Matching Security Policies to Application Needs

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Abstract

The issue of developing complex secure systems is still a great challenge. We claim that in contrast to the well known bottom-up oriented approaches secure concurrent systems should be developed top-down starting with a formal top-level specification. A framework for developing secure systems is needed, which offers means to specify security requirements adapted to the specific demands of application areas. In addition, an appropriate security model is needed to formally describe the behavior and the security properties of systems. We will present a uniform framework which is appropriate to match security policies to application needs.

Secure concurrent systems are modeled with two different levels of abstraction. The action model provides a sound and fine-grained basis to formalize security properties of the system. In order to ease system modeling we introduce the object security model by systematically coarsening the action model. In addition to our security model we will present a security requirement logic. Security policies tailored to the specific requirements of applications may be specified with the formulas of the logic. The security requirement logic allows to specify different security policies such as access control and information flow policies in a uniform way, and allows to compare these policies.

Key words : formal model, security model, security policy, access control, information flow control

1 Introduction

The issue of developing complex secure systems is still a great challenge. Ad hoc solutions which extend existing operating system services with additional security mechanisms and services to enforce security requirements are error prone and not satisfactory. We claim that in contrast to the well known bottom-up oriented approaches secure concurrent systems should be developed top-down starting with a formal top-level specification which contains the integrated specification of security properties. According to the top-down approach the systems are realized on several levels of abstraction by stepwise refining and implementing the specified properties. An integrated approach enables to verify the enforcement of the properties on each level of abstraction. The paper will present a formal and uniform framework which offers means to define formal top-level specifications and, in addition, which offers a security model for secure concurrent systems. Within the paper

we will restrict our attention to the modeling of concurrent secure systems neglecting the efforts needed to realize the modeled systems in a physically distributed environment.

The security requirements of a system specify the allowed or disallowed information flows between users, as well as, access restrictions for single users. Within our framework a security requirement logic has been developed which enables to specify security requirements tailored to application needs. The security requirement logic will be presented.

To describe the behavior and the security properties of a concurrent system an appropriate security model is needed. The lesson learned from studying the well known models is that a security model for concurrent systems is required which enables to model access properties, as well as, information flow properties adapted to the needs of individual application systems. The model should be easy to understand and to use, nevertheless, it must be sound. To achieve these requirements we propose an object-based approach to design secure systems. A concurrent system can be viewed as a set of active and passive objects interacting by means of method calls. The objects are the protected entities which can be specified with fine-grained granularity. Objects are only accessible via well-formed operations comparable with well-formed transactions in the Clark-Wilson model (c.f. [CW87]). An object-based setting provides an appropriate basis to determine fine-grained access rights. The active objects are the subjects of the system acting in behalf of human users. From the point of view of a user the object abstraction is an appropriate level of abstraction to determine access restrictions for users concerning protected objects, and to determine information flow restrictions between users. In order to formalize the behavior of the system we introduce the action model. An action model provides the formal basis needed to define the security properties of a system.

Based on the action model a logic for specifying security requirements will be introduced. Security requirements are expressed by means of logic formulas. The formulas of the logic offer a powerful formalism to specify access control policies, as well as, information flow policies. Using the logic we can specify well known security policies in a uniform manner, for instance, the multi-level security policy [BL75], or the Chinese Wall policy [BN89], as well as, application specific security policies. The model used in our approach may be characterized as information flow model with special support for data integrity based on a computation model supporting concurrency.

The rest of the paper will be organized as follows. In section 2 we introduce the action model and the object security model for secure concurrent systems and define basic security properties. The logic to specify security requirements is defined in section 3. Some examples, for instance the specification of the multi-level security policy and of the Chinese Wall policy, demonstrate the expressiveness of the logic. Finally, we will introduce the ordering on policies which enables us to systematically compare security policies. Section 4 concludes the paper.

2 Models

In this section two levels of abstraction to model secure concurrent systems namely the action model and the object security model are presented. Within the framework of the models basic security properties can be formalized.

2.1 Action Model

A concurrent system is modeled as an abstract machine by an *action model* given in definition 1.

Definition 1 Action Model:

A concurrent system is modeled by a tuple $\mathcal{AM} = (V, \Sigma, \mathcal{A}, \Gamma, S_0)$ with:

1. V is the set of *state objects*.
For each object $v \in V$ the set of values of object v is defined by $Range(v)$.
2. $\Sigma = \prod_{v \in V} Range(v)$ is the set of *states* of the system.
Given a state $s \in \Sigma$, $s[v] \in Range(v)$ describes the value of object $v \in V$ in state s .
3. $\mathcal{A}$ is the set of *atomic actions*. For each $a \in \mathcal{A}$, EN_a describes the *enabling condition* of a , $D_a \subseteq V$ is the domain, and $R_a \subseteq V$ is the range of a .
A *sequence of actions* is denoted by $\langle A \rangle$.
4. Γ is the *state transition relation* with $\Gamma \subseteq \Sigma \times \mathcal{A} \times \Sigma$.
An action $a \in \mathcal{A}$ is called *enabled* in a state $s \in \Sigma$: $\iff$ the enabling condition EN_a of a is true in state s .
The mapping¹ $en : \Sigma \longrightarrow \mathcal{P}(\mathcal{A})$ describes the set of enabled actions in a state s .
A state transition from s to s' by executing action a is denoted by $s \xrightarrow{a} s'$.
5. $S_0 \subseteq \Sigma$ is the set of *initial states*.

