An Ontology of Trust
-- Formal Semantics and Transitivity

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Outline

- Background and Motivations
- Trust Conceptualization
- Ontology of Trust -- Formalizing in Situation Calculus
  - Formal Semantics of Trust
  - Transitivity of Trust
- Example: trust in web services
- Conclusion and Discussion
Problems

- Web activities need people to interact with "strangers"
- Each person only has a finite number of interpersonal trust relationships, which cannot meet the needs of various web activities
- A solution: Social Networks based trust
  - Is trust transitive? What types of trust transitive? Why?
    - No theories & models answer the questions.
  - Trust is context-dependent
    - Few models address context of trust in a formal manner

Research Objective

- Construct a logical theory of trust
  - to have formal semantics of trust
  - to study transitivity
  - to support social networks based trust.
Specific Background: KP

- Our specific interest in trust is from Knowledge Provenance (KP)
  - Anyone can publish information on internet
  - Web info may be true, false, or outdated
  - Need tools to discern the difference

- KP is an approach to determining the origin and validity of web information by modeling and maintaining information sources, information dependencies, and trust structures.

Trust and KP

- Wilson (1983): “we can trust a text if it is the work of an individual or group of individuals whom we can trust”.

- KP uses trust model to determine the trustworthiness of information sources.

- KP different to trust models:
  - KP considers not only trust but also info dependency
  - KP targets web info
  - Trust targets people

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Dynamic KP
- temporal truth values
- temporal trust relationships

Uncertainty KP
- uncertain truth values
- uncertain trust relationships

Static KP
- basic concepts of KP
- certain and static information

Trust Judgment Model
- interpersonal trust/direct trust
- social networks based trust
- system trust (e.g., professional membership based trust)
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Our View of Trust

- Trust is a psychological state comprising:
  - **Expectancy**: expect that a trustee will behave in a particular manner in a specific context
  - **Belief**: trustor believes the expectancy to be true;
  - **Willingness to be vulnerable**: trustor is willing to take risk for that belief.

Types of Trust

- **Trust in performance**
  - trust what trustee performs in a context
e.g. trust ftd.com to deliver a bouquet as ordered.
- **Trust in belief**
  - trust what trustee believes in a context
e.g. trust the opinion of a wine expert regarding the quality of wine products.
Contexts of Trust

- Context of trustee
  - Context of creating a piece of information
  - Context of performing an action
- Context of trustor
  - Context of expectancy
    - Context to use the information
    - Context in which trustor needs the action from trustee
  - Context of willingness (the situation to make trust decision)
- These two contexts may be in the same situation, but trustor and trustee usually have different utilities regarding the expectancy.
  - e.g. in expectancy “drive me to airport”, my utility and driver’s utility is different.

Sources of Trust

- Inter-individual Trust (direct trust): how trust is built up and evolves
  - Most of studies, e.g. Rotter(1967), Deutsch(1962)
  - Luhmann (1973): personal trust;
  - Zucker(1986): process based trust
- Social Networks based Trust (indirect trust via friends): how trust propagates
  - Social reality: Convention of using references/recommendation
  - Trust needs to be transitive
- System Trust (indirect trust via systems): how to evaluate trust
  - Luhmann (1973): trust in the function of a system
  - Barber (1983): expectations on professionals
  - Zucker(1986): characteristic based, institutional based
  - Minsky (2003): regularity-based trust
  - Reputation-based
Logical Theory of Trust

- Goal: to construct a logical theory of trust
  - to have formal semantics of trust
  - to derive transitivity
  - to support social networks based trust.

- Approach:
  - formalizing trust in Situation Calculus
  - Represent fluents as reified (Pinto 1994)
  - Use functions to mimic logical operators among fluents
  - Remain form of state constraints
  - using Gruninger&Fox’s ontology development method

Terminology

- trust_b(d,e,x,k): fluent
  - d trusts e on x, which is believed by e, in context k
  - x: a fluent, representing a thing e believes

- trust_p(d,e,x,k): fluent
  - d trusts e on x created by e in context k
  - x: fluent, info created by e
  - set x = perform(e,a) to represent “e performs action a”

- believe(d, x): fluent, d believes x

- believe(d, k->x): d believes x in context k

- made(x,e,q): fluent, x made by e in context q

- entail(q,k): predicate, context q implies context k

- holds(f,s): predicate, fluent f holds in situation s
Formal Semantics of Trust (1)

- Trust in belief
  - Trustor (d) believes a thing (x) believed by trustee (e) in a context (q) entailing the trustor's context of trust (k).

