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Towards a Reference Ontology of Trust

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Abstract. Trust is a key component of relationships in social life. It is
commonly argued that trust is the "glue" that holds families, societies,
organizations and companies together. In the literature trust is frequently
considered as a strategic asset for organizations. Having a clear under-
standing of the notion of trust and its components is paramount to both
trust assessment and trust management. Although much progress has
been made to clarify the ontological nature of trust, the term remains
overloaded and there is not yet a shared or prevailing, and conceptually
clear notion of trust. In this paper we address this issue by means of
an in-depth ontological analysis of the notion of trust, grounded in the
Unified Foundational Ontology. As a result, we propose a concrete arti-
fact, namely, the Reference Ontology for Trust, in which we characterize
the general concept of trust and distinguish between two types of trust,
namely, social trust and institution-based trust. We also represent the
emergence of risk from trust relations. In addition, we make a compar-
ative analysis of our Reference Ontology to other trust ontologies. To
validate and demonstrate the contribution of our approach, we apply it
to model two application examples.

Keywords: Trust · Ontological Analysis · Unified Foundational Ontol-
ogy.

1   Introduction

Trust is a central component of social life. In the literature, trust is frequently re-
ferred to as the "glue of society", vital in economics, social cooperation, organiza-
tions, groups, etc. Because of its ubiquitous presence, the notion of trust appears
in many contexts and has been defined in a wide number of ways throughout
the years and across several areas [5,9,25,31].

The term trust has been used to refer to different types of relationships, such
as the trust between individuals, as well as between individuals and organiza-
tions, individuals and autonomous agents, between software systems operating in
a network, the trust in the context of offline or online commercial relationships,
and others. Regardless of the context, trust is generally the basis for decision

making closely related to achieving a goal. Therefore, understanding the key factors that play a role in trust assessment is paramount to avoid exposing decision makers to the risk of loss from incorrect decisions due to misplaced trust. Since these factors are numerous, it is not trivial to select the key ones that maximize decision performance, and thus promote effective decision making. In technological contexts, many disciplines, such as human-computer interaction, distributed artificial intelligence, multi-agent systems and networked-computer systems, are working to integrate trust into technological infrastructures. In this scenario, the need for a technology able to deal with typical human cognitive and social features and phenomena, like trust, emerges. To support this, a precise and rigorous conceptualization, based on foundational ontologies, is needed, as well as some theoretical abstraction and some possible modeling of it.

Although much progress has been made to clarify the ontological nature of trust, the term remains overloaded and there is not yet a shared or prevailing, and conceptually clear definition for it [4,22]. In the light of the above, we advocate for the need of a reference ontology of trust to serve as a basis for communication, consensus and alignment among different approaches and perspectives, as well as to foster interoperability across the heterogeneous application domains. In this paper, we address this issue by means of an in-depth ontological analysis of the notion of trust, grounded in the Unified Foundational Ontology (UFO) [11,14]. As a result, we propose a concrete artifact, namely, the Reference Ontology of Trust, which we employ to harmonize different perspectives found in the literature. In our analysis, besides formally characterizing the concept of trust, we distinguish between two types of trust, namely, *social trust* and *institution-based trust*. Moreover, we clarify the relation between trust and risk and represent how risk emerges from trust relations.

This paper is part of a long-term research program that aims at developing ontological foundations for social and organizational modeling. In this context, we have analyzed the notions of *risk*, *value*, *economic preference*, *economic transaction*, *social roles*, *contracts*, *goal*, *capability*, among others [14]. These analysis, in turn, have been later employed to evaluate, integrate and redesign important organizational modeling languages such as ARIS, BPMN, and Archimate [1,16].

The remainder of this paper is organized as follows. First, in Section 2, we introduce the reader to the main notions of UFO. Then, in Section 3, we discuss the ontological nature of trust as discussed in the literature. In Section 4 we describe our view of Social System, an essential concept for the modeling of institution-based trust. In Section 5 we present our proposal, the Reference Ontology of Trust. In Section 6, to validate and demonstrate the contribution of our ontology to the modeling practice, we apply it to model two case illustrations: (i) an example of social trust; and (ii) an example of institution-based trust. We present some related work on section 7 and conclude the paper in Section 8 with some final considerations.

2   Ontological Foundations

In this paper we provide an ontological analysis of *trust*, grounded on the Unified Foundational Ontology (UFO). UFO is an axiomatic domain independent formal theory, developed based on a number of theories from Formal Ontology, Philosophical Logics, Philosophy of Language, Linguistics and Cognitive Psychology. UFO is divided into three incrementally layered compliance sets: UFO-A, an ontology of endurants (objects)[11], UFO-B, an ontology of events (perdurants)[15], and UFO-C, an ontology of social entities built on the top of UFO-A and UFO-B, which addresses terms related to the spheres of intentional and social things [16,13]. For an in-depth discussion and formalization, one should refer to [11,15]. UFO is the theoretical basis of OntoUML, a language for Ontology-driven Conceptual Modeling that has been successfully employed in a number of academic and industrial projects in several domains, such as services, value, petroleum and gas, media asset management, telecommunications, and government [14]. Models created in OntoUML have a formal semantics, and a comprehensive support for model verification, validation and code generation, including in languages such as OWL [14]. The motivation for using UFO is to provide an accessible and sharable modelling of trust that may be applied across domains to foster the interoperability and the mutual understanding among modellers.

