A Computational Model of an Intelligent Agent for Natural Language Dialogue Systems

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Abstract

An intelligent agent always acts according to her intention and belief about the world. The belief has been made from information which the agent gains by observing the world. What is essential to such a situated agent is that the agent herself is an element of the world, and she is able to obtain information about herself by observing herself embedded in the world. The ability of observing herself realizes introspective belief, and enables the agent to act intelligently. We propose a computational model of such an intelligent agent, and show how simple communicative acts are performed in the model.

1 Introduction

An intelligent natural language dialogue system (NLDS) needs to

- infer her user's intention and belief,
- act according to her intention and belief, and
- introspect her own belief.

When she has intention of selling a ticket, and a person says to her

"`I want a ticket to Tokyo.`",

she needs to draw an inference that he intends to buy a ticket from her. After the inference, she should start selling a ticket to him in accordance with her intention, which preconditions are satisfied in her belief. Capability of introspecting her own belief is essential to her when she needs to ascertain whether she has not gotten any information on some propositions. In the situation of selling a ticket, she must have information on the destination of the ticket which the person intends to buy. She should ask him the destination if she believes that she does not have any information on the destination.

It is, moreover, necessary for an intelligent NLDS to have capability of expressing propositions of intention and belief in the system. One of the normal preconditions of α's selling a ticket to β is that α believes that β is intending to buy a ticket. The capability also enables the integration of speech acts like "tell" and "ask" into general acts like "eat" [Searle 1969]. One of the normal preconditions of α's asking β about ϕ is that α does not believe that β does not have any information about ϕ. The integration of speech acts into general acts remarkably reduces the complexity of NLDS and increases the flexibility.

A plan-based model of natural language understanding was first proposed in [Allen and Perrault 1980]. The speaker's plan is inferred from his utterances in terms of intention and belief. As a result, the model can account for responses that provide more information that explicitly requested. However, negative introspective belief (e.g. α's belief that α herself does not believe ϕ) is not handled in the model. As a result, it makes wrong predictions in some circumstances. Thus, [Perrault 1987] made a better model of speech acts with normal defaults in Default Logic [Reiter 1980]. This model can analyze belief revision and account for various defective, non-serious, and indirect uses of declarative sentences. However, it is a model of analyzing utterances.

A computational model of executing various acts including speech acts is required for making an intelligent NLDS which interacts with a person. We propose such a computational model with some of the useful ideas in Autoepistemic Logic [Moore 1985][Konolige 1988a]. In Section 2, normal forms of introspective belief are defined, and a simple method of calculating normal forms is mentioned. In Section 3, a reflective model is proposed, which enables introspective belief to be handled easily and efficiently. In Section 4, we exemplify how speech acts and general acts are executed in our model.

2 Normal Form of Belief

Propositions of introspective belief (introspective propositions) look hard to deal with, because their truth values are closely related with each other. In this section, we will show that such a proposition can be uniquely reduced to its normal form of the form $B\phi$ or $B\neg B\phi$, where ϕ is an ordinary sentence of propositional logic, and the reduction never change the truth values of propositions.

We assume the following set of axioms of belief besides all tautologies of propositional logic.

Definition 1

$$B\phi \wedge B(\phi \rightarrow \psi) \rightarrow B\psi \quad (1)$$
$$B\phi \rightarrow BB\phi \quad (2)$$
$$\neg B\phi \rightarrow B\neg B\phi \quad (3)$$
$$B\phi \rightarrow \neg B\neg\phi \quad (4)$$

The axioms (1)-(3) are often assumed in many belief systems. They are called distribution axiom, introspective axiom, and negative introspective axiom respectively. The axiom (4) says that belief is consistent [1], i.e. believing ϕ implies not believing not ϕ. Under these axioms, the following propositions hold, which will guarantee the semantic equivalence of each introspective proposition and its normal form.

Proposition 1 *Let ϕ be some proposition.*

(1) $\neg BB\phi = B\neg B\phi$

(2) $\neg B\neg B\phi = B\phi$

(3) $BB\phi = B\phi$

We will define normal forms in terms of reduction. The following is the definition of terms of introspective propositions.

