Power and Dependence in Multiagent Systems

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1 Introduction

An important aim in the field of Multiagent Systems is to study emergent social structures, such as groups and collectives. The relevance of social structures in Distributed Artificial Intelligence [5, 6], Artificial Life [7], Sociology [3] necessitates a well motivated definition of their characteristics.

The research question of this paper is to formalize the results obtained by Castelfranchi [3] that try to bridge the gap between the BDI model and the macro-level of Multiagent Systems.

We presented in [2] general social viewpoints on Multiagent Systems and in [1] we have detailed a derivation of coalition structures from power structures. In this paper we continue the research, and we define power in terms of cognitive (or mind) view, i.e., starting from the characteristics of the single agents as their goals and skills. Properties of collectives, as mutual dependence or cooperation, are also hierarchically defined by means of the definition of power. It is shown that upper levels of this hierarchy need mental model of the agents more and more complex.

In real systems some actions can obstruct or ruin the effects of some others, sometimes they simply cannot be performed at the same time, or one of them has the priority over the others. All these features are referred to as the concurrency management problem and we formalize it in our system to improve its expressiveness.

2 Formalization of Multiagent Systems

We start with some logical preliminaries. $P = \{p, r, s...\}$ is a set of propositions, and *Litt* is the set of literals $P \cup \bar{P}$. *Ef* is the set of all the subsets of *Litt* that do not contain conflicting pair p and $\bar{p}$, and *Sw* is the subset of all the complete elements of *Ef*, i.e., if $sw \in Sw$ then for all p in P, either p or $\bar{p}$ is in sw.

A Multiagent System can be viewed as a set of agents populating an environment. The environment is described by means of *Sw*, which describe all its possible states. In order to describe agents we first need to formalize the actions they can perform and the effect rules that relate these actions with the effects on the environment.

Let $A = \{a, b, c, ...\}$ the finite set of all actions that can be performed by the different agents. We formalize not only the fact that an action should be performed to have some effects, but also that an other action does not have to be performed. For this purpose we use the set $\bar{A}$ and denote with *Act* the set of all sets $act \subseteq A \cup \bar{A}$ such that for all $a \in A$, a and $\bar{a}$ cannot belong both to *act*.

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Finally we define a rule as a formula $r \equiv \psi \cup \rho \rightarrow \phi$, where $\psi, \phi \in Ef$, and $\rho \in Act$. Given a set of rules R, for $r \in R$ *effects*(r) denotes ϕ and, given $R' \subseteq R$, *effects*$(R') = \bigcup_{r' \in R'}$ *effects*(r'). In the same manner *precond*$(r) = \psi$, and *actions*$(r) = \rho$.

For example a possible rule is: $\{a, \bar{b}, \bar{p}, s\} \rightarrow \{\bar{s}, q\}$. This rule tells us that in every sw in which $\bar{p}$ and s hold if the action a is performed and the action b is not performed, then in the next state $\bar{s}$ and q hold.

In general, since the agents are autonomous, they act simultaneously and hence they can activate more then one rule at the same time. Considering the union $\{\alpha_1, ..., \alpha_n\} \subseteq P \cup \bar{P}$ of the effects of these activated rules, the whole effect of the agents' activity on sw is denoted by $\{\alpha_1, \ldots, \alpha_n\} \frown sw$ and is defined as:

$$\{\alpha_1, \ldots, \alpha_n\} \cup (sw \setminus \{\beta \in sw \mid \exists\, 1 \leq i \leq n \;\; \alpha_i \equiv \bar{\beta}\})$$

It could happen that $\{\alpha_1, \ldots, \alpha_n\}$ does not belong to *Ef*, i.e., an attribute p exists such that more then one value is present in $\{\alpha_1, \ldots, \alpha_n\}$.

In order to avoid this sort of incompatibility two rules r_1 and r_2 have to satisfy one of the following conditions:

- *effects*$(r_1) \cup$ *effects*$(r_2) \in Ef$
- *precond*$(\psi_1) \cup$ *precond*$(\psi_2) \notin Ef$
- *actions*$(\psi_1) \cup$ *actions*$(\psi_2) \notin Act$

If one of the previous conditions are satisfied, we say that r_1 and r_2 are feasible with each other and, given a set of rules R if any pair of rules in it are feasible, then R is feasible itself.