UFO distinguishes endurant types into *substantial types* and *moment types*. These are sorts of types whose instances are *substantials* and *moments* [11], respectively. *Substantials* are existentially independent objects such as Mick Jagger, the Earth, an organization, a car, a book. *Moments*, in contrast, are existentially dependent individuals such as (a) Alice's capacity to swim (which depends on her) and (b) the marriage between John and Mary (which depends on both John and Mary). Moments of type (a) are termed *modes*; those of type (b) are termed *relators*. *Relators* are individuals with the power of connecting entities. For example, an Enrollment relator connects an individual playing the Student role with an Educational Institution. Furthermore, there is a third sort of moments termed *qualities*. *Qualities* are individual moments that can be mapped to some quality space, e.g., an apple's color which may change from green to red while maintaining its identity [11].

In our analysis, we shall rely mainly on some concepts defined in UFO-C [13,16]. A basic distinction in UFO-C is related to *agents* and (non-agentive) *objects*. An agent is a specialization of a *substantial individual* that can be classified as *physical* (e.g., a person) or *social* (e.g., an organization, a society). *Objects* are non-agentive *substantial individuals* that can also be categorized in *physical* (e.g., a book, a table) and *social objects* (e.g., money, language). A *Normative Description* is a type of *social object* that defines one or more rules/norms recognized by at least one *social agent* and that can define nominal universals such as *social moment universals* (e.g., *social commitment types*), *social objects* (e.g., money) and *social roles* (e.g., president, PhD candidate or pedestrian). Examples of normative descriptions include the Italian Constitution, the University of Bolzano PhD program regulations, and also a set of directives on how to perform some actions within an organization.

Agents can bear special types of *modes* (aspects, features, characteristics, objectified properties) named *intentional moments*. A common characteristic of all modes is that they are *existentially dependent* on their bearers. Intentionality should not be understood as the notion of intending something, but as the capacity to refer to possible situations of reality [1]. Every *intentional moment* has an associated proposition that is called the propositional content of the moment. In general, the propositional content of an intentional moment can be satisfied (in the logical sense) by situations in reality. *Intentional moments* can be *social moments* or *mental moments*. *Mental moments* are specialized in *beliefs*, *desires* and *intentions* (internal commitments). The propositional content of a *belief* is what an agent holds as true. Examples include one's belief that Rome is the Capital of Italy and that the Earth orbits around the Sun. *Desires* and *intentions* can be fulfilled or frustrated. A *desire* expresses the will of an agent towards a possible situation (e.g., a desire that Italy wins the next World Cup), while an *intention* expresses desired states of affairs for which the agent commits to pursuing (internal commitment) (e.g., John's intention of going to Paris to see the Eiffel Tower). *Intentions* may cause the agent to perform *actions* (concept from UFO-B). The propositional content of an *intention* is termed a *goal*. *Social moments* are types of *intentional moments* that are created by *social actions* (e.g., an interaction composed of the exchange of communicative acts). *Social commitments* and *social claims* are types of *social moments*. A *social commitment* is a commitment of an agent A towards another agent B, which inheres in A and is externally dependent on B. The *social commitments* necessarily cause the creation of an internal commitment in A. Also, associated to this internal commitment, a *social claim* of B towards A is created. *Commitments* and *claims* always form a pair that refers to a unique propositional content.

3   On Trust

A wide number of definitions of trust have been proposed along the years, across several areas, such as psychology [25,29], sociology [2,7,19], economics [31], law [5], and more recently, computer science [9,23]. Although much progress has been made to clarify the nature of trust, the term remains semantically overloaded and there is not yet a shared or prevailing, and conceptually clear notion of trust [4].

A classic definition of trust, widely accepted in the literature, was proposed by the sociologist Diego Gambetta, who defines trust as "the subjective probability with which an agent expects that another agent or group of agents will perform a particular action on which its welfare depends" [7]. In his definition it is clear the existence of both a *trustor* and a *trustee*, as well a belief of the trustor about the behavior of the trustee. Gambetta also relates trust to an intention of the trustor regarding her welfare and the uncertainty about the trustee's behavior, which reveals the existence of a certain degree of risk. In fact, this idea that trust presupposes a situation of risk is ubiquitous in the literature. For instance, Luhmann [19] argues that when people trust others, they act "as if they knew

the future", and uncertainty is transformed into risk. Also, Castelfranchi and Falcone [4] state that without uncertainty and risk there is no trust.

A similar concept of trust is proposed by Mayer, Davis, and Schoorman [20], who define trust as "the willingness of a party to be vulnerable to the actions of another party, based on the expectation that the other party will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party". Also here, the authors refer to the expectations (or beliefs) of the trustor regarding the trustee and correlates trust to the trustor's goals (the actions of the other party that are important to the trustor). According to the authors, by trusting another party, the trustor makes herself vulnerable and exposed to the occurrence of risk events.

Rosseau and colleagues relied on a large interdisciplinary literature and on the identification of fundamental and convergent elements to define trust as "a psychological state of a trustor comprising the intention to accept vulnerability in a situation involving risk, based on positive expectations of the intentions or behavior of the trustee" [26]. Note that, also in this definition, the authors reinforce the presence of the trustor's expectations regarding the trustee, as well as the relationship between trust and risk: by trusting, the trustor accepts to become vulnerable to the trustee in terms of potential failure of the expected action and result, as the trustee may not perform the expected action or the action may not have the desired result.

