

# Ontological Foundations for Trust Management: Extending the Reference Ontology of Trust

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**Abstract.** In this paper, we provide a semantic foundation for trust-related concepts in the light of trust management. We extend our previous work, the Reference Ontology of Trust, to clarify and provide a deeper account of some building blocks of trust, such as beliefs and intentions of a trustor, pieces of evidence that indicate that a trustee is trustworthy (or not), as well as the many factors that influence trust. We illustrate our proposal by instantiating and discussing people's trust in vaccines in the time of COVID-19.

**Keywords:** Trust Management · Ontological Analysis · OntoUML.

## 1 Introduction

Trust is about relationships. It is about accepting to be vulnerable to the behavior of others in order to achieve our objectives. A trust relation requires two entities, and can therefore be seen from their two perspectives. The relying agent, the *trustor*, is interested in assessing the trustworthiness of a *trustee*, as correctly as possible. The trustee is interested in identifying what makes it trustworthy, possibly identifying what it could change to increase trust levels, as well as the key capabilities it needs to guarantee well-placed trust. From the trustee's perspective, as important as gaining trust is having the ability to maintain it. Trust may break in an instant or erode gradually. Therefore, it is important to build *sustainable trust* that cannot be easily lost. But how can one manage trust? What makes one trustworthy? And what factors can influence trust? Although a proper conceptualization is fundamental to efficiently manage trust, there is no consensus on a definition of trust in literature [28,33].

In a previous effort [4], we proposed the Reference Ontology of Trust, an ontologically well-grounded reference model that formally characterizes the concept of trust, as well as clarifies the relation between trust and risk, and represents how risk emerges from trust relations. This paper sheds new light on trust-related concepts and relations under the perspective of trust management [18,29]. We extend our previous work to clarify and provide a deeper account of (i) the factors that influence trust, (ii) the complexity of the intentions of a trustor (iii) the pieces of evidence that indicate that a trustee is trustworthy (or not), and (iv) the quantitative perspective of trust.

The remainder of this paper is organized as follows. In Section 2, we introduce the reader to the Reference Ontology of Trust. Then, in Section 3 we present our proposal for extending this ontology. In Section 4, to demonstrate the contribution of our proposal to the modeling practice, we apply it to model an example about vaccines in the time of COVID-19. We conclude the paper in Section 5 with some final considerations.

## 2 The Reference Ontology of Trust (ROT)

The Reference Ontology of Trust<sup>1</sup> (ROT) is a reference model, grounded on the Unified Foundational Ontology (UFO) [11,13], that formally characterizes the concept of trust and represents how risk emerges from trust relations [4]. Some of its main ontological commitments on the nature of trust are listed below:

- **Trust is relative to intentions [5].** An agent, the *trustor*, trusts an individual, the *trustee*, only relative to a certain intention, for the achievement of which she counts upon it.
- **Trust is grounded on beliefs [5].** If we trust an individual, we believe that it can do certain things, that its environment will not prevent it from doing them, and, if it has agency, that it wants to do those things.
- **Trust can be quantified [6].** Our trust in a certain individual can increase or decrease in time, and we can trust certain individuals more than others. To account for these scenarios, ROT assumes that trust can be quantified, even if it does not commit to any particular scale or measurement strategy.
- **A trustee does not need agency [5].** The necessary condition for a trustee is that it is an entity capable of having a (hopefully positive) impact on our intentions by the outcome of its behavior. Thus, a trustee may be an agent (e.g. a person, an animal, an organization) or an object (e.g. a car, a vaccine)

Figure 1<sup>2</sup> depicts a ROT excerpt, which is represented in OntoUML, an ontology-driven conceptual modeling language based in the Unified Foundational Ontology [11]. In ROT, Trust is modelled as a complex mode (an externally dependent entity, which can only exist by inhering in other individuals [11]) composed of an Intention and a set of Beliefs that inhere in the Trustor and are externally dependent on the Trustee and on Dispositions [14] that are expected to inhere in the Trustee. These beliefs include: (i) Capability Belief: a Belief that a Trustee has a Capability required to exhibit a certain behavior; and (ii) Vulnerability Belief: a Belief that the Trustee's Vulnerabilities will not prevent her from exhibiting a desired behavior. When the role of Trustee is played by an Agent, Trust is also composed of Intention Beliefs, namely a Trustor's belief that an Agent Trustee has an Intention to perform the desired action.

