# Logic of Information Flow on Communication Channels (Extended Abstract)

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## ABSTRACT

We develop an epistemic logic to specify and reason about information flow and its underlying communication channels. By combining ideas from Dynamic Epistemic Logic (DEL) and Interpreted Systems (IS), our semantics offers a natural and neat way of modelling multi-agent communication scenarios with different assumptions about the observational power of agents.

## Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*multiagent systems*

## General Terms

Theory

## Keywords

Dynamic epistemic logic, Interpreted system, Communication protocols, Communication channels

## 1. INTRODUCTION

The 1999 'National Science Quiz' of *The Netherlands Organisation for Scientific Research (NWO)*[1] had the following question:

> *Six friends each have one piece of gossip. They start making phone calls. In every call they exchange all pieces of gossip that they know at that point. How many calls at least are needed to ensure that everyone knows all six pieces of gossip?*

To reason about the information flow in such a scenario, we have to take into account the following issues: the messages that the agents possess (e.g. secrets), agents' higher-order knowledge about each other, the dynamics of the system in terms of information passing (e.g. telephone calls), the underlying communication channels (e.g. the network of landlines) and the communication protocols that can be used to reach the goal. More interesting questions arise naturally when we consider *common knowledge* and communicative abilities of agents other than message passing [1, 10]. For example, we may ask whether "everyone knows all the secrets" can become common knowledge if agents can agree on a protocol beforehand and are allowed to inform each other of any proposition e.g., "I have talked with B and she knows $\phi$". To incorporate specific designs for such issues, we base our work on two mainstream logical frameworks for multi-agent systems with both time and knowledge: *Interpreted Systems* [4] and *Dynamic Epistemic Logic* [2].

An Interpreted Systems (IS) is a multi-agent system that combines a given history-based temporal structure with epistemic uncertainty relations among the histories defined by agents's *local states or observations* of the temporal development of the system. On the other hand, Dynamic Epistemic Logics (DEL) focuses on the epistemic impact of explicit actions as the agents perceive them, thus enjoys the flexibility in designing different communicative actions with internal structures. In DEL, the temporal development of a system is essentially generated by executing so-called *action models* on static initial models. This facilitates the comparison of the two approaches (cf., e.g., [8]). However, in practice, the epistemic relations in the initial static model and in the action models are mostly designed by hand, not generated uniformly as in IS. In this paper, we demonstrate the benefits of combining these two approaches by presenting a framework where epistemic relations are generated by matching local observations as in ISs, while keeping the flexibility of explicit actions as in DEL approaches.

Some earlier work on communication w.r.t. underlying channels within standard DEL can be found in [9, Ch. 6.6] and [7], while communication channels in the IS framework made their appearance in [6] and more recently in [1].

## 2. OUR APPROACH

Unlike [1, 7], we follow [10] to start out with a PDL-like language to specify the protocol *explicitly* in the language:

$$\phi ::= \top \mid p \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid \langle\pi\rangle\phi \mid C_G\phi$$
$$\pi ::= \alpha \mid \pi_1;\pi_2 \mid \pi_1 \cup \pi_2 \mid \pi^*$$

with $\langle\pi\rangle\phi$ to be read as "after execution of the protocol $\pi$, $\phi$ holds" and $C_G\phi$ as the common knowledge of $\phi$ among subgroup $G$ of the agent set $I$. The basic propositions $p$ are tailored to handle messages and the constrains of protocols and communication channels naturally:

$$p ::= has_i m \mid com(G) \mid past(\bar{\alpha}) \mid future(\bar{\alpha})$$

where $has_i m$ says that $i$ possesses the message $m$ while $com(G)$ expresses that group $G$ forms a channel in the network where only the group members can observe this action clearly; $past(\bar{\alpha})$ says that the sequence of actions $\bar{\alpha}$ just happened and $future(\bar{\alpha})$ means that $\bar{\alpha}$ can be executed according to the current protocol.

*The first author is supported by Dutch NWO project VEMPS (612.000.528).

[1]For a list of references about the problem c.f. [5].

**Cite as:** Logic of Information Flow on Communication Channels (Extended Abstract), Yanjing Wang, Floor Sietsma, Jan van Eijck, *Proc. of 9th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2010)*, van der Hoek, Kaminka, Lespérance, Luck and Sen (eds.), May, 10–14, 2010, Toronto, Canada, pp. 1447-1448

Similar to the action models in DEL, we let basic action $\alpha$ have a tuple as the internal structure: $\langle G, \phi, M_0 \dots M_{|I|}, \rho\rangle$, where $G$ is the set of agents who can observe $\alpha$, $\phi$ is a formula encoding the precondition for $\alpha$ to be executed, $M_0 \dots M_{|I|}$ are the sets of messages to be delivered to the corresponding agents and $\rho$ is either a $\sharp$ (signifying to continue the current protocol) or a new protocol $\pi$ to be followed. For example, an action $\alpha$ which models that $i$ sends $j$ a message $m$ should have the following internal structure:

$$\langle \{i, j\}, com(\{i, j\}) \wedge future(\alpha) \wedge has_i m, \emptyset \dots M_j \dots \emptyset, \sharp\rangle$$

where $M_j = \{m\}$, $com(\{i, j\})$ and $future(\alpha)$ are required as precondition thus the action has to comply with the communication channels and the current protocol. The action of agent $i$ telling $j$ about $\phi$ can be modelled by an action similar to $\alpha$ but having $K_i\phi$ instead of $has_i m$ as part of the precondition.