Definition 2 *(pre-terms)*
The set of expressions called pre-terms are defined inductively as follows:

- *All sentences of propositional logic are pre-terms.*
- *If ϕ is any pre-term, then $B\phi$ is a pre-term.*
- *If ϕ is any pre-term, then $\neg\phi$ is a pre-term.*

Definition 3 *(terms)*
If ϕ is any pre-term, then $B\phi$ is a term.

Example 1 *"$B\neg BB\neg\neg B\neg president(USA, Bush)$" is a term, but "$\neg B\neg president(USA, Bush)$" is not.*

Then, our reduction of introspective propositions is defined as follows:

[1]Mixed use of intensional entities [Rapaport 1986] and extensional entities in an agent's belief can cause inconsistency of her belief. Extensional entities should not be used in belief.

Definition 4 *(reduction)*
Any (pre-)term $\neg\neg B\phi$, $\neg BB\phi$, $\neg B\neg B\phi$, or $BB\phi$ is called a redex. Contracting an occurrence of a redex in a term U means replacing one occurrence of

$\neg\neg B\phi$ `by` $B\phi$,
$\neg BB\phi$ `by` $B\neg B\phi$,
$\neg B\neg B\phi$ `by` $B\phi$,
$BB\phi$ `by` $B\phi$.

If this changes U to U', we say that U contracts to U'. We say that U reduces to V iff V is obtained from U by a finite series of contractions.

Definition 5 *(normal forms)*
A normal form is a term containing no redexes. If U reduces to a normal form X, then X is called a normal form of U.

The termination property of the reduction with any reduction strategies (strong normalization) can be easily proved. As a result, the following important proposition on normal forms can be proved by induction.

Proposition 2 *Normal forms are terms only of the form*

$B\phi$ *or* $B\neg B\phi$,

where ϕ is an ordinary sentence of propositional logic.

We can also prove the uniqueness of the normal form of each term (introspective proposition) by semantic equivalence of both sides of the reduction rules proved in Proposition 1.

Theorem 3 *If U reduces to X and U reduces to Y, then there exists a Z such that*

X reduces to Z and Y reduces to Z.

We showed that any introspective proposition can be uniquely reduced to its normal form in terms of reduction. As a matter of fact, the reduction is not necessary for calculating normal forms. Just counting the occurrences of "$\neg$" up to the last occurrence of "B" in a term is enough.

3 Computational Model

3.1 Overview of structure

As mentioned in the last section, all introspective propositions can be uniquely reduced to their normal forms of the form $B\phi$ or $B\neg B\phi$, where ϕ is an ordinary sentence of propositional logic. As a result, we have only to manage normal forms in belief. $B\phi$ can be represented as a state of holding ϕ in belief. $B\neg B\phi$ can be represented as a state of not holding ϕ in belief.

In this section, we propose a computational model based on a reflective structure of an intelligent agent as in Figure 1, which enables dynamic introspection of her own belief, and determines truth values of any complex introspective propositions.

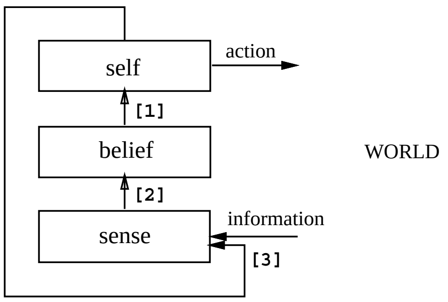

Figure 1: A Reflective Structure

The structure has three levels named "self", "belief", and "sense". On the "self" level, plans are made and feasible acts are executed based on her belief [1]. The "belief" level maintains her belief based on information on the "sense" level [2]. The "sense" level receives information about the world, which includes information about herself [3].

3.2 Syntax

Our language is based on a first-order language, but terms are completely modified. There are two sorts of terms: "entity terms" and "act terms". Entity terms in an agent represent intensional entities in the agent. An entity term consists of a variable, say σ, and a set of propositions on the variable, $pred_i(\sigma)$. It corresponds to a real object π in the world in case that all the propositions $pred_i(\pi)$, which are obtained by replacing every σ by π in $pred_i(\sigma)$, hold in her belief.

