Trust Networks

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Abstract. Dependence networks among agents (describing how each agent can be linked with each other able to satisfy any need/goal/desire) are really important for evaluating future collaborations among them. In fact, the Dependence Networks alone are not sufficient for a real allocation of tasks among the agents. For this allocation, it is also necessary that each agent could satisfy his own expectations about the trustworthiness of the other agents with respect to the specific tasks. We present in this paper a cognitive theory of trust as a capital, which is, in our view, a good starting point to include this concept in the issue of negotiation power. That is to say that if somebody is (potentially) strongly useful to other agents (in the sense that are declared a set of its skills), but it is not trusted, its negotiation power does not improve. Our claim is to underline how (for a set of agents linked to each other) the competitive advantage is not simply of being part of a network, but more precisely of being trusted in that network.

Keywords: Trust, Dependence Networks, Relational Capital.

1 Introduction

In almost the present approaches to the trust study the focus of the analysis is on the trustier and on the ways for evaluating the trustworthiness of other possible trustees. But trust can be viewed at the same time as an instrument both for an agent selecting the right partners in order to achieve its own goals (the trustier's point of view), and for an agent of being selected from other potential partners (the point of view of the trustee) in order to establish with them a cooperation/collaboration and to take advantage from the credit of the accumulated trust.
In this paper we will analyze trust as the agents' *relational capital*. Starting from the classical dependence network (in which needs, goals, abilities and resources are distributed among the agents) with potential partners, we introduce the analysis of what it means for an agent to be trusted and how this condition could be strategically used from him for achieving his own goals, that is, why it represents a form of power.
We address this point, analyzing what it means that trust represents a strategic resource for agents that are trusted, proposing a model of 'trust as a capital' for individuals and suggesting the implication for strategic action that can be performed.

Our thesis is that to be trusted:

i) increases the chance to be requested or accepted as a partner for exchange or cooperation;

ii) improves the 'price', the contract that the trustee can obtain.

The need of this new point of view derives directly from the fact that in human societies as well as in multi-agent systems it is strategically important not only to know who is trusted by who and how much, but also to understand how being trusted can be used by several potential trustiers.

It has been already shown that using different levels of trust represents an advantage in performing some task such as allocating task or choosing between partners. Therefore, having "trust" as a cognitive parameter in agents' decision making can lead to better (more efficient, faster etc.) solutions than proceeding driven by other kind of calculation such as probabilistic or statistical one.

In order to improve this approach and to better understand dynamics of social networks, now we propose a study of what happens on the other side of the two-way trust relationship, focusing on the trustee, in particular on a cognitive trustee. Our aim is an analytical study of what it means to be trusted. The idea of taking the other point of view is particularly important if we consider the judge amount of studies in social science that connect trust with social capital related issues.
Our claims are:

- to be trusted usually is an advantage for the trustee (agent *Y*); more precisely received trust is a capital that can be invested, and that requires decision and costs to be cumulated;

- it is possible to measure this capital, which is relational, that is depends on a position in a network of relationships;

- trust has different sources: from personal experience that the other agents have had with *Y*; from circulating reputation of *Y*; from *Y's* belongingness to certain groups or categories; from the signs and the impressions that *Y* is able to produce;

- the value of this capital is context dependent (and market dependent) and dynamic;

- received trust strongly affects the 'negotiation power' of *Y* that cannot simply be derived from the "dependence bilateral relationships".

Although there is a big interest in literature about 'social capital' and its powerful effects on the wellbeing of both societies and individuals, often it is not clear enough what is it the object under analysis. Individual trust capital (*relational capital*) and collective trust capital not only should be disentangled, but their relations are quite complicated and even conflicting. To overcome this gap, we propose a study that first attempts to understand what trust is as capital of individuals. How is it possible to say that "trust" is a capital? How is this capital built, managed and saved? Then we aim to analytically study the cognitive dynamics of this object, with a particular focus on how they depend on beliefs and goals.

