Managing Authorization Provenance: A Modal Logic based Approach

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Abstract—In distributed environments, access control decisions depend on statements of multiple agents rather than only one central trusted party. However, existing policy languages put few emphasis on authorization provenances. The capability of managing these provenances is important and useful in various security areas such as computer auditing and safeguarding delegations. Based on the newly proposed logic, we define one type of authorization provenances. We exemplify the applications of these provenances by a case study.

Keywords—authorization provenance, authorization logic

I. INTRODUCTION

Recently, major research efforts have applied logics into the design of policy languages to deal with distributed authorizations [1], [2], [4]. The set of policies written in a policy language is regarded as a policy base. When a principal requests resources, the request is translated to a query of the policy base. Then the access is granted if the answer to the query is positive and denied otherwise.

Existing access control systems based on previous policy languages, however, failed to support the management of authorization provenances. Informally, an authorization provenance denotes the set of agents whose statements are referenced in the deduction of an authorization decision. In traditional centralized authorizations, a central trusted party makes authorization decisions and takes the responsibility all by itself. In contrast, no such entity exists in distributed environments and systems have to employ mechanisms like delegations to facilitate distributed authorizations. Accordingly, a set of agents besides the central party (e.g., delegates) may play a role in and be responsible for the decision-making.

There are several reasons why it is important for one to manage authorization provenances. First, host security may be compromised if provenances are not taken into account when making authorization decisions [6], [8]. Wang et al., [8] found that users may abuse delegations to circumvent security policies; and proposed a defending mechanism, source-based enforcement, which checks not only if a subject has a privilege but also who, if any, delegated this privilege to the subject. Again, In [6], authors pointed out that, since existing enforcement of Discretionary Access Control (DAC) models cannot correctly identify the true origins of a request, they fail to defense against trojan horses and buggy programs. To trace the identity of requesters and thus protect against these attacks, the authors then invented a model based on a notion of a contamination source. It is worth noting that both the reasons and defense mechanisms of these security breaches are closely related to authorization provenances.

On the other hand, auditing is an indispensable part of a secure system. One objective of auditing is to identify from where security breaches started. There arises a trend to include proofs of authorization decisions in system logs for auditing [7]. Armed with the ability to reason about authorization provenances, one may make more use of logs. For example, since provenances record the agents involved, they can help trace back to the origins of security compromises.

From the above observations, we attempted to design an authorization logic, named DBT, which treats provenances explicitly [3]. DBT builds upon a logic BT [5]. The BT logic can represent belief and trust (delegation) and their relations. DBT extends the BT logic by introducing a new modal operator $D_i\varphi$ for each agent $i$ into the underlying distributed authorizations. $D_i\varphi$ is designed to express the provenance of $\varphi$. Based on DBT, we define a notion of authorization provenances. To the best of our knowledge, this work is the first to define authorization provenances in logic. More details (e.g., proofs) are presented in an accompanying technical report [3].

II. THE ACCESS CONTROL LOGIC DBT

A. Syntax

Consider a set of agents $\mathcal{A}G = \{1, \ldots, N\}$. We have three types of modal operators for each agent $i$: $B_i$, $T_i^j$, and $D_iB_i\varphi$ means that agent $i$ believes $\varphi$ and $T_i^j\varphi$ reads that agent $i$ trusts agent $j$ on $\varphi$. $D_i\varphi$ means that “due to agent $i$, $\varphi$ holds” or that $i$ causes that $\varphi$ holds. Given an agent expression $AE \subseteq \mathcal{A}G$, we also define an operator $D_{AE}^{\mathcal{A}G}$ based on $D_i$ for each $i \in AE$. $D_{AE}^{\mathcal{A}G}\varphi$ means that the set $AE$ of agents cause $\varphi$. Let $\text{Prop}$ be a set of primitive propositions. The set WFF of well-formed formulas (wff) is defined as follows:
ψ := p | ¬ψ | ψ ∧ ϕ | ϕ ∨ ψ | ϕ → ψ |
B_i ϕ | D_i ϕ | D_{AE} ϕ | T_j ϕ

A policy PB is a finite subset of WFF. We refer to the agent who enforces access control policies in the system in question as Local. Local is the root of trust which protects the requested resources, assembles the policy base, and evaluates queries to make access control decisions.

