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TÜBINGEN AI CENTER  
BMBF Competence Center for Machine Learning



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CyberValley



Intelligente Systeme

ADVANCING MACHINE INTELLIGENCE WITH ROBUST MACHINE LEARNING

# Human and Machine Cognition Lab

*What makes humans so uniquely intelligent?*

*How do people make the best use of limited cognitive resources?*

*What are the unique algorithms we use to learn from other people?*

Lab Rotations and BSc/MSc Thesis Projects

[hmc-lab.com](http://hmc-lab.com)

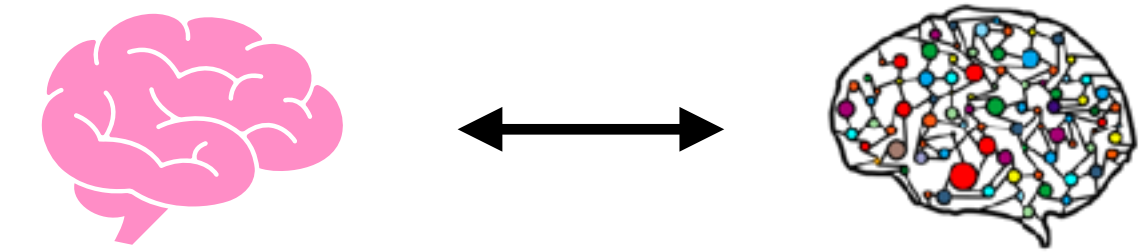
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# About the HMC Lab



The HMC Lab is an Independent Research Group led by Dr. Charley Wu, with the goal of understanding the gap between human and machine learning.



Our research methods include:

- online experiments (commonly in the form of interactive games)
- lab-based virtual reality experiments
- computational modeling of behavior (e.g., decisions, search trajectories, and reaction times)
- evolutionary models and simulations
- developmental studies (comparing children and adults)
- neuroimaging using fMRI/EEG
- analyzing large scale real-world datasets

We also have a rich collaboration network of researchers from Harvard, MIT, Princeton, and multiple Max Planck Institutes around Germany. To find out more, visit the lab website at [www.hmc-lab.com](http://www.hmc-lab.com)



# Project 1: Pedagogy and Tool Discovery

## Research Question

Tool use is a key signature of human intelligence ([Rawlings & Legare, TICS 2020](#)), yet the cognitive mechanisms underlying how we develop and innovate upon tools is not well understood.

Here, we focus on the role of pedagogy in amplifying individual innovations and unlocking cumulative cultural evolution