  - Axiom:
    \[
    \text{hold}(\text{trust}_b(d,e,x,k),s) \iff \forall q, (\text{hold}(\text{believe}(e,q \rightarrow x),s) \land \text{entail}(q,k) \\
    \quad \rightarrow \text{hold}(\text{believe}(d,k \rightarrow x),s))
    \]
    \[
    \text{entail}(q,k) \iff \forall s, \text{hold}(q,s) \rightarrow \text{hold}(k,s)
    \]

Formal Semantics of Trust (2)

- Trust in performance
  - Trust in information: Trustor (d) believes in information (x) created by trustee (e) in a context (q) entailing trustor's context of trust (k);

  - Axiom:
    \[
    \text{hold}(\text{trust}_p(d,e,x,k),s) \iff \forall q, (\text{hold}(\text{made}(x,e,q),s) \land \text{entail}(q,k) \\
    \quad \rightarrow \text{hold}(\text{believe}(d,k \rightarrow x),s))
    \]

  - Trust in action: Trustor (d) believes in the performance committed by trustee (e) in a context (q) entailing trustor's context of trust (k);

  - in above axiom, x is replaced by perform(e,a)
Conditions of Trust Propagation (1): Transitivity of Trust

- if entity $d$ trusts entity $c$ on everything which $c$ believes in context $k$, and $c$ trusts entity $e$ on everything which $e$ believes in context $q$, then $d$ trusts $e$ on everything which $e$ believes in the conjunction of the contexts $k$ and $q$.

- Theorem 8(b):
  
  \[ \text{(for-all } x) \neg \text{(trust_b}(d,c,x,k),s) \]
  
  \[ \land \text{(for-all } x) \neg \text{(trust_b}(c,e,x,q),s) \]
  
  \[ \Rightarrow \text{(for-all } x) \neg \text{(trust_b}(d,e,x,k^q),s) \]

Conditions of Trust Propagation (2)

- If entity $d$ trusts entity $c$ on everything which $c$ believes in context $k$, and $c$ trusts entity $e$ on everything which $e$ performs in context $q$, then $d$ trusts $e$ on everything which $e$ performs in the conjunction of contexts $k$ and $q$.

- Theorem:
  
  \[ \text{(for-all } x) \neg \text{(trust_b}(d,c,x,k),s) \]
  
  \[ \land \text{(for-all } x) \neg \text{(trust_p}(c,e,x,q),s) \]
  
  \[ \Rightarrow \text{(for-all } x) \neg \text{(trust_p}(d,e,x,k^q),s) \]
Conditions of Trust Propagation (3) -- System Trust

- if trustor trusts in the performance of a system (e.g. an organization, or a group whose members have a common set of characteristics related to the trust) in a context, then the entity trusts in the performance of the members of the system in that context.

- Axiom 4:
  
  \[
  \text{holds(trust}_p(d,o,x,k),s) \\
  \wedge \text{holds(memberOf(e,o),s)} \\
  \Rightarrow \text{holds(trust}_p(d,e,x,k),s)
  \]

Example: trust in web services

- Do you have tea set?
- Customer
  - Recommend the tea set
- Online gift store (F)
  - Online porcelain store (P)
  - Porcelain supplier (S) (P's long term partner)
- Web Service registry
  - Who're they?
  - Trust in performance
  - Trust in belief
- Trust in performance
- Porcelain Manufacturer (J)
- #: the order of events
Example (2)

- Process:
  - Gift store (F) do not have “tea set” and find a product by web services, but not sure the quality;
  - F has a number of trust relationships in social networks, in which P is a long term business partner specialized in porcelain, and F has “trust in belief” type of inter-individual trust relationship with P regarding porcelain quality;
  - P has “trust in belief” relationship with a supplier (S); and S has “trust in performance” relationship with manufacture J;
  - By social networks based trust, F indirectly trusts J regarding the quality of J’s porcelain products
- Formal representation:
  - F trusts in P’s belief on porcelain quality
    \[\text{holds}(\text{has\_b\_tr}(P,P,x,\text{in\_Topic}(x, \text{Porc\_Qual}), s))\]
  - P trusts in S’s belief on porcelain quality
    \[\text{holds}(\text{has\_b\_tr}(P,S,x,\text{in\_Topic}(x, \text{Porc\_Qual}), s))\]
  - S trusts J’s performance on high quality porcelain manufacture
    \[\text{holds}(\text{has\_b\_tr}(S,J,\text{perform}(J,\text{mk\_HQ\_porcel}(x)), \text{in\_Topic}(\text{perform}(J,\text{mk\_HQ\_porcel}(x), \text{Porc\_Qual}), s))\]

Conclusion

- Trust in belief is transitive
- In the media of “trust in belief” relation, trust propagates in social networks.

Contributions

To formal trust models:
- An ontology of trust with formal semantics of trust
- Proof of transitivity of trust in belief
- Conditions of trust propagation
- Theoretical evidence supporting trust propagation in social networks.
- Formalization of the context of trust
- Structure of trust decision

To Situation Calculus:
- Trust representation in Situation Calculus
- Potential use in web agents
Further Discussion: Trust Decision

- When belief is uncertain, make decision: willing to be vulnerable or not?
- Condition to choose trusting (Huang & Fox, 2005):
  - expected utility of trusting > expected utility of not trusting
  - $p(\text{"expectancy occurs"}) > \frac{(U_0 - U_c)}{(U_0 - U_t)}$
  - trust degree := $p(\text{"expectancy occurs"})$

This model revises:
- Deutsch (1962)'s model
- Colemon (1990)'s model

Future Work

- To complete social networks based trust
  - To include uncertainty
  - To include distrust
  - To aggregate trusted friends' opinions
  - Efficient methods to search web-based social networks
- To integrate inter-individual trust models
- To further model system trust