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# A Logic for Agent Organizations

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**Abstract.** Organization concepts and models are increasingly being adopted for the design and specification of multi-agent systems. Agent organizations can be seen as mechanisms of social order, created to achieve common goals for more or less autonomous agents. In order to develop a theory on the relation between organizational structures, organizational actions and actions of agents performing roles in the organization we need a theoretical framework to describe and reason about organizations. The formal model presented in this paper is sufficiently generic to enable the comparison of different existing organizational approaches to MAS, while having enough descriptive power to describe realistic organizations.

## 1 Introduction

Organizing is important in distributed computational systems, just as it is important in human systems. Researchers, within both the computer science and the organization theory fields, agree that many concepts and ideas can be shared between the two disciplines to better understand human organizations and to design more efficient and flexible distributed systems ([38, 6, 19]). However, due to its nature, organizational theory research tends to be not very formal from a computational perspective, which makes it difficult when moving from its use as a concept or paradigm towards using social and organizational concepts for the formalization of MAS social concepts. Given such different views, the difficulty of comparing, analyzing and choosing a given approach becomes clear. Even if our aim is not to solve this problem, in this paper we present initial steps towards the specification of a formal model for the study of organizations. The motivations for this model are twofold. On the one hand, the need for a formal, provable representation of organizations, with their environment, objectives and agents in a way that enables to analyze their partial contributions to the performance of the organization in a changing environment. On the other hand, such a model must be realistic enough to incorporate the more ‘pragmatic’ considerations faced by real organizations. Most existing formal models lack this realism, e.g. either by ignoring temporal issues, or by taking a very restrictive view on the controllability of agents, or by assuming complete control and knowledge within the system (cf. [41, 36]).

Formal models for organizations that are able to deal with realistic situations, must thus meet at least the following requirements [11].

1. represent notions of ability and activity of agents, without requiring knowledge about the specific actions available to a specific agent (to enable representation of open environments)

2. accept limitedness of agent capability
3. represent the ability and activity of a group of agents
4. deal with temporal issues, in special the fact that activity takes time
5. represent the concept of 'being responsible' for the achievement of a given state of affairs
6. represent organizational (global) goals and its link to agents' activity, by relating activity and organizational structure

All of the above requirements are related to the more structural properties of an organization and will be met with the theory developed in this paper. In [11] also the following requirements were listed:

1. deal with resource limitedness and the dependency of activity on resources (e.g. costs)
2. represent organizational dynamics (evolution of organization over time, changes on agent population)
3. represent organizations in terms of organizational roles or positions
4. relate roles and agents (role enacting agents)
5. deal with normative issues (representation of boundaries for action and the violation thereof)

These requirements are related to the more operational aspects of an organization. E.g. the notion that agent activity has a cost (that is, choosing one or the other course of action is not only dependent on agent capabilities but also the costs of the action must compare positively to its benefits) is related to actual performance of an agent within the organizational structure. Due to space limitations we will not deal with these requirements in this paper. Some directions for a formal framework dealing with these issues can be found in [11, 7, 22, 40].

This paper is organized as follows: in section 2 we discuss related work and motivate the need for the formal language presented in this paper. In section 3 we define ability and activity of agents and groups. Section 4 presents the formal model for organization including structural and interaction properties. The use of our model for the modelling of organizations is exemplified in section 5. Finally, section 6 presents our conclusions and directions for future work.

## 2 Related Work

Several approaches have already been presented to investigate the complexity of reasoning and analysis of multi-agent systems. In their own way, all approaches are concerned with some of the requirements above and can be basically divided into two categories: formal methods and engineering frameworks. Formal methods for MAS have a logical basis, typically based on dynamic, temporal and/or deontic logics [41, 36, 21]. However, the treatment of organizational concepts is basic and lacks realism. For instance, approaches based on ATL assume complete division of agent capabilities and total control over the domain, and the work presented in [36] lacks temporal issues. Furthermore, in most cases, an axiomatic formalization is provided but not a formal semantics. Engineering frameworks, on the other hand, provide sound representation languages that

include many realistic organizational concepts, but have often a limited formal semantic basis, which makes analysis and comparison difficult [26, 31, 39].

Organization Theory provides very useful concepts, and a pragmatic perspective, based on real world (human) organizations [13, 33, 37]. However, results are often domain oriented and it is not clear how to translate them into formalisms for agent systems. It is often seen as a sound basis for conceptual design, proven in practice of human organizations for many years, but it must be formalized in order to make it usable for computational models of organizations. Computational organizational science is a new perspective that tries to combine the organization theory and engineering framework perspectives. It looks at groups, organizations and societies and aims to understand, predict and manage system level change [3]. Several tools for the analysis and modelling of organizations have been proposed. Computational models, in particular those based on representation techniques and empirical simulation, have been widely used for several decades to analyze and solve organizational level problems. More recently, mathematical tools, including those of decision and game theory, probability and logic are becoming available to handle multiple agency approaches to organizations.

In practice, organizational level solutions are provided by mathematical and computational models based on probabilistic and decision theoretic approaches. A large body of work in this area is that of computational simulation, specifically agent-based social simulation (ABSS) [8]. Computational simulations are based on formal models, in the sense that they provide a precise theoretical formulation of relationships between variables. Simulations provide a powerful way to analyze and construct realistic models of organizational systems and make possible to study problems that are not easily addressed by other scientific approaches [25]. Such formal models are however limited to the specific domain and difficult to validate. Techniques are thus needed that make possible the formal validation, comparison and extendability of simulation models. As far as we are aware of, the language presented in this paper, based on modal logic is a first attempt to provide such a meta model for reasoning about computational models, that has both a formal semantics as well as the capability to represent realistic concepts.

