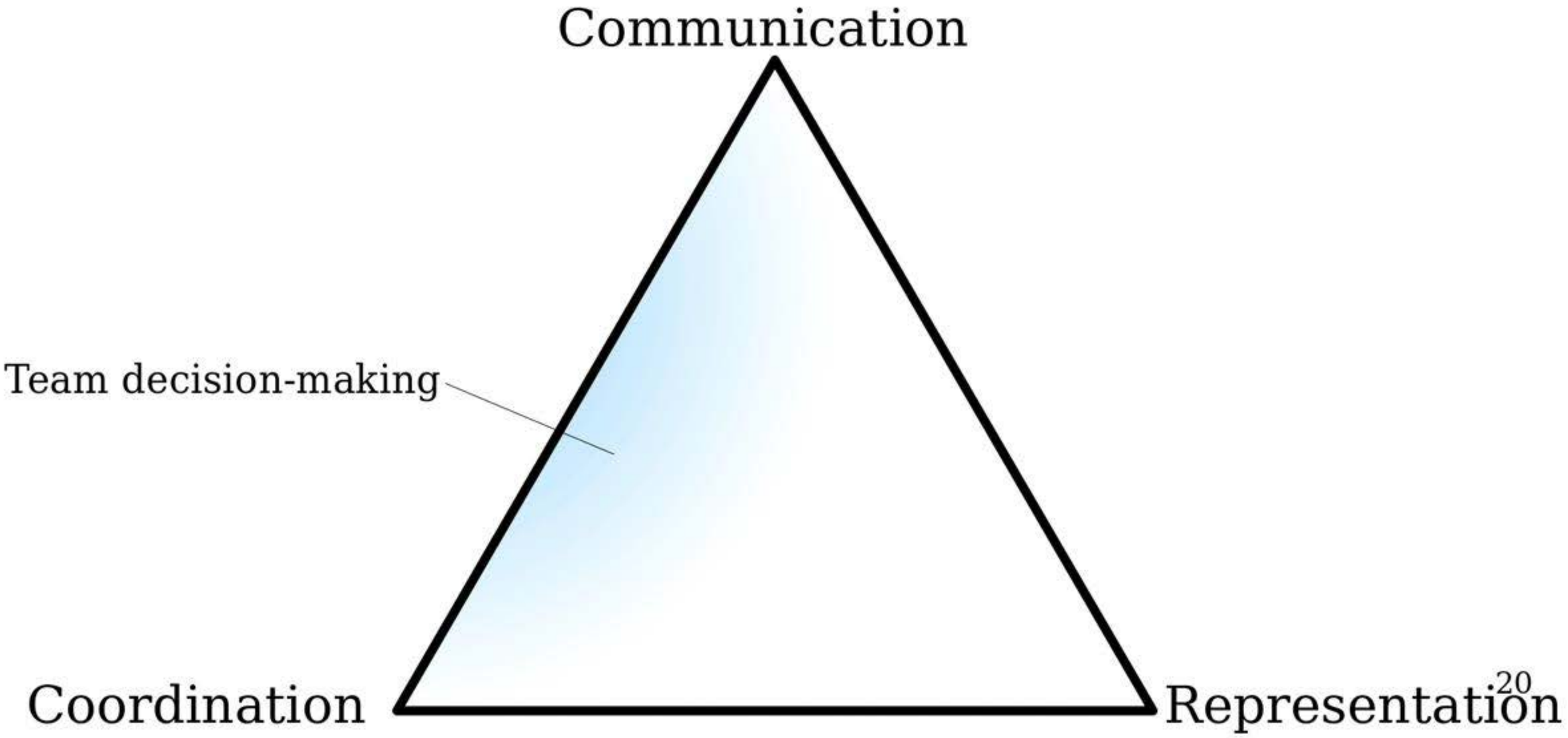


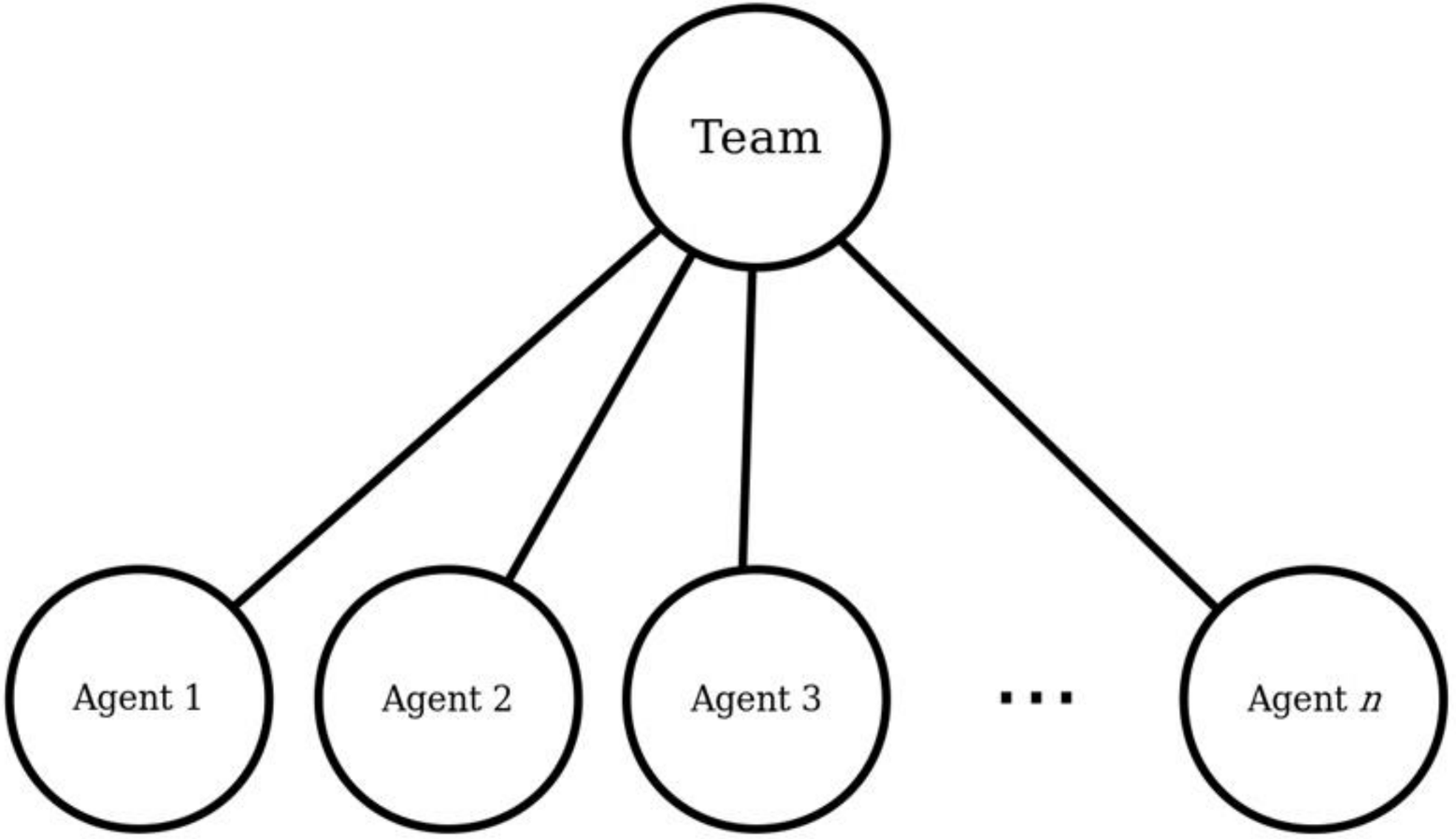
# Teamwork in a Joint Activity



# Basis in Social Science and AI

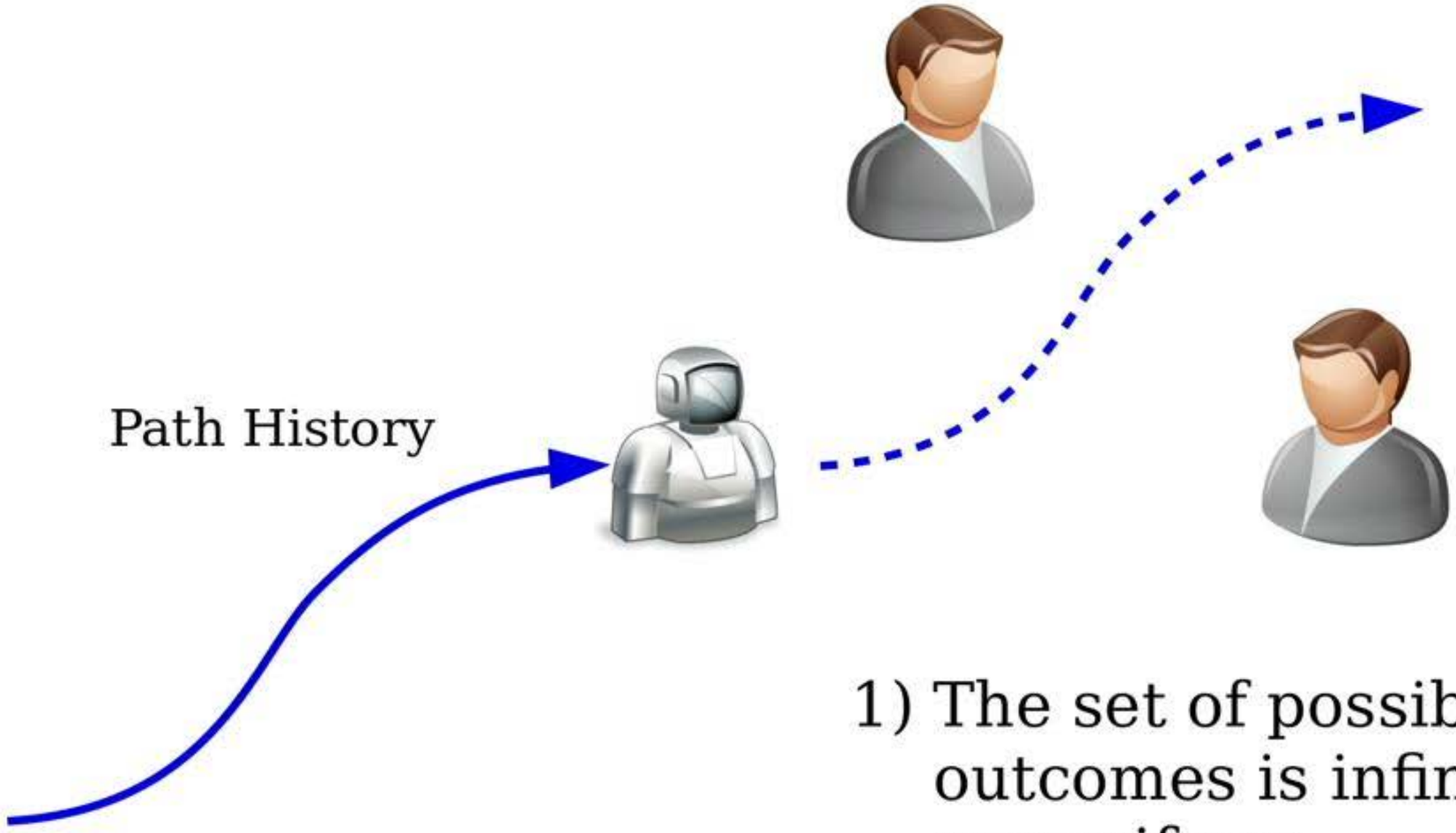
- [Bratman 1987]
  - Framework of belief, desire, intention in teamwork
- [Cohen and Levesque 1990, 1991]
  - Specification for multi-agent teamwork
  - Description of how teams achieve consensus on establishing and completing goals
- [Clark 1994]
  - Dialog mediates a joint activity
  - Repair of failures is a critical component

# $n$+1 Decision-Makers



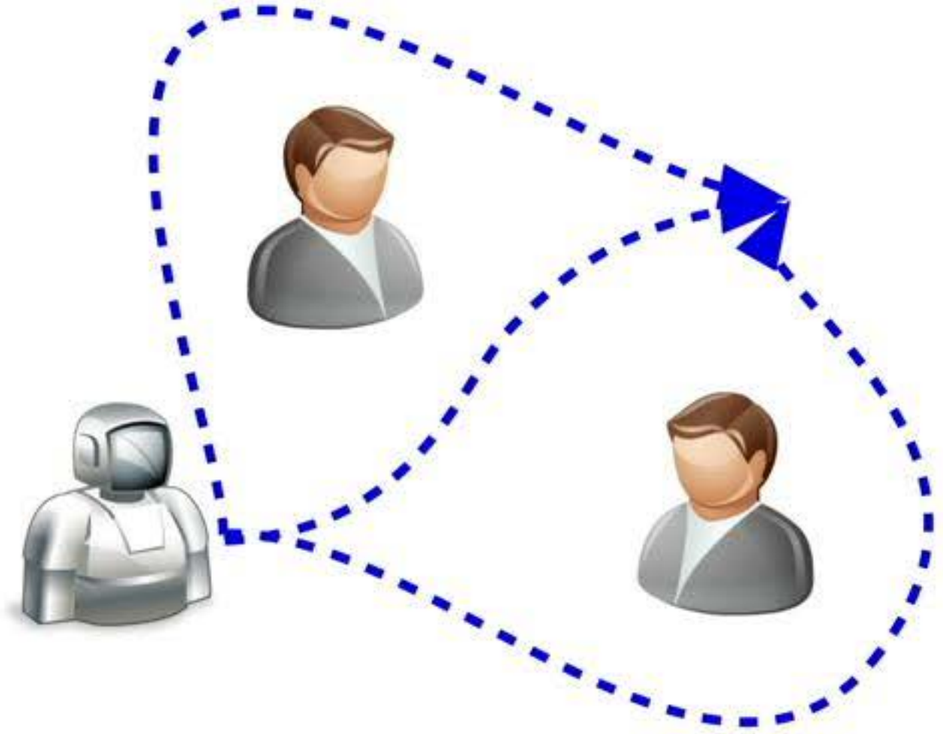
# Teamwork Is a Distributed Systems Problem

- Joint actions
  - Consensus
  - Synchronization
- Communication
  - Multiple modalities
  - Mostly *implicit*
    - Implicit communication: requires context to interpret



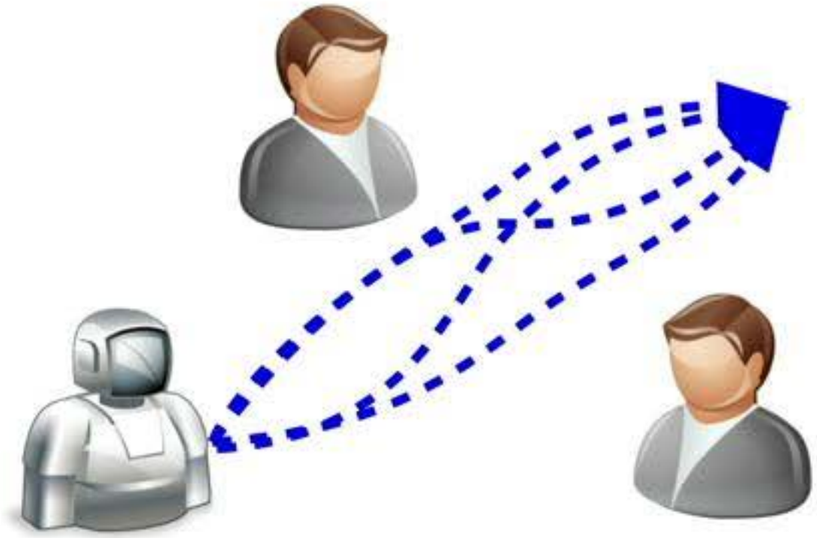

1) The set of possible outcomes is infinite and nonuniform
2) People are reactive