B. Semantics

We describe a semantics of DBT based on Kripke structures. A Kripke structure M is a tuple <W, π, D, T_j> (i, j ∈ AG; i ≠ j), where

- W is a set of possible worlds,
- π : W → 2^{Prop} is a labeling function which maps each world to a subset of Prop such that any p ∈ P is true in this world and any p ∈ Prop \ P is false in this world,
- B_i ⊆ W × W is a serial, transitive and Euclidean binary relation on W,
- D_j ⊆ W × W is a binary relation on W, and
- T_j ⊆ W × 2^W is a binary relation between W and its power set.

Definition 1 (|=): Given a structure M = <W, π, D, T_j>, w ∈ W, and a formula ϕ, let D_{AE} = ∩_{AE} D_j. We define the satisfaction relation |= as follows.

1) \langle M, w \rangle |= p if and only if p ∈ π(w),
2) \langle M, w \rangle |= ¬ϕ if and only if \langle M, w \rangle \not|= ϕ,
3) \langle M, w \rangle |= ϕ_1 ∧ ϕ_2 if and only if \langle M, w \rangle |= ϕ_1 and \langle M, w \rangle |= ϕ_2,
4) \langle M, w \rangle |= ϕ_1 ∨ ϕ_2 if and only if \langle M, w \rangle |= ϕ_1 or \langle M, w \rangle |= ϕ_2, whenever we have \langle M, w \rangle |= ϕ_1,
5) \langle M, w \rangle |= ϕ_1 ⇒ ϕ_2 if and only if \langle M, w \rangle |= ϕ_2, whenever we have \langle M, w \rangle |= ϕ_1,
6) \langle M, w \rangle |= B_i ϕ if and only if \langle M, v \rangle |= ϕ for all v such that (w, v) ∈ B_i,
7) \langle M, w \rangle |= D_i ϕ if and only if \langle M, v \rangle |= ϕ for all v such that (w, v) ∈ D_i,
8) \langle M, w \rangle |= D_{AE} ϕ if and only if \langle M, v \rangle |= ϕ for all v such that (w, v) ∈ D_{AE},
9) \langle M, w \rangle |= T_j ϕ if and only if (w, [ϕ]) ∈ T_j, where [ϕ] = {v ∈ W | \langle M, v \rangle |= ϕ}.

C. The axiomatic system of DBT

To capture the properties of distributed access control, we make the following constraints on the models, and call the class of models satisfying these constraints as models for access control, written MAC.

C1 for all S ∈ T_j(w), if B_j(w) ⊆ S, then D_j ∩ B_j(w) ⊆ S.

1 Suppose that R ⊆ X × Y is a binary relation between X and Y. Let R(x) be the set {y ∈ Y | (x, y) ∈ R}. Assuming Q ⊆ Y × Z, let R ⊗ Q be a binary relation between X and Z such that R ⊗ Q = {(x, z) | ∃y ∈ Y: y ∈ R(x) ∧ z ∈ Q(y)}.

Axioms

P: all tautologies of the propositional calculus;
B1: (B_i ϕ ∧ B_j(ϕ ⇒ ψ)) ⇒ B_j ψ
B2: ¬B_i ⊥
B3: B_i ϕ ⇒ B_j ϕ
B4: ¬B_i ϕ ⇒ B_j ¬B_i ϕ
D1: (D_i ϕ ∧ D_j(ϕ ⇒ ψ)) ⇒ D_j ψ
D2: (D_i ϕ ∧ D_j(ϕ ⇒ ψ)) ⇒ D_j ϕ
D3: D_i D_j ϕ ⇒ D_j D_i ϕ, if AE_1 ⊆ AE_2
D4: D_i D_j ϕ ⇒ D_j ϕ, if AE = [i], i ∈ AG
DBT1 (delegation): T_i ϕ ∧ B_j ϕ ⇒ D_j T_i ϕ
DBT2 (reduction): D_i D_j ϕ ⇒ D_j ϕ
DBT3 (self aware delegation): B_j T_i ϕ ⇒ T_j ϕ
DBT4 (self responsible delegation): D_i T_j ϕ ⇒ T_j ϕ
DBT5 (self responsible belief): D_j B_i ϕ ⇒ B_i ϕ
DBT6 (i-centric delegation): T_i ϕ ∧ T_j ϕ ⇒ D_j T_i ϕ
DBT7 (AE-reduction): D_i D_{AE} ϕ ⇒ D_{AE} ϕ

