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DEPENDENCE RELATIONS AMONG AUTONOMOUS AGENTS

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The main thesis of this work is that human interactions are neither unpredictable nor bounded, but they are undertaken autonomously on the grounds of a number of basic principles and conditions. Among these, a crucial role is played by the objective dependence relationships holding among agents. In this paper we report about a first step in providing a computational theory of dependence as a tool for interaction control. We define non social as well as social dependence, and try to show how dependence relationships are organized into complex patterns (such as multiparty, multigoal, unilateral, and bilateral dependence). We then show how a given set of dependence relationships may produce new dependence relationships. Finally, we explore the relationship between dependence and influencing, describing how an agent's dependence on another is predictive of one's goal of influencing the other, as well as of the latter's power of influencing the former.

1. INTRODUCTION

Communication control has always been a crucial problem in distributed systems. The limited capacity of communication channels represents a bottleneck for the performance of those systems. In Distributed Artificial Intelligence (DAI),

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the problem is amplified because of the continuous need for interaction among agents (e.g., for negotiation). The proposed solutions try either to communicate implicitly using a shared memory (blackboard systems [8]) or, if the single agent is more autonomous, to apply specialized control strategies (see for example [1]). Both approaches use solutions quite different from the behavior of human beings in similar situations. Cognitive agents generally find implausible to put a request message in a mailbox and wait for somebody to answer it; neither do they apply a standard protocol for the interaction. When an agent needs somebody else for achieving a goal, she reasons about knowledge of sociality and social relations. Such knowledge is used both in the stage of decision formation and in actual interaction.

We have been studying human behavior and developing models of it for several years (see [2, 6]). In this paper we attempt to describe the relations upon which context-dependent human interaction is based and try to devise some principles controlling it. Our main argument is that human interactions are neither unpredictable nor bounded but they are undertaken autonomously on the grounds of a number of basic principles. Those principles are formulated in a quasi-formal way, and seem to represent a necessary background for a computational model of context-related social interaction.

One of the fundamental notions of social interaction is the *dependence* relation among agents. In our opinion, the terminology for describing interaction in a multi-agent world is necessarily based on an analytic description of this relation. Starting from such a terminology, it is possible to devise a calculus to obtain predictions and make choices that simulate human behavior.

In this paper, we present our formalism for dependence relation and describe some deductions to be made on the grounds of this relation in order to obtain rational choices. In particular, we distinguish between resource dependence and social dependence, and show properties and special cases of both. We also give some basic axioms and show which types of actual interactions are strongly based on dependence. In particular, we try to show the relation between dependence relationships among agents and the action of influencing an agent from another as probably the most relevant form of interaction in real social contexts.

The paper is structured as follows: in Section 2, we provide our basic definition of dependence and describe its properties; in Section 3, we describe some principles for deriving a dependence relationship from another; in Section 4, we describe the relation between dependence and influencing; in a concluding Section, we point out some aspects still lacking in our theory.

2. DEPENDENCE AND ITS PROPERTIES

As already argued in [5], dependence is undoubtedly the ground relation upon which the whole construction of sociality is based. In the following, we first analyze a non social, or pre-social, form of dependence, namely the one between an agent and a resource. Then we proceed to its social version, the dependence between two agents, and finally try to describe some types of social dependence relationships involving more than two agents.

In the paper we mainly refer to the formal apparatus used by Cohen and Levesque in [3]. In the following, x and y denote agent variables with $x \neq y$ always implicitly stated; a denotes an action variable, r a resource, and p a well formed formula representing a state of the world. The predicate *(RESOURCE r a)* means that r is needed in order to perform a. *(CANDO x a)* means that agent x has the action a in his repertoire, that is he is able to do it by himself. We use the following definition similar to the one in [3]:
(DONE-BY x a) =def (DONE a) ∧ (AGT x a)
whose meaning is quite obvious.

