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Close Enough

How Humans Develop a Simplified Model of Objects & Their Physics

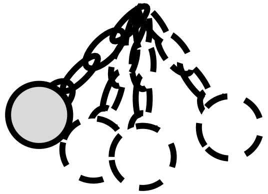
NSF
JACOBS FOUNDATION
John Templeton Foundation
DARPA
HARVARD Mind Brain Behavior

Tomer Ullman, Harvard University

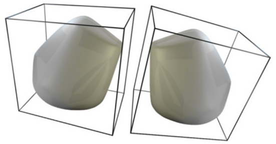
Collège de France, 2024

Overview

"What's Your Deal?"



Intuitive Physics, from Babies to Adults



Approximate Bodies

Partial Simulation

Imagery & Imagination

Non-Commitment

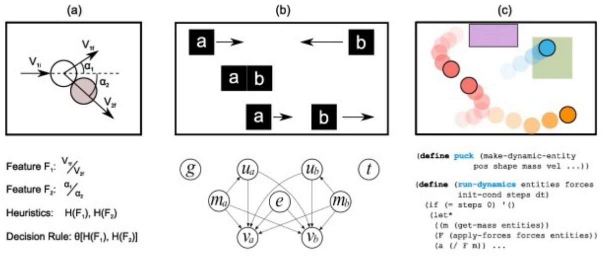
Visual Pretense

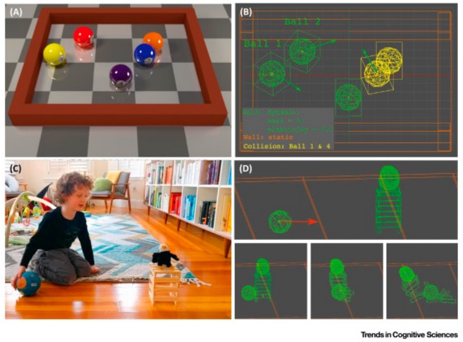
My Background

cocodev

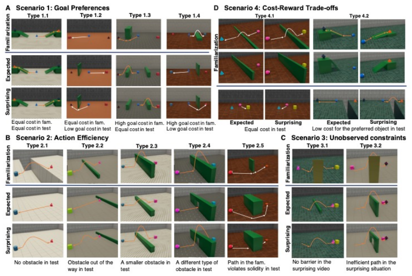
Commonsense Reasoning / Intuitive Theories

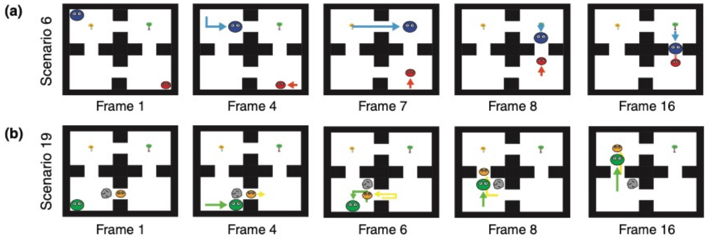
Intuitive Physics



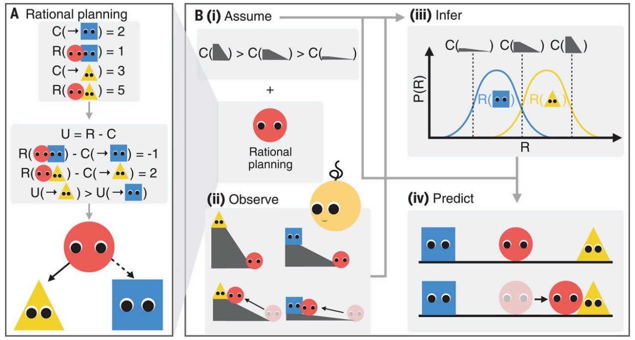


Intuitive Psychology

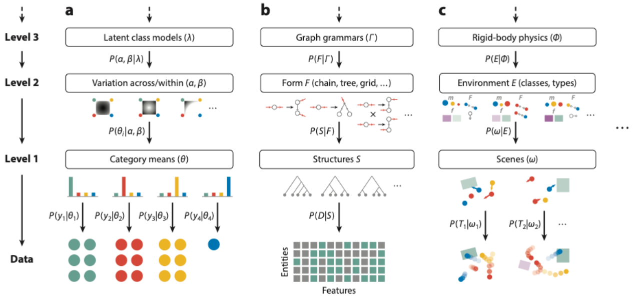




Adults and Children



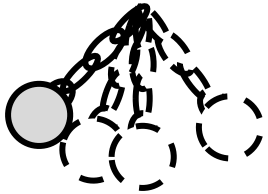
Computational Models and AI



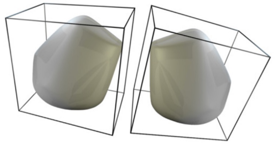
Ullman, T. D., & Tenenbaum, J. B. (2020). Bayesian models of conceptual development: Learning as building models of the world. *Annual Review of Developmental Psychology*, 2, 533-558

Overview

"What's Your Deal?"



Intuitive Physics, from Babies to Adults



- **Approximate Bodies**
- **Partial Simulation**

Imagery & Imagination

- **Non-Commitment**

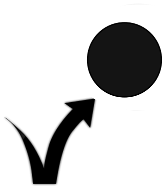
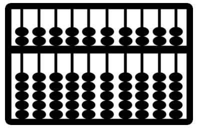
- **Visual Pretense**

Core knowledge

Early developing or innate


Shared with other animals

Few domains

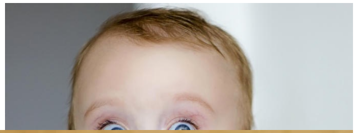





General principles, limited domains

(see Spelke and Kinzler, 2007)

Core Physics Knowledge

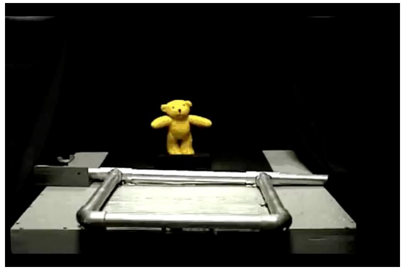
Infants have expectations about objects



Permanence

Cohesive

Solid

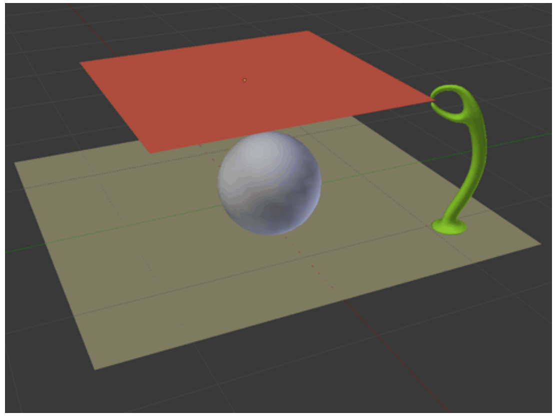


Video by Kristina Pattison
University of Kentucky

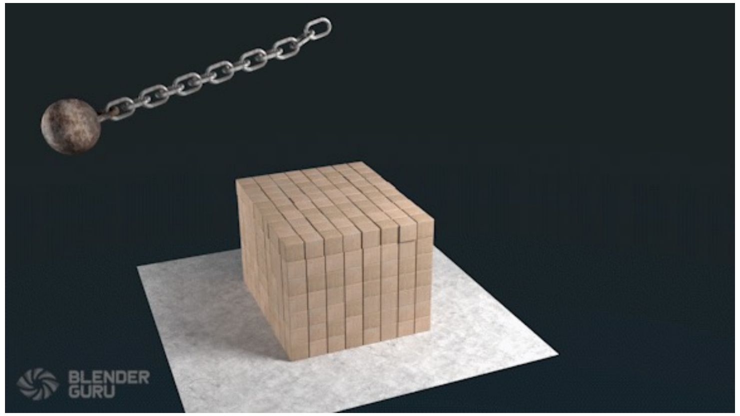
Smooth paths

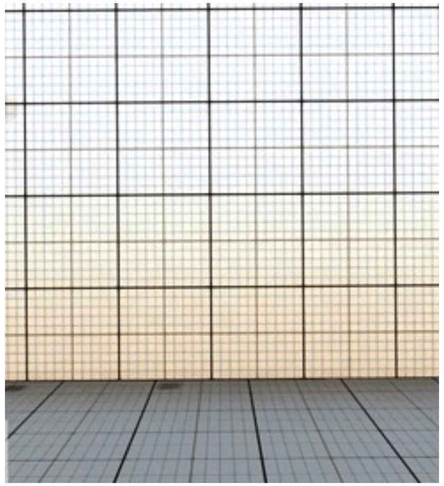
Contact causality

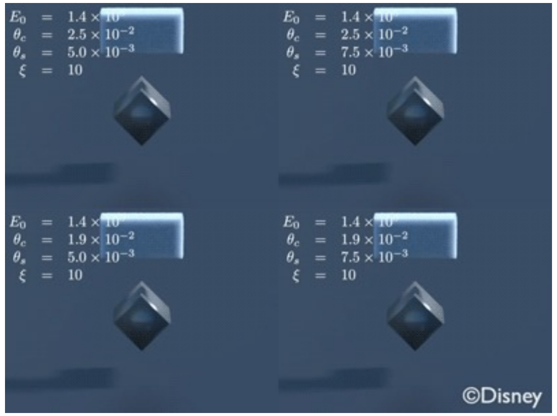
Adults and Intuitive Physics



Game Engine Programs







Game Engines

Game Engine Program

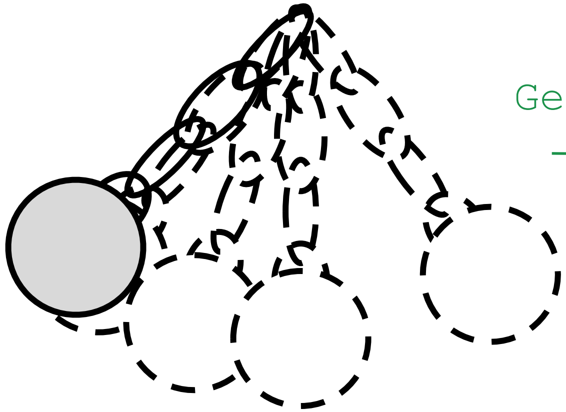
Objects
Properties
Dynamics

↓ Simulate ↑ Infer

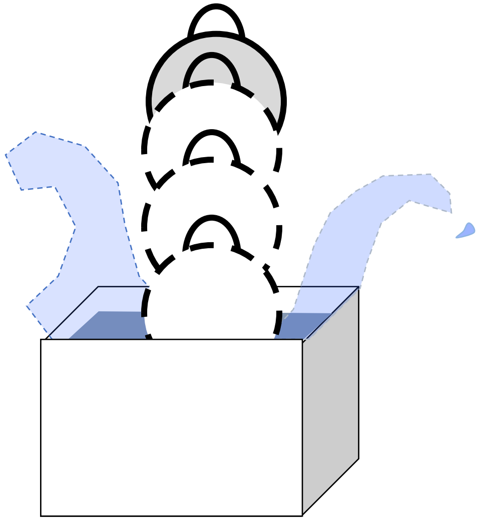
Observation

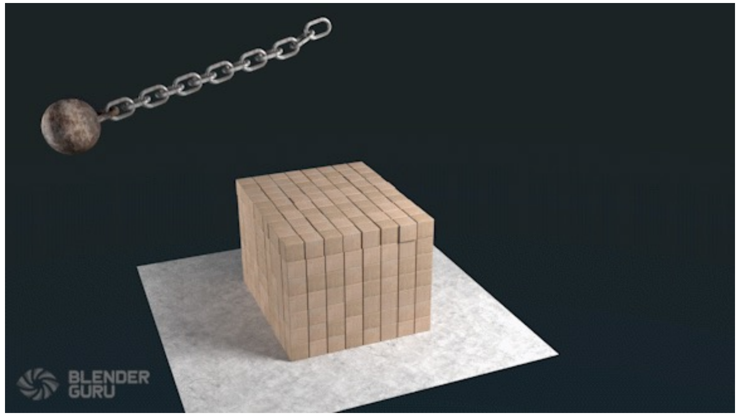
Mass = U(0,100)

F = −10↓

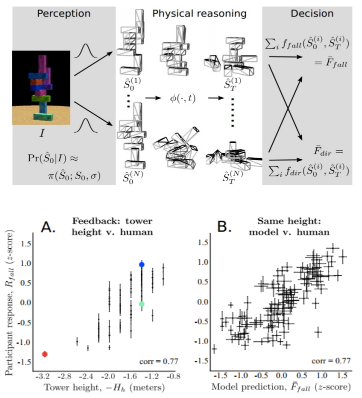


Generalize →

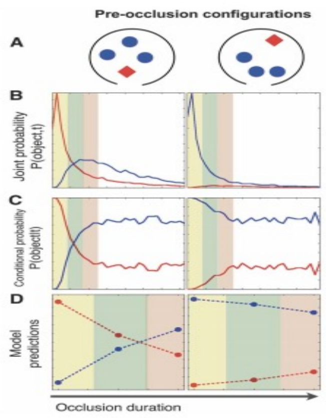




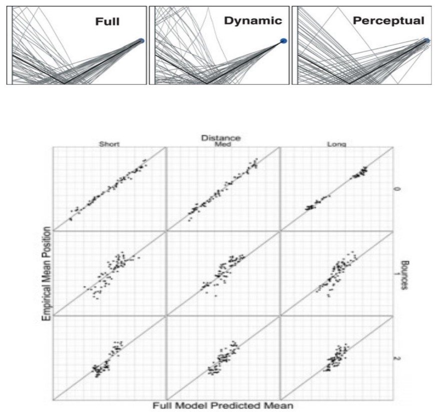
Mental Game Engines



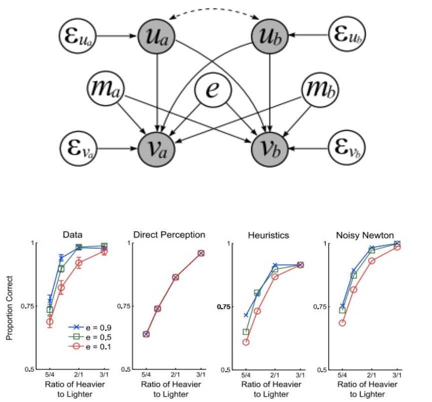
Battaglia et al., *PNAS* (2013)