Definition 6 *(entity term)*
Entities are represented by expressions of the form

$$\ll \sigma \mid pred_1(\sigma), ..., pred_n(\sigma) \gg,$$

where σ is a variable and $pred_i$ is a predicate.

Example 2 *A ticket to Tokyo is represented by*

$$\ll \sigma \mid type(\sigma, ticket), dest(\sigma, \texttt{TOKYO}) \gg .$$

A special entity term called "self" is defined as follows:

Definition 7 *(self)*

$$self \equiv \ll \sigma \mid type(\sigma, object), pos(\sigma, here, now) \gg .$$

This entity term corresponds to the agent herself.

Act terms represent acts like α's eating an apple. Speech acts are also represented by the act terms. An act term is composed of an act type (e.g. "eat") and a set of pairs of a label (name of property) and its value.

Definition 8 *(act term)*
Acts are represented by expressions of the form

$$\ll act\_type, label_1{:}\, value_1, .., label_n{:}\, value_n \gg .$$

Example 3 *The act of John's buying a ticket to Tokyo from Mary is represented by*

$$\ll buy, agent{:}\, \texttt{JOHN}, from{:}\, \texttt{MARY}, \\ obj{:} \ll \sigma \mid type(\sigma, ticket), dest(\sigma, \texttt{TOKYO}) \gg\gg$$

where JOHN *and* MARY *are respectively abbreviations of*

$$\ll \sigma \mid type(\sigma, human), name(\sigma, \text{“}john'') \gg \quad and$$
$$\ll \sigma \mid type(\sigma, human), name(\sigma, \text{“}mary'') \gg .$$

Propositions are described as in an ordinary first-order logic. Three predicates (B, Bi, and I) are introduced to represent propositions of belief and intention.

Definition 9 *(belief)*
Propositions of belief on the "belief" and "sense" level are represented by expressions of the form

$$B(\alpha, \phi)$$

where α is an agent, and ϕ is a proposition that α believes. When α is "self", they are introspective propositions. Propositions of belief on the "self" level in an agent are represented by expressions of the form

$$Bi(\phi)$$

where ϕ is a proposition on the "belief" level. It represents the agent's state of believing "ϕ".

Definition 10 *(intention)*
Propositions of intention are represented by expressions of the form

$$I(\alpha, \phi, \psi)$$

where α is an agent, and ϕ and ψ are propositions. It is read as "α intends ϕ to achieve ψ".

3.3 Semantics

Truth values of introspective propositions in an agent are determined by observing herself (introspection). Her state of believing some proposition is observable from the "sense" level in our reflective structure. The semantics can be specified as follows:

Definition 11

$$\texttt{self} \models Bi(\phi) \textit{ iff } \texttt{belief} \models \phi \quad (5)$$
$$\texttt{sense} \models B(self, \phi) \textit{ iff } \texttt{self} \models Bi(\phi) \quad (6)$$
$$\texttt{sense} \models \neg B(self, \phi) \textit{ iff } \texttt{self} \not\models Bi(\phi) \quad (7)$$
$$\begin{aligned} &\texttt{belief} \models \phi \textit{ iff} \\ &\quad \phi \in \texttt{belief} \textit{ or} \\ &\quad \texttt{sense} \models \phi \textit{ or} \\ &\quad (\texttt{belief} \models \psi \textit{ and } \texttt{belief} \models \phi \leftarrow \psi) \end{aligned} \quad (8)$$

Example 4 *If an ordinary sentence τ of propositional logic is in* belief*, then the following hold:*

$$\texttt{belief} \models \tau,\ \texttt{self} \models Bi(\tau),\ \texttt{sense} \models B(self, \tau),$$
$$\texttt{belief} \models B(self, \tau),\ \texttt{self} \models Bi(B(self, \tau)),\ \ldots$$

Some predicates are necessary for dealing with terms and propositions on the "self" level. We explain two of them, which are used later in this paper. One is for taking out the value of a property from an act term, and the other for transforming an introspective proposition into its normal form.