2.1. Non social dependence

Dependence is not necessarily a social notion. A relation of dependence may be said to occur whenever: a) any object or event in the external world may increase, if used, the probability that a given state of the world be realized, and b) that world state is represented as a goal by at least one agent. In such a case, we say that agent to be *dependent on* the enabling object or event. The latter will then be called a *resource*. Resources enter the structures of actions (see also [9]). An action can be modeled as a relation holding among agent(s), goal(s), and resource(s). A set of resources is required for any action to take place. In our notion, cubes, tables and hands are resources in the block world. In the social world, others may be used as resources (not only in exploitation but also in prosocial action: in help, in a quite abstract sense, the recipient is a resource of the action "give help").

Agents are usually dependent on the existence of resources. We call this type of dependence a *resource dependence* (described by the *R-DEP* predicate), to distinguish it from *social dependence*, *S-DEP* (see below):

D1. (R-DEP x r a p) =def (GOAL x p)
∧ (RESOURCE r a)
∧ ((DONE-BY x a) ⊃ (EVENTUALLY p))

r is then a resource for *x* to achieve his goal that *p*. Thus, for instance, *x* is resource dependent on a hammer for having a nail driven into a wall. [2]

2.2. Social dependence

Our basic definition of social dependence is as follows [6]:

D2. (S-DEP x y a p) =*def* *(GOAL x p)*
$\wedge \neg$ *(CANDO x a)*
$\wedge$ *(CANDO y a)*
$\wedge$ *((DONE-BY y a)* $\supset$ *(EVENTUALLY p))*

that is: *x* depends on *y* with regard to an act useful for realizing a state *p* when *p* is a goal of *x*'s and *x* is unable to realize *p* while *y* is able to do so. In this context, *y*'s action is a resource for *x*'s achieving his goal.

It should be stressed that, unlike what most DAI work seems to take for granted, social dependence as well as resource dependence is *not fundamentally mental*. It is an *objective* relationship, in that it holds *independently* of the agents' awareness of it: *x* may depend on *y* even though they both ignore the fact. However, many relevant consequences may derive from *x*'s and *y*'s (either unilaterally or mutually) becoming aware of it: to mention just the most salient ones, *x* may try to *influence* *y* to pursue *p*, while *y* may choose whether to adopt *x*'s goal or not (see [6]; see also later on in the text).

Moreover, not only a dependence relationship may be *known*; it may also be *wanted*, in that either *x* or *y* may actively "work" on maintaining or strengthening the relationship. And, not only a dependence relationship may be wanted once established: it may even be *created* by the agents, by producing those objective conditions that define a dependence relationship (a certain goal in *x*'s mind; the lack of a certain power condition, etc.). So, for instance, *y* may *influence* *x* and induce him to have *p* as a goal of his own; since *p* cannot be achieved by *x* without *y*'s help, *y* has created a dependence of *x* on her by means of an influencing strategy; otherwise, supposing that *x* already has *p* as a goal of his and is also endowed with the power conditions useful for achieving it, *y* may deprive *x* of some of them (say, by stripping him of a certain resource), thus making *x become* dependent on her relative to *p*.

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[2] We want to point out the difference between the given definition of *R-DEP* and the following one where *w* denotes a plan for achieving *p* (or an <*action-expression*> following [3]):

D1b. (R-DEP x r a p) =def $\forall w$ *(GOAL x p)* $\wedge$ *((ACHIEVE w p)* $\supset$ *(IN a w))* $\wedge$ *(RESOURCE r a)*

which means that *x* depends only on resources of actions which are *essential* to the achievement of his goal. Even if this definition is reasonable, the one we use in the paper is intended to stress the fact that agents may have a number of alternative ways to achieve their goals either acting by themselves or asking others to act. Their behavior is the result of a decision making process. This is true in the case of *S-DEP* as well.

