

BLOCKING UNDERHAND ATTACKS BY HIDDEN COALITIONS

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Abstract: Similar to what happens between humans in the real world, in open multi-agent systems distributed over the Internet, such as online social networks or wiki technologies, agents often form coalitions by agreeing to act as a whole in order to achieve certain common goals. However, agent coalitions are not always a desirable feature of a system, as malicious or corrupt agents may collaborate in order to subvert or attack the system. In this paper, we consider the problem of hidden coalitions, whose existence and the purposes they aim to achieve are not known to the system, and which carry out underhand attacks, a term that we borrow from military terminology. We give a first approach to hidden coalitions by introducing a deterministic method that blocks the actions of potentially dangerous agents, i.e. possibly belonging to such coalitions. We also give a non-deterministic version of this method that blocks the smallest set of potentially dangerous agents. We calculate the computational cost of our two blocking methods, and prove their soundness and completeness.

1 Introduction

1.1 Context and motivation

Similar to what happens between humans in the real world, in open multi-agent systems (Davidsson, 2001) distributed over the Internet, such as online social networks or wiki technologies, agents often form coalitions by agreeing to act as a whole in order to achieve certain common goals. For instance, agents may wish to collaborate in order to jointly create and use a group cryptographic key for ensuring the confidentiality and/or integrity of information shared within the group, e.g. (Rafaeli and Hutchison, 2003), or to partake in a mix network or some other anonymous remailer to achieve unobservability of communications, e.g. (Chaum, 1981), or to create secret interest groups within online social networks, e.g. (Sorniotti and Molva, 2010). However, agent coalitions are not always a desirable feature of a system, as malicious or corrupt agents may collaborate in order to subvert or attack the system. For instance, such agents may collaborate to attack the information in transit over different channels in a web service

architecture or in a distributed wired and/or wireless computer network, e.g. (Wiehler, 2004), or they might forge and spread false information within the system, e.g. (Hahn et al., 2007).

In order to be able to rigorously formalize and reason about such positive and negative properties of agent coalitions, and thereby allow for the prevention or, at least, the identification of the entailed vulnerabilities, a number of different formal approaches have been recently proposed, such as (Ågotnes et al., 2007; Ågotnes et al., 2008; Alur et al., 1998b; van der Hoek et al., 2005; Oravec and Fogel, 2006; Pauly, 2001; Troquard et al., 2009; van der Hoek and Wooldridge, 2005; Wooldridge and Dunne, 2004).

In this paper, we consider the problem of *hidden coalitions*: a coalition is hidden in a system when its existence and the purposes it aims to achieve are not known to the system. Hidden coalitions carry out *underhand attacks*, a term that we borrow from military terminology. These attacks are particularly subtle since the agents that perform them are not outsiders but rather members of the system whose security properties are posed under threat. Moreover, the mere suspect that a group of individuals act as a

whole is typically insufficient to come to a decision about their permanence as members of the system; this, of course, depends also on the nature of the system and the information it contains, since in the presence of highly security-sensitive information, systems may anyway opt for the exclusion of all suspected agents. However, in general, systems, and even more so open ones, will want to adopt a less restrictive policy, excluding only those agents whose malice has indeed been proved. Therefore, the defense against underhand attacks by hidden coalitions is a fundamental but complex matter.

Problems of a similar kind have been studied, for instance, in Game Theory (Aumann and Hart, 1994; Pauly and Parikh, 2003) in relation to the nature of collaboration and competition, and from the viewpoint of modeling group formation under the constraints of possible given goals. However, underhand attacks by hidden coalitions pose security problems that cannot be dealt with such traditional means. Nor can they be solved by a simple, monotonic, approach based on Coalition Logic(s) (Ågotnes et al., 2008; Oravec and Fogel, 2006; Pauly, 2001; van der Hoek and Wooldridge, 2005), which is currently one of the most successful formalisms for reasoning about coalitions.

To illustrate all this further, consider the following concrete example from an online social network such as Facebook, where abuse, misuse or compromise of an account can be reported to the system administration. In particular, a group of agents (in this case, Facebook users) can report a fake profile:

You can report a profile that violates Facebook's Statement of Rights and Responsibilities by clicking the "Report/Block this Person" link in the bottom left column of the profile, selecting "Fake profile" as the reason, and adding the appropriate information. [...] (*Excerpt from* <http://www.facebook.com/help/?search=fake>)

The administrator of the system gives an ultimatum to the agent that uses the reported profile and then may, eventually, close it. An underhand coalition can exploit this report mechanism to attack an agent who possesses a "lawful" original profile: at first they create a fake profile with personal information and photos of the agent under attack, and then they become friends of her. After that, they report the original profile so that the administrator closes it. The report is a lawful action, and by creating the new profile and having a big enough number of agents who report the same profile no suspicion about the hidden coalition is raised, so that the attack succeeds.

1.2 Contributions

A formalism to define and reason about such hidden coalitions is thus needed. Indeed, Coalition Logic allows one to define coalitions that are explicit (i.e. not hidden) and is characterized by monotonic permissions to act in groups and individually. What is missing, however, is the notion of hidden coalition and a method to block the underhand attacks such coalitions carry out. The idea underlying our approach is to circumscribe the problem in algebraic terms, by defining a system that can be represented by a coalition logic, and then activate a non-monotonic control on the system itself to block the underhand attacks that hidden coalitions are attempting to carry out.

More specifically, we consider multi-agent systems whose security properties depend on the values of sets of logical formulas of propositional logic, which we call the *critical (or security) formulas* of the systems: for concreteness, we say that a system is *secure* if all the critical formulas are false, and is thus *insecure* if one or more critical formula is true. (Of course, we could also invert the definition and consider a system secure when all critical formulas are true.) The system agents control the critical formulas in that they control the propositional variables that formulas are built from: we assume that every variable of the system is controlled by an agent, where the variables controlled by an agent are controlled just by that agent without interference by any other agent. The actions performed by each agent consist thus in changing some of the truth values of the variables assigned to that agent, which means that the values of the critical formulas can change due to actions performed by the agents, including in particular malicious insider agents who form hidden coalitions to attack the system by making critical formulas become true. Returning to the Facebook example, this is exactly what happens when agents report the original profile as fake by setting the flag (clicking on the link).¹

At each instant of time, agents ask the system to carry out the actions they wish to perform, i.e. changing the truth value of the variables they control, and the system has to decide whether to allow such actions, but without knowing of the existence of possible hidden coalitions and thus at the risk of the system becoming insecure. To block such attacks, we for-

¹In this paper, we do not consider how the administrator decides to close the profile, nor do we consider in detail the non-monotonic aspects of how agents enter/exit/are banned from a system or enter/exit a hidden coalition, or how members of a hidden coalition synchronize/organize their actions. All this will be subject of future work.

malize here a *deterministic blocking method*, implemented by a greedy algorithm, which blocks the actions of potentially dangerous agents. We prove that this method is sound and complete, in that it does not allow a system to go in an insecure state when it starts from a secure state and it ensures that every secure state can be reached from any secure state. However, this algorithm is not optimal as it does not block the smallest set of potentially dangerous agents.