Definition 12
Let θ and ϕ be any act term and any proposition:

$$\texttt{self} \models label_i(\theta, value_i) \qquad (i = 1, .., n_\theta)$$
$$\texttt{self} \models NF(\phi, \phi') \textit{ iff } \phi' \textit{ is the normal form of } \phi$$

Example 5

$$\texttt{self} \models agent(\ll buy, agent{:}self \gg, self)$$
$$\texttt{self} \models NF(B(self, \neg B(self, B(self, \neg\phi))), B(self, \neg B(self, \neg\phi)))$$
where ϕ is a nonintrospective proposition.

3.4 Basic rules of action

Plans are made in terms of intention on the "self" level in an agent. Her intentional acts which she believes to be feasible are executed. The other's plan making is also simulated by means of treating the other and herself equally, that is, both are elements in the world. The following rules on the "self" level deal with plan making and execution.

Definition 13

$$\begin{aligned} &Bi(I(self, done(\theta), \psi)) \ \wedge\ agent(\theta, self) \wedge \\ &\forall\phi.(Bi(precond(\theta, \phi)) \rightarrow Bi(\phi)) \\ &\Rightarrow\ Doing(\theta) \end{aligned} \quad (9)$$
$$\begin{aligned} &Bi(I(\alpha, done(\theta), \psi)) \ \wedge\ agent(\theta, \alpha) \ \wedge \\ &Bi(precond(\theta, \phi)) \ \wedge\ Bi(\neg B(\alpha, \phi)) \ \wedge \\ &NF(B\phi, B\phi') \\ &\Rightarrow\ Assert(\texttt{belief}, I(\alpha, \phi', done(\theta))) \end{aligned} \quad (10)$$
$$\begin{aligned} &Bi(I(\alpha, \phi, \psi)) \ \wedge \\ &(Bi(effect(\theta, \phi)) \vee Bi(effect(\theta, B(\alpha, \phi)))) \wedge \\ &agent(\theta, \alpha) \\ &\Rightarrow\ Assert(\texttt{belief}, I(\alpha, done(\theta), \phi)) \end{aligned} \quad (11)$$

*The "Doing(θ)" command executes the act θ. The "Assert(*belief*, ϕ)" command adds the proposition ϕ to the "belief" level. During the addition, contradictory propositions are removed from the level.*

Her intentional acts which she believes feasible are executed by the rule (9). When an agent has an intention to achieve an act, the agent hopes by the rule (10) that the preconditions of the act which the agent does not believe true will turn true. An agent intends to achieve an act by the rule (11) in the case that the agent hopes to turn a proposition true, and one of the effects of the act is to turn it true.

Moreover, an agent's intention to achieve an act must disappear when the agent believes herself to have done it. Her hope of turning a proposition true must vanish when she believes that the proposition is turned true. Such deletions of intention are managed by the following rules on the "self" level.

Definition 14

$$\begin{aligned} &Bi(I(\alpha, done(\theta), \psi)) \ \wedge\ Bi(B(\alpha, done(\theta))) \\ &\Rightarrow\ IntRetruct(\texttt{belief}, I(\alpha, done(\theta), \psi)) \end{aligned} \quad (12)$$
$$\begin{aligned} &Bi(I(\alpha, \phi, \psi)) \ \wedge\ Bi(B(\alpha, \phi))) \\ &\Rightarrow\ IntRetruct(\texttt{belief}, I(\alpha, \phi, \psi)) \end{aligned} \quad (13)$$

*The "IntRetruct(*belief*, $I(\alpha, \phi, \psi)$)" command removes the proposition $I(\alpha, \phi, \psi)$ from the "belief" level. Propositions "$I(\alpha, \omega, \phi)$" are also removed when $I(\alpha, \phi, \omega')$ is removed (ω and ω' are any propositions).*

4 Application to NLDS

4.1 Sample definitions of acts

We will now define preconditions and effects of some acts [2], and show how communication is executed in our computational model. Preconditions and effects of acts are defined in terms of propositions of the form

$$precond(\theta, \phi) \quad and \quad effect(\theta, \psi)$$

where θ is an act term, and ϕ and ψ are propositions.