□

The abstract machine modeled by an action model consists of a set of state objects V , for example variables, a set of atomic actions $\mathcal{A}$ defining the computational steps of the machine, the set of states Σ defined by the set of values of the state objects, a state transition relation Γ defining the state transitions of the machine and a set of initial states S_0 . The execution of an action causes a state change. Each action a may contain a precondition, the so called enabling condition EN_a , which must be true before the action may be executed. In addition, for each action two sets of state objects, the domain set D_a

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¹ $\mathcal{P}$ denotes the power set.

and the range set R_a are defined. The state objects of the domain set may be read and the objects of the range set may be modified during the execution of the action. Starting with an initial state $s_0 \in S_0$ the system evolves by executing enabled atomic actions. The state transition relation selects non deterministically an executable action and performs the state change according to the defined effects of the action.

A sequence of actions is called *accepted* in $\mathcal{AM}$ if the first action of the sequence is enabled in one of the initial states of $\mathcal{AM}$. Furthermore, each action of the sequence must be enabled in the state produced by the execution of its predecessor action within the sequence.

The sequence of states associated with an accepted sequence $\langle A \rangle$ of actions is called a *computation* σ_A of the system.

Notation:

Let $\mathcal{A}^\Delta$ denote the set of accepted sequences of actions and let Σ^Δ denote the set of computations of a system.

Let $b \in \langle A \rangle$ denote the membership of action b in the action sequence $\langle A \rangle$.

The granularity and formal semantics of actions depend on the selected level of abstraction. Actions may represent, for instance, atomic statements of a high-level programming language or processor instructions at a lower level of abstraction. In spite of defining the formal semantics of a specific set of actions we will introduce an abstract notion of the *effect* of an action. This level of abstraction is sufficient to formally define the security properties we are interested in. Moreover, it offers the ability to select the appropriate level of abstraction due to modeling requirements.

Definition 2 Effect of an action:

Given a system $\mathcal{AM}$. The *effect* of an action $b \in \mathcal{A}$ in a computation σ_A is defined by the function ef_a .

$$ef_a : \Sigma^\Delta \times \mathcal{A} \longrightarrow \mathcal{P}(\Sigma \times V \times \bigcup_{v \in V} Range(v)) \cup \{nil\} \quad \text{with}$$

$$ef_a(\sigma_A, b) \triangleq \begin{cases} \{(s', v, s'[v]) \mid v \in V : s, s' \in \sigma_A \wedge s \xrightarrow{b} s' \text{ and } s[v] \neq s'[v]\} & \text{if } b \in \langle A \rangle \\ \{nil\} & \text{otherwise} \end{cases}$$

□

The effect of an action b executed within a computation σ_A is given by a set of triples. Each triple stores a modified state object v , the state s' after the modification and the new value $s'[v]$ of object v .

Now we are able to define the security properties of a system $\mathcal{AM}$ with respect to information flows between actions. The security properties describe the relationships between actions according to the abilities of an action to change the effects of other actions, i.e. to *influence* their effects, and to *observe* the effects of other actions.

2.1.1 Influence and Observation

We say that an action a *influences* the effects of an action b by means of a member v of the domain D_b of b if there exists an information flow from action a to action b through object v and if this information flow may be passed on to other actions by executing b . The formal definition is given in definition 4. For shortening the definition we first introduce a function *mask* which formalizes the result of purging the effects of an action from a given action sequence.

Definition 3 Masking effects:

Given a system $\mathcal{AM}$ and a special action a_{id} with $ef_a(\sigma_A, a_{id}) = \emptyset$ for each computation σ_A of the system.

The function *mask* is defined by: $mask : \mathcal{A}^\Delta \times \mathcal{A} \longrightarrow \mathcal{A}^\Delta \cup \{nil\}$ with

$$mask(\langle A \rangle, a) \triangleq \begin{cases} \langle \bar{A} \rangle & \text{if } \langle A \rangle = \langle a_1, \dots, a_k \rangle \text{ and} \\ & \exists a_j \in \langle A \rangle \text{ with } a_j = a \\ \{nil\} & \text{otherwise,} \end{cases}$$

$\langle \bar{A} \rangle$ is defined by: $\langle \bar{A} \rangle \triangleq \langle f(1), \dots, f(k) \rangle$ with

$$f(i) \triangleq \begin{cases} a_i & \text{(if } i < j) \text{ or (if } i > j) \text{ and} \\ & (a_i \in en(\bar{s}_{i-1}) \text{ with } \sigma_{f(1), \dots, f(i-1)} = \bar{\sigma}_0, \bar{s}_1, \dots, \bar{s}_{i-1})) \\ a_{id} & \text{otherwise} \end{cases}$$

□

Given an accepted sequence of actions $\langle A \rangle$ and an action $a \in \langle A \rangle$ the function *mask* generates the sequence of actions $\langle \bar{A} \rangle$ with the following four properties. (1) $\langle \bar{A} \rangle$ contains all actions of $\langle A \rangle$ which have been executed prior to a . (2) $\langle \bar{A} \rangle$ contains the effectless action a_{id} substituted for a . (3) $\langle \bar{A} \rangle$ contains all actions which are still enabled in the state sequence associated with $\langle \bar{A} \rangle$, and (4) $\langle \bar{A} \rangle$ contains the effectless action a_{id} substituted for each action b of $\langle A \rangle$ which is unabled in computation $\sigma_{\bar{A}}$ associated with $\langle \bar{A} \rangle$.