### 3 Agents and Groups: Ability and Activity

The notions of agent capability and action have been widely discussed in MAS. The intuition is that an agent possesses capabilities that make action possible. In the literature, there are many approaches to the formalization of these definitions<sup>1</sup>. Concerning the theory of action, two main perspectives can be distinguished. The first aims at the explicit representation of action by a specific agent, in terms of dynamic logic [24], [32], or situation calculus [29]; whereas the second is concerned with representing the fact that a certain result has been achieved, such as in the *stit* theories [35] or in the notion of agency by Elgesem [14]. In both types of approaches, the notion of action is strongly linked to that of ability. However, there is no consensus on the meaning of ability which is taken to mean competence (the capability of making a certain proposition true), possibility (conditions are right for that activity), opportunity (both competence

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<sup>1</sup> A concise overview can be found in [5]

and possibility), or even permission (there are no prohibitions or constraints on the activity.). As these distinctions are important for organizational theory, we aim to develop a theory in which all these concepts can be expressed properly.

### 3.1 Logic for Agent Organization

We present here a *logic for agent organization* (LAO), as an extension of the well-known branching time temporal logic CTL [15]. LAO includes the CTL modalities  $\diamond$  ('always in the future'),  $\mathcal{U}$  ('until') and  $X$  ('in the next state') extended with modalities for agent ability, capability, attempt and activity introduced in the following subsections. For a set  $\Phi$  of propositional variables, the language,  $\mathcal{L}$  for LAO is the smallest superset of  $\Phi$  such that

1.  $true, false \in \mathcal{L}$
2.  $p \in \Phi \Rightarrow p \in \mathcal{L}$
3.  $\varphi, \psi \in \mathcal{L} \Rightarrow \neg\varphi, (\varphi \vee \psi), X\varphi, \diamond\varphi, \mathcal{U}\varphi \in \mathcal{L}$

To give a precise definition of LAO, we start by introducing the semantic structures over which formulae of LAO are interpreted. A LAO model is a tuple

$$M = (\Phi, A, W, R, T, \pi), \text{ where:}$$

- $\Phi$  is a finite, non-empty set of *propositional variables*,
- $A = \{a_1, \dots, a_n\}$  is a finite, non-empty set of *agents*,
- $W$  is a non empty set of states,
- $R$  is a partial ordered set of (temporal) transitions between two elements of  $W$ ,  
 $R : W \times W$ ,
- $T$  is the set of agent labels on elements of  $R$ ,  $T : R \rightarrow 2^A$ ,
- $\pi$  is a valuation function which associates each  $w \in W$  with the set of atomic propositions from  $\Phi$  that are true in that world,  $\pi : W \rightarrow 2^\Phi$

Each world,  $w \in W$  describes the propositions of  $\Phi$  that are true in that world, and, each proposition in  $\Phi$  corresponds to a set of worlds where it is true. A transition between worlds represents an update of the truth value of (some) propositions in  $\Phi$ . The semantics of LAO are based on those of CTL\* [15], which distinguishes between path and state formulae. A state formula is interpreted wrt a state  $w \in W$  and a path formula is interpreted wrt a path through the branching time structure given by  $R$ . A path (or trace) in  $R$  is a (possibly infinite) sequence  $(w_i, w_{i+1}, \dots)$ , where  $w_i, w_{i+1}, \dots \in W$  and  $\forall i (s_i, s_{i+1}) \in R$ . We use the convention that  $r = (w_0, w_1, \dots)$  denotes a path, and  $t(i)$  denotes state  $i$  in path  $r$ . We write  $M, w \models \varphi$  (resp.  $M, r \models \varphi$ ) to denote that state formula  $\varphi$  (resp. path formula  $\varphi$ ) is true in structure  $M$  at state  $w$  (resp. path  $r$ ). The rules for the satisfaction relation  $\models$  for state and path formulae in LAO are defined as:

- $M, w \models \top$
- $M, w \models p$  iff  $p \in \pi(w)$ , where  $p \in \Phi$
- $M, w \models \neg\varphi$  iff not  $M, w \models \varphi$
- $M, w \models \varphi \vee \psi$  iff  $M, w \models \varphi$  or  $M, w \models \psi$
- $M, w \models \diamond\varphi$  iff  $\forall r \in \text{paths}(W, R)$ , if  $r(0) = w$  then  $(M, r) \models \varphi$

- $M, r \models p$  iff  $M, r(0) \models p$
- $M, r \models \neg\varphi$  iff not  $M, r \models \varphi$
- $M, r \models \varphi \vee \psi$  iff  $M, r \models \varphi$  or  $M, r \models \psi$
- $M, r \models \psi\mathcal{U}\varphi$  iff  $\exists i$  such that  $M, r(i) \models \varphi$  and  $\forall k \leq i, M, r(k) \models \psi$
- $M, r \models X\varphi$  iff  $\forall r'$  if  $(r, r') \in R$  then  $M, r' \models \varphi$

This semantic definition above does not consider the agents in the system, and therefore does not make use of the semantic component  $T$ . Intuitively, the idea is that, in organizations, changes are for some part result of the intervention of (specific) agents. Formally, state transitions are labelled with the set of agents that influence the changes on that transition. That is, for a transition  $r = (w, w') \in R$ ,  $t(r)$  indicates the set of agents that indeed contribute to the changes indicated by that transition. Moreover, for each world  $w \in W$  and each agent  $a \in A$  we can indicate the set of transitions from  $w$  for which  $a$  has influence.

**Definition 1. (Transition influence)**

Given a world  $w \in W$  and an agent  $a \in A$ , the transition influence of  $a$  in  $w$ ,  $T_{aw}$  is defined by:  $T_{aw} = \{r \in R : r = (w, w') \text{ and } a \in t(r)\}$

Agent action is based on the capabilities of the agent, but also on the moment circumstances in which the agent is. In the following, we will introduce extra modal operators to represent capability, ability, attempt and action of agents and groups.

