

Hippoformer

Integrating Hippocampus-inspired Spatial Memory with Transformers

Tiantian Li^{2,*} Xingxing Cao^{1,*} Yifei Wang² Xiaojiao Yang¹
Xiaolong Zou^{1,*} Bo Hong^{1,*}

¹Department of Biomedical Engineering, School of Medicine, Tsinghua University ²Qiyuan Lab

*Equal contribution, ✧Corresponding author



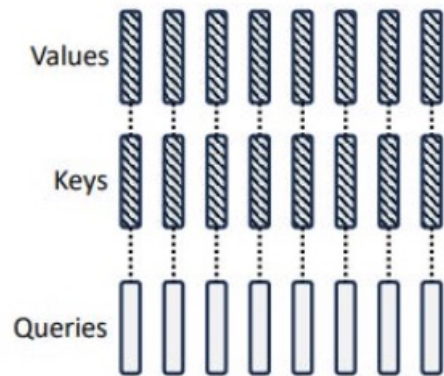
清华大学

启元 启元实验室
QIYUAN LAB

Toward a structured and efficient spatial memory system

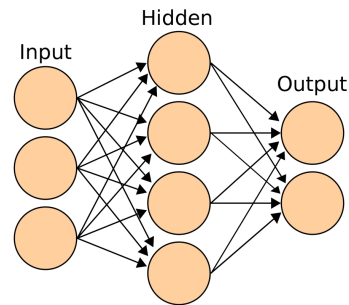
- **Transformer:** Key-value pairs are precisely stored, like a database
- **Titans:** Compress information in a network (finite-sized memory)

Multi-Head Attention (MHA)

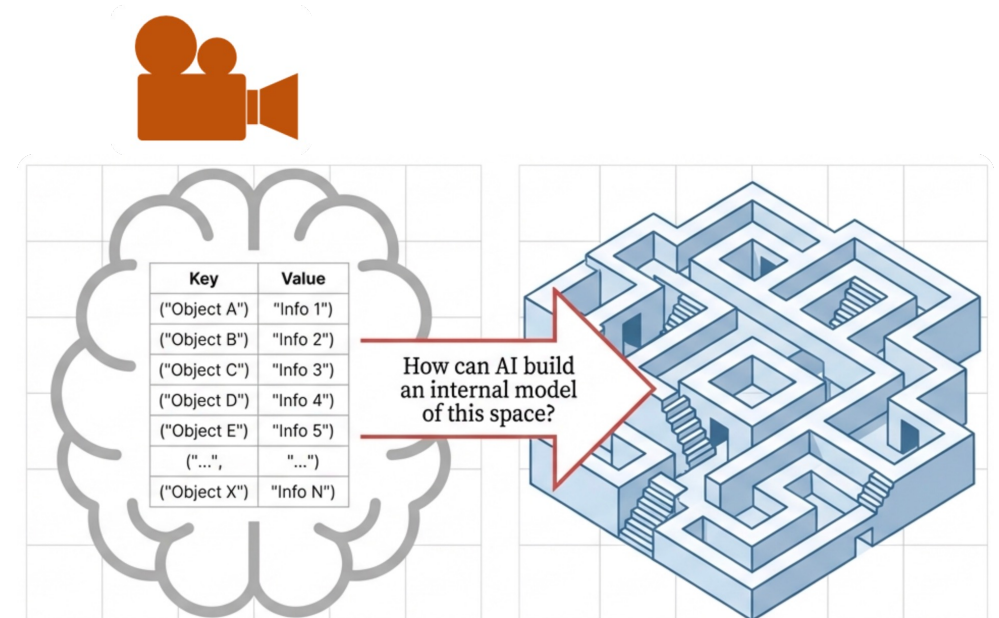


Memory in transformer

Compress memory in a network



Memory in Titans



Associative Memory (Flat & Unstructured)