We thus introduce also a *non-deterministic blocking method*, which we obtain by extending the deterministic method with an oracle to determine the minimum set of agents to block so to ensure the security of the system. We show that the soundness and completeness result extends to this non-deterministic method as well.

We also calculate the computational cost of our two blocking methods. This computational analysis is completed by determining upper bound results for the problem of finding a set of agents to be blocked so to prevent system transitions into insecure states, and the problem of finding an optimal set of agents satisfying the above condition.

1.3 Organization of the paper

In §2, we introduce our approach to the problem of blocking underhand attacks by hidden coalitions. §3 and §4 respectively introduce our deterministic and non-deterministic blocking methods, giving concrete examples for their application. In §5, we study the computational aspects of these two methods, calculating in particular their computational cost, and show that they are both sound and complete. Finally, in §6, we summarize our main results, discuss related work and sketch future work.

2 An approach to the problem of blocking underhand attacks

We introduce our approach to the problem of blocking underhand attacks. We also recall some basic notions and, in particular, the relevant notions of the Coalition Logic of Propositional Control CL-PC (Oravec and Fogel, 2006; van der Hoek and Wooldridge, 2005), which provides a starting point for our approach.

2.1 Syntax

We consider multi-agent systems S that are described by a set of *critical (or security) formulas* Φ and by a temporal sequence $\sigma : T \rightarrow \Theta(\Phi)$, with T the temporal axis and $\Theta(\Phi)$ the propositional assignment in the

set of formulas. In this work, we focus only on the formulas in Φ , which represent the security-critical characteristics of a system (which depend on the application and which we thus do not describe further here, as our approach is independent of the particular application). We say that a system is *secure* if all the critical formulas are false, and it becomes insecure if one or more $\phi \in \Phi$ becomes true.² Hence, the *state* of a system is defined by the value of the propositional variables that occur in the critical formulas of Φ .

The *agents* of a system S control the set Φ and hence the state of S . We require that there is no formula in our systems that cannot change its truth value. Moreover, the distribution of the variables to the agents should be such that one formula cannot be controlled by one single agent, but rather different agents control one formula, and every formula is controlled by some agents. In particular, for a set Ag of system agents:

- every variable of the system is controlled by an agent $a \in Ag$, and
- the variables controlled by an agent are controlled just by that agent without interference by any other agent.

The actions performed by each agent $a \in Ag$ are thus the changing of the truth values of the variables assigned to a . The agents we consider are *intelligent agents* in the sense of (Wooldridge and Jennings, 1995; Wooldridge and Jennings, 1998): they are autonomous, have social ability, reactivity and pro-activeness, and have mental attitudes, i.e. states that classify the relation of the agents and the cognitive environment. In our approach, we consider intelligent agents but do not make specific assumptions about their mental attitudes, except for their collaborative attitudes that constitute a threat to (the security of) the system.³

In Game Theory (van der Hoek et al., 2005), strategies are often associated with a preference relation for each agent that indicates which output the agent is going to select in presence of alternatives. In our approach, agents change the value of “their” variables according to their strategies and create coalitions with other agents so to be more expressive: by collaborating, agents can change the values of different variables and thus, ultimately, of the critical formulas that comprise such variables. The novelty in

²As we remarked above, we could also invert this and call a system secure when all critical formulas are true; we would then just need to modify our methods accordingly.

³An extension of the work presented here with a detailed formalization of the mental and collaborative attitudes of the agents will be subject of future work.

this work is that we don't deal just with coalitions that are known by the system but also with hidden coalitions, whose existence and purposes are unknown by the system.

Let us now formalize the language of our approach. Following CL-PC, given a set Ag of agents, a set $Vars$ of propositional variables, the usual operators \neg and \vee of classic propositional logic, and the *cooperation mode* \diamond , we consider formulas built using the following grammar:

$$\phi ::= \top \mid p \mid \neg\phi \mid \phi \vee \psi \mid \diamond_C \phi$$

where $p \in Vars$, $C \subseteq Ag$, and $\diamond_C \phi$ is a *cooperation formula*. Slightly abusing notation, we denote with $Vars(\phi)$ the set of propositional variables that occur in ϕ and with $Ag(\phi)$ the agents that control the variables in $Vars(\phi)$. $\diamond_C \phi$ expresses that the coalition C has the contingent ability to achieve ϕ ; this means that the members of C control some variables of ϕ and have choices for ϕ such that if they make these choices and nothing else changes, then ϕ will be true.

2.2 Semantics

A model is a tuple

$$\mathcal{M} = \langle Ag, Vars, Vars|_1, \dots, Vars|_n, \theta \rangle,$$

where:

- $Ag = \{1, \dots, n\}$ is a finite, non-empty set of agents;
- $Vars = \{p, q, \dots\}$ is a finite, non-empty set of propositional variables;
- $Vars|_1, \dots, Vars|_n$ is a partition of $Vars$ among the members of Ag , with the intended interpretation that $Vars|_i$ is the subset of $Vars$ representing those variables under the control of agent $i \in Ag$;
- $\theta : Vars \rightarrow \{\top, \perp\}$ is a propositional valuation function that determines the truth value of each propositional variable.

Since $Vars|_1, \dots, Vars|_n$ is a partition of $Vars$, we have:

1. $Vars = Vars|_1 \cup \dots \cup Vars|_n$ i.e. every variable is controlled by some agent;
2. $Vars|_i \cap Vars|_j = \emptyset$ for $i \neq j \in Ag$, i.e. no variable is controlled by more than one agent.