McNight and colleagues [22] compared sixty-five definitions of trust from different sources to propose an interdisciplinary model of conceptual trust types that takes into account several important aspects of trust and some of their mutual interactions. For example, the authors are able to distinguish between a belief and a behavioral component of trust, and to explain that the latter depends on the former. The belief component is related to cognitive perceptions about the attributes or characteristics of others, i.e., the trustor believes, with "feelings of relative security", that the trustee is willing and able to act in her interest. The behavioral component means that a person voluntarily takes actions that makes herself dependent on another person, with a feeling of relative security, even though negative consequences are possible. According to the authors, trust-related behavior comes in a number of subconstruct forms because many actions can make one dependent on another, such as cooperation, information sharing, informal agreements, decreasing controls, accepting influence, granting autonomy, and transacting business.

A further important aspect in the model of McKnight et al. [22] is the distinction between *interpersonal trust* and *institution-based trust*. This distinction is also made by Luhmann [19], who defines:

- **interpersonal trust** as that between individuals that frequently have face-to-face contact and become familiar with each other without substantially taking recourse to institutional arrangements; and
- **institution-based trust** as that in the reliable functioning of certain social systems, which no longer refers to a personally known reality, but is built on

impersonal and generalized "media of communication", such as the monetary system and the legal system.

According to McKnight et al. [22], institution-based trust affects interpersonal trust by "making the trustor feel more comfortable about trusting others, as she securely believes that protective structures (such as guarantees, contracts, regulations, promises, legal recourse, processes or procedures) are in place that are conducive to situational success". For example, people believe in the efficacy of a bank to take care of their money because of the existence of laws and institutions that insure them against loss. Lewis and Weigert [18] argue that institution-based trust is indispensable for the effective functioning of "symbolic media of exchange", such as money and political power. They argue that "without public trust in the reliability, effectiveness, and legitimacy of money, laws, and other cultural symbols, modern social institutions would soon disintegrate".

More recently, Castelfranchi and Falcone [4] analyzed the concept of trust as a composed and "layered" notion, relying on some key aspects: (i) a mental attitude and a disposition towards another agent; (ii) a decision and intention to rely upon the other, which makes the trustor vulnerable; (iii) the act of relying upon the trustee's expected behavior; and (iv) the consequent overt social interaction and relation between the trustor and the trustee.

In their definition of trust, Castelfranchi and Falcone [4] emphasize the role of the trustor's goal by stating that an "agent trusts another only relative to a goal, i.e., for something she wants to achieve, that she desires or needs". They also reinforce the idea of trust consisting of beliefs about the trustee and his behavior: "the belief that the trustee is able and willing to do the needed action; the belief that the trustee will appropriately do the action, as the trustor wishes; and the belief that the trustor can make herself less defended and more vulnerable". As for the behavioral component of trust, Castelfranchi and Falcone [4] argue that there may be mental trust without the corresponding behavioral part (i.e., without an action). That may happen because the level of trust is not sufficient; the level of trust is sufficient, but there are other reasons preventing the action (e.g. prohibitions); or trust is just potential, a predisposition (e.g. "the trustor would, might rely on the trustee, if/when, but it is not (yet) the case").

In summary, what can be extracted from these different proposals is that there is a conceptual core to be enlightened in order to properly define trust. Therefore, to conceptualize trust, one must refer to: (i) *agents and their goals*; (ii) *agents' beliefs*; (iii) possibly executable *actions* of a given type; and (iv) *risk*.

4   Defining Social Systems

A key aspect in the definition of institution-based trust is the reliance on Social Systems. This comes from the sociology tradition positing that people can rely on others because of structures, situations or assigned social roles that provide assurances that things will go well [2]. Institution-based trust refers to beliefs about those protective structures, not about the people involved. In this paper,

we term these protective structures "Social Systems". We adopt the interpretation of Social Systems as orderly arrangements of social entities that interact with each other, based on established and prevalent social rules that structure social interactions. Social Systems create a shared world of clear rules and reliable standards, which no longer refers to a personally known reality, but is built on impersonal and generalized "media of communication" [19], such as the monetary system and the legal system.

A further important aspect, related to the nature of Social Systems, is that they can be seen as *integral wholes*, whose parts play particular *functional roles* that contribute in specific ways to the functionality of the whole [11,28]. UFO includes micro-theories to address different types of *part-whole relations* [11,28] generally recognized in cognitive science [24,8]. Social Systems embody one particular kind of such parthood relations, namely, *component-functional complex* [28]. In UFO's terminology, this "componentOf" relation is used to relate entities that are *functional complexes*. Some examples of functional complexes are an organization, a legal system or a monetary system and their corresponding "componentOf" relations (e.g., presidency-organization, law-legal system, currency-monetary system). Consequently, Social Systems can be defined as functional complexes composed of social entities like the ones mentioned in Section 2 (e.g. social roles, social objects, social relationships, normative descriptions and so on). An example of Social System is the legal system, which is an integral whole composed of a number of social entities, such as social roles (e.g. lawyer, judge, etc.), social objects (e.g. contract, court sentence), normative descriptions (e.g. laws, regulations) and others that contribute in complementary manners to the functionality of the whole.

5   The Ontology of Trust

In this section, we present a well-founded ontology that formalizes the concept of trust as discussed in the previous sections. We formalize the mental aspects of trust in the OntoUML[3] model depicted in Fig. 1, and the particular behavioral aspect of trust, as well as the relation between trust and risk in Fig. 2. In the OntoUML diagrams depicting the Reference Ontology of Trust, we represent types of substantials in pink, events in yellow, modes in blue and situations in orange.

