Context-aware Trustworthiness Evaluation with Indirect Knowledge

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Abstract. Commonly, when a Trustor evaluates a Trustee's trustworthiness, it is assumed that the evaluation is based on information directly available to the Trustor. This can concern for example the reputation and recommendations characterizing the Trustee. In cases of context-aware trust, this is further restricted by concentrating mainly on information in a similar enough context as is effective at trust evaluation time. However, this information is not necessarily available to the Trustor. Surprisingly, in such scenarios the literature suggests either to wait for someone else to collect the needed experience, or to trust blindly. In this paper, we discuss solutions that help the Trustor to conduct its evaluation even if direct knowledge about the Trustee is lacking. We approach this by allowing the Trustor to make use of networks connecting the Trustor and the Trustee, as well as the context information characterizing the entities appearing in these networks.

1 Introduction

Trust is an increasingly important phenomenon to grasp and support in open environments, such as the Internet, where participants are not necessarily in direct contact with each other. A common scenario is that a the subject of trust (Trustor) is searching for a service or a product (Trustee) for a certain purpose. Semi-automatic trustworthiness evaluation is of special relevance on the Semantic Web, where Trustors can be software agents in addition to human beings, and Trustees are software agents or web pages carrying information for Trustors to depend on. To perform an appropriate evaluation, Trustors request Trustees' credentials, often expressed in terms of profiles, reputation descriptions, and recommendations (cf. [1]). The difference between reputation and recommendation is that reputation is based on the Trustor's personal experiences, whereas recommendations are communicated experiences of others.

Context-awareness is also an emerging computer science trend, which takes situational details into account. Generally, in computer science context refers to any information characterizing the situation of any entities considered relevant to the interaction between a user and an application, including the user and the application themselves, as well as their surroundings [2, 3]. Note that since we are operating in environments where the entities are often software programs, it is relevant to consider their context too [4]. In the scope of the Semantic Web, one important task where the notion of context can assist is aggregation, that is, the activity of integrating data or information from multiple sources [5]. In our work aggregation is not so much directed to the semantics of descriptions characterizing various entities, but rather to combining the trustworthiness values of these entities.

Many research efforts in addition to ours also acknowledge that context information may help to define trust credentials (cf. [6, 7, 8]). In [9], we discuss context-aware trust functions; as relevant credentials, we identified the quality attributes of a Trustee, the context attributes (of the Trustee, Trustor, and the surrounding environment), the Trustee's reputation in the eye of the Trustor, as well as recommendations about the Trustee put forward by others.

Trust management frameworks operate under the assumption that the Trustor can directly access the information he requires to complete the trustworthiness evaluation [10]. In the global computing paradigm this assumption seems sometimes too optimistic. Trustee's credentials may not be available (e.g., when a new service is deployed, or when this information is protected by privacy policies), or reputation data and recommendations may refer to Trustee's behavior in contexts which are too different from the present one for them to be of use.

In this paper, we study context-aware trust establishment by considering scenarios where direct information about the Trustee is not necessarily available to the Trustor. We claim that even in such situations there are better options for Trustors to choose from than to trust/distrust blindly. For example, the Trustor can evaluate the trustworthiness of another entity somehow related to the Trustee. In many real situations humans act like this. We trust a car manufactured in a certain country, if our previous experiences with cars manufactured in that particular country are good, even if we have no experiences of that particular make. In many cases this kind of indirect evaluation suffices to accomplish a fair judgment to start with.

The particular cases we consider are the following : (i) Trustee's behavior *across contexts* is unknown to the Trustor, meaning that the Trustor has no previous knowledge of any behavior of the Trustee; (ii) Trustee's behavior in the *current context* is unknown to the Trustor, meaning that the Trustor might know the Trustee, but not how the Trustee behaves in the current context; (iii) Trustee's *recommender* and/or *recommendations* are unknown or unaccessible to the Trustor. Cases (i) and (ii) are targeted to reputation information, as they are dependent on the Trustor's knowledge and opinions on past states-of-affairs. Case (iii) relies on recommendations available to the Trustor, although the mechanisms to be considered in terms of (i) and (ii) could be plugged in it too. Note that we consider the context to be fully observable [11] to the Trustor, meaning that there is access to all relevant contextual information characterizing the Trustee, the environment, as well as the Trustor. In addition, we assume that the Trustee's quality attributes are also available to the Trustor, meaning that we do not tackle the problem of indirect quality attribute information, albeit it could follow the same lines of investigation.