### 3.2 Agent capability, ability and activity

In this section, we draw from work in the area of the well known logical theory for agency and organized interaction introduced by Kanger-Lindahl-Pörn, more specifically from the work of Santos et al.[36] and Governatori et al. [21]. In short, they assume that in organizations not all capabilities are always conducive of successful action - one can attempt to achieve something but without success. They've introduced three operators  $E$ ,  $G$  and  $H$ . The first one,  $E$ , expresses direct and successful actions: a formula like  $E_i\varphi$  means that the agent  $i$  brings it about that  $\varphi$ , that is  $\varphi$  is a necessary result of an action by  $i$ . The second one,  $G_i\varphi$  corresponds to indirect and successful actions, that is,  $G_i\varphi$  means that  $i$  ensures that  $\varphi$ , that is,  $\varphi$  is a necessary result of an action of some agent following an action by  $i$ . Finally, their intended meaning of  $H$  is such that  $H_i\varphi$  means that  $i$  attempts to make it the case that  $\varphi$ . The idea is that  $H$  is not necessarily successful.

In their work, an axiomatic definition of  $E$ ,  $G$  and  $H$  is given. Our approach is to provide a semantical definition of the modal operators for ability, capability attempt and activity. Moreover, we agree with [21] that the assumption taken in [36] that indirect action always implies an impossibility for direct action is rather strong, and will not use it. We furthermore, base our definitions on temporal logic and not just in predicate logic in order to be able to express the notion that activity takes time.

Intuitively, in order to talk about agent activity, that is, that agent  $a$  'causes' an expression  $\varphi$  to hold in some future state in a path from the current moment, we need to establish the control of the agent over the truth value of  $\varphi$ . For instance, it does not make sense to express  $E_a \text{sun.raises}$  because whether the sun raises or not is not something

that an agent can control. Inspired by the work of Boutelier [1], and Cholvy and Garion [4], we define the capabilities of an agent  $a$  as follows:

**Definition 2. (Agent Propositional Capability)**

Given a set of atomic propositions  $\Phi$  and a set of agents  $A$ , for each agent  $a \in A$  we partition  $\Phi$  in two classes: the set of atomic propositions that agent  $a$  is capable of realizing,  $C_a$ , and the set of atomic propositions that  $a$  cannot realize,  $\bar{C}_a$ ,  $\bar{C}_a = \Phi \setminus C_a$ .

In order to be able to formally refer to the capability of an agent to realize any given expression of  $\mathcal{L}$ , we need first to extend the above definition to describe the capability for composed propositions. Given a set  $C_a$  defining the propositional capability of  $a$ , we define  $\Sigma_a$  inductively as follows:

- $\forall p \in C_a, p \in \Sigma_a$
- $\forall p \in C_a, \neg p \in \Sigma_a$
- $\forall \psi_1, \psi_2 \in \Sigma_a, \psi_1 \wedge \psi_2 \in \Sigma_a$

Agent capability  $C_a\varphi$  can now be defined as:

**Definition 3. (Agent Capability)**

Given a formula  $\varphi$  in  $\mathcal{L}$  and an agent  $a \in A$ , agent  $a$  is capable of  $\varphi$ , represented by  $C_a\varphi$  iff  $\not\models \varphi$  and  $\exists \psi \in \Sigma_a$ , such that  $\psi \rightarrow \varphi$ .

Using this definition, it is trivial to prove that  $\forall \psi \in \Sigma_a : C_a\psi$ . The capability operator has the following properties:

- $\neg C_a\top$
- $C_a\varphi \wedge C_a\psi \rightarrow C_a(\varphi \wedge \psi)$

Note that  $C_a\varphi \rightarrow C_a\neg\varphi$  does not hold as it can be seen by the following counterexample. Consider  $\Phi = \{p, q\}$ ,  $\varphi = p \vee q$  and  $C_a p$ . Then,  $C_a(p \vee q)$  (because  $p \rightarrow p \vee q$ ) but  $\neg C_a(\neg p \wedge \neg q)$  (because  $\neg p \not\rightarrow \neg p \wedge \neg q$ ). In the same way, it can be proven that  $C_a\varphi \rightarrow \Diamond\varphi$  also does not hold.

Given a capability  $C_a\varphi$ , we can say that agent  $a$  controls  $\varphi$ , which means that  $a$  is able (possibly under certain conditions) to make  $\varphi$  hold. However, capabilities do not lead directly to ability. Intuitively, the ability of an agent to realize a state of affairs  $\varphi$  in a world  $w$ , depends not only on the capability of the agent but also on the status of that world. Therefore, we define the ability of  $a$  as follows:

**Definition 4. (Agent Ability)**

Given a world  $w \in W$  and an agent  $a \in A$ , the ability of  $a$  to realize  $\varphi$ ,  $G_a\varphi$ , is defined by  $w \models G_a\varphi$  iff  $C_a\varphi$  and  $\exists t \in T_{aw} : t = (w, w'), w' \models \varphi$ .

Agent ability refers to the potential of that agent to act in a world. However, intuitively, the expected result of agent action is that the desired state of affairs will hold in all worlds reachable from the current world. That is, that the agent will indeed influence the future worlds. Obviously, if the agent does not influence all futures from the current world, it cannot guarantee the overall success of its activity. We therefore define agent attempt, as follows:

**Definition 5. (Agent Attempt)**

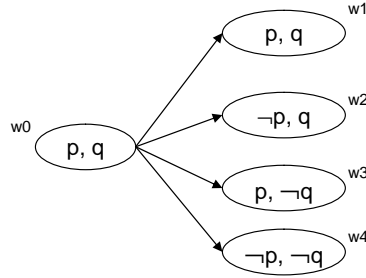
Given a world  $w \in W$  and an agent  $a \in A$ , the attempt of  $a$  to realize  $\varphi$ ,  $H_a\varphi$ , is defined by  $w \models H_a\varphi$  iff  $G_a\varphi$  and  $\forall t \in T_{aw} : t = (w, w'), w' \models \varphi$ .