## Team



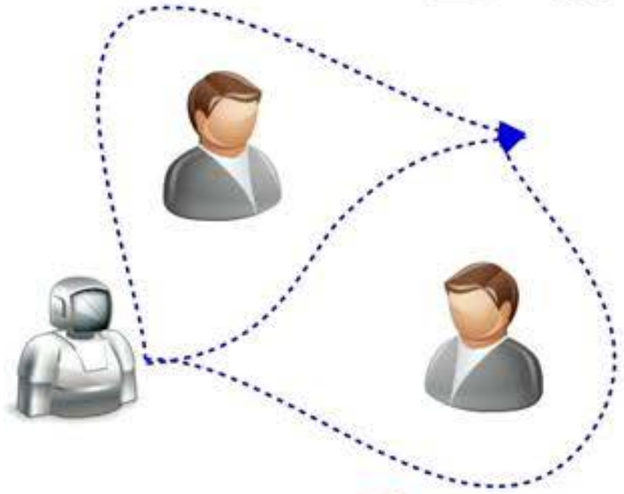
- Collision avoidance
- Consensus

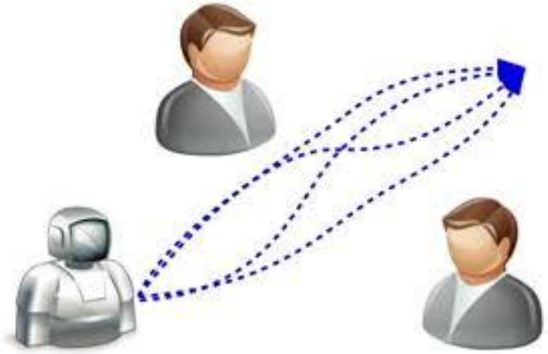
## Individual



- Maneuvering
- Social signaling

# Decision-Making





Agency of Decisions

Team

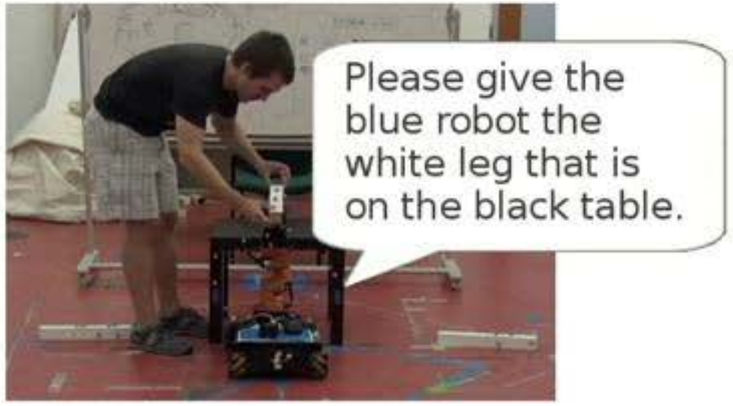
Individual

Granularity of Action

Discrete/coarse

Continuous/fine

# Distributed Algorithms





Communication Bandwidth

Low — High

Control Loop Feedback Rate

Slow — Fast

Granularity of Consensus

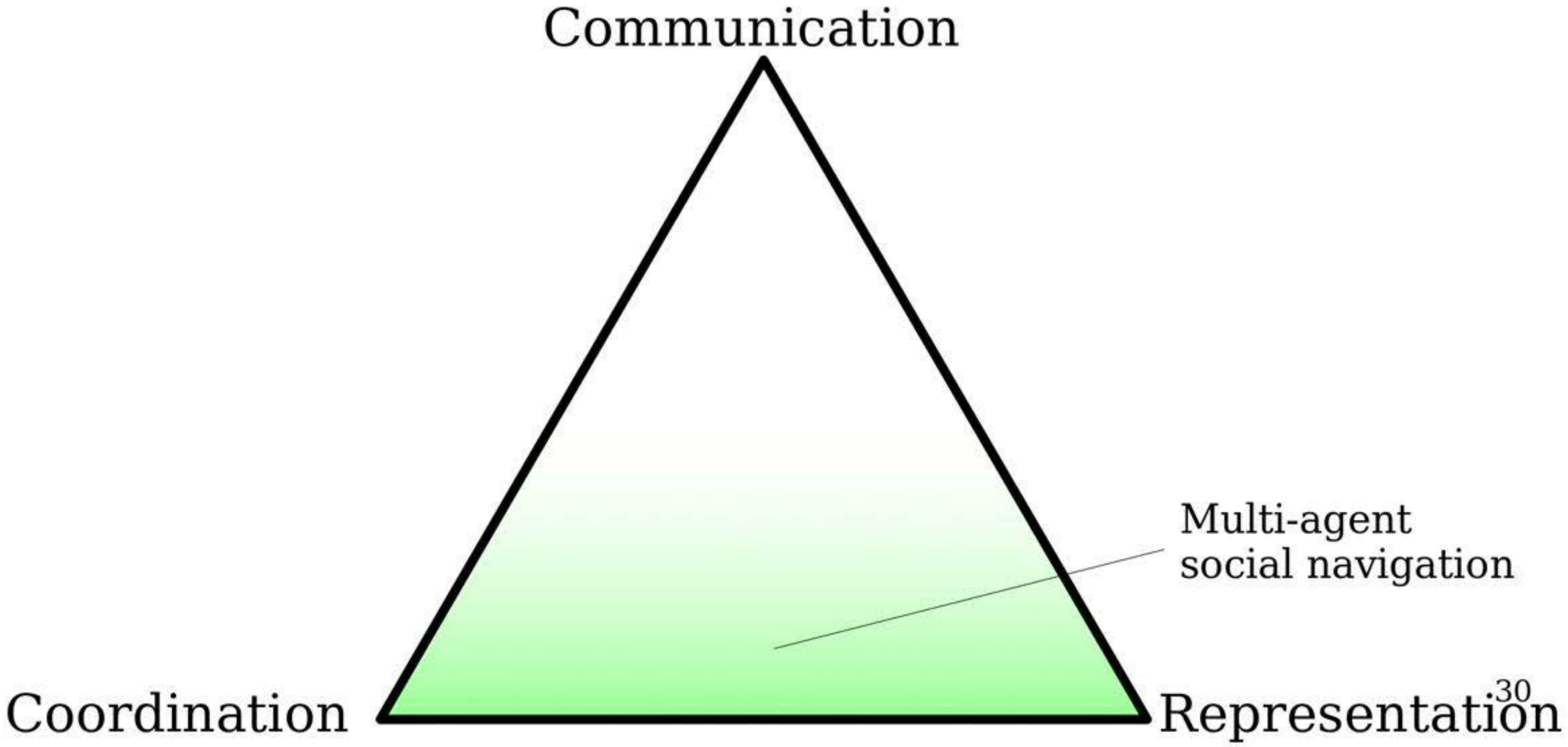
Discrete/coarse — Continuous/fine

# Team State

- Observable
  - Actions
- Hidden
  - Goals
  - Intentions
  - Capabilities

Alfred Jacob Miller
*Breaking up Camp at Sunrise*

# Teamwork in a Joint Activity



# Multi-Agent Socially-Competent Navigation

**[IROS 2017] [HRI 2018] [WAFR 2018] [HRI 2019]**

Christoforos Mavrogiannis

Wil Thomason

Patrícia Alves-Oliveira

Instituto Superior Técnico, Lisbon

Valts Blukis

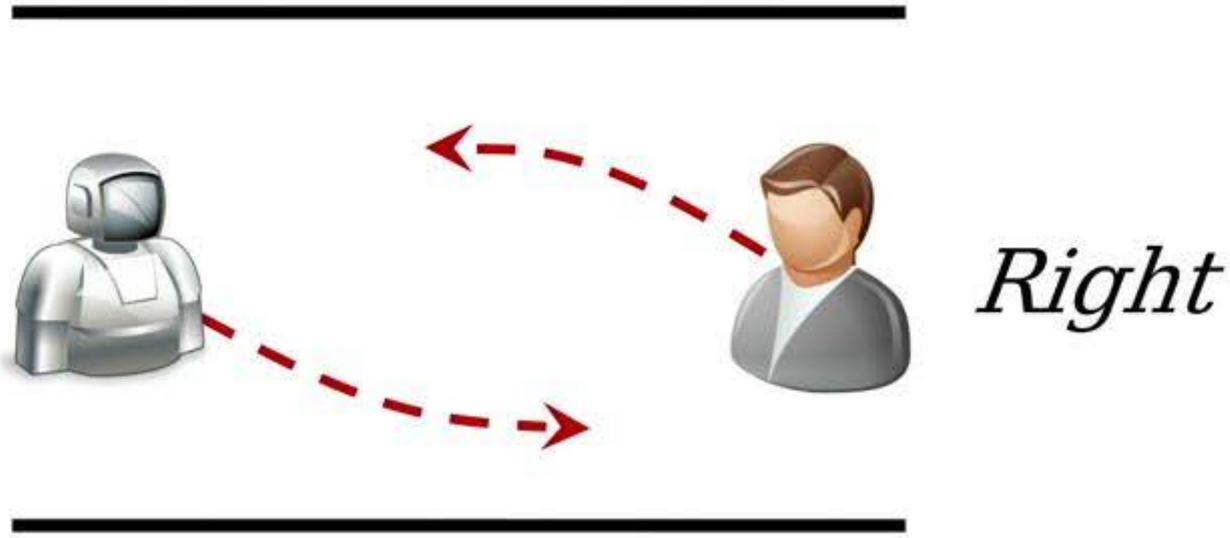
Alena Hutchinson

John Macdonald

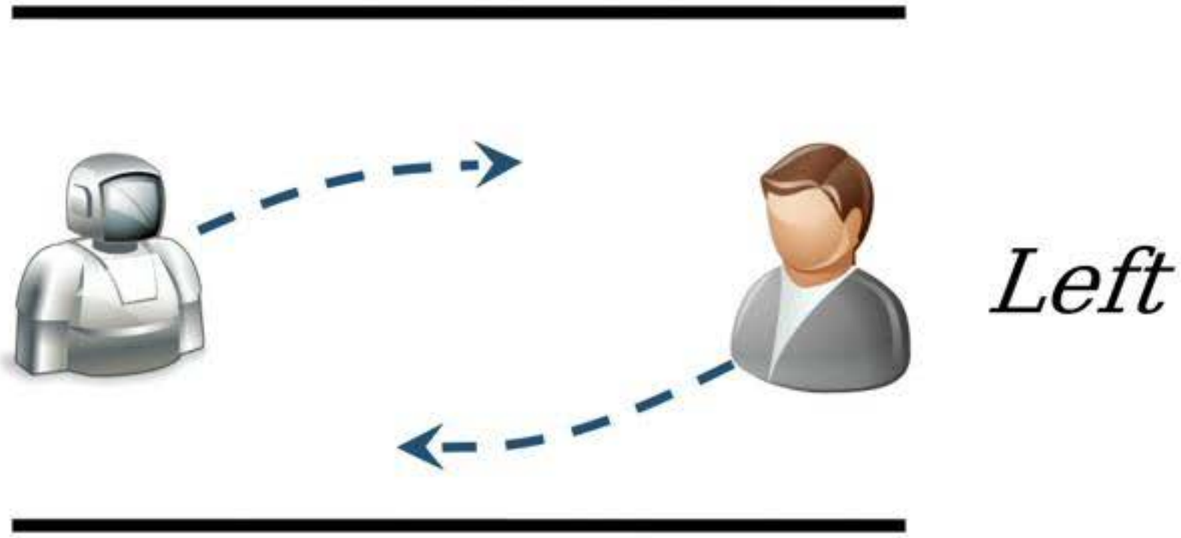
# Two Agents

# Two Agents

# Two Agents



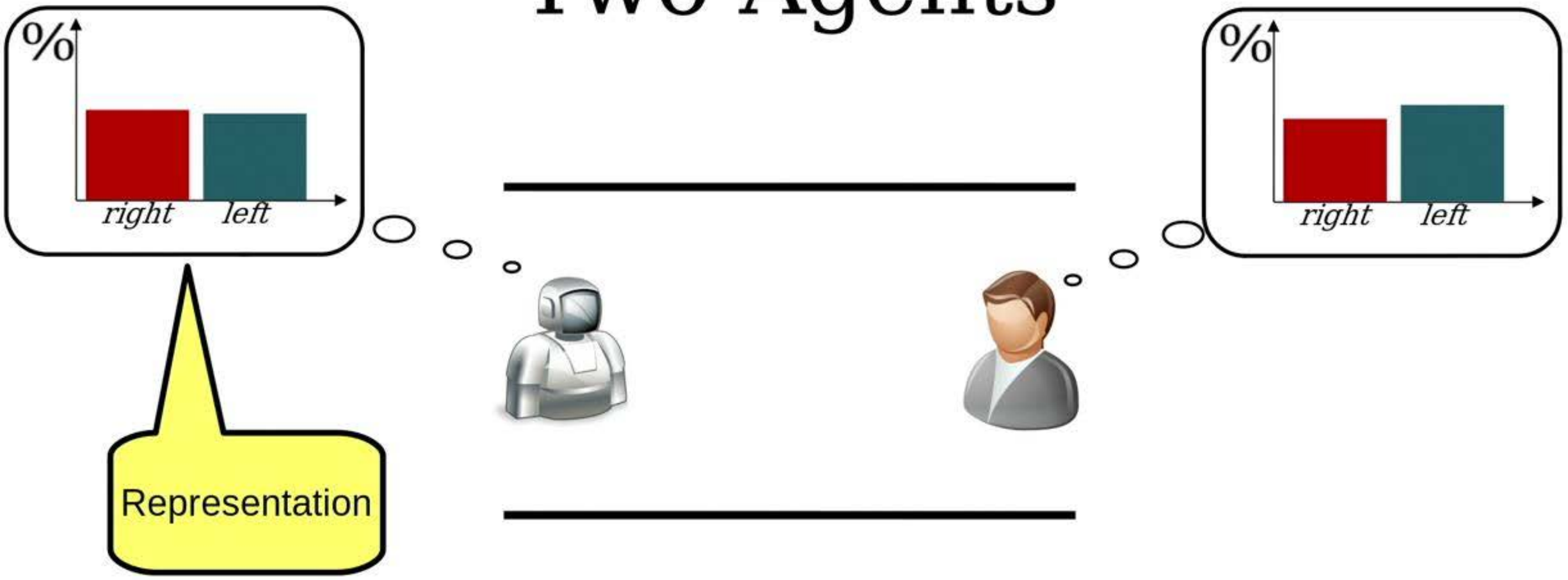
# Two Agents



# Two Agents

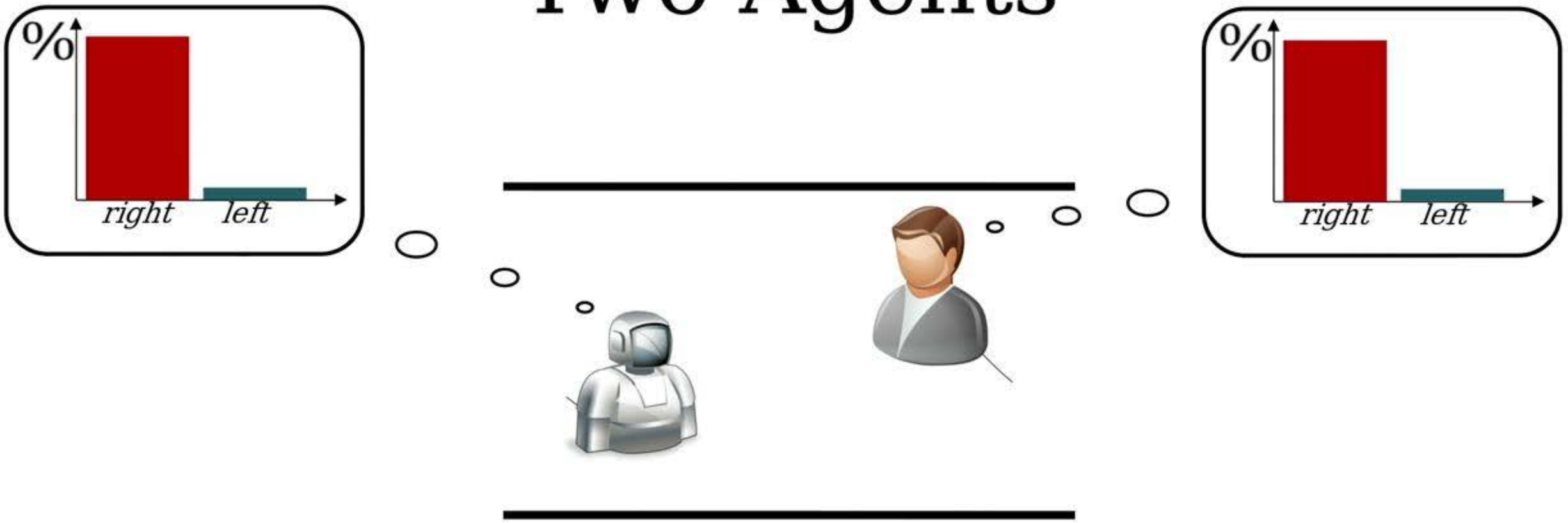

[Mavrogiannis, Blukis, and Knepper, WAFR 2016]

# Two Agents




[Mavrogiannis, Blukis, and Knepper, WAFR 2016]

# Two Agents

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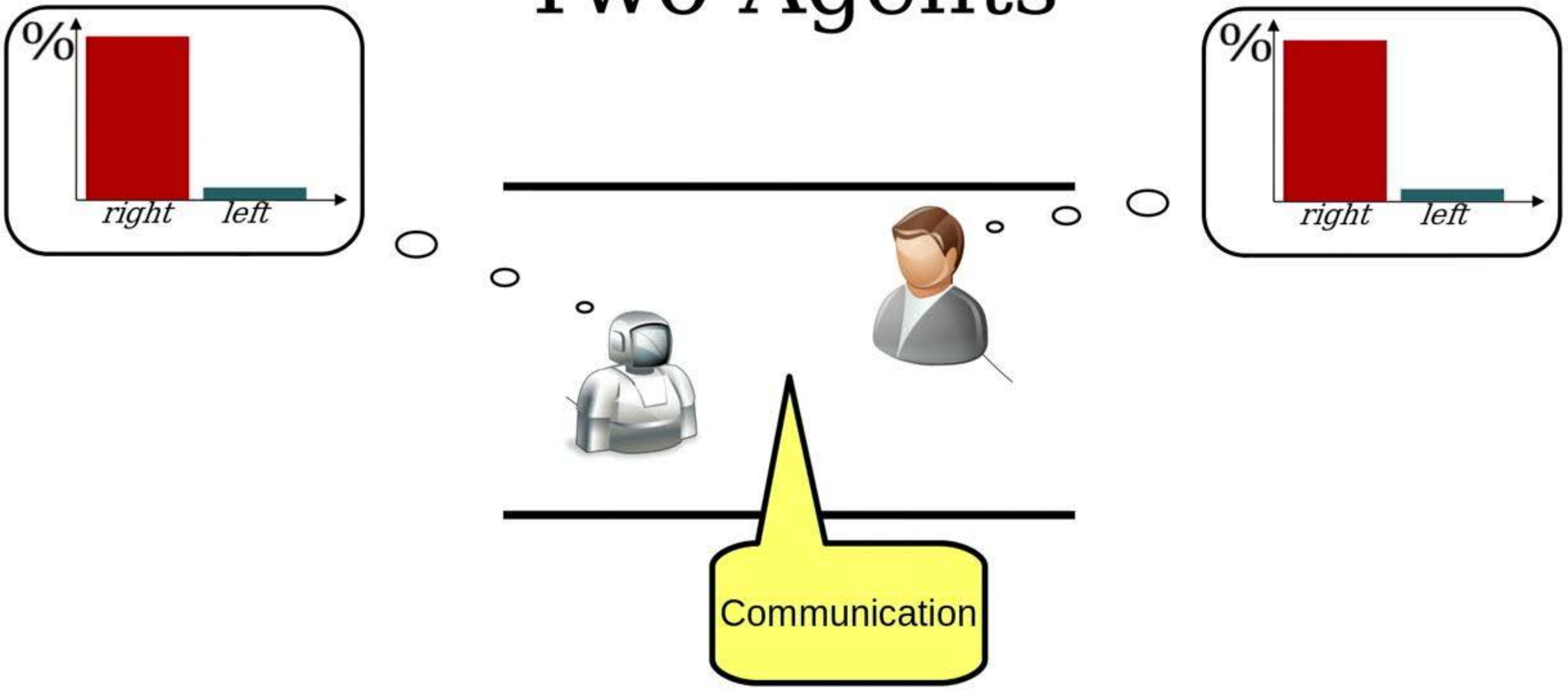


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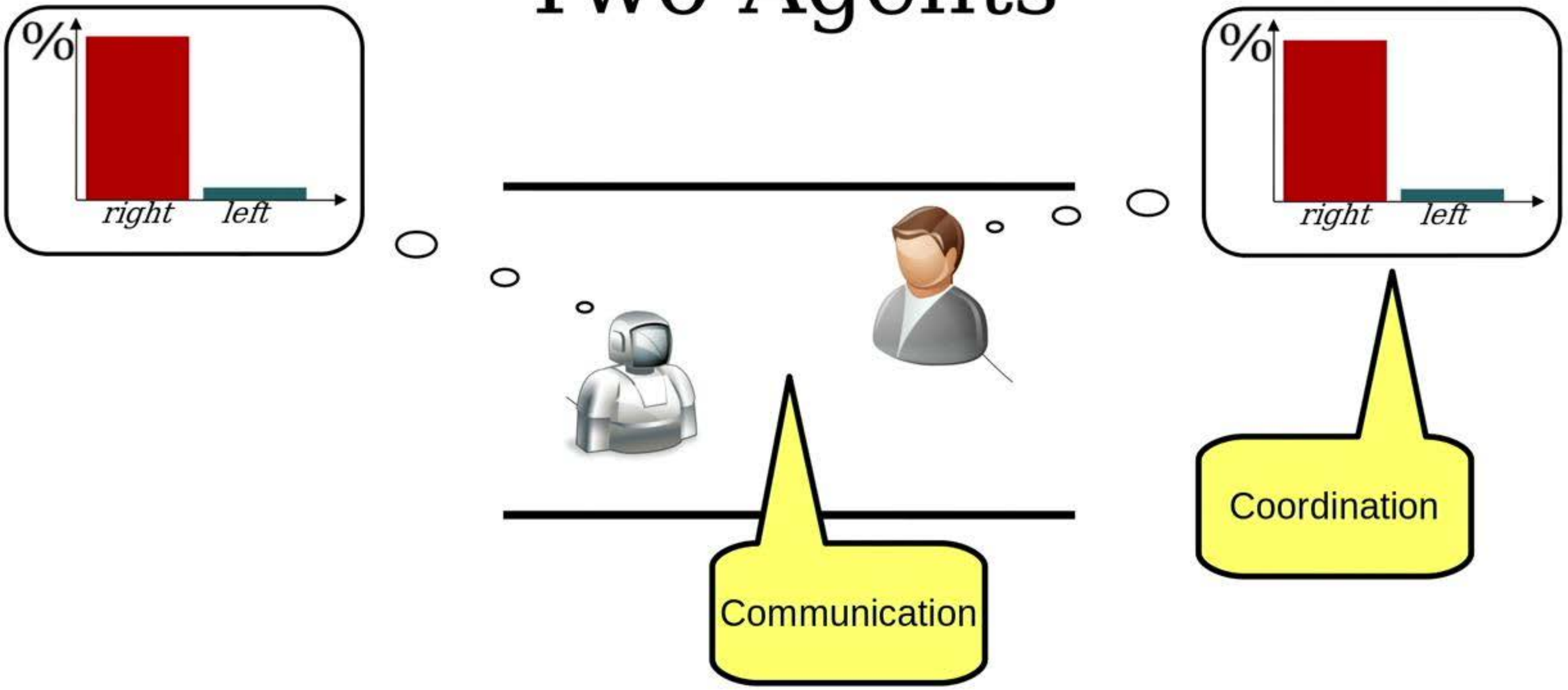
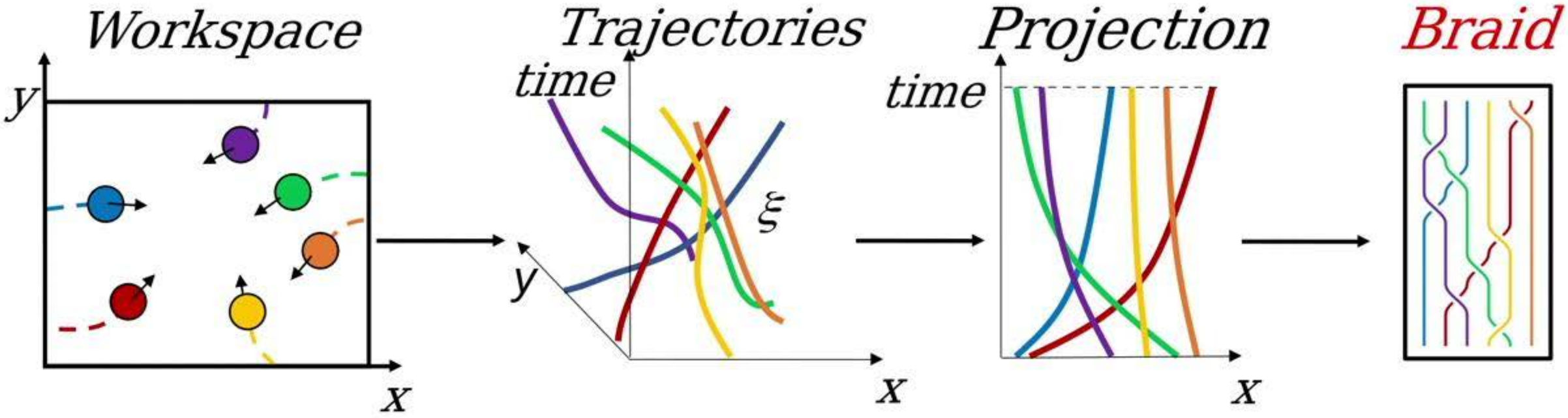



[Mavrogiannis, Blukis, and Knepper, WAFR 2016]

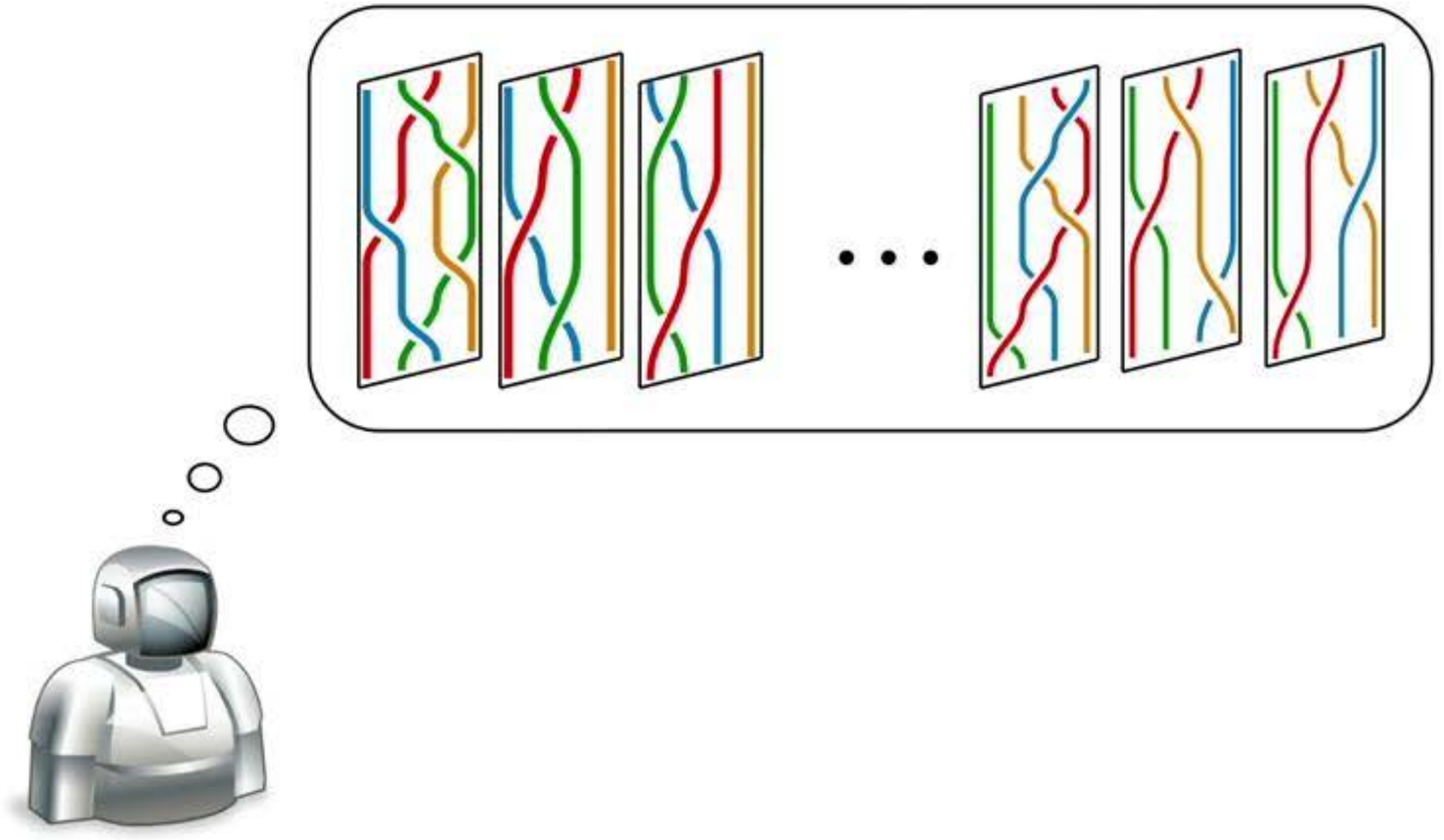
# *n* agents




$$G = \sigma_4 \sigma_2^{-1} \sigma_3^{-1} \sigma_4^{-1} \sigma_1^{-1} \sigma_2^{-1} \sigma_1 \sigma_5^{-1}$$