2 Being Trusted

The theory of trust and the theory of dependence are not independent from each other. Not only because – as we modelled (1, 2, 22), before deciding to actively trust somebody, to rely on him (*Y*), one (*X*) has to be dependent on *Y*: *X* needs an action or a resource of *Y* (at least *X* has to believe so). But also because *objective* dependence relationships (10) that are the basis of adaptive social interactions, are not enough for predicting them. *Subjective* dependence is needed (that is, the dependence relationships that the agents know or at least believe), but is not sufficient; it is also necessary to add two relevant beliefs:
(i) the belief of being dependent, of needing the other;
(ii) the belief of the trustworthiness of the other, of the possibility of counting upon him.
If *X* would not feel dependent on *Y*, she could not rely on him.

2.1 Objective and Subjective Dependence

The theory of dependence includes in fact two types of dependences:
(1) the *objective dependence*, which says who needs whom for what in a given society (although perhaps ignoring this). This dependence has already the power of establishing certain asymmetric relationships in a potential market, and it determines the actual success or failure of the reliance and transaction (see Figure 1).

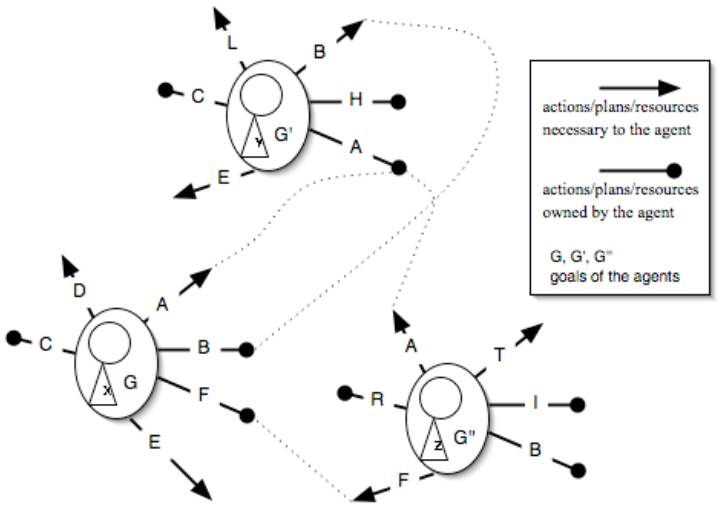

Figure 1: objective dependence network

(2) the *subjective (believed) dependence*, which says who is believed to be needed by who. This dependence is what determines relationships in a real market and settles on

the negotiation power; but it might be illusory and wrong, and one might rely upon unable agents, while even being autonomously able to do as needed. In Figures 2 is shown the dependence relationships as believed by X: it is different from the objective dependence showed in Figure 1.

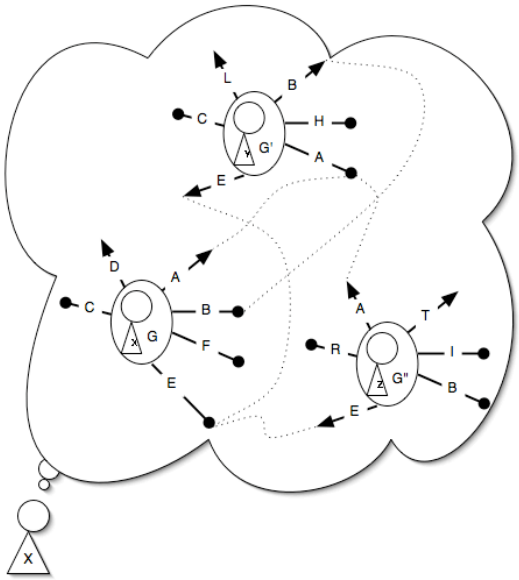

Figure 2: subjective dependence network (believed by *X*)

More Formally, let $Agt=\{Ag_1,..,Ag_n\}$ a set of *agents*; we can associate to each agent $Ag_i \in Agt$:
- a set of *goals* $G_i=\{g_{i_1},..,g_{i_q}\}$;
- a set of *actions* $Az_i=\{\alpha_{i_1},.., \alpha_{i_z}\}$; these are the elementary actions that Ag_i is able to perform;
- a set of plans $\Pi=\{p_{i_1},..,p_{i_s}\}$; the Ag_i's plan library: the set of rules/prescriptions for aggregating the actions; and
- a set of *resources* $R_i=\{r_{i_1},..,r_{i_m}\}$.