We model TRUST as a complex mental state of a TRUSTOR agent, composed of a set of BELIEFS about a TRUSTEE and her behavior. TRUST is always about an INTENTION of the TRUSTOR regarding a goal, for the achievement of which she counts upon the TRUSTEE. Note that in the conceptualization of goal we propose here, the achievement of a goal does not necessarily require an action of the TRUSTEE. Also omissions may be relevant in this context as the TRUSTOR might precisely rely on the fact that the TRUSTEE will not do an specific action or, more generally, that the TRUSTEE will not do anything at all. The TRUSTOR

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[3] Once more, OntoUML is a conceptual modeling language whose primitives reflect the ontological distinctions put forth by the UFO ontology [11]
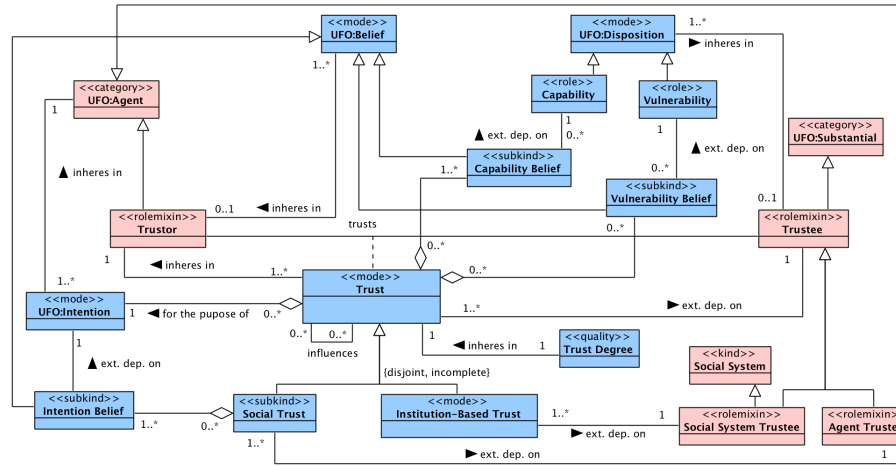
Fig. 1. Modeling the mental aspects of Trust

is necessarily an "intentional entity", that is, a cognitive agent, an agent endowed with goals and beliefs. In UFO, a belief is a special type of mode, named mental moment, which is existentially dependent on a particular agent, being an inseparable part of its mental state. As for the TRUSTEE, it is an entity able to cause a positive impact on a TRUSTOR's goal by the outcome of its behavior, regardless if this involves an action or an omission (e.g. doing nothing, abstaining from doing X). Moreover, note that the TRUSTEE is not necessarily aware of being trusted. An example, given in [4], is a person running to catch a bus. Even if this person is not seen by the bus driver and the people waiting for the bus at the stop, she may attribute to these people the intention to take the bus, and thus the intention to stop it. In such a case, the runner is trusting in the people at the bus stop to do so.

In our ontology, in accordance with [4], the TRUSTEE is not necessarily a cognitive system, or an animated or autonomous agent. It can also be a lot of things we rely upon in our daily activity: rules, procedures, conventions, infrastructures, technology and artifacts in general, tools, authorities and institutions, environmental regularities, as well as different types of social systems. Based on the nature of the TRUSTEE, we have modelled two specializations of TRUST, namely SOCIAL TRUST and INSTITUTION-BASED TRUST. The former stands for the "trust in another agent as an agent" [4]. Consequently, it is externally dependent of an AGENT TRUSTEE. For example, in a social trust relation between a mother that trusts a babysitter to take care of her kids, the babysitter is the AGENT TRUSTEE. The latter builds upon the existence of shared rules, regularities, conventional practices, etc. and is related to a SOCIAL SYSTEM TRUSTEE. An example of SOCIAL SYSTEM TRUSTEE is the monetary system: in the society, individuals provide something of value in return for a token they trust to be able to use in the future to obtain something else of value, as well as they trust that the value of the instrument will be stable in terms of goods and services. A third

example, involving different types of trust, is the case of a person who buys a phone in an e-commerce platform. Here we can identify several trust relations: (i) the buyer's social trust in the seller about her delivering the phone in perfect state; (ii) the buyer's trust in the phone about it behaving as she expects; (iii) the buyer's and the seller's institution-based trust in the monetary system; (iv) the buyer's and the seller's institution-based trust in the legal system (in case of one of the parties does not fulfill its commitments); (v) the buyer's and the seller's trust in the online platform.

As shown in Fig. 1, we modeled TRUST as a complex mode composed of a TRUSTOR INTENTION, whose propositional content is a goal of the TRUSTOR, and a set of BELIEFS that inhere in the TRUSTOR and are externally dependent on the *dispositions* [15,1] that inhere in the TRUSTEE. These beliefs include: (i) the BELIEF that the TRUSTEE has the CAPABILITY to perform the desired action (CAPABILITY BELIEF); and (ii) the belief that the TRUSTEE'S VULNERABILITIES will not prevent him from performing the desired action (VULNERABILITY BELIEF). The TRUSTEE'S VULNERABILITIES and CAPABILITIES are dispositions that inhere in the TRUSTEE, which are manifested in particular situations, through the occurrence of events [15]. In this paper we adopt the interpretation of capability proposed by Azevedo et al. [1], who defined capability as the power to bring about a desired outcome.