[Mavrogiannis and Knepper, WAFR 2016]

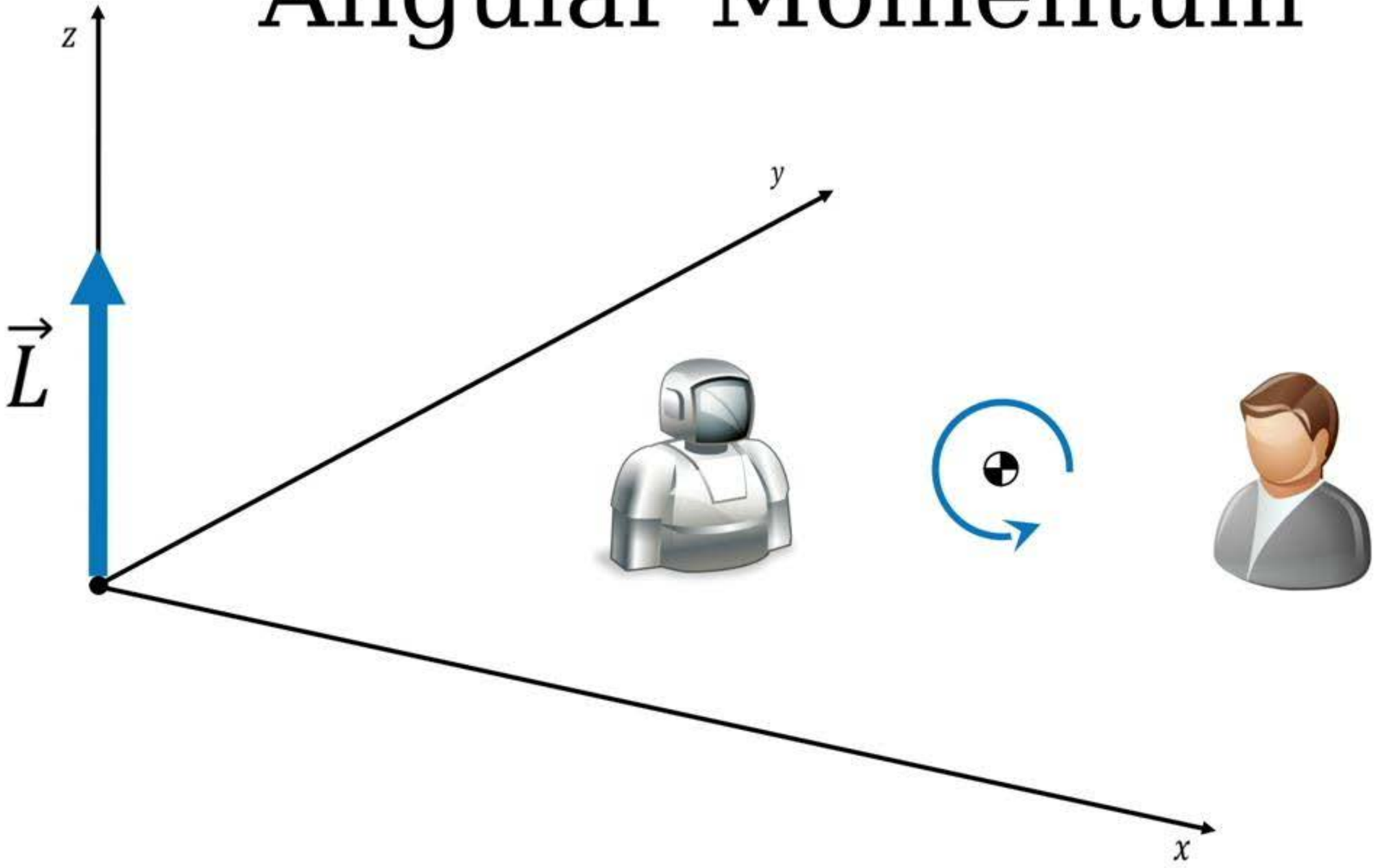
# Reasoning About Joint Navigation



$P(G|\xi)$

[Mavrogiannis, Blukis, and Knepper, WAFR 2016]

# Angular Momentum



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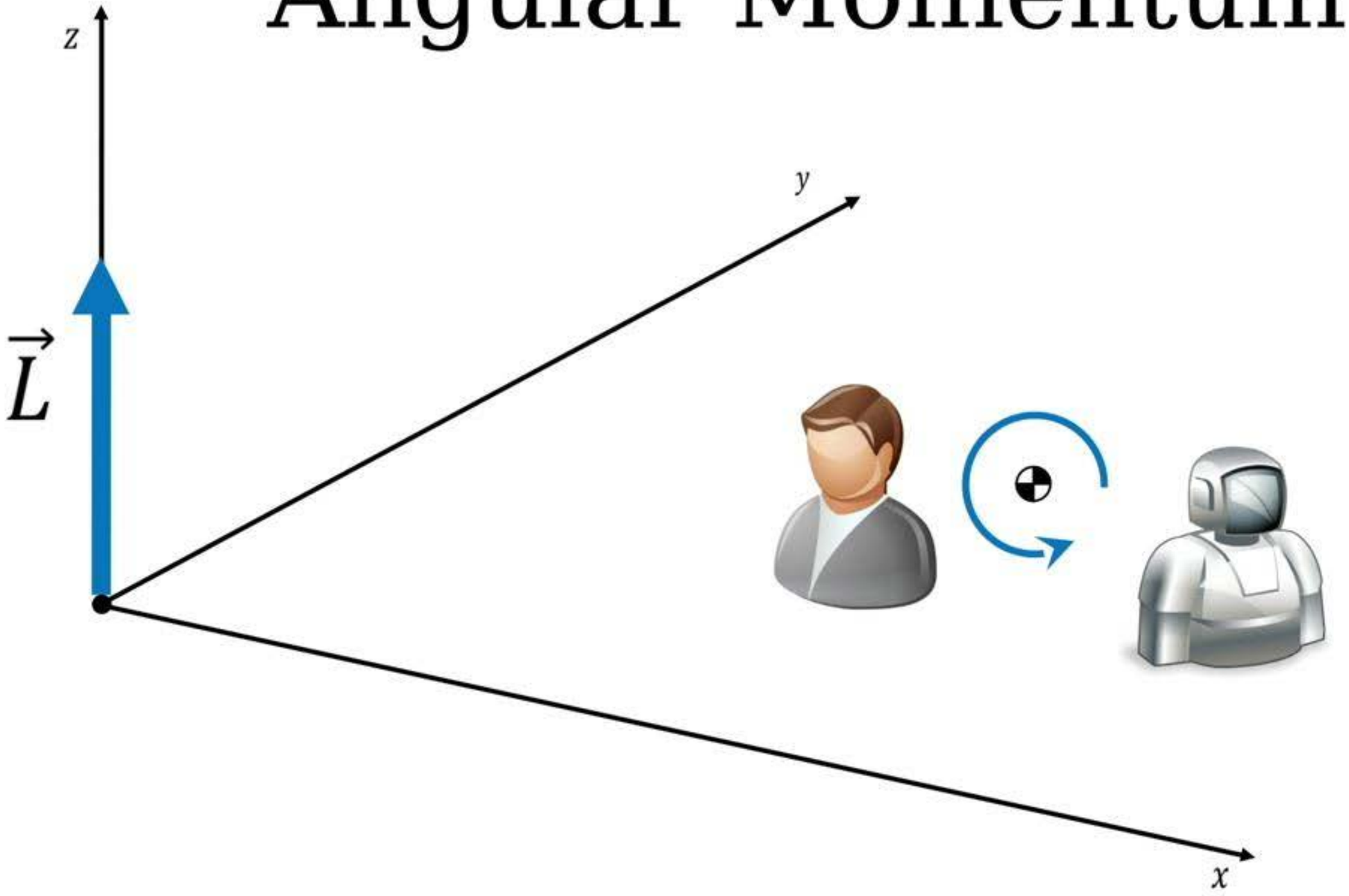
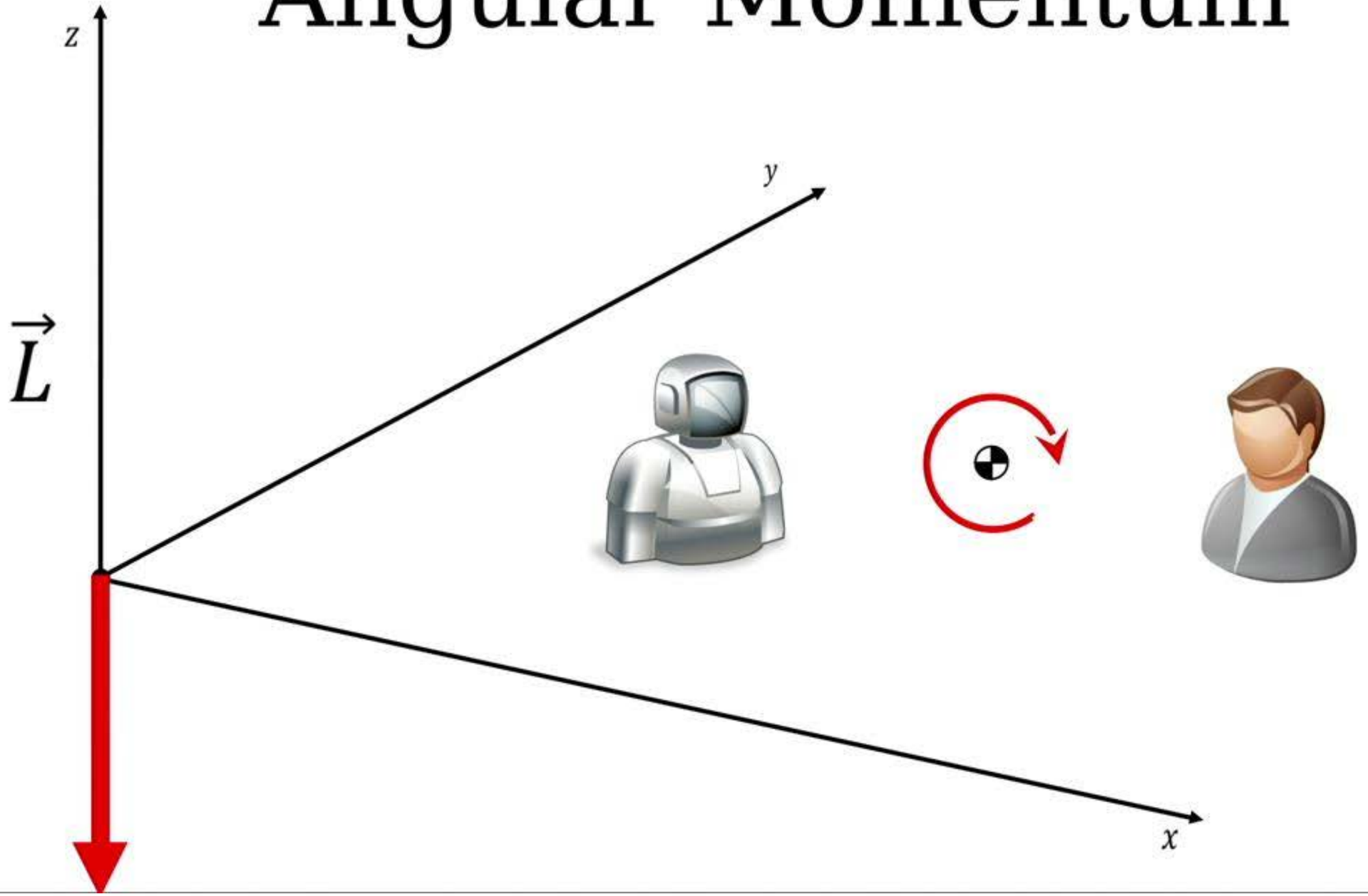


# Angular Momentum



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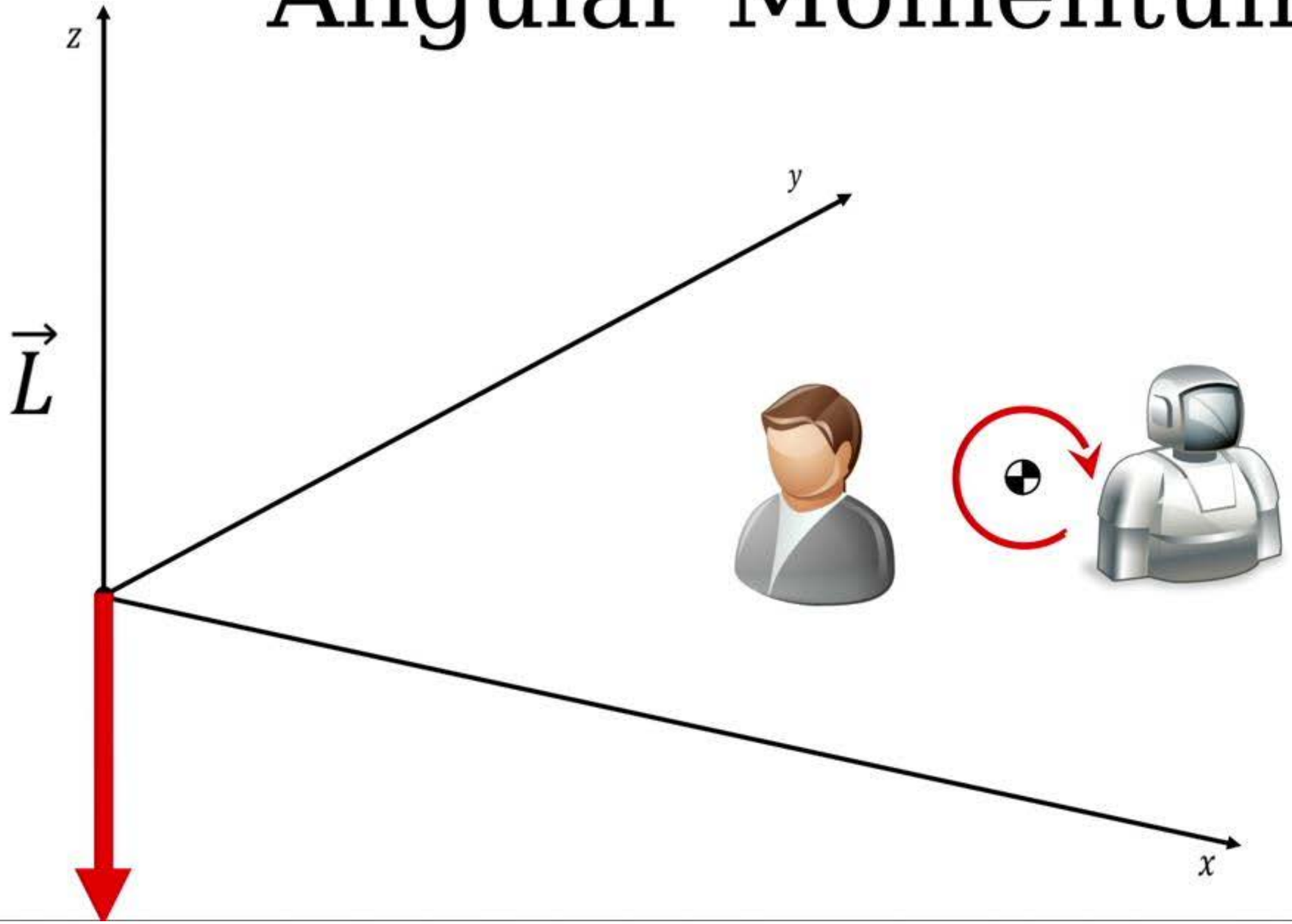
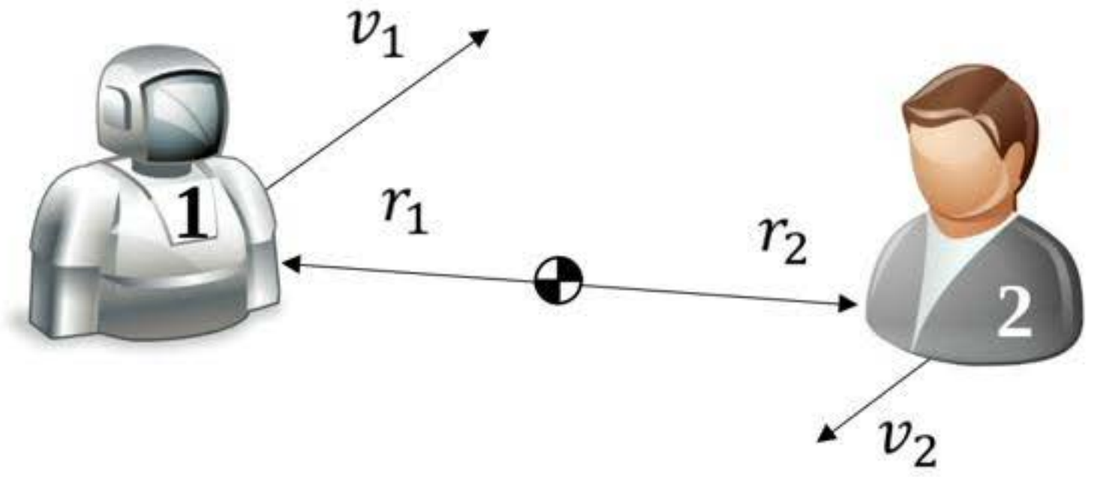


# Maximizing Angular Momentum Models Consensus

Angular momentum

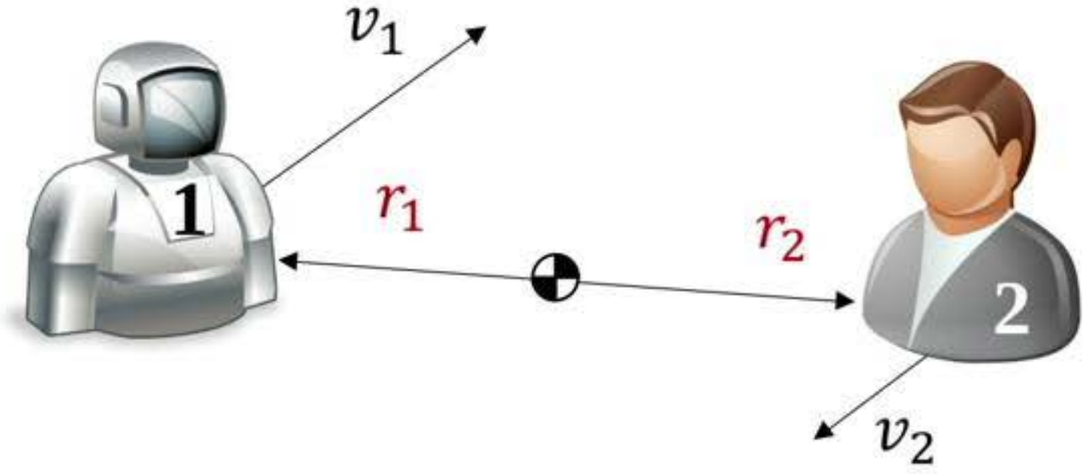
$$\vec{L}_{12} = \vec{r}_1 \times \vec{v}_1 + \vec{r}_2 \times \vec{v}_2$$



# Social Momentum

Angular momentum

$$\vec{L}_{12} = \vec{r}_1 \times \vec{v}_1 + \vec{r}_2 \times \vec{v}_2$$




Encodes:

✓ Clearance

# Social Momentum

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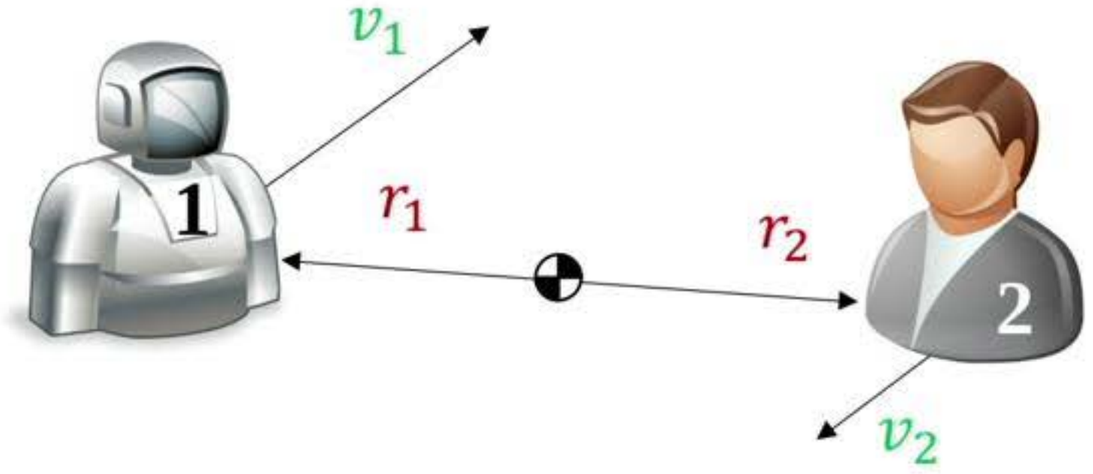


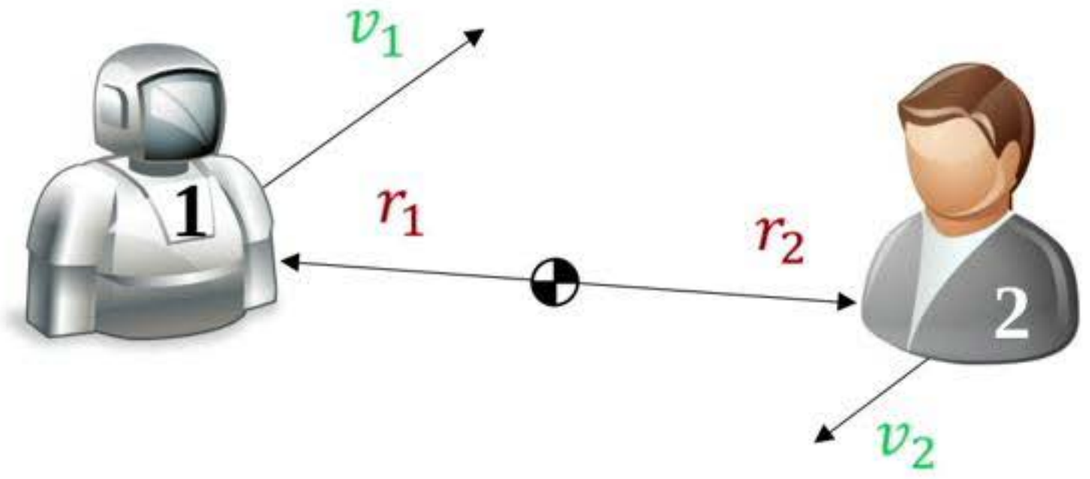

Encodes:

- ✓ Clearance
- ✓ Adaptability

# Social Momentum

Angular momentum

$\vec{L}_{12} = \vec{r}_1 \times \vec{v}_1 + \vec{r}_2 \times \vec{v}_2$




Encodes:

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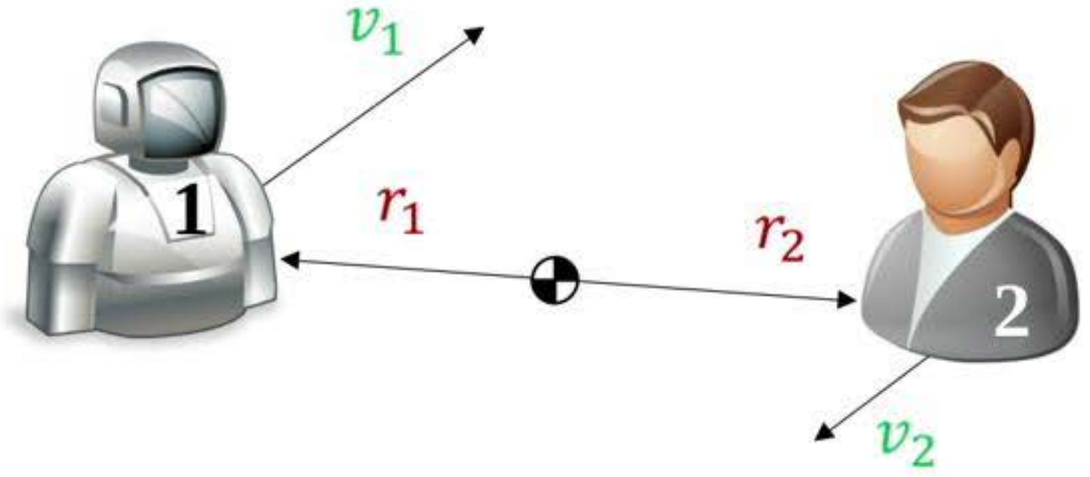



**Manipulate momentum**

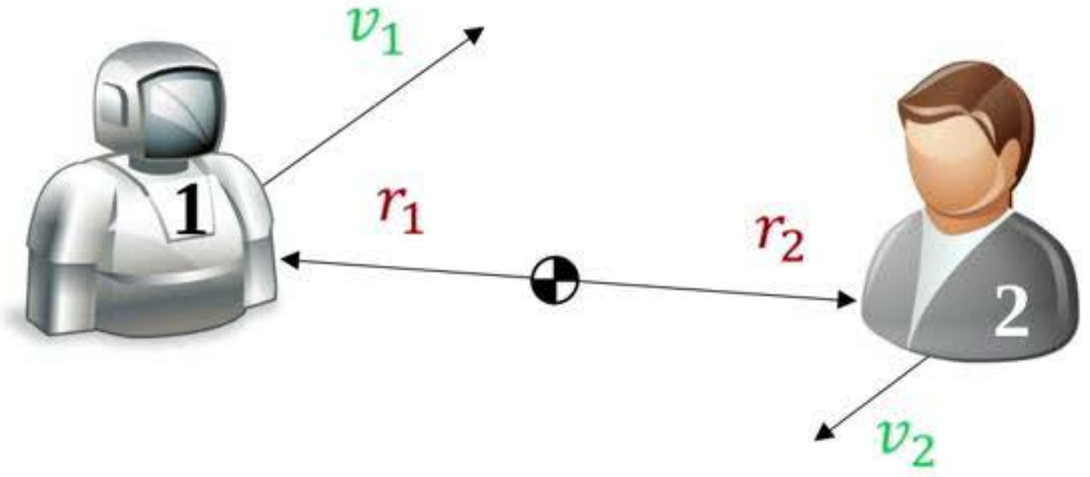
Encodes:

- ✓ Clearance
- ✓ Adaptability
- ✓ Consensus

# Social Momentum

Angular momentum

$$\vec{L}_{12} = \vec{r}_1 \times \vec{v}_1 + \vec{r}_2 \times \vec{v}_2$$

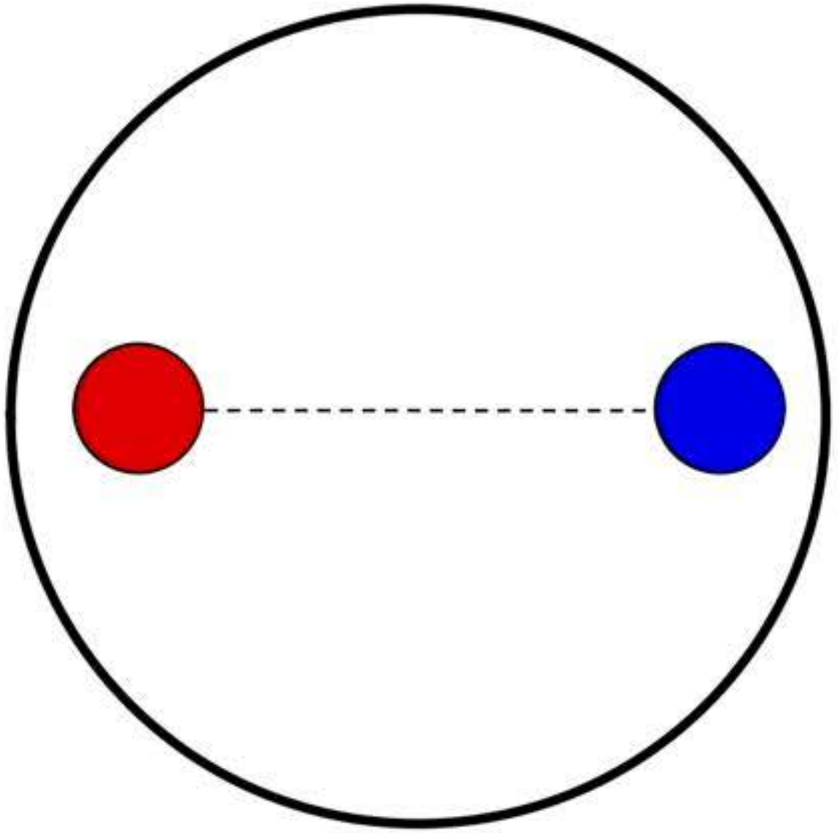



**Manipulate momentum to convey intent**

Encodes:

- ✓ Clearance
- ✓ Adaptability
- ✓ Consensus

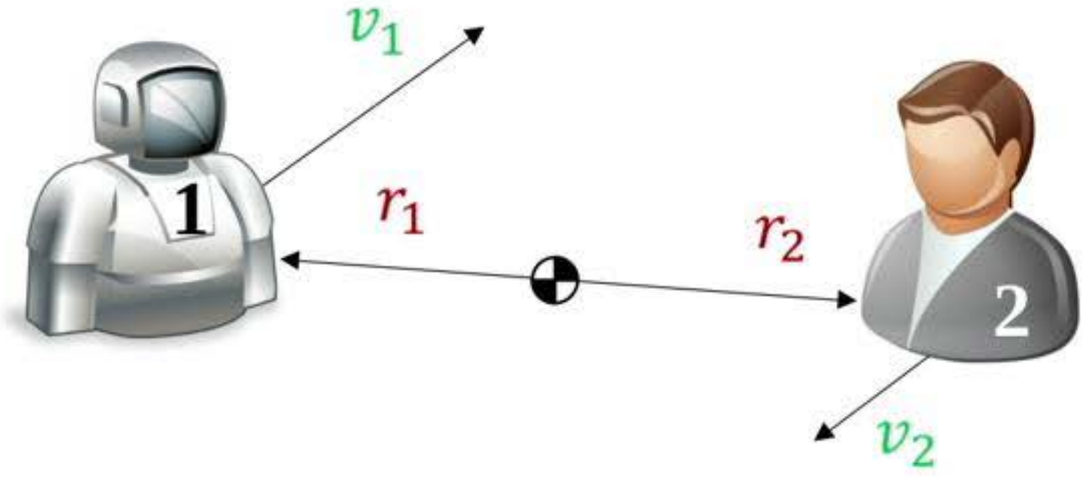
# Collision Avoidance



# Social Momentum

Angular momentum

$$\vec{L}_{12} = \vec{r}_1 \times \vec{v}_1 + \vec{r}_2 \times \vec{v}_2$$

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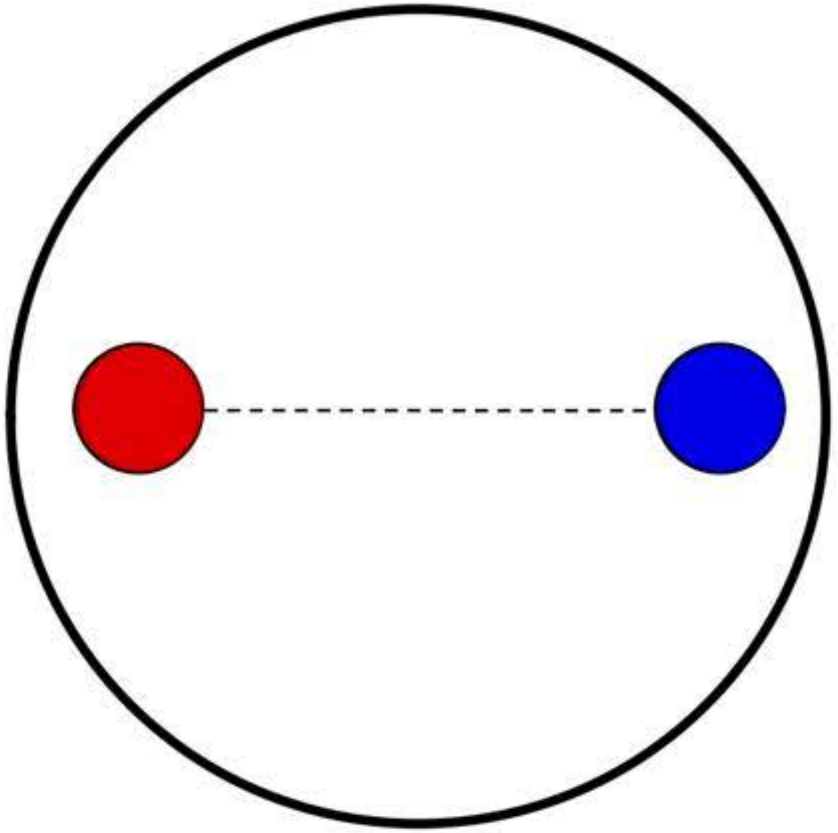
# Collision Avoidance



# Vortex Dynamics for Collision Avoidance

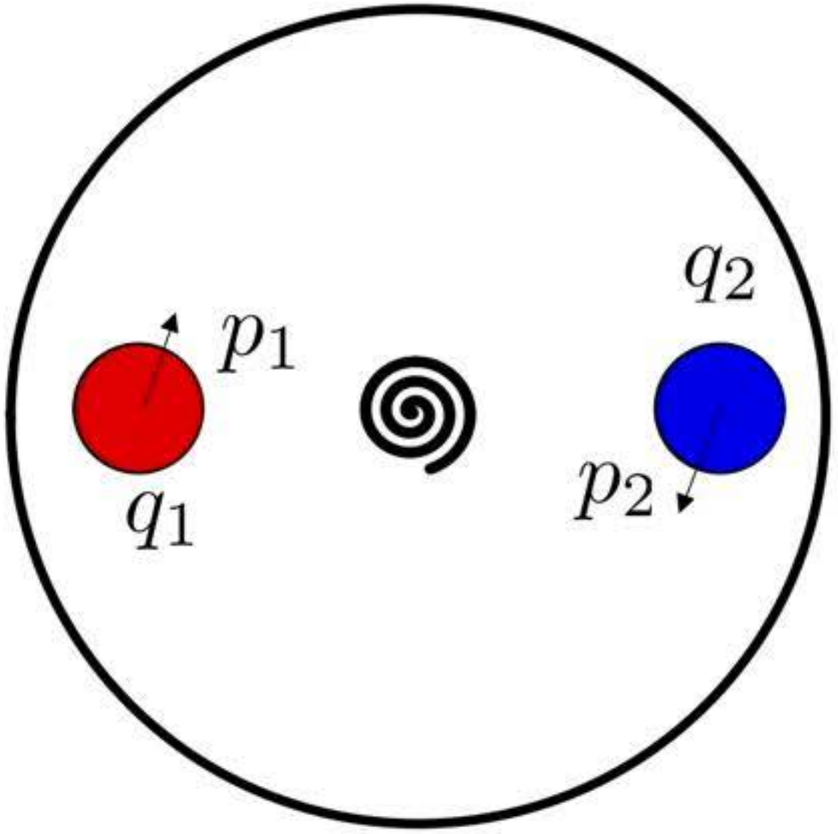
***Hamiltonian Formalism***

$$H = -\frac{1}{2\pi} log|r(t)|$$

$$\dot{q}_j = \frac{\partial H}{\partial p_j} \quad , \quad \dot{p}_j = -\frac{\partial H}{\partial q_j}$$

$q_j$ : generalized coordinate

$p_j$ : conjugate momentum




Defines geodesic as an "orbit" around another agent

Conjugate momentum is constant

# Vortex Dynamics for Collision Avoidance

*Hamiltonian Formalism*

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$$\dot{q}_j = \frac{\partial H}{\partial p_j} \quad , \quad \dot{p}_j = -\frac{\partial H}{\partial q_j}$$

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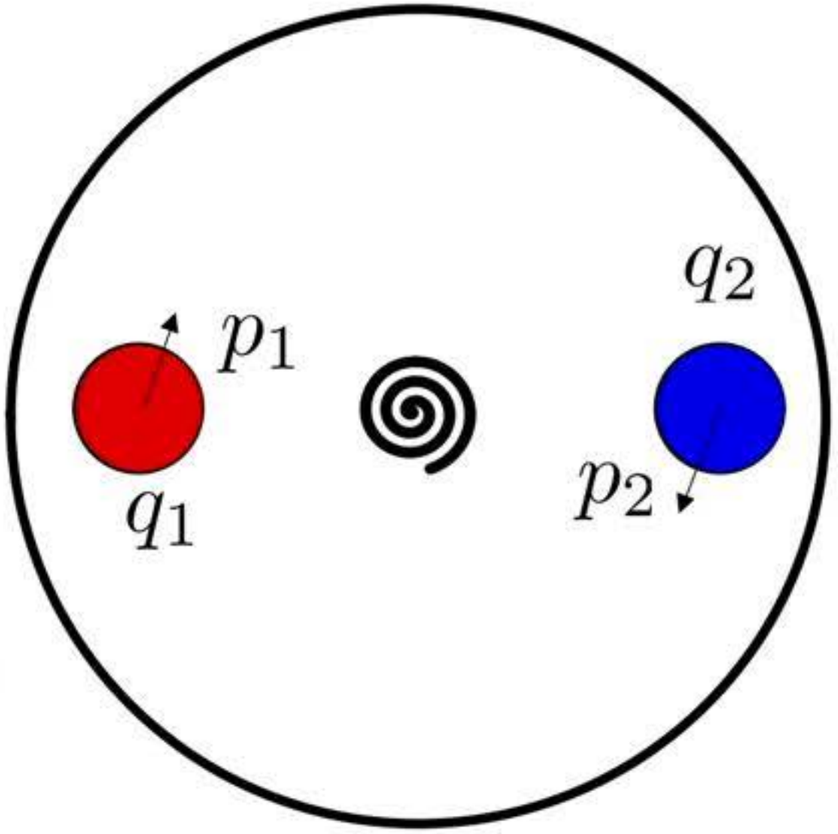
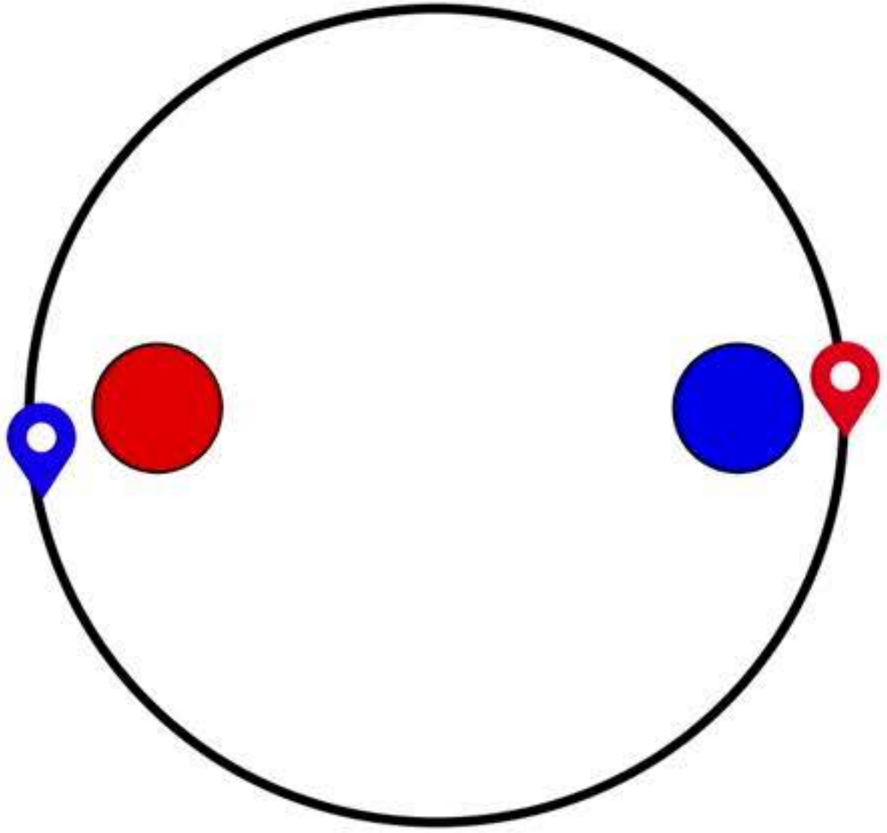



*Hamiltonian Motion follows direction of maximum increase of winding number.*

[Berger '01]

# Vortex Dynamics for Collision Avoidance

*Two agents*



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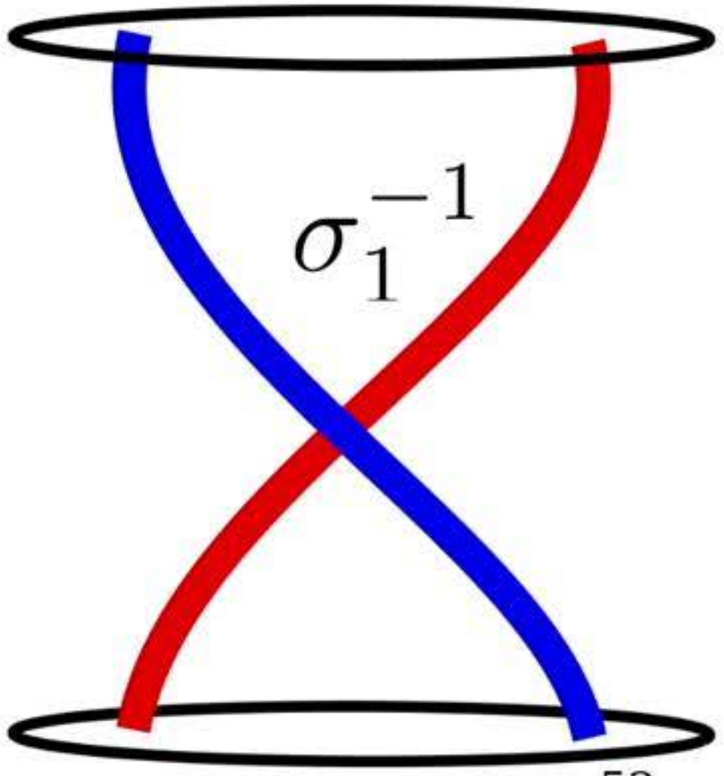
*Vortex Dynamics*

$w_{12} < 0$

=

*Desired Trajectory Topology*

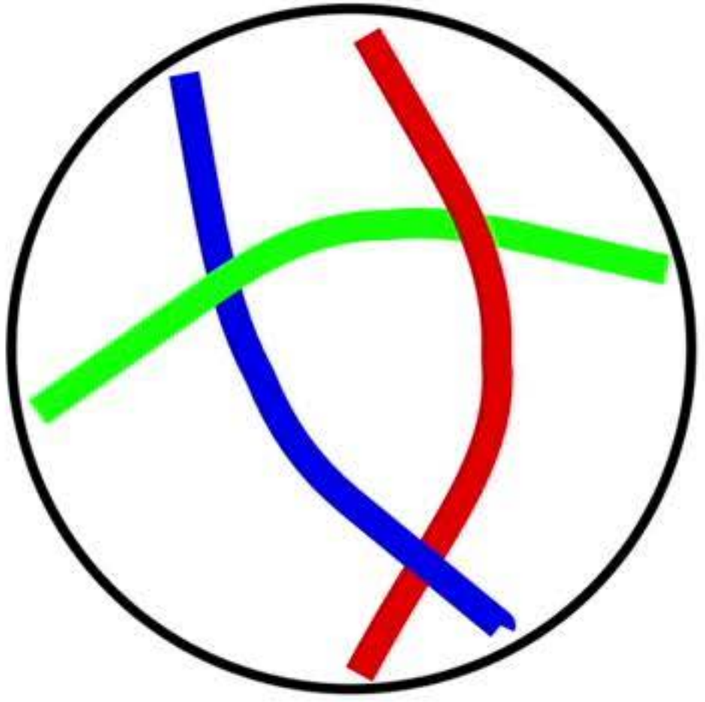


# Hamiltonian Topological Trajectory Generation (HTTG)

$$\mathbf{w} = (w_{12}, w_{13}, w_{23})$$

Topological Specification

→ HTTG →



- Hamiltonian gradients as repulsive potentials.
- Attractive potentials to drive agents to goals.

Trajectory in the Cartesian space

Thomas Cole
*The Course of Empire: The Arcadian or Pastoral State*

# Social Momentum User Study


# Hypotheses

(H1): In close proximity (<1m) with humans:

- *ORCA* generates the most geometrically efficient paths
- *SM* generates the highest acceleration paths
- *TE* generates the most energy-efficient paths.

(H2): Humans in close proximity (<1m) with the robot follow the lowest acceleration paths when the robot runs *SM.*

(H3): Participants consider the behavior generated by *TE* as more socially compliant, intelligent and safe than the rest of the strategies.