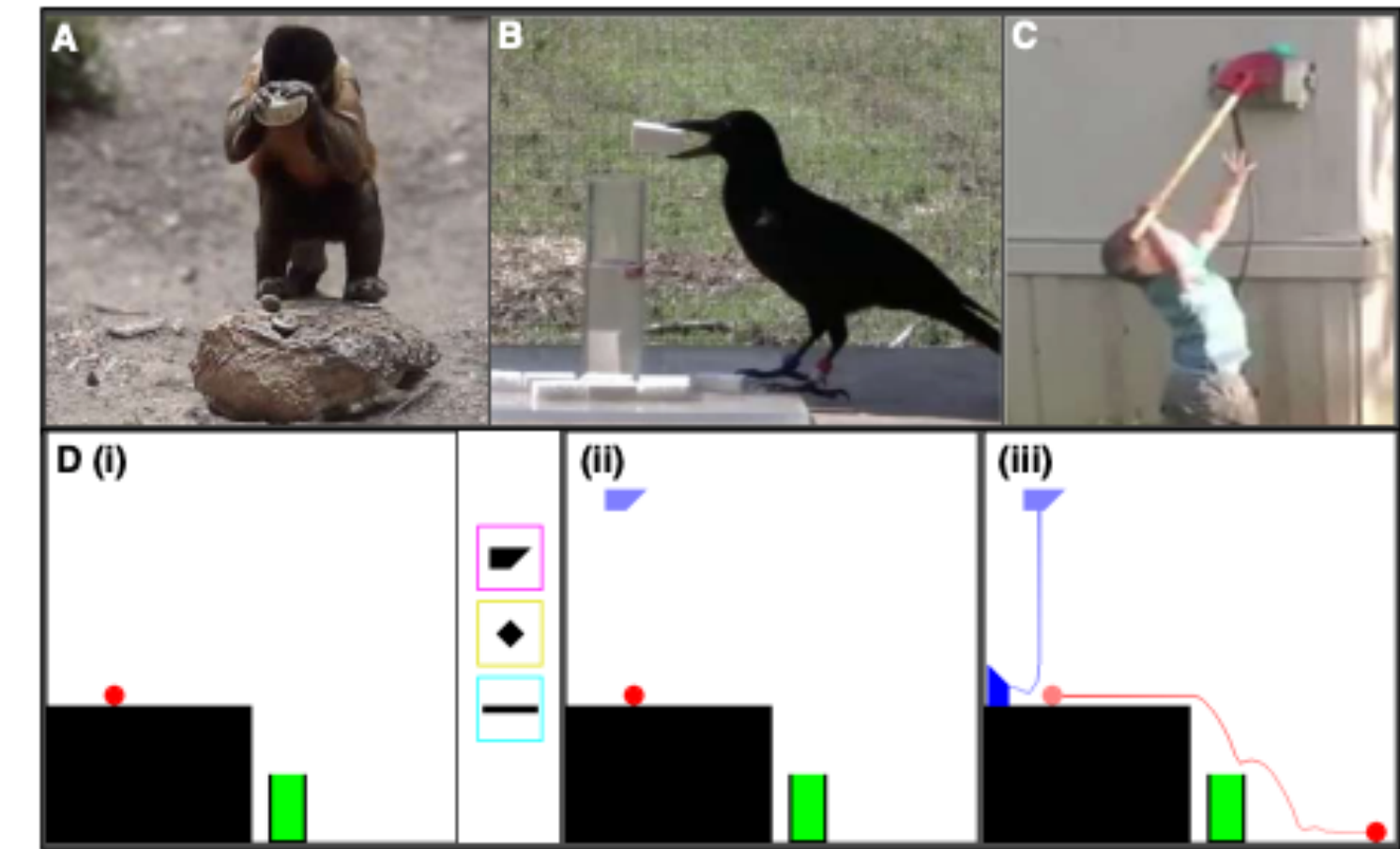
## Approach

- Innovate upon a previous experiment ([Allen\\*, Smith\\*, & Tenenbuam, PNAS 2020](#)), where participants selected which tool they found most useful
- Here, we will allow people to develop their own tools and implement a transmission chain, where the solutions or instructions from one generation of participants will be passed along to the next
- Study the key ingredients for cumulative culture in tool use (e.g., observational learning vs. explicit pedagogy) and which task dimensions are most sensitive to pedagogy (e.g, opaque vs. transparent causal structure)

## Scope

- Learn to design and implement an online experiment based on previous online experiment code (experience with Javascript/HTML/PHP highly recommended)
- Analyze data and perform statistical analyses (experience with Python/R encouraged)
- Collaboration with MIT and Deepmind

Tool use in animals and humans



[Allen\\*, Smith\\*, & Tenenbuam \(PNAS 2020\)](#)

Cumulative culture



[Kurzban & Barrett \(Sci, 2012\)](#)

# Project 2: Designing a MuJoCo environment for intuitive physical reasoning tasks

## Research Question

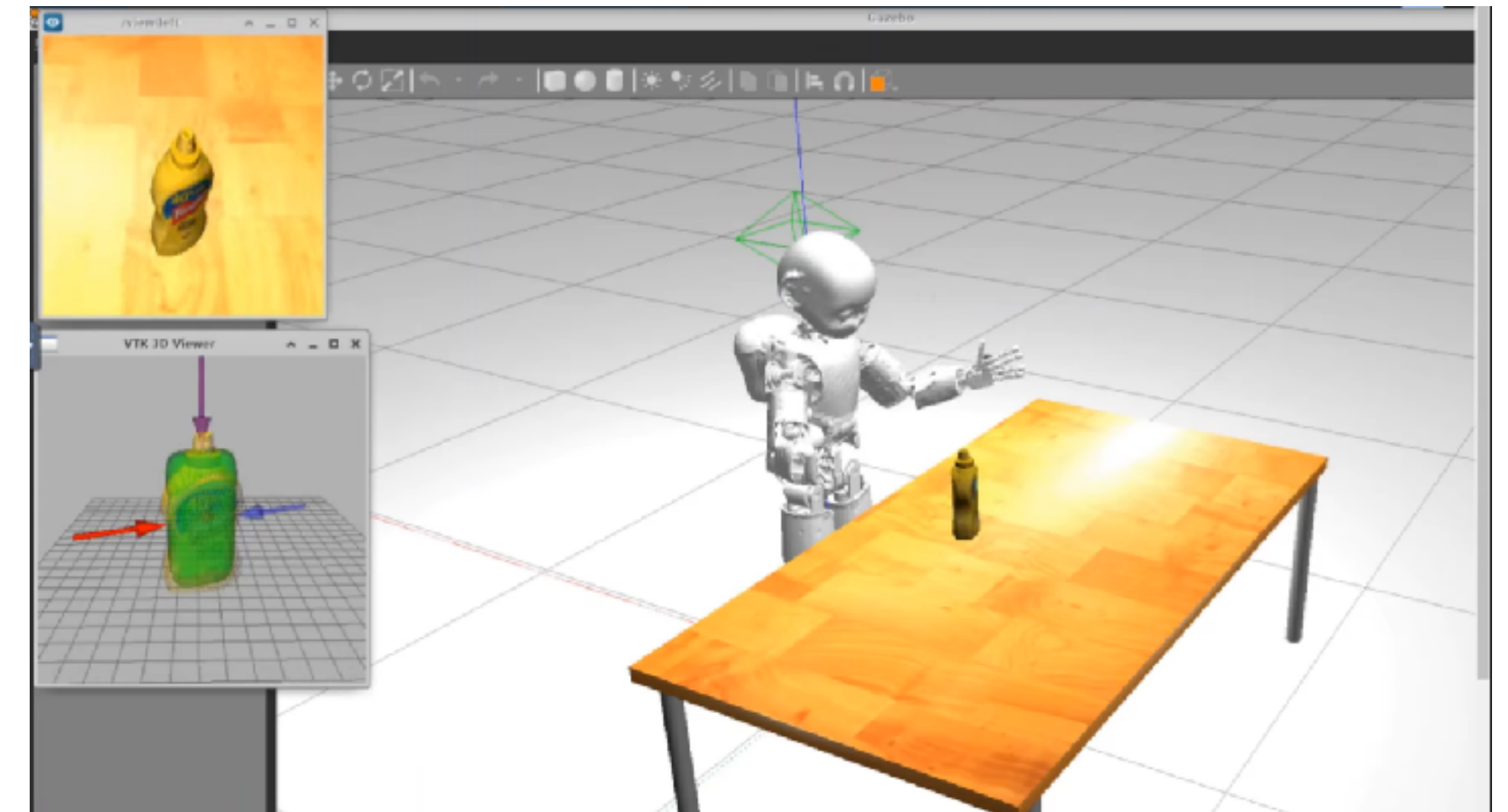
According to Piaget, infants gradually learn to successfully search for hidden objects which points to the lack of *object permanence* as a cognitive concept in newborn's mind ([Piaget, 1954](#)). Other physical reasoning concepts like *continuity*, *solidity*, *gravity* and *inertia* also mature later during infant's cognitive development ([Spelke et al., 1992](#)). Smith and Gasser claim these reasoning abilities emerge in the interaction of an agent with an environment ([Smith & Gasser, 2005](#)). Taking inspiration from cognitive development literature, several attempts have been made to replicate intuitive physics reasoning in machines ([Chang et al., 2017](#), [Piloto et al., 2022](#), [Agrawal et al., 2016](#), [Smith et al., 2019](#)). But none of these attempts have incorporated the idea from Smith and Gasser that intuitive physics understanding emerges from agent-environment interactions of the embodied agents. To implement this in practice, a simulated playground is necessary for the machine to interact in. The goal of this project is to build such an environment.