The achievement/maintenance of each goal needs of actions/plans/resources.
Then, we can define the *dependence relationship* between two agents (Ag_j and Ag_i) with respect a goal g_{jk}, as *Obj-Dependence* (Ag_j, Ag_i, g_{jk}) and say that:
An agent Ag_j has an Objective Dependence Relationship with agent Ag_i with respect to a goal g_{jk} if for achieving g_{jk} are necessary actions, plans and/or resources that are owned by Ag_i and not owned by Ag_j.
More in general, Ag_j has an Objective Dependence Relationship with Ag_i if for achieving at least one of its goals $g_{jk} \in G_j$, are necessary actions, plans and/or

resources that are owned by Ag_i and not owned by Ag_j (or, that is the same, they are owned by Ag_j but not usable by it for several reasons).

As in (12) we can introduce the *unilateral*, *reciprocal*, *mutual* and *indirect* dependence (see Figure 3). In very short and simplified terms, we can say that the difference between reciprocal and mutual is that the first is on different goals while the second is on the same goal.

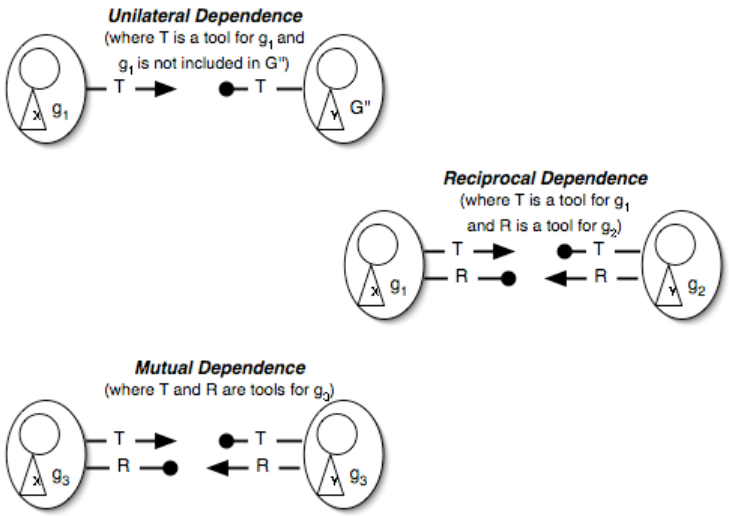

Figure 3

We introduce the formulas Bel_kG_z that represents Ag_z's Goal set as believed by Ag_k. The same for Bel_kAz_z, $Bel_k\Pi_z$, and Bel_kR_z, respectively for actions, plans and resources. In practice, the dependence relationships should be re-modulated on the basis of the agents' subjective interpretation. The thing really operative in the resulting interactions among the agents is due to their beliefs about the reciprocal dependences rather than the objective dependences.
We call *Subj-Dependence(Ag_j, Ag_i, g_{jk})* for representing the Ag_j's point of view with respect its dependence relationships with Ag_i about its k-th goal g_{jk}. Analogously, we call *Obj-Dependence(Ag_j, Ag_i, g_{jk})* for representing the objective dependence relationship of Ag_j with Ag_i about its k-th goal g_{jk}.
We define *Dependence-Network(Agt,t)* the set of dependence relationships (both subjective and objective) among the agents included in *Agt* set at the time *t*:
Dependence-Network(Agt,t) = Obj-Dependence(Ag_j, Ag_i, g_{jk}) ∪ Subj-Dependence(Ag_j, Ag_i, g_{jk}) with Ag_j ,$Ag_j \in Agt$.

2.2 Power of Negotiation in the Dependence Networks

Given a *Dependence-Network(Agt,t)*, we define

Objective Potential for Negotiation of $Ag_j \in Agt$ about an its own goal g_{jk} -and call it $OPN(Ag_j, g_{jk})$- the following function:

$$OPN(Ag_j, g_{jk}) = f(\sum_{i=1}^{l} \frac{1}{1+p_{ki}}) = \sum_{i=1}^{l} \frac{1}{1+p_{ki}}$$

Where:
- f is in general a function that preserves monotonicity (we will omit this kind of functions in the next formulas);
- l represents the number of agents in the set Agt that have a objective dependence relation with Ag_j with respect to g_{jk};
- p_{ki} is the number of agents in Agt that are objectively requiring the same actions/plans/resources (as useful for g_{jk}) to Ag_i on which is based the dependence relation between Ag_j and Ag_i and that in consequence are competitors with Ag_j on that actions/plans/resources in a not compatible way (Ag_i is not able to satisfy at the same time all the agents: there is a saturation effect). See Figure 4 for an example.