<sup>1</sup> The complete version of ROT in OntoUML and its implementation in OWL are available at <http://purl.org/krdb-core/trust-ontology>.

<sup>2</sup> We adopt the following color coding in the OntoUML diagrams: substantials are represented in pink, qualities in blue, relators and extrinsic-modes in green, events in yellow, and classes whose instances might be of different ontological nature in gray.

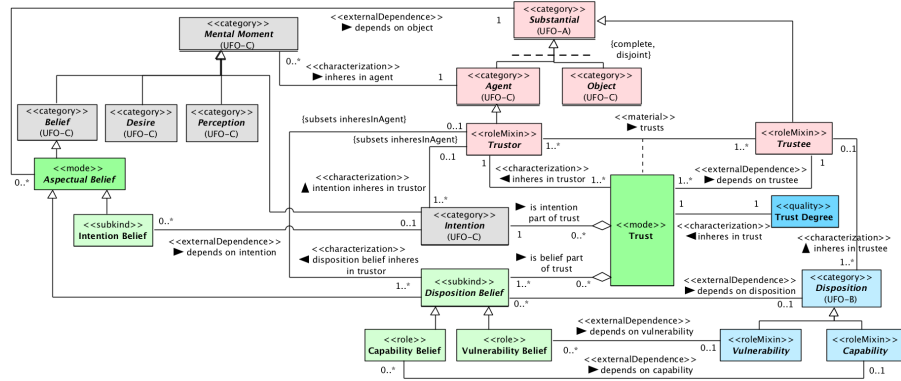


Fig. 1: The Reference Ontology of Trust

### 3 Extending the Reference Ontology of Trust

#### 3.1 Detailing Intentions

Trust is always about an intention of the trustor, for the achievement of which she counts upon the trustee. Such an intention is not always atomic. For instance, consider the following trust relation “Mary trusts her doctor to diagnose a disease she may have”. In this case, trust is about an atomic intention of the trustor, namely “having a disease diagnosed”. Differently, in the trust relation “Bob trusts a certain airline to take him on his holiday trip comfortably and safely”, trust is about a complex intention, composed of (i) Bob’s intention of traveling; (ii) his intention of being safe; and (iii) his intention of being comfortable. Let us now consider a situation in which Mary trusts an application provider for collecting her location data, except when she is in sensitive places such as a cancer treatment center for her medical treatment, since such information may lead to disclosing her disease. In this example, trust is also about a complex intention, composed of (i) Mary’s intention of having her location data collected; (ii) Mary’s intention of not having her diseased disclosed to others; and (iii) Mary’s intention of preserving her location privacy when she is in sensitive places.

We have extended the Reference Ontology of Trust to support the representation of complex intentions. As depicted in Figure 2, Trust is related to an intention of the Trustor, which can be atomic or complex. While atomic intentions have no proper parts, complex intentions are aggregations of at least two disjoint intentions.

#### 3.2 Quantifying Beliefs

According to ROT, trust is a complex mental state of a trustor regarding a trustee and her behavior, which is composed of an intention of the trustor and a set of her beliefs about dispositions that inhere in the trustee. In general, a trustor’s beliefs on a trustee’s dispositions are not black and white, in the sense that a trustor needs to believe that a trustee either has a certain disposition or not. In fact, they have an intrinsic quality that