## Approach

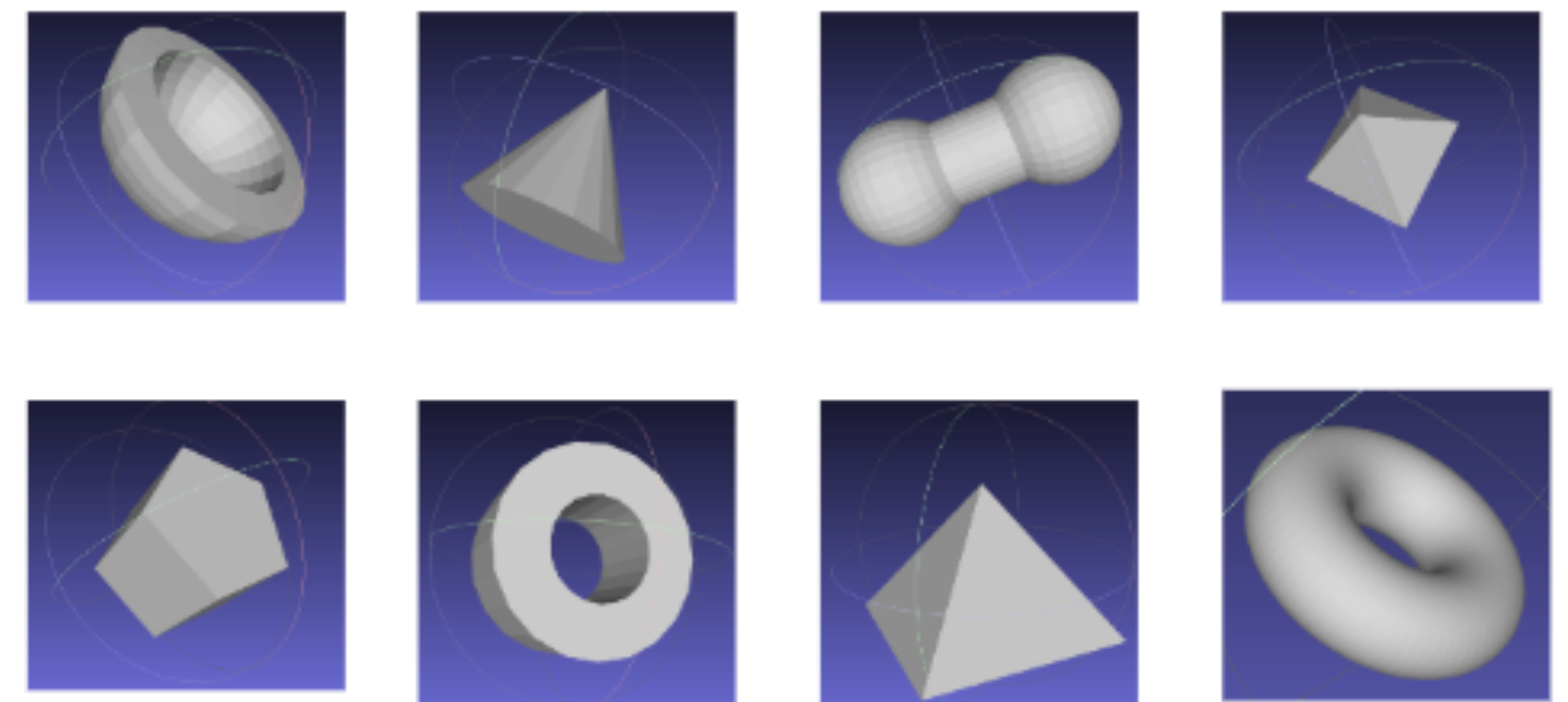
- Improve upon the existing [MuJoCo](#) environment
- Add a curriculum of tasks with different objects for the [iCub](#) robot to interact with in the simulation
- Create an [OpenAI gym](#) environment from the MuJoCo environment