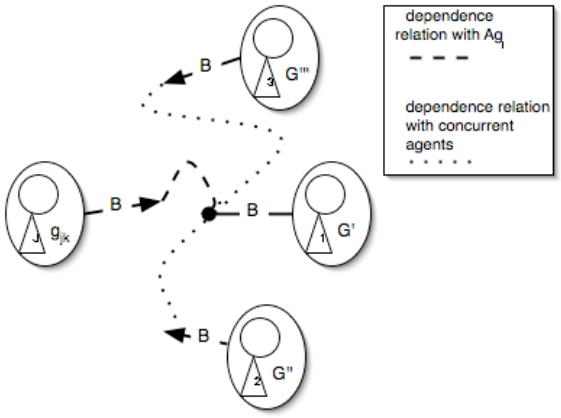

Figure 4

So, if there are no competitors with Ag_j ($p_{ki}=0$ for each $i \in \{1,\ldots, l\}$) we have:

$$OPN(Ag_j, g_{jk}) = f(\sum_{i=1}^{l} \frac{1}{1+p_{ki}}) = l$$

In general, we can represent the objective dependence of Ag_j as shown in Figure 5: *set1* represents the set of agents who depend from Ag_j for something (actions, plans, resources), *set2* represents the set of agents from which Ag_j depends for achieving an own specific goal g_{jk}. The intersection between *set1* and *set2* (part *set3*) is the set of agents with whom Ag_j could potentially negotiate for achieving g_{jk}. The greater the overlap the greater the *negotiation power* of Ag_j in that context.

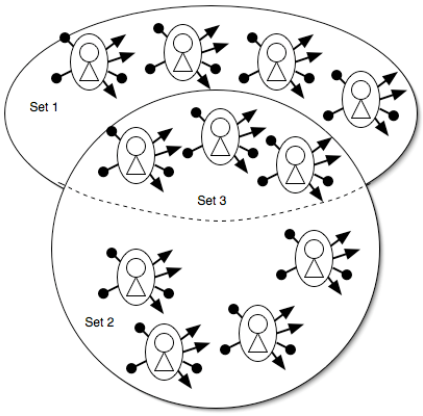

Figure 5

However, the negotiation power of Ag_j also depends on the possible alternatives that its potential partners have: the few alternatives to Ag_j they have, the greater its negotiation power (see Figure 4).
We can define the *Subjective Potential for Negotiation* of $Ag_j \in Agt$ about an its own goal g_{jk} -and call it $SPN(Ag_j, g_{jk})$- the following function:

$$SPN(Ag_j, g_{jk}) = Bel_j(\sum_{i=1}^{l} \frac{1}{1+p_{ki}})$$

where we have the same meanings as for the previous formula but now we make reference to the believed (by Ag_j) dependence relations.
More in general, we can say that:
the *Average Subjective Potential for Negotiation* of $Ag_j \in Agt$ about the whole set of its own goals (G_j) in the *Dependence-Network(Agt,t)* is:

$$SPN(Ag_j, G_j) = Bel_j(\frac{1}{s}\sum_{k=1}^{s}\sum_{i=1}^{l_k} \frac{1}{1+p_{ki}})$$

Where s is the number of goals of Ag_j, and l_k is the number of other agents in the set Agt, that have a dependence relation with Ag_j with respect to the specific goal g_{jk}.

2.3 Trust Role in Dependence Networks

We are interested now to introduce into the dependence network also the trust relationships. In fact, the dependence network alone is not sufficient for a real allocation of tasks among the agents. It is true that Ag_i should be able and willing to realize the action α_k: But how? And, it will be sufficient given Ag_i's expectations? Would be it more or less trustworthy than Ag_z? For answering to these questions the

agents in the dependence network have to establish among them also the reciprocal trust about the different tasks they can allocate to each other.
Indeed, *although it is important to consider dependence relationship between agents in a society, there will be not exchange in the market if there is not trust to enforce these connections*. Considering the analogy with the Figure 4, we will have now a representation as given in Figure 6 (where *Set 4* includes the set of agents that Ag_j considers trustworthy for achieving g_{jk}).