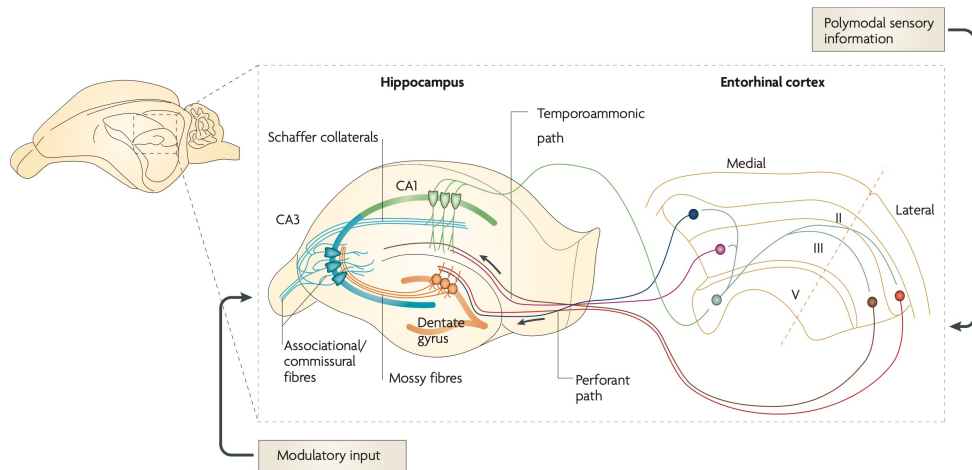
The Real World (Structured & Spatial)

Conventional sequence memory:
the previous state must reconstruct the entire content of the next state

[1] Ashish Vaswani, et al. Attention is all you need. NeurIPS, 2017.

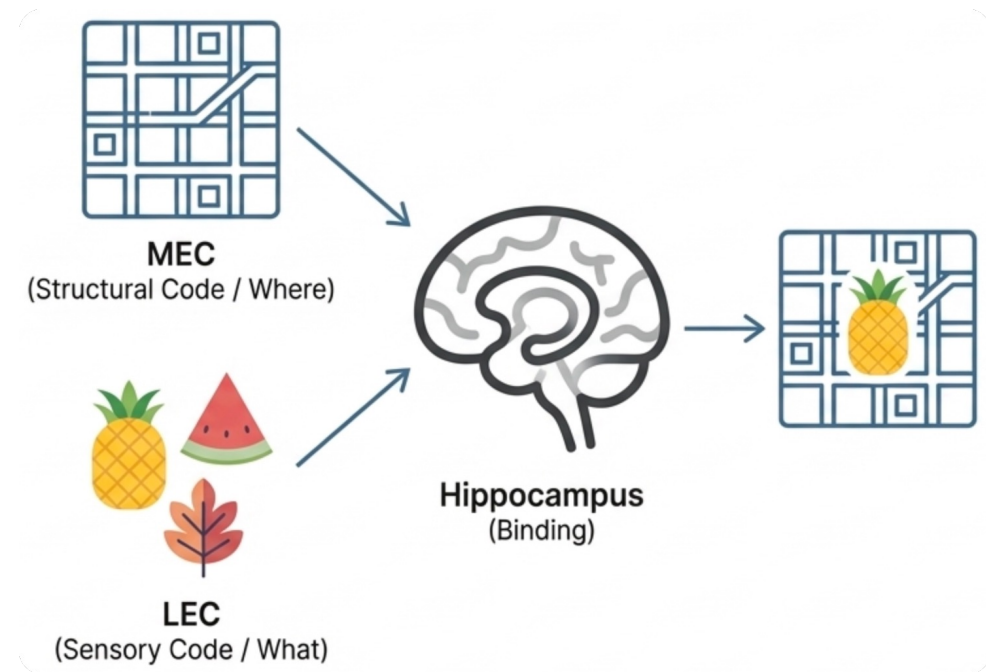
[2] Ali Behrouz, et al. Titans: Learning to memorize at test time. NeurIPS, 2025.

