Towards Distributed Logic Programming based on Computability Logic

Keehang Kwon
Department of Computing Sciences, DongA University, South Korea. khkwon@dau.ac.kr

Abstract:
Computability logic (CoL) is a powerful computational model which views computational problems as games played by a machine and its environment. In this paper, we show that CoL naturally supports multiagent programming models with distributed control. To be specific, we discuss a distributed logic programming model based on CoL (CL1 to be exact), which we call CL1Ω. The key feature of this model is that it supports dynamic/evolving knowledgebase of an agent. This model turns out to be a promising approach to reaching both general AI and future computing model.

Keywords: Computability logic; MultiAgent Programming; General Artificial Intelligence.

1 Introduction
Computability logic (CoL)[2]-[5], is an elegant theory of (multi-)agent computability. In CoL, computational problems are seen as games between a machine and its environment and logical operators stand for operations on games. It understands interaction among agents in its most general — game-based — sense. On the other hand, other formalisms such as situation calculus appear to be too rudimentary to represent complex interactions among agents. In particular, CoL supports query/knowledge duality (or we call it ‘querying knowledge’): what is a query for one agent becomes new knowledge for another agent. This duality leads to evolving knowledgebase and has many attractive features such as local namespace. Note that traditional agent/object-oriented approaches[1] fail to support this duality. Therefore, CoL provides a promising basis for multiagent programming.

In this paper, we discuss a distributed agent programming model based on CoL, which can also be seen as a distributed logic programming model with distributed processing. In CoL, the environment is assumed to be an unpredictable, capricious user. In contrast, we make it possible for an environment to be specified as a machine with determined, algorithmic behavior.

We assume the following in our model:

• Each agent corresponds to a memory location or a web site with a URL. An agent’s knowledgebase(KB) is stored in its location.

• Agents are initially inactive. An inactive agent becomes activated when another agent invokes a query for the former.

• Our model supports query/knowledge duality and querying knowledge. That is, knowledge of an agent can be obtained from another agent by invoking queries to the latter.

To make things simple, we choose CL1 – the most basic fragment of CoL – as our target language. CL1 is obtained by adding to classical propositional logic two additional choice operators: disjunction (∨) and conjunction (∩) operators. The choice disjunction ∨ models decision steps by the machine. The choice conjunction ∩ models decision steps by the environment. For example, green ∨ red is a game where the machine must choose either green or red, while green ∩ red is a game where the environment must choose
either green or red. In the former, if the machine chooses green(red), then we say green ⇐ red evolves to green(red). Similarly for green ▷ red.

In this paper, we present CL1Ω which is a web-based implementation of CL1. This implementation is simple and straightforward. What is interesting is that CL1Ω is a novel and promising distributed (logic) programming model with evolving knowledgebase. It would provide a good starting point for future distributed logic programming as well as high-level web programming.

2 Preliminaries

In this section a brief overview of CoL is given.

There are two players: the machine ⊤ and the environment ⊥.

There are elementary atoms p, q, . . . to represent elementary games.

Constant elementary games ⊤ is always a true proposition, and ⊥ is always a false proposition.

Negation ¬ is a role-switch operation: For example, ¬(0 = 1) is true, while (0 = 1) is false.

Choice operations The choice group of operations: ⊓, ⊔ are defined below.

A0 ⊓ A1 is the game where, in the initial position, only ⊥ has a legal move which consists in choosing i in {0, 1}. After ⊥ makes a move i ∈ {0, 1}, the game continues as Ai. ⊔ is symmetric to ⊓ with the difference that now it is ⊤ who makes an initial move.

Parallel operations Playing A1 ∧ . . . ∧ An means playing the n games concurrently. In order to win, ⊤ needs to win in each of the n games. Playing A1 ∨ . . . ∨ An also means playing the n games concurrently. In order to win, ⊤ needs to win one of the games. To indicate that a given move is made in the ith component, the player should prefix it with the string “i.”