Attempt contains an element of uncertainty. Even if it is necessary that the agent has the capability to achieve a certain state of affairs, it can happen that, due to activity by other agents, with the same capability, the state of affairs will not hold in all worlds whose transitions are under the influence of the agent. That is, the definition of attempt yields that, in the case that there are other agents capable of realizing  $\varphi$ , those agents either have no influence over transitions in  $T_{aw}$  or also made an attempt to achieve  $\varphi$ . Formally:

$$\text{If } w \models H_a\varphi \text{ then } \forall b \in A, b \neq a : (\neg C_b\varphi \vee H_b\varphi \vee (\forall t \in T_{aw} : t \notin T_{bw}))$$

As an example, consider model  $M = (\{p, q\}, \{a\}, \{w_0, \dots, w_4\}, \{(w_0, w_1), \dots, (w_0, w_4)\}, T, \pi)$ , as depicted in figure 1. We furthermore define that  $C_ap$  and  $(w_0, w_1) \in T_{aw_0}$ . In this model, it holds that:

- $w_0 \models G_ap$  (because  $C_ap$  and  $w_1 \models p$ );
- $w_0 \models H_ap$  iff  $T_{aw} = \{(w_0, w_1), (w_0, w_3)\}$ ;
- $w_0 \not\models C_a(p \wedge q)$ ;
- $w_0 \not\models G_a(p \wedge q)$  (because  $\neg C_a(p \wedge q)$ )



**Fig. 1.** Example for capability, ability and attempt.

The notion of ability expresses the fact that an agent  $a$  has the capability to bring  $\varphi$  about. It does not mean that the agent will indeed ever do it. On the other hand, the notion of attempt expresses the fact that an agent tries to achieve a certain state of affairs, but does not guarantee success. Obviously, agents must be able to *act* on the world and as such bring states of affairs to happen.

Because we abstract from the internal motivations of individual agents, we need ways to describe the result of agent action that are independent of particular actions available to the agent. The *stit* operator,  $E_a\varphi$  ('agent  $a$  sees to it that  $\varphi$ '), introduced by Pörn [35] allows to refer to the externally '*observable*' consequences of an action instead of the action itself. *Stit* can be seen as an abstract representation of the family of actions that result in  $\varphi$ . In our approach we refine the definition of *stit* to include a



temporal component that indicates the notion that action takes time.

Only when the agent influences all possible worlds out of the current one, we can say that the agent can see to it that a given state of affairs is achieved. In the special case in which all next possible states from a given state are influenced by an agent  $a$ , we say that  $a$  is **in-control** in  $w$ , represented by  $IC_a$  and defined formally as:

**Definition 6. (Agent In-control)**

$$w \models IC_a \text{ iff } \forall w' : (w, w') \in R \Rightarrow (w, w') \in T_{aw}$$

In the following we give our semantics of *stit*, in terms of agent attempt (definition 5) and in-control (definition 6).<sup>2</sup>

**Definition 7. (Agent Activity)**

Given a world  $w \in W$  and an agent  $a \in A$ ,  $a$  sees to it that  $\varphi$  holds,  $E_a\varphi$ , is defined by  $w \models E_a\varphi$  iff  $H_a\varphi$  and  $IC_a$ .

$E_a\varphi$  represents the actual action of bringing  $\varphi$  about. From the semantics above: if  $a$  is able of  $\varphi$  and attempts to realize it in a world where it is in control, then  $E_a\varphi$  ‘causes’  $\varphi$  to be true in all next states from the current state. Furthermore, it is important to notice that we provide a temporal definition of  $E_a$ , that is,  $E_a\varphi \not\rightarrow \varphi$  but  $E_a\varphi \rightarrow X\varphi$ . This provides a more realistic notion of *stit* by incorporating the fact that action takes time and is not instantaneous, as we have discussed before (cf. [12]) but is different from many other authors, e.g. [36].

The operator  $E$  has the following properties:

- $\neg E_a \top$
- $E_a\varphi \rightarrow X\varphi$
- $E_a\varphi \rightarrow C_a\varphi$
- $E_a\varphi \rightarrow H_a\varphi$
- $E_a\varphi \rightarrow IC_a$
- $E_a\varphi \wedge E_a\psi \rightarrow E_a(\varphi \wedge \psi)$

### 3.3 Group Capability, Ability and Activity

By definition, agents are limited in their capabilities, that is, on what states of affairs they can bring about in the world. This implies that in MAS certain states of affairs can only be reached if two or more agents cooperate to bring that state about. One of the main ideas behind organizations is the notion that the combined action of two or more agents can result in an effect that none of the involved agents could bring about by themselves. In MAS there is very little research done on the notion of ability in a multi-agent context [5]. In the following, we define the concept of combined capability, or *group capability*. As for single agents, we need to start by defining the capabilities of a group over atomic propositions. The idea behind this definition, is that atomic propositions can be made ‘small’ enough to be controlled by a single agent. A group combines results from different agents into more complex actions.

<sup>2</sup> This notion of stit provides a *necessary* interpretation of action, and as such is related to the dynamic operator  $[a]p$ , meaning that after performing action  $a$  it is necessarily the case that  $p$ .

**Definition 8. (Group Propositional Capability)**

Given a set of agents  $S = \{a_1, \dots, a_n\} \subseteq A$  and the sets  $C_{a_i}$  of atomic propositions controllable by each agent  $a_i \in S$ , we define  $C_S$  as the union of the controllable propositions by all agents in  $S$ :  $C_S = \bigcup_{i=1}^n C_{a_i}$

In the same way as for single agents, we define composed capability of a group  $\Sigma_S$  as follows:

- $\forall p \in C_S, p \in \Sigma_S$
- $\forall p \in C_S, \neg p \in \Sigma_S$
- $\forall \psi_1, \psi_2 \in \Sigma_S, \psi_1 \wedge \psi_2 \in \Sigma_S$

Group capability  $C_S\varphi$  can now be defined as:

**Definition 9. (Group Capability)**

Given a formula  $\varphi$  in  $\mathcal{L}$  and a set of agents  $S \subseteq A$ ,  $S$  is capable of  $\varphi$ , represented by  $C_S\varphi$  iff  $\not\models \varphi$  and  $\exists \psi \in \Sigma_S$  such that  $\psi \rightarrow \varphi$ .