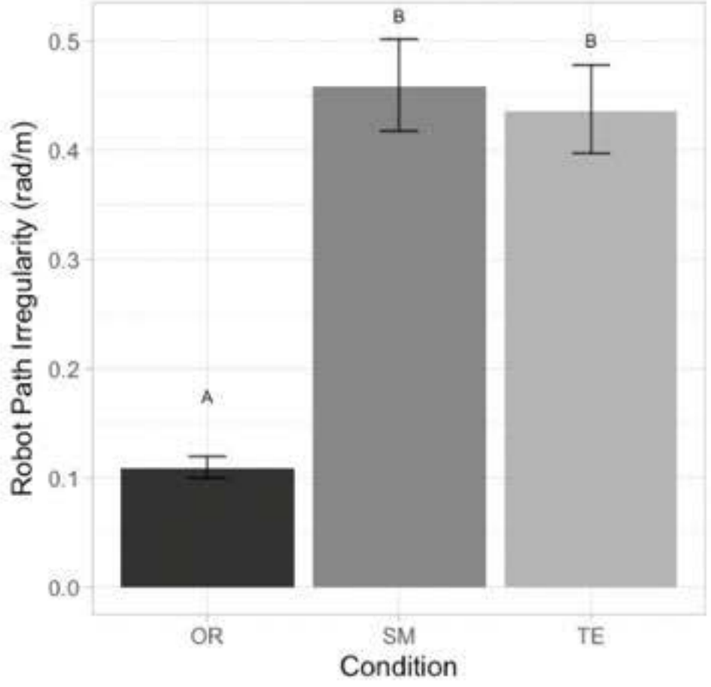
# Sample

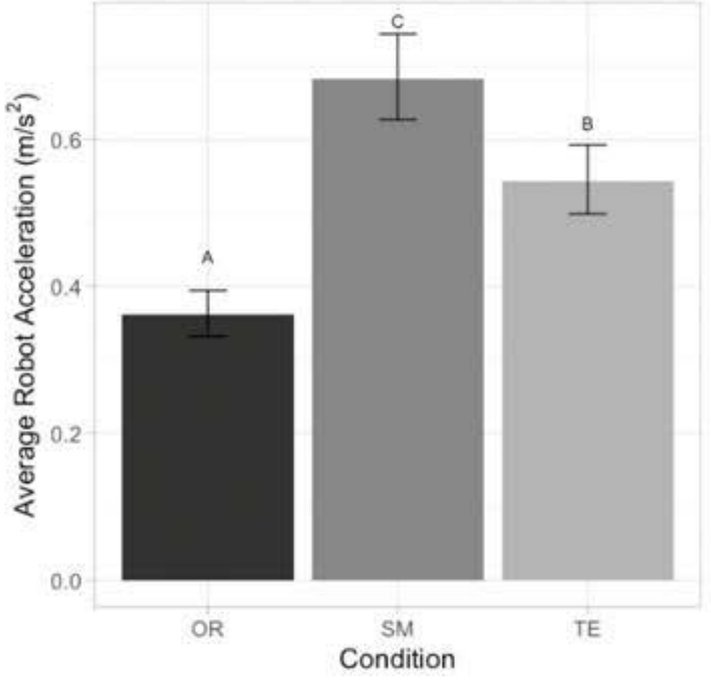
- 105 participants
- Student population
- 59 female, 45 male, 1 Unidentified
- Age 21.45 (SD=3.19 years)
- 57 with prior experience of user studies
- Familiarity with robotics: 2.47/5 (SD=1.27)

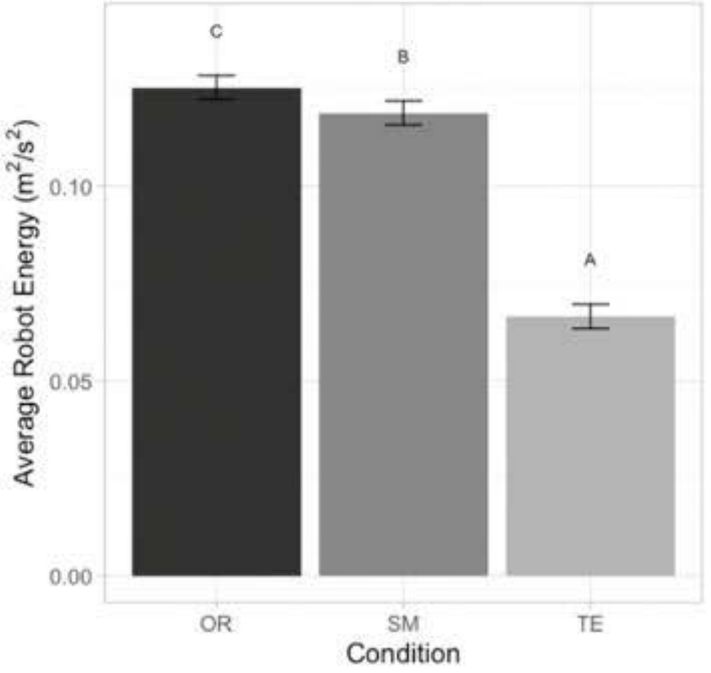
# Robot Behavior

(H1): In close proximity (<1m) with humans:

- *ORCA* generates the most geometrically efficient paths
- *SM* generates the highest acceleration paths
- *TE* generates the most energy-efficient paths.

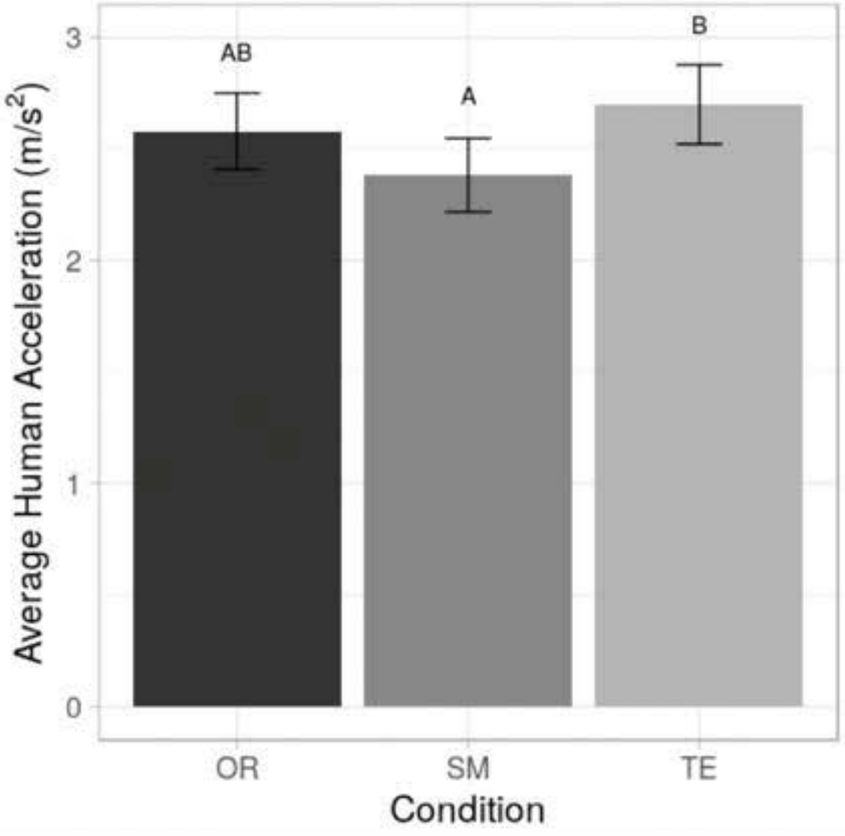


# Human Behavior

(H2): Humans in close proximity (<1m) with the robot follow the lowest acceleration paths when the robot runs *SM* (F = 3.888, p = 0.02173).



# Human Impressions

(H3): Participants consider the behavior generated by *TE* as more socially compliant, intelligent and safe than the rest of the strategies.

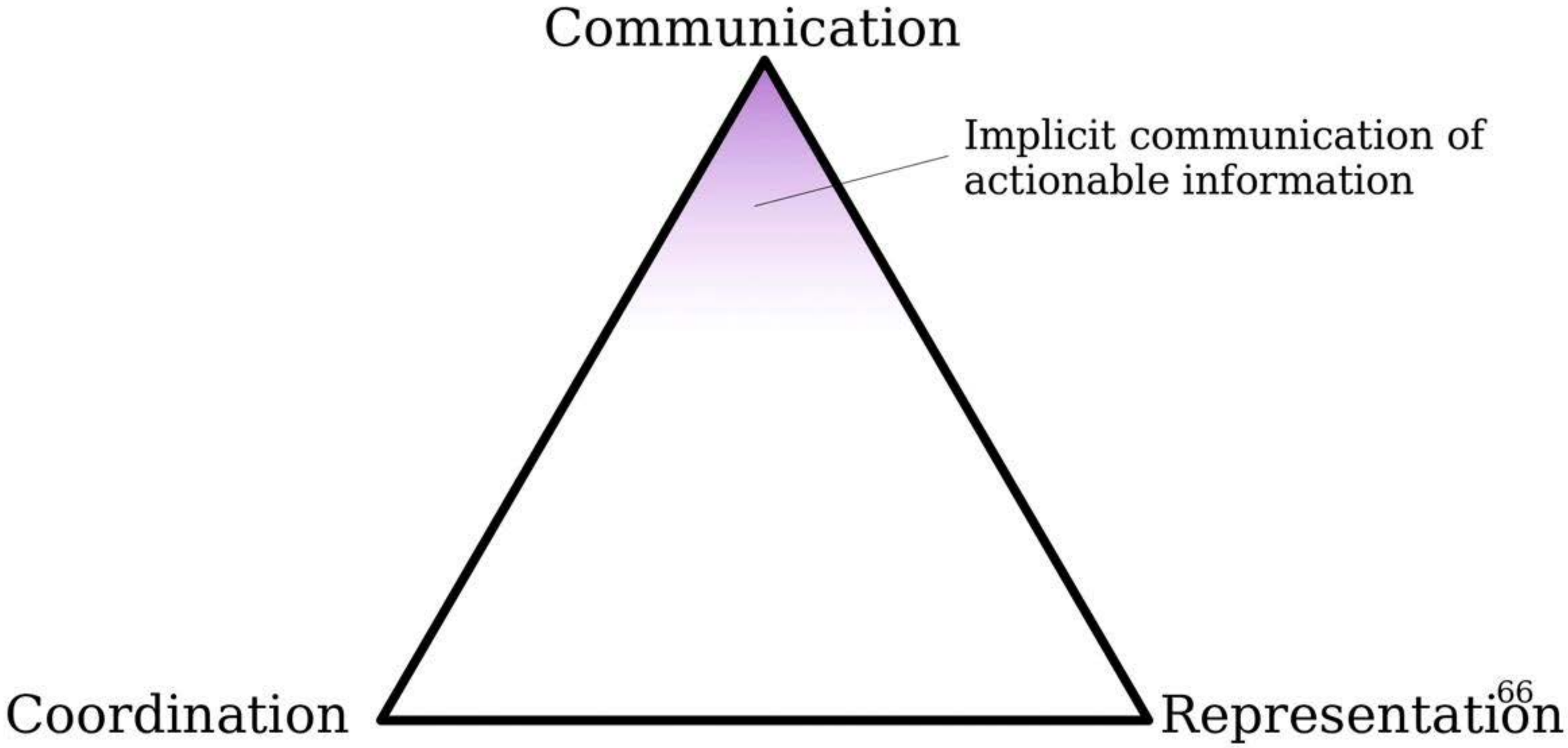
# Human Impressions

(H3): Participants consider the behavior generated by *TE* as more socially compliant, intelligent and safe than the rest of the strategies.

| | Sum Sq | Mean Sq | NumDF | DenDF | F value | Pr(>F) |
|---|---|---|---|---|---|---|
| Competent | 4.213 | 2.106 | 2 | 281.8 | 2.461 | 0.08718 |
| Responsible | 0.5827 | 0.2914 | 2 | 283.6 | 0.3275 | 0.721 |
| Predictable | 0.8303 | 0.4151 | 2 | 283.5 | 0.3567 | 0.7003 |
| Compliant | 4.485 | 2.242 | 2 | 281.8 | 2.859 | 0.05898 |
| Sensible | 2.252 | 1.126 | 2 | 281.3 | 1.298 | 0.2746 |
| Friendly | 2.969 | 1.485 | 2 | 281.9 | 1.621 | 0.1995 |
| Safe | 0.3328 | 0.1664 | 2 | 282 | 1.579 | 0.2081 |
| Pleasant | 1.751 | 0.8757 | 2 | 282.5 | 1.045 | 0.353 |
| Polite | 0.8741 | 0.437 | 2 | 281.8 | 0.6325 | 0.532 |
| Coordinated | 3.725 | 1.862 | 2 | 281.8 | 1.787 | 0.1693 |
| Intelligent | 4.485 | 2.243 | 2 | 282.7 | 2.948 | 0.05408 |
| Trustworthy | 0.7167 | 0.3583 | 2 | 281.4 | 0.5948 | 0.5524 |
| Socially Aware | 0.4268 | 0.2134 | 2 | 282.1 | 1.904 | 0.1509 |
| Discreet | 0.5737 | 0.2868 | 2 | 281.7 | 3.064 | 0.04824 |
| Relaxed | 0.3005 | 0.1503 | 2 | 283 | 1.613 | 0.2012 |
| Calm | 2.75 | 1.375 | 2 | 282.3 | 1.266 | 0.2836 |
| Tranquil | 0.2294 | 0.1147 | 2 | 284.5 | 0.1209 | 0.8861 |
| Robot noticeable | 3.25 | 1.625 | 2 | 283.2 | 1.399 | 0.2486 |
| Predict future | 0.3725 | 0.1862 | 2 | 283.5 | 0.1566 | 0.8551 |
| Bump future | 6.883 | 3.442 | 2 | 282.6 | 2.415 | 0.09117 |

Questionnaire based on [Bartneck et al., '09]

# Teamwork in a Joint Activity



# Implicit Communication In a Joint Action

**[Knepper, Mavrogiannis, Proft, and Liang, HRI 2017]**

Christoforos Mavrogiannis

Julia Proft

Claire Liang

# Implicit Communication In a Joint Action

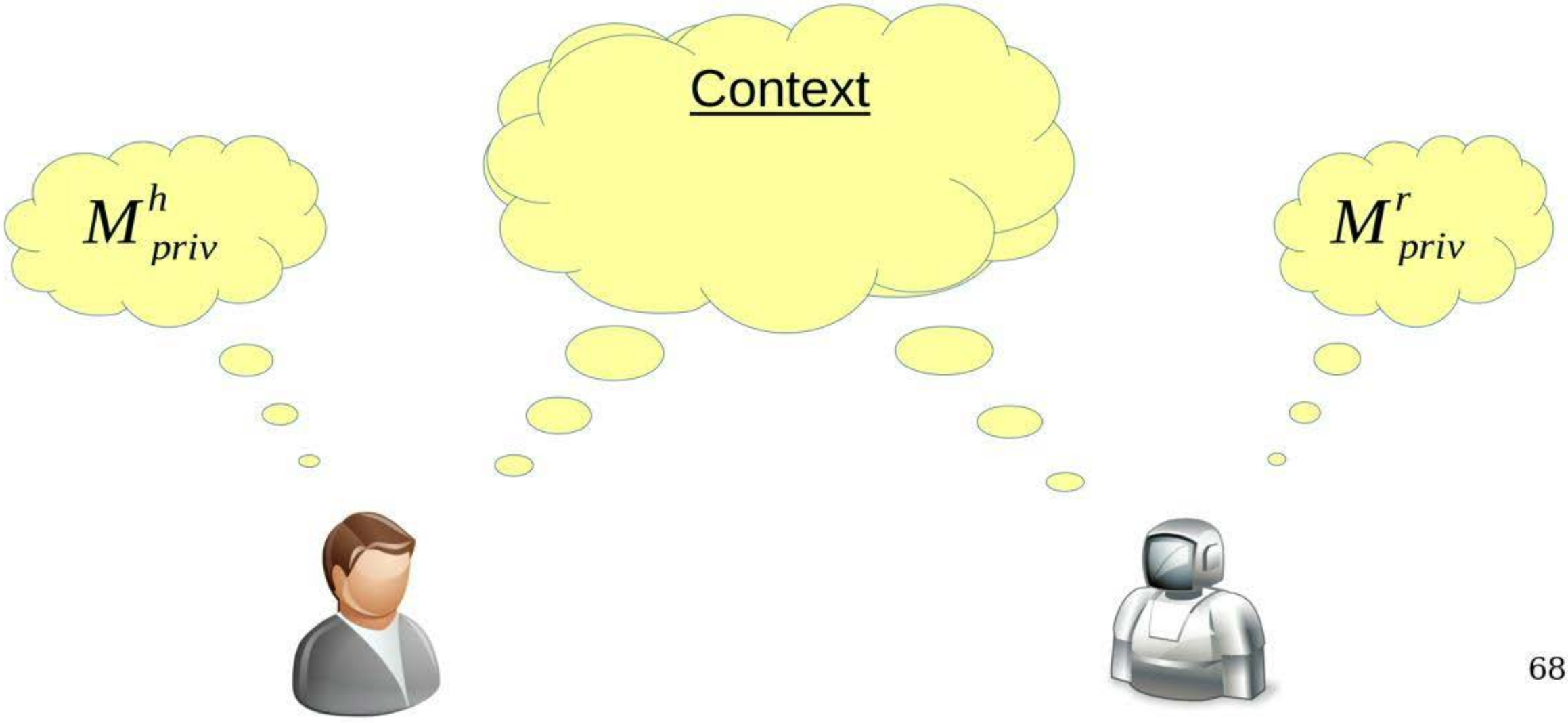
**[Knepper, Mavrogiannis, Proft, and Liang, HRI 2017]**

# Implicit Communication Model

$M^{h}_{priv}$

$M^{r}_{priv}$

# Implicit Communication Model



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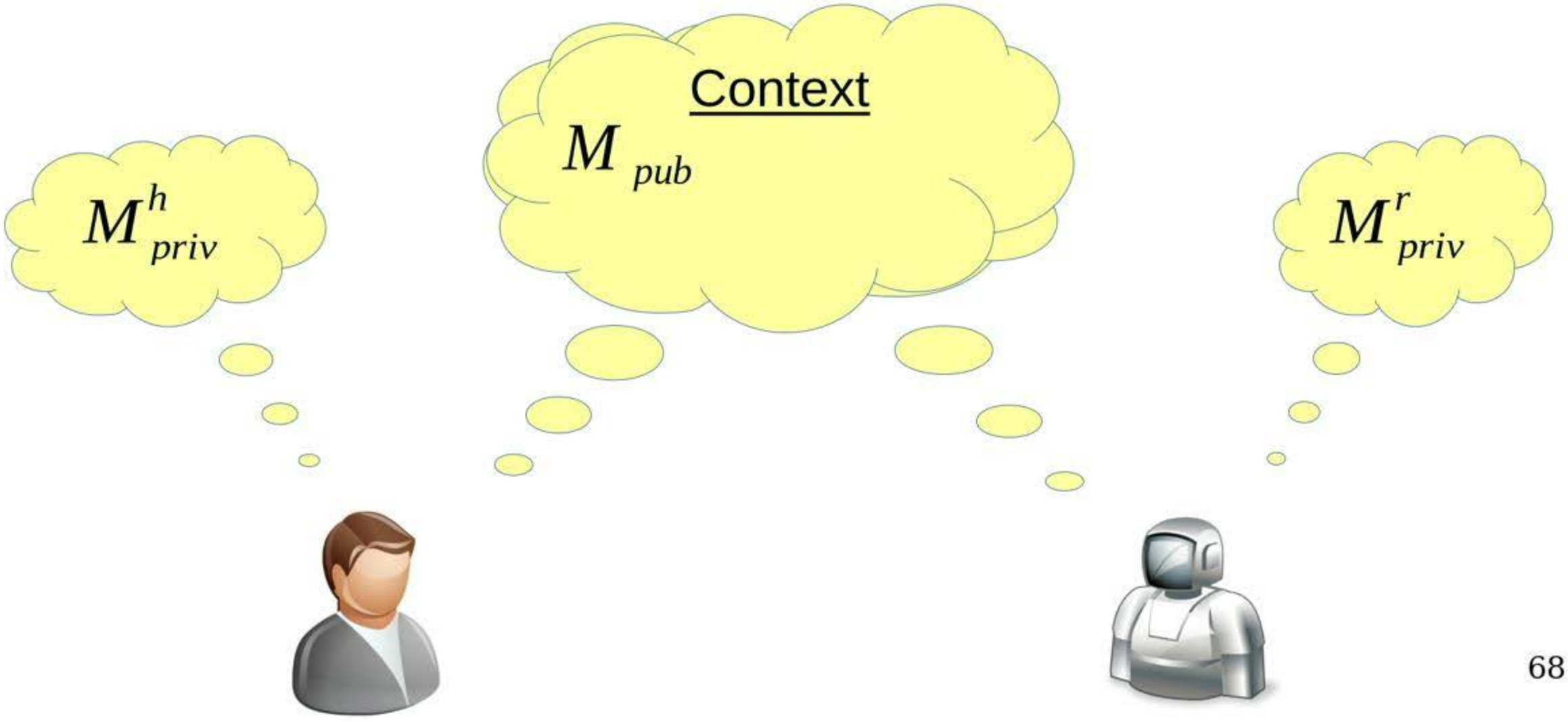

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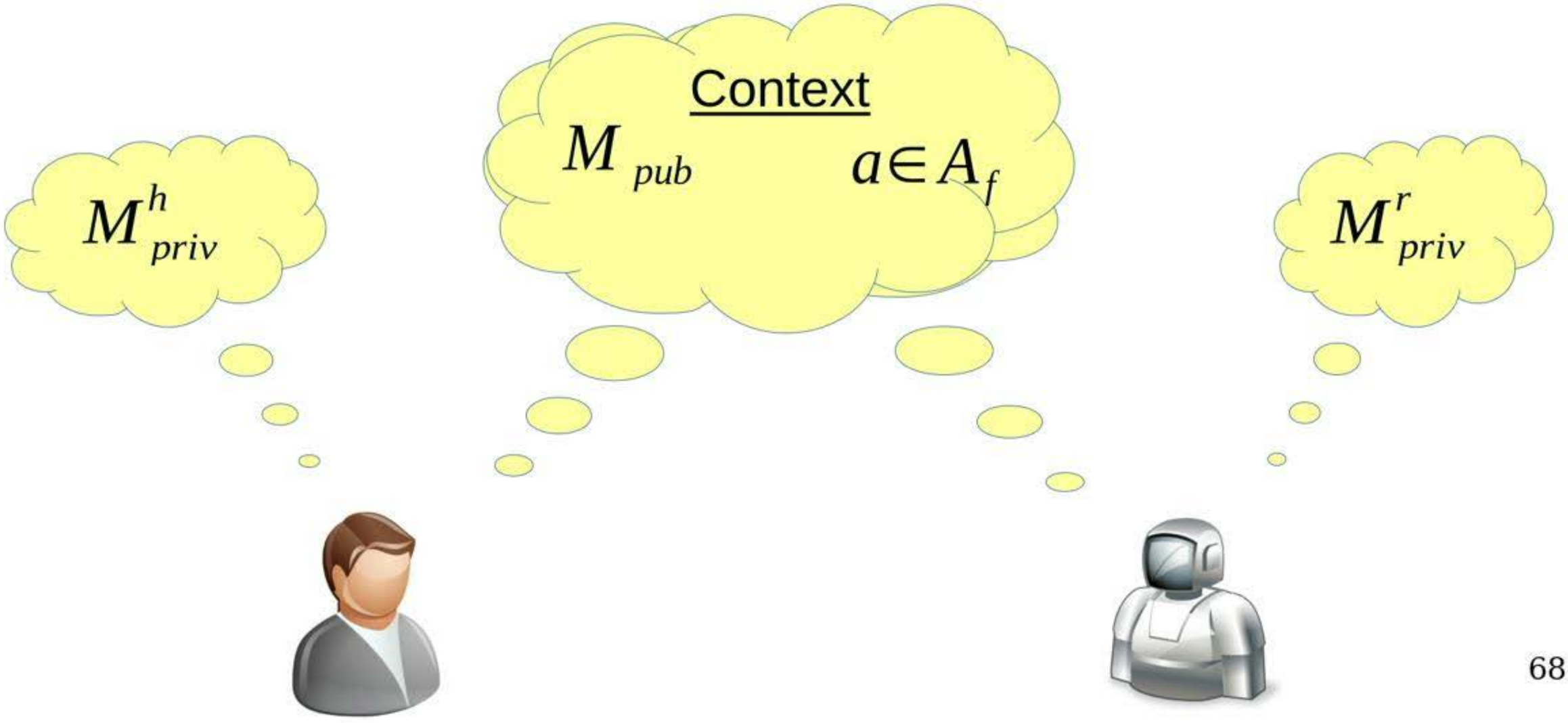