Reduction A → B is defined by ¬A ∨ B. Intuitively, A → B is the problem of reducing B (consequent) to A (antecedent).

3 General AI

In this section, we present a promising approach to reaching general AI. Central to our approach is the concept of games[2, 4]. This concept makes it possible to build intelligent AI in a simplest possible way, as complex interactions among agents can be captured by games. That is, general AI is nothing but a group of agents playing games (or providing services to ) against others.

To be specific, we use the following idea:

Agent = KB + Query

where an agent tries to solve Query using its knowledgebase KB. Note that here KB and Q both represent games and thus evolving.

The following is a motivating example of CL1Ω with agents x, y, z, w, v, u, m, n and o.

\[
\begin{align*}
x &= p(3) \land \neg p(100) \ % p(x) \text{ mean } x \text{ is prime.} \\
y &= (p(3) \lor p(5))^x \\
z &= (p(4) \lor p(5))^x \\
w &= \neg (p(9) \land p(100))^x \\
v &= (\neg p(9) \lor \neg p(100))^x \\
m &= \top, [(p(0) \lor p(3))^y \to (p(0) \lor p(3))^u] \\
o &= \top, [(p(0) \lor p(3))^z \to (p(0) \lor p(3))^v] \\
n &= \top, [(p(100) \lor \neg p(100))^w \to (p(100) \lor \neg p(100))^u]
\end{align*}
\]

Activating y means y is required to solve the incoming queries using the knowledgebase of y.

Now consider the machine m. It tries to solve the problem \((p(0) \lor p(3))^y \to (p(0) \lor p(3))^u\) with empty knowledgebase, denoted by ⊤. m activates y which then tries to solve the goal \((p(0) \lor p(3))^m\) using \((p(0) \lor\)
Given a service model $\omega$ is said to be valid if, for every interpretation $H$, there is a machine who wins the game $\omega$. Note that $v$ is logically equivalent to $w$.

4 \textbf{CL1$^\Omega$}

We review the most basic fragment of propositional computability logic called \textbf{CL1} [3]. Its language extends that of classical propositional logic by incorporating into it $\cap$ and $\sqcup$. As always, there are infinitely many atoms in the language, for which we will be using the letters $p, q, r, \ldots$ as metavariables. The two atoms: $\top$ and $\bot$ have a special status in that their interpretation is fixed. Formulas of this language, referred to as \textbf{CL1-formulas}, are built from atoms in the standard way:

\textbf{Definition 4.1} The class of \textbf{CL1-formulas} is defined as the smallest set of expressions such that all atoms are in it and, if $F$ and $G$ are in it, then so are $\neg F$, $F \land G$, $F \lor G$, $F \to G$, $F \sqcap G$, $F \sqcup G$.

\textbf{Definition 4.2} Let $F$ be a \textbf{CL1-formula}. An interpretation is a function $^*$ which sends $F$ to a game $F^*$. $F$ is said to be valid if, for every interpretation $^*$, there is a machine who wins the game $F^*$ for all possible scenarios corresponding to different behaviors by the environment.

Now we define \textbf{CL1$^\Omega$}, a slight extension to \textbf{CL1} with environment parameters. Let $F$ be a \textbf{CL1-formula}. We introduce a new \textit{env-annotated} formula $F^\omega$ which reads as ‘play $F$ against an agent $\omega$’ or ‘provide a service $F$ to $\omega$’. For an $\cap$-occurrence $O$ in $F^\omega$, we say $\omega$ is the \textit{matching} environment of $O$. For example, $(p \sqcap (q \sqcap r))^\omega$ is an agent-annotated formula and $\omega$ is the matching environment of both occurrences of $\cap$. We extend this definition to subformulas and formulas. For a subformula $F'$ of the above $F^\omega$, we say that $\omega$ is the \textit{matching} environment of both $F'$ and $F$.