The rest of the paper is organized as follows. In Section 2, we present some relevant related work. In order to pinpoint the contribution of this paper, in Section 3 we then present the baseline case where there is complete and direct information influencing trustworthiness evaluation available. We also formalize operational semantics for the trustworthiness evaluation process; it will help us later on to discuss the changes in the trustworthiness evaluation process when only indirect information is available. In Section 4, we delve into the scenarios where the Trustor has little or no reputation knowledge about the Trustee. Section 5 considers the case where recommender is not known to the Trustor. Finally, Section 6 concludes the paper and outlines some future work.

2 Related Work

The interaction between trust and context has attracted the attention of researchers only recently, and from different perspectives. In the Web Services domain, for example, context is used to anonymize the authentication procedure [12], or to decide whether granting the access to distributed resources [13, 4]. Here, differently from our approach, context is not used to evaluate the degree of users' trustworthiness. Instead, users' credentials are assumed to originate from trusted certification authorities and, together with the context, it is checked to satisfy the access conditions.

In [14], the authors use context in conjunction with content to label Semantic Web data. Only trustful (vs. merely known or untrustful) data satisfies the user-defined trust policies and is recognized by web consumers. We do not discern between trusted and merely known data in an a-priori fashion, but instead rely on recommendations and reputations to smooth out the negative effect of potentially malicious information in the evaluation process.

The problem of inferring trust from recommendations has appeared in the literature for a long time. Yahalom *et al.* [15] were one of the first to separate direct trust from recommendation-based trust and to propose an algorithm to derive new trust values given a graph of trust relationships. In [16], Beth *et al.* quantify trust, both direct and recommendation-based, as probability of the Trustee to behave as expected, and as a degree of similarity between Trustor's and recommenders' respective experiences with the Trustee. Subsequent solutions are, synthetically, extensions of the previous approaches. For example, Subjective Logic's (SL) opinions are used to model the degree of trust as well as the degree of distrust and uncertainty [17]. Alternatively, SL can be used to aggregate trust across different recommendation paths and to concatenate trust along recommendation chains [18].

Richardson *et al.* explicitly address belief composition in the Semantic Web domain [19]. They suggest software agents to maintain a table where to store their friends' beliefs as a group of statements (directed to Semantic Web data) and the agents' personal trust in their friends. The belief in unknown statements is derived though iterative merging of beliefs along paths of trust. In that work, differently from ours, there is no distinction between trust on an entity's opinion (direct trust) and trust on an entity in recommending someone else's opinion (recommendation, or referral, trust). Also, the notion of context is not visible in that work.

O'Hara *et al.* analyze costs and benefits in different paradigms (optimism, pessimism, centralized, investigation, and transitivity) of dealing with trust in Semantic Web [20]. They also identify the challenges that have motivated our research. First of all, trust must be subjective and distributed, and it also needs to be combined with personal experiences of agents. Secondly, trust should approached as context-dependent, and it needs a bootstrap procedure when there are not enough transactions to make firm judgments. Our proposal of using indirect information is an attempted answer to the bootstrap problem. It must be emphasized that existing approaches to trust management are able to deal with incomplete knowledge and uncertainty (cf. [21, 22]), but they resort mainly on the existence of recommendations. This would be impossible in case of a completely new Trustee, for example. In this paper, we argue that a Trustor can benefit from indirect sources to bring the trustworthiness evaluation to a start, and we propose methods for doing it.

3 Baseline: Direct Information Available to the Trustor

This section summarizes the formal definitions of context-aware trust evaluation functions we introduced in [9]. Additionally, it introduces and discusses an abstract operational semantics for the trustworthiness evaluation process. The operational semantics show the dynamics of the trustworthiness evaluation process when the Trustor has direct access to information characterizing the Trustee. Sections 4 and 5, which capture the main contribution of this paper, will show how this dynamics changes in reaction to using indirect knowledge.

3.1 From Context-independent to Context-aware Trust Evaluation Functions

In [9] we formalized a *context-independent* trust evaluation function as follows:

$$\mathtt{trust}_{A,\sigma} : \mathtt{Quality} \times \mathtt{TValues} \times 2^{\mathtt{TValues}} \rightarrow \mathtt{TValues} \tag{1}$$

Here, $\mathtt{trust}_{A,\sigma}$ is A's subjective function that returns a measure $m \in \mathtt{TValues}$ of A's trust in a Trustee. The trust purpose σ (cf. [23]) indicates for what target A should trust the Trustee e.g., performing a certain task. $\mathtt{TValues}$ can be a set of binary values (e.g., trusted, not trusted), or discrete (e.g., strong trust, weak trust, weak distrust, strong distrust), or continuous in some form (e.g., measure of a probability or a belief). The special symbol $\perp$ represents an undefined trust measure. In all the examples of this paper we will assume $\mathtt{TValues}$ to be the so called "triangle of opinion" [24]; thus, a trust value is a triple $(b, d, u) \in [0, 1]^3$, and it represents the Trustor's subjective belief, disbelief and uncertainty respectively (with $b + d + u = 1$) in the Trustee to be trustworthiness for the purpose σ.