Notation :

Given two computations $\sigma, \sigma' \in \Sigma^\Delta$ with $\sigma = s_0, \dots, s_j$ and $\sigma' = s_0, \dots, s_r$ and the state object $v \in V$.

$$\tilde{s}_r \triangleq s_r \left[\begin{array}{c} v \\ s_j[v] \end{array} \right]$$

denotes the substitution of the value of object v in state $s_r \in \sigma'$ by the value of v in state $s_j \in \sigma$. That is, in state $\tilde{s}_r$ all state objects $x \neq v$ contain the value of state s_r , that is $\tilde{s}_r[x] = s_r[x]$, and for v holds: $\tilde{s}_r[v] = s_j[v]$.

Note: The evaluation of predicates in a state of a computation is defined by the function ω .

Definition 4 Influences:

Given a system $\mathcal{AM}$, the finite prefix $\langle A \rangle$ of an accepted sequence $\langle A' \rangle \in \mathcal{A}^\Delta$, $s_0 \xrightarrow{\langle A \rangle} s_k$ and $s_0 \in S_0$ with the associated computation σ_A , two actions $a, b \in \mathcal{A}$, an object $v \in V$, and a state $s_l \in \sigma_A$.

The action a *directly influences* the action b in the sequence $s_l, \dots, s_k$ of σ_A by means of the state object v if and only if the predicate $\text{inf}_a^d(l, a, b, v)$ is true in state s_k .

$$\omega(\text{inf}_a^d(l, a, b, v), s_k) = \text{true} : \iff$$

- (C1) $\exists s_i, s_j \in \sigma_A$ with $i, j < k \wedge i < j \wedge j \geq l \wedge$
 $\exists s'_i, s'_j \in \sigma_A$ with $i', j' \leq k$ with $i' \leq j$ and
 $s_i \xrightarrow{a} s'_i \wedge s_j \xrightarrow{b} s'_j$ and $v \in D_b$ and
 $\langle \bar{A} \rangle \triangleq \text{mask}(\langle A \rangle, a)$ with $\sigma_{\bar{A}} = \bar{s}_0, \bar{s}_1, \dots, \bar{s}_k$.
 and
 (C2) $b \notin \text{en}(\bar{s}_j)$

or

- (C1) $\exists s_i, s_j \in \sigma_A$ with $i, j < k \wedge i < j \wedge j \geq l \wedge$
 $\exists s'_i, s'_j \in \sigma_A$ with $i', j' \leq k$ with $i' \leq j$ and
 $s_i \xrightarrow{a} s'_i \wedge s_j \xrightarrow{b} s'_j$ and $v \in D_b$ and
 $\langle \bar{A} \rangle \triangleq \text{mask}(\langle A \rangle, a)$ with $\sigma_{\bar{A}} = \bar{s}_0, \bar{s}_1, \dots, \bar{s}_k$.
 and
 (C3) $b \in \text{en}(\bar{s}_j) \wedge s_j[v] \neq \bar{s}_j[v] \wedge \exists x \in R_b : s_j[x] \neq \bar{s}_j[x]$.
 and
 (C4) $\tilde{s}_j \triangleq s_j \left[\frac{v}{\bar{s}_j[v]} \right]$ and $b \notin \text{en}(\tilde{s}_j)$
 or $b \in \text{en}(\tilde{s}_j)$ and $\tilde{s}_j \xrightarrow{b} \tilde{s}'_j \wedge \exists y \in R_b : s_j[y] \neq \tilde{s}'_j[y]$.

□

Condition C1 holds if: Actions a and b have been executed prior to state s_k . Action a has been executed in a state s_i prior to the execution of b in state s_j . b has been executed within the sequence $s_l, \dots, s_k$, and object v is a member of the domain of b , i.e. v may be read during the execution of b .

Condition C2 holds if: The action b is unabled in the modified action sequence $\langle \bar{A} \rangle$ masking the effect of action a .

If conditions *C1* and *C2* hold action a directly influences action b , because the enabling condition of b depends on the execution of action a .

Condition C3 holds if: The action b is still enabled in the modified sequence and the value of v depends on the execution of action a , i.e. the object v contains different values in the state s_j and $\bar{s}_j$ just before the execution of b in σ_A and in $\sigma_{\bar{A}}$. Moreover, there exists an object x in the range of b which contains different values after the execution of b in the computation σ_A and in $\sigma_{\bar{A}}$.

Condition C4 holds if: The different effects of b in the computation σ_A and $\sigma_{\bar{A}}$ are caused

by the different values of the object v in the domain of b in computation σ_A and $\sigma_{\bar{A}}$, respectively.

If conditions $C1$, $C3$ and $C4$ hold action a directly influences action b , because the value of the object x in the range of b depends on the execution of action a .

Note that definition 4 makes no assumptions about the properties of actions c lying between action a and b in the sequence $\langle A \rangle$. These properties are covered implicitly by the definition above. Consider, for instance, an action c which modifies the value of object v as well and which is unabled in $\langle \bar{A} \rangle$. That is, v contains different values after the execution of c in σ_A and after the execution of the substitute action a_{id} for c in $\sigma_{\bar{A}}$. As the masking of a in $\sigma_{\bar{A}}$ causes c to become unabled, action a is responsible for the different values of v and, therefore, influences action b . This relationship between actions a , b and c is covered by definition 4.

In addition to the influence-property of an action we will define the property of an action to *observe* an influence by means of objects in its range. That is, we will define the property of an action b to observe information flows from other actions by observing the values of objects in its own range. In contrast to the influence-property the observation-property requires that the influenced action is still enabled after purging the influencing action from the action sequence. That is, the influence on the action is really mirrored by the the value of at least one object in the range of the action.