In introducing environments to a formula $F$, one issue is whether we allow ‘env-switching’ formulas of the form $(F[R^\omega])^\omega$. Here $F[R]$ represents a formula with some occurrence of a subformula $R$. That is, the machine initially plays $F$ against agent $\omega$ and then switches to play against another agent $u$ in the course of playing $F$. This kind of formulas are difficult to process. For this reason, in this paper, we focus on non ‘env-switching’ formulas. This leads to the following definition:

\textbf{Definition 4.3} The class of \textbf{CL1$^\Omega$-formulas} is defined as the smallest set of expressions such that (a) For any \textbf{CL1-formula} $F$ and any agent $\omega$, $F^\omega$ are in it and, (b) if $H$ and $J$ are in it, then so are $\neg H$, $H \land J$, $H \lor J$, $H \to J$.

In the above, $F^\omega$ denotes that the (current) machine provides a service $F$ to $\omega$. $\neg(F^\omega)$ denotes that the machine receives a service $F$ from $\omega$ (i.e. the exchange of roles). $F^\omega \land G^\mu$ denotes that the machine provides a service $F$ to $\omega$ and a service $G$ to $\mu$. Similarly for $\lor, \to$.

For example, suppose kim, pete are agents and $p$ denotes a proposition. Then, $p^{kim} \to p^{pete}$ denotes the following: if kim claims $p$ to the machine, then the machine can claim $p$ to pete. This is clearly valid.

We often use $F$ instead of $F^\omega$ when it is irrelevant. For example, $p \to p^{pete}$ denotes the following: if some (unspecified) agent claims $p$ to the machine, then the machine can claim $p$ to pete. Again, this is valid.

Most old concepts such as validity extend to this new language.

\textbf{Definition 4.4} Let $J$ be a \textbf{CL1$^\Omega$-formula}. An interpretation is a function $^*$ which sends $F$ to a game $F^*$. $J$ is said to be valid if, for every interpretation $^*$, there is a machine who wins the game $J^*$ for all possible scenarios corresponding to different behaviors by \textit{any} environments.

\textbf{Definition 4.5} Given a \textbf{CL1$^\Omega$-formula} $J$, the skeleton of $J$ denoted by $\text{skeleton}(J)$ is obtained by replacing every occurrence $F^\omega$ by $F$. 

3
For example, skeleton((p \land (q \land r))^\omega) = p \land (q \land r).

We assume that each agent is identified with a physical location and the KB of an agent is stored in its location.

The following definitions comes from \[3\]. They apply both to \textbf{CL1} and \textbf{CL1}^\Omega.

Understanding \( E \rightarrow F \) as an abbreviation of \( \neg E \lor F \), a positive occurrence of a subformula is one that is in the scope of an even number of \( \neg \)’s. Otherwise, the occurrence is negative.

A surface occurrence of a subformula means an occurrence that is not in the scope of a choice (\( \lor \) or \( \land \)) operator.

A formula is elementary iff it does not contain the choice operators.

The \textit{elementarization} of a formula is the result of replacing, in it, every surface occurrence of the form \( F_1 \lor \ldots \lor F_n \) by \( \bot \), and every surface occurrence of the form \( F_1 \land \ldots \land F_n \) by \( \top \).

A formula is stable iff its elementarization is valid in classical logic, otherwise it is \textit{instable}.

\( F \)-specification of \( O \), where \( F \) is a formula and \( O \) is a surface occurrence in \( F \), is a string \( \alpha \) which can be defined by:

- \( F \)-specification of the occurrence in itself is the empty string.
- If \( F = \neg G \), then \( F \)-specification of an occurrence that happens to be in \( G \) is the same as the \( G \)-specification of that occurrence.
- If \( F \) is \( G_1 \land \ldots \land G_n \), \( G_1 \lor \ldots \lor G_n \), or \( G_1 \rightarrow G_2 \), then \( F \)-specification of an occurrence that happens to be in \( G_i \) is the string \( i \alpha \), where \( \alpha \) is the \( G_i \)-specification of that occurrence.