Function (1) inputs a description of the Trustee in terms of the following parameters: (a) a set $Q \in \mathtt{Quality}$ of Trustee's quality attributes; (b) a trust value $m \in \mathtt{TValues}$; (c) a set $M \subseteq \mathtt{TValues}$ of trust values. Set Q models any information that A knows directly about Trustee, such as the Trustee's profile. Value m models the Trustee's reputation in the viewpoint of A, that is a trust value stored in A's local space. Set M

represents recommendations, which are Trustee's trust values based on the viewpoints of recommenders.

It is recognized that trust changes over time [25]. If we assume a discrete time-line, A's trust at time $i+1$ can differ from A's trust at time i. With $\mathtt{trust}^i_A(B)$ we represent the trust that A has in B at time $i \geq 0$. It results from calling (1) on the inputs available to A at time i.

$$\begin{aligned} \mathtt{trust}^0_{A,\sigma}(B) &:= \mathtt{trust}_{A,\sigma}(Q^0_B, \bot, M^0_B) \\ \mathtt{trust}^i_{A,\sigma}(B) &:= \mathtt{trust}_{A,\sigma}(Q^i_B, m^i_B, M^i_B) \end{aligned} \quad (2)$$

where $Q^i_B \in \mathtt{Quality}$ are the quality attributes of B at time i, $\bot$ is an undefined trust measure, $m^i_B \in \mathtt{TValues}$ is the reputation of B (recommendation in A's viewpoint) at time i, and $M^i_B \subseteq \mathtt{TValues}$ are recommendations on B at time i.

Definitions (1) and (2) can be extended to deal with context. Their *context-aware* counterpart is written as follows [9]:

$$\mathtt{ctrust}_{A,\sigma} : \mathtt{Quality} \times \mathtt{Context} \times \mathtt{TValues} \times 2^{\mathtt{TValues}} \rightarrow \mathtt{TValues} \quad (1')$$

Here, $\mathtt{Context}$ models the set of context attributes, which can concern the Trustor, the Trustee, and of their interaction. An empty context is denoted with ϵ. Following the notation used for context-independent trust, with $\mathtt{ctrust}^i_A(B)$ we represent the result of (1′) called on the inputs, among which the context $\mathcal{C}^i_{AB}$, available to A at time i. This is plugged in the context-independent trust evaluation as follows:

$$\mathtt{ctrust}^i_A(B) := \mathcal{C}^i_{AB} \odot \mathtt{trust}^i_A(B) \qquad i \geq 0 \quad (2')$$

The operator $\odot$, such that $\epsilon \odot m = m$, returns a context-aware measure of trust, given a context-independent trust value m and a context. In [9], where we assumed $\mathtt{TValues} = [0, 1]$, the operator $\odot$ updates the current trust value by processing each contextual attributes in sequence. The amount of update depends on the weighting that the attributes have in Trustor's viewpoint.

3.2 Inference Rules for Context-aware Trustworthiness Evaluation

Definitions (2) and (2′) describe only partially the evolution of the trustworthiness evaluation process. Its understanding requires an operational formalization, that we now give in terms of an inference system. Each step of evaluation is described by an inference rule with the premises and the conclusion as predicates in the form:

$$A \xrightarrow[\mathcal{C}]{*;(i,m)}_{\sigma} B$$

stating that, for the trust purpose[4] σ, A has m degree of context-dependent $*$-trust on B, when context is $\mathcal{C}$ and time is i. Here, "$*$" stands for a class of trust. For example, we distinguish between two classes of trust relation: *functional* trust and *referral* trust [17].

[4] In the following we assume trust always implicitly referring to the same trust purpose σ, and we omit the subscript σ to make the notation more readable.