Teglas et al., *Science* (2011)



Smith et al., *Cogsci* (2012)



Sanborn et al., *Psych Rev* (2013)

More examples (partial)

Collisions and noise e.g. Smith & Vul (2013)

Liquids e.g. Bates et al. (2015)

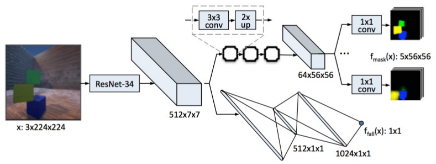
Counterfactual / causal e.g. Gerstenberg et al. (2017)

Theory search e.g. Ullman et al. (2018)

Active learning e.g. Bramley et al. (2018)

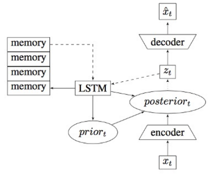
Alternatives in ML/AI (partial)

Feedforward Deep Nets



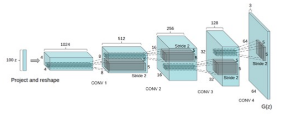
e.g. Lerer et al. (2016)

VRNN + LRU Memory



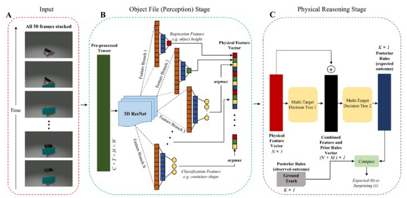
Piloto et al. (2018)

Modified DCGAN



Riochet et al. (2018)

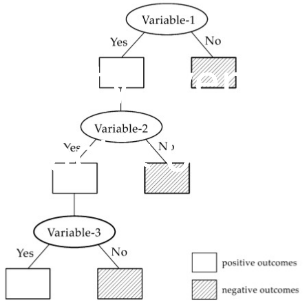
Feature-based decision-trees



Dasgupta et al. (2021)

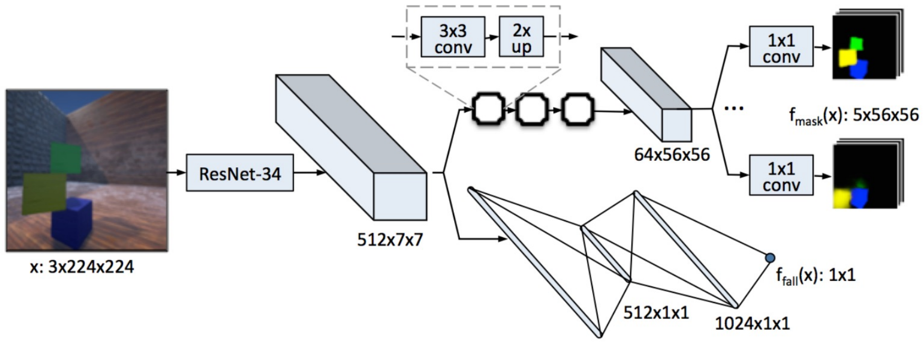
Alternative Models of Core Physics

Physical Reasoning System

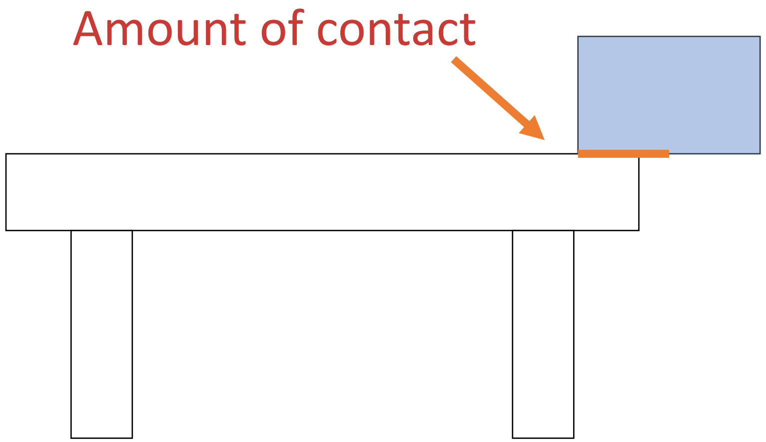


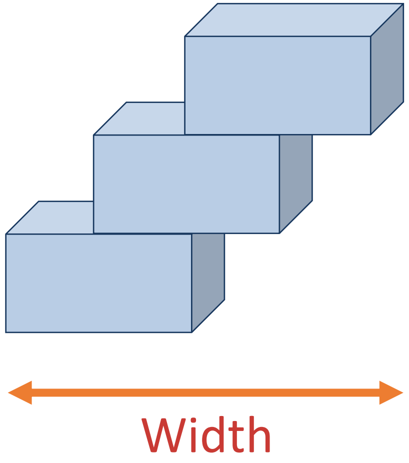
e.g. Luo & Baillargeon (2005)

Feedforward Deep Nets



e.g. Lerer et al. (2016)

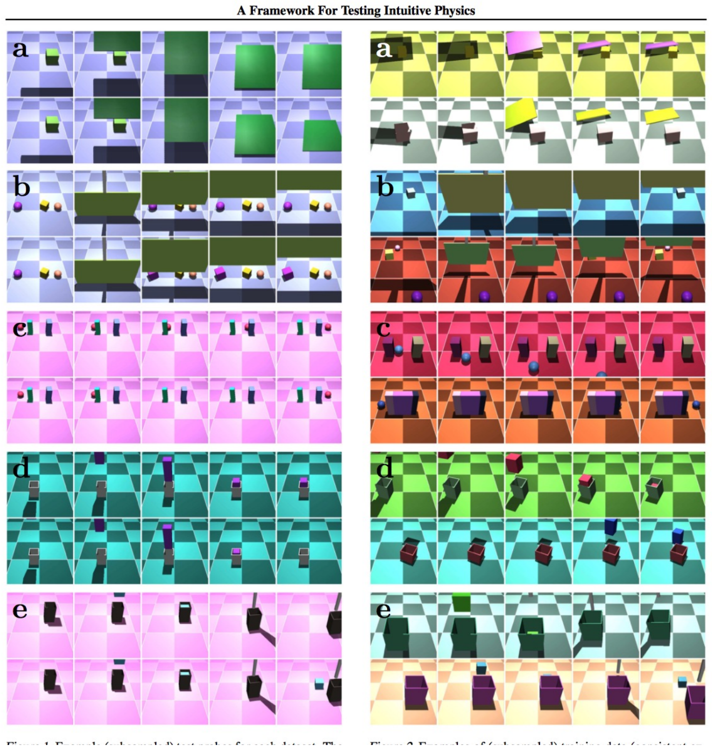


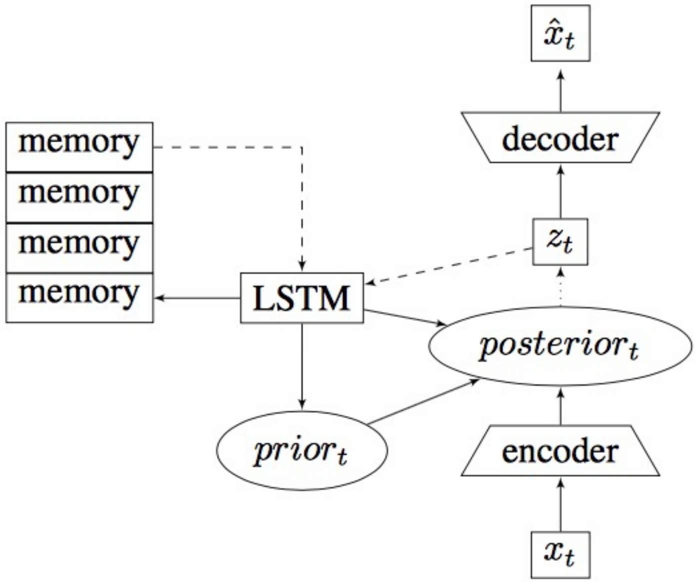


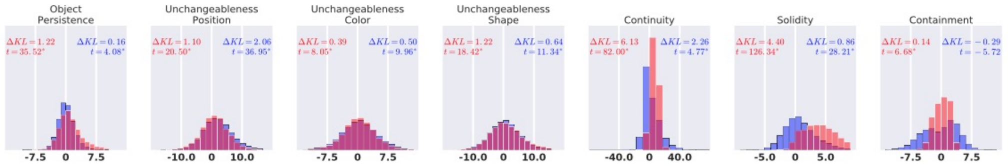
Alternative Models of Core Physics II

Probing Physics Knowledge Using Tools from Developmental Psychology

Luis Piloto [1,2,*] Ari Weinstein [1,*] Dhruva T.B. [1] Arun Ahuja [1] Mehdi Mirza [1] Greg Wayne [1] David Amos [1]
Chia-chun Hung [1] Matthew Botvinick [1]







Alternative Models of Core Physics III

IntPhys: A Benchmark for Visual Intuitive Physics Reasoning

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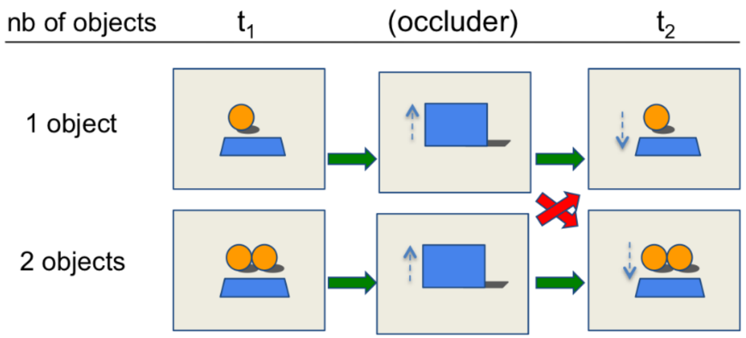
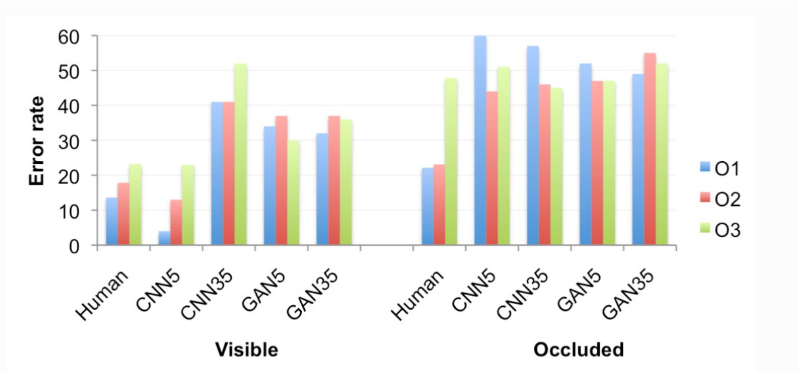




A Minimal Game Engine

Full mental game engine as adult state

Minimal game engine with:

- Approximate Objects
- Dynamics (+ noise + collision detection)
- Priors and re-sampling
- Memory/tracking