The proof system of \( \textbf{CL1}^\Omega \) is identical to that \( \textbf{CL1} \) and has the following two rules, with \( H, F \) standing for \( \textbf{CL1}^\Omega \)-formulas and \( \bar{H} \) for a set of \( \textbf{CL1}^\Omega \)-formulas:

Rule (A): \( \bar{H} \vdash F \), where skeleton(\( F \)) is stable and, whenever \( F \) has a positive (resp. negative) surface occurrence of \( G_1 \land \ldots \land G_n \) (resp. \( G_1 \lor \ldots \lor G_n \)) whose matching environment is \( \omega \), for each \( i \in \{1, \ldots, n\}, \bar{H} \) contains the result of replacing in \( F \) that occurrence by \( G_i^\omega \).

Rule (B): \( H \vdash F \), where \( H \) is the result of replacing in \( F \) a negative (resp. positive) surface occurrence of \( G_1 \land \ldots \land G_n \) (resp. \( G_1 \lor \ldots \lor G_n \)) whose matching environment is \( \omega \) by \( G_i^\omega \) for some \( i \in \{1, \ldots, n\} \).

**Example 4.6** \( \textbf{CL1}^\Omega \vdash ((p \land q) \land (p \land q))^\omega \)

where \( p, q \) represent distinct non-logical atoms, and \( \omega \) is an agent. Note that \( \omega \) plays no roles in the proof procedure.

1. \( (p \land p) \rightarrow p^\omega \), rule A, no premise
2. \( (q \land q) \rightarrow q^\omega \), rule A, no premise
3. \( ((q \land p) \land p) \rightarrow p^\omega \), rule B, 1
4. \( ((p \land q) \land (q \land p)) \rightarrow p^\omega \), rule B, 3
5. \( ((p \land q) \land q) \rightarrow q^\omega \), rule B, 2
6. \( ((p \land q) \land (p \land q)) \rightarrow q^\omega \), rule B, 5
7. \( ((p \land q) \land (p \land q)) \rightarrow (p \land q)^\omega \), rule A, 4 6

**Example 4.7** \( \textbf{CL1}^\Omega \vdash p \rightarrow (q \lor p)^\omega \)

where \( p, q \) represent distinct non-logical atoms.

1. \( p \rightarrow p^\omega \), rule (A), no premise
2. \( p \rightarrow (q \lor p)^\omega \), rule B, 1
In our setting, an agent has knowledgebase and receives multiple queries. CL1Ω is a set of agent declarations of the following form:

\[ \alpha_1 = H_1, Q_1 \]
\[ \vdots \]
\[ \alpha_n = H_n, Q_n \]

In the above, each \( \alpha_i \) is an agent, each \( H_i \) is the knowledgebase of \( \alpha_i \) written in CL1Ω and each \( Q_i \) is a queue for storing the incoming queries. We often omit \( Q_i \) if it is initially empty.

### 5.1 An Execution Model for a Query

We first consider a machine model with empty knowledgebase and a single query to process. This machine is designed to decide whether the query is valid or not.

The machine model of CL1 is designed to play against any environment, and thus easily extended to the case of CL1Ω. In our system, however, for each occurrence of \( F^\omega \), we need to differentiate \( F \) which is already in session from those who are not. That is, we invoke \( F \) to \( \omega \) only when \( F \) is not in session. Below the notation \( F^\omega \) represents a formula \( F \) together with some positive occurrence of a subformula \( E \).