Besides the conventional communicative actions, we can also define actions which do not respect the channel or the current protocol, to enforce some assumptions about the system. For example, the public announcement of the new protocol and propositional facts can be modeled by the actions $exprot(\pi) = \langle I, \top, \bar{\emptyset}, \pi\rangle$ and $exinfo(\phi) = \langle I, \phi, \bar{\emptyset}, \sharp\rangle$ respectively.

The semantics is given on single-state models which encode the action history and the future protocol to be executed:

$$s = \langle net, M_0, \dots, M_{|I|}, \bar{\beta}, \pi\rangle$$

where $net \subseteq \mathcal{P}(\mathcal{P}(I))$ is the communication network, $M_0 \dots M_{|I|}$ represent the initial distribution of the messages, $\bar{\beta}$ is the past history and $\pi$ is the protocol to be followed in the future. Intuitively, each state represents a deterministic temporal development of the system with its constraint for the future actions. Note that the past is linear as $\bar{\beta}$ is a single sequence of actions, while the future can be branching since $\pi$ may allow several possible sequences of actions.

For the semantics, the non-trivial cases are for formulas in the shapes of $\langle\pi\rangle\phi$ and $C_G\phi$. We let $s \vDash \langle\pi\rangle\phi \Leftrightarrow \exists s' : s[\![\pi]\!]s'$ and $s' \vDash \phi$ and $[\![\pi]\!]$ are based on $[\![\alpha]\!]$ and usual operations on relations corresponding to sequential composition, union and reflexive transitive closure. We say $s[\![\alpha]\!]s'$ if the precondition of $\alpha$ is satisfied at $s$ and $s'$ is the updated state with the updated message sets and the remaining protocol after executing $\alpha$. Intuitively, the remaining protocol $(\pi\backslash\alpha)$ is the regular expression corresponding to the collection of all the suffixes of sequences in $\pi$ which start with $\alpha$. It can be derived syntactically by regular expression derivatives as axiomatized in [3], for example: $(\alpha \cup (\beta;\gamma))^*\backslash\beta = \gamma; (\alpha \cup (\beta;\gamma))^*$.

For the interpretation of $C_G\phi$, we define epistemic relation $\sim_i$ among states as in IS. $s \sim_i s'$ iff $s$ and $s'$ have the same initial sets of messages for $i$ and the same observable action histories w.r.t. $i$. Clearly, an agent can only observe the actions which use the communication channels that she has available. Based on such observable actions, agents can still have a spectrum of different observational powers, e.g., an agent might be aware or not of a non-observable action has happened and remember all or part of the past actions. Our framework allows the flexibility of choosing different observational powers. Note that the external announcements $exprot(\pi)$ and $exprot(\phi)$ will make $\phi$ and $\pi$ common knowledge since all the agents can observe them.

Taking advantage of our semantics, we propose the following general modeling method when given an informal scenario:

*1.* Select a finite set of suitable actions $A$ with internal structures to model the communications in the scenario.

*2.* Design a *single* state as the *real world* to model the initial setting, i.e., $s = \langle net, \bar{M}_i, \epsilon, (\Sigma A)^*\rangle$ where $net$ and $\bar{M}_i$ models the initial network setting and message distribution respectively, where the initial record of the action history is assumed to be empty and where the default protocol $(\Sigma A)^*$ says all the actions are possible.

*3.* Translate the informal assumptions of the scenario into formulas $\phi$ and protocols $\pi$ in our language.

Finally formal verification of some property $\psi$ against a given scenario becomes checking whether $s \vDash [exinfo(\phi)][exprot(\pi)]\psi$.

In the full paper, we show that our semantics essentially generate an IS from a single state and the language can then be considered as the standard PDL restricted to such generated models. On the other hand, a fragment of our logic with certain assumptions of observational power can be translated back to DEL. Our logic can be viewed as a tailored cocktail of IS and DEL approaches balancing both expressiveness and flexibility, which we hope makes the modeling of communication and knowledge more transparent. The general philosophy is to use explicit finite representations as much as possible and leave the uniform procedure to the semantics. Our framework also facilitates the comparison between different approaches due to its flexibility in modeling different observational powers of agents and various communicative actions. The table below summarizes the setting of our framework compared to others:

| Reference | Actions | Information flow | Obs. Power |
|---|---|---|---|
| [7] | inform | propositions | perfect recall |
| [6] | download | Boolean atomic propositions | perfect recall |
| [1] | inform | positive atomic propositions | observable set |
| Our work | by design | messages or formulas | by design |

As a case study in the full paper, we model the telephone communications among agents as in the quiz. We show that it is possible to obtain common knowledge that everyone has all the secrets if a protocol is agreed on beforehand. On the other hand, common knowledge is not obtainable without the agreement, even if the girlfriends can not only send messages but also inform each other about the facts they learned.

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