



# A modal type theory for formalizing trusted communications

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## ABSTRACT

This paper introduces a multi-modal polymorphic type theory to model epistemic processes characterized by trust, defined as a second-order relation affecting the communication process between sources and a receiver. In this language, a set of senders is expressed by a modal prioritized context, whereas the receiver is formulated in terms of a contextually derived modal judgement. Introduction and elimination rules for modalities are based on the polymorphism of terms in the language. This leads to a multi-modal non-homogeneous version of a type theory, in which we show the embedding of the modal operators into standard group knowledge operators.

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## 1. Introduction

This paper introduces a multi-modal type-theoretic system to model trust-qualified communication processes ongoing among rational agents. The formulation of such a language and the analysis of its properties contributes to the epistemic debate on testimony and it provides a novel analysis of trust-based knowledge representation in a multi-agent system. Provided the syntactic nature of the language, the resulting semantics is easily adapted to computation within distributed networks: we focus here only on the analogy with testimony relations.

In the epistemic debate, testimony is commonly understood as the assertion of a declarative sentence carrying the message of a sender ( $S$ ) to a receiver ( $R$ ),<sup>1</sup> who then accepts it as true, without checking its truthfulness. From an epistemological point of view, true beliefs acquired through testimony are not (yet) justified, because they (still) lack any verification of their truthfulness. So it seems that testimony allows the agents in the system only to achieve a weak epistemic status, whereas a strong epistemic status can be obtained only once the receiver of the message verifies its truthfulness.

The formal model proposed in this paper rests on two conceptual pillars, the definition of trust as second-order property qualifying first-order relations [72] and the analysis of testimony proposed in [73]. Before focusing on the analysis of testimony we shall briefly recall the reader's attention on the novelty of the definition of trust as second-order property. Such definition clarifies that, contrary to what a first analysis would suggest, trust is not a relation occurring among the agents of a system. Rather it is a way in which such relations may occur. In particular, trust qualifies a relation making it more convenient for the agent who decides to trust (the trustor) another agent (the trustee), as in doing so the trustor

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<sup>1</sup> In this paper we will refer to 'sender' and 'receiver' of a message rather than to 'speaker' and 'hearer' to indicate the agents involved in a testimony scenario. 'Speaker' and 'hearer', although common terms in the philosophical literature on testimony, specifically refer to verbal communication, which is only one of the possible ways in which testimony can occur, while 'sender' and 'receiver' generally refer to a case of communication among agents, without specifying the nature of the communication. For this reason the latter is more appropriate to describe testimony scenarios.

saves the resources (time and energy) that he would deploy to perform a given task. When considered with respect to an epistemic context, this definition of trust becomes extremely useful in understanding its role in the processes of communication of information and knowledge among the agents of a distributed system. This is particularly true when considering the occurrences of testimony. According to the analysis of testimony provided in [73] on the basis of this definition of trust, testimony is the occurrence of first-order relations of communication qualified by the second-order property of trust. This is the definition interpreted by the formal model described in this paper, which interprets communication in a multi-agent system by focusing on the distinction among agents that hold directly the relevant information and those that have to rely on others in order to possess it. In this way, we design communication chains that inherently use the notion of trust, defined as the result of linking two epistemic states by way of a message passing system.

Our language is an extension of the modal polymorphic type theory with partial term-assignment on judgements developed in [65]. The polymorphic language serves the task of formalizing the two kinds of epistemic states involved by a communication act: a standard constructive *type* preserves verification-terms on propositions and qualifies them as ‘known contents’; a type with partial-terms *type<sub>inf</sub>* preserves only consistency and qualifies its contents as ‘information’, in the sense of communicated but not verified contents. For each of the two kinds of contents, an appropriate portion of the language is used. A side property of the system is the extension of a strongly constructive language with a fragment that accommodates a weaker epistemic notion, to use it for knowledge representation purposes. The language has also a modal extension, based on the judgemental modalities introduced in [64]: judgements  $\Box/\Diamond(A \text{ true})$  are defined to express the reducibility of the corresponding proof constructions. Modalities are then generalized to collections of judgements used in contexts  $\Gamma, \Delta$ , interpreted as knowledge states. Multi-modalities are used to formalize the occurrence of distinct, prioritized sources in the communication act.

We can sum up the novelties offered by the present contribution as follows:

1. We present the first type-theoretic model of trusted communications; in this way we extend the range of syntactic approaches to group knowledge and provide a novel research direction for type systems;
2. The model relies on an effective representation of different epistemic states for rational agents, thus making an effort in the direction of realistic representation of human knowledge processes;
3. The model endorses an innovative definition of trust. Rather than focusing on the traditional conceptualization of trust as a relation, it endorses a recently provided account of this phenomenon, according to which trust is a second-order property qualifying first-order relations. Such a definition not only constitutes quite an innovative approach to the analysis of trust when compared to the relevant literature, it also allows for developing a completely new analysis of trust-communications and of their role in the processes of knowledge communication in a distributed system, as described in Section 2.
4. We make use of the notion of refutable content for a type system, introduced in [65]; we consider this a crucial notion for the development of epistemic logics for defeasible reasoning and, in particular, consider it especially important in its present combination with a strong verificationist semantics, in order to combine different aspects of knowledge acquisition processes that often are difficult to highlight in a formal setting;
5. Finally, we explore the relation of this syntactic model and the thereby defined notion of trusted communications with the well-known notions of Distributed and Common Knowledge from epistemic logic; this direction of research is still very young but we provide a first interesting connection between two fields that grow largely separated from one another.

There is a growing literature on trust and the formalization of communication acts that uses modal logics; such literature is for the greatest part developed in the vein of model-theoretic, Kripke- and Dynamic semantics of modal logics, whereas little is done in the area of proof-theoretic approaches. Our work especially aims at providing the *first type-theoretic* treatment of the notion of trusted communication. The greatest advantage of such language is that it provides a syntax with embedded meanings, so that its rules immediately define corresponding semantic notions and a procedural semantics comes entirely natural, as done in [66] for a model of safe distributed programming. Moreover, we exploit the predicative structure of Dependent Types in order to mimic the behavior of communication acts. This approach is, to our knowledge, entirely new especially because it relies on a syntactic distinction between constructors that accommodate partial terms. Finally, we induce a modal extension of the language which differs both from the original formulation of the type theory in use and from the already existing contextual modal extensions.

In providing this language, we focus on the concurrent combination of the two epistemic states that we consider essentially involved in the act of trusted communication. Also in this case, we believe this is a rather novel approach. The largest part of the work done in modeling trusted communications and distrust relations comes from computer science and network analysis, where such distinction is treated in terms of authorizations. Our treatment is clearly more focused on the epistemic relations occurring among rational human agents. The formal representation of epistemic acts combining weaker and stronger attitudes represents a step forward towards more realistic approaches of human-based communications.

As mentioned above, a conceptual novelty of this paper is related to the definition of trust as a second-order property and the reference to testimony as the specific instance of trusted communications. This point is largely addressed in Section 2.

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