Nature's ultimate navigator: The brain's hippocampus



The hippocampal–entorhinal system constitutes the core substrate of spatial memory:

- **MEC:** path-integration–based structural codes
- **LEC:** sensory codes
- **HPC:** associative memory



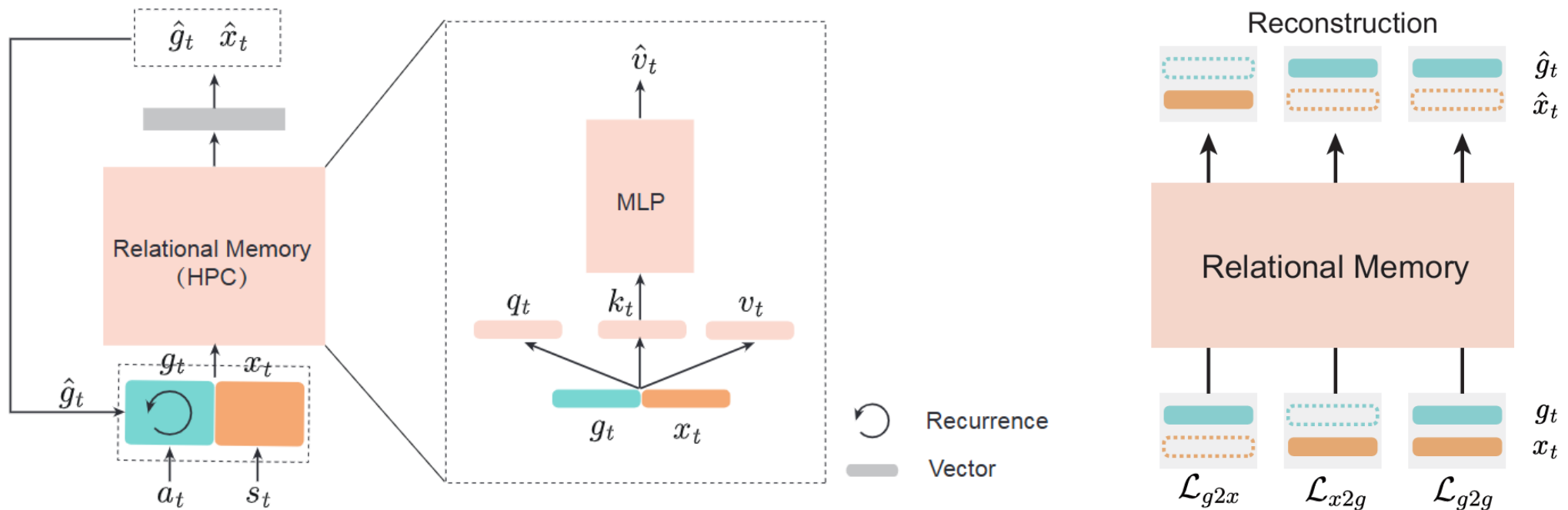
Structured spatial memory:
dissociates 'what' from 'where', reasoning in a low-dim space

[3] Neves, et al. Synaptic plasticity, memory and the hippocampus: a neural network approach to causality. Nature reviews neuroscience, 2008.

[4] Howard Eichenbaum, et al. The medial temporal lobe and recognition memory. Annual review of neuroscience, 2007.