ADEPT

Approximate De-renderer, Extended Physics, and Tracking

Kevin Smith

Lingjie (Jerry) Mei

Shunyu Yao

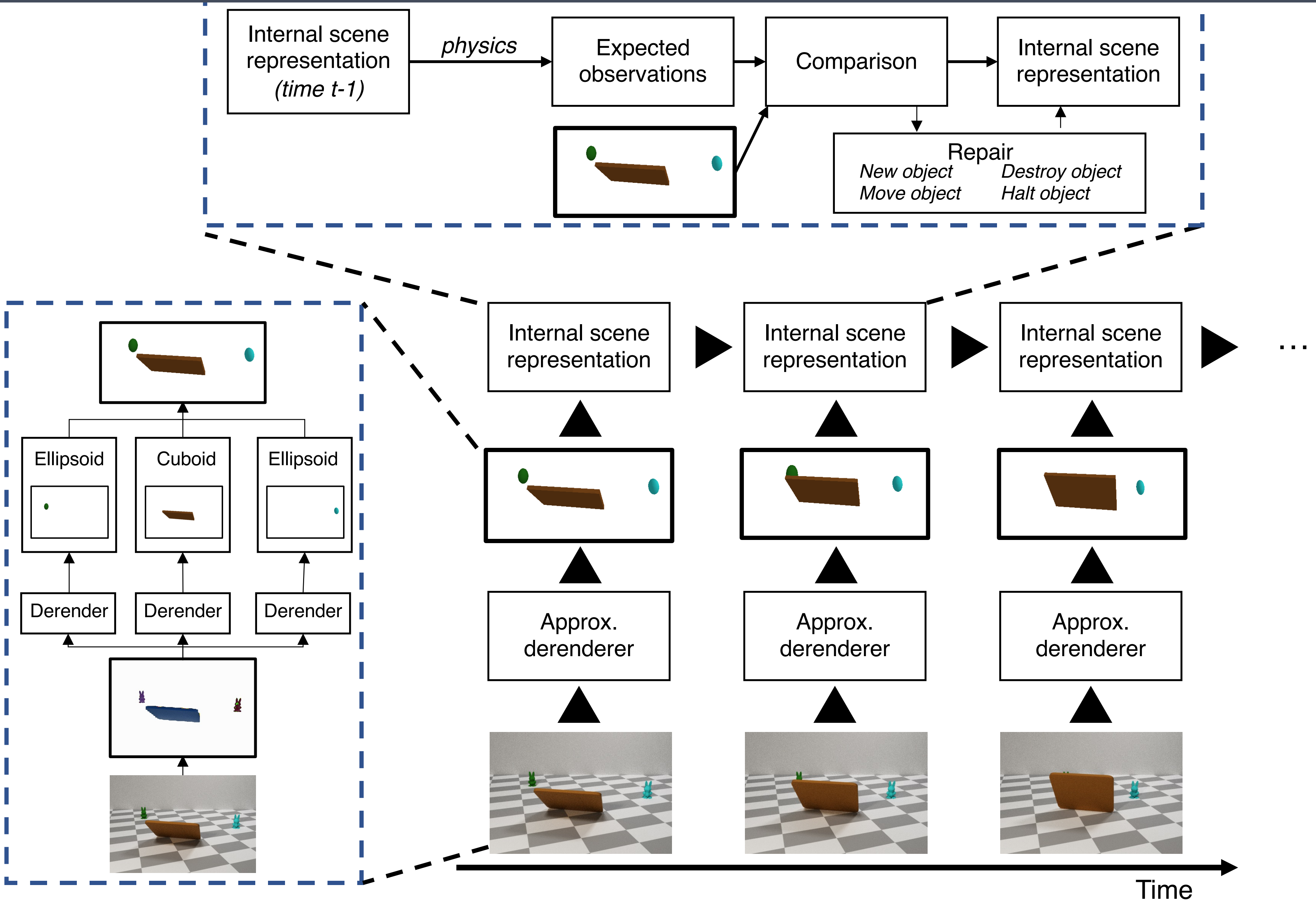
Jiajun Wu

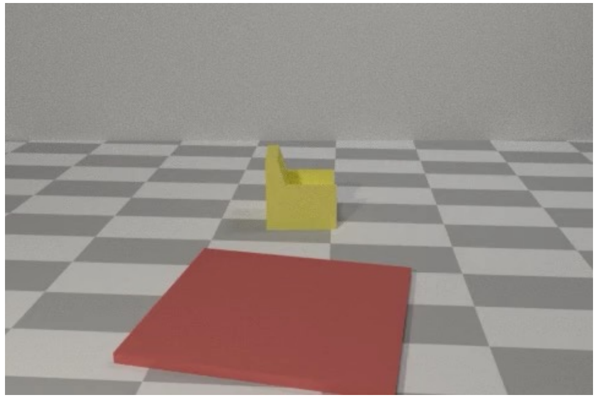
Liz Spelke

Josh Tenenbaum

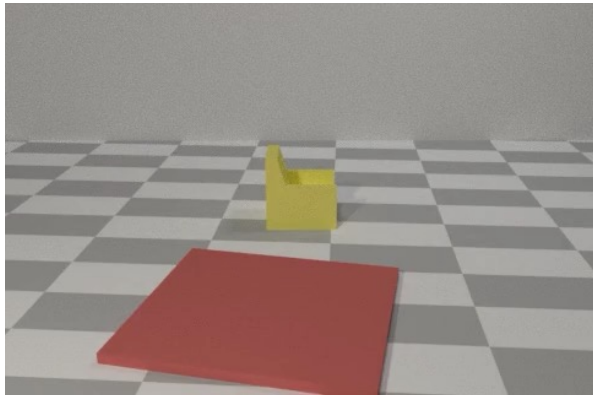
Smith, K.*, Mei, L.*, Yao, S., Wu, J., Spelke, E., Tenenbaum, J.B., Ullman, T.D., (2019),
Modeling Expectation Violation in Intuitive Physics with Coarse Probabilistic Object Representations,
Advances in Neural Information Processing Systems

ADEPT Overview





$\boldsymbol{x}^{(1)}$(surprising)



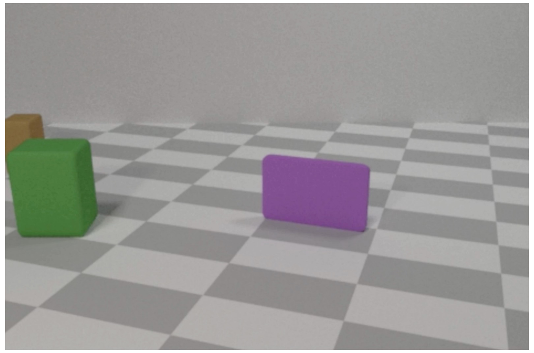
$\boldsymbol{x}^{(2)}$(not surprising)

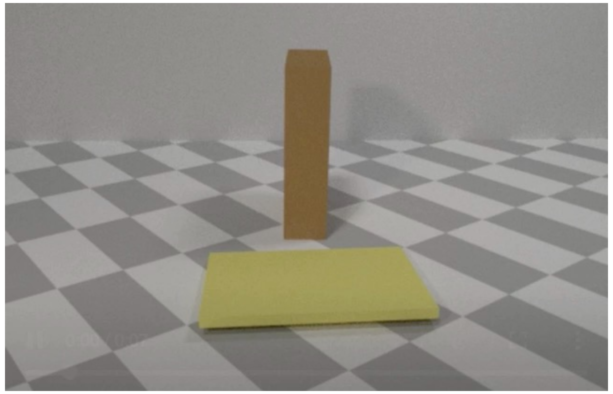
$c(\boldsymbol{x}^{(1)}) > c(\boldsymbol{x}^{(2)})$ is expected to hold, where c() is level of surprise

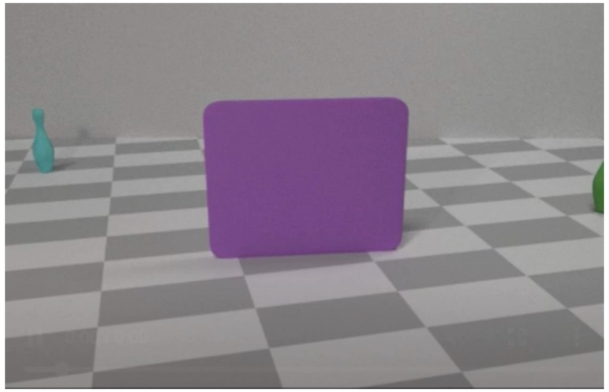
Violation types

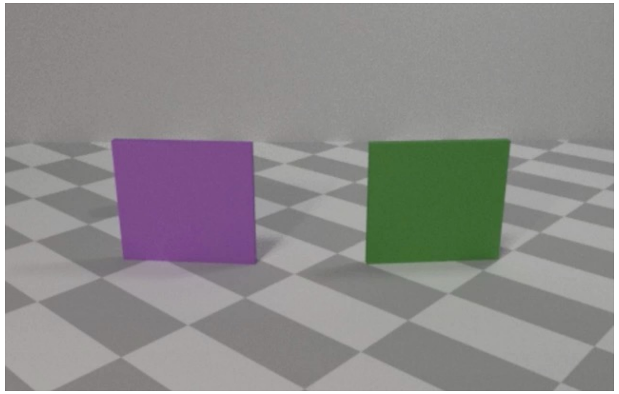
1. Create
2. Vanish
3. **Overturn (short)**
4. Overturn (long)
5. Discontinuous (invisible)
6. Discontinuous (visible)
7. Delay
8. Block