2.3. Patterns of dependence relationships

Dependence relations set up a social network (that we call the *DEP*-net, to stress the fact that it is a baseline for the socalled contract net [7]) among agents, independent of, and often preceding, their awareness. Several special cases of net can be recognized:

a) *OR-Dependence*. Very often, there exist disjunctive compositions of dependence relations; that is, x may depend on y_1 *OR* on y_2 (or on y_3, etc.) for the same p, for at least two possible reasons:

- the same action a useful for realizing p is performable by a number of agents (each independent of the other); so, it is sufficient for x to have a performed by one of them (say, the most available or willing):

$$(GOAL\ x\ p) \wedge \neg\ (CANDO\ x\ a) \wedge (H_{i=1,n}\ (CANDO\ y_i\ a)) \wedge ((\ G_{i=1,n}\ (DONE\text{-}BY\ y_i\ a)) \supset (EVENTUALLY\ p))$$

- alternative actions are useful for realizing p, and for each of them x is dependent on a different agent. In such a case, x's dependence with regard to p varies with the act, and then the agent, considered:

$$(GOAL\ x\ p) \wedge (H_{i=1,n}\ \neg\ (CANDO\ x\ a_i)) \wedge (H_{i=1,n}\ (CANDO\ y_i\ a_i)) \wedge ((\ G_{i=1,n}\ (DONE\text{-}BY\ y_i\ a_i)) \supset (EVENTUALLY\ p))$$

b) *AND-dependence*. Two cases may be distinguished in which there is a conjunction of dependence relations, namely the *multiparty* and the *multigoal dependence*:

- we call *multiparty dependence* the case in which x depends on more than one agent for realizing p; this happens when more than one single act is needed for achieving one and the same goal, and for each act x depends on a different agent: $H_{i=1,n}\ (S\text{-}DEP\ x\ y_i\ a_i\ p)$;

- *multigoal dependence* occurs when x depends on the same agent for realizing a number of unrelated goals: $H_{i=1,n}\ (S\text{-}DEP\ x\ y\ a_i\ p_i)$.

c) *Bilateral dependence*. So far, just cases of unilateral dependence (of x on y) have been described. However, dependence may also be bilateral (of x on y and of y on x). Bilaterality should not be confused with symmetry. The *DEP* predicate is in fact asymmetrical, in the sense that x's dependence on y relative to a certain action for a given goal does *not* imply y's dependence on x relative to the same action for the same goal, and vice versa. On the contrary, in bilateral dependence either the actions or both the actions and goals implied are not the same for x and y. There are in fact two possible kinds of bilateral dependence:

- *mutual dependence*, which occurs when x and y depend on each other for realizing a *common goal* p, which can be achieved by means of a plan including at least two *different* acts such that x depends on y's doing a_1, and y depends on x's doing a_2:

  $(S\text{-}DEP\ x\ y\ a_1\ p) \wedge (S\text{-}DEP\ y\ x\ a_2\ p)$

  As observed in a previous work [6], *cooperation* is a function of mutual dependence: there is no cooperation in the strictest sense without mutual dependence;

- *reciprocal dependence*, which occurs when x and y depend on each other for realizing different goals, that is, when x depends on y for realizing x's goal that p_1, while y depends on x for realizing y's goal that p_2:

  $(S\text{-}DEP\ x\ y\ a_1\ p_1) \wedge (S\text{-}DEP\ y\ x\ a_2\ p_2)$

  Reciprocal dependence is to *social exchange* what mutual dependence is to cooperation.

3. SOME PRINCIPLES OF A THEORY OF DEPENDENCE

So far we have attempted to provide some definitions of various forms of dependence (resource dependence vs. social dependence) and of different patterns of dependence relationships. Now, a number of interesting consequences may be drawn from the above. We do not aim here at showing all the possible principles according to which a dependence relationship can be derived from another; we just outline some of the most common ones.

3.1. From resource dependence to social dependence

Resource dependence is likely to produce social dependence. In order to describe this property we introduce the notion of resource control. An agent x *controls* a resource r when he is able to do an action a_1 by which he allows any other agent to perform any action requiring the resource:

$$D3.\ (CONTROL\ x\ r) =_{def} \forall y\ \exists a_1\ \forall a_2\ (CANDO\ x\ a_1) \wedge \neg (CANDO\ y\ a_1) \wedge (RESOURCE\ r\ a_2) \wedge ((DONE\text{-}BY\ x\ a_1) \supset (CANDO\ y\ a_2))$$

If agent x depends on resource r for a given p, and agent y controls r, then agent x depends on agent y for using r. So, in this context social dependence (of x on y) is the joint result of resource dependence (of x on r) and resource control (of y over r):

$$A1.\ \exists a_1\ ((R\text{-}DEP\ x\ r\ a\ p) \wedge (CONTROL\ y\ r)) \supset (S\text{-}DEP\ x\ y\ a_1\ p)$$

There exist, then, at least two sources of social dependence relationships:
a) *x* directly depends on some action of *y*'s;
b) *x* depends on some resource which is controlled by *y*; hence, he depends on *y*.

