A security property for processes in dynamic contexts*

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Abstract

We study a security property for processes in dynamic contexts, i.e., contexts that can be reconfigured at runtime. The security property that we propose, named *Persistent_BNDC*, is such that a process is "secure" when every state reachable from it satisfies a basic Non-Interference property. We define a suitable equivalence notion among processes, that allows us to express the new property as a single equivalence check, thus avoiding the universal quantifications over all the reachable states (required by *Persistent_BNDC*) and over all the possible hostile environments (implicit in the basic Non-Interference property we use). We briefly discuss how *Persistent_BNDC* can be verified through model checking.

1 Introduction

In the recent years, systems are becoming more and more complex, and the security community has to face this by considering, e.g., issues like process mobility among different architectures and systems. A mobile process moving on the network can be influenced and reconfigured by the environments it crosses, possibly leading to new security breaches. As an example, consider a mobile agent that collects confidential data (e.g., marketing information) from different commercial hosts. It could be the case that one of the commercial hosts is malicious and tries to deduce some confidential information about the commercial hosts previously visited by the process. We should thus guarantee that the process is protected from the different visited hosts, that could be running different operating systems on different architectures.

In a complex setting like the one described above, we can abstractly think that the (possibly) hostile environment in which a system or an application is running can be dynamically reconfigured at run-time, changing in unpredictable ways. A program executing in a "secure way" inside one environment could find

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itself in a different setting (with different malicious attackers) at runtime, e.g., if the process decides to migrate during its execution like in the "collecting agent" example above. This could lead to unexpected dangerous situations as a program which is in a secure state for a certain environment might find itself with no protection if the environment itself suddenly changes.

A number of formal definitions of security properties (see, for instance, [1, 3, 4, 7, 8, 13, 14, 15]) has been proposed in the literature.

In this paper we face the problem of defining a security property based on the idea of Non-Interference [10] (formalized as *BNDC* [6]), which is suitable to analyze processes in completely dynamic hostile environments. The basic idea is to require that every state which is reachable by the system still satisfies a basic Non-Interference property. If this holds, we are assured that even if the system migrates during its execution no malicious attacker will be able to compromise it, as every possible reachable state is guaranteed to be secure.

This extension of *BNDC*, called *Persistent_BNDC* (*P_BNDC*, for short), leads also to some interesting results, as we are able to prove that it may be equivalently defined by considering the *BNDC* property with a different underlying equivalence notion, i.e., adopting a different discriminating power on processes. This result places this new property in the already studied taxonomy of Non-Interference properties [6] and gives a quite efficient way of verifying *P_BNDC*, as it allows us to avoid both the universal quantification over all the possible attackers, which is present in the *BNDC* basic definition, and the universal quantification over all possible reachable states, required by the definition of *P_BNDC* itself. Finally, as we show that *P_BNDC* is equivalent to an already proposed property called *SBSNNI* [6], this work also contributes in giving new verification techniques for such a property.

The paper is organized as follows. In Section 2, we introduce the *Security Process Algebra* (SPA) language and recall the notion of *weak bisimulation* over SPA terms. In Section 3, we give the definitions of *BNDC* and *P_BNDC*, we state some results that relate the new property with already studied security properties and we characterize *P_BNDC* through a new definition of *weak bisimulation up to high level actions*. In Section 4, we report an example of a system which satisfies *P_BNDC* and, finally, in Section 5, we briefly discuss how *Persistent_BNDC* can be verified through model checking and conclude.

2 The SPA language

The *Security Process Algebra* (SPA, for short) [6] is a slight extension of Milner's CCS [11], where the set of visible actions is partitioned into high level actions and low level ones in order to specify multilevel systems. SPA syntax is based on the same elements as CCS that is: a set $\mathcal{L}$ of *visible* actions such that $\mathcal{L} = I \cup O$ where $I = \{a, b, \ldots\}$ is a set of *input* actions and $O = \{\bar{a}, \bar{b}, \ldots\}$ is a set of *output* actions; a complementation function $\bar{\cdot} : \mathcal{L} \rightarrow \mathcal{L}$, such that $\bar{\bar{a}} = a$, for all $a \in \mathcal{L}$; a special action τ which models internal computations. $Act = \mathcal{L} \cup \{\tau\}$ is the set of all *actions*. Function $\bar{\cdot}$ is extended to Act by defining $\bar{\tau} = \tau$. In order

to obtain a partition of the visible actions into two levels we consider also two sets, Act_H and Act_L, of high and low level actions such that $\overline{Act_H} = Act_H$ and $\overline{Act_L} = Act_L$; moreover $Act_H \cup Act_L = \mathcal{L}$ and $Act_H \cap Act_L = \emptyset$.