## Scope

- This is meant as a lab rotation project
- Learn to code MuJoCo environments and turn them into an OpenAI gym environment
- Time permitting, the environments can be tested with existing neural network architectures



<https://github.com/robotology/icub-gazebo-grasping-sandbox>



[Kachergis et al. \(2021\)](#)



# Project 3: Semantic Foraging and Cognitive Flexibility

## Research Question

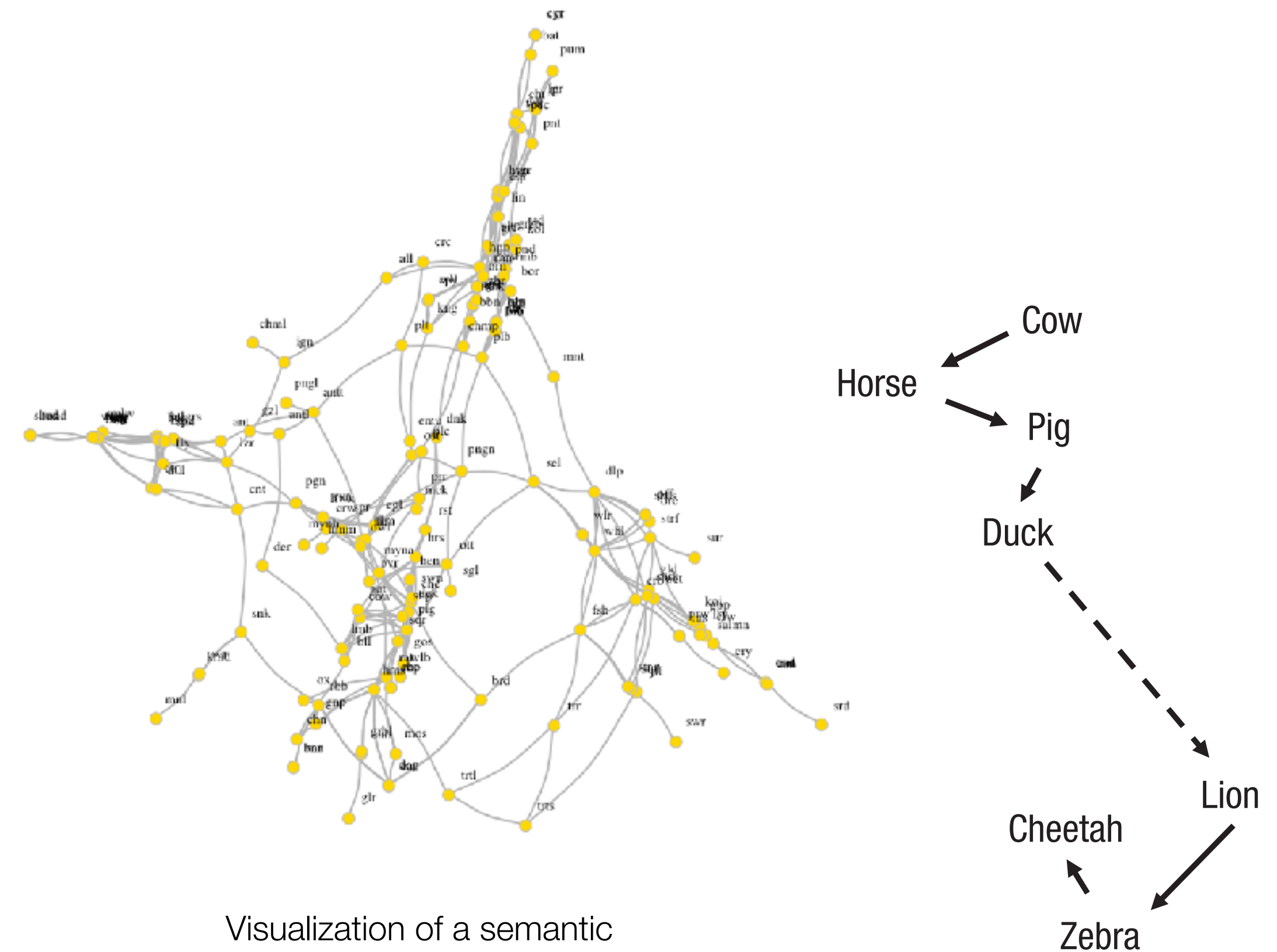
In the human mind, concepts are organized into clusters. Differences in the way each of us navigates this conceptual space can inform us about individual differences in our cognitive functioning. The cognitive function we focus on here is *cognitive flexibility* – the ability to switch rapidly between attentional states, linked to creativity. In this project, we analyze temporal dynamics of “semantic foraging” across conceptual clusters to better understand cognitive flexibility and creativity.