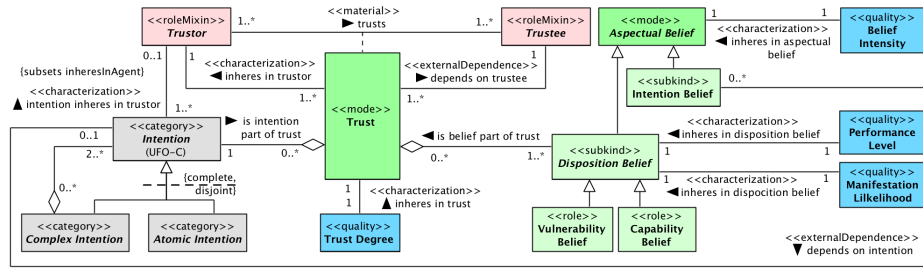


Fig. 2: ROT - Intention and Belief extensions

corresponds to the strength of a trustor’s belief [16]. For instance, it may be the case that “Alice believes more strongly that Burger King is capable of making a good hamburger than it is capable of delivering orders on time”. Another example, which considers the same capability and different trustees, is “people believe more strongly that an adult is capable of lifting a heavy object than a child”. Note that in this case, we are not comparing the performance of an adult with that of a child when lifting a heavy object, because the child may not even be able to lift it. Nevertheless, performance levels are an important aspect to be considered with respect to capability beliefs. For example, a project manager may believe that both a junior and a senior analysts are capable of performing a particular task. However, he probably believes that the senior analyst is able to perform the task with a higher level of performance than the junior analyst. In [5] Castelfranchi and Falcone claim that the degree of trust is a function of (i) the estimated quantitative level of the trustee’s quality on which the positive expectation is based and (ii) how much the trustor is sure of her evaluation about the trustee’s quality. In our approach, the belief intensity and the performance level are analogous to, respectively, (ii) and (i) in Castelfranchi and Falcone’s proposal [5].

Finally, another important aspect to be considered, related to beliefs about trustee’s dispositions, is how strongly the trustor believes a disposition may be manifested through the occurrence of certain events. For example: “although Charlie believes that he can get a flat tire during a trip (which corresponds to a vulnerability belief about his car), he believes that the likelihood of this happening is very small”.

Note that the very same disposition may play the role of a capability, a vulnerability, or even a threat capability<sup>3</sup>. For example, in the scope of military operations, information can be seen both as a capability (as digital data and networks support and facilitate the achievement of military objectives) and a vulnerability (as confidential information can be disclosed as a consequence of a cyber-attack). For this reason, both capabilities and vulnerabilities are represented as roles of dispositions (Figure 1).

Based on these considerations, we propose that the above-mentioned measures (belief intensity, performance level, and manifestation likelihood) be considered when quantifying trust. To account for this quantitative perspective of disposition beliefs, we

<sup>3</sup> Capabilities are usually perceived as beneficial, as they enable the manifestation of events desired by an agent. However, when the manifestation of a capability enables undesired events that threaten an agent’s abilities to achieve a goal, it can be seen as a threat capability [30].

have extended ROT to include these three belief-related measures (Figure 2), representing them as qualities<sup>4</sup> that inhere in aspectual (belief intensity) and disposition beliefs (performance level and manifestation likelihood). This means that they can be mapped into quality spaces, such as a discrete scale like <Low,Medium,High> or a continuous one like <0-100> [1,7,19].

### 3.3 Dispositional Evidence

It is generally accepted in the literature that by trusting, the trustor accepts to become vulnerable to the trustee, based on the expectation that the latter will perform a particular action or exhibit a particular behavior important to the trustor [20,28,5]. Therefore, it is probably that the trustor only decides to make herself vulnerable if she has reasons to believe that the trustee is *trustworthy*.