The syntax of SPA *agents* (or *processes*) is defined as follows:

$$E ::= \mathbf{0} \mid a.E \mid E + E \mid E|E \mid E \setminus v \mid E[f] \mid Z$$

where $a \in Act$, $v \subseteq \mathcal{L}$, $f : Act \to Act$ is such that $f(\bar{\alpha}) = \overline{f(\alpha)}$ and $f(\tau) = \tau$, and Z is a constant that must be associated with a definition $Z \stackrel{\text{def}}{=} E$.

Intuitively, $\mathbf{0}$ is the empty process that does nothing; $a.E$ is a process that can perform an action a and then behaves as E; $E_1 + E_2$ represents the non deterministic choice between the two processes E_1 and E_2; $E_1|E_2$ is the parallel composition of E_1 and E_2, where the executions of the two processes are interleaved, possibly synchronized on complementary input/output actions, producing an internal action τ; $E \setminus v$ is a process E prevented from performing actions in v[1]; $E[f]$ is the process E whose actions are renamed *via* the relabelling function f. For the definition of security properties it is also useful the *hiding* operator, /, of CSP which can be defined as a relabelling as follows: for a given set $v \subseteq \mathcal{L}$, $E/v \stackrel{\text{def}}{=} E[f_v]$ where $f_v(x) = x$ if $x \notin v$ and $f_v(x) = \tau$ if $x \in v$.

Let $\mathcal{E}$ be the set of SPA agents, ranged over by E and F. Let $\mathcal{L}(E)$ denote the *sort* of E, i.e., the set of the (possibly executable) actions occurring syntactically in E. The sets of high level agents and low level ones are defined as $\mathcal{E}_H \stackrel{\text{def}}{=} \{E \in \mathcal{E} \mid \mathcal{L}(E) \subseteq Act_H \cup \{\tau\}\}$ and $\mathcal{E}_L \stackrel{\text{def}}{=} \{E \in \mathcal{E} \mid \mathcal{L}(E) \subseteq Act_L \cup \{\tau\}\}$, respectively. Note that $\mathcal{E}_H \cup \mathcal{E}_L \subset \mathcal{E}$, i.e., there exist systems that execute both high and low level actions allowing communications between the two levels.

The operational semantics of the SPA language is the *Labelled Transition System* (LTS) $(\mathcal{E}, Act, \to)$, where the states are the terms of the algebra $\mathcal{E}$ and the transition relation $\to \subseteq \mathcal{E} \times Act \times \mathcal{E}$ is defined by axioms and inference rules driven by the syntactic structure of expressions. The operational semantics for an agent E is the subpart of the SPA LTS reachable from the initial state E.

The concept of *observation equivalence* between two processes is based on the idea that two systems have the same semantics if and only if they cannot be distinguished by an external observer. This is obtained by defining an equivalence relation over terms of the SPA LTS, equating two processes when they are indistinguishable. In this paper we consider the *weak bisimulation* equivalence. The general notion of *bisimulation* [11] consists of a mutual step-by-step simulation, i.e., given two processes E and F, when E executes a certain action moving to E' then F must be able to simulate this single step by executing the same action and moving to an agent F' which is again bisimilar to E', and vice-versa. A weak bisimulation is a bisimulation which does not care about internal τ actions. So, when F simulates an action of E, it can also execute some τ actions before or after that action. We will use the following notations.

If $t = a_1 \cdots a_n \in Act^*$, then we write $E \stackrel{t}{\to} E'$ if $E \stackrel{a_1}{\to} \cdots \stackrel{a_n}{\to} E'$. We also write $E \stackrel{t}{\Longrightarrow} E'$ if $E(\stackrel{\tau}{\to})^* \stackrel{a_1}{\to} (\stackrel{\tau}{\to})^* \cdots (\stackrel{\tau}{\to})^* \stackrel{a_n}{\to} (\stackrel{\tau}{\to})^* E'$ where $(\stackrel{\tau}{\to})^*$ denotes a

[1] Notice that in CCS the operator $\setminus$ requires that the actions of $E \setminus v$ do not belong to $v \cup \bar{v}$.