We denote with $Vars|_C$ the variables controlled by the agents that are part of the coalition $C \subseteq Ag$. Given a model $\mathcal{M} = \langle Ag, Vars, Vars|_1, \dots, Vars|_n, \theta \rangle$ and a coalition C , a C -valuation function is $\theta_C : Vars|_C \rightarrow \{\top, \perp\}$. Valuations θ extend from variables to formulas in the usual way and for a model $\mathcal{M} = \langle Ag, Vars, Vars|_1, \dots, Vars|_n, \theta \rangle$ we write $\mathcal{M} \models \phi$ if $\theta(\phi) = \top$. We write $\models \phi$ if $\mathcal{M} \models \phi$ for all \mathcal{M} .

2.3 Secure and insecure systems

All the semantic notions introduced above actually depend on the current time, and we will thus decorate them with a superscript S_t denoting the system state at time t , e.g. θ^{S_t} and \models^{S_t} . Time is discrete and natural, and is defined with a non empty set of time points T and a transitive and irreflexive relation \prec such that $t \prec u$ means that t comes before u for $t, u \in T$. In our case, since $t, t+1 \in T$ it follows naturally that $t \prec t+1$.

The passing of time is regulated by a general *clock*, which ensures that the system can execute a definite number of actions in an instant of time: at every clock of time, the system changes its state, which is thus defined by the actions that the system executes. Even if there are no actions to execute, the system changes its state from S_t to S_{t+1} , which in this case are equal.

We assume that each system S starts, at time t_0 , from a secure state S_0 , i.e. a state in which all the critical formulas of Φ are false, so that none of the features of the system is violated. In general:

$$S \text{ is secure at a state } S_t \text{ iff } \not\models^{S_t} \phi \text{ for all } \phi \in \Phi$$

and

$$S \text{ is secure iff } \not\models^{S_t} \phi \text{ for all } \phi \in \Phi \text{ and all } S_t$$

At time t , the system is in state S_t and goes to state S_{t+1} and executes all the actions of the agents that want to change the value of their variables. Denoting with Γ_{t+1} the set of actions that the agents want to execute at the time instant t , we can write

$$S_t \xrightarrow{\Gamma_{t+1}} S_{t+1}.$$

and the aim of our approach is to guarantee that each reachable state S_{t+1} is secure, where the differences between S_t and S_{t+1} are in their respective Θ .

Since a coalition can change the value of the variables it controls, it can attempt to change the value of a critical formula to true; formally, for a coalition C and a formula ϕ if $\diamond_C \phi$ is true then it means that C can make ϕ true and thus the system insecure, which we can write by negating the above definition or alternatively, and basically equivalently, as:

$$S \text{ is insecure at a state } S_t \text{ iff } \models^{S_t} \diamond_C \phi \text{ for some } C \subseteq Ag \text{ and some } \phi \in \Phi$$

To help the control of the system (but without loss of generality), we can create a *filter* for the actions that imposes a limit on the number of the actions that can be executed in an instant of time. This can decrease the performance of the system, so we need a trade-off between control and performance.