## Approach

- Analyze temporal patterns in Verbal Fluency (word production) data that has already been collected from 275 adult participants.
- Use NLP methods like word vectors to define the semantic space within which semantic foraging is performed
- Statistical comparison of semantic foraging metrics with cognitive flexibility measures

## Scope

- This project is a collaboration with the University of Cambridge and Nanyang Technological University, Singapore.
- Opportunity for co-authorship in a journal article.



Visualization of a semantic network derived from data we collected from a “high cognitive flexibility” group

Illustration of a transition between semantic clusters in the Verbal Fluency task (“name as many animals as you can in 1 minute”)

# Project 4: Episodic and model based control

## Research question

Humans construct internal models to predict the consequences of possible actions. However in a newly encountered environment, limited experience can make it unfeasible to fit a parametric model. Therefore in the early stages of learning, relying on experiences directly may be more efficient (Lengyel & Dayan, 2009). It has been hypothesised that this constitutes a normative rationale for two complementary learning systems, one that constructs a parametric model (typically associated with the neocortex) and a non-parametric one (typically associated with episodic memory and hippocampal regions) (Kumaran et al, 2016, Nagy & Orban, 2006). We are interested in how the brain arbitrates between these two controllers as well as better understanding the computational trade-offs that they make.

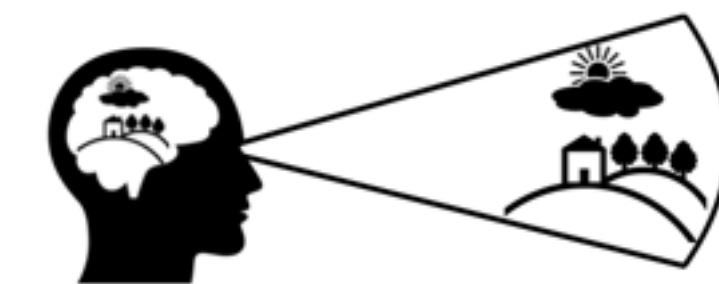
## Approach

- Explore the interaction between parametric and non-parametric learning systems in a behavioural experiment, building on the setting of Xiong, Moneta, Banyai, & Wu, 2023
- Investigate how the contents of episodic memory are selected, specifically whether they are optimised to support the construction of the model
- We use a reinforcement learning framework and bayesian methods for computational modelling

## Scope

- Implement an online experiment (experience with Javascript/HTML/PHP will be required)
- Option to construct computational models and analyse data (Python knowledge useful)
- Project in collaboration with MPI for Biological Cybernetics