(possibly empty) sequence of τ labelled transitions. If $t \in Act^*$, then $\hat{t} \in \mathcal{L}^*$ is the sequence gained by deleting all occurrences of τ from t. Note, in particular, that $\widehat{\tau^n} = \epsilon$ (the empty sequence). As a consequence, $E \stackrel{\hat{a}}{\Longrightarrow} E'$ stands for $E \stackrel{a}{\Longrightarrow} E'$ if $a \in \mathcal{L}$, and for $E(\stackrel{\tau}{\rightarrow})^* E'$ if $a = \tau$ (note that $\stackrel{\tau}{\Longrightarrow}$ requires at least one τ labelled transition while $\stackrel{\hat{\tau}}{\Longrightarrow} \equiv (\stackrel{\tau}{\rightarrow})^*$ means zero or more τ labelled transitions). We say that E' is reachable from E when there exists t such that $E \stackrel{t}{\rightarrow} E'$. The notion of *weak bisimulation* is defined as follows.

Definition 2.1 (Weak Bisimulation) A binary relation $\mathcal{S} \subseteq \mathcal{E} \times \mathcal{E}$ over agents is a *weak bisimulation* if $(E, F) \in \mathcal{S}$ implies, for all $a \in Act$,

- whenever $E \stackrel{a}{\rightarrow} E'$, then there exists F' such that $F \stackrel{\hat{a}}{\Longrightarrow} F'$ and $(E', F') \in \mathcal{S}$
- whenever $F \stackrel{a}{\rightarrow} F'$, then there exists E' such that $E \stackrel{\hat{a}}{\Longrightarrow} E'$ and $(E', F') \in \mathcal{S}$.

Two agents $E, F \in \mathcal{E}$ are *observation equivalent*, denoted by $E \approx F$, if there exists a weak bisimulation $\mathcal{S}$ containing the pair (E, F). In [11] it is proved that $\approx$ is an equivalence relation.

3 Security Properties

In this section, we give some definitions that try to capture every possible information flow from a *classified* (*high*) level of confidentiality to an *untrusted* (*low*) one. A strong requirement of these definitions is that no information flow should be possible even in the presence of malicious processes that run at the classified level. The main motivation is to protect a system also from internal attacks, which could be performed by the so called *Trojan Horse* programs, i.e., programs that are apparently honest but hide inside some malicious code. This programs might be for example downloaded from the network or sent by e-mail, and executed by a high level user at the classified level. In the presence of mobility this becomes of course more and more crucial, as a Trojan Horse program could just enter the system through some transparent mechanism (like, e.g., the download of an applet), and the high level user could never be aware of being executing some downloaded (potentially malicious) code.

The definitions we are going to present are all based on the basic idea of Non-Interference [10]: "No information flow is possible from high to low if what is done at the high level *cannot interfere* in any way with the low level".

3.1 Non Deducibility on Compositions

The security property called *Bisimulation-based Non Deducibility on Compositions* (*BNDC*, for short) is based on the idea of checking the system against all high level potential interactions, representing every possible high level malicious program. A system E is *BNDC* if for every high level process Π a low level user cannot distinguish E from $(E|\Pi) \setminus Act_H$ (see Fig. 1). In other words,

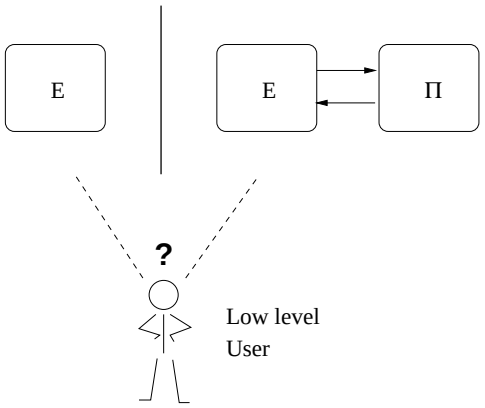

Figure 1: The *BNDC* property

a system E is *BNDC* if what a low level user sees of the system is not modified by composing any high level process Π to E.

Definition 3.1 (BNDC) Let $E \in \mathcal{E}$.

$$E \in BNDC \text{ iff } \forall\ \Pi \in \mathcal{E}_H,\ E \setminus Act_H \approx (E|\Pi) \setminus Act_H.$$

We show how *BNDC* works through some simple examples.