The definitions of group ability, group attempt, group in-control, and group stit are similarly derived from the respective definitions for a single agent.

**Definition 10. (Group Ability)**

Given a world  $w \in W$  and a group  $S \subseteq A$ , the ability of  $S$  to realize  $\varphi$ ,  $G_S\varphi$ , is defined by:  $w \models G_S\varphi$  iff  $C_S\varphi$  and  $\exists t \in T_{Sw} : t = (w, w'), w' \models \varphi$

**Definition 11. (Group Attempt)**

Given a world  $w \in W$  and a group  $S \subseteq A$ , the attempt of  $S$  to realize  $\varphi$ ,  $H_S\varphi$ , is defined by  $w \models H_S\varphi$  iff  $G_S\varphi$  and  $\forall t \in T_{Sw} : t = (w, w'), w' \models \varphi$ .

**Definition 12. (Group In-control)**

$w \models IC_S$  iff  $\forall w' : (w, w') \in R \Rightarrow S \subseteq t((w, w'))$

**Definition 13. (Group Stit)**

Given a world  $w \in W$  and a group  $S \subseteq A$ ,  $S$  sees to it that  $\varphi$  holds,  $E_S\varphi$ , is defined by  $w \models E_S\varphi$  iff  $H_S\varphi$  and  $IC_S$ .

Consider again the example in figure 1, in which agent  $a$  with  $C_a p$  did not have the ability for  $(p \wedge q)$ . Now, suppose that there is an agent  $b$  such that,  $C_b q$ . In the same way,  $\neg G_b(p \wedge q)$ . However, if we consider the group  $S = \{a, b\}$  we get  $C_S(p \wedge q)$ , and thus  $G_S(p \wedge q)$  when  $t_1 \in T_{Sw}$ . That is, together  $a$  and  $b$  are able of realizing  $(p \wedge q)$ .

Group ability has the following properties (comparable to those of single agents):

- $\neg C_G \top$
- $C_G\varphi \wedge C_G\psi \rightarrow C_G(\varphi \wedge \psi)$
- $\forall a \in G : C_a\varphi \rightarrow C_G\varphi$

Note that agent ability is a special case of group control when  $S = \{a\}$ . That is, all expressions controlled by one agent are also controlled by all groups in which that agent participates. This is different from the assumption made by e.g. [41] who use group control to refer to those formulas that are only controlled by the whole group, (and thus not controlled by any of its subgroups). In our model, this can be represented as a extra requirement on the definition 9 for group capability, as follows:

**Proposition 1. (Joint Capability)**

A group  $S \subseteq A$  of agents is said to have joint capability for an expression  $\varphi$  iff  $C_S\varphi$  and  $\forall S' \subset S, \neg C_{S'}\varphi$

Informally, whenever each of the agents in  $S$  leaves, the group loses the capability for  $\varphi$ . Finally, group activity,  $E_S\varphi$ , has the following properties:

- $E_G\varphi \rightarrow C_G\varphi$
- $E_G\varphi \rightarrow X\varphi$
- $E_G\varphi \wedge E_G\psi \rightarrow E_G(\varphi \wedge \psi)$
- $\neg E_G\top$

## 4 Organizations: Structure and Strategy

The idea behind organization is that there are global objectives, not necessarily shared by any of the agents, that can only be achieved through combined agent action. In order to achieve its goals, it is thus necessary that an organization employs the relevant agents, and assures that their interactions and responsibilities enable an efficient realization of the objectives.

In its most simple expression, an organization consists of a set of agents (together with their capabilities and abilities) and a set of objectives. In each moment, the state of the organization is given by a certain state of affairs that hold in that state. Formally, given a world  $w \in W$ , an *organization*  $O$  is defined by a set of agents, a set of objectives (missions or desires), and a set of assets. Agents are the active entities that realize organizational activity. Organizational objectives are the issues that the organization ‘wishes’ to be true in the world. Organizational assets are the issues that are true (and relevant to the organization) at a given moment.<sup>3</sup>

Worlds are represented as a set of propositions in  $\Phi$ . Furthermore the agents that participate in the organization may leave or enter the organization, and the objectives of the organization may change. We therefore define an organizational instance to represent the organization in a given world  $w \in W$  as  $O^w = \{A_O^w, D_O^w, S_O^w\}$ . The current state of the organization,  $S_O^w$ , corresponds to the set of formulas that are true in world  $w$  and relevant to  $O$ , and the objectives or desires of the organization,  $D_O^w$ , characterize the worlds (sets of formulas) that, at moment  $w$ , the organization wishes to reach<sup>4</sup>. Note that, organizational change means that the organization’s composition (agents) and objectives may differ from world to world.

Based on the definitions given in the previous sections, we are now in state to define organization capability (or scope of control). In fact, an organization is only as good as its agents. In this sense the scope of organizational control is defined by the union of the scopes of its agents’ control together with the control of groups of its agents. Formally:

<sup>3</sup> Note that, for the purposes of this paper, we see agents purely as actors in a organization, with no goals of themselves. We assume that, by acting according to their capabilities, agents work towards organizational objectives. That is, we abstract here from the motivation an individual agent may have to take up those organizational positions [7].

<sup>4</sup> From now on, whenever clear from the context, we’ll drop the subscripts and superscripts.