semantic model



$$p(x, z, \theta | \mathcal{D})$$

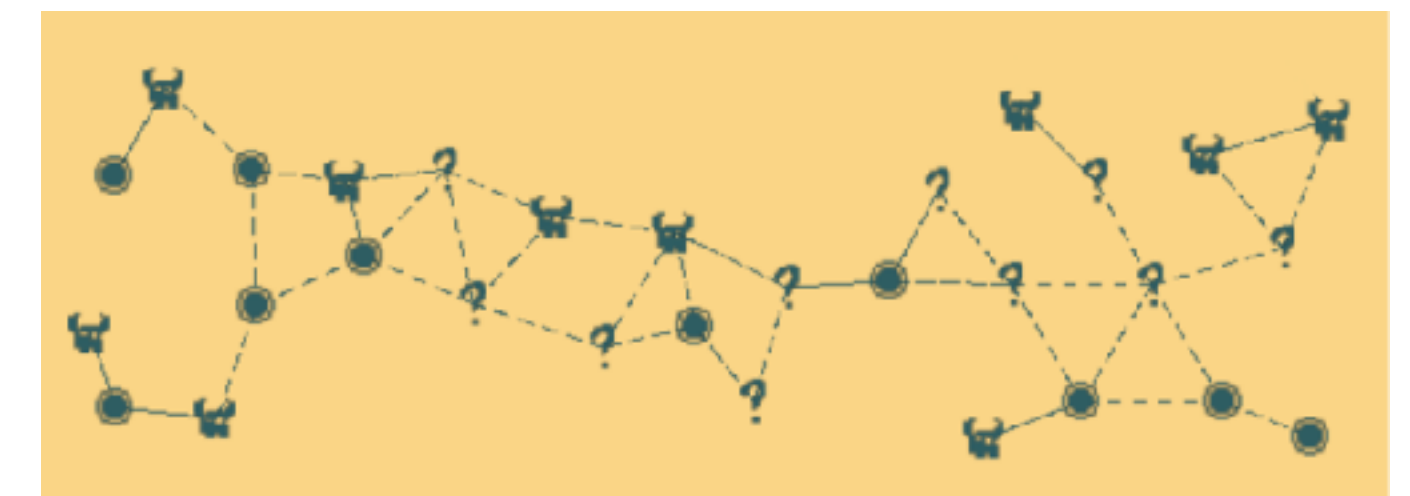
episodic memory



$$\{x_t\} \subset \mathcal{D}$$



Xiong, Moneta, Banyai, & Wu (CCN 2023)





# Project 5: Neural correlates of reward generalization and exploration

## Research Question

How do people integrate observations of reward when they also generalize to similar options?

## Approach

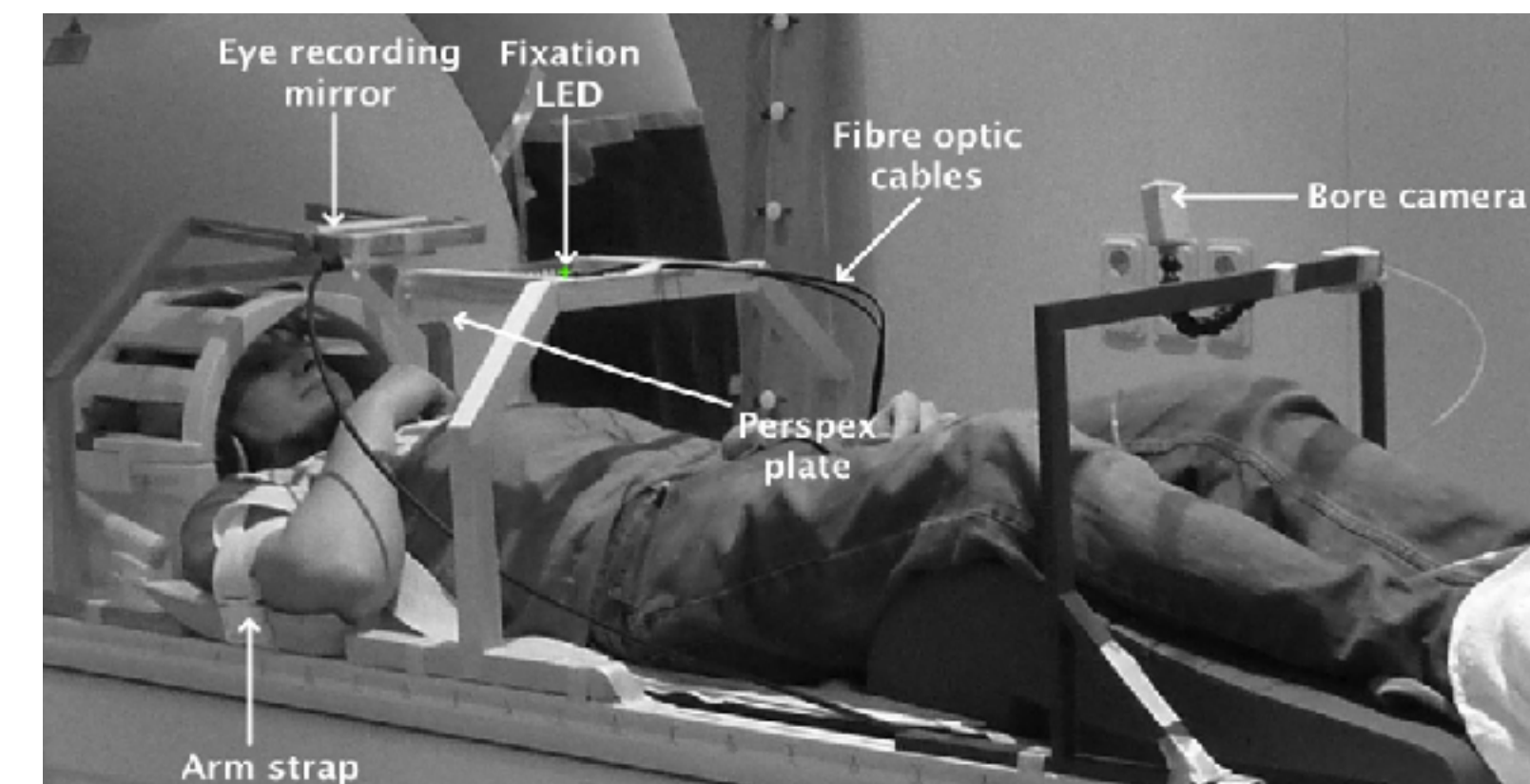
- Simultaneous fMRI and eye-tracking study planned for early 2023, using a modified version of the Spatially correlated bandit task
- Use eye-tracking to improve our process-level understanding of previous computational models ([Wu et al., 2018](#); [Wu et al., 2020](#))
- Relate model predictions and parameters to understand the neural mechanism underlying reward generalization and exploration