Below we will introduce an algorithm that executes a formula \( J \) which has a CL1Ω-proof. The algorithm contains two stages:

**Algorithm Ex(J): % J is a CL1Ω-formula with a proof**

1. First stage is to initialize a temporary variable \( E \) to \( J \), activate all the resource agents specified in \( J \) by invoking proper queries to them. That is,
   - for each negative occurrence \( F^\omega \) in \( J \) which is not already in session, activate \( \omega \) by querying \( F^\mu \) to \( \omega \). Here \( \mu \) is the current machine. Mark \( F \) in session for \( \omega \)’s sake.
   - for each positive occurrence \( F^\omega \) in \( J \) which is not already in session, we first replace it with \( \neg(\neg F^\omega) \) and then activate \( \omega \) by querying \( (\neg F^\omega)^\mu \) to \( \omega \). Here \( \mu \) is the current machine; Mark \( \neg F \) in session for \( \omega \)’s sake.

2. The second stage is to play \( J \) according to the following loop procedure (which is from [3]):

**procedure loop(Tree): % Tree is a proof tree of \( J \)**

- **Case** \( E \) is derived by Rule (A):
  Wait for the matching adversary \( \omega \) to make a move \( \alpha = \beta_i \), where \( \beta \) \( E \)-specifies a positive (negative) surface occurrence of a subformula \( G_1 \sqcap \ldots \sqcap G_n (G_1 \sqcup \ldots \sqcup G_n) \) and \( i \in \{1, \ldots, n\} \). Let \( H \) be the result of substituting in \( E \) the above occurrence by \( G_i \). Then update \( E \) to \( H \).

- **Case** \( E \) is derived by Rule (B):
  Let \( H \) be the premise of \( E \) in the proof. \( H \) is the result of substituting, in \( E \), a certain negative (resp. positive) surface occurrence of a subformula \( G_1 \sqcap \ldots \sqcap G_n \) (resp. \( G_1 \sqcup \ldots \sqcup G_n \)) by \( G_i \) for some \( i \in \{1, \ldots, n\} \). Let \( \beta \) be the \( E \)-specification of that occurrence. Then make the move \( \beta_i \), update \( E \) to \( H \). Let \( \omega \) be the matching environment. Then inform \( \omega \) of the move \( \beta_i \).

The following proposition has been proved in [3].

**Proposition 5.1** CL1 ⊢ \( F \) iff \( F \) is valid (any CL1-formula \( F \)).
The following proposition follows easily from Proposition 5.1 together with the observation that \( \text{CL1}\)-proof of \( F \) encodes an environment-independent winning strategy for \( F \). The following is our theorem [3].

**Proposition 5.2** Let \( m \) be a machine above with empty knowledgebase and a \( \text{CL1}\)\( \Omega \)-formula query \( J \). Then the following holds:

1. \( \text{CL1}\)\( \Omega \) \( \vdash J \) iff \( J \) is valid.

2. Furthermore, the following holds:
   - If \( \text{CL1}\)\( \Omega \) \( \vdash J \), then \( m \) wins \( J^* \) for every interpretation \( * \).
   - If \( \text{CL1}\)\( \Omega \) \( \vdash J \) does not hold, then \( J^* \) is not computable for some interpretation.

**Proof.** Let \( F \) be skeleton(\( J \)). It is known from [3] that every \( \text{CL1}\)\( \Omega \)/(\( \text{CL1} \))-proof of \( J \) encodes an environment-independent winning strategy for \( J \). It follows that a machine with such a strategy – \( \text{Ex}(J) \) – wins \( J \) against any environment. In particular, if \( J \) is stable, \( \alpha = H, F^p_\alpha \) is in \( J \) and \( H \rightarrow F_1 \) does not have a proof, \( \alpha \) does not make any moves and \( m \) wins because \( J \) is stable. Hence \( J \) is valid. Conversely, suppose there is no \( \text{CL1}\)\( \Omega \)/\( \text{CL1} \)-proof of \( J \). Since \( \text{CL1}\)\( \Omega \)-proof of \( J \) is in fact identical to \( \text{CL1} \)-proof of \( F \), it follows from [3] that there is no machine who can win \( F^* \) for some interpretation \( * \). Therefore \( F \) is not valid. ■

### 5.2 Execution Model for Multiple Queries

We now describe a machine model with nonempty knowledgebase and a sequence of queries to process. It is designed to solve these queries using its knowledgebase.