Riegelsberger et al. [27] discuss the importance of signaling the existence of trust-warranting properties and providing evidence of trustworthy behavior of the trustee. In a previous work [2], we have proposed the modeling of trust-warranting signals that should be emitted by the trustee in order to ensure trustworthy behavior and promote well-placed trust. In this paper, we leverage this analysis to explore a broader view on the factors that indicate that the trustee is capable of successfully realizing the capabilities and prevent the manifestation of the vulnerabilities, which we name here *dispositional evidence* (in line with Vinkovits et al. [32]). Examples of dispositional evidences are certifications by trusted third parties (e.g. Mary has a TOEFL certification. This makes me believe that she can speak English, because I trust the certificate issuing authority); trustee's credentials (degrees, accreditations, awards) that suggests the trustee is doing a good job and the like; history of performance (e.g. number of accurate diagnosis issued by a medical diagnosis system); information on the trustee track record (such as reviews from service recipients and statistics on its experience); recommendations (e.g. my brother trusts a car mechanic and recommends his services to me); reputation records (e.g. the number of positive evaluations received by an Uber driver); reliability (e.g. a doctor who has a history of delivering reliable healthcare services to its patients); availability (e.g. a medical doctor you rarely succeed to make an appointment with is not trustworthy); past successful experiences (e.g. for all the purchases I made at Amazon the products arrived on time and in perfect conditions); transparency (e.g. offering information on what a software system is doing, as well as rationale for its decisions (aka explainability)); longevity (e.g. indications that a vendor has been in the market for a long time and that it is interested in continued business relationship with the client); presence of risk mitigation measures (which indicates that measures have been taken in order to prevent the manifestation of the vulnerabilities), among others.

Ontologically speaking, Dispositional Evidences are *social entities*, typically *social relators* (e.g. a relator binding the certifying entity, the certified entity and referring to a capability, vulnerability, etc.), but also documents (*social objects* themselves)

<sup>4</sup> In UFO, a quality is an objectification of a property that can be directly evaluated (projected) into certain value spaces [11]. Common examples include a person's weight, which can be measured in kilograms or pounds, and the color of a flower, which can be specified in the RGB or HSV color models.

that represent these *social entities* (e.g., in the way a marriage certificate documents a marriage as a social relator). As illustrated in Figure 3 we extended ROT to model Dispositional Evidences as roles played by *endurants* (objects, relators, etc.) related to a Disposition of a Trustee.

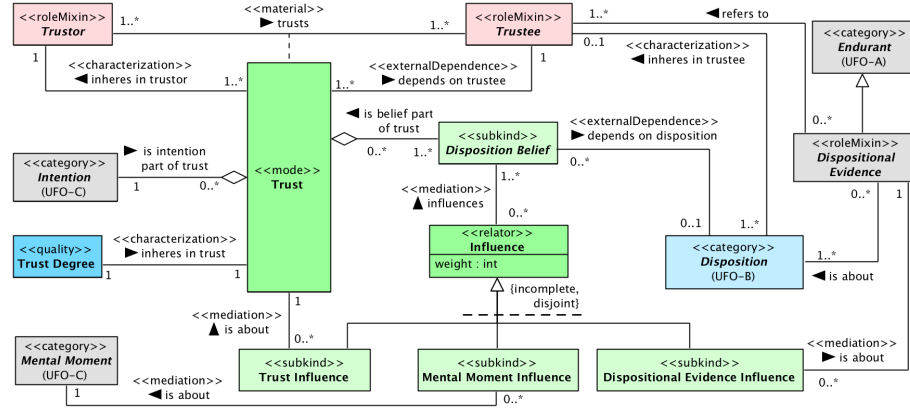


Fig. 3: ROT - Trustworthiness Evidence and Influence Extensions

### 3.4 The Role of Influences

We previously mentioned that trust is composed of a trustor’s intention and a set of her beliefs about the trustee and her behavior. However, several other factors that influence the formation of trust are often discussed in the literature. For instance, Mayer et al. [20] present a review of factors that lead to trust, while Castelfranchi and Falcone [5] argue that “trust changes with experience, with the modification of the different sources it is based on, with the emotional or rational state of the trustor, with the modification of the environment in which the trustee is supposed to perform, and so on”. According to them, as trust depends on dynamic phenomena, it is itself a dynamic entity. Here, we rely on the ontological nature of the sources of influence to propose a set of categories to classify the many factors that can affect a trustor’s beliefs about a trustee’s dispositions and, consequently, influence trust. We distinguish the sources of influence between (i) other trust relationships, (ii) mental moments, and (iii) dispositional evidence, explained as follows.