Rules of Inference

R1 (Modus ponens, MP): from ⊢ ϕ and ⊢ ϕ ⇒ ψ infer ⊢ ψ
R2 (Generalization, Gen): from ⊢ ϕ infer ⊢ B_i ϕ and ⊢ D_j ϕ
R3: from ⊢ ψ infer ⊢ T_i ϕ ⇒ T_j ϕ

Figure 1. The axiomatic system AC
A. Definitions of $WFF_{AP}$

We denote the set of $\eta$ formulas satisfying the following syntax as $WFF_{AP}$. Given $p \in \text{Prop}$,

$$\phi ::= T_j \cdot p \mid B \cdot p \mid \text{D} \cdot \phi$$

$$\eta ::= \phi \land \phi_1 \land \cdots \land \phi_n \Rightarrow \phi \quad (n \geq 0)$$

Since policy languages in the literature [2], [4] have taken similar forms as $WFF_{AP}$, policy bases written in $WFF_{AP}$ is expressive enough for typical authorization situations. Unless otherwise stated, when referring to a policy base we mean a policy base specified using $WFF_{AP}$.

We say that an $\eta \in WFF_{AP}$ is a B-formula if $\eta$ is of the form $B \cdot \phi$, a T-formula if $\eta$ is of the form $T_j \cdot \phi$, and a D-formula if $\eta$ is of the form $\text{D} \cdot \phi$, where $i$ and $j$ ($i \neq j$) are any agents and $AE$ is an agent expression. We say that a formula is a $DBT$-formula if it is either a B-formula, a T-formula, or a D-formula.

Since provenances concern the agents whose statements contribute to the derivation of conclusions, we abstract agents from each formula in policy bases. On the other hand, we also need to extract the authorization-related contents from each formula. Thus, we define two mappings, $U$ and $CC$, on the structures of $\eta \in WFF_{AP}$.

- The mapping $U : WFF_{AP} \rightarrow \mathcal{AG}$ is defined as:
  1) $U(B \cdot \phi) = U(T_i \cdot \phi) = i$,
  2) $U(\text{D} \cdot \phi) = U(\phi)$,
  3) $U(\phi_1 \land \cdots \land \phi_n \Rightarrow \phi) = U(\phi)$.

- The mapping $CC : WFF_{AP} \rightarrow WFF_{AP}$ is defined as:
  1) if $\eta$ is a B-formula or a T-formula, then $CC(\eta) = \eta$,
  2) if $\eta$ is a D-formula of the form $\text{D} \cdot \phi$, then $CC(\eta) = CC(\phi)$, and
  3) otherwise, $CC(\eta) = \eta$.

Example 1: $T_{\text{Alice}} \cdot B_{\text{Bob}} \cdot \text{goodPeer}(\text{David})$ is from the agent Alice, namely $U(T_{\text{Alice}} \cdot B_{\text{Bob}} \cdot \text{goodPeer}(\text{David})) = \text{Alice}$; and Bob issues the statement $B_{\text{Bob}} \cdot \text{goodPeer}(\text{David})$, thus $U(B_{\text{Bob}} \cdot \text{goodPeer}(\text{David})) = \text{Bob}$. Though $D_{\text{Bob}} \cdot B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$ means that Bob causes Alice to believe goodPeer(David), Alice is still responsible for, if any, conclusions derived from this formula. Therefore, $U(D_{\text{Bob}} \cdot B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})) = \text{Alice}$. And for this formula, the authorization-related content is that Alice believes goodPeer(David); namely, $CC(D_{\text{Bob}} \cdot B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})) = B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$.

Definition 2 (Trace): Given a formula $\eta$, we define the trace of $\eta$, written $Tr(\eta)$, on the structure of $\eta$.

1) if $\eta$ is a D-formula of the form $\text{D} \cdot \phi$, where $\phi$ is not a D-formula, $Tr(\eta) = AE_1 \parallel \cdots \parallel AE_n$.
2) otherwise, $Tr(\eta) = \emptyset$.