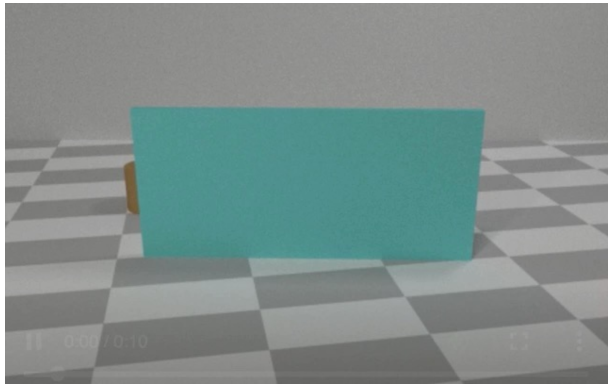
ADEPT Train and Test



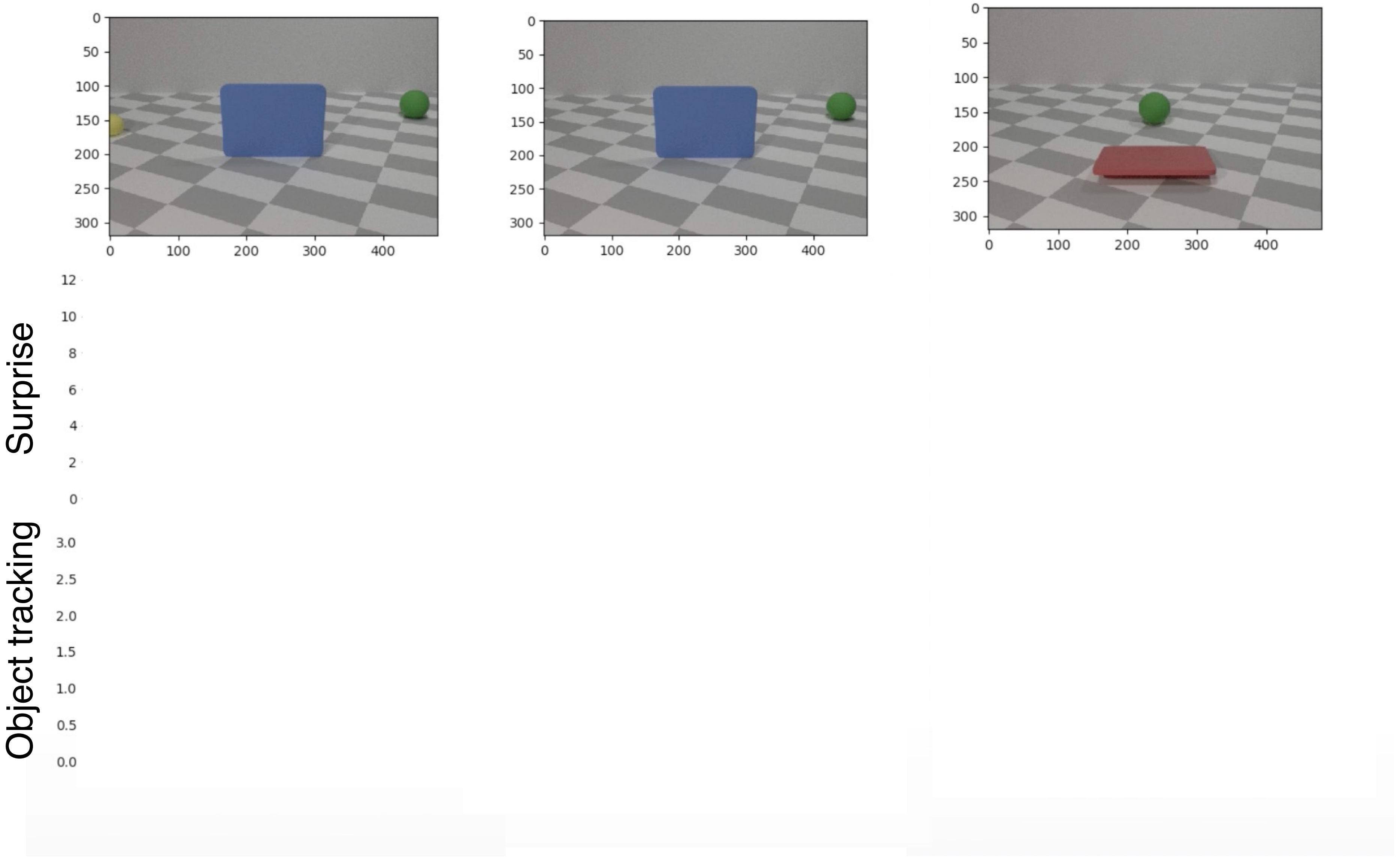








ADEPT Train and Test



ADEPT Comparisons

Relative accuracy $\frac{1}{n_+ n_-} \sum_{i,j} 1[c(x_i^+) > c(x_j^-)]$

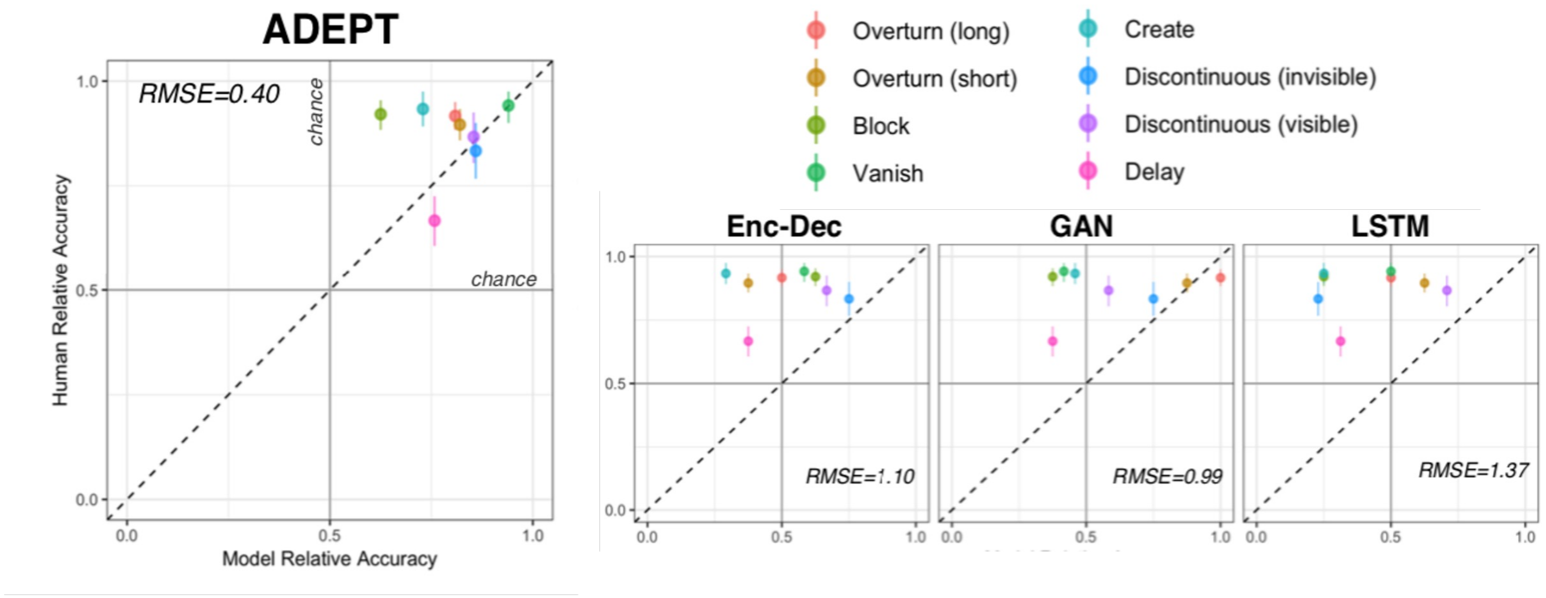
~1,500 videos (8 scenario x shapes types)

Baselines Encoder-decoder, GAN (Riochet 2018); LSTM

	Encoder-decoder	GAN	LSTM	ADEPT
Average				

Human Studies

Compare model & human by stimuli type

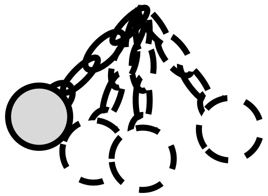


ADEPT closest by a factor of 2, above chance on all scenarios ✓

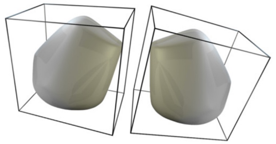
Other models <= chance for half of scenarios ✗

Overview

"What's Your Deal?"



Mental Game Engines



Approximate Bodies

Partial Simulation

Imagery & Imagination

Non-Commitment

Visual Pretense

Approximations in Game Engines

Simulators use ‘hacks’

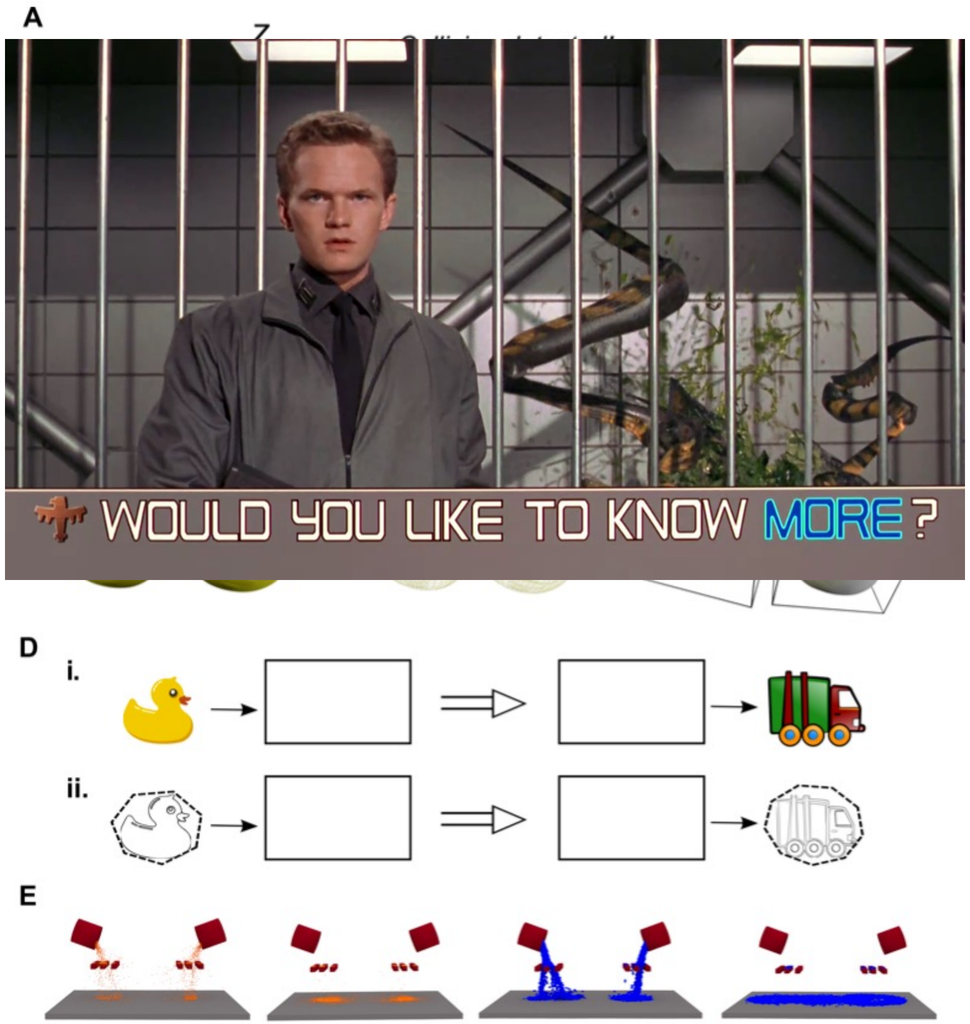
Constraints
[time, memory, …]

Machines

Minds

approximations
in simulators

working
hypotheses for
intuitive physics



Ullman, T. D., Spelke, E.S., Battaglia, P. and Tenenbaum, J.B. (2017),
Mind Games: Game Engines as an Architecture for Intuitive Physics.
Trends in Cognitive Science

Approximate Bodies

Yichen Li

YingQiao Wang

Tal Boger

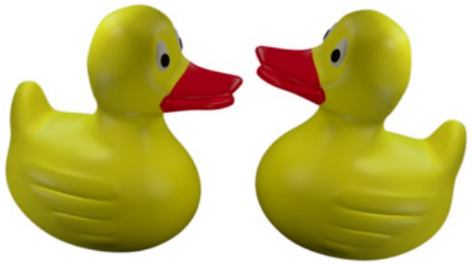
Kevin Smith

Sam Gershman

Li, Y., Wang, Y., Boger, T., Smith, K., Gershman, S. J., & Ullman, T. D. (in press). JEP: General, An Approximate Representation of Objects Underlies Physical Reasoning

Approximate Bodies

Shape

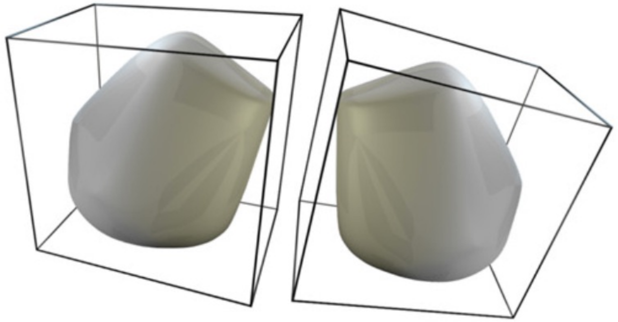


Rendered

Fine-grain form

Texture, color

Body



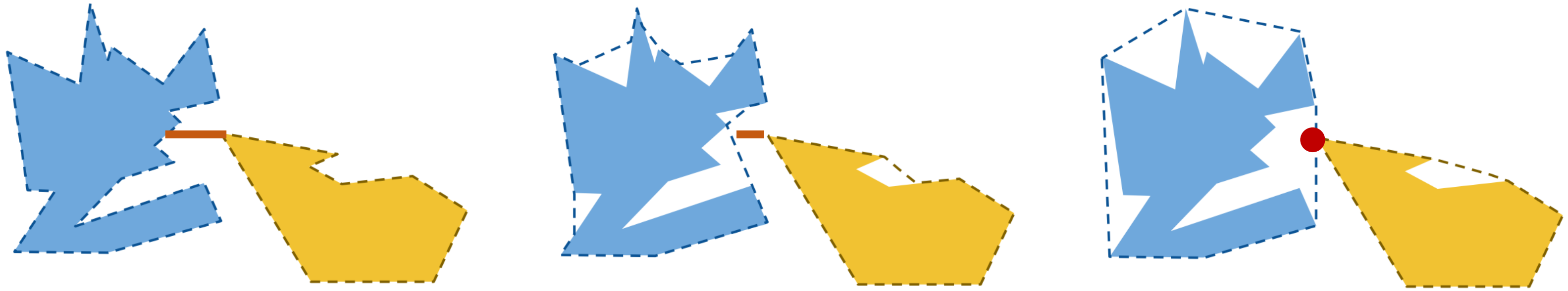
Tracking / collisions

Rough form

Elasticity, mass

Approximate Bodies

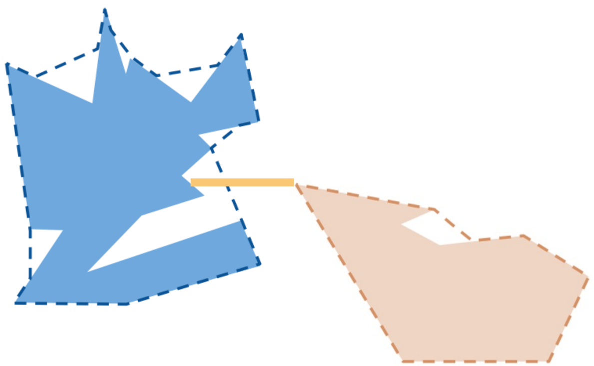
Tasks that dissociate body from shape



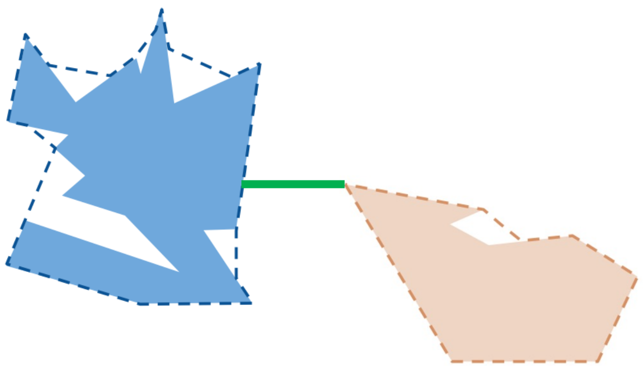
Greater body approximation →

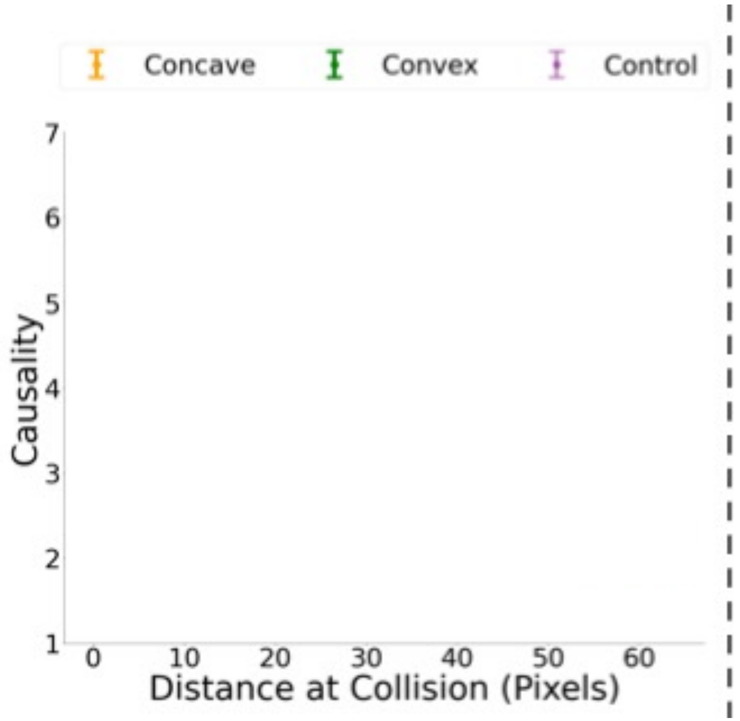
Causality & Approximate Bodies

Concave collision



Concave collision





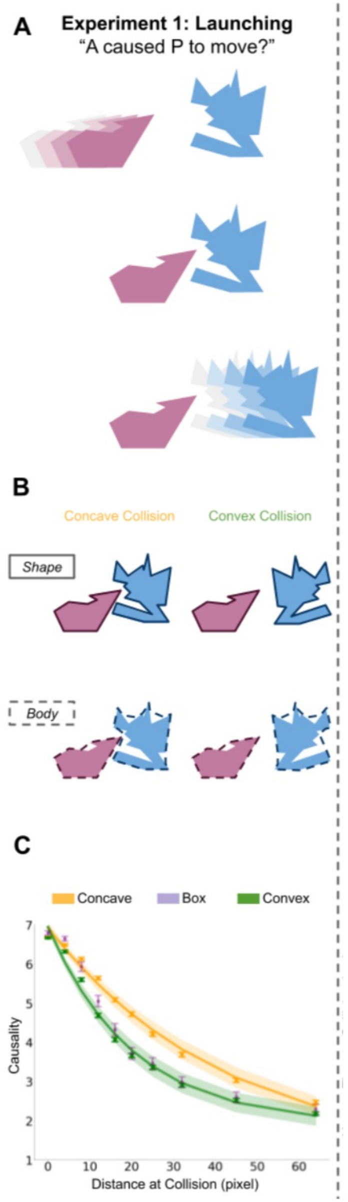
Approximate Bodies

Perception of Causality

Time-to-Collision

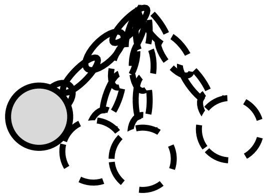
Change detection

(approximation model)