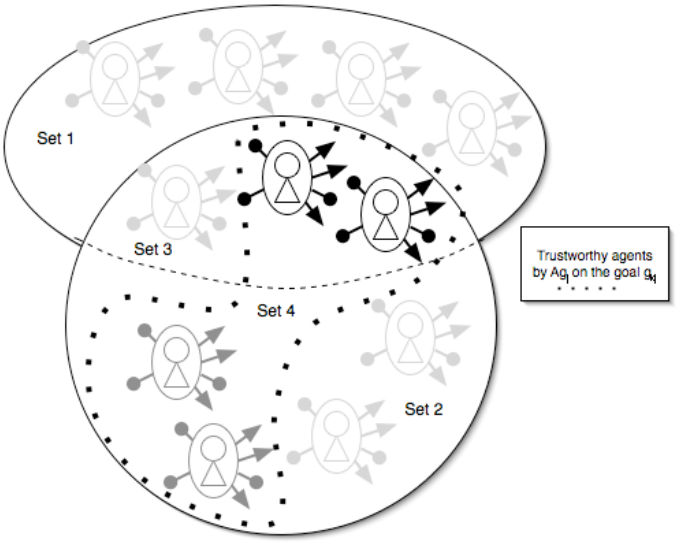

Figure 6

We have now a new subset (darked agents in Figure 7) containing the potential agents for negotiation.
Introducing in the *Subjective Potential for Negotiation* (of $Ag_j \in Agt$ about an its own goal g_{jk}) also the basic beliefs about trust (we introduce the superscript index *T* for differentiate from the *SPN* without trust), we have:

$$SPN^T(Ag_j, g_{jk}) = Bel_j\left(\sum_{i=1}^{l} \frac{DoA_{ik} * DoW_{ik}}{1 + p_{ki}}\right) \qquad 1 \geq DoA_{ik}, DoW_{ik} \geq 0$$

DoA_{ik} and DoW_{ik} are, respectively, the degree of ability and willingness (with respect the goal g_{jk}) of the agent Ag_i as believed by Ag_j ($Bel_j(DoA_{ik})$ and $Bel_j(DoW_{ik})$).
Analogously, but less relevant in this case, we can introduce the *Objective Potential for Negotiation* (of $Ag_j \in Agt$ about an its own goal g_{jk}), we have:

$$OPN^T(Ag_j, g_{jk}) = \sum_{i=1}^{l} \frac{DoA_{ik} * DoW_{ik}}{1 + p_{ki}}$$

When a cognitive agent trusts another cognitive agent, we talk about social trust.
We consider that the set of actions, plans and resources owned/available by an agent that can be useful for achieving a set of tasks (τ_1, …, τ_r).
We take now the point of view of the trustee in the dependence network: so we present a cognitive theory of trust as a capital. That is to say that if somebody is (potentially) strongly useful to other agents, but it is not trusted, its negotiation power is not good.
As showed in (2) we call *Degree of Trust* of the Agent Ag_j on the agent Ag_i about the task τ_k ($DoT(Ag_j\ Ag_i\ \tau_k)$):

$$DoT(Ag_j,Ag_i,\tau_k) = Bel_j(DoA_{ik}) * Bel_j(DoW_{ik})$$

At the same way we can also define the *self-trust* of the agent Ag_i about the task τ_k:

$$ST(Ag_i,\tau_k) = Bel_i(DoA_{ik}) * Bel_i(DoW_{ik})$$

We call the *Objective Trust Capital* of $Ag_i \in Agt$ about a potential delegable task τ_k:

$$OTC(Ag_i,\tau_k) = \sum_{j=1}^{l} Bel_j(DoA_{ik}) * Bel_j(DoW_{ik}) = \sum_{j=1}^{l} DoT(Ag_j,Ag_i,\tau_k)$$