Basically, traces capture the agents whose statements are used in the reasoning process of a formula. If curious about from where a belief is concluded, one can query $q$ with $CC(q)$ being the belief but with variable $Tr(q)$.

Example 2: Consider $q_1 = D_{\text{Bob}} \cdot B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$, $Tr(q_1) = \text{Bob}$; if querying $q_1$ against the policy base, one is asking if it is Bob who causes $B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$ to be concluded. One can also ask if Alice has the belief that goodPeer(David) because of Cathy by the query $D_{\text{Cathy}} \cdot B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$. For any B-formula or T-formula, say $q_2 = B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$, $Tr(q_2) = \emptyset$ because $q_2$ denotes that $B_{\text{Alice}} \cdot \text{goodPeer}(\text{David})$ holds just because of $U(q_2) = \text{Alice}$ herself but no agent else.

Supposing a trace $Tr(q) = AE_1 \parallel \cdots \parallel AE_n$, we define the set of agents that appear in $Tr(q)$ as $\text{AgentsIn}(Tr(q)) = \{i \in \mathcal{AG} \mid \text{there exists } 1 \leq l \leq n \text{ such that } i \in AE_l\}$. When $AE$ is a singleton set, say $\{i\}$, we write $i$ to denote $AE$.

B. Authorization-provenance-aware (AP) policy bases and queries

Given a policy base $PB$, we say $PB$ is an AP policy base if, for each $\eta \in PB$, $SR_1$, $SR_2$, and $SR_3$ are satisfied.

$SR_1$: When $\eta$ is of the form $\phi_1 \land \cdots \land \phi_n \Rightarrow \phi_0$, if $\phi_i$ is $D_{\text{Alice}} \cdot B \cdot p$ or $D_{\text{AE}} \cdot T_j \cdot p$ for any $0 \leq i \leq n$, then $i \equiv \text{Local}$.

$SR_2$: If $\eta$ is not a D-formula.

$SR_2$: simply prevents traces from being forged. If an agent Alice can issue that $\eta = D_{\text{Alice}} \cdot B \cdot \phi$, Alice is able to forge arbitrary traces $AE$ for $B_{\text{Bob}} \cdot \phi$; then traces of conclusions, which are derived from $\eta$, are unreal as a result.

$SR_3$: If $\eta$ is of the form $\phi_1 \land \cdots \land \phi_n \Rightarrow \phi$, then

$$A \equiv U(\phi) = U(\phi_i), \quad \text{for } 1 \leq l \leq n.$$  

$$B \equiv \text{for any } 1 \leq l \leq n \text{ if } i \in \text{AgentsIn}(Tr(\phi_i)) \text{ then } i \in \text{AgentsIn}(Tr(\phi)).$$

In $SR_3$, item A is met by many policy languages in literature such as [2], [4]; so it does not restrict expressiveness as to security policy specifications. Item B simply records provenances.

Definition 3 (AP queries): An AP query $q$ is a formula such that (1) $q \in WFF_{AP}$, (2) taking form of $B \cdot \phi$, $D \cdot \phi$, or $T_j \cdot \phi$, (3) $U(q) = \text{Local}$ and (4) $Tr(q) \neq \emptyset$.

For example, $q_1 = B_{\text{Local}} \cdot \phi_1$ and $q_2 = D_{\text{Alice} \cdot \text{Bob}} \cdot B_{\text{Local}} \cdot \phi_2$ are AP queries, whereas $q_3 = D_{\text{Alice}} \cdot B_{\text{Cathy}} \cdot \phi_3$ and $q_4 = D_{\text{Alice} \cdot \text{Bob}} \cdot B_{\text{Local}} \cdot \phi_2$ are not.

Proposition 2: Given an AP PB and an AP query $q$,

$PB \models MAC \cdot q$ if and only if $PB' \models MAC \cdot q$,

where $PB'$ is a subset of PB such that for all $\eta \in PB$, $U(\eta) \in \text{AgentsIn}(Tr(q)) \cup \{U(q)\}$ if and only if $\eta \in PB'$.

Proposition 2 shows the basic motivation of AP policy bases and queries. Accordingly, for an AP query $q$, $Tr(q)$ includes the agents whose statement are referenced in the deduction of $q$. 