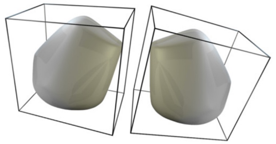


Overview

"What's Your Deal?"



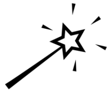
Mental Game Engines



Approximate Bodies

Partial Simulation

Imagery & Imagination



Magic

Non-Commitment

Visual Pretense

Partial Simulation

Bass, I., Smith, K., Bonawitz, E., & Ullman, T. D. (2021).
Partial Simulation Explains Fallacies in Physical Reasoning.

The Problem

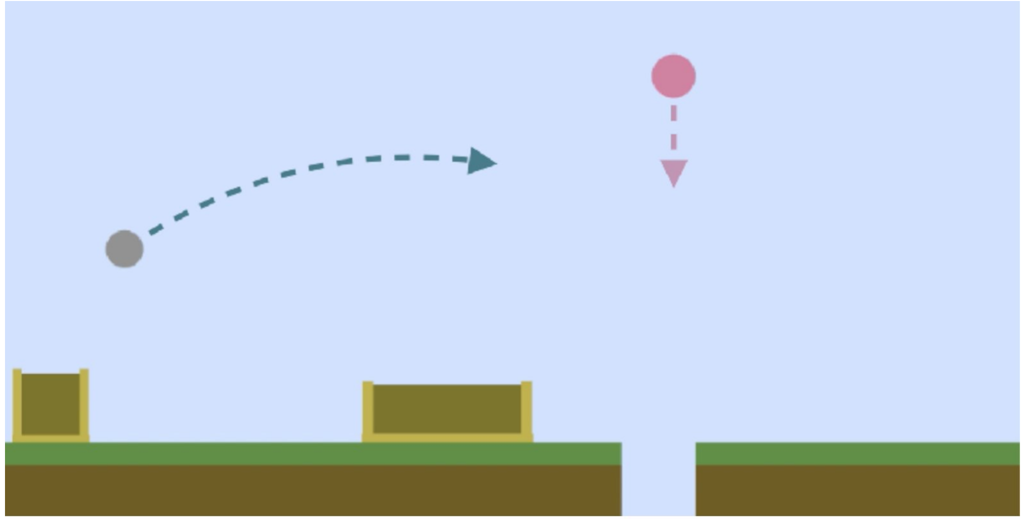
Physics Engines…

…Should obey probability

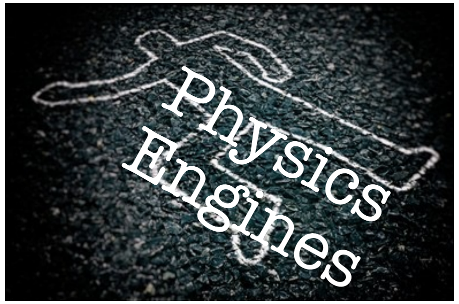
$$P(A) >= P(A \& B)$$

Ludwin-Peery, E., Bramley, N. R., Davis, E., & Gureckis, T. M. (2020). Broken physics: A conjunction-fallacy effect in intuitive physical reasoning. *Psychological Science*, *31*(12), 1602-1611.

The Physical Conjunction Fallacy



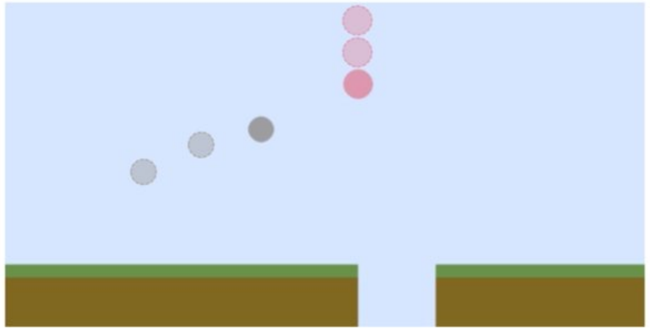
G: Sphere on Grass
H: Cannonball Hit



P(G) < P(H&G)

Ludwin-Peery, E., Bramley, N. R., Davis, E., & Gureckis, T. M. (2020). Broken physics: A conjunction-fallacy effect in intuitive physical reasoning. *Psychological Science*, *31*(12), 1602-1611.

Partial simulation model



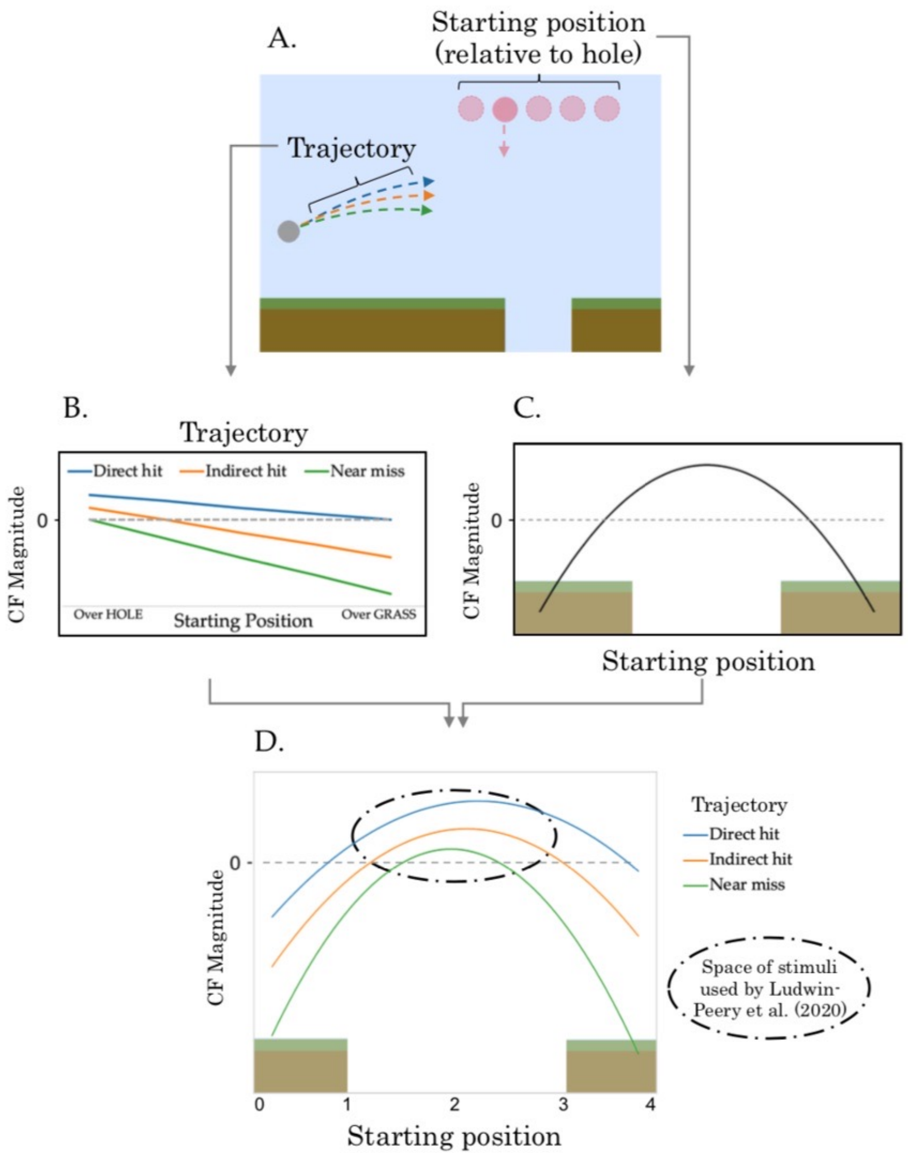
p(G): *"How likely is it that the pink sphere will end up on the grass?"*

Model Predictions

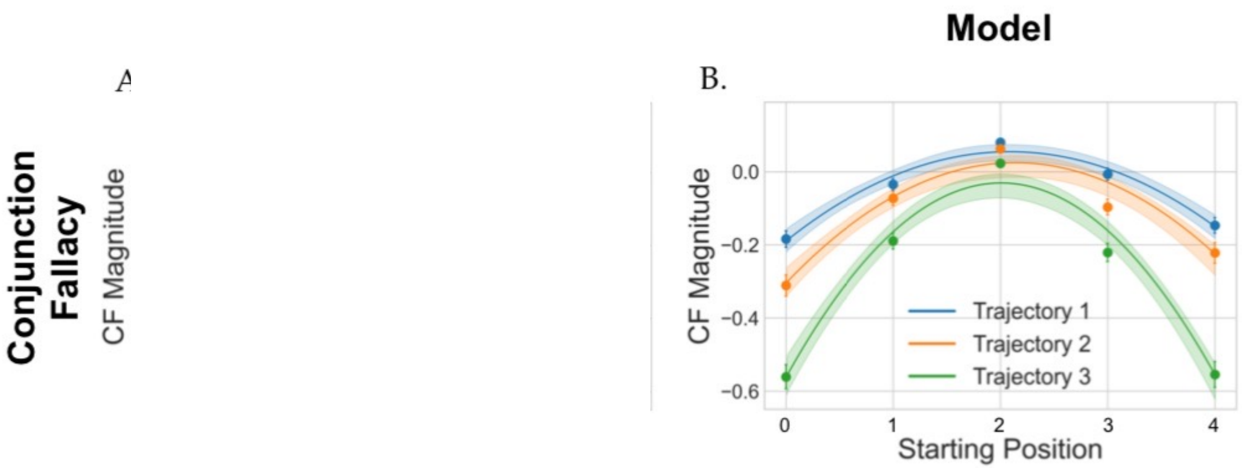
Direct-hits CF goes up

Sphere starting further
from hole center CF goes down

Together: Inverse-U with position of sphere
Moved up/down by P(collision)



Empirical Results

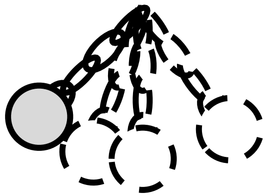


Does *not* negate Ludwin-Peery et al.

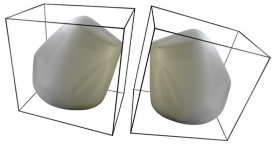
Partial simulation not fallacy per se; is useful

Overview

“What’s Your Deal?”