Now we have all the ingredients to define a Multiagent System. Informally a Multiagent System is a composed by a set of agents and a set of effect rules. Any agent is able to perform a set of actions and has a set of desires, each of them expressed as an element of *Ef*, i.e., a conjunction of no conflicting literals:

Definition 1 *Let P a set of propositions, A a set of actions, Ef defined in P, a Multiagent System, MaS, is tuple*

$$\langle Ag, goals\colon Ag \rightarrow 2^{Ef}, skills\colon Ag \rightarrow 2^{A}, R\colon Ef \cup Act \rightarrow Ef \rangle$$

where Ag is a set of agents, goals is a function that associates to each agent a set of desires, skills is a function that describes the actions each agent can perform and R is a set of feasible effect rules.

3 Formalization of Power and Dependence

In this section we define the relation of power as in Castelfranchi [3], i.e. the capability of a set of agents to achieve some effects, useful from some agent, independently from the activity of the others.

Before defining the relation of power we first formalize when, in a state sw, a set of agents Q would be able to achieve the set of effects

G by means of the actions $K \in Act$. First of all Q should be able to perform all the positive actions belonging to K, moreover there should be some rules such that: they involve in sw all the effects in G, the conditions to apply these rules are satisfied by sw, finally the actions that these rules prescribe (to perform or to not perform) are all listed in K.

Definition 2 (Able) *A set of agents $Q \subseteq Ag$ is able to achieve the effects $G \in 2^{Ef}$ by the actions $K \in Act$ in the state $sw \in SW$, $Able(Q, G, K, sw)$, iff:*

1. $K \cap A \subseteq \bigcup_{ag \in Q} skills(ag)$
2. $\exists \hat{R} \subseteq R\ [\bigcup_{g \in G} g \subseteq effects(\hat{R}) \frown sw\ \wedge$

   $\bigcup_{\hat{r} \in \hat{R}} actions(\hat{r}) = K\ \ \wedge\ \ \forall \hat{r} \in \hat{R}\ precond(\hat{r}) \subseteq sw]$

It is easy to see that the following theorem holds:

Theorem 1 *The relation Able is monotonic with respect to the union of sets of agents:*

$$Able(Q, G, K, sw) \Longrightarrow \forall \hat{Q} \subseteq Ag\ Able(\hat{Q} \cup Q, G, K, sw)$$

This is correct from an ontological point of view since, when an agent is added to a group, then the set of effects the new group should be able to achieve have to grow. Nevertheless an important feature is the property of minimality, i.e., Q is the minimal set of that are able to achieve G. This involves the definition of *Min_Able*:

Definition 3 *Suppose that $Able(Q, G, K, sw)$ holds, then $Min\_Able(Q, G, K, sw)$ holds iff:*

$$\forall \hat{Q} \subset Q\ \neg Able(\hat{Q}, G, K, sw)$$

What does the *Able* definition lack of to be a definition of power? First of all power concerns the possibility to use some skills in order to achieve some own goals or as exchange goods for other agents' goals [3]. To have skills that all the community considers useless do not add any power to a set of agents. Furthermore there should be no way, for the other agents, to obstruct Q to achieve G.

So, in order to define a power relation, we define a relation that regards the capability of a set of agents Q_1 to obstruct another set Q_2 in the achievement of a set of effects G. First of all Q_2 should be able to achieve G by means of some actions K, then Q_1 can obstruct Q_2 if one of its agents is skilled to perform an action and K prescribes that it should not be performed. This is not the only way Q_2 can obstruct Q_1. Suppose that the current state sw is equal to $\{s, \bar{r}\}$ and that two rules can be used: $a \rightarrow r$ and $b \rightarrow \bar{s}$. If the goal of Q_2 was $\{s, r\}$ and one of its agents was able to perform a, then Q_2 would be able to achieve its goal. Nevertheless suppose that one of the agents of Q_1 was able to perform b, so it could nullify the efforts of Q_2 making s false. The previous considerations lead to:

Definition 4 (Obstruction) *A set of agents Q_1 can obstruct another set Q_2 in the achievement of the set of effects G by means of K, $Can\_obstruct(Q_1, Q_2, G, K, sw)$, iff $Able(Q_2, G, K, sw)$ and one of the following conditions holds:*