The former concerns A's trust in B performing a task; the latter concerns A's trust in B giving a recommendation about someone else doing a task. Functional trust can easily be reformulated in a context-dependent manner if it concerns A's trust in B performing a task (trust purpose) in a certain context $\mathcal{C}$. Referral trust, instead, is left context-independent: A's trust in B as a recommender does not depend on any context attributes. Naturally, this restriction could be relaxed too by letting the recommenders' contexts have influence on the trustworthiness evaluation. The predicates expressing context-dependent functional trust and referral trust, respectively, are as follows:

$$A \circ\!\xrightarrow[\mathcal{C}]{(i,m)} B \qquad A \xrightarrow{rt;(i,m)} B \tag{3}$$

Martinelli [26] adopts a similar notation for modeling functional and referral trust, but without any reference to time or context. We also identify two sub-relations of context-aware functional trust: *direct* and *indirect* trust (also pointed out in [17]). Direct trust emerges when the Trustor's trust is based on at least some personal experiences, that is, quality attributes and reputation; indirect trust is established when the Trustor judgement is based on someone else's opinions only (i.e., recommendations). We write the predicates expressing direct and indirect functional trust, respectively, as follows:

$$A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m)} B \qquad A \circ\!\xrightarrow[\mathcal{R},\mathcal{C}]{it;(i,m)} B \tag{4}$$

Here, $\mathcal{R}$ is the set of recommenders whose opinion has been considered when composing m. The semantics of context-aware trust evaluation is defined as an inference system, as depicted in Figure 1. We now comment each rule separately.

Rule (5) defines the scheme of our inference system's axioms. If A's subjective evaluation of B's qualities at time i evaluates to m and if $\mathcal{C}$ is the context available at time i, then A trusts B in measure $m' = \mathcal{C} \odot m$, where the operator $\odot$ is that of equation (2′). Premises in brackets (e.g., $[\mathtt{trust}_A(Q^i_B)] = m$) are evaluated at a meta level.

Rules (6) formalize the operational management of recommendations. In particular, rule (6.a) shows that an indirect trust on B derives from A's referral trust in D and from the (direct) trust that D already has in B; rule (6.b) and rule (6.c) show how to concatenate referral trust along a chain of reference and how to aggregate indirect trust across multiple paths of recommendations, respectively. Accordingly to [17], rules (6.a)-(6.c) show that indirect trust always originates from a direct trust at the end of a chain of references. Referral trust can be computed as stated in [23]; we do not give the specification here. In Section 5 we will show how (6) can be applied in case the Trustor does not have a measure of referral trust in the available recommenders. Finally, rule (6.d) formalizes our proposal of dealing with context in recommendations. Context acts as a filter in favor of those recommendations experienced in contexts that are $\equiv$-related with the present context $\mathcal{C}$.

Note 1. The semantics of rules (6) are incomplete unless we give the semantics of the two operators $\otimes$ and $\oplus$.

Reasonably, $\oplus$ must be at least associative and commutative (to be order-independent) and $\otimes$ at least associative (along a chain of recommendations). Some authors (e.g.,

[27]) suggest the use of semirings [28] to deal with a network of recommendations. Alternative solutions are described in [18]. Throughout the paper we assume trust values to be Subjective Logic's opinions, and $\oplus$ and $\otimes$ to be operators on opinions called Bayesian consensus and discounting, respectively [24]. Given the opinions m, m', ω, the opinion $m \oplus m'$ reflects m and m' in a fair and equal way, whilst $\omega \otimes m$ is the opinion expressing once applied the discount rate w to m.

Note 2. Relation $\equiv \subseteq$ `Context` $\times$ `Context` needs to be instantiated to complete the semantics of rules (6) and (7).

In its simplest form, $\equiv$ interprets as identity: a reputation or recommendation is adequate only if performed in the same context. Alternatively, $\equiv$ can be an equivalence relation between contexts—only experience performed within an equivalent context can contribute to present trust—or $\equiv$ can be a reflexive and symmetric relation modeling a semantic closeness. For example, if d is a distance between contexts, $\equiv$ can be $d(\mathcal{C}, \mathcal{C}') \leq r$, where r is the radius of the neighborhood. In case $\equiv$ is not the identity, it is reasonable to expect the derived trust to be $< m \oplus m'$. Closer study of this modified version of the rule is left as future work.

Rules (7) define how to obtain direct functional trust. More specifically, rule (7.a) models the aggregation of a direct functional trust. Rule (7.b) models our approach of dealing with reputation as a (direct) past experience that is combined with the present direct trust. Similarly to the recommendation rules, here context acts as a filter in favor of those experiences occurred in a $\equiv$-related context. Finally, rule (7.c) states that a past experience can be used as if it was a new experience presently, at the price of some trust decay (here represented by the constant discount ω).

Note 3. In rules (7.b) and (7.c) constraints over time can guide the search strategy in the past. Each strategy reflects a different attitude in considering reputation (e.g., choosing a maximal j implies the consideration of most recent experience stored in the reputation base).

Rules (8) define functional trust (the goal of our proof system) as a generalization of direct and indirect trust.