Mental Game Engines



Approximate Bodies

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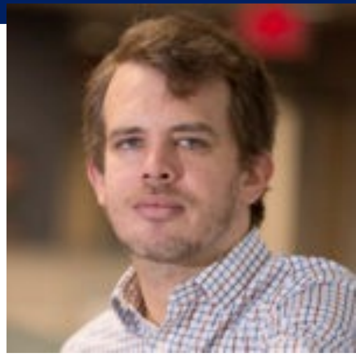
Visual Pretense

Non-Commitment in Imagery

Eric Bigelow

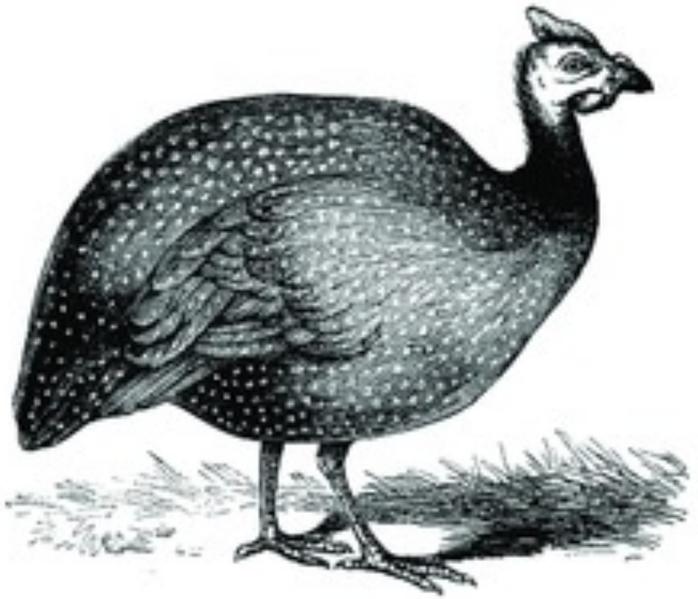


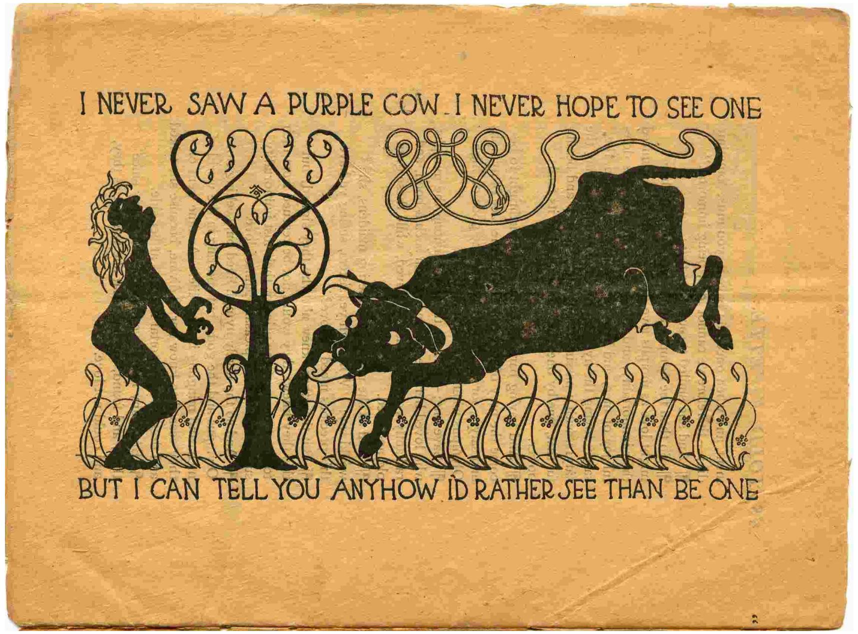
John McCoy

"A Person Walks into a Room and Knocks a Ball off a Table"

Bigelow, E. J., McCoy, J., & Ullman, T. (*2023*). Non-Commitment in Mental Imagery. *Cognition*

Non-Commitment in Imagery

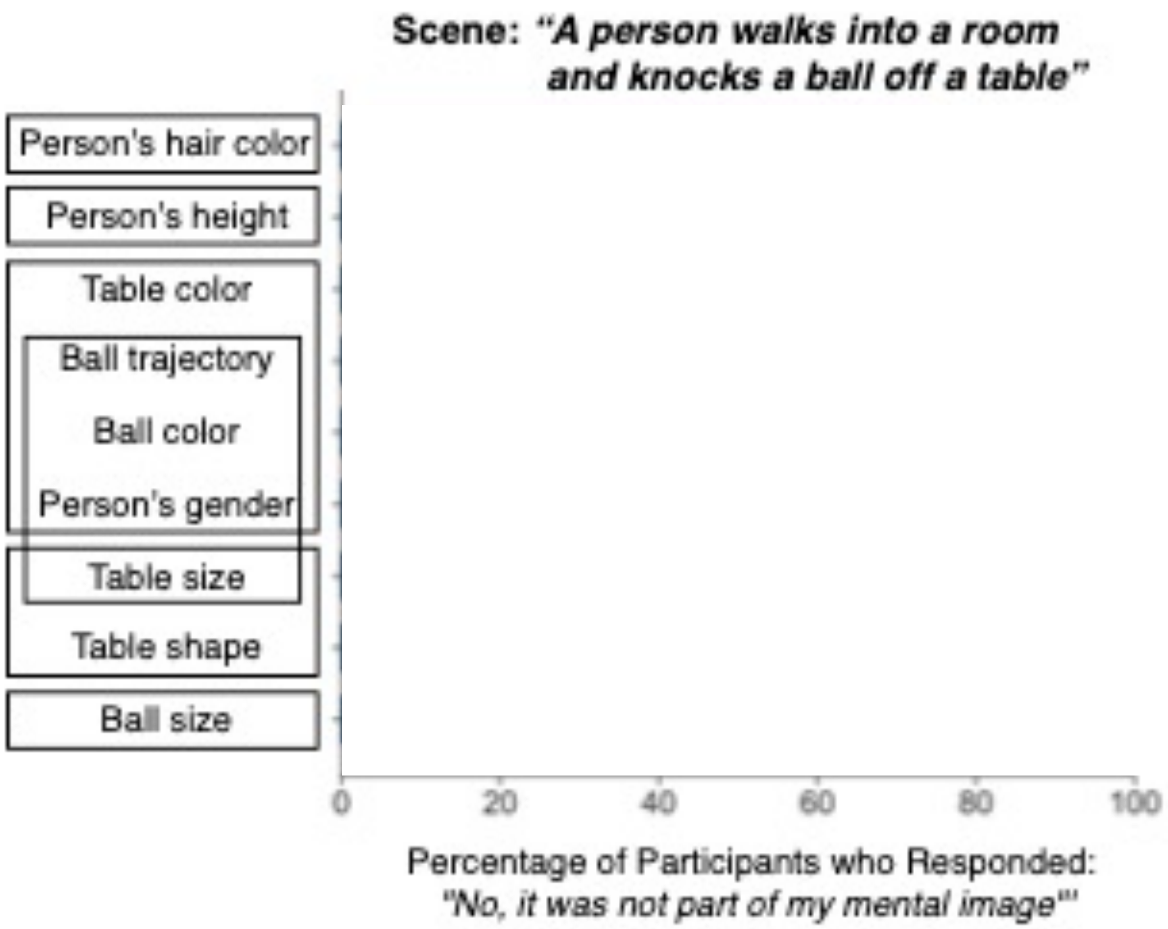




Ayer (1940), Shorter (1952), Block (1983), Dennett (1986, 1993), Pylyshyn (1978, 2002), Kosslyn et al. (2006)

Also see: Nanay (2015, 2016), Kind (2017)