Example 3.2 First, consider process $E_1 = l_1.h.\bar{l_2}.\mathbf{0}$, where h is the only high level action. It basically accepts the low level input l_1 and then gives $\bar{l_2}$ as output only if h is executed. Note that we have a direct causality between the high level input h and the low level output $\bar{l_2}$, representing a direct information flow. As expected, this system is not *BNDC*. It is sufficient to consider $\Pi = \bar{h}.\mathbf{0}$. In this case it is straightforward to see that $(E_1|\Pi) \setminus Act_H \approx l_1.\bar{l_2}.\mathbf{0}$ while $E_1 \setminus Act_H \approx l_1.\mathbf{0}$. Note that the latter can never execute $\bar{l_2}$, thus $E_1 \setminus Act_H \not\approx (E_1|\Pi) \setminus Act_H$.

Example 3.3 The next example aims at showing that *BNDC* is powerful enough to detect information flows due to the possibility for a high level malicious process to block or unblock a system. Let us just extend system E_1 as follows: $E_2 = l_1.h.\bar{l_2}.\mathbf{0} + l_1.\bar{l_2}.\mathbf{0}$. We have basically added the trace $l_1.\bar{l_2}$ in order to break the direct causality between h and $\bar{l_2}$. As a matter of fact, now $\bar{l_2}$ may be executed even without h has been previously performed. However, consider the same process $\Pi = \bar{h}.\mathbf{0}$ as before. We again have that $(E_2|\Pi) \setminus Act_H \approx l_1.\bar{l_2}.\mathbf{0}$, but now $E_2 \setminus Act_H \approx l_1.\mathbf{0} + l_1.\bar{l_2}.\mathbf{0}$. Note that the latter may (nondeterministically) block after the l_1 input. Having many instances of this process, a low level user could deduce if $\bar{h}$ is executed by observing whether the system always performs $\bar{l_2}$ or not. More discussion about how this can be exploited to actually implement a communication channel from high to low may be found in [6]. Process E_2 may be "repaired" and made *BNDC*, by including the possibility of choosing to

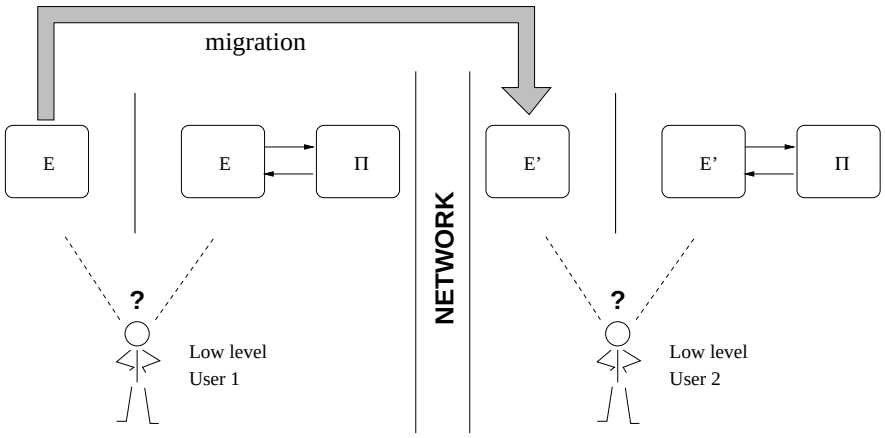

Figure 2: The *P_BNDC* property

execute $\bar{l_2}$ or not inside the process, thus completely masking high level activity. Indeed, process $E_3 = l_1.h.\bar{l_2}.\mathbf{0} + l_1.(\tau.\bar{l_2}.\mathbf{0} + \tau.\mathbf{0})$ can be proved to be *BNDC*.

3.2 Persistent_BNDC

We define a security property which is stronger than *BNDC* but which allows us to deal with possibly dynamic attackers, i.e., high level processes which can be dynamically reconfigured. The novel security property is named *Persistent_BNDC* (*P_BNDC*, for short). The idea is that a system E is *P_BNDC* if for every high level process Π and for every state E' reachable from E a low level user cannot distinguish E' from $(E'|\Pi) \setminus Act_H$ (see Fig. 2). This is equivalent to say that E is *P_BNDC* if for every state E' reachable from E, E' is *BNDC*.