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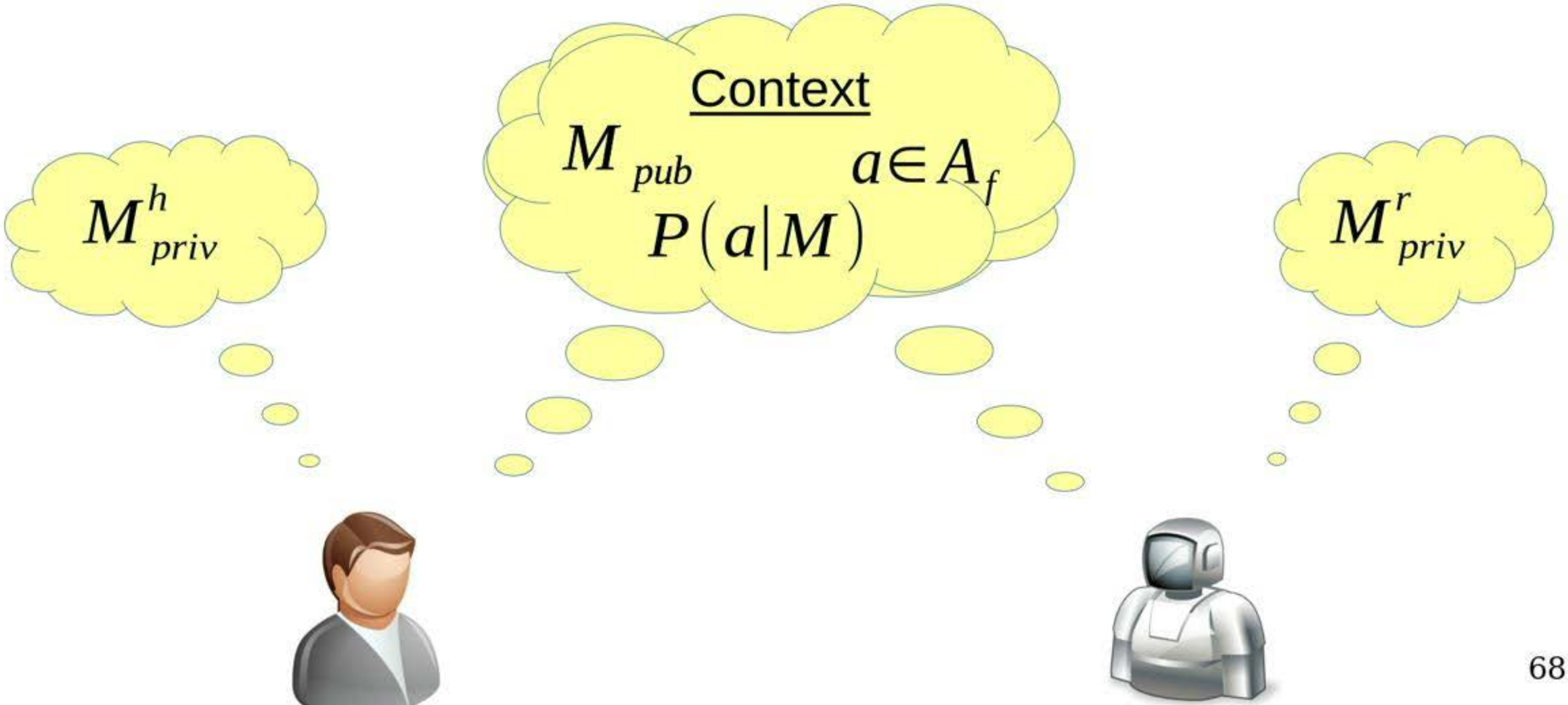


# Implicit Communication Model

$\hat{m}$

$M^{h}_{priv}$

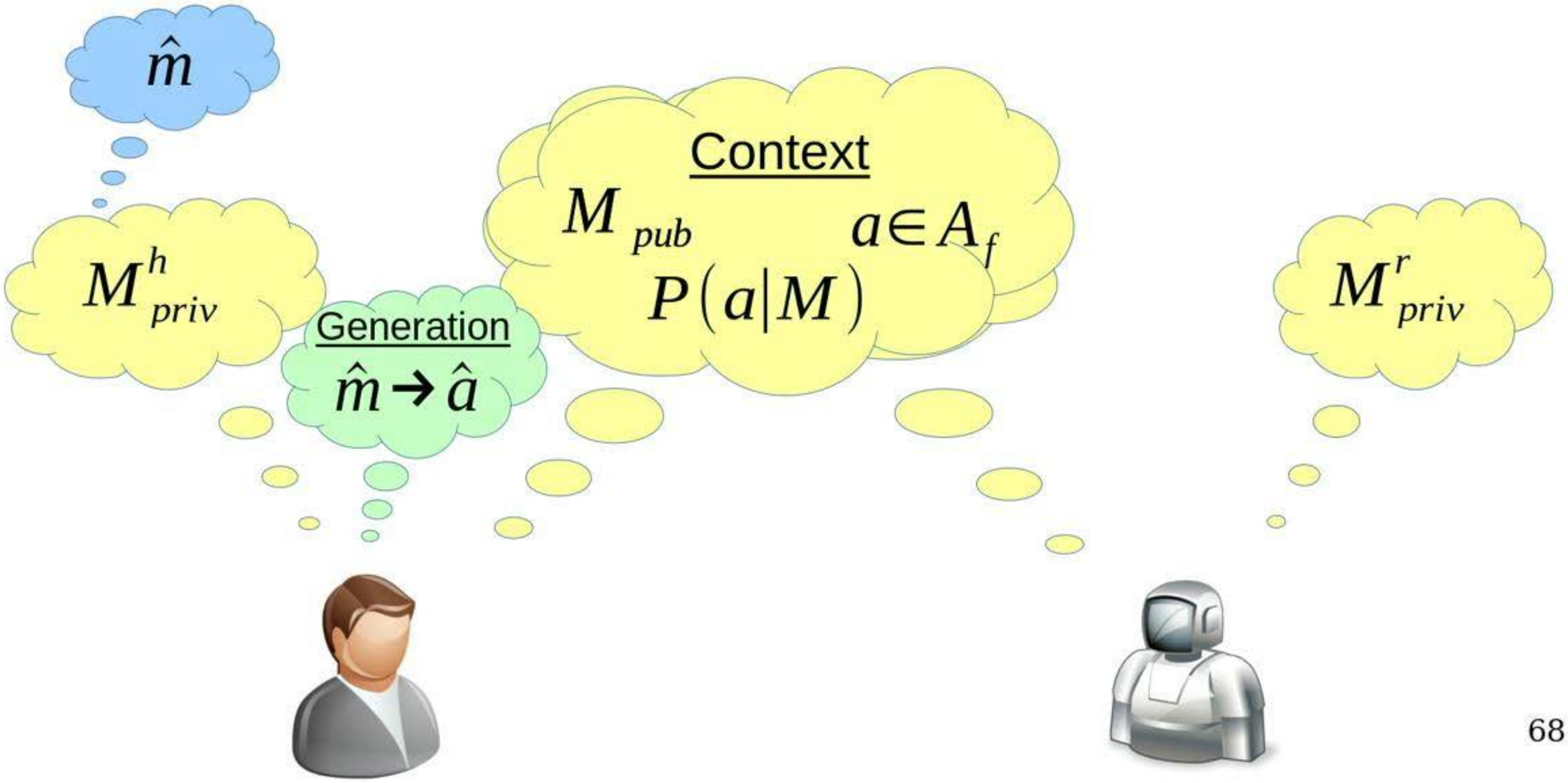
Context

$M_{pub}$ $a \in A_f$

$P(a|M)$

$M^{r}_{priv}$

# Implicit Communication Model



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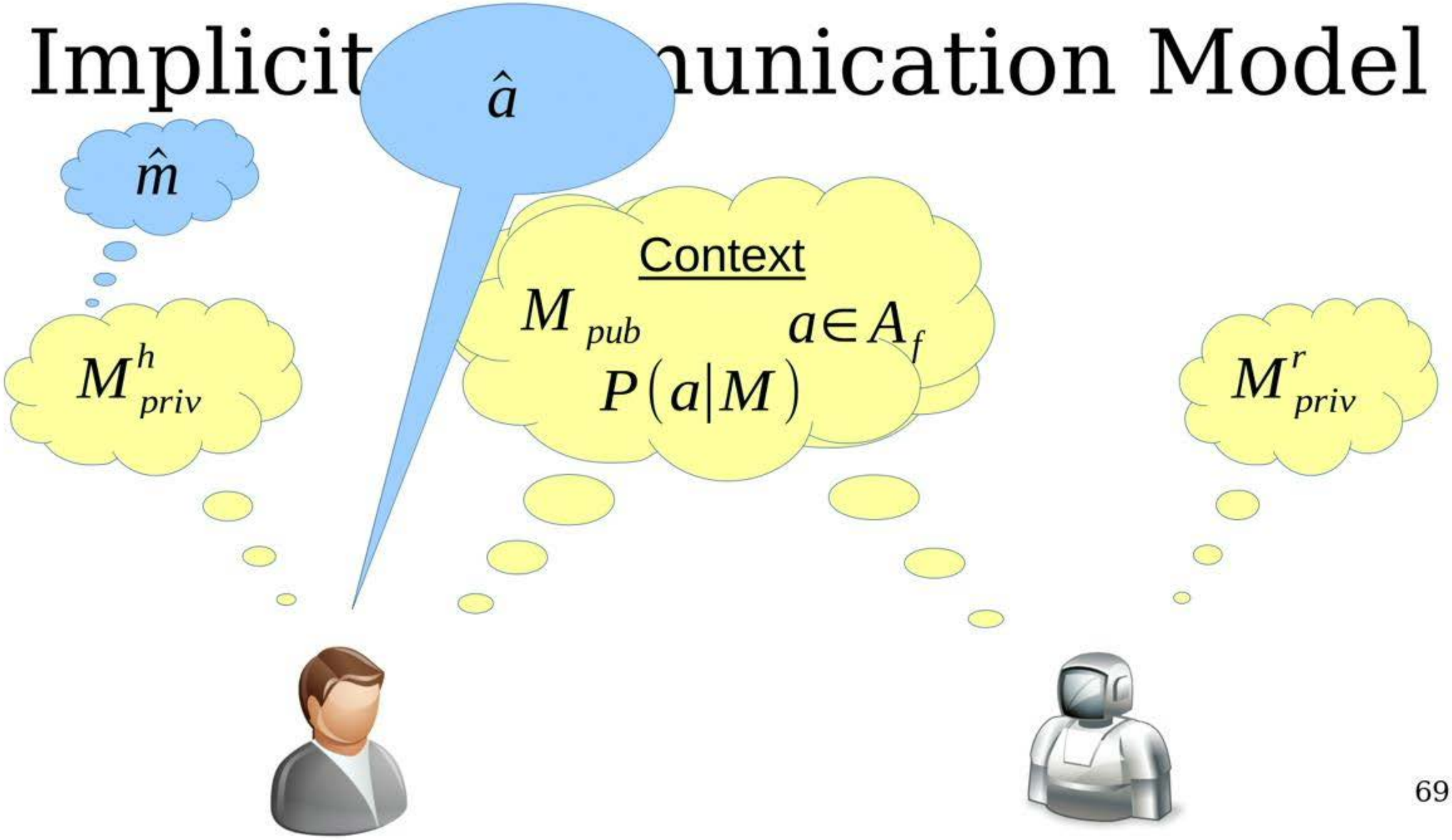

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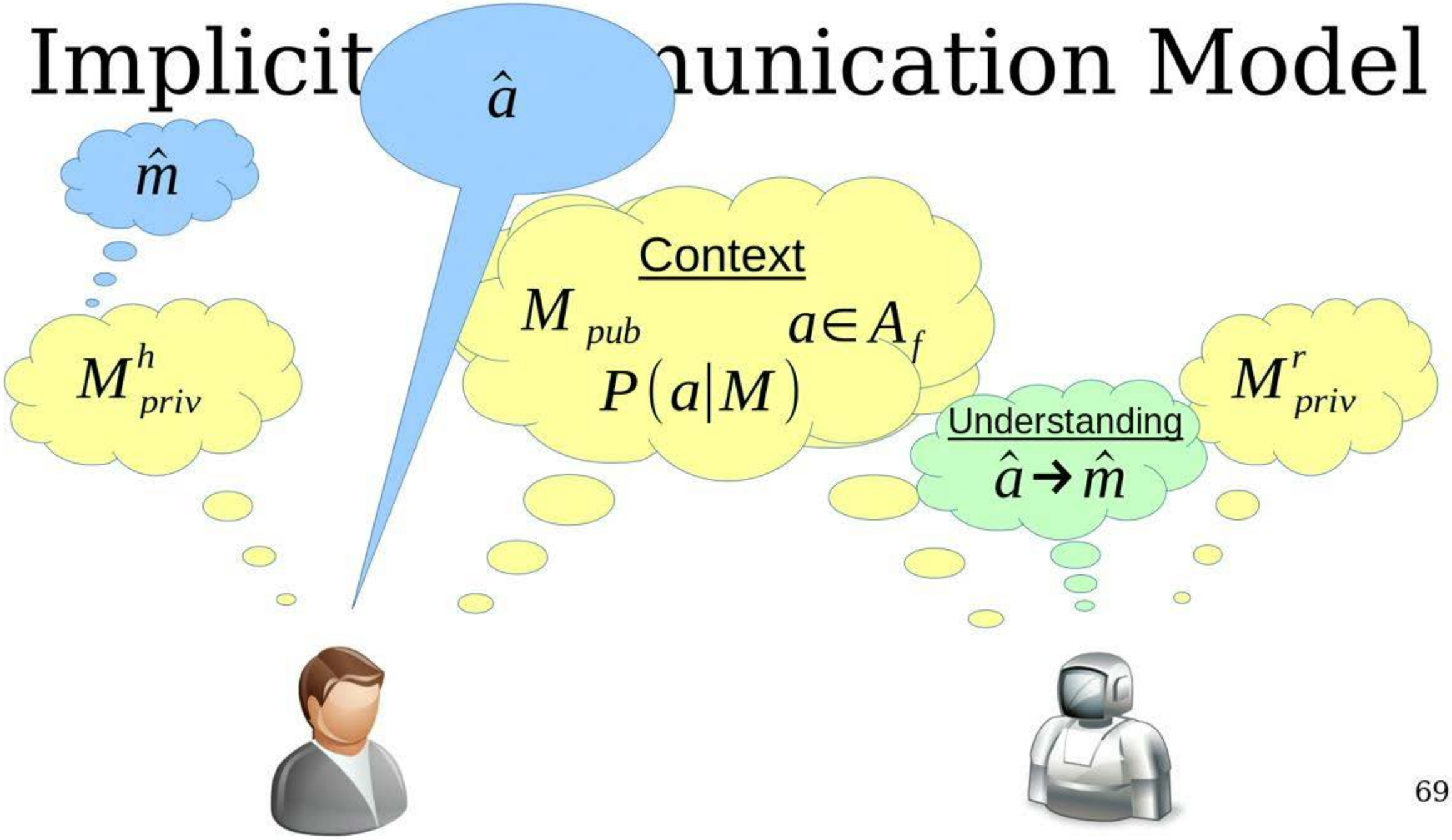

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$M^r_{priv}$

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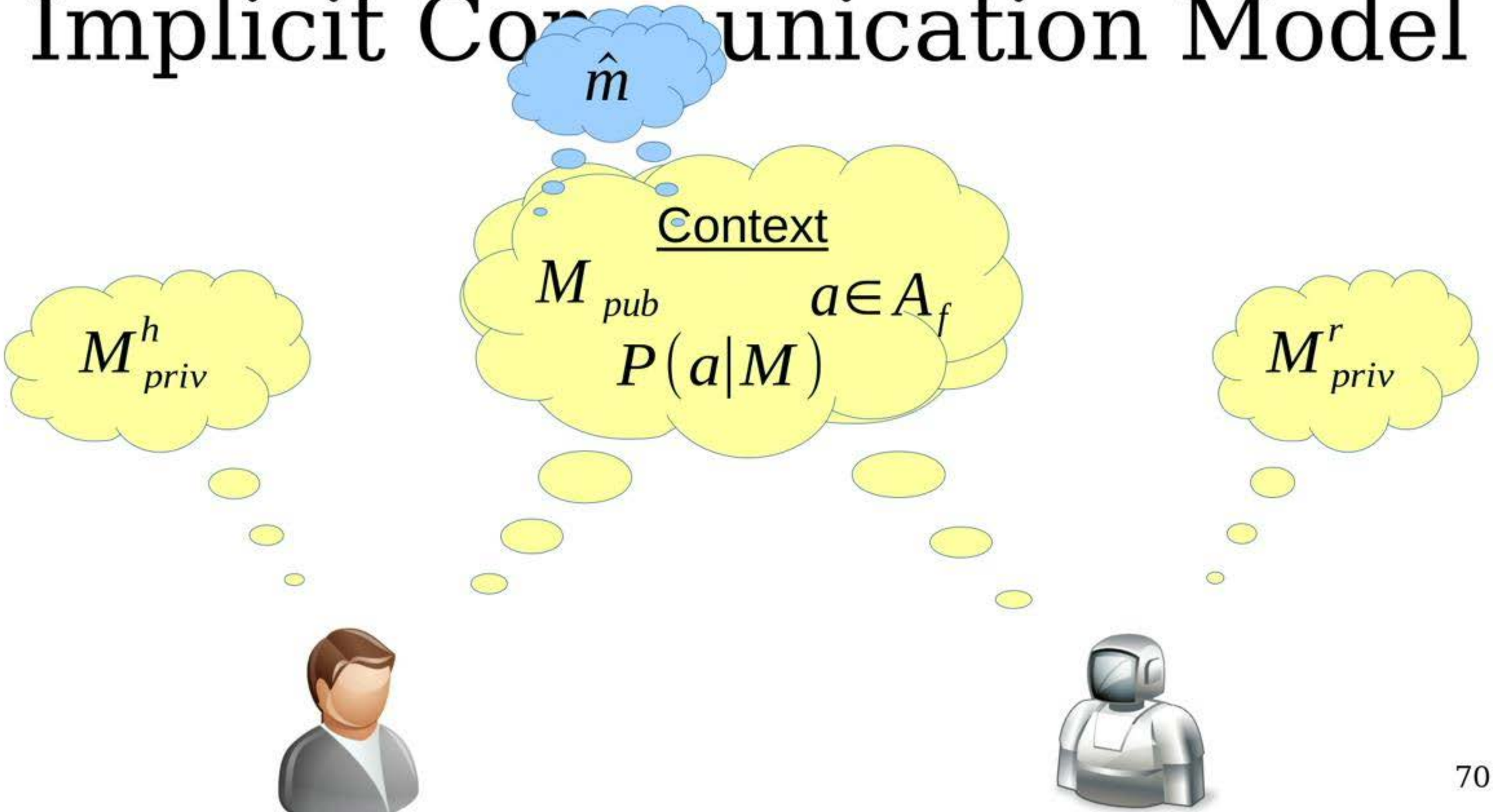

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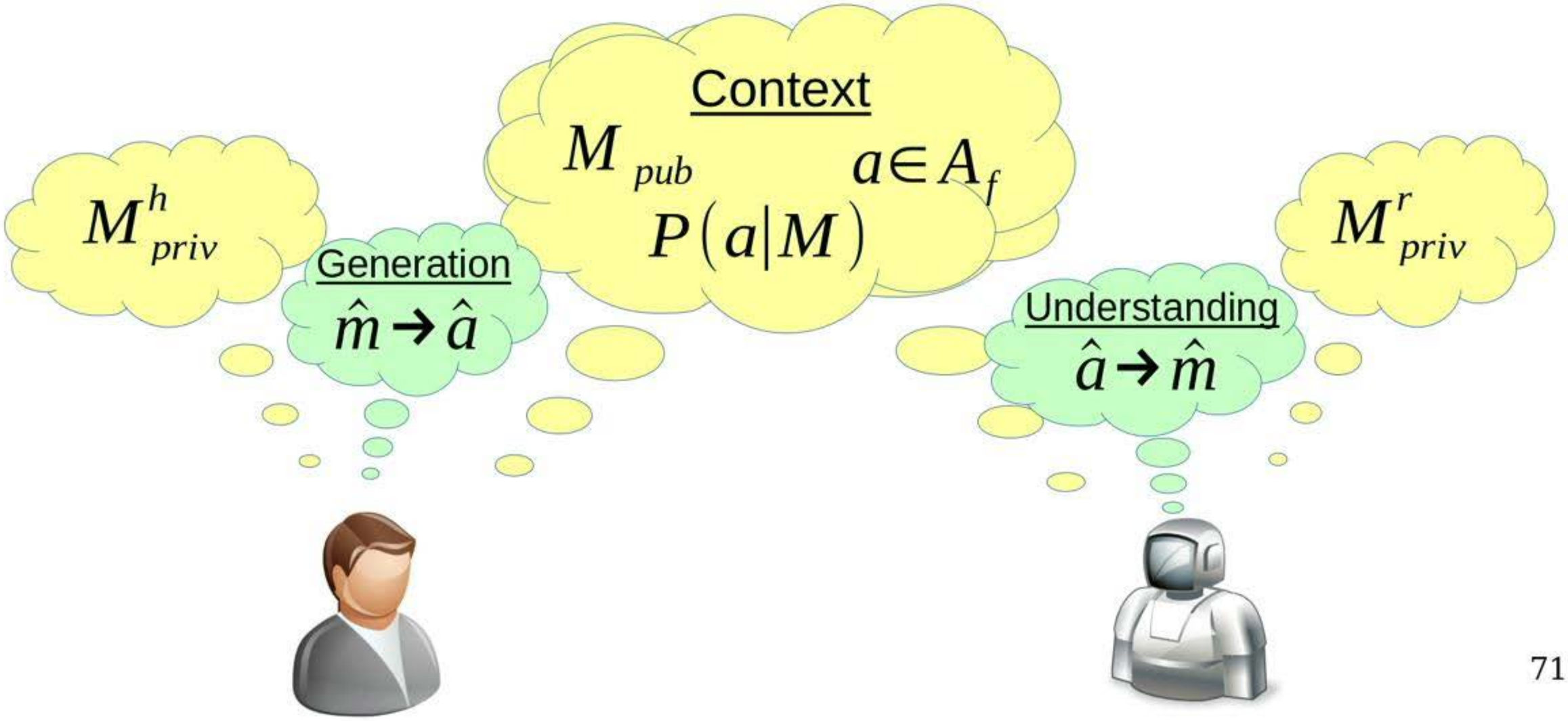
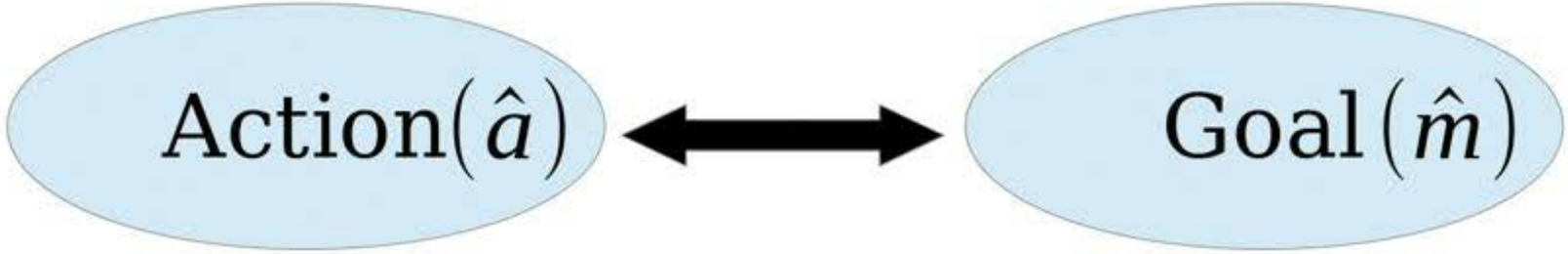