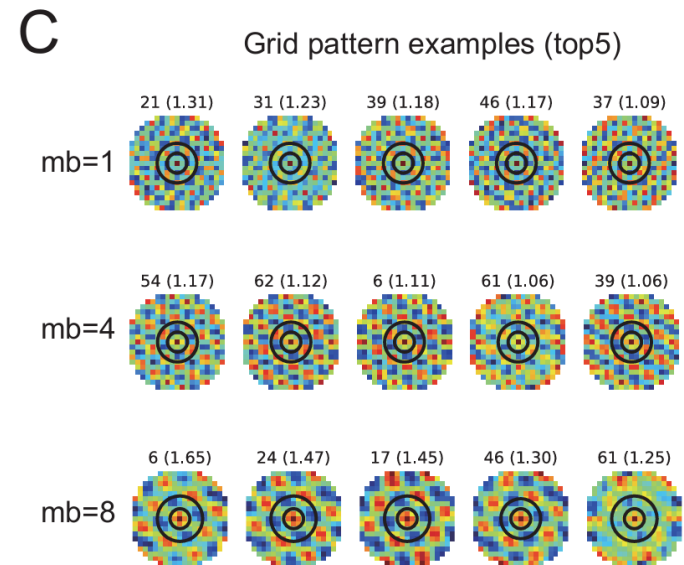
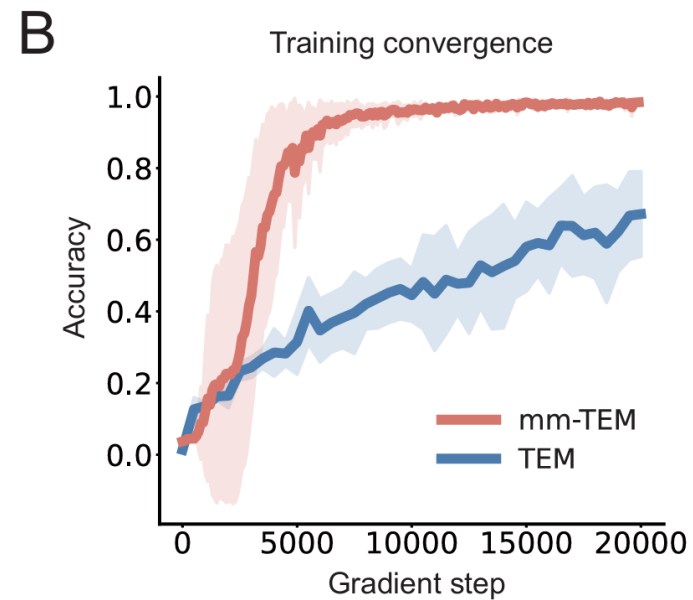
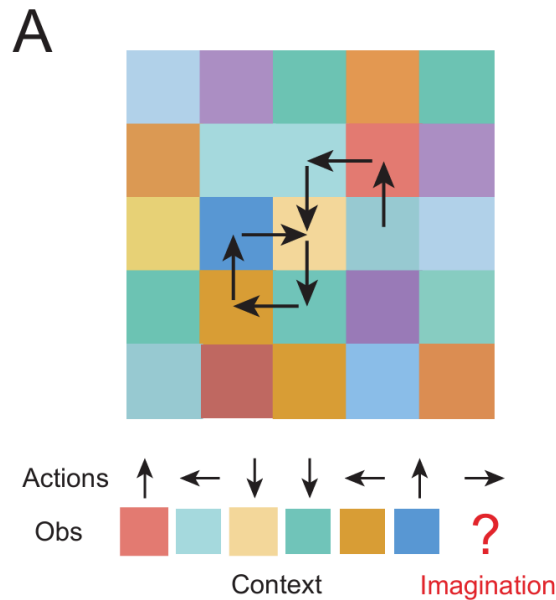
mm-TEM: a scalable and efficient structural memory

- **Path integration Network**: an MLP-based transformation network to capture spatial constraints
- **Parametric Relational Memory**: using a MLP as memory, meta-trained via auxiliary relational loss
- **Error correction**: using sensory observations to correct structural code