**Trust Influence.** This category represents the situation in which trust is influenced by the existence of another trust relationship. According to Castelfranchi and Falconi [5] “in the same situation trust is influenced by trust in several rather complex ways”. In [8] the authors also discuss “how trust creates a reciprocal trust” and “how A’s trusting B can influence C trusting B or D, and so on”. In fact, countless examples can be found in real life about trust influencing trust, either positively or negatively. In a previous paper, [3] we discussed the case of a recent study published in The Lancet journal [24], which relied on data gathered by a US healthcare analytics company to report issues on the efficacy and safety of hydroxychloroquine for treating COVID-19. When the study was

first published, it prompted the WHO along with several countries to pause trials on this drug. However, this very study was retracted [25] a few days later (and the clinical trials resumed), as concerns were raised with respect to the veracity of the data. In this example, we have that: as (1) “WHO trusts The Lancet” and (2) “The Lancet trusts the Publication Authors”, consequently, to some extent (3) “WHO trusts the Publication Authors”, and in this case both (1) and (2) positively influences (3). In [17] Josang et al. mention examples of trust influence observed among animals: “when bees signal to each other where to find pollen, the other bees can derive trust in a specific pollen harvesting area; when animals give warnings about danger, it can be interpreted as a recommendation about distrust, as in the case of a presence of potential predator”.

**Mental Moment Influence.** This category represents situations in which trust is influenced by *mental moments* (a concept from UFO). In UFO, agents can bear special types of modes (aspects, features, characteristics, objectified properties) named *intrinsic moments*. *Mental moment* is a special type of intrinsic moment that is existentially dependent on a particular agent, being an inseparable part of its mental state (Figure 1). Examples of mental moments include perceptions, beliefs, desires and intentions (internal commitments). Perception is a relevant concept to express the relation of agents to events sensed from the environment and from other agents [15]. Belief regards information the agent has about the environment and about other agents. The propositional content of a belief is what an agent holds as true (e.g., one’s belief that 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 (e.g., Mary’s intention of going to Paris to see the Eiffel Tower). For an extensive discussion of mental moments, please refer to [12].

Mental moments can play an important role in influencing trust. Let us consider the example of a person who desires to travel on the next summer break and receives an email containing an amazing offer for an exceptional and hard to refuse destination that expires in a short period of time which she can’t miss. Although it might look like a travel scam, the person’s desire to travel may influence her to trust the email offer. Internal commitments may also influence one’s trust. For instance, people strongly committed to environmental preservation tend to trust companies that support environmental sustainability. There is also the case of trustor’s beliefs, not related to the trustee’s dispositions, which can influence trust. Examples are some religious beliefs, which prescribe honesty and mutual love [21], leading people to assume general others are usually honest, benevolent, competent, and predictable [22].

Another important aspect is the occurrence of events that can affect the trustor’s perception regarding a particular trustee. In [23] McKnight et al. discuss how trust changes in response to external events and propose a model that addresses the mental mechanisms people use as they are confronted by trust-related events, which “indicates that trust may be sticky or resistant to change, but that change can and will occur” [23]. According to Castelfranchi and Falconi [9], the success of an action performed by the trustee in order to reach a goal of the trustor depends not only on the trustee’s capabilities but also on external conditions that allow or inhibit the realization of the task. To illustrate this, the authors mention the case of a violinist that has to do the concert

in an open environment and the weather conditions are particularly bad (very cold). In general, people trust the violinist to play a good performance, but their trust level may decrease due to the bad weather, as people may infer that these conditions can modify his specific hand abilities and his performance. Similarly, in financial systems, the arrival of bad news about a financial agent can lead others to lose confidence in it, which in turn can spread across the entire system.

**Dispositional Evidence Influence.** This category represents the situation in which trust is influenced by dispositional evidences. As aforementioned, dispositional evidences are related to dispositions of the trustee, such as certificates, history of performance, recommendations, reputation records, past successful experiences, among others, which can influence the trustor’s beliefs about the trustee and, consequently, influence trust.