SOCIAL TRUST is a specialization of TRUST in which the TRUSTEE is an AGENT. Therefore, this form of trust is also composed of the TRUSTOR's BELIEF that the TRUSTEE has the INTENTION to perform the desired action (INTENTION BELIEF). INSTITUTION-BASED TRUST is a specialization of TRUST in which the TRUSTEE is a SOCIAL SYSTEM. The relation INFLUENCES, holding between TRUST entities represents, as noted by Castelfranchi and Falcone [4], that "trust influences trust in several rather complex ways". McNight et al. [22] argues that INSTITUTION-BASED TRUST affects SOCIAL TRUST by making the TRUSTOR feel more comfortable about trusting others in a given situation. For example, regulations and institutions may enable people to trust each other not because they know each other personally, but because licensing, auditing, laws or governmental enforcement bodies are in place to make sure the other person is either afraid to harm them or punished if they do so. This influence may also hold in the opposite direction. SOCIAL TRUST may influence INSTITUTION-BASED TRUST by generating positive beliefs about established social systems. For example, one's trust in the local police officer may increase one's trust in the "judiciary system".

The TRUSTS relation between the TRUSTOR and the TRUSTEE is a relation that is *non-symmetric*, *non-reflexive* and *non-transitive*. An example that evinces the non-symmetry is a child that trusts her father to lift a heavy object, but the father does not trust his child to do so. However, it is possible that the father trusts the mother to take care of their kids and vice-versa. Trust is non-reflexive because an agent may or may not trust herself to perform actions. For example, an athlete may trust herself to run one kilometer in ten minutes, but not to cook a sophisticated meal. Lastly, it is non-transitive because agents might have different evaluations about the same entity's trustworthiness. For instance, it is

very well possible that Alice trusts Bob for performing certain actions and Bob trusts Charlie for performing the same actions, but it is not the case the Alice trusts Charlie to perform them.

We represent the quantitative perspective of trust by means of the TRUST DEGREE moment (*quality*) inhering in the TRUST entity. In UFO, a quality is an objectification of a property that can be directly evaluated (projected) into certain value spaces [11]. An example is a person's weight, which can be measured in kilograms or pounds. Thus, representing trust as a quality means that it can also be measured according to a given scale, such as a simple discrete scale like <Low,Medium,High> or a continuous scale (e.g. from 0.0 to 100.0).

We analyze the relation between trust and risk, based on the Common Ontology of Value and Risk (COVER) proposed by Sales et al.[27]. COVER proposes an ontological analysis of notions such as Risk, Risk Event (Threat Event, Loss Event) and Vulnerability, among others. This ontology characterizes and integrates different perspectives on risk. Given the objectives of this paper, we focus here on the perspective of risk as a chain of events that impacts on an agent's goals, which the authors named Risk Experience. Risk Experiences focus on unwanted events that have the potential of causing losses and are composed by events of two types, namely threat and loss events. A THREAT EVENT is the one with the potential of causing a loss, which might be intentional or unintentional. A THREAT EVENT might be the manifestation of a VULNERABILITY (a special type of disposition whose manifestation constitutes a loss or can potentially cause a loss from the perspective of a stakeholder). The second mandatory component of a Risk Experience is a LOSS EVENT, which necessarily impact intentions in a negative way (captured by a HURTS relation between LOSS EVENT and INTENTION) [27].

We represent the relation between trust and risk, together with its embedded concepts, in the OntoUML model depicted in Fig. 2. As part of the behavioral perspective of trust, the TRUSTOR may take some ACTIONS, motivated by her INTENTIONS and based on her TRUST in the TRUSTEE. These ACTIONS may in-
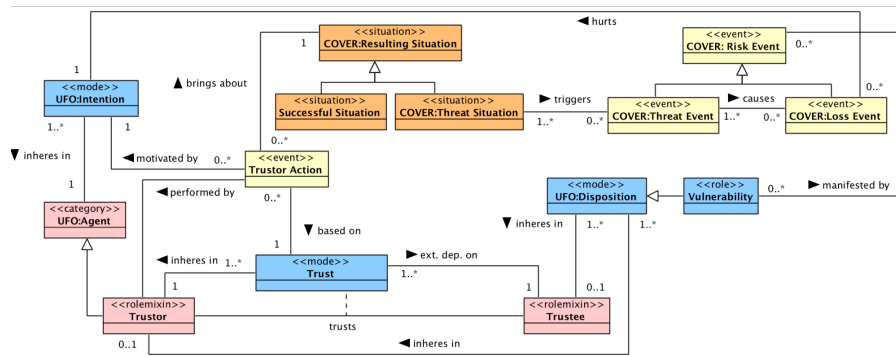

Fig. 2. Modeling the emergence of Risk from Trust relations

volve the TRUSTEE or not (some examples are cooperation, information sharing, informal agreements, decreasing controls, accepting influence, granting autonomy, and transacting business [22]), however they are taken considering that the TRUSTEE will behave according to the TRUSTOR's BELIEFS. As previous mentioned, a TRUSTOR may *trust* in a TRUSTEE but not take any ACTION based on this TRUST. For this reason, the relationship between TRUST and the TRUSTOR's ACTIONS is optional.

An ACTION performed by the TRUSTOR based on her TRUST in the TRUSTEE brings about a RESULTING SITUATION, which may satisfy her goals (and in this case it is considered a SUCCESSFUL SITUATION) or, in the worst case, may not have the desired result and the TRUSTOR will not be able to achieve her goal. In this case, the RESULTING SITUATION stands for a THREAT SITUATION that may trigger a THREAT EVENT, which may cause a loss. The LOSS EVENT is a RISK EVENT that impacts intentions in a negative way, as it hurts the TRUSTOR's INTENTIONS of reaching a specific goal.