1. $\exists \bar{c} \in K \cap \bar{A}\ \ \exists ag \in Q_1\ \ c \in skills(ag)$
2. $\exists e \in Ef\ \exists \hat{W} \in Act\ \ [Able(Q_1, e, \hat{W}, sw)\ \wedge$

   $e \cup \bigcup_{g \in G} g \notin Ef\ \ \wedge\ \ (K \cap A) \cup (\hat{W} \cap \bar{A}) \in Act]$

Now we define the relation of power as the capability of a group Q to perform some actions that achieve, without the possibility to be obstructed, some effects G in which any element is a goal of at least one agent. We define a minimality condition also for power and we will use it later to define the dependence relation.

Definition 5 (Power) *Let $Q \subseteq Ag$, $G \in 2^{Ef}$, $K \in Act$, then the set of agents Q has the power to achieve the set of goals G by means of the actions K in the state of the world sw, $Pow(Q, G, K, sw)$, iff all following items are satisfied:*

1. $G \subseteq \bigcup_{ag \in Ag} goals(ag)$
2. $Able(Q, G, K, sw)$
3. $\neg \exists \bar{Q} \subseteq (Ag \setminus Q)\ \ Can\_obstruct(\bar{Q}, Q, G, K, sw)$

If the previous conditions are satisfied with Min_Able instead of Able, then $Min\_Pow(Q, G, K, sw)$.

We also define $Lack\_pow(Q, G, sw)$ when a set of agents Q desires some set of goals G but it has not the power to achieve it.

Definition 6 (Lack of power) *A set of agents $Q \subseteq Ag$ lacks the power to achieve a set of goals, $G \in 2^{Ef}$, $Lack\_pow(Q, G, sw)$, iff these two items are satisfied:*

1. $\forall g \in G\ \forall ag \in Q\ \ g \in goals(ag)$
2. $\neg \exists K \in Act\ \ Pow(Q, G, K, sw)$

Now the concept of dependence is formalized. A dependence exists when a group Q_1 lacks the power to achieve some goals, whereas some other group Q_2 can achieve it. Obviously the agents in the group Q_2 should be all necessary for the fulfillment of the goals, because we do not want to formalize the dependence on useless agents, so we consider the definition *Min_Pow* shown in the previous section that, satisfying the minimality condition, does not allow the presence of useless members.

Definition 7 (Dependence) *The set of agents Q_1 depends on the set of agents Q_2 to achieve, in the state sw, the goals G by the actions $K \in Act$, $Dep(Q_1, Q_2, G, K, sw)$, iff the following items hold:*

1. $Lack\_pow(Q_1, G, sw)$
2. $Min\_Pow(Q_2, G, K, sw)$

Pow, *Lack_pow* and *Dep* are the basic relations on which it is possible to describe social relations among set of agents. In particular it is possible to define the mutual dependence of two groups to achieve common goals:

Definition 8 (Mutual dependence) *Two sets of agents Q_1, Q_2, such that $Q_1 \cap Q_2 = \emptyset$, mutually depend on each other to achieve the goals G by means of the actions $K \in Act$, $Mutual\_depend(Q_1, Q_2, G, K, sw)$, iff:*

$$Dep(Q_1, Q_1 \cup Q_2, G, K, sw)\ \wedge$$
$$Dep(Q_2, Q_1 \cup Q_2, G, K, sw)$$

4 Formalization of Cooperation

In this section we formalize the notion of cooperation among agents. The reason for cooperating is the existence of a mutual dependence. If mutual dependence is a relation still untied to the intentions of the agents, in contrast cooperation concerns what they actually want to achieve and the actions they are going to perform. In order to describe agent's intentions we extend the definition of a Multiagent System (Definition 1) with a function $intend : Ag \rightarrow Act$ that maps any agent to the actions it intends to perform. We assume that if ag intends to perform some actions, then he is also skilled to, so $\forall ag \in Ag\ \ intend(ag) \subseteq values(skills(ag))$.

