Multi-Causal Intelligence (MCI)

Foundations and Structures

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§1 Introduction

The theory of **Multi-Causal Intelligence (MCI)** arises from the intersection of computer science, category theory, and causal inference. It seeks to formalize and implement agents capable of recursively reasoning across multiple layers of causal abstraction.

While conventional AI systems operate within singular or static causal frameworks, MCI proposes a dynamic, compositional, and multi-layered approach, where causal relationships are not fixed but generated, transformed, and recursively reasoned over.

§2 Causal Graphs and Structural Foundations

Let us define a **causal graph** $G = (V, E)$, where V is a set of nodes (representing variables or events), and $E \subset V \times V$ is a set of directed edges (representing causal relationships).

A causal model $\mathcal{M}$ is defined as:

$$\mathcal{M} = \langle G, \mathcal{F}, \mathcal{P} \rangle$$

where:

- G is a causal graph.
- $\mathcal{F} = \{f_v \mid v \in V\}$ is a set of structural functions.
- $\mathcal{P}$ is a probability distribution over exogenous variables.

MCI extends this notion by considering multiple causal models $\mathcal{M}_1, \ldots, \mathcal{M}_n$, with a meta-structure defining relationships between them.

2.1 The Multiway Causal Structure

We define a **multiway causal system** $\mathcal{W}$ as:

$$\mathcal{W} = (\{\mathcal{M}_i\}_{i \in I}, \mathcal{T})$$

where $\mathcal{T} : \mathcal{M}_i \to \mathcal{M}_j$ represents transitions such as interventions or structural updates.

This defines a branching, non-deterministic causal space akin to Wolfram's multiway systems.

2.2 Categorical Abstractions

In MCI, causal graphs and transformations are modeled in a category **Causal**. Each causal model is an object, and each morphism represents a transformation preserving causal structure.

Definition: A *Causal Category* **Causal** has:

- Objects: causal models $\mathcal{M}$
- Morphisms: functorial transformations
- Composition: models composite reasoning

Functors, 2-categories, limits, and colimits all play roles in MCI for aligning and transforming knowledge layers.

2.3 Recursive Reasoning Agents

Define a recursive agent $\mathcal{A}$ by:

$$\mathcal{A} = \langle \Sigma, \delta, \mu, \rho \rangle$$

where:

- Σ: internal symbolic state
- δ: transition on observations
- μ: model proposal function
- ρ: recursive introspection

Agents not only traverse models but propose and revise them through symbolic recursion.

2.4 Implementation Outline

The implementation of MCI includes:

- **Graph Layer**: DAGs with interventions
- **Multiway Engine**: branching causal paths
- **Category Engine**: transformations and abstractions
- **Agentic Kernel**: recursive and symbolic agents

This supports both symbolic and probabilistic reasoning and meta-model operations.

2.5 Applications and Future Work

MCI supports:

- Scientific hypothesis generation
- Multi-agent epistemic alignment
- Adaptive ontologies
- Reflexive symbolic-causal fields

Future work involves recursive agents that not only navigate causal spaces but *generate* and *transcend* them.

§3 Constructing a Minimal MCI Agent
Recursive Traversal of Multiway Causal Systems

3.1 Agent Architecture

We define a minimal recursive agent $\mathcal{A} = \langle \Sigma, \delta, \mu, \rho \rangle$ as in § 2. The goal of this section is to instantiate $\mathcal{A}$ with computable structures and demonstrate recursive traversal across a multiway causal system.

Definition 1. *A* ***symbolic state space*** Σ *is a finite set of strings* $s \in \Sigma$*, each representing an encoded causal hypothesis or intervention path.*

Definition 2. *The* ***transition function*** $\delta : \Sigma \times \mathcal{M} \to \Sigma$ *is a computable function that updates the agent's internal state based on observations from a causal model* $\mathcal{M}$*.*

Definition 3. *The* ***model proposal function*** $\mu : \Sigma \to \mathcal{M}$ *maps a symbolic state to a new causal model via decoding and instantiation.*

Definition 4. *The* ***recursive operator*** $\rho : \Sigma \to \mathcal{P}(\Sigma)$ *generates a set of internal reflections, supporting higher-order introspection and structural correction.*

3.2 Minimal Construction

Let us define a finite set of causal models $\mathcal{M}_0, \mathcal{M}_1, \ldots, \mathcal{M}_n$, each represented as a DAG over Boolean variables. The models evolve via a multiway system $\mathcal{T}$ where each transition corresponds to a possible intervention or structural mutation.

Let the symbolic state space Σ encode tuples (i, h), where:

- i is the current model index in $\{0, \ldots, n\}$
- h is a hash of past interventions

The agent iteratively updates $(i, h) \to (j, h')$ via:

1. Querying $\mathcal{M}_i$ for inconsistencies
2. Selecting a transition $\mathcal{T}(i) = j$
3. Updating $h \mapsto h'$ via an introspective function ρ

§4 Recursive Traversal Algorithm

Let us define the recursive traversal algorithm as:

Algorithm: RecursiveTraverse
Input: Initial state $s_0 = (i_0, h_0)$, depth limit d
Output: Set of reachable states Σ'

1. Initialize $\Sigma' \leftarrow \{s_0\}$
2. For $k = 1$ to d:
   - For each $s = (i, h) \in \Sigma'$:
     (a) Query $\mathcal{M}_i$ and update state via δ
     (b) Apply $\rho(s) \to \{s_1, \ldots, s_m\}$
     (c) Apply $\mu(s_j)$ to construct new models $\mathcal{M}_j$
     (d) Extend $\Sigma' \leftarrow \Sigma' \cup \{s_1, \ldots, s_m\}$
3. Return Σ'

4.1 Soundness and Coherence

Theorem 1. *If δ, μ, and ρ are computable and $\mathcal{T}$ is finite, then RecursiveTraverse terminates and explores a sound subspace of the multiway system.*

Proof. Each recursive step operates on a finite symbolic state and terminates in bounded time. Since $\mathcal{T}$ and Σ are finite and traversal depth is bounded by d, the algorithm must halt. Soundness follows from the well-defined update and introspection semantics.

□

Theorem 2. *If causal models are aligned via functorial morphisms, then traversal paths form a coherent diagram in the category* **Causal**.

Proof. Let each model transition $f : \mathcal{M}_i \to \mathcal{M}_j$ be a morphism in **Causal**. Then compositions $f \circ g$ satisfy associativity and identity properties by category axioms. The recursive diagram thus commutes.

□

4.2 Conclusion

We have constructed a minimal recursive MCI agent and proven its sound traversal within a bounded multiway causal space. Further work may generalize the state space, introduce higher categories, and relax determinism for non-linear inference chains.