Definition 3.4 (Persistent_BNDC) Let $E \in \mathcal{E}$.

$$E \in P_BNDC \quad \text{iff} \quad \forall\ E' \text{ reachable from } E \text{ and } \forall\ \Pi \in \mathcal{E}_H,\ E' \setminus Act_H \approx (E'|\Pi) \setminus Act_H., \text{ i.e., } E' \in BNDC.$$

We show the idea of *P_BNDC* through a simple example.

Example 3.5 Consider again the *BNDC* process E_3 of Example 3.3, $E_3 = l_1.h.\bar{l_2}.\mathbf{0} + l_1.(\tau.\bar{l_2}.\mathbf{0} + \tau.\mathbf{0})$. Suppose it may be moved in the middle of a computation. This might happen when it find itself in the state $h.\bar{l_2}.\mathbf{0}$ (after the first l_1 is executed). Now it is clear that this process is not secure, as a direct causality between h and $\bar{l_2}$ is present. In particular $h.\bar{l_2}.\mathbf{0}$ is not *BNDC* and this gives evidence that E_3 is not *P_BNDC*. The process may be "repaired" as follows: $E_4 = l_1.(h.\bar{l_2}.\mathbf{0} + \tau.\bar{l_2}.\mathbf{0} + \tau.\mathbf{0}) + l_1.(\tau.\bar{l_2}.\mathbf{0} + \tau.\mathbf{0})$. It may be proved that E_4 is *P_BNDC*. Note that, from this example it follows that *P_BNDC* is strictly stronger that *BNDC*, i.e., *P_BNDC* $\subset$ *BNDC*.

We proved that property *P_BNDC* is equivalent to the already proposed security property *SBSNNI* [5, 6] defined as follows.

Definition 3.6 (SBSNNI) Let $E \in \mathcal{E}$.

$$E \in SBSNNI \text{ iff } \forall\ E' \text{ reachable from } E,\ E' \setminus Act_H \approx E'/Act_H.$$

Proposition 3.7 $P_BNDC = SBSNNI$.

SBSNNI was introduced to automatically check *BNDC*, i.e., to bypass the quantification over all the possible malicious high level processes. However, we still have to verify a property (which is simpler than *BNDC*) over all the possible reachable states from the initial process E. We show that this can be avoided by including the idea of "being secure in every state" directly inside the bisimulation equivalence notion. We do this in two steps: (*i*) we define a quite "natural" notion of bisimulation which implicitly contains a quantification over all possible malicious contexts; (*ii*) we show that such an equivalence notion may be also defined in a simpler way, which do not require any universal quantification (neither on malicious contexts/processes nor on reachable states).

The universal quantification on high level processes can be moved from the definition of *P_BNDC* to the definition of a suitable equivalence relation, named $\approx_{hc}$, as follows. We use this notion of hostile context.

Definition 3.8 (Context) A *hostile context* $C[_]$ denotes a term of the form $(_ \mid \Pi) \setminus Act_H$ where $\Pi \in \mathcal{E}_H$, which can be regarded as a mapping from $\mathcal{E}$ to $\mathcal{E}$ that associates with each process $E \in \mathcal{E}$ the process $C[E] \equiv (E|\Pi) \setminus Act_H$.

Observe that for any hostile context $C[_]$ and process E, all the processes reachable from $C[E]$ have the form $C'[E']$ with $C'[_]$ being a hostile context too.

We introduce the concept of *weak bisimulation on hostile contexts*: the idea is that, given two processes E and F, when a hostile context $C[_]$ filled with E executes a certain action moving E to E' then the same context filled with F is able to simulate this step moving F to F' so that E' and F' are again weakly bisimilar on hostile contexts, and vice-versa. This must be true for every possible hostile context $C[_]$. It is important to note that the quantification over all possible hostile contexts is re-iterated for E' and F'.

We use these notations. If $t \in Act^*$ and $C[_]$ is a hostile context, then we write $E \stackrel{t}{\rightarrow}_C E'$ if $C[E] \stackrel{t}{\rightarrow} C'[E']$; we write $E \stackrel{t}{\Longrightarrow}_C E'$ if $C[E] \stackrel{t}{\Longrightarrow} C'[E']$. Thus, $E \stackrel{\hat{a}}{\Longrightarrow}_C E'$ stands for $C[E] \stackrel{a}{\Longrightarrow} C'[E']$ if $a \in \mathcal{L}$, and for $C[E](\stackrel{\tau}{\rightarrow})^* C'[E']$ if $a = \tau$.