# Mechanism

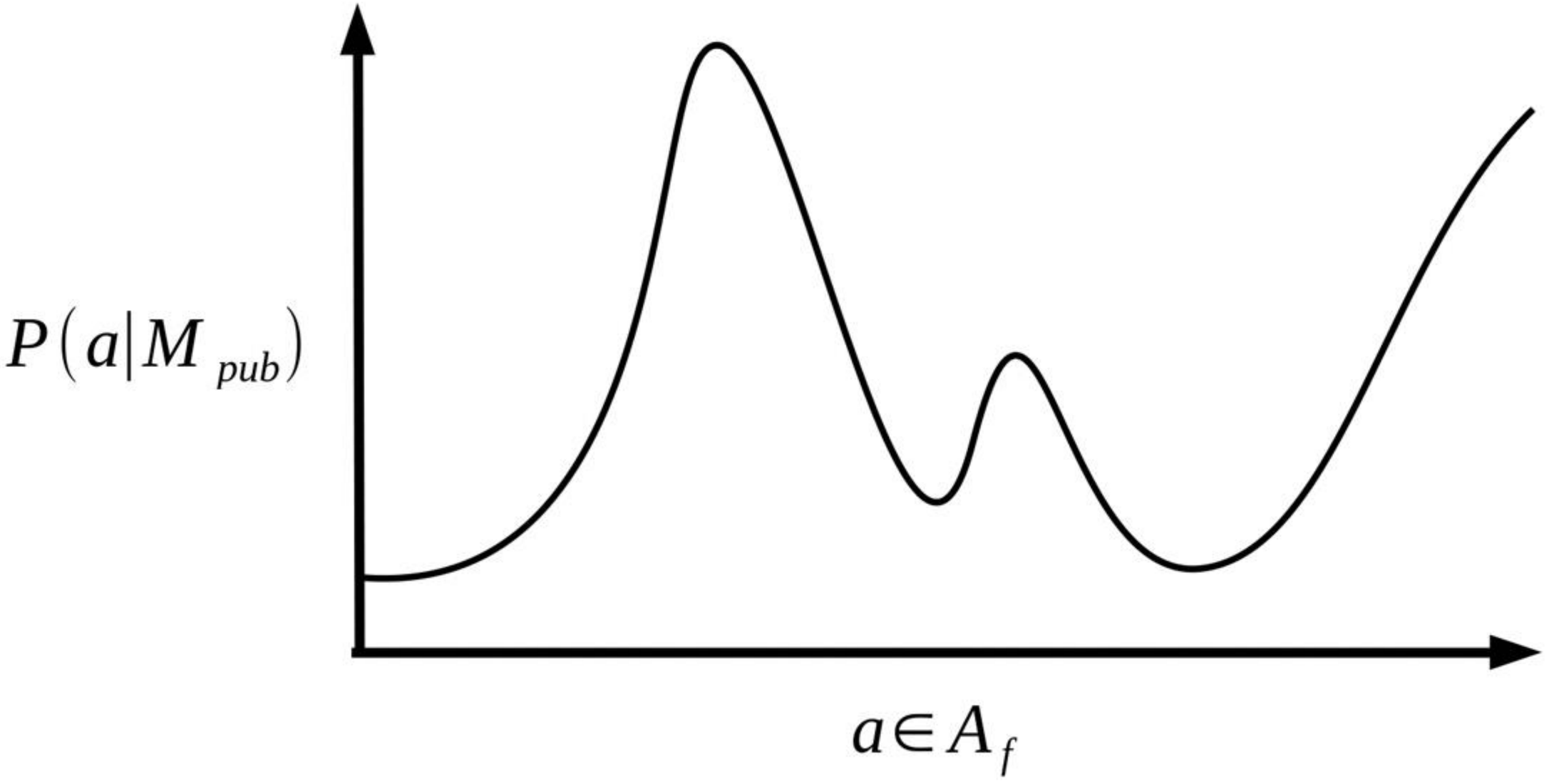
- Teleological reasoning:




**[Csibra and Gergely, 2007]**


**[Dragan and Srinivasa, 2014]**

# How to Encode the Message?



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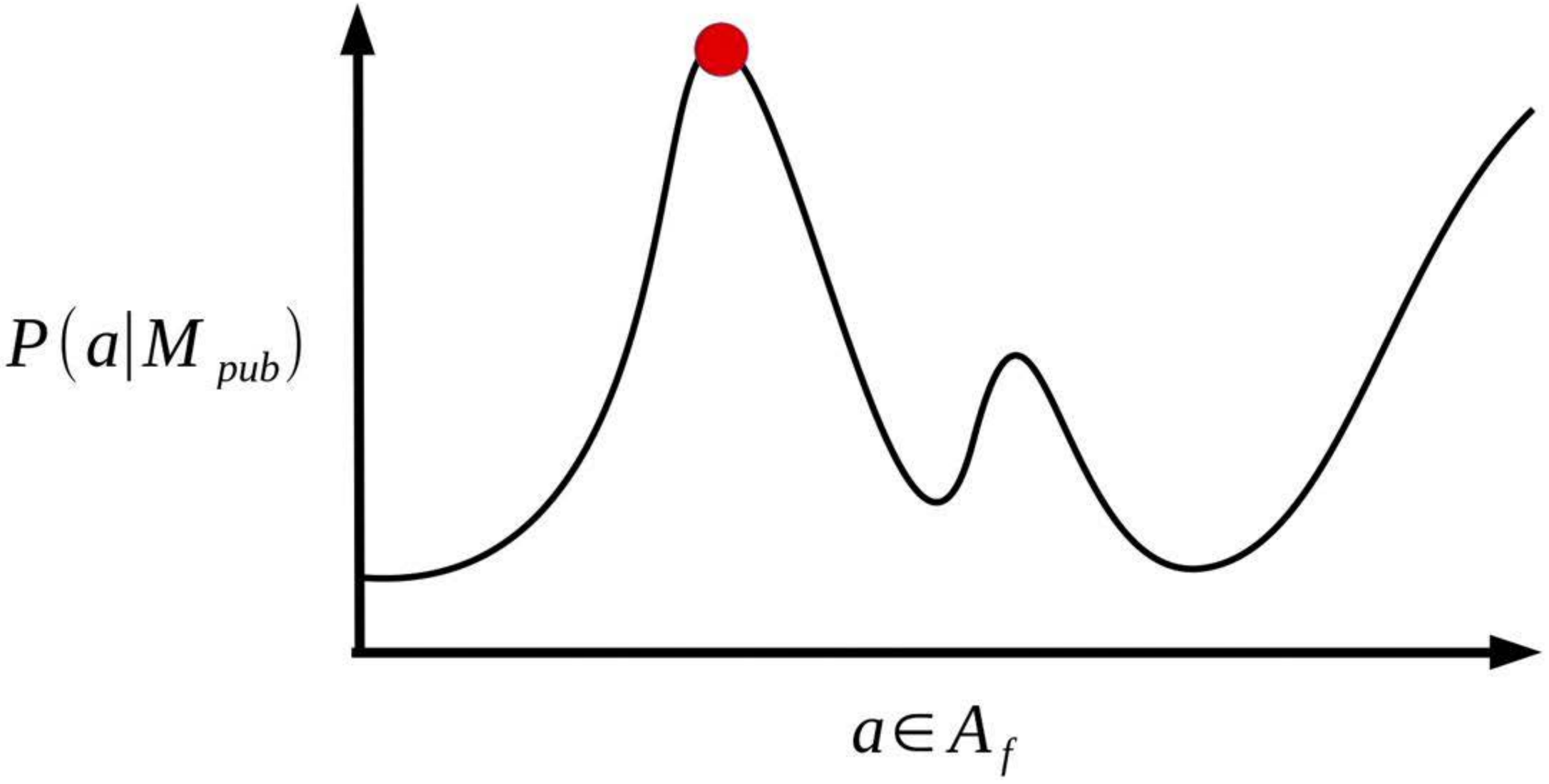

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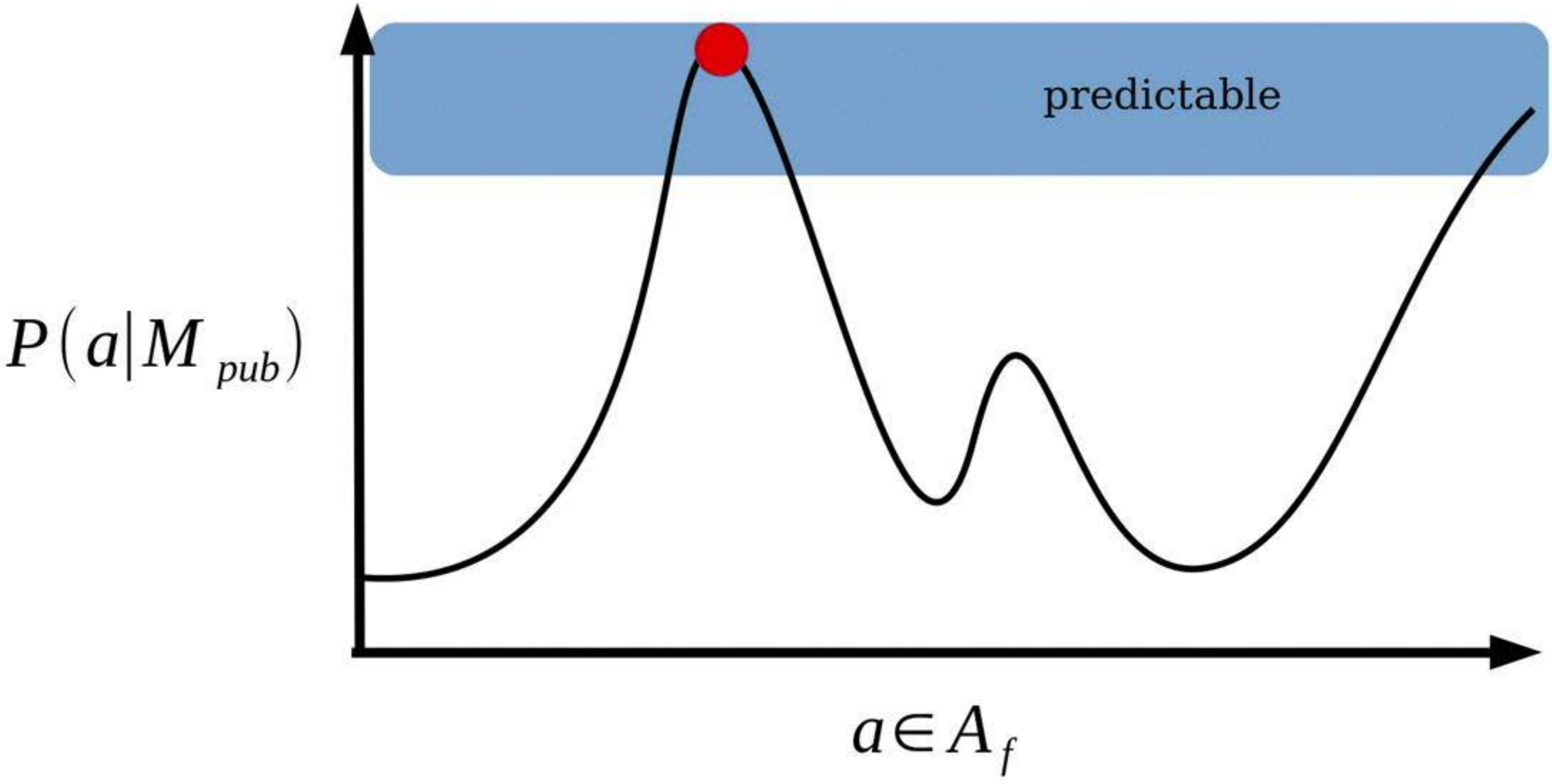

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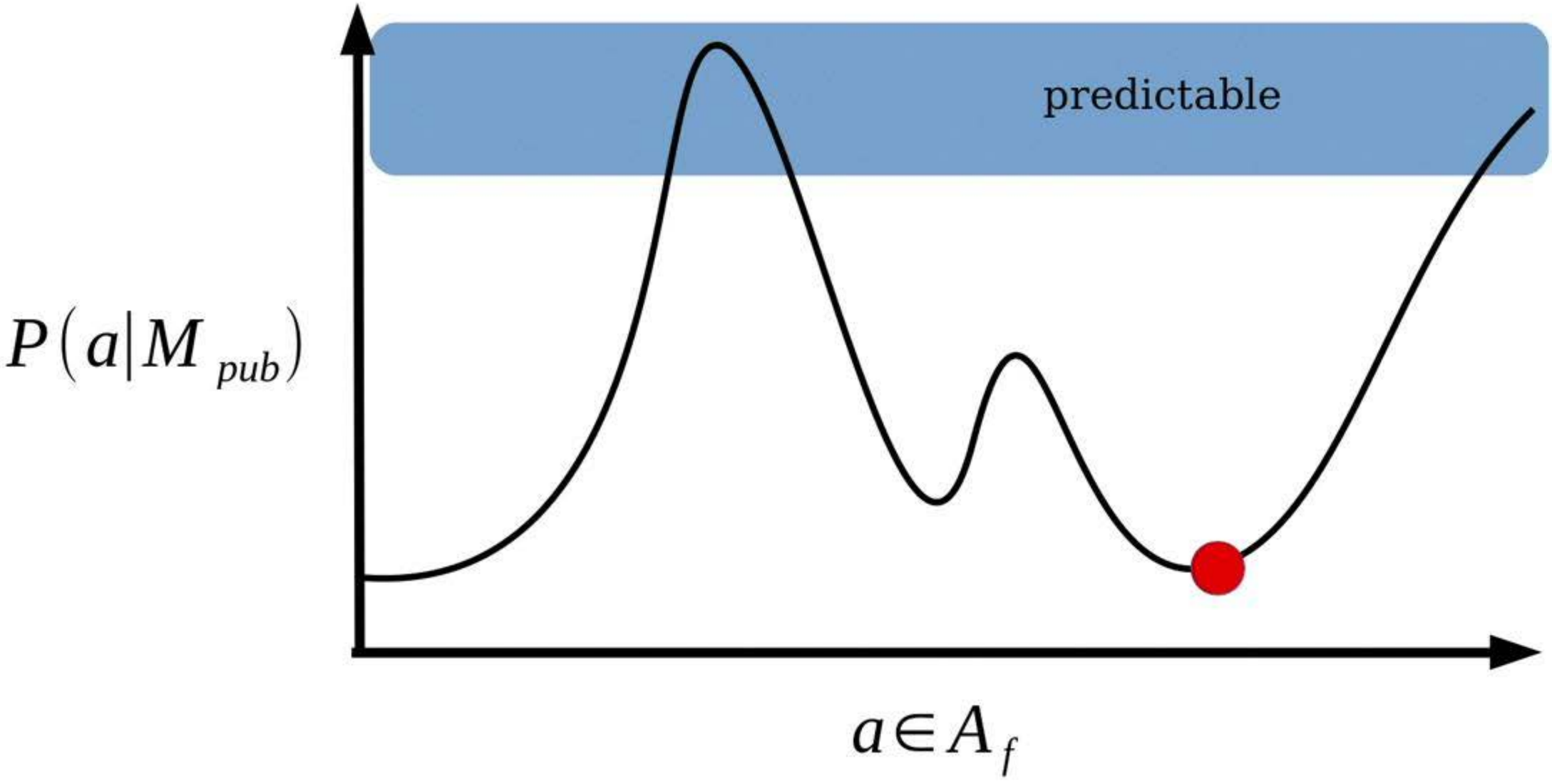

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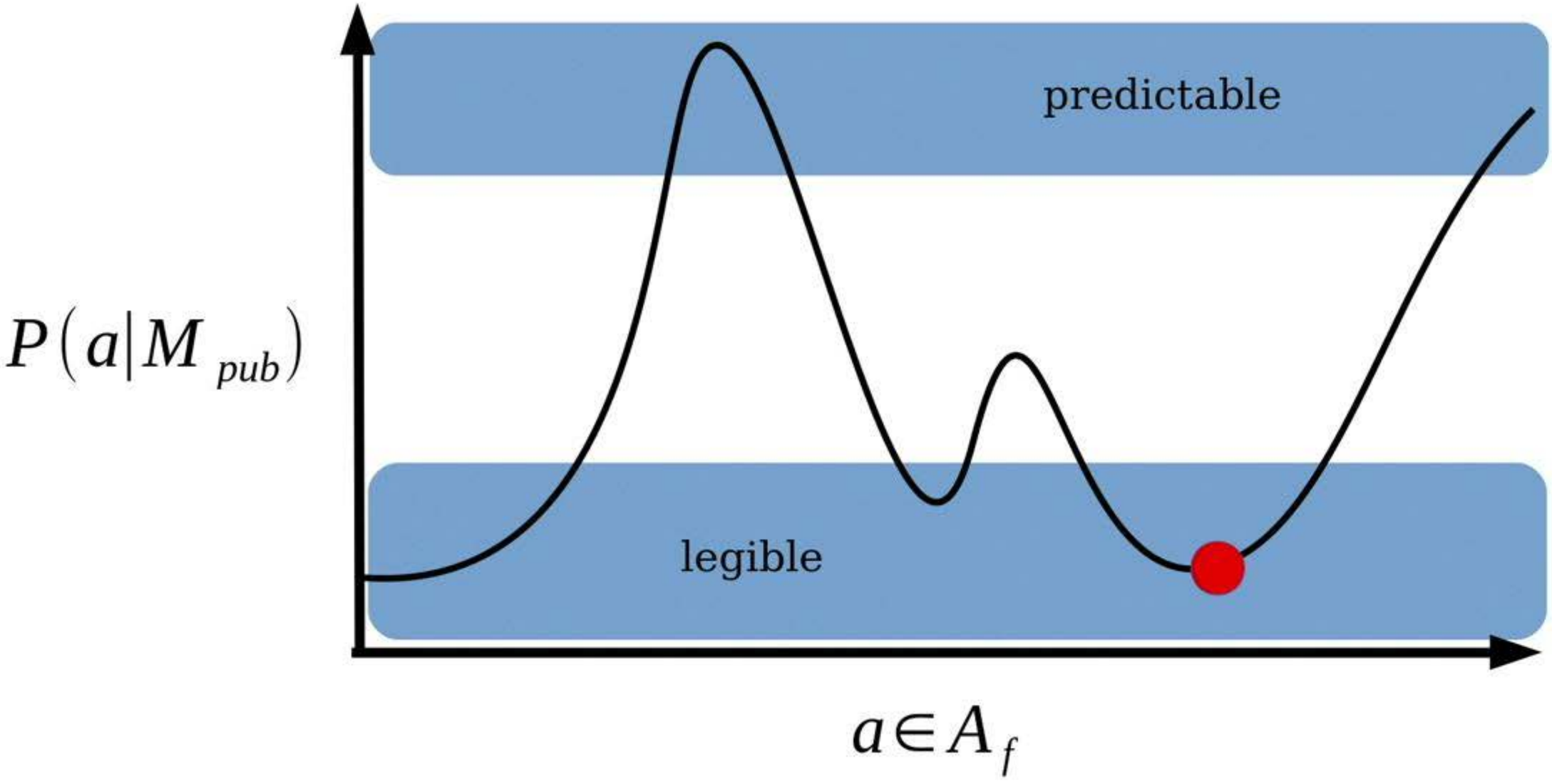