Definition 5 Observations:

Given the assumptions of definition 4. The action b *directly observes* the action a in the sequence $s_1, \dots, s_k$ of σ_A by means of the state object x if and only if the predicate $obs_a^d(l, b, a, x)$ is true in state s_k .

$$\omega(obs_a^d(l, b, a, x), s_k) = true : \iff$$

$$(C1) \quad \exists v \in D_b : \omega(inf_a^d(l, a, b, v), s_k) = true \quad \text{and} \quad s_j \xrightarrow{b} s_{j'} \quad \text{and} \\ \langle \bar{A} \rangle \triangleq mask(\langle A \rangle, a) \quad \text{with} \quad \sigma_{\bar{A}} = \overline{s_0}, \overline{s_1}, \dots, \overline{s_k}$$

and

$$(C2) \quad x \in R_b \wedge s_{j'}[x] \neq \overline{s_{j'}}[x] \quad \text{and} \quad \text{with} \\ \tilde{s}_j \triangleq s_j \left[\begin{array}{c} v \\ \overline{s_j[v]} \end{array} \right] \quad \text{holds :} \\ b \in en(\tilde{s}_j) \wedge s_{j'}[x] \neq \tilde{s}_{j'}[x].$$

□

Condition C1 holds if: Action b is influenced by the execution of action a by means of a state object v in the domain of b .

Condition C2 holds if: This influence is mirrored by the value of object x in the range of b . That is, there exists an information flow from action a to action b through object v to object x . To catch this relationship between v and x we mask the effects of action

a and substitute the value of v prior to the execution of b with the value of v in the modified action sequence. The different values of v (according to condition $C1$) cause different effects of b observable in different values of object x in computation σ_A and $\sigma_{\bar{A}}$, respectively.

The properties defined in 4 and 5 can be extended to general definitions of influences and observations between two actions by defining an influence-chain and observation-chain, respectively, between two actions a and b . The predicate $inf_a(l, a, b, v)$ holds if an influence occurs between action a and action b and predicate $obs_a(l, b, a, v)$ holds if action b observes effects of action a . The formal definitions are omitted here.

2.2 Object Security Model

An action model completely describes the behavior of a system but its fine-grained level of description is cumbersome to handle. So we coarsen the model. This leads to the *object security model* of a system. Based on the detailed action model the defined influence and observation properties can easily be transmitted to the coarser model. That is, we will define the property of a user to influence the effects of activities performed by other users or to observe the effects of activities performed by other users.

The object security model is given in definition 6.

Definition 6 Object security model :

The tuple $\mathcal{MS} = (\mathcal{AM}, (\mathcal{K}, \mathcal{O}, \mathcal{B}, urep), R, RL, rl_b, rl_k)$ models a secure concurrent system with

1. $\mathcal{AM}$ is an action model of the system.
2. $(\mathcal{K}, \mathcal{O}, \mathcal{B}, urep)$ is the object model of the system with:
 $\mathcal{K}$ is a set of *objects* and $\mathcal{K}' \subseteq \mathcal{K}$ is a set of *user representatives*.
 For each $k \in \mathcal{K}$, $E(k)$ defines the set of methods of object k .

$\mathcal{O}$ is the set of *operations*. For each $op \in \mathcal{O}$, $in(op)$ and $out(op)$ define the set of input and output parameters of operation op .

For each invocation $inst\_op$ of an operation $op \in \mathcal{O}$ the mapping ρ defines the sequence of actions $\rho(inst\_op) = \langle a_1, \dots, a_m \rangle, a_i \in \mathcal{A}$, which describes the computational steps of $inst\_op$. $\rho(inst\_op)$ is called the *action refinement* of $inst\_op$.

The set V of state objects contains special objects called *access control lists*:

$\forall k \in \mathcal{K} \exists acl_k \in V : \forall s \in \Sigma :$

$s[acl_k] = \{(k', OP) \mid k' \in \mathcal{B} \cup R \cup \mathcal{O} \cup \mathcal{K} \wedge OP \subseteq E(k)\}.$

acl_k is called the access control list of k .

$\mathcal{B}$ is the set of *users*.

The mapping $urep : \mathcal{B} \longrightarrow \mathcal{P}(\mathcal{K}')$ associates with each user of the system a set of user representatives: $\forall b, b' \in \mathcal{B} : b \neq b' \implies urep(b) \cap urep(b') = \emptyset.$

The mapping $ass\_u(ur) : \mathcal{K}' \longrightarrow \mathcal{B}$ associates a user with a user representative: $ass\_u(ur) = b \iff ur \in urep(b).$

3. R is a set of *access rights*², with $\mathcal{O} \subseteq R$.
4. $RL = \{R_1, \dots, R_m\}$ is the set of *roles*.
5. The mapping $rl_b : \mathcal{B} \longrightarrow \mathcal{P}(RL)$ associates with each user a set of roles.
6. The mapping $rl_k : \mathcal{K}' \longrightarrow RL$ with

$$rl_k(ur) = R_j : \Longleftrightarrow \exists b \in \mathcal{B} : R_j \in rl_b(b) \wedge b = ass.u(ur)$$

associates with each user representative ur a role R_j . A representative ur is active in behalf of user $b = ass.u(ur)$ in the associated role $rl_k(ur)$.

It holds: $\forall b \in \mathcal{B} : \forall ur, ur' \in u.rep(b) : ur \neq ur' \Longleftrightarrow rl_k(ur) \neq rl_k(ur')$.