Definition 3.9 (Weak Bisimulation on hostile contexts) A binary relation $\mathcal{S} \subseteq \mathcal{E} \times \mathcal{E}$ over agents is a *weak bisimulation on hostile contexts* if $(E, F) \in \mathcal{S}$ implies, for all context $C[_]$ and for all $a \in Act$,

- whenever $E \stackrel{a}{\rightarrow}_C E'$, then there exists F' such that $F \stackrel{\hat{a}}{\Longrightarrow}_C F'$ and $(E', F') \in \mathcal{S}$;

- whenever $F \stackrel{a}{\rightarrow}_C F'$, then there exists E' such that $E \stackrel{\hat{a}}{\Longrightarrow}_C E'$ and $(E', F') \in \mathcal{S}$.

We say that two processes $E, F \in \mathcal{E}$ are *weakly bisimilar on hostile contexts*, written $E \approx_{hc} F$, if $(E, F) \in \mathcal{S}$ for some weak bisimulation on hostile contexts $\mathcal{S}$. It is easy to prove that $\approx_{hc}$ is the largest weak bisimulation on hostile contexts and it is an equivalence relation.

Theorem below gives a characterization of *P_BNDC* in terms of $\approx_{hc}$.

Theorem 3.10 [9] Let $E \in \mathcal{E}$. Then, $E \in P_BNDC$ iff $E \setminus Act_H \approx_{hc} E$.

This characterization for *P_BNDC* processes is still difficult to use in practice, because of the implicit quantification over all hostile contexts. The next step, is thus to show that the same equivalence notion may be expressed in a rather simpler way by just focusing on observable actions which do not belong to Act_H. More in detail, we define an observation equivalence where actions from Act_H *may* be ignored, i.e., they may be matched by zero or more τ actions.

We use the following notations. For an action $a \in Act$, we write $(\stackrel{a}{\rightarrow})^{\{0,1\}}$ to denote a sequence of zero or one a actions. The expression $E \stackrel{\hat{a}}{\Longrightarrow}_{\setminus Act_H} E'$ is a shorthand for $E \stackrel{\hat{a}}{\Longrightarrow} E'$ if $a \notin Act_H$, and for $E(\stackrel{\tau}{\longrightarrow})^*(\stackrel{a}{\longrightarrow})^{\{0,1\}}(\stackrel{\tau}{\longrightarrow})^*E'$ if $a \in Act_H$. Notice that the relation $\stackrel{\hat{a}}{\Longrightarrow}_{\setminus Act_H}$ is a generalization of the relation $\stackrel{\hat{a}}{\Longrightarrow}$ used in the definition of weak bisimulation [11]. In fact, if $Act_H = \emptyset$ then for all $a \in Act$, $E \stackrel{\hat{a}}{\Longrightarrow}_{\setminus Act_H} E'$ coincides with $E \stackrel{\hat{a}}{\Longrightarrow} E'$.

We define the concept of weak bisimulation up to Act_H.

Definition 3.11 (Weak Bisimulation up to Act_H) A binary relation $\mathcal{S} \subseteq \mathcal{E} \times \mathcal{E}$ over agents is a *weak bisimulation up to* Act_H if $(E, F) \in \mathcal{S}$ implies, for all $a \in Act$,

- whenever $E \stackrel{a}{\rightarrow} E'$, then there exists F' such that $F \stackrel{\hat{a}}{\Longrightarrow}_{\setminus Act_H} F'$ and $(E', F') \in \mathcal{S}$;
- whenever $F \stackrel{a}{\rightarrow} F'$, then there exists E' such that $E \stackrel{\hat{a}}{\Longrightarrow}_{\setminus Act_H} E'$ and $(E', F') \in \mathcal{S}$.

We say that two agents $E, F \in \mathcal{E}$ are *weakly bisimilar up to* Act_H, written $E \approx_{\setminus Act_H} F$, if $(E, F) \in \mathcal{S}$ for some weak bisimulation $\mathcal{S}$ up to Act_H. One can prove that $\approx_{\setminus Act_H}$ is the largest weak bisimulation up to Act_H and it is an equivalence relation.

The next theorem states that the relations $\approx_{hc}$ and $\approx_{\setminus Act_H}$ are equivalent.

Theorem 3.12 [9] Let $E, F \in \mathcal{E}$. Then, $E \approx_{hc} F$ iff $E \approx_{\setminus Act_H} F$.