**Definition 14. (Organization Capability)**

Given a organization  $O$  such that  $A_O$  is the set of agents in  $O$ , organizational capability  $C_O$  is defined as:  $C_O = C_{A_O}$ . That is,  $C_O\varphi$  iff  $\exists S \subseteq A_O : C_S\varphi$ .

In practice, no organization will employ all agents in the world, nor control all possible states of affairs. One of the main reasons for creating organizations is efficiency, that is, to provide the means for coordination that enable the achievement of global goals in an efficient manner. Organization Theory has for many decades investigated the issue of organizational structure. Organizational structure has essentially two objectives [13]: Firstly, it facilitates the flow of information within the organization in order to reduce the uncertainty of decision making. Secondly, the structure of the organization should integrate organizational behavior across the parts of the organization so that it is coordinated. This raises two challenges: division of labor and coordination [33]. The design of organizational structure determines the allocation of resources and people to specified tasks or purposes, and the coordination of these resources to achieve organizational goals [20]. Ideally, the organization is designed to fit its environment and to provide the information and coordination needed for its strategic objectives.

According to this definition of organization, even if the agents in the organization have group control over all organizational objectives, they still need to coordinate their activities in order to efficiently achieve those objectives. Furthermore, in most cases, the objectives of the organization are only known to a few of the agents in the organization, who may have no control over those objectives. It is therefore necessary to structure agents in a way that enables objectives to be passed to those agents that can effectively realize them. We need therefore to extend our organizational definition to include coordinating and task allocation concepts.

**4.1 Organizational Structure**

Often organizations use the notion of roles to distribute the responsibilities necessary for the functioning of the organization. *Role dependencies* indicate how the goals of different roles depend on each other, and how interaction is to be achieved. Depending on the specific implementation of the dependency relationship, this means that a role can demand the realization of a goal from another role, or request goals from another role. In organizational contexts this can also mean that the responsibility of some tasks lays with the role in the top of the hierarchy. As before, for simplicity sake, we will for the moment, abstract from the concept of role, and define dependencies between agents (seen as role enacting actors) as follows. A *structural dependency* relation between a set of agents  $S = \{a_1, \dots, a_n\}$ ,  $\leq_S : S \times S$  is a poset satisfying the following properties:

- $\forall a \in S : a \leq_S a$  (reflexive)
- $\forall a, b, c \in S$ : if  $a \leq_S b$  and  $b \leq_S c$  then  $a \leq_S c$  (transitive)

We are now able to extend the definition of organization to include the notion of dependency:

**Definition 15. (Organization)**

Given a model  $M = (\Phi, A, W, R, T, \pi)$ , a organization in a world  $w \in W$  is defined

by  $O^w = \{A_O^w, \leq_O^w, D_O^w, S_O^w\}$  where  $A_O^w = \{a_1, \dots, a_n\}$ ,  $(A_O^w, \leq_O^w)$  is a structural dependency relation in  $A_O^w$ ,  $D_O^w \subseteq \Phi$ ,  $S_O^w \subseteq \Phi$  and  $w \in W$ .

Given an organization structure, we can define dependency chains between two agents, or between agents and groups as follows:

**Definition 16. (Dependency chain)**

Given a structured organization  $O^w = \{A_O^w, \leq_O^w, D_O^w, S_O^w\}$ , a dependency chain between two agents in  $A$  is defined as  $chain(a, b)$  iff (1)  $a = b$ , or (2)  $\exists c \in A$  such that  $a \leq_O^w c$  and  $chain(c, b)$ . Given a group  $S \subseteq A_O^w$ , there is a  $chain(a, S)$  iff  $\forall b \in S : chain(a, b)$ .

Intuitively, the ordering relation in the set of agents stands for the interaction possibilities between agents. Organizational structures influence the way that agents in the organization can interact. The relation  $a \leq_O b$  indicates that  $a$  is able to interact with  $b$  in order to request or demand some result from  $b$ . In this paper, we will not further detail the types of interactions between agents (delegation, request, bid, ...) but assume that the relationship will achieve some result, through a more or less complex interaction process. More on this issue can be found in [9].

## 4.2 Responsibility

To further refine the concept of organization, we need to be able to talk about the responsibilities<sup>5</sup> of agents in the organization. Responsibilities within an organization enable agents to make decisions about what each member of the organization is expected to do, and to anticipate the tasks of others [23]. Informally, by responsibility we mean that an agent or group has to make sure that a certain state of affairs is achieved,  $R_a\varphi$  either by realizing it itself or by delegating that result to someone else. In order to describe this notion of responsibility and delegation, we introduce a new operator,  $R_a$ , such that  $R_a\varphi$  means that  $a$  is responsible for, or in charge of, achieving  $\varphi$ . Note that responsibility for a state of affairs does not guarantee successful achievement of that state of affairs. As such, we formally define responsibility in terms of attempt, as follows:

**Definition 17. (Responsibility)**

Given an organization  $O = (A_O, \leq_O, D_O, S_O^w)$  in a model  $\mathcal{E}$ , and an agent  $a \in A_O$ , responsibility  $R_a\varphi$  is such that:

$R_a\varphi \equiv \diamond(H_a\varphi \vee H_aR_b\varphi)$ , for some  $b \in A_O$

The responsibility operator has the following properties:

- $E_a\varphi \rightarrow R_a\varphi$
- $R_a\varphi \wedge R_a\psi \rightarrow R_a(\varphi \wedge \psi)$
- $\neg R_a\top$

<sup>5</sup> In reality, responsibilities are associated with roles or positions in an organization. However, due to the simplification we make in this version of LAO, we do not - yet - distinguish between role and the role enacting agent.

Delegation of tasks is defined as the capability to make an agent, or group, responsible for that task. In an organization, delegation is associated with structural dependencies. That is, by nature their dependencies, some agents are in state of delegating their tasks to other agents, to make it the case that a result is achieved. Formally,

**Definition 18. (Structured delegation)**

Given an organization  $O = (A_O, \leq_O, D_O, S_O^w)$  in a model  $M$ , delegation of  $\varphi$  between two agents  $a, b \in A$  is defined as: if  $(a \leq_O b)$  then  $C_a R_b \varphi$ .