As illustrated in Figure 3, in order to represent the role of influences, we extended ROT to include the *Influence* relator, which connects the sources of influence to the disposition beliefs of the trustor under their influence. We distinguish *Influence* according to the source of influence into: (i) *Trust Influence*, associated to a *Trust* relationship; (ii) *Mental Moment Influence*, associated to a *Mental Moment*; and (iii) *Dispositional Evidence Influence*, associated to a *Dispositional Evidence*. The property weight corresponds to the weight of an influence over a particular belief, as certain influences may weight more heavily than others.

#### 4 The Case of Vaccines in the Time of COVID-19

According to the World Health Organization (WHO), there are currently more than 50 COVID-19 vaccine candidates in trials [34]. Naturally, each of them may present differences when it comes to efficacy. A study found that Pfizer-BioNTech vaccine efficacy was 52% after the first dose and 95% after the second [26]. This stands for a dispositional evidence that can positively influence people’s trust in the vaccine (a dispositional evidence influence), as it can lead people to believe that Pfizer-BioNTech vaccine is capable of protecting from COVID-19 (capability belief) with a high performance level. Let us suppose that another study shows that the efficacy of a second candidate is lower. This is a dispositional evidence that may lead people to believe that the performance level of the second candidate’s capability of protecting from COVID-19 is lower than Pfizer-BioNTech’s. Consequently people’s trust degree will be higher in their trust relationship with Pfizer than in their trust relationship with the second candidate. Considering that Pfizer and BioNTech are, respectively, from the USA and Germany, it is possible that citizens of these two countries have more trust in the Pfizer-BioNTech vaccine than in the ones produced by pharmaceutical companies from other countries. That is because people’s trust in the science and technology capacity of a particular country positively influences their trust in the pharmaceutical companies from that country (a trust influence).

Now let us consider the case of two friends, Tom and Jerry (trustors), who trust Pfizer-BioNTech COVID-19 vaccine (trustee) with different trust degrees. They trust the vaccine to safely protect them from COVID-19. Note that their trust is about a complex intention, composed of (i) the intention of being protected from getting



COVID-19; and (ii) the intention of not experiencing side effects from the vaccine. Tom does not have any health issues. He strongly believes (belief intensity) that the vaccine can protect him from COVID-19 (a capability belief) and that its side effects (a threat capability) will not harm him (a capability belief). Jerry is allergic. His trust degree in the vaccine is lower than Tom's, as he believes that there is a small likelihood (manifestation likelihood) that the side effects (a threat capability) will harm him (a capability belief). Unfortunately, Jerry saw on the news that three Alaska health care workers had an allergic reaction after receiving a dose of the new Pfizer COVID-19 vaccine [10]. His perception about this event negatively influenced his trust in the vaccine (a mental moment influence), as he started to believe that there is a high likelihood (manifestation likelihood) that the vaccine side effects will harm him. Conversely, people been vaccinated around the world and reporting just mild side effects are events that can be perceived by people in a positive way and consequently, positively influence people's trust in the vaccine (a mental moment influence). Hopefully, in Jerry's case, the influence weight of "people having just mild side effects" will be higher than the influence weight of the news about "the Alaska health care workers having allergic reactions". If we consider the case of people who opposes vaccines, their anti-vaccination beliefs (a mental moment) negatively influence their trust in a COVID-19 vaccine (a mental moment influence).

Finally, the US President-elect Joe Biden receiving the first dose of COVID-19 vaccine on live television and stating that "I'm doing this to demonstrate that people should be prepared when it's available to take the vaccine" [31] is an event that can be perceived by people in a positive way, thus positively influencing people's trust in the vaccine (a mental moment influence).

## 5 Final Remarks

In this paper, we conducted an ontological analysis to investigate the proper representation of the factors that influence trust as well as other trust-related concepts, such as beliefs and intentions of a trustor and pieces of evidence that indicate a trustee's trustworthiness. Additionally, we provided an ontological account for the quantitative perspective of a trustor's beliefs. To demonstrate the applicability of our proposal, we instantiated our ontology with an example in the context of COVID-19 vaccines. As future work, we plan to use our ontology as a foundation for designing a modeling framework that allows for the quantification and reasoning about trust and trustworthiness.

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