Corollary 3.13 Let $E \in \mathcal{E}$. Then, $E \in P_BNDC$ iff $E \setminus Act_H \approx_{\setminus Act_H} E$.

In practice, we have proven that a process is *P_BNDC* if and only if it is equivalent – with respect to a particular bisimulation-like equivalence relation – to the same process prevented from performing high level actions.

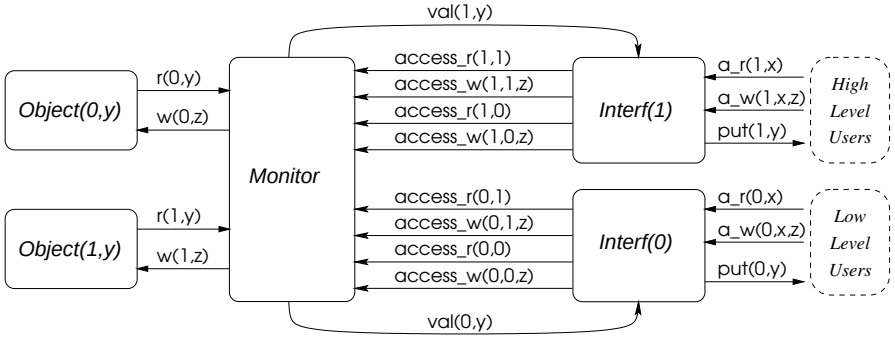

Figure 3: The *P_BNDC Access_Monitor*

4 An example

In this section we report from [5, 6] a non trivial example of a system which is *SBSNNI* and thus *P_BNDC*. Our aim is to give evidence that the proposed property is not too restrictive. Moreover, in [5, 6], *SBSNNI* was used to prove that the system was *BNDC* (as a sufficient condition). Following the intuition of *P_BNDC* we can now state that such a system is secure even when its execution environment is dynamic and changes at runtime. The system itself could be seen as a very simple mobile "colelcting agent" (as the one described in the introduction) that may be accessed in different hosts.

The example reported here is an access monitor which handles read and write requests on two binary variables enforcing the Multilevel Security Policy [2], an access control policy which has the aim of ensuring that no information flow is possible from high level to low one. The policy is based on two access rules: *no read up*, i.e., no subject can read from an object with a higher level; *no write down*, i.e., no subject can write to an object with a lower level. In particular, the access monitor process handles read and write requests from high and low level users on two binary objects: a high level variable and a low level one. It achieves *no read up* and *no write down* access control rules allowing a high level user to read from both objects and write only on the high one; conversely, a low level user is allowed to write on both objects and read only from the low one.

The access monitor system [2] is reported in Fig. 4 (see also Fig. 3). In such a system we have that $k \in \{0, 1, err\}$, $L = \{r, w\}$, $N = \{val, access_r, access_w\}$ and $a_r(1, x)$, $a_w(1, x)$, $put(1, y) \in Act_H$ $\forall x \in \{0, 1\}$ and $\forall y \in \{0, 1, err\}$, while the same actions with 0 as first parameter belong to Act_L. Users interact with the monitor through the following access actions:

- $a_r(l, x)$, a read request from level l to object x;

[2] Note that the system is specified using a value-passing extension of SPA. We will briefly explain its translation to the "pure" calculus in the following.

$$
\begin{array}{rcl}
Access_Monitor & = & (AM \mid Interf) \setminus N \\
AM & = & (Monitor \mid Object(1,0) \mid Object(0,0)) \setminus L \\
Monitor & = & access_r(l,x). \\
 & & (\ \textbf{if}\ x \leq l\ \textbf{then}\ r(x,y).\overline{val}(l,y).Monitor \\
 & & \ \textbf{else}\ \overline{val}(l,err).Monitor) \\
 & & + \\
 & & access_w(l,x,z). \\
 & & (\ \textbf{if}\ x \geq l\ \textbf{then}\ \overline{w}(x,z).Monitor \\
 & & \ \textbf{else}\ Monitor) \\
Object(x,y) & = & \overline{r}(x,y).Object(x,y) + w(x,z).Object(x,z) \\
Interf & = & Interf(0) \mid Interf(1) \\
Interf(l) & = & a_r(l,x).\overline{access_r}(l,x).val(l,k).\overline{put}(l,k).Interf(l) \\
 & & + \\
 & & a_w(l,x,z).\overline{access_w}(l,x,z).Interf(l)
\end{array}
$$

Figure 4: The *Access_Monitor* System.