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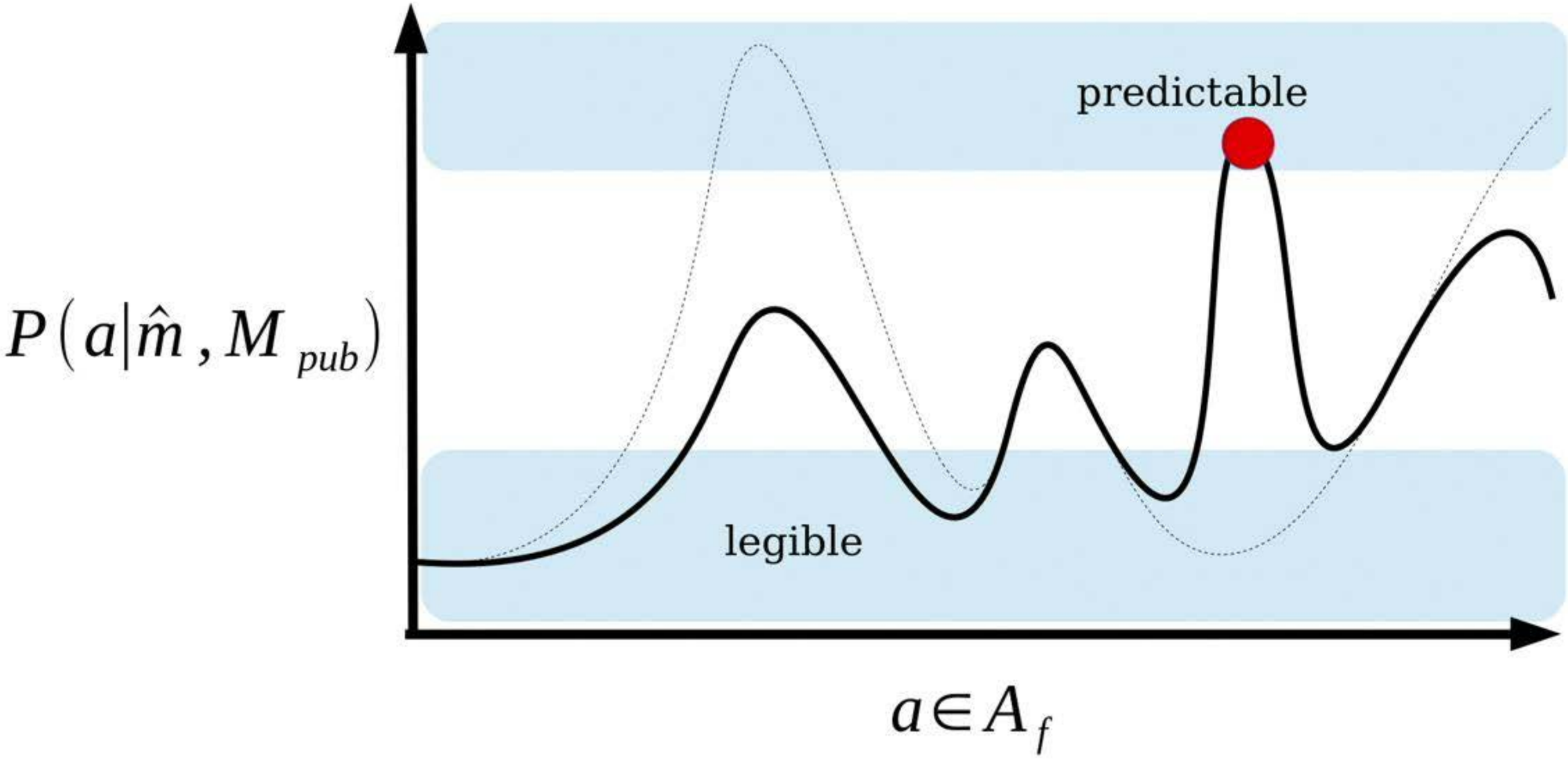


# How to Encode the Message?

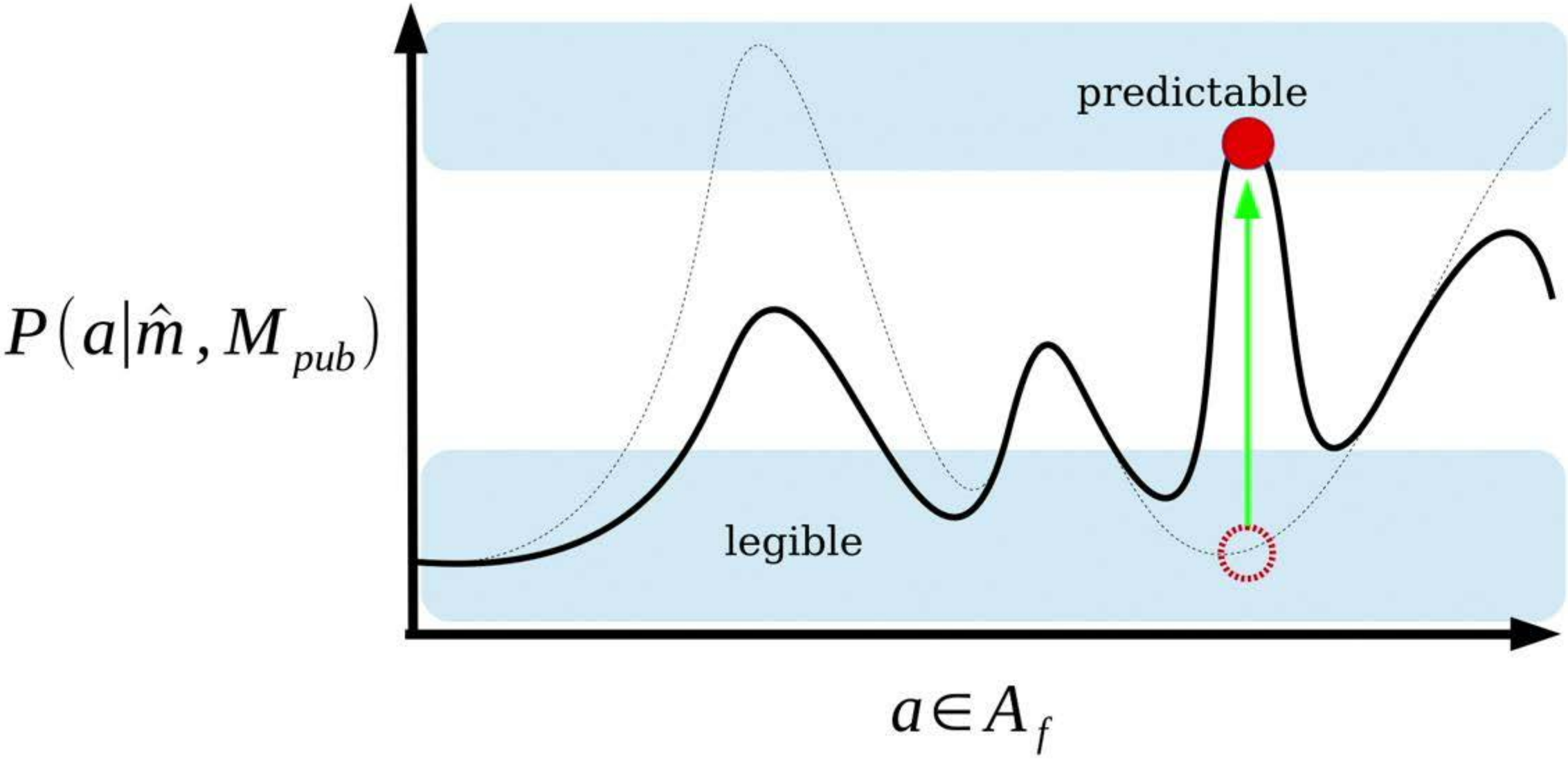
Understanding: $\hat{m} \leftarrow \underset{m \in M}{argmax}\, P\left(m|\hat{a}, M_{pub}\right)$

$$\hat{m} \leftarrow \underset{m \in M}{argmax}\, P\left(\hat{a}|m, M_{pub}\right) P\left(m|M_{pub}\right)$$

Generation: $\hat{a} \leftarrow \underset{a \in A_f}{argmax}\, P\left(\hat{m}|a, M_{pub}\right)$

$$\hat{a} \leftarrow \underset{a \in A_f}{argmax} \frac{P\left(a|\hat{m}, M_{pub}\right)}{P\left(a|M_{pub}\right)}$$

# How to Encode the Message?



# How to Encode the Message?

**Common goal: maximize confidence of observer!**

Understanding: $\hat{m} \leftarrow \underset{m \in M}{argmax}\, P\left(m|\hat{a}, M_{pub}\right)$

$$\hat{m} \leftarrow \underset{m \in M}{argmax}\, P\left(\hat{a}|m, M_{pub}\right) P\left(m|M_{pub}\right)$$

Generation: $\hat{a} \leftarrow \underset{a \in A_f}{argmax}\, P\left(\hat{m}|a, M_{pub}\right)$

$$\hat{a} \leftarrow \underset{a \in A_f}{argmax} \frac{P\left(a|\hat{m}, M_{pub}\right)}{P\left(a|M_{pub}\right)}$$

# Practical Examples in Prior Work

Motion

Convey car intentions
[Huang, et al arXiv 2017]

Socially competent navigation
[Mavrogiannis and K WAFR 2016]

Legibility
[Dragan and Srinivasa HRI 2013]

Conveying weight by lifting
[Sciutti, et al TAMD 2014]

Language

Inverse semantics
[K, et al AuRo 2015]

Convey uncertainty
[Hough and Schlangen HRI 2017]

Implicature
[Grice 1975]
[Goodman and Stuhlmüller 2013]
[Vogel, Potts, and Jurafsky 2013]

# Types of Inference

- Deduction
  - A→B: Powering off results in missing data.
  - A: I was powered off.
  - *B: I have missing data.*
- Induction
  - A: I was powered off.
  - B: I have missing data.
  - *A→B: Powering off results in missing data.*
- Abduction
  - A→B: Powering off results in missing data.
  - B: I have missing data.
  - *A: I was powered off.*

Traditional logic

Machine learning, Bayesian inference

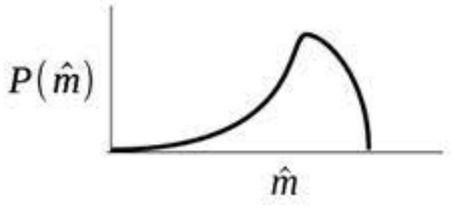
Inference to the best explanation

**[CS Peirce, 1901]**

# Inductive inference in robotics

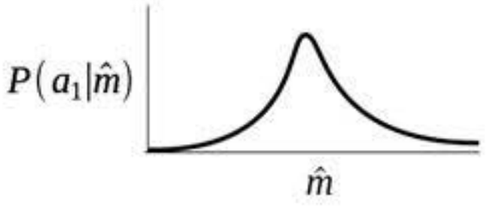
Bayes Filter

Prior

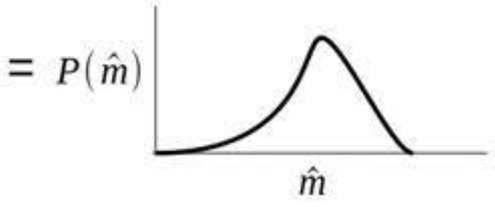



x

Observation

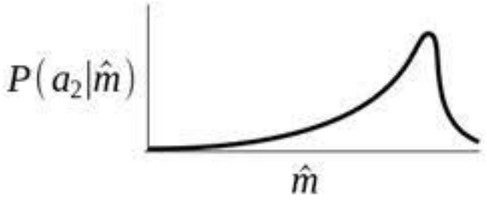



Posterior

= 


x

Observation

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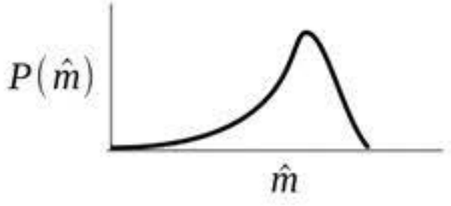
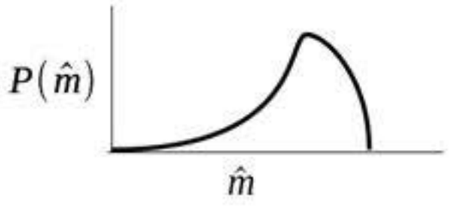



# Abductive inference in robotics

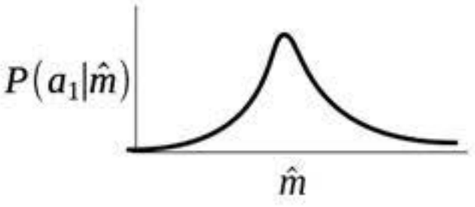
"Abductive Filter" = Scientific Method

Prior

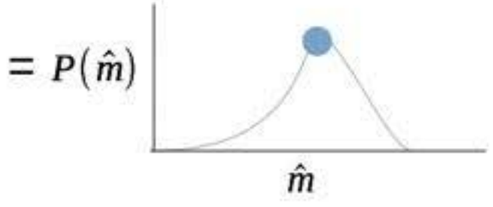



x

Observation

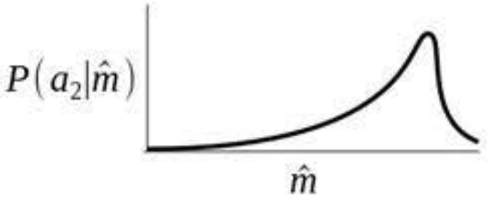



Posterior

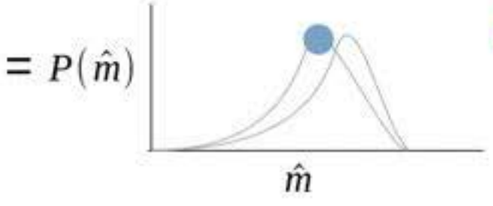
= 


x

Observation



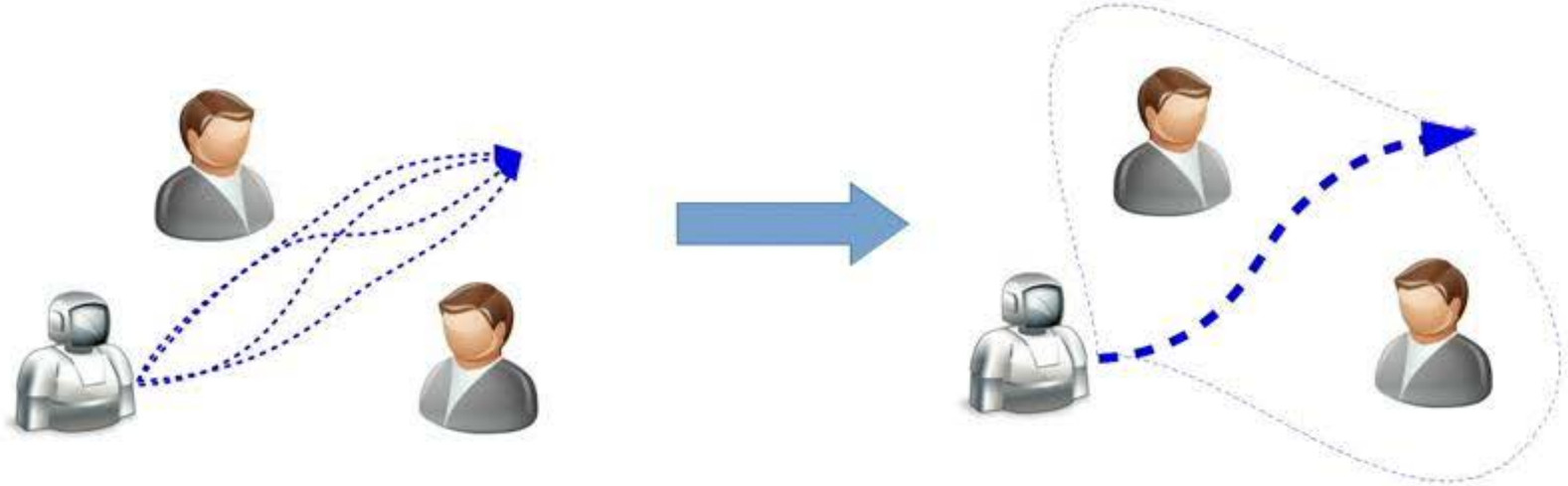

Posterior




**Accept or Reject Hypothesis**

# Abduction In Teams

- Robustness to perturbations
- Promotes team confidence



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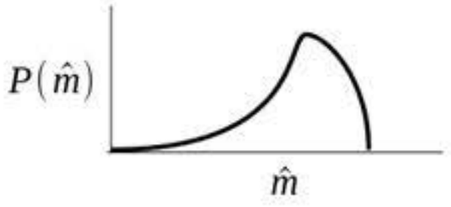
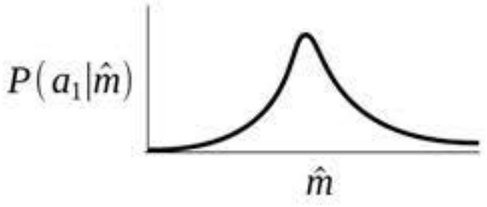
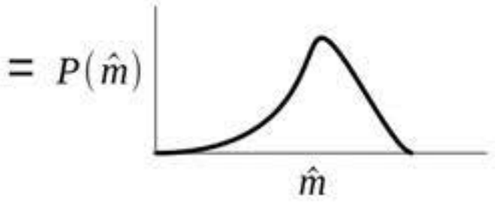



x

Observation

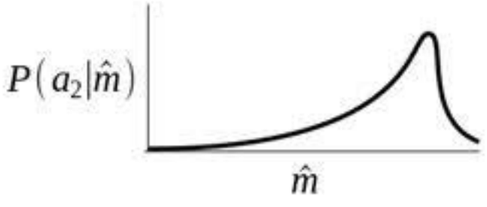



Posterior

= 


x

Observation

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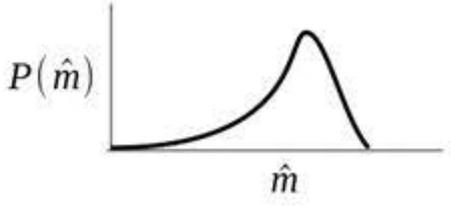


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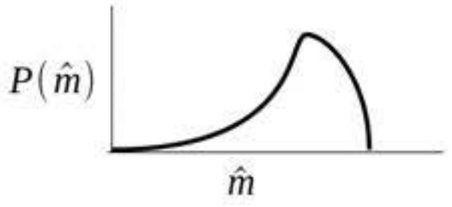
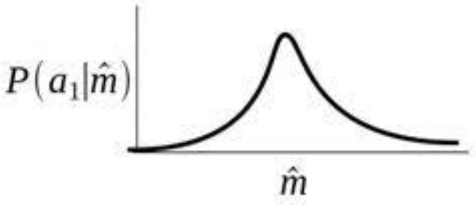
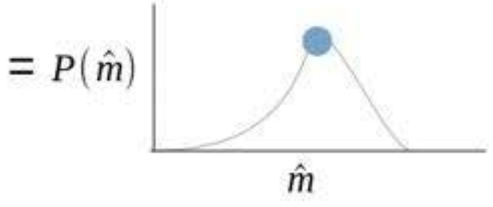



x

Observation

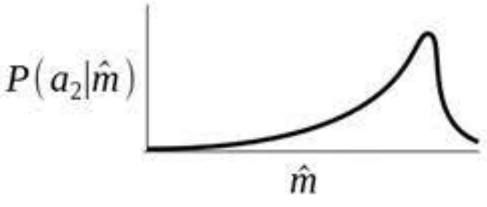



Posterior

= 


x

Observation

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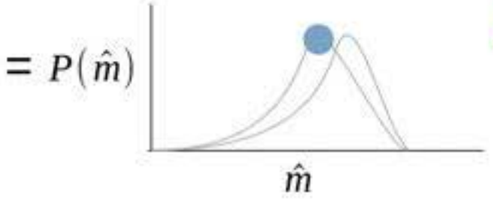


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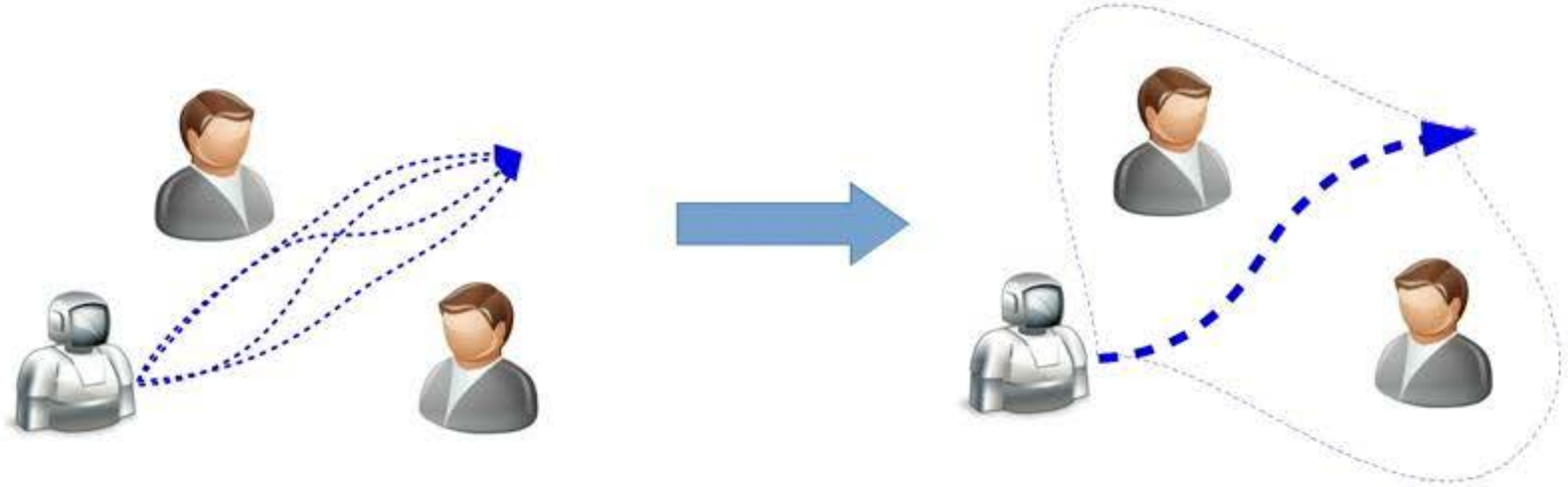
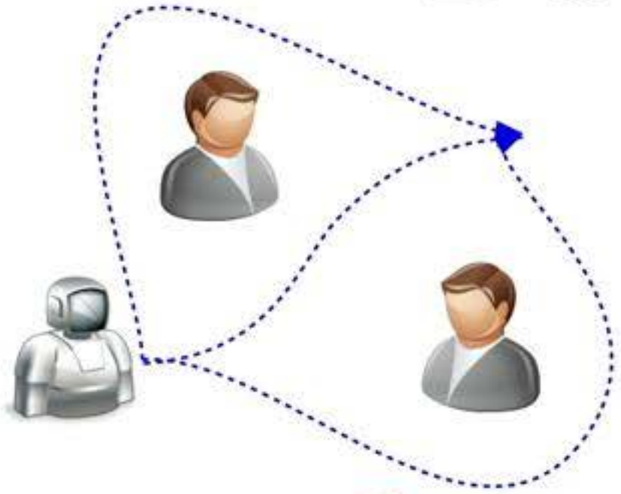
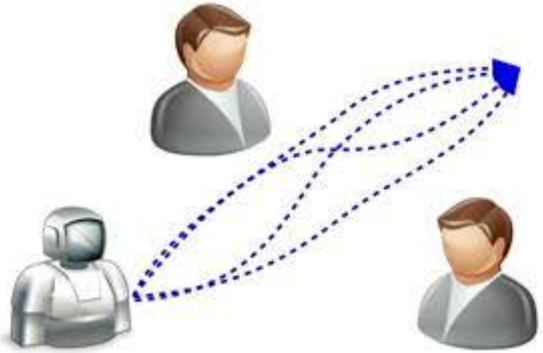
- Robustness to perturbations
- Promotes team confidence



# Decision-Making





Agency of Decisions

Team

Individual

Granularity of Action

Discrete/coarse

Continuous/fine

Emanuel Gottlieb Leutze
*Westward the Course of Empire Takes Its Way*

# Closing the Frontier

- Fewer, larger problems
- More replication of results
- More scientific, less engineering outlook
- More standardized metrics and benchmarks
  - without being beholden to them