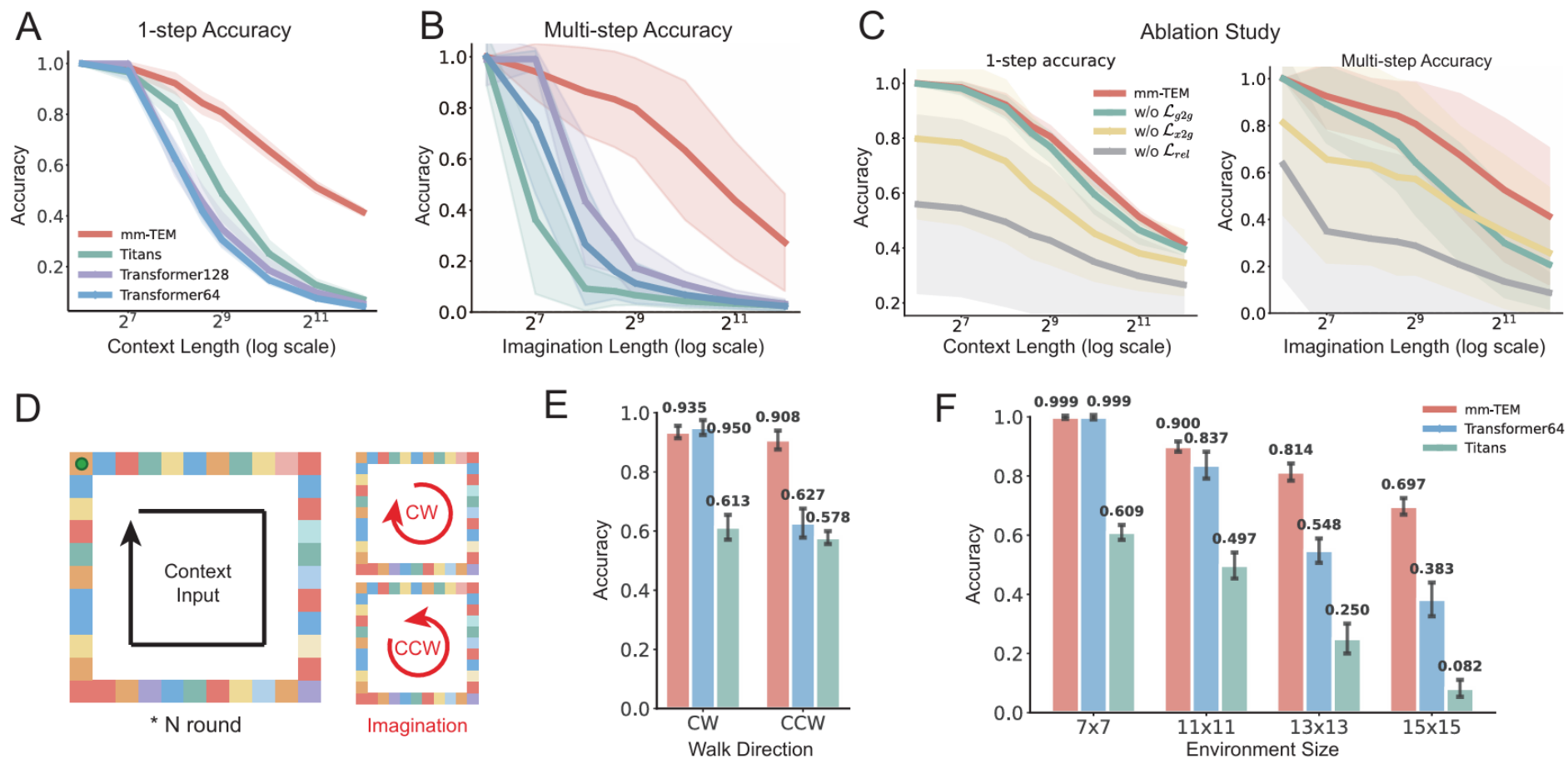
Efficient training and Grid-like pattern

- mm-TEM trains more efficiently and converges faster.
- It exhibits the **emergence of grid-like representations** in the path integration network.
- The emerged **grid scale varies with hyperparameter mb** which controls the update frequency of relational memory.