Abbreviation 1 *We abbreviate*

$$\ll buy, agent{:}\alpha, from{:}\beta, obj{:}\gamma \gg$$
$$\quad to\ [buy, \alpha, \beta, \gamma],$$

[2] The way of execution of each act also needs to be defined. We define it by means of prolog program so far.

$$\ll sell, agent{:}\alpha, to{:}\beta, obj{:}\gamma \gg$$
$$\quad to\ [sell, \alpha, \beta, \gamma],\ \ and$$
$$\ll \sigma \mid type(\sigma, ticket), dest(\sigma, \delta) \gg$$
$$\quad to\ [ticket, \delta].$$

When some values are not determined, "_" is used for them.

An agent α normally believes a proposition ϕ when α tells the other agent β the proposition ϕ. After α's telling β ϕ, α also believes that β believes ϕ. In case that α asks β about $\phi(x)$, α does not believe that β does not have information of $\phi(x)$. After α's asking β about $\phi(x)$, α waits until β gives an answer t. Then, α believes that β believes $\phi(t)$. Therefore, the definitions of telling and asking are as follows:

Definition 15 *(telling and asking)*

$$precond([tell, \alpha, \beta, \phi], B(\alpha, \phi))$$
$$effect([tell, \alpha, \beta, \phi], B(\alpha, B(\beta, \phi)))$$
$$precond([ask, \alpha, \beta, \phi(x), t], \neg B(\alpha, \neg B(\beta, \phi(x))))$$
$$effect([ask, \alpha, \beta, \phi(x), t], B(\alpha, B(\beta, \phi(t))))$$

It should be noted that these definitions are not perfect, but enough to demonstrate how our computational model works in the domain of communication.

For increase of readability, the following predicates are introduced.

Abbreviation 2

$$Precond(\theta, \{\phi_1, .., \phi_n\}) \ \equiv$$
$$\quad precond(\theta, \phi_1) \wedge .. \wedge precond(\theta, \phi_n)$$
$$Effect(\theta, \{\phi_1, .., \phi_n\}) \ \equiv$$
$$\quad effect(\theta, \phi_1) \wedge .. \wedge effect(\theta, \phi_n)$$

Then, the preconditions and effects of α's buying γ from β are defined as follows:

Definition 16 *(buying)*

$$Precond([buy, \alpha, \beta, \gamma], \{$$
$$\quad I(\beta, done([sell, \beta, \alpha, \gamma]), \_),$$
$$\quad B(\beta, I(\alpha, done([buy, \alpha, \beta, \gamma]), \_))\})$$
$$Effect([buy, \alpha, \beta, \gamma], \{$$
$$\quad have(\alpha, \gamma),$$
$$\quad B(\beta, done([sell, \beta, \alpha, \gamma]))\})$$

That is, when an agent α buys an object γ from β, β must intend to sell γ to α, and believe α's intention of buying. The definition of selling is similar to the definition of buying.

Definition 17 *(selling)*

$$Precond([sell, \alpha, \beta, \gamma], \{$$
$$\quad I(\beta, done([buy, \beta, \alpha, \gamma]), \_),$$
$$\quad B(\beta, I(\alpha, done([sell, \alpha, \beta, \gamma]), \_))\})$$
$$Effect([sell, \alpha, \beta, \gamma], \{$$
$$\quad have(\beta, \gamma),$$
$$\quad B(\beta, have(\beta, \gamma)),$$
$$\quad B(\beta, done([buy, \beta, \alpha, \gamma]))\})$$

In case of selling a ticket, a seller α must have information of the destination of the ticket which the buyer β wants. Thus, the following precondition is necessary in addition to the above.

Definition 18 *(selling a ticket)*

$$Precond([sell, \alpha, \beta, [ticket, \delta]], \{$$
$$\quad B(\alpha, B(\beta, dest([ticket, \delta], \delta)))\})$$
$$B(\beta, dest([ticket, \delta], \delta)) \leftarrow$$
$$\quad I(\beta, done([buy, \beta, \_, [ticket, \delta]]), \_) \wedge$$
$$\quad \mathtt{reflect}(constant(\delta)).$$

"$\mathtt{reflect}(\kappa)$" is a special predicate of computational reflection. The predicate is needed by technical reason [Smith 1982], and the following is its semantics.