□

A concurrent system is modeled by a set of objects $\mathcal{K}$. For each object $k \in \mathcal{K}$ a set of operations or methods $E(k)$ may be defined. The elements of $E(k)$ may be invoked by other objects. The set of all operations of the system is given by $\mathcal{O}$. An object may be active (process) or passive (monitor, module). The set of users is given by the set $\mathcal{B}$. Within the object model each user b is represented by a set of active objects $u.rep(b)$, the so called user representatives, which execute operations in behalf of the user.

Operations are invoked by users and executed by the associated user representatives. Each invocation creates an instance of the operation and the computational steps of the instance are defined by a sequence of actions called action refinement of the operation invocation. An action refinement of an operation invocation starts with an action creating an instance of the operation and performing the input parameter association. The last element of the refinement sequence of an invocation is the termination action which associates the output parameters and deletes the operation instance.

Concurrency between user activities is modeled by the interleaved execution of sequences of actions belonging to different action refinements of operations being called by the users' representatives.

An object is a protected entity and its methods determine the access rights which can be granted to users. The set of rights is given with R .

For each object $k \in \mathcal{K}$ of the system a special state object called access control list is introduced. The access control list is used to protect objects from unauthorized access. The value of an access control list acl_k in a given state s of the system is given by $s[acl_k]$. The value of acl_k may change dynamically according to changing access restrictions concerning object k .

At a given time a user may perform different tasks within the system and each task may require special access rights. We introduce the notion of a role to abstractly describe the task of a user (for instance the administrator role or the statistic role for users performing statistical analyses). The set of roles is given with RL and the mapping rl_b associates with each user a set of roles. For each role of a user there must exist a user representative acting in behalf of the user in the specific role. This relationship is expressed by

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² R may include an owner-right (c.f. [BL75]).

the mapping rl_k . The access control list of an object describes, for example, the allowed access for users or for roles.

The object security model enables to model fine-grained protected entities (the objects of set $\mathcal{K}$) adapted to the level of granularity the system being modeled requires. The operations of the set $\mathcal{O}$ define well-formed transactions, i.e. access rights for well-formed operations can be modeled. The role mechanism enables to grant a user different sets of access rights depending on his specific task within the system.

Example 1:

We will model a simple message transport system with the object security model, but neglecting the action parts. The system consists of an object *buffer* which buffers messages and three user representatives sending and receiving messages in behalf of two users U_1 and U_2 . *send* and *receive* are the methods of the object *buffer*. Messages are stored in the state object *queue*.

Security requirements: Permission to access the operation *send* should be granted to users performing tasks in the role *SENDER* and to the user U_1 . Permission to access the operation *receive* should only be granted to users working with the role *RECEIVER*, and the user may not invoke the method *receive*.

A system enforcing these requirements can be modeled as follows:

The set of users is given by $\mathcal{B} = \{U_1, U_2\}$, and $RL = \{SENDER, RECEIVER\}$ defines the set of roles.

The set of user representatives is given by $\mathcal{K}' = \{sender_1, sender_2, receiver\}$. *buffer* $\in \mathcal{K}$ is a passive object with the associated access control list acl_{buffer} .

The mappings are defined by:

$$\begin{aligned} u_{rep}(U_1) &= \{sender_1, receiver\}, u_{rep}(U_2) = \{sender_2\}; \\ rl_b(U_1) &= \{SENDER, RECEIVER\}, rl_b(U_2) = \{SENDER\}; \\ rl_k(sender_1) &= \{SENDER\}, rl_k(sender_2) = \{SENDER\}, \\ rl_k(receiver) &= \{RECEIVER\}. \end{aligned}$$

In the initial state $\{s_0\} = S_0$ the following property holds for the access control list acl_{buffer} of the object *buffer* :

$$\begin{aligned} (SENDER, \{send\}) &\in s_0[acl_{buffer}] \quad \wedge \quad (U_1, \{send\}) \in s_0[acl_{buffer}] \\ &\wedge \quad (RECEIVER, \{receive\}) \in s_0[acl_{buffer}] \end{aligned}$$

▲

2.2.1 Influences and Observations between Users

The influence and observation properties of actions will be re-defined in the context of the object security model, i.e. we will define information flows between users.

Definition 7 Influences between users:

Given a system $\mathcal{MS}$, the finite prefix $\langle A \rangle$ of an accepted sequence $\langle A' \rangle \in \mathcal{A}^\Delta$,

$s_0 \xrightarrow{<A>} s_r$ with $s_0 \in S_0$ and the associated computation σ_A , two user representatives $ur_1, ur_2 \in \mathcal{K}'$, two operations $op_1, op_2 \in \mathcal{O}$, a state object $v \in V$, and a state $s_l \in \sigma_A$.

User representative ur_1 *influences* user representative ur_2 in the sequence $s_1, \dots, s_r$ of σ_A by means of the state object v and operations op_1 and op_2 if and only if the predicate inf_k is true in state s_r .

$$\omega(inf_k(l, ur_1, ur_2, op_1, op_2, v), s_r) = true : \iff \exists inst\_op_1 \exists inst\_op_2 : \\ inst\_op_1 \text{ is an invocation of } op_1 \text{ invoked by } ur_1 \text{ in } \sigma_A \text{ and} \\ inst\_op_2 \text{ is an invocation of } op_2 \text{ invoked by } ur_2 \text{ in } \sigma_A \text{ and} \\ \exists a \in \rho(inst\_op_1) \exists b \in \rho(inst\_op_2) : \omega(inf_a(l, a, b, v), s_r) = true$$

□

We say, there exists an influence between user representatives ur_1 and ur_2 with respect to operations op_1 and op_2 in a given computation if the action refinement of an invocation $inst\_op_1$ of operation op_1 invoked by ur_1 contains an action which influences an action contained in the action refinement of an invocation $inst\_op_2$ of operation op_2 invoked by ur_2 . As user representatives act in behalf of users an information flow between those users is established.