We assume that every agent processes multiple queries in a sequential fashion. To do this, it maintains a queue for storing multiple queries \( [Q_1,\ldots,Q_n] \). We assume that an agent \( m = H_1 \) processes \( [Q_1,\ldots,Q_n] \) by executing the following \( n \) procedures sequentially:

\[
\text{Ex}(H_1 \rightarrow Q_1), \text{Ex}(H_2 \rightarrow Q_2), \ldots, \text{Ex}(H_n \rightarrow Q_n)
\]

Here we assume that, for \( i = \{1,\ldots,n-1\} \), \( H_i \) evolves to \( H_{i+1} \) after performing \( \text{Ex}(H_i \rightarrow Q_i) \).

The following is a straightforward generalization of Proposition 5.1.

**Proposition 5.3** Let \( m \) be a machine with empty knowledgebase and incoming queries \( [J_1,\ldots,J_n] \). Then the following holds:

1. For all \( i \), \( \text{CL1}\)\( \Omega \) \( \vdash J_i \) iff \( J_i \) is valid (any \( \text{CL1}\)\( \Omega \)-formula \( J_i \)).

2. Furthermore, the following holds:
   - If \( \text{CL1}\)\( \Omega \) \( \vdash J_i \), then \( m \) wins \( J_i^* \) for every interpretation \( * \).
   - If \( \text{CL1}\)\( \Omega \) \( \vdash J_i \) does not hold, then \( J_i^* \) is not computable for some interpretation.

Now we consider a machine with nonempty knowledgebase. An agent with nonempty knowledgebase processes queries in a way that it preserves soundness but not completeness. For example, suppose \( m \) has knowledgebase \( p \sqcap q \) with two queries \( [p \sqcap p, p \sqcap q] \). Although both queries are a logical consequence of \( m \), solving the second query will fail. This is because \( m = p \sqcap q \) would evolve to \( m = p \) after solving the first query.

**Proposition 5.4** Let \( m \) be a machine with nonempty knowledgebase \( H \) and incoming queries \( [J_1,\ldots,J_n] \). Assume \( H \) evolve to \( H_i \) after solving \( J_1,\ldots,J_{i-1} \). Then the following holds:

1. \( \text{CL1}\)\( \Omega \) \( \vdash H_i \rightarrow J_i \) iff \( H_i \rightarrow J_i \) is valid (any \( \text{CL1}\)\( \Omega \)-formula \( H_i, J_i \)). Furthermore,

   if \( \text{CL1}\)\( \Omega \) \( \vdash H_i \rightarrow J_i \), then \( m \) wins \( (H_i \rightarrow J_i)^* \) for every interpretation \( * \).
2. If $\text{CL}_1^\Omega \vdash H_i \rightarrow J_i$, then $\text{CL}_1^\Omega \vdash H \rightarrow J_i$.

3. (Soundness:) If $m$ wins $(H_i \rightarrow J_i)^*$ for every interpretation $*$, then $H \rightarrow J_i$ is valid.

**Proof.** Proof of (1): It is an easy consequence of Proposition 5.1.

Proof of (2): It is easy to observe that if $H$ evolves to $H_i$, then $H_i$ is a logical consequence of $H$. Hence, $J_i$ is a logical consequence of $H$.

Proof of (3): If $m$ successfully solves $H_i \rightarrow J_i$, then it follows from (1) that $H_i \rightarrow J_i$ has a proof. Then it follows from (2) that $H \rightarrow J_i$ has a proof. It follows from Proposition 5.1 that $H \rightarrow J_i$ is valid.