6   Use Case Illustrations

In this section, in order to illustrate the applicability of our proposal, we apply the Reference Ontology of Trust to model two examples. First, we model an instance of social trust using the case of a working mother who trusts a babysitter to take care of her children. Then, we model an instance of institution-based trust related to the trust of a person in the monetary system.

6.1   Social Trust Example: Babysitter

In this section we take the case of a mother who trusts a babysitter, to present an example of social trust. Firstly, we illustrate, in Fig. 3, the model regarding the mental aspect of trust, which is composed of a set of beliefs. In the example, the mother has the intention of "having an adult to take care of her kids while she is out" and she trusts in a specific babysitter to do this task. Her TRUST is composed of a set of BELIEFS regarding: (i) the CAPABILITIES of the babysitter (the babysitter has experience in caring for children and is First Aid trained); (ii) the babysitter's INTENTIONS (the mother believes that the babysitter is willing to take good care of her children); and (iii) the babysitter's VULNERABILITIES (the babysitter is well and probably is not going to have health issues).

Secondly, in Fig 4, we illustrate the behavioral aspect of trust, i.e. the ACTIONS that the TRUSTOR performs relying on the behavior of the TRUSTEE. In the example, the mother believes that the babysitter is a good candidate and decides to count on her to take care of the kids. The mother arrives at a decision that is based on trust and eventually expresses her trust through an official delegation, which is the action of hiring the babysitter.

Finally, also in Fig. 4, we illustrate the emergence of risk from the trust relation. When the mother hires the babysitter, the latter commits to take care of the former's children. With the commitment of the babysitter, the mother

becomes vulnerable and may be exposed to unanticipated risks. Considering a situation in which the babysitter gets sick during the term of the employment contract, it can be considered a THREAT SITUATION that may trigger a THREAT EVENT if, for example, the babysitter does not go to work because she is no feeling well. In this case, the babysitter not going work is a THREAT EVENT that may trigger a LOSS EVENT, which would be the children getting unattended while the mother was out. This LOST EVENT hurts the mother's INTENTION of having an adult to take care of her kids while she is out.

6.2   Institution-based Trust Example: Monetary System

This section illustrates the trust of a person in the monetary system, which is a case of institution-based trust. In this example, a person has the INTENTION of "selling a house and use the money to buy an apartment" and she TRUSTS the monetary system as a protective structure, which assures that things will go well. Hinged on her INSTITUTION-BASED TRUST in the monetary system, the individual provides something of value in return for a "token" she trusts to be able to use in the future to obtain something else of value.

Fig. 5 illustrates the model regarding the mental aspect of TRUST, which is composed of a set of BELIEFS about:

(i) the CAPABILITIES of the monetary system:

- **the function of money as a medium of exchange**: related to the capability of money (which is a social object and a component of the monetary system) to function as a means of payment with a value that everyone trusts.
- **the function of money as a unit of account**: related to the capability of money to function as a standard numerical unit for the measurement of value and costs of goods, services, assets and liabilities.
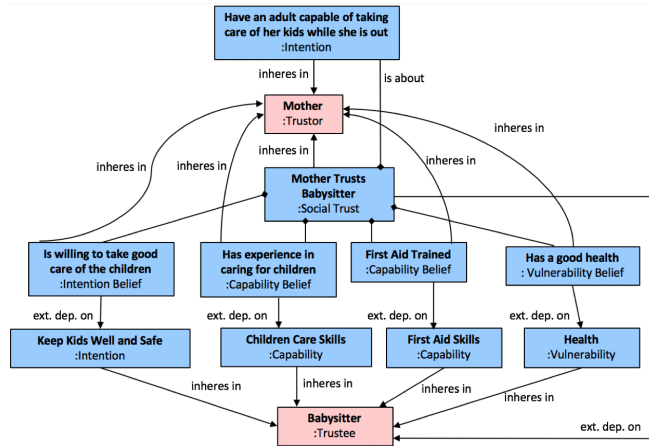

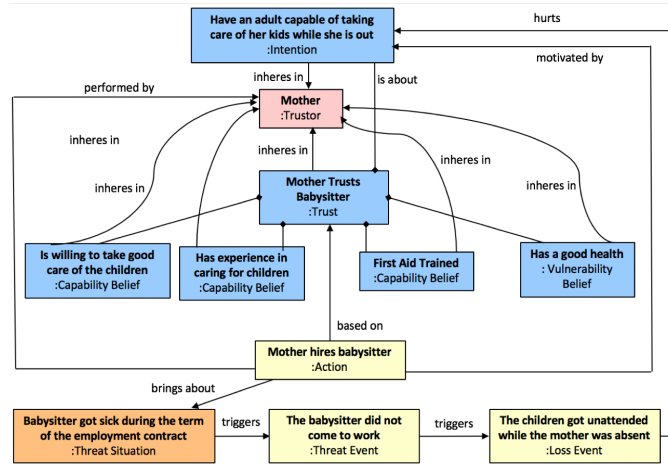**Fig. 3.** Social Trust: Mother trusts a babysitter

Fig. 4. The emergence of Risk from the Trust Relation

- **the function of money as a store of value**: related to the capability of money that allows it to be saved and retrieved in the future.

- **inflation is controlled**: related to the capability of the monetary system to have structures and mechanisms to maintain price stability and inflation control.

- **the value of money is stable**: related to the capability of the monetary system to ensure the stability of the currency's purchasing power.

(ii) the VULNERABILITIES of the monetary system:

- **economy is healthy**: related to changes in the economy that may impact the monetary system.

- **the international scenario is favorable**: related to changes in the international scenario that may impact the monetary system.