The influence property defined in 7 is a generalization of the non-interference property of Goguen and Meseguer [GM82], because our model describes concurrent systems as well. Moreover, based on the action model the internal actions of the systems and their effects can be modeled and, therefore, the properties of these actions with respect to influences and observations can be determined. This allows us in contrast to [GM82] to model systems which create classified information caused by the execution of such internal actions.

Example 2:

Consider again the message transport system given in example 1. Let $< A1 >$ be a sequence of actions which contains the execution of the actions of the user representatives $sender_1$ and $sender_2$ to enqueue new messages in the state object *queue*, as well as, the actions of the user representative *receiver* to dequeue a message from *queue*. The actions of the $sender_1$ have been executed prior to the actions of the $sender_2$ and of the *receiver*. The following predicates hold for the computation $\sigma_{A1}, s_0 \xrightarrow{<A1>} s_r$:

$$\omega(inf_k(0, sender_1, receiver, send, receive, queue), s_r) = true,$$

$$\omega(inf_k(0, sender_1, sender_2, send, send, queue), s_r) = true.$$

That is, the execution of an invocation of operation *send* invoked by $sender_1$ influences the execution of invocations *receive* and *send* invoked by *receiver* and $sender_2$, respectively.

▲

To be able to distinguish between information flows which can be encapsulated and hidden within an operation and those which are observable outside of an operation we translate the property of observability to the object security model.

Definition 8 Observations between users:

Given the assumptions of definition 7.

User representative ur_2 *observes* user representative ur_1 in the sequence $s_1, \dots, s_r$ of σ_A by means of the state object v and operations op_2 and op_1 if and only if the predicate obs_k is true in state s_r .

$$\omega(obs_k(l, ur_2, ur_1, op_2, op_1, v), s_r) = true : \iff \exists inst\_op_2 \exists inst\_op_1 : \\ inst\_op_2 \text{ is an invocation of } op_2 \text{ invoked by } ur_2 \text{ in } \sigma_A \text{ and} \\ inst\_op_1 \text{ is an invocation of } op_1 \text{ invoked by } ur_1 \text{ in } \sigma_A \text{ and} \\ v \in out(op_2) \wedge \exists b \in \rho(inst\_op_2) \exists a \in \rho(inst\_op_1) : \omega(obs_a(l, b, a, v), s_r) = true$$

□

The activity of a user representative ur_1 is observable by a representative ur_2 if the value of an output parameter of at least one operation instance executed by ur_2 depends on the effects of the execution of at least one operation instance executed by ur_1 .

Example 3:

Given the sequence of actions $\langle A1 \rangle$ as described in example 2. Let y be the output parameter of operation *receive* and let $out(send) = \emptyset$.

Security requirements (cont.): In addition to the security requirements given in example 1 concerning the access restrictions of the system we require that there may not exist an observable information flow between the two senders of the system.

The following two predicates hold:

$$(1) \omega(obs_k(0, receiver, sender_1, receive, send, y), s_r) = true$$

$$(2) \forall v \in V : \omega(obs_k(0, sender_2, sender_1, send, send, v), s_r) = false$$

Predicate (1) is true in computation σ_{A1} , because the execution of the *send* operation is observable by executing the *receive* operation.

Predicate (2) is false, because the *send* operation does not specify any output parameters, and, therefore, no observable influences may occur. That is, the influence of $sender_1$ on $sender_2$ according to the influence property inf_k stated in example 2 is encapsulated within operation *send* and is therefore not observable by user U_2 associated with the user representative $sender_2$. User U_2 may not observe any activity of user U_1 by executing the operation *send* in computation σ_{A1} . This non-observability property holds for each computation and the system enforces the security requirement stated above.

▲

The definitions introduced describe the semantics of influences and observations between users of a system in a universal way. We are free to choose an appropriate specification and implementation language to design secure systems. We just have to define an action semantics for the selected languages.

The security requirements of a system – the security policy – must be stated in terms of the allowed or disallowed influences and observations between the subjects of the system, as well as, in terms of the permitted accesses to system objects.

In the next section we will introduce the logic formulas used to specify security policies.

The semantics of the formulas are formalized based on the influence and observe properties of the underlying models.

Within our framework systems and security policies are uniformly modeled and specified. The uniform formalism enables the verification of security properties with respect to specified requirements. Furthermore, within the universal framework it is possible to compare and evaluate security policies.

3 Security Requirements

To specify disallowed influences and observations between users we will define *conditional non-influencing* requirements and *conditional non-observing* requirements. Disallowed and allowed accesses are specified by *access restriction* requirements. Definition 9 introduces the logic to specify security requirements.

Definition 9 Security requirement logic:

Given an object security model $\mathcal{MS}$. The set of state objects V of $\mathcal{MS}$, a set of predicate symbols PS with $\{cninf, cnobs, acc, in\} \subseteq PS$, and the temporal operator $\Box$ form the syntactic basis of the logic.