Algorithm 1 A GREEDY, DETERMINISTIC BLOCKING METHOD

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1: Simulate( $\Gamma_{t+1}$ ) = [ $\Phi' \mathcal{A}'$ ];
2: while ( $\Phi' \neq \emptyset$ ) do
3:   Create the matrix with  $\Phi'$  and  $\mathcal{A}'$ ;
4:    $\forall a_i \in \mathcal{A}' : a_i \rightarrow c_i, c_i = \text{count}(\phi_i)$ ;
5:   Quicksort( $c_1, \dots, c_k$ ) = ( $c_x, \dots$ );
6:    $\mathcal{B} = \mathcal{B} \cup a_x$ ; {where  $a_x$  is the agent associated to  $c_x$ , that is the maximum counter of the marked cells}
7:   Simulate( $\Gamma_{t+1} \setminus \Gamma_{a_x}$ ) = [ $\Phi' \mathcal{A}'$ ];
8: end while
```

3 A deterministic blocking method

Our aim is to introduce a method that guarantees the security of the system, which amounts to blocking the actions of hidden coalitions. Indeed, in the case of “normal” coalitions, the property $\diamond_C \phi$ allows us to list the actions of the agents in C , while if the coalition is hidden then we cannot block any action as we cannot directly identify the participants of a coalition we do not even know to exist. Since the actions of participants of hidden coalitions are not predictable, we cannot oppose these coalitions using \diamond , so we introduce a method that disregards the existence of this property.

Our (main) method for the protection of the system is a *blocking method* based on the *greedy* Algorithm 1: the agents make a request to the system for the actions Γ_{t+1} they wish to execute at time t , and the system then simulates (via a method *Simulate* we assume to exist) the actions in order to control whether the system after the execution of the actions is still secure or not. The simulation says if the system can proceed with the execution of the actions or not, in which case it is given a list of the formulas Φ' that became true along with the set of agents \mathcal{A}' that made them become true.

If the simulation says that the system can go in an insecure state, the blocking method constructs a matrix: in every column of the matrix there is one of the agents given by the simulation and in every row there is one of the formulas that became true during the simulation. We mark each cell that has as coordinates the agent that has variables in that formula, and then we eliminate the column that has more marked cells.⁴

⁴It would be more efficient to consider only the variables of the formulas that become true, but if we take only these variables, we cannot prevent long-term strategies of hidden coalitions, consisting in the progressive reduction of the number of steps needed for making a security formula

The corresponding agent is not eliminated, rather he is just blocked and his actions are not executed (by subtracting Γ_{a_x}): the “dangerous” agents found in this way are put in a set \mathcal{B} of blocked agents. The simulation is called again and so on, until the output of the simulation is an empty set of formulas, which means that by executing the remaining actions the system does not go in an insecure state. It is important to note that this method does not prevent the creation of hidden coalitions but can guarantee the system security from the attacks made by these coalitions.

The most important property of Algorithm 1 is that it never brings the system in an insecure state, as it blocks the actions of agents that can make the system insecure. We do not commit to a specific way that the blocking is actually done, as it depends on the particular observed systems and on the particular goals. For instance:

- Block the agent from changing the value of his variables until a precise instant of time. During this period, his variables are left unchanged or are controlled by the superuser/system administrator.
- Block the agent for an interval of time, which can be a default value or can be chosen in a random way, e.g. so that a hidden coalition doesn't know when the agent can be active and thus cannot organize another attack.
- Block the agent and remove his actions for that instant of time. At the next instant, the agent has the possibility to ask for his actions to be executed.
- Leave the variables unchanged, without making known to the agent if the value of the variables has been changed or not. This method can be improved by blocking the agent if he attempts to change the truth value of those variables again.

Other, more complex, blocking strategies can of course be given, e.g. by combining some of the above.

Note also that, depending on the system considered, it could be that not all the requests for execution can be satisfied: *the maximum number n of actions that can be executed in an instant of time* can be chosen in different ways, with respect to the characteristics of the system. Here, we choose n to be the cardinality $|\Phi|$ of the critical formulas. The order used for taking these actions and executing them respects a FIFO queue, so the first n actions are executed.

Example 1 As a concrete example of the application of the blocking method, consider a system S defined

true. An optimization of the choice of variables to be considered in order to reduce the effectiveness of such long-term strategies will be subject of future work.

by the critical formulas

$$\begin{aligned}
\phi_1 &= v_1 \wedge v_2 \wedge (\neg v_3 \vee v_5 \vee \neg v_4) \\
\phi_2 &= (\neg v_5 \vee \neg v_3) \wedge \neg v_6 \\
\phi_3 &= v_7 \wedge (\neg v_8 \vee \neg v_6) \\
\phi_4 &= (v_8 \vee v_5 \vee \neg v_9) \wedge v_2 \wedge v_1
\end{aligned}$$

so that number of the action to be executed in an instant of time is $n = 4$ (the cardinality of the set of critical formulas that define the system), and let $\text{Ag} = \{a_1, a_2, a_3, a_4, a_5\}$ and $\text{At} = \{v_1, \dots, v_9\}$. Further, consider the following distribution of the variables to the agents:

$$\begin{aligned}
a_1 &= \{v_1, v_7, v_8\} \\
a_2 &= \{v_3\} \\
a_3 &= \{v_2, v_6\} \\
a_4 &= \{v_4, v_5\} \\
a_5 &= \{v_9\}
\end{aligned}$$

Let us assume that the state S_t at time t is

$$\begin{aligned}
\theta^{S_t}(v_1) &= \theta^{S_t}(v_5) = \perp \\
\theta^{S_t}(v_2) &= \theta^{S_t}(v_3) = \theta^{S_t}(v_4) = \theta^{S_t}(v_6) = \theta^{S_t}(v_7) \\
&= \theta^{S_t}(v_8) = \theta^{S_t}(v_9) = \top
\end{aligned}$$

and that we have the following actions Γ_{t+1} to be executed at time t in the FIFO queue:

$$\begin{aligned}
\theta^{S_{t+1}}(v_1) &\leftarrow \top, \\
\theta^{S_{t+1}}(v_3) &\leftarrow \perp, \\
\theta^{S_{t+1}}(v_4) &\leftarrow \perp, \\
\theta^{S_{t+1}}(v_6) &\leftarrow \perp, \\
&\dots
\end{aligned}$$

That is, v_1 should be set to \top at state S_{t+1} , and so on. The algorithm simulates the first $n = 4$ actions, so that $\Phi' = \{\phi_1, \phi_2, \phi_3, \phi_4\}$ and $\mathcal{A}' = \{a_1, a_2, a_3, a_4\}$, and the matrix of Table 1 is constructed, which the algorithm sorts by the highest counter to produce the matrix in Table 2. a_3 is thus put into \mathcal{B} . The simulation takes place again, taking into account that we have blocked the value of the variables controlled by a_3 at the truth value of the instant of time t . The simulation gives as result the set $\Phi' = \{\phi_1, \phi_4\}$ e $\mathcal{A}' = \{\phi_1, \phi_2, \phi_4\}$. The matrix of Table 3 is created, which is already ordered (so the sorting will return the same matrix). So, we put in \mathcal{B} the agent a_1 , block its actions and make the simulation with the remaining actions. This simulation gives $\Phi' = \emptyset$, and thus the remaining actions can be executed without any risk for the system S .

Table 1: Matrix constructed by the blocking algorithm for Example 1.

	a_1	a_2	a_3	a_4
ϕ_1	X	X	X	X
ϕ_2		X	X	X
ϕ_3	X		X	
ϕ_4	X		X	X

Table 2: Matrix of Table 1 sorted in a decreasing order of counters.

	a_3	a_1	a_4	a_2
ϕ_1	X	X	X	X
ϕ_2	X		X	X
ϕ_3	X	X		
ϕ_4	X	X	X	

4 A non-deterministic blocking method

As we will see in §5, the above deterministic blocking method based on a greedy algorithm is sound and complete. However, this algorithm is not optimal as it cannot block the smallest set of potentially dangerous agents. We now introduce a non-deterministic method, which can be used for identifying optimal solutions. The method, which is implemented in Algorithms 2 and 3, is obtained by introducing an oracle (to determine the minimum set of agents to block so to ensure the security of the system) within the deterministic version, which makes the soundness and completeness results directly applicable to the non-deterministic version as well.

The idea is that the result given by the simulation is passed to the method *ScanOracle*, which creates all the subsets of the given set \mathcal{A}' with cardinality $|\mathcal{A}' - 1|$ and finds the subsets with the maximum number of critical formulas that remain false, using the simulation. The simulation of all the subsets is done in parallel; the *ScanOracle* is the non-deterministic part of our algorithm. The result is passed to the main algorithm: if we find a subset of agents such that when executing their actions all critical formulas are false, then we have finished and we block the remaining agents that are not part of this subset; if not all the critical formulas remain false the result is passed recursively to *ScanOracle* until it is given a set of agents such that all the critical formulas stay false when simulating their actions. The rest of the agents in \mathcal{A}' that are not part of the given subset are blocked. Using this method, we can have different best solutions but we choose one in a random way, where with “best so-

Table 3: Matrix of Table 2 after the block of agent a_3 .

	a_1	a_2	a_4
ϕ_1	X	X	
ϕ_4	X		X

Algorithm 2 A NON-DETERMINISTIC BLOCKING METHOD