**6 Examples**

One example is provided by the following “weather” agent which contains today’s weather (we assume today is cloudy) and temperature (we assume today is hot).

\[ \text{weather} = \text{cloudy} \land \text{hot}. \]

Our language permits ‘querying knowledge’ of the form $Q^\omega$ in KB. This requires the current machine to invoke the query $Q$ to the agent $\omega$. Now let us consider the dress agent which gives advice on the dress codes according to the weather condition. It contains the following four rules and two querying knowledges ($\text{cloudy} \sqcup \text{sunny}$) and ($\text{hot} \sqcup \text{cold}$) relative to the weather agent.

\[ \text{dress} = \]

\begin{align*}
% & \text{dress codes} \\
(\text{cloudy} \land \text{hot}) & \rightarrow \text{green}. \\
(\text{sunny} \land \text{hot}) & \rightarrow \text{yellow}. \\
(\text{cloudy} \land \text{cold}) & \rightarrow \text{blue}. \\
(\text{sunny} \land \text{cold}) & \rightarrow \text{red}.
\end{align*}

\begin{align*}
(\text{cloudy} \sqcup \text{sunny})^{\text{weather}} \\
(\text{hot} \sqcup \text{cold})^{\text{weather}}.
\end{align*}

Now, consider a machine $m$ trying to solve the query $\text{?-} (\text{green} \sqcup \text{blue} \sqcup \text{yellow} \sqcup \text{red})^{\text{dress}} \rightarrow (\text{green} \sqcup \text{blue} \sqcup \text{yellow} \sqcup \text{red})^{\text{user}}$ with respect to empty knowledgebase. This is written as

\[ m = \top, \]

\[ [(\text{green} \sqcup \text{blue} \sqcup \text{yellow} \sqcup \text{red})^{\text{dress}} \rightarrow (\text{green} \sqcup \text{blue} \sqcup \text{yellow} \sqcup \text{red})^{\text{user}}]. \]

Solving this goal has the effect of activating dress and invoking two queries ($\text{cloudy} \sqcup \text{sunny}$) and ($\text{hot} \sqcup \text{cold}$) to the weather agent. At this stage, the dress and weather agents remain active and communicate with each other. To be specific, the weather solves these two queries using $\text{CL}_1^\Omega$ proof and the $\text{Ex}$ procedure in the previous section. This would result in replacing ($\text{cloudy} \sqcup \text{sunny}$) with cloudy and ($\text{hot} \sqcup \text{cold}$) with hot. Now the dress agent – again via the $\text{CL}_1^\Omega$ proof and the $\text{Ex}$ procedure – will answer green$^\top$ to the machine. The machine chooses green$^{\text{user}}$ and informs the user. Note that two queries to weather execute concurrently within weather.

**7 Conclusion**

In this paper, we proposed a multi-agent programming model based on $\text{CL}_1$. Unlike other formalisms such as LogieWeb[7] and distributed logic programming[1], this model supports evolving knowledgebase which is essential for future computing model. Our next goal is to replace $\text{CL}_1$ with much more expressive $\text{CL}_1^2[4]$. 


8 Acknowledgements

We thank Giorgi Japaridze for many helpful comments.

References

[1] E.S. Lam and I. Cervesato and N. Fatima. Comingle: Distributed Logic Programming for Decentralized Mobile Ensembles. LNCS 9037. 2015.

[2] Japaridze G. Introduction to computability logic. Annals of Pure and Applied Logic, 2003, 123(1/3): 1-99.

[3] Japaridze G. Propositional computability logic I. ACM Transactions on Computational Logic, 2006, 7(2): 302-330.

[4] Japaridze G. Towards applied theories based on computability logic. Journal of Symbolic Logic, 2010, 75(2): 565-601.

[5] Japaridze G. On the system CL12 of computability logic. http://arxiv.org/abs/1203.0103 June 2013.

[6] Kwon K, Hur S. Adding Sequential Conjunctions to Prolog. International Journal of Computer Technology and Applications, 2010, 1(1): 1-3.

[7] S.W. Loke and A. Davison: LogicWeb: Enhancing the Web with Logic Programming. Journal of Logic Programming, 1998, 36(3): 195-240.