However, (b) can be seen as a sub-case of (a), in that also in (b) *x* comes to depend on some action of *y*'s: if *r* is controlled by *y*, *x* depends on *y*'s action of "letting *x* use *r*".

By the way, *CONTROL* should be articulated into at least three possible sub-cases, each implying a particular action by *y* of "letting *x* use *r*"; these cases might be unformally described as follows:
1) *y possesses r*; hence, a condition for *x*'s using *r* is *y*'s *permission* to use it; *y*'s act on which *x* depends is exactly *y*'s permission;

2) *y is using r* at the same time when *x* would like to use it, and *r* is a resource that cannot be used by different agents at the same time. So, *x* depends on *y*'s act of *stopping* using *r*;

3) *r* is *spatially available* to *y*, while it is not available to *x*, in the sense that *r*'s location coincides with *y*'s, and *x* cannot use *r* unless *y* makes *r*'s location change from hers to *x*'s, that is, unless *y gives r* to *x*.

Thus, it might be concluded that social dependence of *x* on *y* relative to *p* is always a dependence on *y*'s actions of two sorts: either actions which cause *r* to be available to *x* for *p* (stopping using *r*, giving *r* to *x*, permitting *x* to use *r*), or actions which directly produce *p*[3] .

3.2. Dependence via influencing

Another interesting case of generation of *DEP* relations implies the mediating role of some agent's power of influencing another. Our basic definition of the power of influencing, *INFL-POWER*, is the following:

D4. (INFL-POWER x y a p) =def (CANDO x a)
∧ ((DONE-BY x a) ⊃ (EVENTUALLY (GOAL y p)))

That is: *x* has the power of influencing *y* if he *CANDO* such an act that makes *y* have *p* as a goal of her own. As we shall see in Section 4, this action generally implies making *y believe* something which is somehow related to *p*. For instance,

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[3] Moreover, a number of distinctions can be done modifying definition *D3*, where an agent is seen as the *administrator* of a resource. Alternatively an agent can be described as the only one able to do something by means of a given resource:
D3b. (CONTROL x r) =def ∀y ∀a (CANDO x a) ∧ (RESOURCE r a) ∧ ¬ (CANDO y a).
A third and stronger definition describes a controller as the agent who *prevents* others from using the resource:
D3c. (CONTROL x r) =def ∀y ∃a1 ∀a2 (CANDO x a1) ∧ ¬ (CANDO y a1) ∧ (RESOURCE r a2)
∧ ((DONE-BY x a1) ⊃ ¬ (CANDO y a2))

an act of that sort might be a threat ("If you don't pursue p, I will thwart you in q"-- where q is some other goal of y's).

If x depends on y relative to a for realizing p, and z has the power of influencing y to do a, then x depends also on z for realizing p:

A2. $((S\text{-}DEP\ x\ y\ a_1\ p) \wedge (INFL\text{-}POWER\ z\ y\ a_2\ (DONE\text{-}BY\ y\ a_1\ ))) \supset (S\text{-}DEP\ x\ z\ a_2\ p)$

We will discuss in more detail both the goal and the power of influencing and their relation with dependence in the next Section.

3.3. Generative power of multiparty dependence

Let us suppose a simple case of *AND* dependence, where x depends on more than one agent (say, on y and on z) for realizing p: $((S\text{-}DEP\ x\ y\ a_1\ p) \wedge (S\text{-}DEP\ x\ z\ a_2\ p))$. This *AND* dependence may generate a further dependence of y on z, *in case y is benevolent toward x***.** In [2] and [6], we argue against the notion of benevolence, suggesting some further refinement of it; however, to our current purposes, it is sufficient to refer to a simpler definition, in line with Cohen & Levesque's [4]:

D5. $(BENEVOLENT\ y\ x\ p) =def (BEL\ y\ (GOAL\ x\ p)) \supset (EVENTUALLY\ (GOAL\ y\ p))$

So, if y believes that x has the goal p then also y comes to have the same goal p.