## Scope

- Learn to design and implement an fMRI experiment based on previous online experiment code (Javascript/HTML)
- Learn to work with the analysis of eye-tracking data
- Collaboration with MPI Berlin and University of Hamburg

## Spatially correlated bandit

7	5	10	22	32	32	28	24	22	26	33
6	11	19	29	38	41	42	40	37	36	40
22	27	30	35	43	50	53	53	51	49	46
45	44	38	36	40	46	47	49	54	55	48
61	55	46	40	37	32	27	31	44	52	44
62	59	57	54	44	27	14	17	33	46	45
53	59	68	71	59	36	17	15	28	45	51
48	57	71	77	67	47	26	18	27	45	56
45	56	65	67	60	46	29	20	27	42	55
51	57	58	53	47	40	30	23	28	40	49
60	62	58	47	39	38	35	31	35	41	46





# Project 6: Experiments in Virtual Reality (VR)

## Research Question

VR provides naturalistic and immersive setting for human experiments, combined with total control over environmental factors ([ICON](#)). This allows us to effectively study several cognitive processes like navigation ([Kuhrt et al., 2022](#)), cognitive load ([Albus et al., 2021](#)), and memory ([Plancher et al., 2018](#)), in social and individual settings.

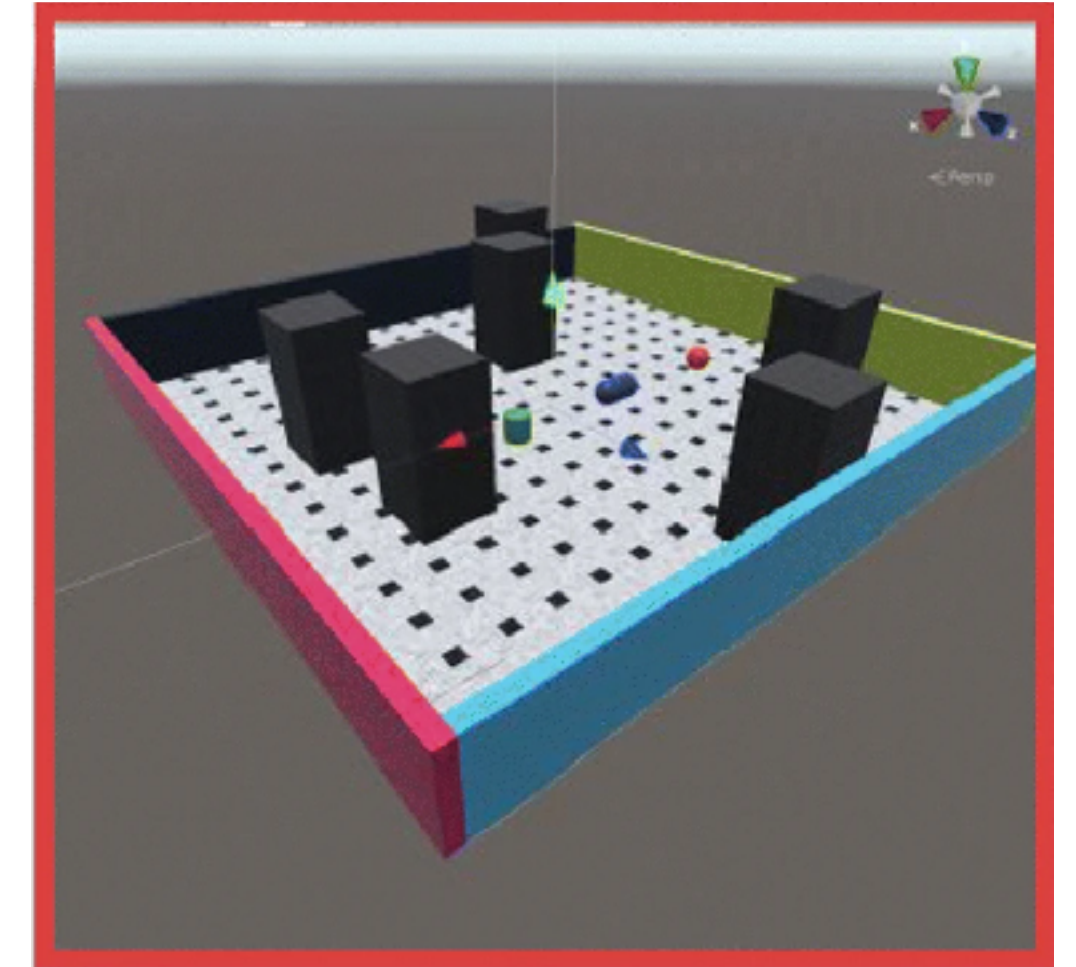
We are currently interested in understanding the role of social learning in competitive settings like Hide and Seek ([Shen et al., 2019](#), [Crawford et al., 2007](#), [Wang et al., 2019](#)).