As a final remark, we observe that our inference systems allows different proof searches with different result for the same goal. Various implementations and optimization strategies are possible, but we do not discuss them in this paper.

4 Indirect Reputation Information

So far we have implicitly assumed that the Trustee's quality and contextual attributes needed in order to evaluate trust are directly available to the Trustor. In real situations, we may be obliged to relax this assumption. Consider, for example, a situation where we would like to evaluate the quality of a new scientific conference. Due to its newness, the conference is not ranked yet. Moreover, we will not find anyone known to us recommending it either. In such a situation, we basically have only two alternatives: to give up the evaluation (i.e., blindly trust/distrust), or to look for and rely on indirect information. For example, we can evaluate the prestige of the publisher of the conference

(INIT-RULES)

$$\frac{[\mathtt{trust}_A(Q^i_B) = m] \qquad [C^i_{AB} = \mathcal{C}]}{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,C\odot m)} B} \tag{5}$$

(RECOMMENDATION-RULES)

$$(a)\ \frac{A \xrightarrow{rt;(i,m)} D \quad D \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i-1,m')} B}{A \circ\!\!\xrightarrow[\{D\},\mathcal{C}]{it;(i,m\otimes m')} B}\ {\scriptstyle i>0} \qquad (b)\ \frac{A \xrightarrow{rt;(i,m)} D \quad D \xrightarrow{rt;(i,m')} B}{A \xrightarrow{rt;(i,m\otimes m')} B} \tag{6}$$

$$(c)\ \frac{A \circ\!\!\xrightarrow[\mathcal{R},\mathcal{C}]{it;(i,m)} B \quad A \circ\!\!\xrightarrow[\mathcal{R}',\mathcal{C}]{it;(i,m')} B}{A \circ\!\!\xrightarrow[\mathcal{R}\cup\mathcal{R}',\mathcal{C}]{it;(i,m\oplus m')} B} \qquad (d)\ \frac{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m)} B \quad A \circ\!\!\xrightarrow[\mathcal{R},\mathcal{C}']{it;(i,m')} B \quad [\mathcal{C}' \equiv \mathcal{C}]}{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m\oplus m')} B}$$

(REPUTATION-RULES)

$$(a)\ \frac{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m)} B \quad A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m')} B}{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m\oplus m')} B} \tag{7}$$

$$(b)\ \frac{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m)} B \quad A \circ\!\!\xrightarrow[\mathcal{C}']{dt;(j,m')} B \quad [\mathcal{C}' \equiv \mathcal{C}]}{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m\oplus m')} B}\ {\scriptstyle j<i} \qquad (c)\ \frac{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i-1,m)} B}{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,\omega\otimes m)} B}\ {\scriptstyle i>0}$$

(ADDITIONAL-RULES)

$$(a)\ \frac{A \circ\!\!\xrightarrow[\mathcal{C}]{dt;(i,m)} B}{A \circ\!\!\xrightarrow[\mathcal{C}]{(i,m)} B} \qquad (b)\ \frac{A \circ\!\!\xrightarrow[\mathcal{R},\mathcal{C}]{it;(i,m)} B}{A \circ\!\!\xrightarrow[\mathcal{C}]{(i,m)} B} \tag{8}$$

Fig. 1. Abstract inference systems for context-aware trust evaluation.

proceedings, or we can look for the reputation of its program chairs and committees. In the case of a new workshop colocated with a conference having a history, we can also consider the quality of the conference when evaluating the workshop. This section studies how trust can be evaluated in such situations.

4.1 Absent Reputation Information Across Contexts

If we come across a Trustee not known to us, that is, we possess no prior reputation information about the Trustee, how should we go about evaluating the trustworthiness? One well-known solution in the literature is to ask for recommendations. In Section 5 we discuss recommendations and how to deal with them. Here, instead, we analyze a complementary solution, namely utilizing direct information of entities known to the Trustor and "related" to the Trustee (see Figure 2 (a)). Let us consider again the example about evaluating the trustworthiness of a new scientific conference. Due to the absence of any information about the conference, we can find it satisfactory to evaluate the trustworthiness of the conference proceedings publisher, as well as those of the program chairs and committee members.