Now, if y is benevolent toward x and believes that x has the goal that p, also y (besides x) comes to depend on z (provided y is unable to perform a_2), since z's action a_2 is necessary for realizing p:

A3. $((S\text{-}DEP\ x\ y\ a_1\ p) \wedge (S\text{-}DEP\ x\ z\ a_2\ p) \wedge (BENEVOLENT\ y\ x\ p)) \wedge (BEL\ y\ (GOAL\ x\ p)) \supset (S\text{-}DEP\ y\ z\ a_2\ p)$

Of course, if in turn also z is benevolent toward x, y and z will mutually depend on each other relative to p.

4. PREDICTIVE POWER OF DEPENDENCE RELATIONSHIPS: FROM DEPENDENCE TO INFLUENCING

One of the most interesting aspects of the *DEP* relations lays in their predictive power, that is, in the possibility to predict *other social relationships* and goals from dependence relationships.

4.1. From dependence to the goal of influencing

Among the social goals predictable from a dependence relationship, a crucial role is played by the *goal of influencing*. In our view, one's goal of influencing another is the goal of increasing the probabilities that the other pursues (or does

not pursue) a certain goal that p [2]. However, here we can propose a simplified version of that definition: so, by x's *goal of influencing* y,
INFL-GOAL, we mean x's goal that y *has* a certain goal p:

D6. (INFL-GOAL x y p) =def (GOAL x (GOAL y p))

Let us start from our basic definition of social dependence (see *D2*). First of all we need that this objective social relationship between x and y is assumed by x. In fact, one of the ways in which new goals are acquired implies that people learn they are involved in certain relationships. Now, by assuming his dependence on y relative to a, x will also assume that he can achieve his goal that p by means of y's performing a: *(BEL x (S-DEP x y a p)) ⊃ (BEL x ((DONE-BY y a) ⊃ (EVENTUALLY p))*. Then, according to a condition-action rule formulated as follows:

A4. ((BEL x (q ⊃ p)) ∧ (GOAL x p)) ⊃ (GOAL x q)

x will come to have the goal that *(DONE-BY y a)*, in order to achieve his goal that p:

T1. (BEL x (S-DEP x y a p)) ⊃ (GOAL x (DONE-BY y a))

So, if x believes he is dependent on y relative to a, then he will have the goal that y performs a. But given the postulate on rational agenthood, according to which, in order to perform an action, an agent must want that action, *(GOAL x (DONE-BY y a))* is actually equivalent to *(GOAL x (GOAL y (DONE-BY y a)))*.Then x's dependence on y, when assumed, will also imply x's goal that y *has the goal to do* a:

(BEL x (S-DEP x y a p)) ⊃ (GOAL x (GOAL y (DONE-BY y a)))

Now, being *(GOAL x (GOAL y (DONE-BY y a)))* nothing but a goal of influencing y relative to the goal that *(DONE-BY y a)* (see *D6*), x's dependence on y relative to a certain a useful for p will imply, when assumed, x's goal of influencing y to perform a:

T2. (BEL x (S-DEP x y a p)) ⊃ (INFL-GOAL x y (DONE-BY y a))

So, if an agent assumes to be dependent on another relative to some goal, he will have the goal of influencing the other to perform the (set of) action(s) that allows him to achieve his goal. And, on the grounds of a given assumed *DEP*-net, a network is derivable of possible goals and actions of influencing (*INFL*-net).

4.2. From dependence to power of influencing

However, the goal of influencing is not sufficient for an agent to succeed in influencing another. Also the *power* of influencing is necessary, that is, the power of making someone do what we want. We have already provided a simplified definition of the power of influencing (see *D4*).

Many are the possible bases of one's power of influencing. What we are mainly interested in here is the power of influencing derivable from a dependence relationship. If *x* is (and assumes to be) dependent on *y*'s performing a certain act in view of *p, y* is quite likely to have the power of influencing *x* relative to some other goal of *x*'s. We will try to describe the main steps of what --it should be stressed-- is but a rough derivation, and would surely benefit from a number of refinements.