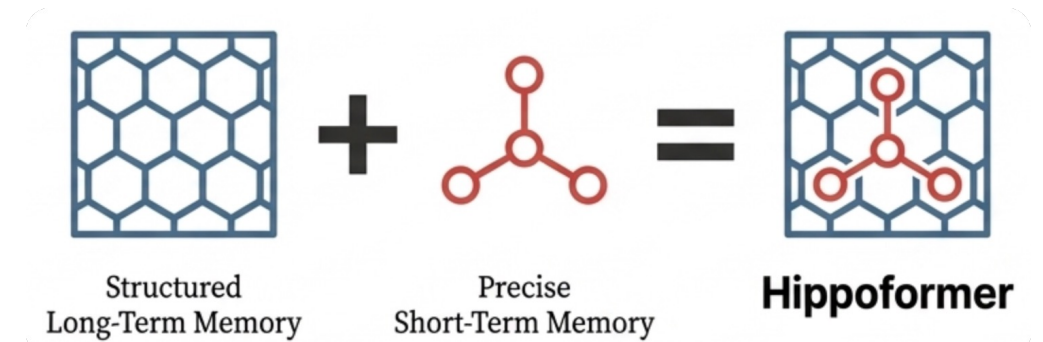
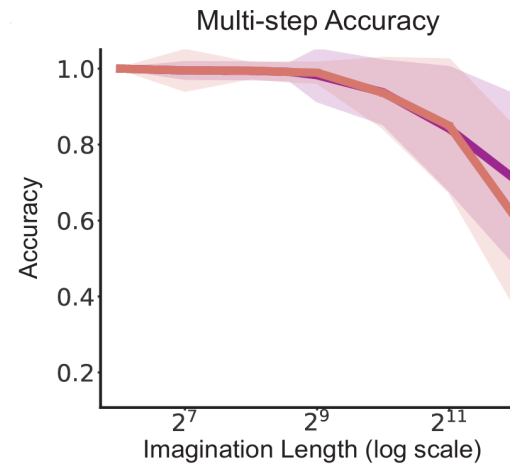
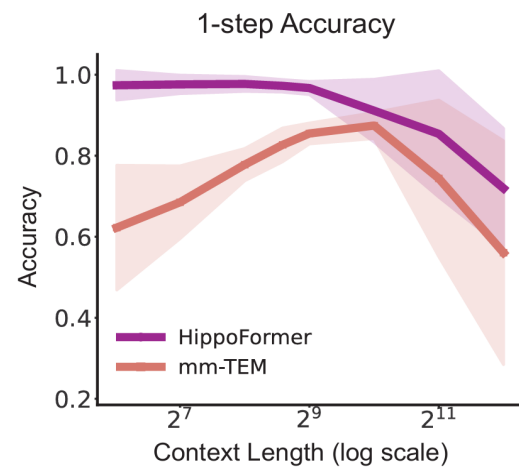
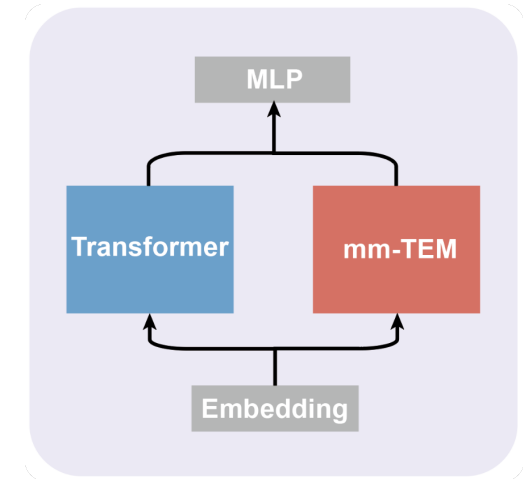
Better generalization in 2D tasks

On synthetic 2D tasks, mm-TEM shows **better long-range memory, more accurate reasoning, and stronger generalization** to reverse prediction and larger unseen environments.