From a formal point of view, the previous solution is expressed by the following additional (to the INIT-RULE) inference rule (9) where a trust relationship with B in a certain context $\mathcal{C}$ is deduced by a trust relationship with another Trustee "related" to B in the same context.

$$\frac{A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m)} D \qquad [D \sim B]}{A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m')} B} \quad m' \leq m \tag{9}$$

Here, the semantics of the rule requires us to instantiate the relation $\sim$; it can be an equivalence relation, or a reflexive and symmetric relation among Trustees that defines the concept of entity neighborhood. For example, Figure 2 (a) suggests the use of a measure of closeness among entities (see also Section 5). In this case $A \sim B$ if and only if $\texttt{cls}(A, B) \geq th$ where th is a threshold. In the following, we assume the closeness metric ranging in $[0, 1]$ where 1 stands for maximal closeness. In (9) we constrained m' to be at most m; more solutions are possible, so we left the way to calculate it unspecified. Reasonably m' depends on m and on the nature of the relationship between D and B. For example, $m' = \omega_s \otimes m$ where the opinion $\omega_s = (s, 1-s, 0)$ is the discount that reflects the closeness $s = \texttt{cls}(D, B)$ between D and B.

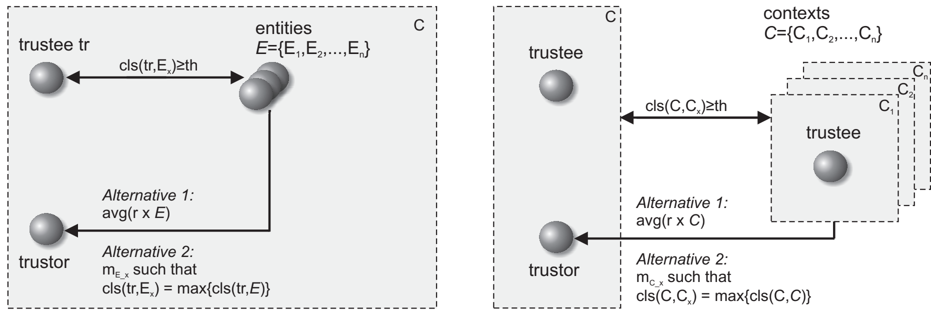
Figure 2(a) suggests also a generalization of rule (9); it considers a set of entities from which to extrapolate a measurement of B's trustworthiness. Formally the rule can be expressed as follows:

$$\frac{\bigcup_{k=1}^{N} \{A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m_k)} D_k\} \qquad [D_k \sim B]}{A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m')} B} \quad m' \leq m \tag{9'}$$

Here, m' can be computed either as $\oplus_k m_k$ (e.g., the consensus among all the trust values) or as the trust value of the entity, amongst $D_1, \ldots, D_N$ that has maximal closeness with B.

4.2 Absent Reputation Information in the Current Context

This section describes the case, where the Trustor wishes to evaluate the trustworthiness of a Trustee so that albeit knowing the Trustee beforehand, the Trustor has no idea of how the Trustee will behave in the current context. The Trustor has the possibility of adopting the same approach as presented above, namely, considering entities which are close enough to the Trustee and utilize their behavior as a guideline for evaluating the



(a) (b)

Fig. 2. (a) Considering past behavior of similar (e.g., closer than a certain threshold) entities as the Trustee in the current context. The reputation taken is either that of the entity the most similar to the Trustee, or an average reputation among the chosen entities. (b) Considering Trustee's past behavior in similar context(s) as the current one. The reputation is calculated as the reputation of the Trustee in contexts that are close enough (e.g., closer than a certain threshold) to the current context. Either the Trustee's reputation in the closest context, or the average of the reputations among the selected contexts is then chosen.

trusworthiness of the Trustee (Figure 2 (a)). However, it is envisaged that often more appropriate results can be obtained by considering the Trustee itself, and its behavior in contexts which are similar enough with the current one (Figure 2 (b)).

Let us continue with the scientific conference example, but this time from the conference chair's point of view. Suppose that the chair is gathering a program committee for the new conference. Here subject areas of the conference call for papers constitute the relevant attributes, which guide the conference chair in inviting appropriate members for the program committee. More specifically, the chair has two major options: In the case of previous conference chair experience in similar enough conferences, the chair can go about evaluating the performance of the PC members in those conferences and make up his mind based on that. Alternatively, the chair can look up other good and similar enough conferences, and count the most frequent PC members and invite them to join.