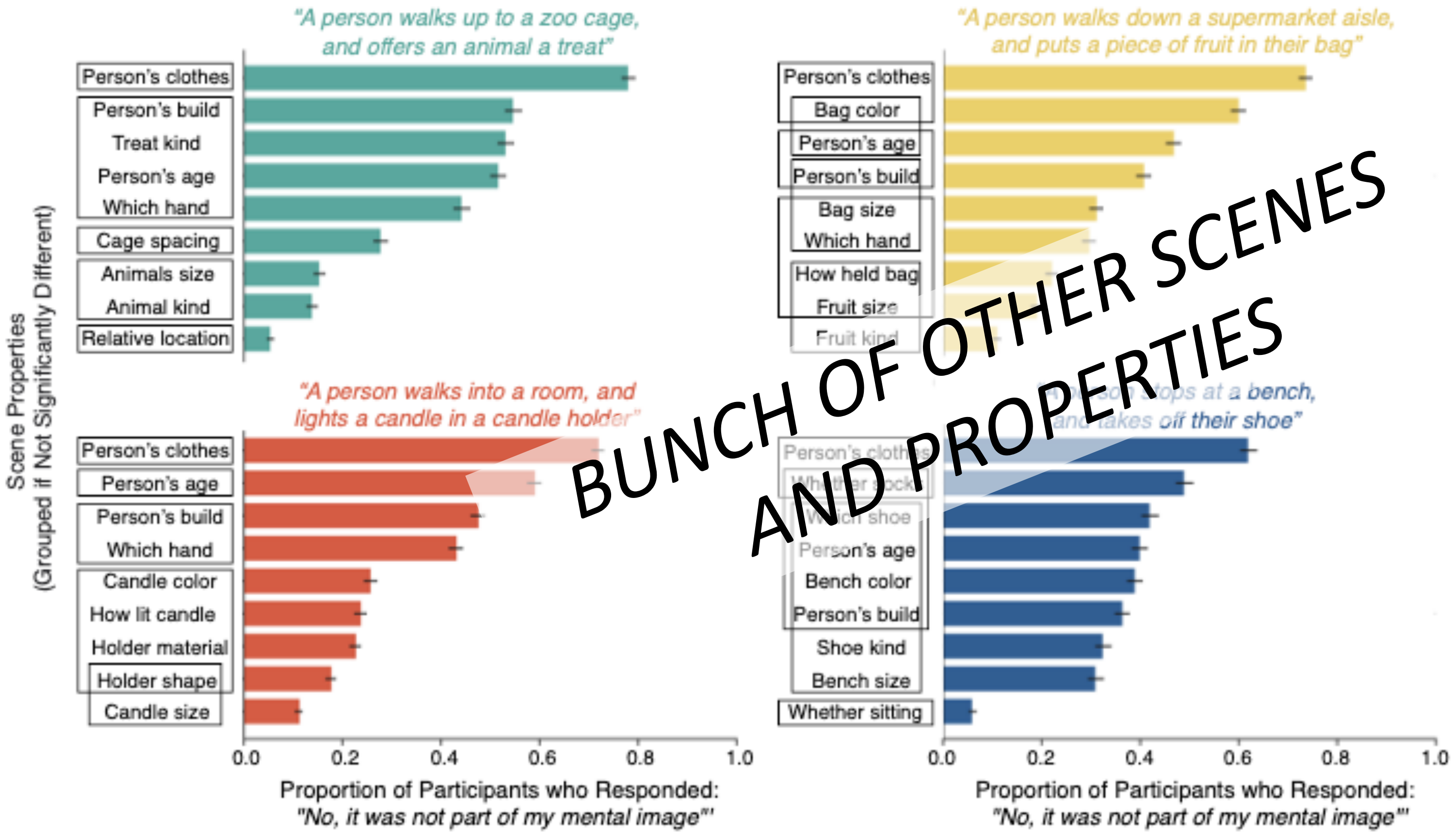
Non-Commitment in Imagery



For every property, some people didn't commit to it

Some properties more than others

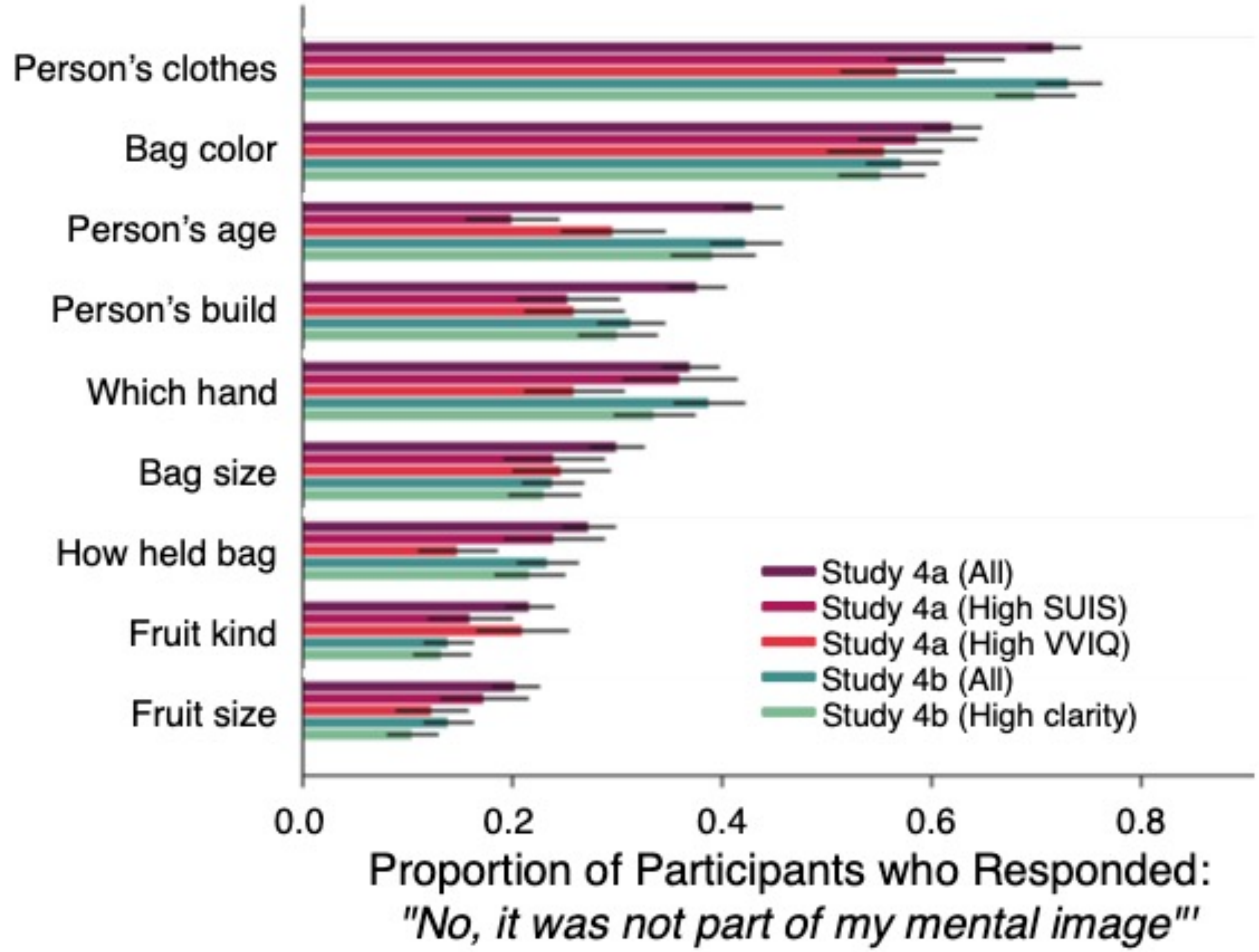
Non-Commitment in Imagery



For every property, some people didn't commit to it

Some properties more than others

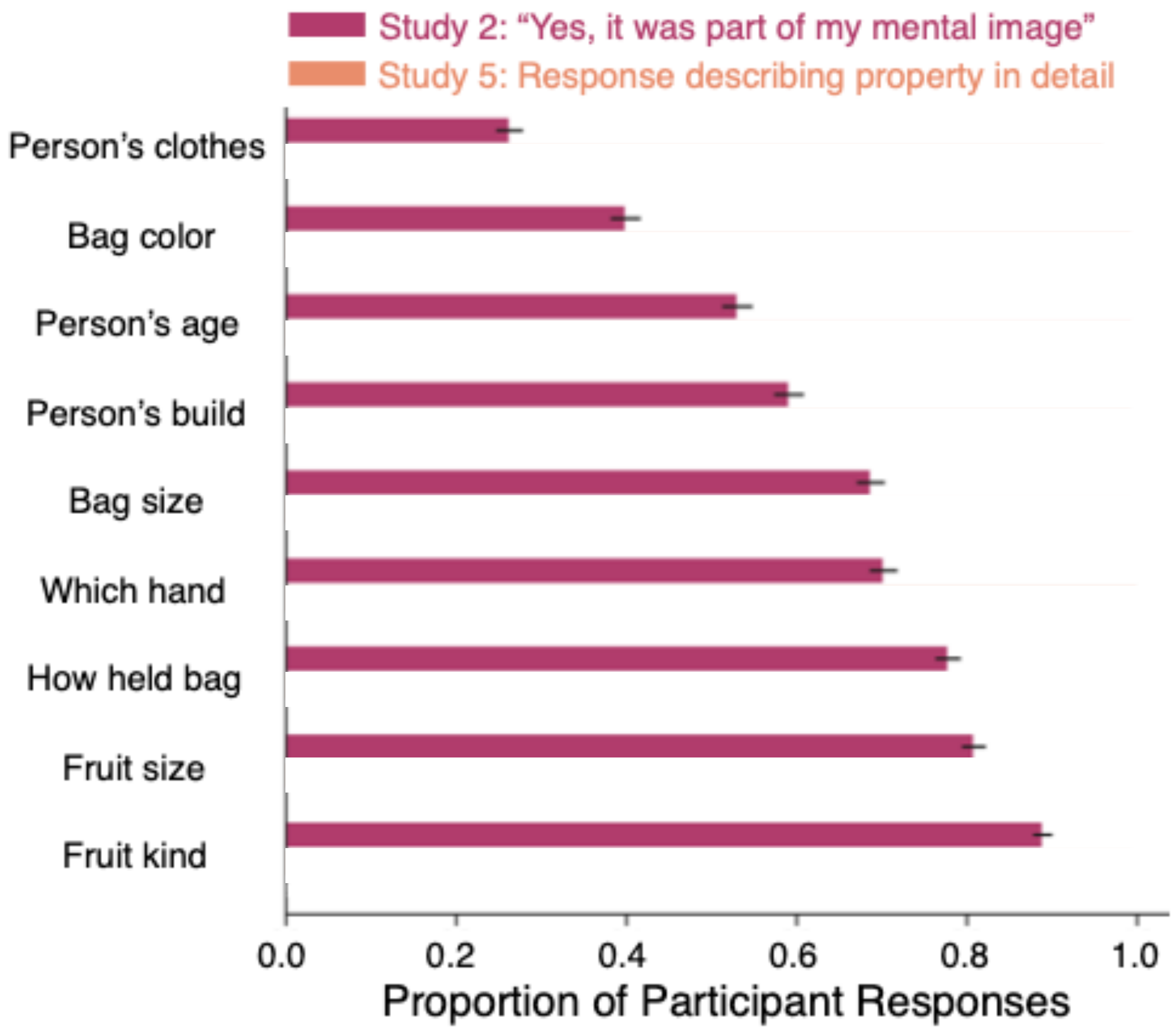
Non-Commitment and Vividness



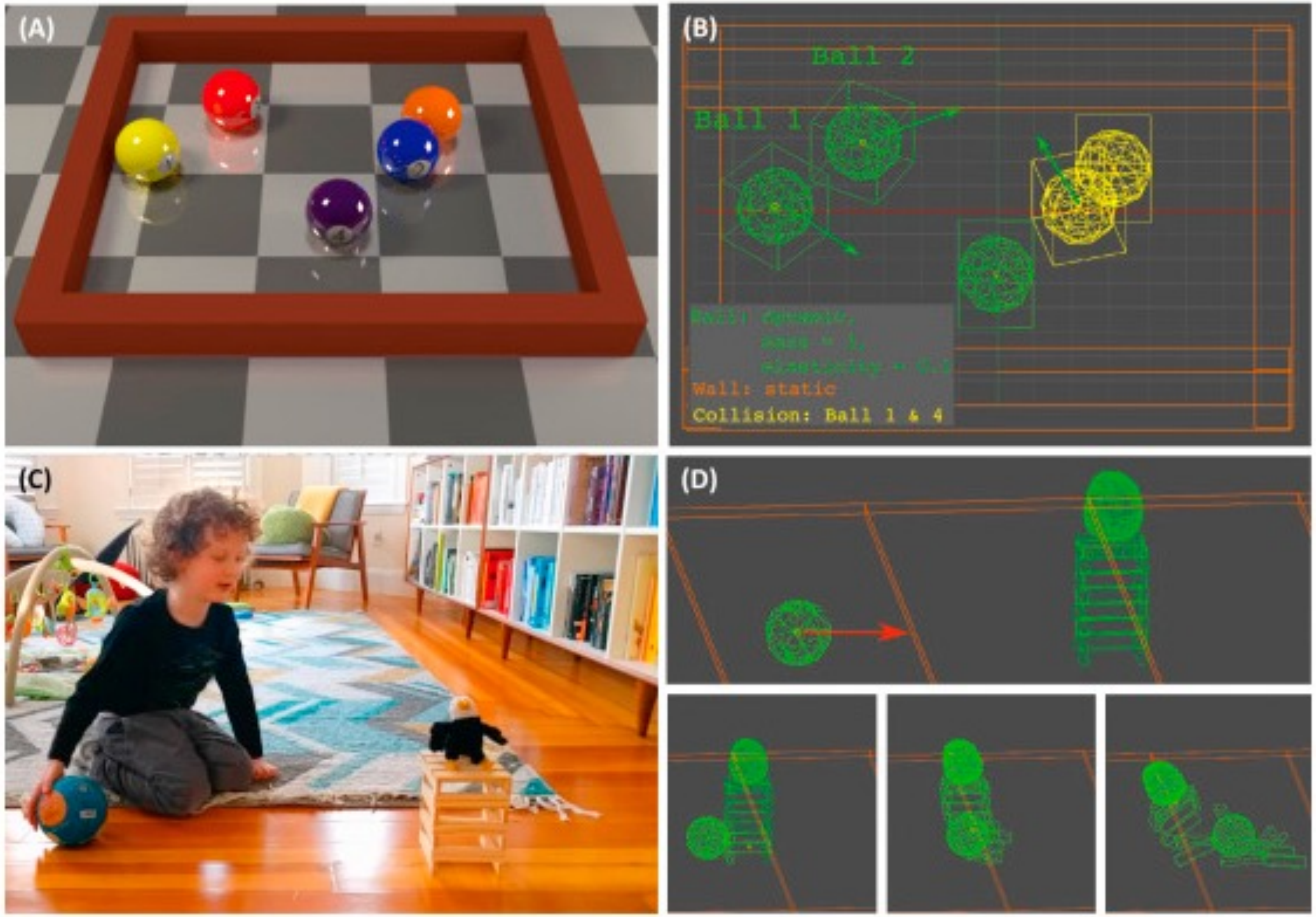
Non-commitment only weakly related to "vividness" (VVIQ)

Cf. Kind (2017)

Confabulation(?)



Non-Commitment in the Imagination



Trends in Cognitive Sciences

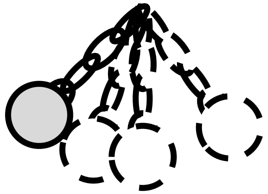
Hierarchical scene construction

+ simulation != rendering

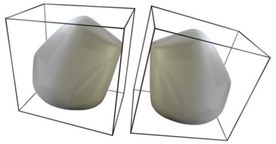
+ lazy evaluation

Overview

"What's Your Deal?"



Mental Game Engines



Approximate Bodies

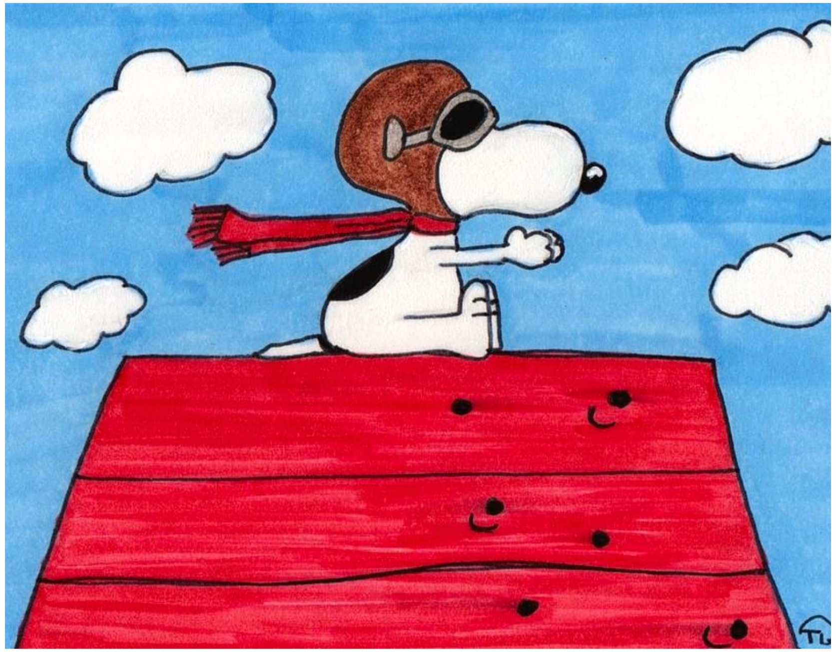
Partial Simulation

Imagery & Imagination

Non-Commitment

Visual Pretense

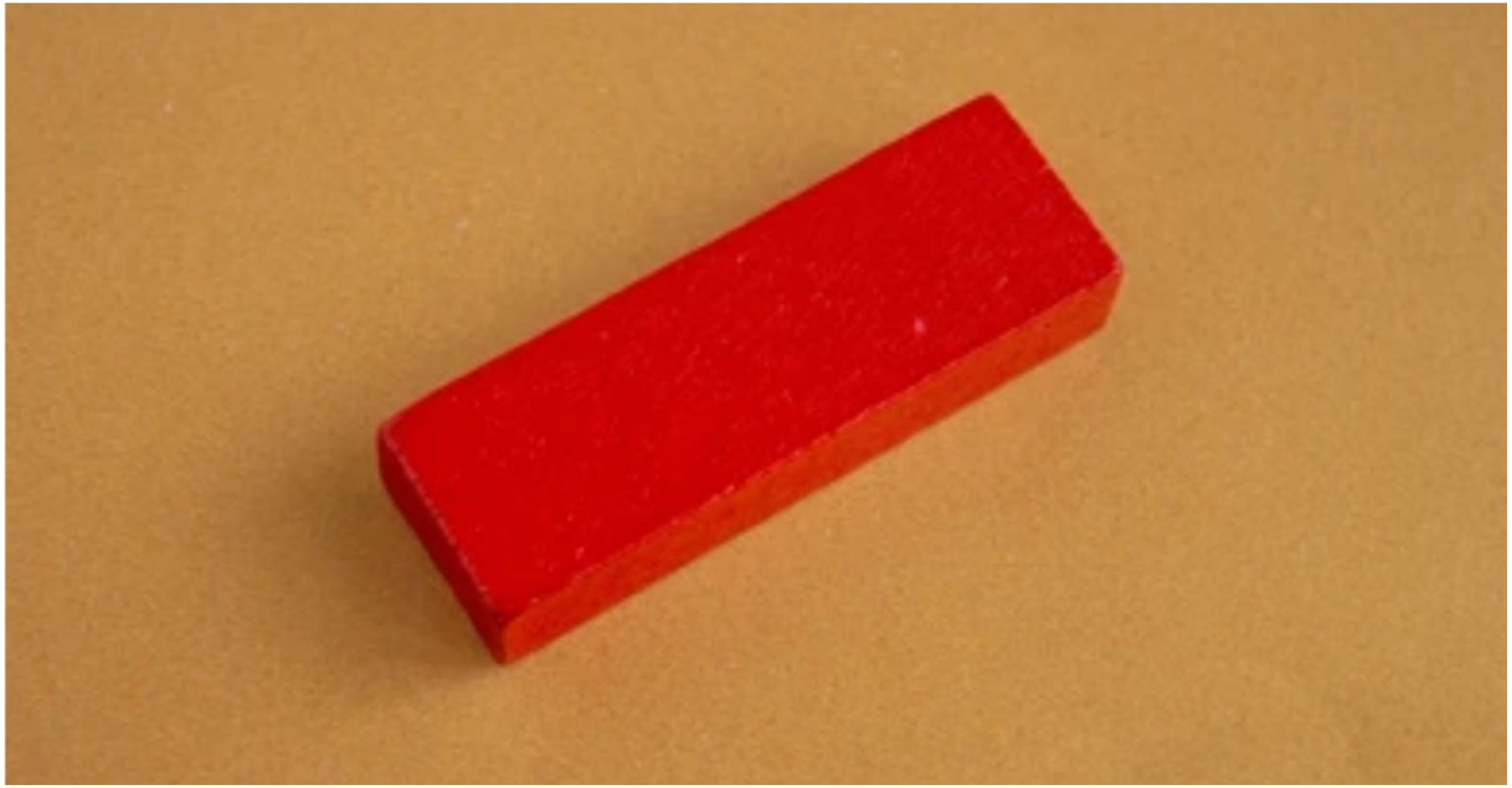
Visual Pretense and Physical Properties



Peng Qian

Qian, P. and Ullman, T.D. Shape Guides Visual Pretense (*psyArxiv*, 2024)

Building Intuition



Puzzles / Questions

Q1: Is there a preference in pretense?