Where l is the number of agents (included in the dependence network) needed for the task τ_k. We call the *Subjective Trust Capital* of $Ag_i \in Agt$ about a potential delegable task τ_k the function:

$$STC(Ag_i,\tau_k) = Bel_i(\sum_{j=1}^{l} Bel_j(DoA_{ik}) * Bel_j(DoW_{ik})) = Bel_i(\sum_{j=1}^{l} DoT(Ag_j,Ag_i,\tau_k))$$

Subjectivity means that both the network dependence and the believed abilities and willingness are believed by (the point of view of) the agent Ag_i.
Starting from the Trust Capital we would like evaluate its usable part. In this sense, we introduce the *Subjective Usable Trust Capital* of $Ag_i \in Agt$ about a potential delegable task τ_k as:

$$SUTC(Ag_i,\tau_k) = Bel_i(\sum_{j=1}^{l} \frac{DoT(Ag_j,Ag_i,\tau_k)}{1+p_{kj}})$$

where p_{kj} is (following the Ag_i's belief about the beliefs of Ag_j) the number of other agents in the dependence network that can achieve the same task to whom Ag_j can delegate the task τ_k (see Figure 8). We have two *comparable trust values* when the difference between them is in a range under a given threshold that could be considered meaningless with respect to the achievement of the task. In Figure 8, Ag_1 and Ag_2 strengthen the trust capital of Ag_i (they are concurrent with Ag_j about the task τ); while Ag_3, Ag_4 and Ag_5 weaken the trust capital of Ag_i because they are concurrent with Ag_i in offering (at the same trustworthy value) the task τ.

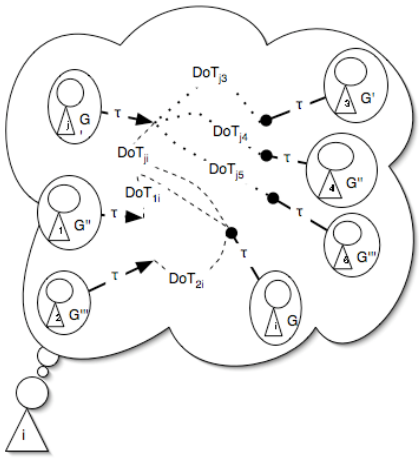

Figure 8

Of course, we can analogously introduce the *Objective Usable Trust Capital* of $Ag_i \in Agt$ about a potential delegable task τ_k as:

$$OUTC(Ag_i,\tau_k) = \sum_{j=1}^{l} \frac{DoT(Ag_j,Ag_i,\tau_k)}{1+p_{kj}}$$

In this paragraph we have introduced in the dependence network (that establishes, objectively or subjectively, how each agent can potentially depend from other agents for solving its own tasks) the trust relationships (that introduce an additional dimension, again assessable both objectively and subjectively, in a potential partner selection for achieving tasks). In general, we can say that the introduction of trust relationships reduces the set of potential partners for each agent and for each task, with respect to the situation with the dependence relationships alone: $OPN > OPN^T$, and $SPN > SPN^T$.

3 Dynamics of Relational Capital

What has not been considered enough in organization theory is the fact that the *relational capital* is peculiar in its being crucially based on beliefs: again, what makes relationships become a capital is not simply the structure of the networks (who "sees" whom and how clearly) but the levels of trust which characterize the links in the networks (who trusts whom and how much). Since trust is based on beliefs – including, as we said, also the believed dependence (who needs whom) – it should be clear that relational capital is a form of capital, which can be manipulated by manipulating beliefs.

Thanks to a structural theory of what kind of beliefs are involved it is possible not only to answer some very important questions about agents' power in network but also to understand the dynamical aspects of relational capital. In addition, it is possible to study what a difference between trustee's beliefs and others' expectations on him implies in terms of both reactive and strategic actions performed by the trustee itself.

3.1 Changing Trust Capital

For what concerns the dynamic aspects of this kind of capital, it is possible to make hypotheses on how it can increase or how it can be wasted, depending on how each of basic beliefs involved in trust could be manipulated.

In general, starting from the analysis of the previous paragraph, we can see how matching the different terms we have different interesting situations.

First of all, even if $OTC(Ag_i,\tau_k)$ is a relevant factor for the agent Ag_i (it shows in absolute terms how is recognized the trustworthiness of Ag_i), in fact the really important thing for an agent cumulating trust capital is $OUTC(Ag_i,\tau_k)$ that indicates not only the trustworthiness cumulated on the dependent agents, but also the number of possible other concurrent agents on that offered task.