- $a_w(l,x,z)$, a write request from level l to object x of value z;
- $put(l,y)$, the response to level l for a previous read request; y is the returned (read) value.

As an example, consider $a_r(0,1)$ which represents a low level user ($l=0$) read request from the high level object ($x=1$), and $a_w(1,0,0)$ which represents a high level user ($l=1$) write request of value 0 ($z=0$) on the low object ($x=0$). Read results are returned to users through the output actions $put(l,y)$. This can be an error in case of a read-up request.

The *Access_Monitor* is the parallel composition of the actual monitor AM and an interface for each level which temporarily stores the output value of the monitor (passing it later to the users and thus making communication asynchronous) and that guarantees mutual exclusion within the same level. This interface is crucial to guarantee *P_BNDC* property as without it an high level user could block the monitor process indefinitely, by never accepting the response of a read request (output value) leading to an indirect information flow.

In order to understand how the system works, let us consider the following transitions sequence representing the writing of value 1 in the low level object, performed by the low level user:

$$
\begin{array}{ll}
 & (AM \mid Interf(0) \mid Interf(1)) \setminus N \\
\xrightarrow{a_w(0,0,1)} & (AM \mid \overline{access_w}(0,0,1).Interf(0) \mid Interf(1)) \setminus N \\
\xrightarrow{\tau} & ((\overline{w}(0,1).Monitor \mid Object(1,0) \mid Object(0,0)) \setminus L \mid Interf) \setminus N
\end{array}
$$

$$\stackrel{\tau}{\longrightarrow} \quad ((Monitor \mid Object(1,0) \mid Object(0,1)) \setminus L \mid Interf) \setminus N$$

The trace corresponding to this sequence of transitions is $\langle a_w(0,0,1)\rangle$ and so we can write:

$$(AM \mid Interf(0) \mid Interf(1)) \setminus N$$
$$\stackrel{a_w(0,0,1)}{\Longrightarrow} \quad ((Monitor \mid Object(1,0) \mid Object(0,1)) \setminus L \mid Interf) \setminus N$$

Note that, after the execution of the trace, the low level object contains value 1.

Access_Monitor is a value passing specification of an access monitor. Its translation into pure SPA is described in detail in [5, 6]. The idea is to translate each possible combination of the values into different SPA actions and different SPA processes. As an example, here we provide the translation of $Object(x,y)$ into the pure calculus by means of the following four constant definitions:

$$\begin{aligned}
Object_{00} &= \overline{r}_{00}.Object_{00} + w_{00}.Object_{00} + w_{01}.Object_{01} \\
Object_{01} &= \overline{r}_{01}.Object_{01} + w_{00}.Object_{00} + w_{01}.Object_{01} \\
Object_{10} &= \overline{r}_{10}.Object_{10} + w_{10}.Object_{10} + w_{11}.Object_{11} \\
Object_{11} &= \overline{r}_{11}.Object_{11} + w_{10}.Object_{10} + w_{11}.Object_{11}
\end{aligned}$$

5 Conclusion

We presented a security property, named *Persistent_BNDC*, which is based on the idea of Non-Interference and it is suitable to deal with processes in dynamic environments. We characterized *P_BNDC* through a local property (with no quantification on the states and on the hostile contexts) by using a new definition of *weak bisimulation up to high level actions*, denoted by $\approx_{\setminus Act_H}$. This result allows us to apply the model-checking technique for verifying *P_BNDC*. In fact, using the well-known greatest fixpoint characterization of bisimulation-like relations [12], one can easily derive modal mu-calculus formulae characterizing finite-state processes up to the equivalence relation $\approx_{\setminus Act_H}$. Indeed, if $\phi^{\approx_{\setminus Act_H}}$ is a characteristic formulae for a finite state process E up to $\approx_{\setminus Act_H}$, then $E \in P_BNDC$ if and only if $E \setminus Act_H \models \phi^{\approx_{\setminus Act_H}}$ [16, 17].

Actually, the compositional security checker described in [5] provides an automatic tool for verifying *P_BNDC* over finite state processes by checking *SBSNNI*. The results presented in this paper give insights on how to improve the *P_BNDC* checker by extending our tool in order to deal with the novel equivalence relation $\approx_{\setminus Act_H}$. We plan to work on this subject in the next future.

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