Knowledge Construction in Human-Human-Agent Learning: Modeling Collaborative Dialogues with Hidden Markov Models

Daniel Fritsch, Paras Sharma, Erin Walker

University of Pittsburgh

Background

Collaborative learning in human-human-agent settings introduces complex interactional dynamics that shape how knowledge is constructed through dialogue.

Stahl's framework treats learning as a recursive cycle at the group level, where:

- individual ideas are externalized through articulation.
- shared understanding emerges through cycles of negotiation and clarification.
- knowledge artifacts are co-constructed and refined across speakers.

Our dataset consists of 26 recorded sessions of triadic collaborative problem-solving, where two students work with a robot agent. In each session, students are tasked with teaching the agent how to solve problems in an HCI context. Utterances from all three interlocutors were transcribed and used as input to the modeling pipeline (fig. 1).

Motivation

- **Knowing where to intervene.** Modeling the interaction as states and transitions allows us to understand how a dialogue trajectory shifts, and thereby investigate how these shifts happen and what individual dialogue acts or sequences elicit them.
- **Understanding the agent's actual role.** The agent occupies a different structural role than the learners in these asymmetric dialogues, receiving reasoning only after the learners have negotiated it. Characterizing that position clearly within existing frameworks of knowledge construction will inform intelligent agent design with regards to this dynamic.
- **Informing LLM-based agents.** Modeling the dialogue as interactional states would allow informed LLM intervention strategies in LLM-based agents and interfaces, letting an agent condition what it says on where the group actually is.

Research Questions

RQ1: What latent interactional states emerge in a triadic human-human-agent collaborative learning dialogues?
RQ2: When a shared understanding is achieved in human-human-agent collaborations?
RQ3: What role does the agent play in achieving this shared understanding?

This work is funded by the National Science Foundation under grants DRL-1811086 and DRL-1935801.

Speaker	Utterance	Recipient
Emma	I actually have another battery I can use that is smaller and maybe more efficient. Can you help me figure out how long this whole battery will last? I know how much of my battery I use for half an hour.	Student B
Student B	For half an hour? Okay, so.	Student A
Student B	That means we'll divide battery power by half hour.	Student A
Student A	Yeah.	Student B
Student B	First try to get the proportion between battery power and time, so divide two fifteenth by 0.5 hours.	Emma
⋮	⋮	⋮
Student A	Find the proportion by dividing the battery usage over the time in step zero.	Emma
Emma	Okay. So we know how much battery I use in half an hour. Student A. So then do we multiply half an hour by that same number, fifteen over two, which gives us one whole battery?	Student A
Student A	Yes.	Emma
Emma	So then one half times fifteen over two is fifteen over four. Student A. Is that the answer?	Student A
Student A	Yes.	Emma
Emma	You are so awesome. I'll change fifteen over four to a mixed fraction and put the answer is three and three quarters.	Student A