4.2.1. Dependence as a basis for the power of influencing

As we know from *T1*, if *x* assumes his dependence on *y* relative to a certain a (say, painting a wall) useful for *p* (having the wall painted), *x* will have the goal that *y* performs that action: *(GOAL x (DONE-BY y a))*, e.g., the goal that *y* paints the wall.

Now we need some other condition --some sort of "persuasive" power of *y* over *x* about a means-end relationship between some action on *x*'s part and *y*'s action a. Suppose *y* has an action a_1 such that *x* comes to believe that *y* will do a (painting the wall) if *x* performs some other action a_2 (say, giving *y* some money). We can write something like:

$$(CANDO\ y\ a_1) \wedge ((DONE\text{-}BY\ y\ a_1) \supset (EVENTUALLY\ (BEL\ x\ ((DONE\text{-}BY\ x\ a_2) \supset (DONE\text{-}BY\ y\ a)))))$$

Action a_1 can be either a communicative act of promise (as in this case) or even threat, or any "demonstrative" behavior useful for making *x* believe the means-end relation between *x*'s action and *y*'s.

Suppose also that *(DONE-BY y* a_1*)* holds. Now, as we know from the condition-action rule, *A4*, if *x* believes that *q* implies *p* and has the goal that *p*, then he will also have the goal that *q*. Applying the condition-action rule to *x*'s goal that *(DONE-BY y a),* we obtain:

$$((BEL\ x\ ((DONE\text{-}BY\ x\ a_2) \supset (DONE\text{-}BY\ y\ a))) \wedge (GOAL\ x\ (DONE\text{-}BY\ y\ a))) \supset (GOAL\ x\ (DONE\text{-}BY\ x\ a_2))$$

That is, *x* will come to have the goal of giving *y* the money *(GOAL x (DONE-BY x* a_2 *))*, in order to obtain that *(DONE-BY y a)* -- on condition that the value of *(DONE-BY y a)* be greater than the cost of pursuing *(DONE-BY x* a_2 *)*: only in this case, in fact, *x* would accept *(DONE-BY x* a_2 *)* as a goal of his own, in view of *(DONE-BY y a)*. So, *y* is in fact endowed with an action a_1 such that *(GOAL x (DONE-BY x* a_2 *))*. This equals to saying that *y*, in virtue of both *x*'s dependence on her and her ability to make *x* believe the implication *(DONE-BY x* a_2 *) ⊃ (DONE-BY y a)*, has the power of influencing *x* to *(DONE-BY x* a_2*)*:

T3. ((BEL x (S-DEP x y a p)) ∧ (CANDO y a_1)
∧ ((DONE-BY y a_1) ⊃
(EVENTUALLY (BEL x ((DONE-BY x a_2) ⊃ (DONE-BY y a))))) ⊃
(INFL-POWER y x a_1 (DONE-BY x a_2))[4]

4.3. The act of influencing: goal plus power of influencing

So far, we have observed that: *x* (the dependent agent) has the *goal* of influencing *y*, while *y* has the *power* of influencing *x*. But, in this situation, *x* is the one who is the most interested in influencing *y*. And having a goal is a necessary, but not sufficient, condition for pursuing it, that is, for transforming that goal into an actual *intention*. A rational agent *x*, who is interested in influencing *y* relative to *p*, will pursue his goal of influencing *y* if he believes that goal to be achievable; in particular, he must believe he has the *power* of influencing *y*. Now, what can he do in order to have that power?

Of course, he can do a lot of things, among which just appealing to *y*'s benevolence. But, again, in the context of dependence relationships, the strategy of greatest interest would be *trying to find out some "dependence" of y on him*. In other words, *x* may try to derive his power of influencing *y* from *y*'s dependence on him relative to some goal. The goal in question might even be the same *p* relative to which he depends on *y*: in that case, *x* will try to persuade *y* that *p* is a *common* goal and that they (*x* and *y*) are related to each other by a *mutual DEP*-link; as already observed, this kind of dependence is typical of *cooperation*. Otherwise, *x* will try to find out some other goal *q* relative to which *y* may depend on him, and persuade *y* of their *reciprocal* dependence, that is typical of *social exchange*.