```

1: Simulate( $\Gamma_n$ ) =  $[\Phi' \mathcal{A}']$ ;
2:  $I = \mathcal{A}'$ ;  $j = 0$ ;
3: while ( $\Phi' \neq \emptyset$  &  $I \neq \emptyset$  &  $j < |\mathcal{A}'|$ ) do
4:    $I' = \text{ScanOracle}(I)$ ;
5:   For a random  $I_i \in I'$ 
6:   if  $|\{\phi_i \mid \not\models \phi_i \text{ at the current state}\}| = |\Phi'|$  then
7:      $I = \emptyset$ ;
8:   else
9:      $I = I'$ ;
10:  end if
11:   $j++$ 
12: end while
13: Choose a subset  $I_i \in I'$  and put  $\mathcal{A}' \setminus I_i$  in  $\mathcal{B}$ 

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Algorithm 3 SCANORACLE

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1: Generate the subset of  $I$  with cardinality  $|I| - 1$ 
2: Execute the simulation in parallel for each subset  $I_i$ , where  $i \in \{1, \dots, |I|\}$ 
3: Take the  $I_i$  with the maximum number of  $\{\phi_i \mid \not\models \phi_i\}$  and put them in  $I'$ 
4:  $I' = I' \cup I_i$ 
5: Eliminate the duplicates in  $I'$ 
6: Return  $I'$ 

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lutions” we mean sets that have the same cardinality and are the biggest sets that make the critical formulas stay false, so that we block the smallest set of agents that make the critical formulas true.

Example 2 As a concrete example of the application of Algorithm 2 (and of Algorithm 3), consider again the system of Example 1, with the same data. The simulation of the first 4 actions yields again $\mathcal{A}' = \{a_1, a_2, a_3, a_4\}$, which is passed to ScanOracle, which in turn creates the subsets:

$$\begin{aligned}
I_1 &= \{a_1, a_2, a_3\} \\
I_2 &= \{a_1, a_3, a_4\} \\
I_3 &= \{a_1, a_2, a_4\} \\
I_4 &= \{a_2, a_3, a_4\}
\end{aligned}$$

The oracle takes these subsets and gives as results at

the current state

$$\begin{aligned}
I_1 &: \models \phi_1, \models \phi_2, \models \phi_3, \models \phi_4. \\
I_2 &: \models \phi_1, \models \phi_2, \models \phi_3, \models \phi_4. \\
I_3 &: \models \phi_1, \not\models \phi_2, \not\models \phi_3, \models \phi_4. \\
I_4 &: \not\models \phi_1, \models \phi_2, \models \phi_3, \not\models \phi_4.
\end{aligned}$$

The two subsets with maximum number of false critical formulas are I_3 and I_4 , so $I' = I_3 \cup I_4$. Note that, since I_3 and I_4 have the same number of false formulas, it is enough to test just one of them to see if all the formulas are false or not; in this case, we have just two formulas. The ScanOracle is then called again with $I' = I_3 \cup I_4$ and it yields the subsets

$$\begin{aligned}
I_5 &= \{a_1, a_2\} \\
I_6 &= \{a_1, a_4\} \\
I_7 &= \{a_2, a_4\} \\
I_8 &= \{a_2, a_3\} \\
I_9 &= \{a_2, a_4\} \\
I_{10} &= \{a_3, a_4\}
\end{aligned}$$

and thus the following results

$$\begin{aligned}
I_5 &: \models \phi_1, \not\models \phi_2, \not\models \phi_3, \models \phi_4. \\
I_6 &: \not\models \phi_1, \not\models \phi_2, \not\models \phi_3, \models \phi_4. \\
I_7 &: \not\models \phi_1, \not\models \phi_2, \not\models \phi_3, \not\models \phi_4. \\
I_8 &: \not\models \phi_1, \models \phi_2, \models \phi_3, \not\models \phi_4. \\
I_9 &: \not\models \phi_1, \not\models \phi_2, \not\models \phi_3, \not\models \phi_4. \\
I_{10} &: \not\models \phi_1, \models \phi_2, \models \phi_3, \not\models \phi_4.
\end{aligned}$$

Then $I' = I_7 \cup I_9 = I_7$ as these two subsets are identical. Using I' , all the critical formulas are false, so it is the maximum subset of agents with which the system is secure. Hence, we block the remaining agents in \mathcal{A}' , which is the minimum set of agents for the blocking of which the system remains secure:

$$\{a_1, a_2, a_3, a_4\} \setminus \{a_2, a_4\} = \{a_1, a_3\}.$$

5 Computational cost, Soundness and Completeness

In this section, we calculate the computational cost of both the blocking methods we have given, and then show that the greedy deterministic method is sound and complete (which implies the same for the non-deterministic method). Recall that the maximum number n of actions that can be executed in an instant of time corresponds to the cardinality of the formulas in Φ . So, in the worst case, at each instant of time, there are n different agents that want to change the value of n different variables.

Theorem 1 *The computational cost of the greedy blocking method, Algorithm 1, is $O(n^3)$.*

Proof The simulation costs n^2 because if we have n variables and all of them are part of all the formulas, we need to do n^2 assignments. The while cycle needs to be executed at worst n times as it blocks an agent per cycle and we may need to block all the n agent. The cost of a single while cycle is $3n^2$ due to the sum of: the cost of the matrix creation, which is n^2 , the cost of the association of the counter, which is n^2 , and the cost of the quicksort algorithm, which we take to be n^2 , instead of $n \log n$ (as the simulation has an n^2 complexity). So, the total cost of the algorithm is $n^2 + (n \times (3n^2 + n^2)) = O(n^3)$. \square

Theorem 2 *The computational cost of the non-deterministic blocking method, Algorithm 2, is $O(n^3)$.*

Proof Also this algorithm uses the simulation, which costs n^2 . In the worst case, we need to call the *ScanOracle* (Algorithm 3) n -times, where the generation of the subsets costs n^2 , the oracle (that performs the simulations in parallel) is linear and the elimination of the duplicates is n^2 , so the cost of the *ScanOracle* algorithm is $O(n^2)$. The cost of putting the agents in \mathcal{B} is a constant. So, the total cost of the algorithm is $n^2 + n \times O(n^2) + C = O(n^3)$. \square

The computational cost of the non-deterministic method implemented in Algorithm 2 is the same of the deterministic algorithm. This can be puzzling for the reader, who can be expecting a lower cost, since the non-deterministic version is obtained from the deterministic version by using an oracle. In particular, the reduction by an oracle can be used to prove that a problem of polynomial complexity on deterministic machines can be solved in logarithmic time on non-deterministic machines. We made a different choice, for specific reasons. First of all, we employ the simulation step, that is not incorporated into the first part of the method, and thus the solution cannot be computed in a time lower than polynomial, in a non-deterministic fashion, even if we use, as we did, the oracle call. As a consequence of this choice, we could define, by using the same structure of the non-deterministic algorithm, a variant of the algorithm in which the solutions of the oracle are compared to each other, to choose the optimal one.