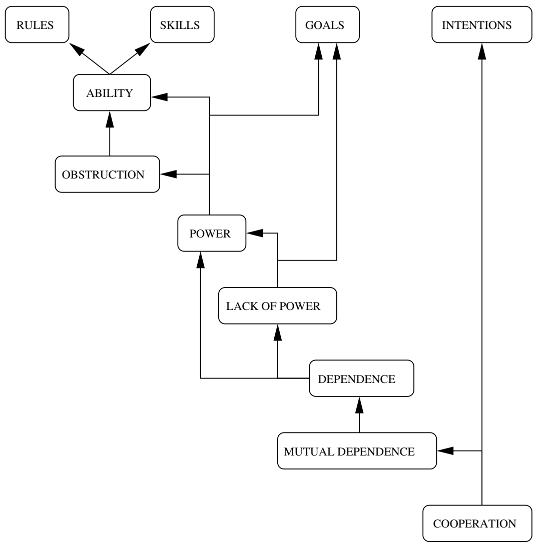

Figure 1. *Ontology of group relations*

The elements in $\mathit{intend}(ag)$ that belong to A are the actions ag intends to perform, the elements that belongs to $\bar{A}$ are the actions the agent wants to be not performed, finally the actions not mentioned will not be performed but only for an economical principle (in other words, ag guesses that actions will not entail particular benefits or damages).

We now need a formalization of the actions a set of agents intends to perform, starting form the individual intentions. We preliminarily define:

Definition 9 (Positive union) *Let $p_1, p_2 \subseteq A \cup \bar{A}$, then the positive union $p_1 \oplus p_2$ between p_1, p_2 is:*

$$p_1 \oplus p_2 \equiv p_1 \cup p_2 - \{\bar{a} \in \bar{A} \mid a \in p_1 \cup p_2\}$$

Given two agents ag_1 and ag_2, if I_1 is the intention of the former and I_2 of the latter, then the intentions of both of them will be $I_1 \oplus I_2$ since all the positive actions listed in I_1 and I_2 will be performed by one agent, even if the others refrain from performing it. Stated this, we can formalize the notion of intentions for sets of agents.

Definition 10 (Collective intentions) *Given $\mathit{intend}\colon Ag \to Act$ and $Q \subseteq Ag$, then the intention of the group Q is:*

$$\mathit{intend}(Q) \equiv \bigoplus_{ag \in Q} \mathit{intend}(ag)$$

Now a cooperation between two groups exists when they mutual depend in the achievement of a set of goals and the actions they intend to perform enable the satisfaction of this dependence.

Definition 11 (Cooperation) *We say that the two groups $Q_1, Q_2 \subseteq Ag$ are cooperating to achieve the set of goals G in the state sw given their intentions $\mathit{intend}(Q_1)$, $\mathit{intend}(Q_2)$; $Cooperating(Q_1, Q_2, G, \mathit{intend}(Q_1), \mathit{intend}(Q_2), sw)$ iff:*

1. $\exists K \in Act : \mathit{Mutual\_depend}(Q_1, Q_2, G, K, sw) \wedge K \subseteq \mathit{intend}(Q_1) \oplus \mathit{intend}(Q_2)$

5 Conclusion and related works

Our approach gives a description of power and dependence, relating them to the definition of a Multiagent System. In this way it is shown how these concepts, involving sets of agents, emerge from a description of single agents.

The basic important issues emphasized in [3] are addressed in our framework, as the relation of power with the goals and the skills of the single agents or the description of mutual dependence. All these relations are defined in a formal context, quite expressive to take into account not only the capability of the agents to help, but also to obstruct each other.

We also formalize the relation between mutual dependence and cooperation distinguishing the possibilities agents have to help each other from what they actually intend to do.

Sichman and Conte [4] use graph theory to emphasize the topology of dependencies, but many simplifications reduce the expressiveness of their framework, for example they do not formalize the concurrency management problem so they do not take in account the possibility to obstruct the achievement of a goal. Moreover our framework describes powers and dependencies for sets of agents allowing to scale on the structure of the system.

Figure 1 describes an ontology of the relations defined in the previous sections. It is possible to distinguish two dimensions: a vertical one and an horizontal one. The former shows how a stack of properties, built one by means of another, proceeds from the description of the single agents towards the description of collectives of agents. In this sense we say that this stack shows the emergence of social levels. In the latter dimension it is possible to recognize how, growing in the emergence levels, more and more cognitive features of the agents are involved, so ability needs only the agent's skills and the effect rules, power also the agent's goals, and, finally, intentions of sets of agents are necessary to describe cooperation.

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