For each computation σ of $\mathcal{MS}$ let $<$ define the linear ordering on states of the sequence σ . Let TFO be the set of all formulas over the syntactic basis. $\omega : TFO \times \sigma \rightarrow \{true, false\}$ defines the semantics of formulas in a computation σ of $\mathcal{MS}$. Given $Cond \in TFO$, $ur_1, ur_2 \in \mathcal{K}'$, $op_1, op_2 \in \mathcal{O}$, and $k \in \mathcal{K}$ the mapping ω is defined as follows:

1. Given a formula $P \in TFO$:
 $\omega(\Box P, s) = true : \iff \forall s' \in \sigma : s' \leq s : \omega(P, s') = true.$
2. The semantics of the *conditional non-influencing predicate* $cninf$ is defined by:
 $\omega(cninf(ur_1, ur_2, op_1, op_2, Cond), s) = true : \iff$
 $\omega((\omega(Cond, s) = true \implies P), s) = true$ with P is given by
 $P : \exists s' \in \sigma : \forall v \in V : \omega(inf_k(s', ur_1, ur_2, op_1, op_2, v), s) = false$ with
 $s' < s \wedge \omega(Cond, s') = true \wedge \forall s'' \in \sigma : s' < s'' < s \text{ holds} : \omega(Cond, s'') = true \wedge$
 $s' \notin S_0 \implies (\exists s''' \in \sigma : s''' \longrightarrow s' \wedge \omega(Cond, s''') = false).$
3. The semantics of the *conditional non-observing predicate* $cnobs$ is defined by:
 $\omega(cnobs(ur_2, ur_1, op_2, op_1, Cond), s) = true : \iff$
 $\omega((\omega(Cond, s) = true \implies Q), s) = true$ with Q is given by
 $Q : \exists s' \in \sigma : \forall v \in V : \omega(obs_k(s', ur_2, ur_1, op_2, op_1, v), s) = false$ with
 s' is the state in the state sequence σ with the same properties as stated above.
4. The semantics of the *access restriction predicate* acc is defined by:
 $\omega(acc(ur_1, op, k, Cond), s) = true : \iff$
 $\omega((\omega(Cond, s) = false \implies R), s) = true$ with R is given by
 $R : \nexists a \in en(s) : a$ is the first action of an action refinement sequence
of an invocation of op invoked by ur_1 .

5. $\omega(in(ur, op), s) = true : \iff$ there exists an invocation $inst\_op$ of operation op invoked by representative ur and the last element of the action refinement sequence $\rho(inst\_op)$ has not been executed in the prefix $\sigma' = s_0, \dots, s$ of σ .

□

The temporal operator $\Box$ expresses the usual 'henceforth' semantics.

A conditional non-influencing requirement between two user representatives ur_1 and ur_2 with respect to two operations requires that as long as the condition $Cond$ within the requirement specification holds there may not occur an influence from ur_1 on ur_2 by executing the specified operations. The meaning of a conditional non-observing requirement can be stated in an analogous way. An access restriction requirement concerning a user representative, an object and an operation exported by the object requires that the representative may not execute the specified operation if the condition $Cond$ within the requirement does not hold.

With the predicate in we are able to express control conditions. This is useful if we want to restrict, for instance, granted access rights to be used only within well-defined execution domains (see example below).

The conditional predicates offer a powerful formalism to specify security requirements tailored to the individual requirements of applications. With the access restriction predicates access control policies may be specified. Dynamically changing access rights may be expressed by specifying appropriate conditions within the predicates, for example, with conditions concerning the value of the access control list of the object being protected. Fine-grained information flow restrictions may be specified by using the $cninf$ and $cnobs$ predicates.

Example 4:

1. Given the ordered set of labels $L = \{unclassified, confidential, secret, top\ secret\}$ and the labeling function $l : \mathcal{K}' \longrightarrow L$.

The formula:

$$\forall op, op' \in \mathcal{O} \quad \Box cninf(ur_1, ur_2, op, op', (l(ur_1) > l(ur_2)))$$

requires that there may not exist an influence from ur_1 on ur_2 if the classification of ur_1 is greater than the classification of ur_2 . If we specify such a requirement for all user representatives and for all operations we will obtain the requirements of the multi-level security policy of the Bell LaPadula model [BL75].

2. Replacing the non-influencing formula given above with the non-observing formula:

$$\forall op, op' \in \mathcal{O} \quad \Box cnobs(ur_2, ur_1, op, op', (l(ur_2) < l(ur_1)))$$

weakens the multi-level security requirements by just disallowing observable information flows from higher to lower levels. This specification still covers the intended information flow requirements but is less restrictive than the original multi-level security policy.

3. The formula:

$$\Box acc(ur, op, k, (ass\_u(ur), \{op\}) \in acl_k \wedge in(ur, op'))$$

specifies that user representative ur is permitted to access operation op of k if its associated user $ass\_u(ur)$ is contained in the access control list of k and if the access to op is performed within the execution of operation op' , $in(ur, op')$. That is, the right to access op is restricted to a specified execution context.

▲

The examples demonstrate the expressiveness of the logic formulas. Requirements to restrict an allowed access to certain execution domains or to restrict the access by other conditions can not be expressed by the formalism of access control matrix approaches. The non-observability requirement of the example shows that multi-level security requirements can be specified in a less restrictive way, i.e. requirements are specified which are not expressible by the known formalisms.

We are now able to specify security policies for a system.

3.1 Security Policies

Definition 10 Security policy:

Given a system $\mathcal{MS}$. A *security policy* P for $\mathcal{MS}$ is a formula of the security requirement logic defined by a conjunction of one initial formula, of non-influencing, non-observing, and of access restriction formulas.

An *initial formula* P_0 specifies the allowed and disallowed accesses in the initial states $s_0 \in S_0$.