We say that a blocking method, and thus the corresponding algorithm, is *sound* if it does not allow a system to go in an insecure state when it starts from a secure state S_0 .

Theorem 3 *The greedy blocking method, Algorithm 1, is sound.*

Proof For the sake of contradiction, assume that the greedy blocking method brings a system in an inse-

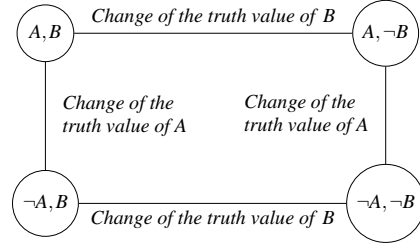


Figure 1: A state graph for a system with two variables.

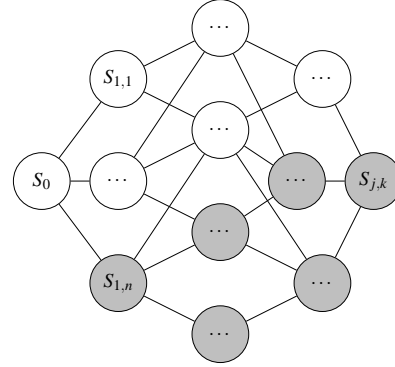


Figure 2: A state graph with secure and insecure states.

ure state. This means that the algorithm allowed a Γ_{t+1} to execute such that $S_t \xrightarrow{\Gamma_{t+1}} S_{t+1}$ where S_{t+1} is insecure while S_t is secure. But, by definition, our algorithm allows only transitions that bring the system in a secure state, thanks to the simulation. \square

Let us now define the notion of a *state graph*. Recall that every state of the system is defined by an assignment of truth values to the variables, and a state is secure if it falsifies all security-related formulas. As a very simple example, in Figure 1 we give the state graph of a system with two variables $\{A, B\}$.

In general, to denote the transitions executed by a system, we build a state graph as follows: every state is represented as a vertex of the graph, and every pair of vertices is connected by an edge when and only when the two edges differ by the truth value of one single variable, where the edge is labeled by the name of the agent that controls that variable. The resulting graph is *indirected*. In Figure 2, we give an example of such a graph, where we omit to specify all the values of the variables for readability, but instead denote with gray vertices the insecure states and with white vertices the secure ones.

We say that a blocking method, and thus the corresponding algorithm, is *complete* if every secure state can be reached from any secure state. To prove the completeness of the greedy blocking method, we pur-

sue the following strategy:

1. First we prove that the state graph of the system is connected.
2. We prove that the subgraph formed by the vertices representing secure states is connected when the security formulas can be written as a set of Horn clauses.
3. We prove that every formula that we consider can be written as a disjunction of Horn clauses.
4. We show that two secure states, whose security formulas can be written as Horn clauses, are connected if and only there is a path of secure states in the above mentioned subgraph that can be traversed by the algorithm.
5. We show that the set of agents that have to be blocked, defined by a rewriting into Horn clauses of a security formula, is the union of agents that control variables occurring in one single Horn clause, and that can modify the value of the formula.
6. We show that the set of agents blocked by the greedy algorithm is a superset of the set of agents that control variables occurring in one single Horn clause in any rewriting of the formula.

In particular, we write $\mathcal{H}(\Phi, \Phi')$ to denote the set of the agents that control at least one variable of one Horn clause in one rewriting Φ' of the security formula Φ , in such a way that by changing the value of one of these variables the value of the security formula can pass from \perp to \top .

Before we carry out this sequence of proof steps, let us observe a few simple facts that will be useful in the following. First of all, every secure state corresponds to a formula, obtained as the conjunction of the literals representing the truth values of the variables in that state. Since the single elements of the set of security formulas have to be false for the system to be secure, we can describe this situation directly by the set of secure states. Indeed, guaranteeing falseness of each security formula corresponds to falsifying the disjunction of the logical expressions representing the secure states.

Lemma 1 *The state graph is connected.*

Proof This follows straightforwardly by the definition of state graph. \square

It would be tempting to presume that not only the set of states is connected, but also the set of secure states. However, this is untrue. Consider namely the case in which the system has two variables, A and B , so that there are four states as shown in Figure 1. Suppose that the security formula is $(\neg A \wedge B) \vee (A \wedge \neg B)$. The set of secure states is formed by the state in which

both A and B are false and the state in which they are both true. Clearly the set of secure states is then disconnected.

Conversely, if the set of secure states is connected, the security formula can be written as a Horn clause (or a set of clauses, which is equivalent). To do so, we introduce the notion of *Horn rewriting* of a formula: a propositional formula is a *Horn clause* iff it can be written in *Conjunctive Normal Form* (i.e. as a conjunction of disjunctions of literals) in which every conjunct is formed by at most one positive literal (This is the standard notion of Horn clause, which we recall for preserving self-containedness.) It is well-known that every propositional formula can be written as a disjunction of Horn clauses.

A *Horn labeling* λ of the states of a system is an assignment of the system variables to one of the corresponding literals. Whenever, in a Horn labeling, $\lambda(v) = v$ for a variable v , the literal v will be considered positive by that labeling, and consequently literal $\neg v$ will be considered negative. If $\lambda(v) = \neg v$, then the literal v will be considered negative, and consequently literal $\neg v$ will be considered positive. We henceforth generalize the notion of Horn clause, by stating that a formula is a Horn clause when there exists a Horn labeling for it that makes it a Horn clause.