In the sequel, Fig 6 illustrates the behavioral aspect of trust, i.e. the ACTIONS that the TRUSTOR (the person) performs relying on the TRUSTEE (the monetary system). In the example, the person believes in the stability and efficiency of the monetary system and decides to sell the house to buy an apartment. The person arrives at a decision based on her INSTITUTION-BASED TRUST in the monetary system and eventually expresses her TRUST through the ACTION of selling the house.
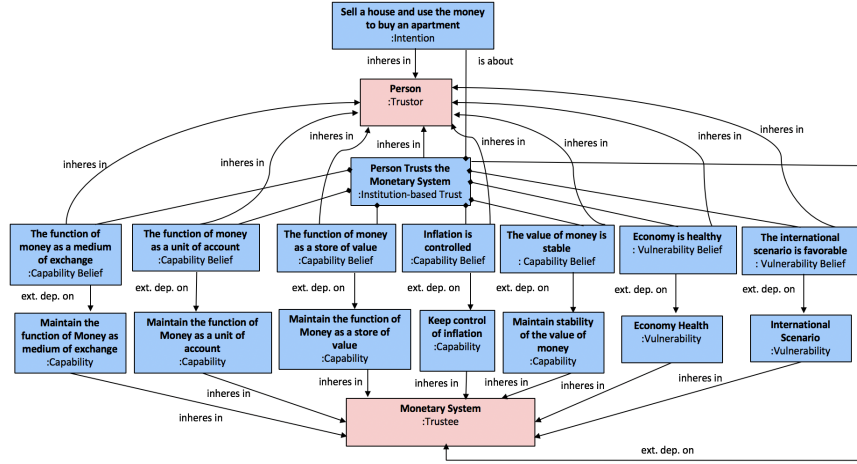
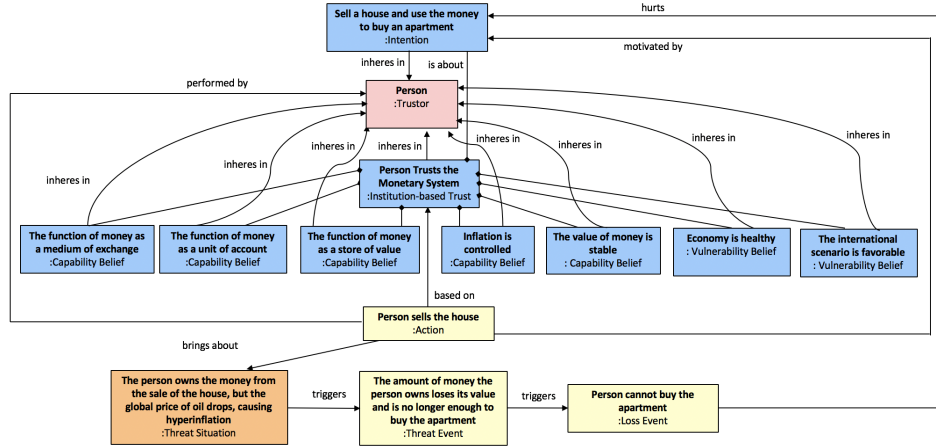**Fig. 5.** Institution-based Trust: Person trusts the monetary system

Fig. 6. The emergence of Risk from the Trust Relation

The person sells the house in exchange for an amount of money she trusts to be able to use in the future to buy an apartment. By selling the house, the person becomes vulnerable to the stability of the monetary system (which in turn has its own vulnerabilities) and may be exposed to unanticipated risks. In order to illustrate the emergence of risk, let us consider that in this example the economy is highly dependent on oil exports. Thus, the price of oil can be considered a VULNERABILITY of the monetary system regarding the international scenario. If the global price of oil falls to the point of causing a disruption in the economy, currency may lose value and the price of goods goes up. In this

case, the situation in which "the person owes a large amount of money at the time when the global price of oil drops, causing hyperinflation" can be considered a THREAT SITUATION that may trigger a THREAT EVENT if, for example, the amount of money the person owns loses its value and is no longer enough to buy the apartment. In this case, the amount of money loosing its value is a THREAT EVENT that may trigger a LOSS EVENT, which would be the person no longer being able to buy the apartment. This LOST EVENT hurts the person's INTENTION of selling the house and use the money to buy an apartment.

7 Related Work

Several trust-modeling approaches have been proposed over the years. In the context of the semantic web and social networks, most approaches focused simply on the representation of trust relations. One example is the work of Golbeck et al. [10], which proposes an extension of the Friend of a Friend (FOAF) ontology to allow users to state and represent their trust in individuals they know. Another example is the Proof Markup Language Trust Ontology (PML-T) [21], which provides an extensible set of primitives for encoding trust information associated with information sources. PML-T was created as part of the Proof Markup Language, a standard developed by the Stanford University that defines primitive concepts and relations for representing knowledge provenance [21]. It defines trust and belief relations involving a trustor, a trustee (the information source), and pieces of information. Although providing a framework for encoding trust relations, PML-T does not prescribe a way for representing trust itself.

Moreover, Dokoohaki and Matskin [6] propose a trust ontology for the design of trust networks on semantic web-driven social systems. The main component of their ontology is the trust relation that represents the connection between entities on the network. Every relation has a set of main properties that describe its nature and purpose, such as a topic and a value that represents the trust level. The authors also define a set of auxiliary properties for the trust relation, such as a goal that stands for the reason for establishing the relation and a recommender, which is a person on the network that has recommended the trustee. Furthermore, the relation between trust and risk is not mentioned. An important difference between these ontologies and our proposal is that they are not based on foundational ontologies, but are built on semantic web languages that give precedence to computational tractability over expressiveness. As discussed in [12], a number of semantic interoperability problems that cannot be handled by semantic web languages, such as OWL and RDF, as their expressivity is purposefully limited so that they remain computationally tractable.