□

The security of a system is a measure of the system's ability to enforce a security policy P . A computation of the system is called *secure with respect to* P , if formula P holds in each state of the computation. The system $\mathcal{S}$ is called *secure with respect to* P if the formula P holds in each computation of $\mathcal{S}$.

Example 5:

A security policy P_{MTS} of the simple message transport system (MTS) may now be stated formally:

$$\begin{aligned} &P_0 \\ &\wedge \text{cnobs}(\text{sender}_1, \text{sender}_2, \text{send}, \text{send}, \text{true}) \\ &\wedge \text{cnobs}(\text{sender}_2, \text{receiver}, \text{send}, \text{receive}, \text{true}) \\ &\wedge \bigwedge_{ur \in \mathcal{K}'} : \\ &\quad \Box acc(ur, \text{send}, \text{buffer}, (ass\_u(ur)\{\text{send}\}) \in acl_{\text{buffer}} \vee rl_k^{-1}(ur) = \text{SENDER}) \\ &\wedge \bigwedge_{ur \in \mathcal{K}'} : \Box acc(ur, \text{receive}, \text{buffer}, rl_k^{-1}(ur) = \text{RECEIVER}). \end{aligned}$$

with

$$P_0 = (SENDER, \{send\}) \in s_0[ac_{buffer}] \wedge (U_1, \{send\}) \in s_0[ac_{buffer}] \\ \wedge (RECEIVER, \{receive\}) \in s_0[ac_{buffer}]$$

P_0 is the initial formula of P_{MTS} . The access restrictions permit the accesses to object *buffer* according to the informally stated restrictions in example 1. The policy specifies that user U_2 is not allowed to observe the activities of user U_1 . In example 3 we have already argued that this non-observability property holds for each computation of the system. The system is secure with respect to policy P_{MTS} .

▲

Example 6:

We will specify the Brewer and Nash [BN89] Chinese Wall security policy with the formalism of the security requirement logic. According to the Chinese Wall model the objects of the system are grouped together in company data sets containing objects concerning the same company and in conflict of interest classes containing company data sets whose companies are in competition. The labeling functions x and y specify for each object the conflict of interest class and the company data set, respectively. Public available information is labeled with the special company data set y_0 . We introduce the special state object N to store the access history of the system. N is a boolean matrix with $N(k, ur) = true$ if user representative ur has accessed object k .

Now we are prepared to specify the policy.

In the initial states of the system all users are permitted to access any object, i.e. the initial formula is given with $P_0 = true$.

For each passive object $k \in \mathcal{K}$ and for all operations $op \in E(k)$ we specify access restriction formulas:

$$\bigwedge_{ur \in \mathcal{K}'} : \Box acc(ur, op, k, \forall k' \in \mathcal{K} : (N(k', ur) = true \implies x(k') \neq x(k) \vee y(k') = y(k))).$$

That is, access is only permitted for ur if k is in the same data set as an object k' already accessed by ur or if k belongs to a completely different conflict of interest class.

The information flow restrictions of the Chinese Wall policy are specified by conditional non-influencing formulas for each user representative ur and for each pair of passive objects k and k' :

$$\Box cninf(ur, ur, k.read, k'.write, y(k) \neq y(k') \wedge y(k) \neq y_0)$$

That is, write access to object k' (denoted by $k'.write$) is not permitted if there does exist any object k which has already been read by ur and which is a member of a different company data set and which does not contain public informations.

With the specified formulas the Chinese Wall policy is given.

▲

Given a system modeled by the object security model. Different policies may be stated for the system. The formal basis presented permits to define a partial dominance ordering on these policies. We say, a policy P_1 dominates a policy P_2 if P_1 is at least as restrictive as P_2 , i.e. information flows which are not allowed according to policy P_2 are not allowed

according to P1, too, and each disallowed access in policy P2 is disallowed in P1 as well. Consider for instance example 4. Replacing the *cninf* requirements with *cnobs* requirements now permits information flows which are not allowed with respect to the *cninf* specification. The policy consisting of the *cninf* formulas dominates the policy consisting of the *cnobs* formulas.

The formalism provides an appropriate basis for comparing security requirements and thus for strengthening or weakening the requirements systematically by adding or removing information flow or access restrictions or by strengthening or weakening the conditions within the requirement formulas.

4 Conclusion

We have presented a uniform framework to model secure concurrent systems and to specify security requirements. The action model provides the sound basis needed to formalize security properties of the modeled system. Based on an action model we introduced our object security model. With the formalism of the object security model fine-grained protected entities, together with access rights for well-formed operations, and application specific user roles defining protection domains for users can easily be modeled. The object security model models concurrent systems with integrity and confidentiality properties. Security requirements for secure distributed systems should be formally stated to enable the verification of the system's security properties with respect to specified requirements. The security requirement logic presented offers a powerful formalism to express fine-grained information flow restrictions as well as access restrictions tailored to the individual needs of applications. We have demonstrated the expressiveness of the logic by specifying well-known security policies, and requirements which can not be expressed by the known formalisms.

We are able to specify access control and information flow policies uniformly by using the formulas of the logic. This uniform specification framework offers for the first time the possibility to formally compare and evaluate security policies.

The models together with the security requirement logic can be applied to each level of implementation during the software engineering process of developing systems. On each level an action semantics of the language (for instance specification language, or high-level programming language) to be used to implement the system must be defined and the formalism of the framework is usable to specify and verify security properties on the selected level of abstraction.

To implement specified security policies we have extended a high-level programming language with language concepts for access and information control. The development and implementation of appropriate operating system services based on a Mach3.0-Kernel to systematically realize secure systems in a physically distributed environment is still ongoing.

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