In the above example, the formula can be rewritten, by applying the distributive property, as $(A \vee B) \wedge (\neg A \wedge \neg B)$ and there exists a Horn labeling that makes the formula a Horn clause: $\lambda(A) = \neg A$ and $\lambda(B) = B$.

We can now prove a property that will be useful in the following.

Lemma 2 *If the set of states that correspond to a security formula is connected, then the security formula is a Horn clause.*

Proof As said above, the security formula Φ can be written as the disjunction of the conjunctions of literals representing the interpretation of letters⁵ occurring in the formula itself for all the secure states. We henceforth say, when no confusion arises, that Φ is the disjunction of secure states.

There are two methods to obtain an equivalent formula Φ' from Φ . We can use the distributive property or we can negate the formula obtained by considering the insecure states.

- For the first approach, since the variables of the system all occur in each single state, the distribution provides two types of subformulas in Φ' , that are conjuncts of the security formula: complete

⁵A letter is interpreted in classical semantics. The truth value \top is represented by the positive literal, whilst the value \perp is represented by the negative literal.

conjuncts, obtained by the combination of all variables, and incomplete conjuncts, obtained by the combination of a subset of the variables occurring in the set of secure states. The incomplete conjuncts can occur only when some variables only occur in one form as a literal in the single disjuncts of the formula Φ .

- For the second method, consider the insecure states, which form the complement set of the secure states in the system. Clearly, the security formula can be written as the negation of the formula obtained as a disjunction of the insecure states. Since the negation of a disjunctive formula is a conjunctive formula, the obtained object is in conjunctive normal form.

The new formula is a conjunction of disjunctions of literals, in which every literal is the disjunction of the complemented literals of an insecure state.

We prove that, regardless of the number of involved variables, there is always a valid Horn labeling by means of a rewriting that is, depending on the number of involved states, either based on the distributive property or on the negation of insecure states. In fact, given the number of states s in the set of secure states for a given formula Φ and the number n of variables of the system, we can have $s < n + 1$, $s = n + 1$ or $s > n + 1$.

($s < n + 1$) If the number of secure states is less than or equal to the number of variables, since this set has to be connected, by hypothesis, then the number of complete conjuncts cannot be greater than the number of variables. Therefore, there is always at least one incomplete conjunct in Φ' formed by one single literal v . If this happens, every time that the value of that literal is $\neg v$, the security formula is false, so we can rewrite the formula as the conjunction of the single literal conjuncts, and consider, as Horn labeling, the one obtained by associating to the variables in the single literal conjuncts the negation of the literals occurring in those conjuncts.

($s = n + 1$) If the number of disjuncts in Φ , namely the number of secure states, is exactly the number $n + 1$, two situations can occur, in principle. Either there are single literal conjuncts or there are not. Actually, due to the connectedness of the state graph, the former is impossible. If there are single literal conjuncts, then one variable always occurs in the same literal form in all the disjuncts of Φ . Consider one state in the set of secure states. To obtain all the other states in the set, we should be able to change one variable at a time and generate in this way a new state. If the system contains

k elements, then the above described process generates $k - 1$ new states. But if there is one single literal conjunct in the rewriting Φ' , then at least one variable cannot change ever during this process. Therefore, we can only generate $n - 1$ new states contrary to the hypothesis. When a set of states is formed in the way described above, then every single state always contains the same number of positive and negative literals (with respect to the trivial Horn labeling), apart from one that contains one positive or one negative literal more than the others. This special state can be used to generate the correct Horn labeling for this set by inverting each literal in the λ function (positive literals make the variables corresponding to negative literals and vice versa).

($s > n + 1$) If the number of secure states is greater than $n + 1$, then we can consider the rewriting of Φ obtained by negating the disjunction of insecure states, that we call Φ_U . In other words, $\Phi = \neg\Phi_U$. If we distribute the literals within Φ_U and obtain the conjunctive normal form of Φ_U , then applying the negation and again distributing the literals, we finally have a conjunctive normal form for Φ that, based on the properties of the graph, enjoys the same property of existence of single literal conjuncts discussed for the case $s < n + 1$. Therefore the claim is proved. □

Let us now consider a generic set of states that is not connected. As we show in Figure 1, this may anyhow correspond to a valid Horn labeling. This, however, does not occur for every security formula. Conversely, every set of states can be written as the intersection of connected sets of states. Therefore, given any security formula, we can represent it as the disjunction of the Horn clauses that are obtained by the sets of connected states.

The purpose of Algorithm 1 is to block the agents that apply for changing variables so to make true a critical formula. Since a critical formula can be made true by making true one of its disjuncts, Lemma 2 can be used directly to prove the following Lemma 3.

More specifically, the greedy blocking works by blocking agents when they apply for the modification of the truth value of a variable, where the blocking condition is: an agent cannot perform an action when this performance brings the system in an insecure state. The synchronization proposed by the algorithm is based on application time: the system simulates the result of performing all (up to the maximum) actions that agents applied for at that instant of time. The system denies the execution to those agents that modify variables involved in the transition of the sys-

tem into an insecure state. Since this may correspond to more than one combination, the resulting blocked agent set may be larger than needed. We can assume, therefore, without loss of generality, that the algorithm blocks all the agents that applied for modifying variables that bring the system into an insecure state. This assumption is sufficient to employ fruitfully the generalization of Lemma 2 to generic formulas. Remember that $\mathcal{H}(\Phi, \Phi')$ denotes the set of the agents that control variables of one Horn clause in the rewriting Φ' of Φ and bring the system into an insecure state.

Lemma 3 *If no agent in $\mathcal{H}(\Phi, \Phi')$ modifies variables occurring in Φ , and Φ is false, then Φ is false after the modifications.*

Proof This is a direct consequence of the proof of Lemma 2. \square

Since the agents blocked by the algorithm are all those that bring the system into an insecure state, then every agent controls variables that certainly occur in at least one disjunct of Φ . If we rewrite Φ as a disjunction of Horn clauses (following the standard notion of formula rewriting into disjunction of Horn clauses)

$$\Phi = \Phi'_1 \vee \Phi'_2 \vee \dots \vee \Phi'_k,$$

then, by definition of this rewriting, every variable controlled by a that occurs in Φ , occurs in at least one of these disjuncts. If an agent that controls one variable is blocked by our algorithm, then, by definition of the simulation, at least one of the conjuncts in which the variable occurs in Φ' is true. This means that given any pair of secure states s and s' , the algorithm never blocks an agent that brings the system directly from s to s' . The extension of this property to paths is proved in the following theorem.