Huang and Fox [17] proposed a logical theory of trust in the form of an ontology that gives formal and explicit specification for the semantics of trust. The authors define two types of trust, namely, trust in belief and trust in performance. In the former, the trustor believes that something the trustee believes is true (for example: Mary wants to order a product and her friend John suggests she buys it from an online store he believes always delivers the orders on time.

Mary does not know the online store at the time, but she believes what John believes, which is that the store delivers the orders on time). In the latter, the trustor believes in a piece of information created by the trustee or in the performance of an action committed by the trustee, both in a context within the trustor's context of trust. These two types refer to the general form of trust. The institution-based trust is not represented in Huang and Fox's ontology [17] nor is the relation between trust and risk.

Viljanen [30] surveyed and classified thirteen computational trust models to create an ontology of trust. In his proposal, trust is represented as a relation between a trustor and a trustee, which depends on the action that the trustor is attempting and on the competence of the trustee. Additionally, Viljanen defines an element of confidence attached to the trust relationship, as well as a set of third party opinions in the form of reputation information. The author uses the concept of business value to represent both value and risk associated to the trustor's action. By attaching business values to the action, the ontology is able to represent the potential impact, positive or negative, of the action that the trustor is attempting. However, the representation of the relation between trust and risk lacks a more detailed description. For example, the ontology does not make it explicit how risk events are triggered, nor how they affect the trustor.

Secure Tropos [9] is a security-oriented extension of the agent-oriented software development methodology Tropos [3] that adds both security and trust as part of the software development process. In Secure Tropos the concepts of trust and delegation are combined to represent dependence relations between agents. Their constructs for trust refer to existent trustworthiness between actors along trust relations rather than specify the nature of the concept of trust. Secure Tropos differs from our approach not only regarding this particularity, but also because it does not represent the close relation between trust and risk. Moreover, although supporting a role-based approach to trust [9], in which the trustee is represented by roles or positions rather than by individual agents, it does not address explicitly the notion of institution-based trust.

In [4], Castelfranchi and Falcone investigate what kind of beliefs and goals are necessary for trust to formulate several necessary conditions, such as the trustor having a goal and the belief that the trustee is competent and willing to achieve this goal. Moreover, the authors consider a behavioral aspect of trust, which is related to the notion of acting on trust. In our proposal we rely largely on their theory to formalize the general concept of trust, as well as the concept of social trust. As for the institution-based trust, Castelfranchi and Falcone [4] state that it "builds upon the existence of shared rules, regularities, conventional practices, etc. and relies on this, in an automatic, non-explicit, mindless way", however the authors do not formalize this aspect of trust. Likewise, the relation between trust and risk is emphasized in their theory, but is not formalized.

Table 1 summarizes some important aspects of our *Reference Ontology of Trust* and compare them to the other trust ontologies discussed in this section, such as : (i) the scope of the analysis of the trust concept; (ii) the types of

Table 1. The Reference Ontology of Trust and related trust ontologies

Ontology	Scope	Trust Types	Relation to Risk	Modeling Language	Foundational Ontology
Reference Ontology of Trust	Analyzes the nature of the concept of trust and trust relations.	General trust, social trust, and institution-based trust.	Models the emergence of risk from trust relations.	OntoUML	UFO
Golbeck et al. [10]	Analyze the existence of trust relations between two agents.	General trust	- - -	RDF/OWL	- - -
PML-T [21]	Analyzes the existence of trust and belief relations between agents and information sources.	General trust	- - -	RDF/OWL	- - -
Dokoohaki and Matskin [6]	Analyze trust relations and some properties about them.	General trust	- - -	RDF/OWL	- - -
Huang and Fox [17]	Analyze the nature of the concept of trust and trust relations.	General trust	- - -	Situation calculus	- - -
Viljanen [30]	Analyzes the nature of the concept of trust and trust relations.	General trust	Relates risk to actions on trusting, but does not detail how it emerges.	UML	- - -
Secure Tropos [9]	Refers to existent trustworthiness between actors along trust relations.	Socio-technical trust	- - -	Datalog	- - -
Castelfranchi and Falcone [4]	Analyze the nature of the concept of trust and trust relations.	Social trust (institution-based is only mentioned)	Emphasizes the relation between trust and risk, but does not model it.	First-order Logic	- - -

trust modeled; (iii) the relation between trust and risk; (v) the language used to represent the ontology; and (vi) the ontological foundations adopted.

8   Final Remarks

In this paper, we presented an initial proposal for a Reference Ontology of Trust. We first investigated the ontological nature of trust and formalized its general concept in an OntoUML model. This investigation lead to the identification and the formal characterization of two types of trust, namely social trust and institution-based trust. We also presented a description of our view of social system as it is an essential concept for the modeling of institution-based trust. Lastly, we leverage the analysis of the behavioral aspect of trust to explain the emergence of risk from trust relations.

As a next direction, we plan to further validate our ontology and expand our analysis to explain the factors that affect trust assessment, both under the perspective of the trustor and to the perspective of the trustee. We also plan to use the presented ontology to analyze and redesign existing modelling languages (e.g. Archimate) to enable them to consistently describe trust assessment.

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