From a formal point of view, the previous solution is expressed by the following additional rule (as part of REPUTATION-RULES):

$$\frac{A \circ\!\xrightarrow[\mathcal{C}']{dt;(i,m)} B \qquad [\mathcal{C}' \equiv \mathcal{C}]}{A \circ\!\xrightarrow[\mathcal{C}]{dt;(i,m')} B} \tag{10}$$

Again, $\equiv$ can be an equivalence relation, or a reflexive and symmetric relation among contexts that defines the concept of context neighborhood. Figure 2(b) suggests one implementation of relation $\equiv$ based on context similarity; $\mathcal{C} \equiv \mathcal{C}'$ when $\texttt{cls}(\mathcal{C}, \mathcal{C}')$ is greater than a threshold th. The inferred trust value m', here left unspecified, reasonably depends on m and on the nature of the relationship between $\mathcal{C}'$ and $\mathcal{C}$. For example,

$m' = \omega_s \otimes m$ where $\omega_s = (s, 1-s, 0)$ is the discount build from $s = \texttt{cls}(\mathcal{C}, \mathcal{C}')$ between $\mathcal{C}$ and $\mathcal{C}'$.

Figure 2(b) suggests also a generalization of rule (10); it considers a set of $\equiv$-related contexts where B acted. Formally the rule can be expressed as follows:

$$\frac{\bigcup_{k=1}^{N}\{A \overset{dt;(i,m_k)}{\underset{C_k}{\circ\!\!\longrightarrow}} B\} \qquad [C_k \equiv \mathcal{C}]}{A \overset{(i,m')}{\underset{\mathcal{C}}{\circ\!\!\longrightarrow}} B} \tag{10'}$$

Here, m' can be computed either as $\oplus_k m_k$ (e.g., the consensus among all the trust values) or as the trust value of the context that has maximal similarity with $\mathcal{C}$.

5 Indirect Recommendation Information

In rules (6) recommendations carry the context $\mathcal{C}'$ they relate to. Recommendations are considered only if $\equiv$-related with the current context $\mathcal{C}$. Dealing with recommendations in this way is possible only if the Trustor knows the recommenders. We now loosen this requirement. In essence, we allow entities not directly known to the Trustor to be included in the trustworthiness evaluation process as recommenders. In this case, a Trustor may deduce indirect trust directly from an entity, if the entity is “close enough” to the Trustor. In other words, referral trust is approximated by the semantic distance between entities, with the intuitive meaning that “the closer, the more trusted”. Formally, this new evaluation step is synthesized by the following variant of rule (6.a):

$$(a)\ \frac{[A \sim D] \quad D \overset{dt;(i-1,m)}{\underset{\mathcal{C}}{\circ\!\!\longrightarrow}} B}{A \overset{it;(i,m')}{\underset{\{D\},\mathcal{C}}{\circ\!\!\longrightarrow}} B} \quad m' \leq m \tag{6.a'}$$

Here, the calculus of m' depends on the nature of the relation between A and D; for example, $m' = \omega_s \otimes m$ where ω_s is the discount $(s, 1-s, 0)$ that reflects the closeness s between A and D. The relative importance of a given recommender is estimated based on its relation with the Trustor.

The closeness between two entities can be grounded on the number of links between the Trustor and the recommender. Figure 3 depicts this. Note that there can be multiple parallel paths from the Trustor to the recommender, and they can be taken into account in differing ways. Only the shortest path can be considered, or alternatively all (or some reasonable amount of the) paths can be included in the calculation. The underlying idea is that the more paths there are between the Trustor and the recommender and the shorter they are, the more relevant the recommender is in the eye of the Trustor. Closeness is expressed by the following formula:

$$\texttt{cls}(A, D) = \sum_{k \in I} \frac{1}{\sqrt[\sharp|p_k|]{|p_k| + 1} \cdot k}$$

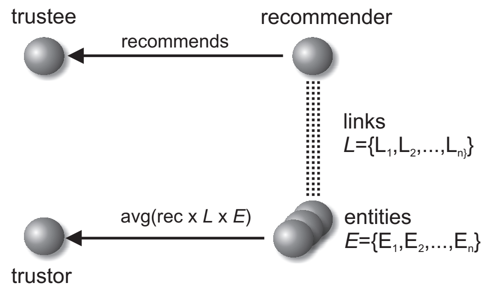


Fig. 3. Considering the opinion of a recommender unknown to the Trustor, but connectable to entities known to the Trustor.

where $p_1, p_2, ..., p_n \in P$ is the ordered set of alternative parallel paths found between the Trustor and the recommender so that $|p_1|$ indicates the number of links in the shortest path, $|p_2|$ in the second-shortest, and so on.

Note that there can be multiple paths that have the same amount of links. As a representative for each set of paths that have an equal amount of links we choose the path with the smallest index. An ordered set of indexes I is created so that only the indexes of the representatives $\in I$. If all paths $\in P$ have a different amount of links, then $I = \{1, \ldots, n\}$. With $\sharp|p_k|$ (for all $k \in I$) we mark the number of paths, in the set of equal length paths, represented by p_k.