Cf. Currie and Ravenscroft, 2002; Mollerup, 2019

Q2: What determines that preference?

e.g. Harris, 2000; Byrne, 2007; Nichols, 2006, McCoy & Ullman, 2019

Hypotheses

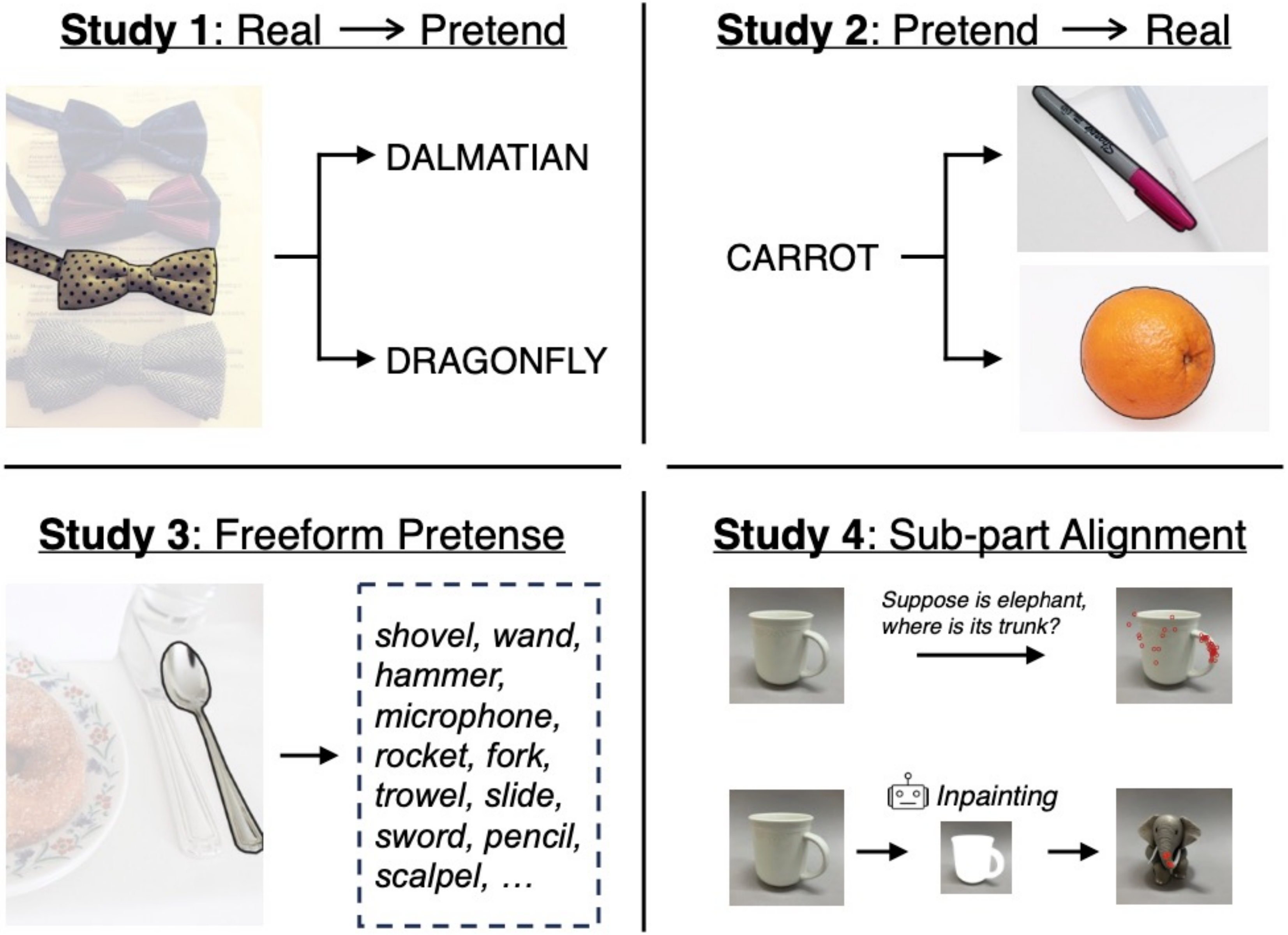
H1: Some visual pretenses systematically preferred

H2: Pretense preferences determined by hierarchy of features

H3: In hierarchy ^, physical/spatial features > surface features

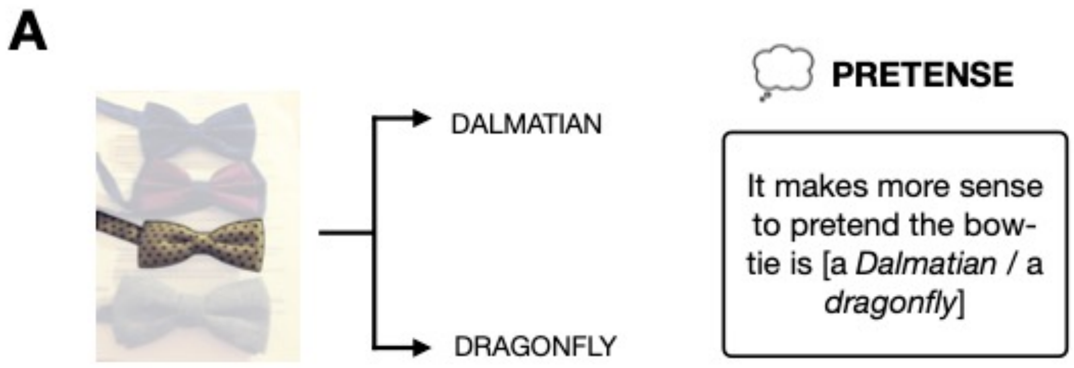
H4: Current ML models do not capture human hierarchy

Empirical Studies



PREREGISTERED

Experiments – Study 1



Study 3: "Freeform"

Suppose you pretend the **spoon** is something else.

What would it make sense to pretend the spoon is?

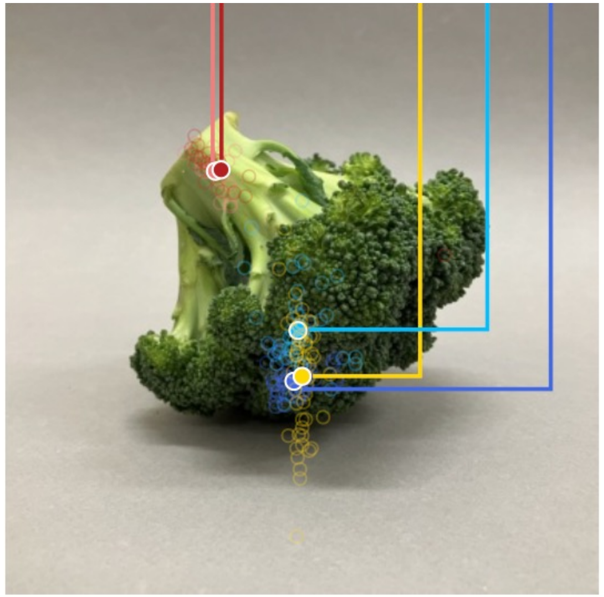
(I) PROMPT

Study 4: Alignment and Filling in

Suppose the mug is an elephant, where is the elephant's **trunk**?

Alignment and Filling in

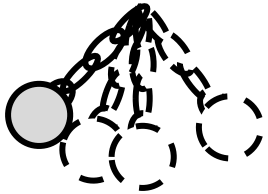
Alignment and Filling in



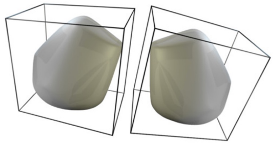
Alignment in Metamorphoses

Overview

"What's Your Deal?"



Mental Game Engines



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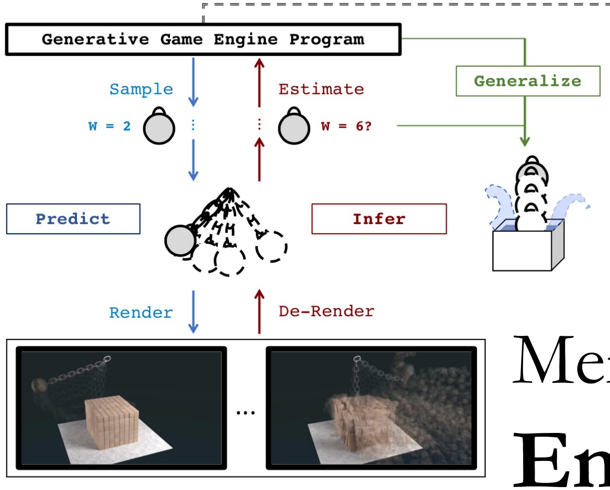
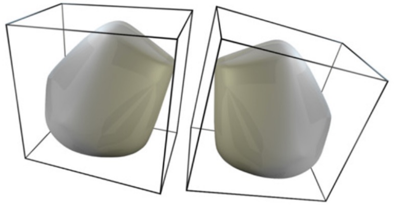
Summary

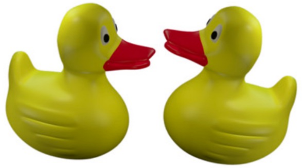



```
Weight     ← Uniform(1,10)
Shape      ← SampleRandomShape()
Loc        ← Normal([0,0],5)
Vel        ← Normal([0,0],2)
NumObj ← Geometric(0.5)
Objects    ← []
for i in [1 ... NumObj]
    NewObject ← AddObj(Weight, Shape,
                       Loc, Vel)
    AddItem(Objects, NewObj)
end
while t≠T do
    world ← InitializeWorld(Objects)
    world ← updateWorld(world)
end while
```

Mental **Game Engines** are **Useful**

Approximations in Engineering & Cognition

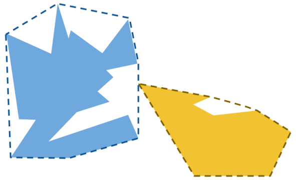


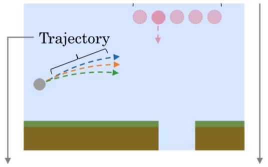


Constraints [time, memory, …]

Machines   Minds

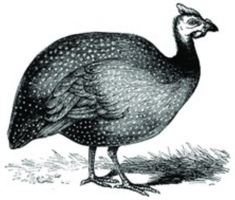
Approximate bodies

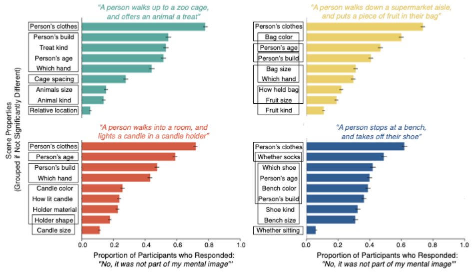




Partial Simulation

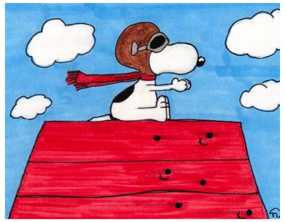
Non-Commitment

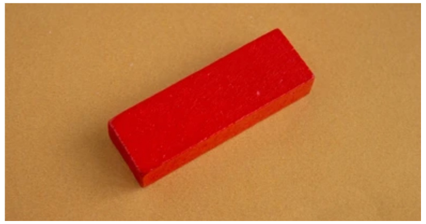


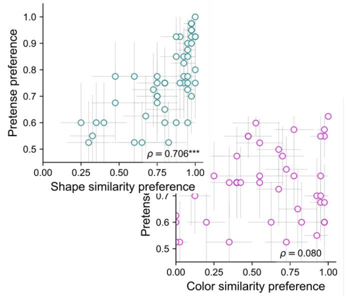


…Lazy evaluation in hierarchical scene construction?

Visual Pretense preferences







Guided by **physics**