Again more interesting is to consider the $SUTC(Ag_i,\tau_k)$ factor (in which a relevant role is played by the beliefs of the involved trustee) and its relationships with $OUTC(Ag_i,\tau_k)$, $SPN^T(Ag_j,g_{jk})$, and $OPN^T(Ag_j,g_{jk})$ factors. As we have seen in the previous paragraph, these factors are constituted by the beliefs of the trustee or the trustier, so can be interesting to analyze the different situations matching them and evaluating the consequences of their coherence or incoherence.

Let us consider what kind of strategies can be performed to enforce the other's dependence beliefs and his beliefs about *agent's competence*. If Ag_i is the potential trustee (the collector of the trust capital) and Ag_j is the potential trustier we can say:

i) Ag_i can make Ag_j dependent on him by making Ag_j lacking some resource or skill (or at least inducing Ag_j to *believe* so). He has to work on $SPN^T(Ag_j,g_{jk})$.

ii) Ag_i can make the Ag_j dependent on him by activating or inducing in her a given goal (need, desire) on which Ag_j is not autonomous (14) but is dependent from Ag_i (or in any case she believes so). In this case he has to find the way for including in G_j an additional g_{jk} such that Ag_j is dependent from Ag_i for that goal (and she believes that).

iii) Since dependence beliefs are strictly related with the possibility of the others (for example Ag_j) to see the agent (for example Ag_i) in the network and to know her ability in performing useful tasks, the goal of the agent who wants to improve his own relational capital will be to *signaling* his presence and his skills (15,16,17). While for showing his presence he might have to shift his position (either physically or figuratively like, for instance, changing his field), to communicate his skills he might have to hold and show something that can be used as a signal (such as certificate, social status, proved experience, and so on). It is important to underline that using these signals often implies the participation of a third subject in the process of building trust as a capital: a third part which must be trusted (2).

Obviously also Ag_i's *previous performances* are 'signals' of trustworthiness. And this information is also provided by the circulating *reputation* of Ag_i (18, 19).

iv) Alternatively, Ag_i could work for reducing the believed (by Ag_j) value of ability of each of the possible competitors of Ag_i (in number of p_{kj}) on that specific task τ_k: he has again to work $SPN^T(Ag_j,g_{jk})$.

Let us now consider how *willingness beliefs* can be manipulated. In order to do so, consider the particular strategy performed to gain the other's good attitude through gifts (20). It is true that the expected reaction will be of reciprocation, but this is not enough. While giving a gift Ag_i knows that the Ag_j will be more inclined to reciprocate, but Ag_i also knows that his action can be interpreted as a sign of the good willingness he has: since he has given something without being asked, Ag_j is driven to believe that Ag_i will not cheat on her. Then, the real strategy can be played on trust, sometimes totally and sometimes only partially – this will basically depend on specific roles of agents involved.

Again in formal terms, we can say that Ag_i has to work for increasing his DoW_i as believed by Ag_j ($Bel_j(DoA_i)$).

Alternatively, it could work for reducing the believed (by Ag_j) value of willingness of each of the possible competitors of Ag_i (in number of p_{kj}) on that specific task τ_k.

An important consideration we have to do is that a dependence network is mainly based on the set of actions, plans and resources owned by the agents and necessary for achieving the agents' goals (we considered a set of tasks each agent is able to achieve). The interesting thing is that the dependence network is modified by the dynamics of the agents' goals: from their variations (as they evolve in time), from the emergency of new ones, from the disappearance of old ones, from the increasing request of a subset of them, and so on (21). On this basis, changing the role of each agent in the dependence network, changes in fact the trust capital of the involved agents.

4 Conclusions

Individual trust capital (relational capital) and collective trust capital not only should be disentangled, but their relations are quite complicated and even conflicting. In fact, since the individual is in competition with the other individuals, he has a better position when trust is not uniformly distributed (everybody trusts everybody), but when he enjoys some form of concentration of trust (an oligopoly position in the trust network); while the collective social capital could do better with a generalized trust among the members of the collectivity.

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