Given the notions of responsibility and structural dependency introduced above, we can define a good organization, as being an organization  $O = (A_O, \leq_O, D_O, S_O^w)$  that satisfies the following requirement:

$$C_{A_O} \varphi \wedge R_a \varphi \rightarrow \text{chain}(a, B) \wedge C_B \varphi, \text{ for } a \in A_O \text{ and } B \subseteq A_O$$

Good organizations satisfy  $R_a \varphi \rightarrow \Diamond \varphi$ , which informally says that if there is an agent responsible for a given state of affairs, then eventually that state will be reached. The responsibility operator is also defined for a group  $G$  of agents,  $R_G$  in a similar way. In the following, we provide an example of structured organization. Consider the organization  $O = ((A, \leq_O, D, S^0)$ , where:

$$\begin{aligned} A &= \{a, b, c, d\}, \\ \leq_O &\text{ is such that } (a \leq_O b, a \leq_O c \leq_O d), \\ D &= \{\rho\}, \text{ where } \rho = (p \wedge q) \vee r, \\ S^0 &= \{R_a \rho, C_b p, C_d q, C_{\{a,c\}} r\} \end{aligned}$$

Note that the initial organizational state  $S^0$  describes the capabilities of the agents in  $A$  and that agent  $a$  is responsible for the achievement of the organizational goal. This example also shows that organizations are dependent on the capabilities of their agents to achieve their objectives. In this case, without agent  $b$ , the organization can never achieve its goals. In the above organization, there are several ways for agent  $a$  to realize the organizational goal  $\rho$ , a possible strategy being:

$$\begin{aligned} s_1: & E_a R_b p \wedge E_a R_c q \\ \dots & \dots \\ s_i: & R_b p \wedge E_c R_d q \\ s_{i+z}: & R_b p \wedge R_d q \\ \dots & \dots \\ s_N: & p \wedge q \end{aligned}$$

Different properties can be defined for the responsibility operator, which identify different types of organizations. For example, a *well-defined organization* is such that  $\forall \varphi \in D_O, \exists a \in A_O : R_a \varphi$ .

### 4.3 Types of Organizations

Organizations come in many sorts and sizes. Notable is the work of Mintzberg on the classification of organizational structures [33]. According to Mintzberg, environmental variety is determined by both environmental complexity and the pace of change. Inspired by and extending the work of Mintzberg, researchers in Organizational Theory

have proposed a growing number of classifications for organization structures, e.g. simple, bureaucracy, matrix, virtual enterprise, network, boundary-less organizations, conglomeration, alliance, etc. just to name a few forms. However, definitions and naming of organizational forms are often unclear and the classification of a specific organization into one of the proposed classes is not trivial, often resulting in hybrid forms. Based on the structure of control, Burns and Stalker distinguish two main types of organization structures: hierarchies and networks [2]. Using the formal definition of organization presented in the previous sections, we are able to specify the structural characteristics of these two types of organizations. In a hierarchy organizational goals are known to the managers who delegate them to their subordinates who have the capabilities and resources to realize them. Formally,

**Definition 19. (Hierarchy)**

A structured organization  $O = (A_O, \leq_O, D_O, S_O^w)$  is said to be an hierarchy if

- $\exists M \subset A_O, M \neq \emptyset : \forall m \in M \exists \varphi \in D_O : R_m \varphi$  and  $\forall \varphi \in D_O \exists m \in M : R_m \varphi$
- $\forall a \in A_O, a \notin M, \exists m \in M : chain(m, a)$

That is, there is a group of managers  $M$  that together is responsible for all organizational goals and have a chain of command to all other agents in the organization. In a simple, flat, hierarchy, the manager group furthermore meets the following requirements:

$M = \{m\}$  and  $\forall a \in A_O, m \leq_O a$ .

In the same way, we formally define a network organization as:

**Definition 20. (Network)**

A structured organization  $O = (A_O, \leq_O, D_O, S_O^w)$  is said to be an network if

- $\forall a \in A_O : R_a \cap D_O \neq \emptyset$  and  $\forall \varphi \in D_O : \exists a \in A_O : R_a \varphi$
- $\forall a \in A_O, \exists b \in A_O : chain(a, b)$

That is, every agent in the organization is responsible for some of the organizational goals, and have a delegation relationship to some other agent in the organization. A fully connected network also meets the following requirement:

$\forall a, b \in A_O : a \leq_O b$ . A team is also a special case of network that meets the symmetry requirement:  $chain(a, b) \rightarrow chain(b, a)$ .

From the organization examples above, it can be seen that by the formal definition of properties for organizations, different organization types can be specified and verified. Other organizational types can be defined by the specification of other properties.

## 5 Case Study

We have applied the model presented in this paper to formally describe several existing agent systems that simulate organizations and organizational adaptation. Those systems were taken from the literature and include such different domains as architectures for Command and Control [28], RoboSoccer [27], market regulation [34] and sensor networks [30]. The original work on those cases use different frameworks and were developed independently by other research groups. Due to space limitations, we will

only discuss here one of the studied cases, namely the architecture for Command and Control presented in [28].

Over the past several years, researchers within the A2C2 research program (Adaptive Architectures for Command and Control) have investigated the notion of organizational congruence [28, 16, 18, 17]. In order to test their theories, in a laboratory experiment, a set of scenarios was developed to exploit the differences between organizational structures. Their idea was to design two different types of organizations and two different scenarios in order to test organizational congruence which distinguish between functional organizations and divisional/geographically-based organizations. Two types of scenarios were designed: one scenario would be congruent with divisional organizations but would be a misfit, or incongruent to functional organizations. Conversely, the second scenario would be congruent with functional organizations but misfit to divisional organizations.