Figure 1. Sample Dialogue Excerpt

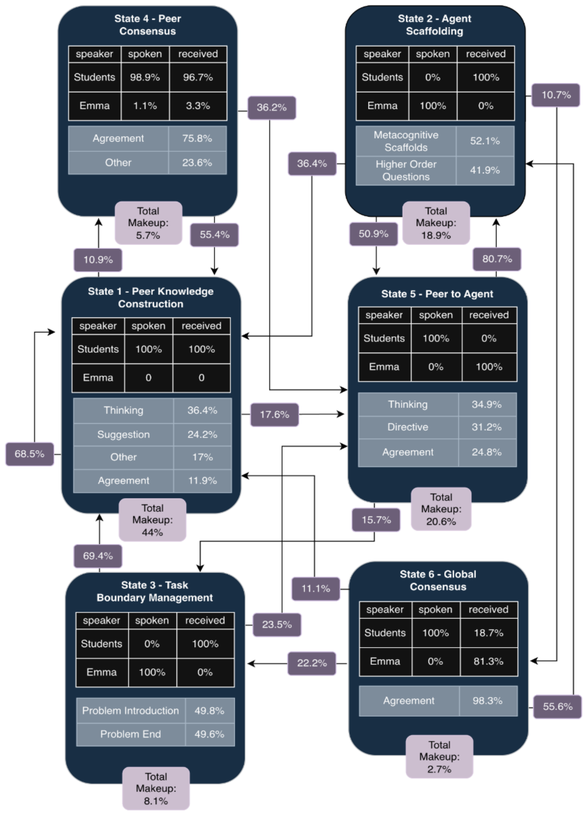
Method

Representation. Each utterance becomes a sentence embedding. Speaker and addressee encoded as explicit dimensions, prepended and appended to the embedding, preserving dialogue directionality. No human annotations enter the model.
Model. Gaussian HMM, trained with Expectation-Maximization. Each of the 216 problem episodes is an independent observation sequence.
Selection. We experiment with embedding size (40–1024), hidden states (3–9), and evaluate the models using 5-fold cross-validation. Compared via AIC, BIC, and log-likelihood.

Dialogue Act	Direction	Definition	Examples	%
Suggestion$_2$	Learner→ Learner	Proposes a potential method or next step without commitment.	*"Maybe we just multiply by three?" "Okay. Maybe we need to tell what the number is, thirty point twenty five, that's two dollars and fifteen cents per hotdog. Is that correct?"*	10.7%
Explanation$_3$	Learner→ Learner/Agent	Elaborates reasoning, performs calculations, or builds on prior ideas.	*"Basically you do sixty six divided by fifteen over four, which becomes sixty six times four over fifteen. Two sixty four divided by fifteen." "And then multiply by 5."*	21.3%
Agreement$_6$	Learner→ Learner/Agent	Affirms correctness of an idea or reasoning without elaboration.	*"Yes!" "Yeah, that's right."*	16.3%
Disagreement$_1$	Learner→ Learner/Agent	Rejects a specific idea or line of reasoning.	*"No, that's incorrect." "No, that's incorrect. You would do two-thirds of an hour times three over two to get one hour."*	1.1%
Questioning & Confusion$_4$	Learner→ Learner/Agent	Requests clarification or expresses lack of understanding.	*"What do you mean?" "I'm confused. What are you multiplying?"*	3.6%
Directive$_5$	Learner→ Agent	Issues an instruction to Emma without explanation.	*"Just multiply by three." "Okay. Emma, what's thirty-two point twenty-five divided by fifteen?"*	5.9%
Metacognitive Scaffold	Agent→ Learner	Guides students toward a solution path through confirmatory or leading prompts.	*"So eight times three is twenty-four?" "We know I can ride my bike for ten miles in one hour. We multiply the ten miles per hour times seven point two five?"*	9.0%
Higher-Order Question	Agent→ Learner	Elicits justification, reasoning, or explanation from students.	*"How do we know we multiply?" "I know I should know it, but I don't remember. Would you mind telling me what it is?"*	7.2%
Problem Boundary	Agent→ Learner	Introduces or closes a problem context.	*"Can you help me figure out how much forty five hot dogs will cost?" "That sounds brilliant. I need eighteen batteries because I need more than seventeen."*	7.2%
Other	Any → Any	Utterances outside of problem context or not classifiable under other acts.	*"Sweet! Should we go to the next problem?" "I'm just going to go ahead and click on the button."*	17.8%

Figure 2. Dialogue Act Annotations

Figure 3. Hidden Markov Model for a 6 State Model of Knowledge Construction



Results

The resulting model describes 6 states. We use dialogue act tags (fig. 2) to interpret the states. Figure 3 shows the dialogue acts and their transition probabilities. They are further grouped into the Peer Reasoning phase (Peer Knowledge Construction and Peer Consensus), and the Shared Scaffolding Phase (Peer to Agent and Agent Scaffolding)

Discussion

What distinguishes productive agreement is the peer reasoning that precedes it. This is observable as sustained peer reasoning phases rather than as the agreement itself.

Different-correct episodes hold sound reasoning the agent cannot recognize and spend their extra turns translating it; wrong episodes never establish a peer position and the agent ends up supplying the answer.

Latent states recovered by the HMM align with theory-grounded phases of knowledge construction. States correspond to recognizable phases from Stahl's framework, and extend it into the Human-Human-Agent setting (fig. 4).

Figure 4. Reformulation of Stahl's Theory of Knowledge Construction for Human-Human-Agent Context