As an illustrative example, consider again the conference chair as Trustor A and the proposed PC member's colleague or boss as recommender D and two paths between them. One of the paths has one link and the other two. (If only the shortest path was considered, the closeness metric of the recommender would be $\frac{1}{2 \cdot 1} = .5$). The closeness metric taking into account both paths is $\frac{1}{2 \cdot 1} + \frac{1}{3 \cdot 2} = \frac{2}{3} \approx .67$, and $I = \{1, 2\}$. If we add yet another path to the picture, this time with five links, the closeness metric is $\frac{1}{2 \cdot 1} + \frac{1}{3 \cdot 2} + \frac{1}{6 \cdot 3} = \frac{13}{18} \approx .72$. Here $I = \{1, 2, 3\}$. Now, consider there are three paths between the Trustor A and Trustee D, two having one link each and one having five links. The set of indexes becomes $I = \{1, 3\}$ and the closeness metric becomes $\frac{1}{\sqrt[2]{2 \cdot 1}} + \frac{1}{6 \cdot 3} \approx .76$

Two main approaches concerning different link kinds can be distinguished. In the first of these approaches, all link kinds $L_1, L_2, ..., L_n \in L$—be they based on profession, kin, plain acquaintance, and so on—are considered as equally important with regard to the trustworthiness evaluation. The second, in turn, makes distinctions between different link kinds and values some over others. For example, with regard to the program committee membership, professional links can be put more emphasis than acquaintanceships or family relations.

To make distinctions between different link kinds $\in L$ we add a weighting to them. Let $w_{p_{k_j}} \in \mathbb{R}$ be a weighting for a link in path p_k, where $j = 1, \ldots, |p_k|$. The mean link weight for path p_k is defined as

$$W_{p_k} = \frac{\sum_{j=i}^{|p_k|} w_{p_{k_j}}}{|p_k|}.$$

For a set of paths $P = p_1, p_2, \ldots, p_n$, we normalize the path weights W_{p_k} to $[0,1]$ as follows:

$$W'_{p_k} = \frac{W_{p_k}}{max\{W_{p_j} \mid j = 1, \ldots, n\}}.$$

In case there are paths that have an equal amount of links, the mean of their normalized path weights is used. Finally, the weighted closeness metric $\texttt{wcls}(A, D)$ becomes

$$\texttt{wcls}(A, D) = \sum_{k \in I} \frac{W'_{p_k}}{\sqrt[\sharp|p_k|]{|p_k| + 1} \cdot k}$$

Let us continue with the conference example. Suppose we have the same two paths between the Trustor A and recommender D as earlier. But now the shorter path consists of one link of type "family relation", weighted at 2.5, whereas the path with two links consists of professional links with corresponding weights 4 and 6. The mean link weight for the shorter path is 2.5, and 5 for the longer path. The normalized link weights are thus $\frac{1}{2}$ and 1, respectively. The weighted closeness metric of these paths is $\frac{\frac{1}{2}}{2 \cdot 1} + \frac{1}{3 \cdot 2} = \frac{5}{12} \approx .42$. Suppose that at a later time the family member whose relation was weighted at 2.5 becomes an assistant, and the weight of this relation is 4. In this case the weighted distance metric of these paths becomes $\frac{\frac{4}{5}}{2 \cdot 1} + \frac{1}{3 \cdot 2} = \frac{17}{30} \approx .57$.

6 Conclusions and Future Work

We described and formalized means for evaluating trustworthiness in cases where the Trustor does not possess direct information about the Trustee. We considered both the absence of direct reputation information, that is, lack of Trustor's personal experiences of the Trustee, and the absence of direct recommendation information, that is, lack of recommendations transmitted to the Trustor by entities known to the Trustor. We discussed cases where the Trustee/Recommender is unknown to the Trustor across contexts, meaning that the Trustor has no knowledge whatsoever about the actions taken by the Trustee/Recommender. In addition, we considered cases where the Trustor has some knowledge about the Trustee/Recommender, but not in the current context.

As a solution we propose to use measures of similarities among entities, and among contexts. Similar entities to the Trustee and a recommender can be used instead, in case Trustee and/or recommenders are unreachable to the Trustor. Additionally, the Trustor can search for a Trustee's reputation in a similar context, if information concerning the Trustee's reputation in the present context is missing. Whilst formalizing our approach, we illustrated its usage via a running example.

Our future work around the area includes further investigating the relationships between the Trustor and the Trustee. Research questions are for example comparing different similarity metrics connecting the Trustor with the Trustee (via multiple paths containing recommenders and other acquaintances, as well as varying contexts). In addition, we plan to empirically test and evaluate these metrics.

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