A Framework for Understanding Spatial Reasoning

Liam Taylor[1] and Eric Chown[2]

[1]Department of Biology [2]Department of Computer Science, Bowdoin College, Brunswick, ME

What is spatial reasoning?

Agents (e.g., ants, humans, robots) use behavioral tools to navigate, remember, understand, and manipulate space. Walking down a hallway, remembering the shape of your childhood bedroom, and running across campus are all applications of our spatial systems. In complex **animals**, these behaviors have **evolved** in conjunction with **neural substrates**, and sometimes rely on complex **cognition**. In **robotic** agents, these behaviors must be mapped out and programmed to function effectively and efficiently.

How was the framework built?

A variety of dichotomies constrain traditional analyses:

- **Empirical behavioral data** *vs.* **quantitative models**
- **Evolution** (local optima) *vs.* **Computation** (absolute optima)
- **Modularity** (individual behaviors) *vs.* **Integration** (full system)
- **Human** reasoning *vs.* **non-human** behavior

We aimed to balance our perspectives across these divides. We reviewed literature from a diverse array of disciplines, including Biology, Robotics, Psychology, and Cognitive Science.

This framework is a ***hypothesis***, meant to spur our thinking on the ways in which spatial behaviors can and should fit together.

Why are spatial problems important?

Any agent that exists in a real or virtual world must deal with that world's environment.

Survival and reproductions of all organisms is constrained by the efficiency of spatial reasoning. Individuals must perform complex spatial tasks to accomplish both short- and long-term goals (e.g., foraging, migration).

Artificial agents (e.g., self-driving cars, autonomous robots) must efficiently conquer spatial challenges to operate effectively. The strategies implemented in robotics may be derived from quantitative rules or may be co-opted from observations of biological behavior.

Representations

External Representations (Socio-cognitive Maps)

Systems that allow organisms to input and output physical or chemical indicators of spatial information onto the environment itself (e.g., ant pheromone trails, bee dances, paper maps). These can be parsed using simpler neural systems than those required for full internal representations.

Internal Representations

R-Nets

Networks of local maps, associating them with their spatial position.

Local Maps

Sequences of scenes found at different angles at a given position.

Route Maps

Networks of landmarks and their associated spatial information.

Survey Maps

Predictive models of metric landscapes.

Object Representations

Internal representations of individual objects that are recognized and parsed *outside of the spatial system*. Objects are recognized and developed as prototypes via Hebbian learning rules. They store both constituent features of an object and its connections to other objects.

External References

Scenes

Perceptual units from a single viewpoint. Scenes can allow for simple associations with stored memories (e.g., retinal matching) or can be parsed for features containing more subtle geometric or metric information (e.g., edges, corners, frames). Scenes contain no objects, but can be linked to them.

Landmarks

Stored objects that contain particular spatial features. Landmarks can be connected to spatial information (coordinate location, navigable heading) or connected to one another (distance and direction to another landmark).

Error Correction

Referencing information in the environment allows agents to update accumulators, correct for slippage, or localize in a coordinate space.

Automated Bio/mechanics

Stimulus-Response Behaviors

Agents react to environmental or internal cues with simple, deterministic behaviors. These behaviors can rely on simple (neural) circuits, mechanical responses, or chemical reactions. In the simplest agents, such as those that lack memory, these form the entire spatial system.

(Start Here!)

Path Integration

Dead Reckoning

Agents keep track of the distance and direction of each leg of a journey, and can use vector subtraction to find a direct route back to a home-base or forward towards a new goal.

Errors

Misfiring accumulators (slippage) or environmental changes along past or future paths are an unavoidable part of path integration and result in increasing errors in distance/direction predictions.

Accumulators

Counters that record net changes in distance or direction to be consulted during vector calculations. These counters can rely on internal feedback (e.g., idiothetic cues, magnetic compasses) or sequences of external cues (e.g., optic flow).

→ = Connections between systems

→ = Details within a system

For more information or a bibliography, contact ltaylor2@bowdoin.edu