Definition 19 *(computational reflection)*

$$\mathtt{belief} \models \mathtt{reflect}(\kappa)\ \textit{iff}\ \mathtt{self} \models \kappa$$

4.2 An example in communication

α's telling β a sentence ϕ is generally formalized as a proposition

$$I(\alpha, B(\beta, I(\alpha, B(\beta, \phi), \_)), \_)$$

on the basis of the Speech Act Theory. Therefore, after α's telling β a sentence ϕ, β believes that α intends β to believe ϕ. Then, "$B(\beta, \phi)$" can be deduced in normal conditions by the following rule.

$$B(\beta, \phi) \leftarrow$$
$$\quad B(\beta, I(\alpha, B(\beta, \phi), \_)) \wedge$$
$$\quad \neg B(\beta, \neg reliable(\alpha))$$

Below is a simple example in the domain of communication, so we simply make "$B(\beta, \phi)$" true after α's telling β ϕ.

Consider an initial situation in which an agent has an intention to sell a ticket to her user, and the agent believes that the user believes the intention. The agent's belief of this situation is described with the following two proposition on the "belief" level in the agent.

$$B(u, I(s, done([sell, s, u, [ticket, \_]]), \_)) \quad and$$
$$I(s, done([sell, s, u, [ticket, \_]]), true) \qquad (14)$$

where "s" and "u" are abbreviations of "$self$" and "$user$" respectively. In this situation, the agent can not do anything besides waiting for changes of situation. Thus, after activating the agent, the agent waits.

Activating...

$$I(s, done([wait, s]), true)$$

Waiting...

Now, we assume that the user says to the agent "I want a ticket." Then, the following propositions are added to the agent's belief in the order.

`User :` "`I want a ticket.`"

$$I(u, have(u, [ticket, \_]), true) \quad (15)$$

$$I(u, done([buy, u, \_, [ticket, \_]]), 15)$$

$$I(s, B(s, B(u, dest([ticket, \_], x))), 14) \quad (16)$$

$$I(s, done([ask, s, u, dest([ticket, \_], x), \_]), 16)$$

At this point, the agent asks the user the destination of the ticket which the user wants in accordance with the agent's intention. We assume that the user answers "Tokyo".

Asking the user the destination of the ticket...

`User :` "`Tokyo.`"

$$done([ask, s, u, dest([ticket, \_], x), \texttt{TOKYO}])$$

$$B(u, dest([ticket, \texttt{TOKYO}], \texttt{TOKYO}))$$

Finally, all preconditions of the agent's selling a ticket to the user are satisfied in her belief, and the act is executed.

In case that the user says "I want a ticket to Tokyo." instead of "I want a ticket.", the agent does not need to ask the destination of the ticket. The following is the result of tracing.

Example 6

Initial State :

$$B(u, I(s, done([sell, s, u, [ticket, \_]]), \_))$$

$$I(s, done([sell, s, u, [ticket, \_]]), true)$$

Activating...

$$I(s, done([wait, s]), true)$$

Waiting...

`User :` "`I want a ticket to Tokyo.`"

$$I(u, have(u, [ticket, \texttt{TOKYO}]), true) \quad (17)$$

$$I(u, done([buy, u, \_, [ticket, \texttt{TOKYO}]]), 17)$$

Selling a ticket to Tokyo...

. . . . .

5 Conclusion

We have proposed a computational model of an intelligent agent, and showed how simple communicative acts are performed in the model. Information which an agent gains by observing the world forms the agent's belief about the world, and the agent always acts according to her intention and the belief. What is essential to such a situated agent is that the agent herself is an element of the world, and she can obtain information about herself by observing herself embedded in the world. The ability of observing herself realizes introspective belief, and enables the agent to act intelligently.

However, we have not completely formalized the model of inferring the other's plan in our computational model. As a result, our agent can not receive her user cooperatively when the agent does not have the intention which the user believes the agent has. We must investigate much further towards a complete formalization of the processes of inferring the other's plan in the computational model.

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