Theorem 4 *The greedy blocking method, Algorithm 1, is complete.*

Proof Consider two secure states s and s' , and one agent a that controls variables occurring in Φ . Suppose that s and s' are connected by a path of length k . If we can connect s to s' by a path of length k , then we can connect s to s'' by a path of length $k - 1$ and directly s'' to s' . Suppose, by contradiction, that the greedy method blocks too many agents, so that the system would be able to move from s'' to s' but not from s to s'' . By Lemma 3, if one agent that is not blocked by the algorithm does not apply for changing one variable that occurs in one of the Horn clauses that appear in a rewriting of Φ , then the formula remains false. This would mean that at least one agent, able to perform the changes of variable values that would bring the system from s to s' , controls at least one variable that does not occur in each possible rewriting of Φ . This leads to the conclusion

that at least one variable is controlled by one agent a , blocked by the greedy method, since a is able to bring the system into an insecure state, from s'' to s' , the same variable is controlled by another agent a' , that vice versa could move the system to an insecure state and occurs in one Horn disjunct of one of the possible rewritings of Φ , and brings the system from s to s'' . As a consequence, one variable would be controlled by two agents, which is contrary to the definition of agent control of variables in the system definition adopted here. \square

Soundness and completeness of the deterministic algorithm directly extend to the non-deterministic one.

Theorem 5 *The non-deterministic blocking method, Algorithm 2, is sound.*

Proof The non-deterministic blocking method is an extension of the greedy blocking method of Algorithm 1 by means of an oracle. This means that every solution of Algorithm 1 is also a solution of Algorithm 2. \square

Theorem 6 *The non-deterministic blocking method, Algorithm 2, is complete.*

Proof The same reasoning used to prove Theorem 5 applies for completeness. \square

Let us call *optimal* a method that blocks the smallest sets of agents to ensure the security of the system. The greedy blocking method guarantees just one of the optimality properties, i.e. security, but it cannot guarantee to block the smallest sets of agents. We thus say that the greedy blocking method is a *sub-optimal solution*.

What can further be proved is that the comparison of the solutions computed in the non-deterministic method generates an optimal solution. This is quite obvious, since the solutions computed are all the possible combinations, and thus the best solution is included in this set. What the algorithm does is find the smallest set of agents that need to be blocked.⁶

Theorem 7 *Algorithm 2 computes an optimal solution.*

We consider here the specific problem of blocking underhand attacks as the problem of keeping the security formula false when agents apply for changing variables. The computational complexity of a problem is defined as the cost of the best solution. In this case, we cannot claim that the solution is optimal and therefore we only have an upper bound result.

⁶There may exist more than one solution with the smallest number of agents blocked. The approach of Algorithm 2 is to compare everything with everything, so the chosen solution is the last examined one.

Theorem 8 *Blockage of underhand attacks is a polynomially solvable problem on deterministic machines.*

Proof Algorithm 1 is deterministic, sound and complete, and its cost is polynomial. \square

Analogously, the next result is a consequence of the results about soundness, completeness and cost of Algorithm 2, again in form of an upper bound.

Theorem 9 *Optimal blockage of underhand attacks is a polynomially solvable problem on non-deterministic machines.*

6 Conclusions

In this work, we have dealt with multi-agent systems whose security properties depend on the values of sets of logical formulas (the critical formulas of the systems). We assumed that the values of these formulas can change due to actions performed by the agents of the system, and that some attacks can be performed by malicious agents that are authorized within the system itself (in other terms, users of the system). These attacks conducted from inside are underhand, and we focus specifically on those attacks that are performed by groups of individuals that do not reveal their belonging to such groups, that we call hidden coalitions.

We have introduced a deterministic method, implemented by the greedy blocking algorithm, which prevents attacks to the system carried out by hidden coalitions formed by agents that are users of the system itself. The method based on this algorithm is sound and complete, but the algorithm is not optimal as it cannot block the smallest set of potentially dangerous agents. The method is thus extended to a non-deterministic version that can be used, in future investigations, to identify optimal solutions and to study extensively the computational properties of the solution, from both deterministic and non-deterministic sides. The method is obtained by introducing an oracle within the deterministic version, which makes the soundness and completeness results directly applicable to the non-deterministic version as well.

The starting point of our approach to model multi-agent systems is Coalition Logic (Pauly, 2001; Pauly, 2002; Pauly and Parikh, 2003), a cooperation Logic that implements ideas of Game Theory. Another cooperation logic that works with coalitions is the Alternating-time Temporal Logic (Alur et al., 1998a; Alur et al., 1998b; Walther et al., 1997). A widely used logic, specifically thought for dealing with strategies and multi-agent systems, is the Quantified Coalition Logic (Ågotnes et al., 2007; Ågotnes et al., 2008; Wooldridge and Dunne, 2004). A specific

extension, also used for agents in multi-agent systems is CL-PC (van der Hoek and Wooldridge, 2005; Troquard et al., 2009), and this is indeed the version of Coalition Logic that we started from.

The notion of hidden coalition is a novelty, and more generally, to the best of our knowledge, no specific investigation exists that deals with security in open systems by means of a notion of underhand attack. The system presented here is a multi-agent one, where we did not discuss how these coalitions are formed or the negotiations that can take place before the creation of the coalitions (Sandholm, 2004; Kraus, 1997). For future work, it will be interesting to consider in more detail the non-monotonic aspects underlying the problem of underhand attacks by hidden coalitions, e.g. to formalize: the mental attitudes and properties of the intelligent agents that compose the system, how agents enter/exit/are banned from a system or enter/exit a hidden coalition, and the negotiations between the agents for establishing the common goal and synchronizing/organizing their actions. In this work, we give a way to protect the system, without making a distinction between the case in which the agents that make the attack are actual members of a coalition or not. If the system is equipped with explicit/implicit coalition test methods, this can make up a significant difference in terms of usefulness of our approach.

A specific analysis of the computational properties of our blocking methods, in particular an analysis of worst, average, and practical cases, will be subject of future work. Results of lower bound for the blocking problem and the optimal blocking problem, and the computational cost of the optimal blocking problem on deterministic machines are in particular important aspects to be investigated.

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