## Approach

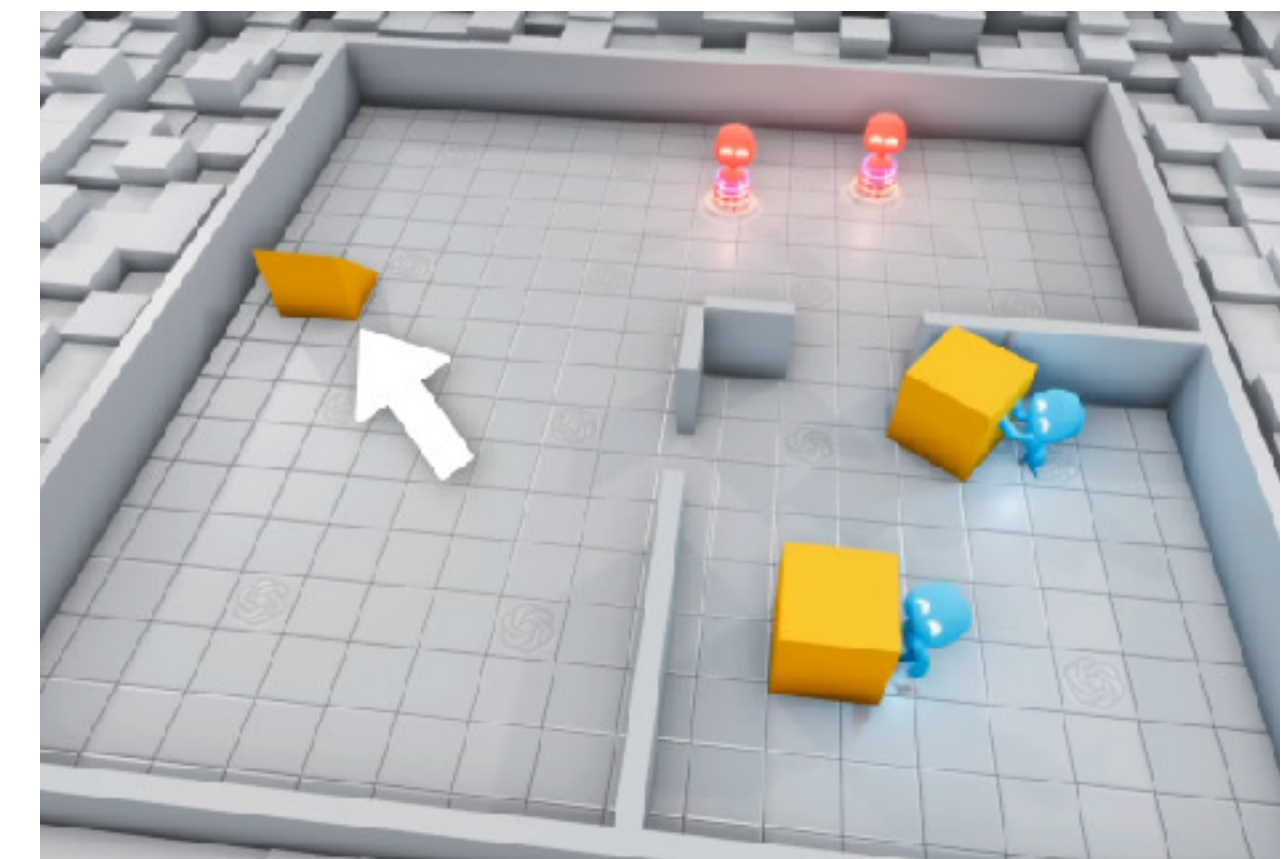
- Develop experiments in Virtual Reality using [Unity](#). You can build off of an existing multiplayer hide and seek environment
- Collect data from players in Virtual Reality setting.
- Study the cognitive process in question using the collected data.

## Scope

- Formulate research question to study relevant cognitive process (theory of mind, navigation, memory, etc.)
- Learn to develop environment using Unity or other VR toolboxes. Collect and analyze data using Python or R.



[Landmarks: A solution for spatial navigation and memory experiments in virtual reality](#)



[OpenAI: Multi-Agent Hide and Seek](#)



# Project 7: Propose your own project!

- Take the reigns and propose your own research project! To make things feasible within the rotation period or for a thesis, here are some suggestions of projects with existing data/code that could be built upon:
- How does cooperation arise in competitive environments?** Through a series of [agent-based](#) and [evolutionary simulations](#), we found that unconditional sharing of information can be beneficial, even in the absence of traditional reciprocity or reputation-based mechanisms. Many open questions, new environments, and learning mechanisms that can be tested
- Why do people systematically under-generalize? Why are people systematically biased towards performing local search?** These are unexplained questions from a series of previous papers studying the search for rewards in spatially structured ([Wu et al., 2018](#)) and conceptually structured ([Wu et al., 2020](#)), and graph-structured environments ([Wu et al., 2021](#)). All the code and data are publicly available ([1](#), [2](#), [3](#))
- Note:** proposing your own project requires a high level of independent thinking and ability to craft an interesting and obtainable research question

## Evolutionary simulations