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[4] The expression

(CANDO y a_1)
∧ ((DONE-BY y a_1) ⊃ (EVENTUALLY (BEL x ((DONE-BY x a_2) ⊃ (DONE-BY y a)))))

can be seen as an instantiation of a more general case of a relationship between two agents, where the former is able to make the latter believe something. In other words a new predicate might be introduced, *BEL-POWER*, defined as follows:

D7. (BEL-POWER x y a p)= def (CANDO x a) ∧ ((DONE-BY x a) ⊃ (EVENTUALLY (BEL y p)))

that is: *x* has the power to make *y* believe *p* if he can do an action *a* (be it a simple communication of a fact *p* -- for instance, saying "It is raining" -- or a more indirect and subtle persuasive strategy -- for instance, taking an umbrella before going out) such that *y* comes to believe *p* (for instance, that it is raining). A particular instantiation of *D7* is the case when *p* corresponds to the implication between *x*'s doing a_2 and *y*'s doing *a*.

So, *T3* might be rephrased as follows:

T3b. ((BEL x (S-DEP x y a p)) ∧ (BEL-POWER y x a_1 ((DONE-BY x a_2) ⊃ (DONE-BY y a)))) ⊃
(INFL-POWER y x a_1
(DONE-BY x a_2))

5. CONCLUSIONS AND FURTHER DEVELOPMENTS

In this paper we have tried to move some steps toward a theory of dependence in decentralized intelligent systems. Our aim has been to clarify how to apply such a theory to the problem of communication control among agents. We have tried to show that dependence is the basis and the reason for social interaction, and sketched how, starting from knowledge about dependence, it is possible for an agent to devise actions of influencing other agents that are "realistically" able to do what he needs. In our view, the realism stems from the agent's coming to believe that he is involved in a dependence relation, and reasons and chooses to act according to that belief.

The present stage of our study is strongly based on the analysis of human social behavior. Further efforts must be carried out in order to achieve a satisfactory theory of both formal and computational aspects. Moreover, a number of interesting aspects have been neglected here, and should be addressed in a further development of the model.

First of all, one would need an analysis of the criteria for inference control in this model. In fact, innumerable dependence relationships may stem from all the possible benefits/detriments any agent may cause to another agent: if *y*'s action repertoire includes an action whose effect avails or damages a goal of *x*'s, *x* depends on *y* relative to that goal. Moreover, dependence relationships are in principle transient: a dependence relationship between *x* and *y* may arise from *x*'s *temporary* lack of an enabling condition for pursuing a given goal. And the goal itself may be a very contingent one in *x*'s mind. Hence, the risk that dependence relationships proliferate without any possible control.

In order to be able to select the most *relevant* dependence relationships within a given social world, and to predict various forms of social interaction on the grounds of these relevant relations, some criteria for the relevance of dependence relationships should be postulated. Among them, a few criteria might be: the presence vs. absence of *x*'s (the dependent person's) power of influencing *y* to perform the action *a* needed for realizing *p*; the "importance" of the goals with regard to which dependence occurs; the frequency of those goals; their being "active", that is, their entering the agent's actual decision processes, versus "inactive"; the contingency versus permanence of the lack of power conditions producing dependence.

Some quantitative aspects of dependence relationships would also improve the predictive power of the model. In particular, dependence may vary in its *degree*. The degree of dependence of *x* on *y* relative to *p* might be defined as the ratio between the *strength* of a *DEP*-link, which is a function of the coefficient of value of the goal that *p*, and the *number of alternatives* (agents other than *y* on which *x*

may depend) available to *x*. The higher the degree of dependence the more relevant the dependence relationship in question.

Finally, possible predictions might be put forward about the communicative acts occurring between agents in a dependence relationship: in fact, various communicative acts (requests, commands, etc.) might be inferred on the grounds of, say, the type of resource *x* needs from *y* (information, physical action, etc.) and the particular goal *x* needs to influence *y* to pursue.

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