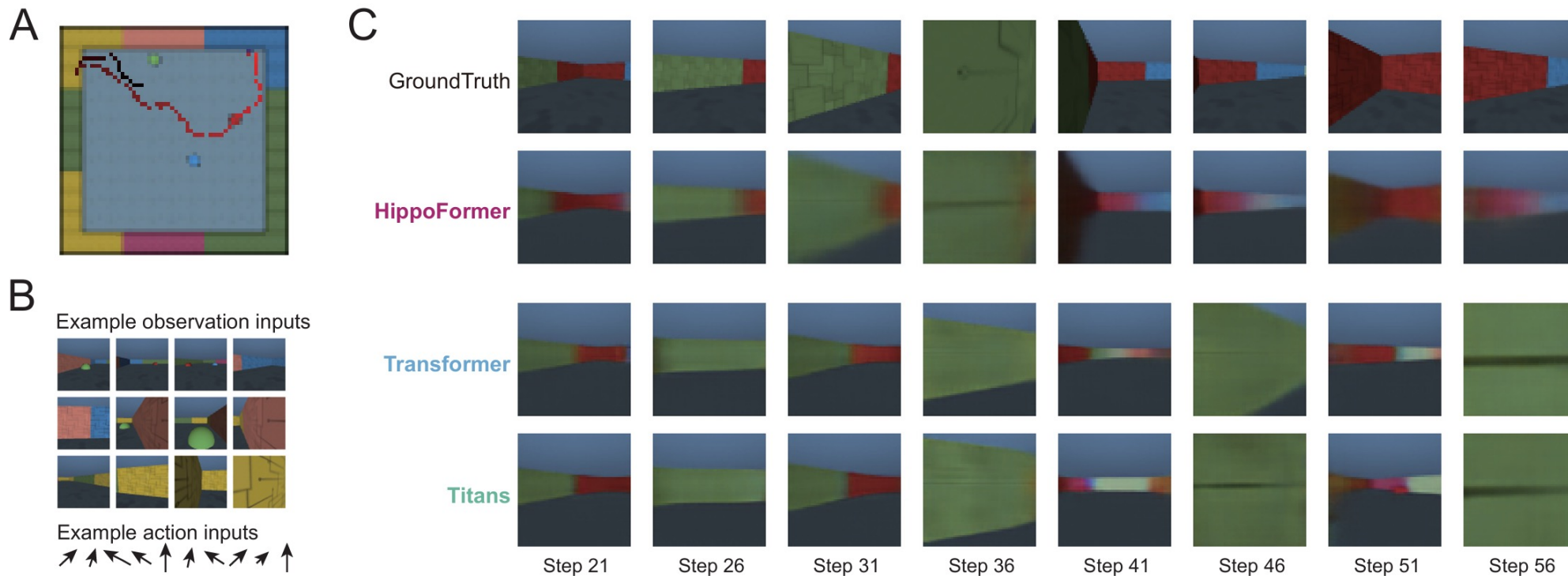


Hippoformer: a hybrid architecture for spatial intelligence

- **Transformer** with limited window size as a **precise short-term memory**
- **mm-TEM** as a **long-term and structured spatial memory**
- Their combination enhances adaptability in complex tasks



Hippoformer demonstrates superior generalization in 3D tasks



Models	1-step Prediction Error (1e-3)			m-step Imagination Error (1e-3)		
	Full	Visible	Not Visible	Full	Visible	Not Visible
Transformer	1.29±0.00	0.67±0.00	2.15±0.00	36.13±5.0	11.49±3.3	38.07±13
Titans	1.32±0.00	0.69±0.00	2.20±0.05	33.42±4.6	10.60±2.4	35.21±13
mm-TEM	5.10±0.05	4.23±0.05	6.53±0.05	14.30±0.36	13.23±3.05	14.40±0.16
Hippoformer	1.27±0.00	0.67±0.00	2.09±0.05	9.71±0.04	2.72±0.01	10.27±3.6

Thank you!



清華大學

启元 启元实验室
QIYUAN LAB