Semantic Lightcones and Propagation Limits

In this section, we define the concept of **semantic lightcones**—regions of causal influence in a semantic knowledge graph. This extends the relativistic concept of a lightcone into the domain of inference, belief propagation, and semantic reachability.

1. Semantic Distance and Causal Structure

Let $G = (V, E)$ be a directed knowledge graph, where V are knowledge nodes (observations, beliefs, facts) and E are transformations (proof steps, inferences, semantic transitions).

We define the **semantic distance** $d_{\text{sem}}(v_i, v_j)$ as the minimal weighted path length from node v_i to node v_j under valid transformation rules. These rules preserve semantic coherence and may include context-dependent constraints.

A node v_j is said to be **semantically reachable** from v_i if there exists a valid path:

$$P = \{v_i \to \cdots \to v_j\} \quad \text{with total cost } d_{\text{sem}}(v_i, v_j) < \infty$$

2. Definition of the Semantic Lightcone

We define the *forward semantic lightcone* of a node v as:

$$\mathcal{C}^+(v, t) = \{u \in V : d_{\text{sem}}(v, u) \leq c_{\text{sem}} \cdot t\}$$

and the *backward lightcone* as:

$$\mathcal{C}^-(v, t) = \{u \in V : d_{\text{sem}}(u, v) \leq c_{\text{sem}} \cdot t\}$$

This defines the region of semantic space that can be influenced by (or influence) node v within propagation time t, assuming c_{sem} is the maximal semantic propagation speed.

3. Semantic Causality and Isolation

If $v_j \notin \mathcal{C}^+(v_i, t)$ for any finite t, then v_j is semantically **causally disconnected** from v_i.

This provides a test for:

- Semantic irrelevance
- Topic drift beyond recoverability
- Logical disconnection or contradiction

4. Observation Delays and Cone Asymmetry

Observation introduces delay due to finite resolution and processing latency. Thus:

$$\mathcal{C}^+_{\text{obs}}(v, t) \subseteq \mathcal{C}^+(v, t)$$

The true region in which semantic influence has been realized is *strictly smaller* than the potential causal region. This allows us to define drift zones:

$$\mathcal{D}(v, t) = \mathcal{C}^+(v, t) \setminus \mathcal{C}^+_{\text{obs}}(v, t)$$

which encode zones of unreconciled knowledge flow.

5. Implications for System Design

- In AI systems: limits update diffusion and knowledge coherence.
- In human cognition: defines what can be recalled or referenced coherently.
- In epistemology: introduces a formal limit on semantic influence.

Future work includes defining field equations over lightcones, and integrating the structure into predictive graph traversals and loss functions.