The study considers different types of agents. For simplicity, we assume 2 agents,  $a_1$  and  $a_2$ , with search & rescue (SR) capabilities, and 2 agents,  $a_3$  and  $a_4$ , with mine clearance (MC) capabilities. That is:  $C_{a_1}SR_1$ ,  $C_{a_2}SR_2$ ,  $C_{a_3}MC_3$ , and  $C_{a_4}MC_4$ <sup>6</sup>. Furthermore, there are 4 agents with decision making responsibilities (DM): the search & rescue commander  $src$ , the mine clearance commander  $mcc$ , and the commanders of two bases  $b1c$  and  $b2c$ . Different organizations result from possible agent combinations:

- $O_1 : A_{O_1} = \{src, a_1, a_2\}$  and  $\leq_{O_1} = \{src \leq a_1, src \leq a_2\}$
- $O_2 : A_{O_2} = \{mcc, a_3, a_4\}$  and  $\leq_{O_2} = \{mcc \leq a_3, src \leq a_4\}$
- $O_3 : A_{O_3} = \{b1c, a_1, a_3\}$  and  $\leq_{O_3} = \{b1c \leq a_1, b1c \leq a_3\}$
- $O_4 : A_{O_4} = \{b2c, a_2, a_4\}$  and  $\leq_{O_4} = \{b2c \leq a_2, b2c \leq a_4\}$

According to the definitions used by A2C2 researchers, organizations  $O_1$  and  $O_2$  are functional organizations and  $O_3$  and  $O_4$  are divisional. The idea behind organizational congruence is that a certain organizational structure and population is in better state of achieving a desired state of affairs than others. So, divisional organizations will be better in achieving objectives that require different types of capabilities, while functional organizations are better when objectives require one specific type of capabilities.

A2C2 researchers designed different organizational scenarios to be congruent with one type of organization and incongruent with the other. A functional scenario is such that the mission, or objective, of the organization requires the use of all tools of one kind, in different places, a divisional scenario requires a combination of different tools in one place. Example of a functional scenario is to search & rescue, or to clear mines in an area. Divisional scenarios require the combination of both types of operations. In our model, different scenarios are represented as desired states of affairs. For instance, the following scenarios can be considered:

- Functional Scenarios:  $D_1 = SR_1 \wedge SR_2$  and  $D_2 = MC_1 \wedge MC_2$
- Divisional Scenarios:  $D_3 = MC_3 \wedge SR_1$  and  $D_4 = MC_4 \wedge SR_2$

Given the organizations defined above, it is easy to see that for example, the divisional organization  $O_3$  is congruent with a divisional scenario, that is  $C_{O_3}D_3$ , and the functional organization  $O_1$  is congruent with  $D_1$ , that is  $C_{O_1}D_1$ .

<sup>6</sup> Capabilities of the same sort may be slightly different.



In the case that scenarios are incongruent with the organization, organizations will need to reorganize in order to fulfil their missions. For instance, organization  $O_3$  is incongruent with  $D_1 = SR_1 \wedge SR_2$  as  $\neg C_{O_3} D_1$ . Specifically,  $O_3$  cannot realize this objective because it has no control over  $SR_2$ , that is,  $\neg C_{O_3} SR_2$ . In practice, there are many ways to achieve the enlistment of  $a_2$ . Typically, in the defense domain, commander  $b1c$  will request current  $a_2$ 's superiors  $src$  or  $b2c$  for recruiting  $a_2$ . The resulting organizations is described by:  $O_3 = ((\{b1c, a_1, a_3, a_2\}, \{b1c \leq a_1, b1c \leq a_3, b1c, \leq a_2\}), D_1, \{R_{b1c}(D_1), C_{a_1} SR_1, C_{a_3} MC_3, C_{a_2} SR_2\})$  which is indeed congruent with the functional scenario  $D_1$ .

In our current work, we are extending LAO to include the formal specification of reorganization operators [11, 10]. The resulting extension to LAO, LAO-R, enables represent and reason about changes in the organization, in a way that abstracts from the specifics of the reorganization process, that is, we refer to the resulting state of affairs without the need to specify the (communication) processes involved in achieving that state. In practice reorganization operations can be classified into three types: *staffing*, i.e. changes in the set of agents in the organization and their capabilities, *structuring*, i.e. changes in the organizational structure  $\leq_O$ , and, *strategic*, i.e. changes in the objectives of the organization. A reorganization process takes into account the current performance and determine which characteristics of the organization should be modified in order to achieve a better performance. The general idea behind reorganization is that one should be able to evaluate the utility of the current state of affairs (that is, what happens if nothing changes), and the utility of future states of affairs that can be obtained by performing reorganization actions. The choice is then to choose the future with the highest utility.

## 6 Conclusions

Organization concepts and models are increasingly being adopted for the design and specification of multi-agent systems. The motivations for this model are twofold. In the one hand, the need for a formal, provable representation of organizations, with their environment, objectives and agents in a way that enables to analyze their partial contributions to the performance of the organization in a changing environment. On the other hand, such a model must be realistic enough to incorporate the more 'pragmatic' considerations faced by real organizations. In this paper we presented a first attempt at a formal model for organizational concepts, based on modal temporal logic. We have applied the proposed model to existing domain-specific systems proposed in recent literature. The current model is based on the notions of capability, *stit*, attempt and responsibility.

The theoretical framework presented in this paper can be extended to represent and analyze performance and dynamics of organizations. We are currently involved in an extension to LAO that enables reasoning about reorganization both from an endogenous as from an exogenous perspective. In the future, we will extend the model to include deontic concepts and their relation to the operational concepts presented in this paper. Also we will add the formal distinction between roles and agents. These elements are already described in other work, but need to be carefully merged with the current basic

framework. Finally, we are engaged on developing a full axiomatization of LAO as well as on an implementation for simulating the reorganization process.

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