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C. A Case Study

We use an example from [8] to illustrate the motivations of AP policy bases.

In a company, the task of issuing checks is modeled by two authorizations pre and app, which stand for “check preparation” and “approval”, respectively. In order to prevent fraudulent transactions, pre and app must be performed by two different members of the role Treasurer (Tr for short). Also, for the sake of resiliency, the company allows a Treasurer to delegate his/her role to a Clerk (Cl for short) in case he/she is not able to work due to sickness or some other reasons.

Alice is a Treasurer and Bob is a Clerk of the company. They decided to collude to issue checks for themselves.

As noted in [8], Alice and Bob are able to issue checks for themselves, through the following actions: (A1) Alice delegates the role Treasurer to Bob; (A2) Bob performs pre to prepare a check for Alice; and (A3) Alice performs app to approve the check prepared by Bob.

One may formally represent the scenario as follows.

\[ B_{\text{Local}}(\text{InRole}(\text{Bob}, \text{Cl}) \land \text{InRole}(\text{Alice}, \text{Tr})) \]

\[ \Rightarrow T_{\text{Local}}(\text{InRole}(\text{Bob}, \text{Tr})) \] (1)

\[ D_{\text{Alice}} B_{\text{Local}} \text{InRole}(\text{Bob}, \text{Tr}) \Rightarrow D_{\text{Alice}} T_{\text{Local}} \text{pre}(\text{check}) \] (2)

\[ B_{\text{Local}} \text{InRole}(\text{Alice}, \text{Tr}) \Rightarrow T_{\text{Local}} \text{app}(\text{check}) \] (3)

From the assumption that Alice is a Treasurer and Bob is a Clerk and that (1), (4) holds. With action (A1), Bob brings a credential (5) which, together with (4), derives (6) by the axiom DBT1. From the implication (2), we have (7). With action (A2), it holds that \( B_{\text{Bob}} \text{pre}(\text{check}) \). Then by (self responsible belief) axiom DBT5, we have \( D_{\text{Bob}} B_{\text{Bob}} \text{pre}(\text{check}) \); further by axiom D3 it follows that (8). Again, by the axiom D3 it follows from (7) that (9) holds. Then, from (8) and (9), it follows that (10) by applying the axioms D2, DBT1, D3, and DBT7 in sequence. With action (A3), it holds that \( B_{\text{Alice}} \text{app}(\text{check}) \). Likewise, from (3), one can reach that (11).

\[ T_{\text{Local}} \text{InRole}(\text{Bob}, \text{Tr}) \] (4)

\[ B_{\text{Alice}} \text{InRole}(\text{Bob}, \text{Tr}) \] (5)

\[ D_{\text{Alice}} B_{\text{Local}} \text{InRole}(\text{Bob}, \text{Tr}) \] (6)

\[ D_{\text{Alice}} T_{\text{Local}} \text{pre}(\text{check}) \] (7)

\[ D_{\text{Alice, Bob}} B_{\text{Local}} \text{pre}(\text{check}) \] (8)

\[ D_{\text{Alice, Bob}} T_{\text{Local}} \text{pre}(\text{check}) \] (9)

\[ D_{\text{Alice, Bob}} B_{\text{Local}} \text{pre}(\text{check}) \] (10)

\[ D_{\text{Alice, Bob}} B_{\text{Local}} \text{app}(\text{check}) \] (11)

Then one may query \( q_s = D_{\text{Alice}} B_{\text{Local}} \text{pre}(\text{check}), q_a = D_{\text{Bob}} B_{\text{Local}} \text{pre}(\text{check}), q_7 = D_{\text{Alice, Bob}} B_{\text{Local}} \text{pre}(\text{check}) \).

IV. CONCLUDING REMARKS

We define the notion of authorization provenances in DBT logic, and show its usefulness through a case study. However, authorization provenances can be more complex when, for example, attribute-based delegations are allowed. We have defined a notion of strong authorization provenance (SAP) accordingly to capture those situations. Space limitations preclude the presentation of SAP; readers are referred to [3].

As future work, we are in the process of formalizing the transformation from a policy base to an SAP one and related properties. In addition, we are working on a type of SAP queries whose traces encode their provenances.

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