SecPAL: Design and Semantics of a Decentralized Authorization Language

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SecPAL versus Cassandra

SecPAL can be described as a successor to Cassandra, but there are important differences between the two.

- Cassandra supports distributed query evaluation with automated credential retrieval, while a SecPAL query is evaluated against a local assertion context (authorization policy and imported credentials).
- The answer to a Cassandra query is a set of constraints, while a SecPAL query returns a finite set of substitutions of constants for variables.

Discussion: Why do you think that the designers of SecPAL chose not to support these Cassandra features?

Facets of SecPAL

- SecPAL provides a readable, English-like language for policy assertions and authorization queries. (Note that assertions and authorization queries have different syntaxes with different expressive power.)
- SecPAL provides a set of safety conditions that guarantee that query evaluation will be sound, complete, and tractable.
- SecPAL specifies a deterministic evaluation algorithm for queries based on translation into Datalog with constraints.

Syntax of SecPAL Policy Assertions

- A SecPAL policy is a set of assertions of the form A says : *fact* if $fact_1, \ldots, fact_n$ where c.
- The issuer A must be a constant.
- Each fact consists of a subject and a verb phrase.
- Verb phrases use application-specific predicates written in infix notation.
- The only requirement on constraints is that the validity of ground constraints must be decidable in polynomial time.
- An assertion is either locally defined by the policy or can be imported in a credential.

Grammar for Facts

$$
\begin{array}{rcll}
e & ::= & x & \text{(variables)} \\
 & | & A & \text{(constants)} \\
pred & ::= & \text{can read [-]} & \text{(predicates)} \\
 & | & \text{has access from [-] till [-]} & \\
 & | & \ldots & \\
D & ::= & 0 & \text{(no re-delegation)} \\
 & | & \infty & \text{(with re-delegation)} \\
verbphrase & ::= & pred\ e_1 \ldots e_n & \text{for } n = Arity(pred) \\
 & | & \text{can say}_D\ fact & \text{(delegation)} \\
 & | & \text{can act as } e & \text{(principal aliasing)} \\
fact & ::= & e\ verbphrase &
\end{array}
$$

Delegation

- The special verb phrases "can say$_\infty$," "can say$_0$," and "can act as" have built-in semantics.
- They allow one principal to delegate authority to another principal and export this delegation as a credential.
- If A says B can say$_\infty$ *fact* and B says *fact* are deducible, then A says *fact* is deducible.
- B can redelegate with B says C can say$_\infty$ *fact*. This means that A says *fact* if C says *fact*.
- If A says B can say$_0$ *fact*, then B is not allowed to redelegate.
- A says B can act as C means that whenever A says C *verbphrase*, then A says B *verbphrase*.

Semantics of SecPAL Policy Assertions

$$\text{(cond)}\ \frac{\begin{array}{c}(A \text{ says } \mathit{fact} \text{ if } \mathit{fact}_1, \ldots, \mathit{fact}_k, c) \in \mathcal{AC} \\ \mathcal{AC}, D \models A \text{ says } \mathit{fact}_i\theta \quad \text{for all } i \in \{1..k\} \\ \models c\theta \qquad\qquad \mathit{vars}(\mathit{fact}\theta) = \emptyset\end{array}}{\mathcal{AC}, D \models A \text{ says } \mathit{fact}\theta}$$

$$\text{(can say)}\ \frac{\begin{array}{c}\mathcal{AC}, \infty \models A \text{ says } B \text{ can say}_D\ \mathit{fact} \\ \mathcal{AC}, D \models B \text{ says } \mathit{fact}\end{array}}{\mathcal{AC}, \infty \models A \text{ says } \mathit{fact}}$$

$$\text{(can act as)}\ \frac{\begin{array}{c}\mathcal{AC}, D \models A \text{ says } B \text{ can act as } C \\ \mathcal{AC}, D \models A \text{ says } C\ \mathit{verbphrase}\end{array}}{\mathcal{AC}, D \models A \text{ says } B\ \mathit{verbphrase}}$$

Translation into Datalog

Example 7.3. For example, the assertion

$$A \text{ says } B \text{ can say}_\infty\ y \text{ can say}_0\ C \text{ can read } z \text{ if } y \text{ can read } \mathrm{Foo}$$

is translated into

$$A \text{ says}_k\ B \text{ can say}_\infty\ y \text{ can say}_0\ C \text{ can read } z \leftarrow A \text{ says}_k\ y \text{ can read } \mathrm{Foo}$$

$$A \text{ says}_\infty\ y \text{ can say}_0\ C \text{ can read } z \leftarrow$$
$$x \text{ says}_\infty\ y \text{ can say}_0\ C \text{ can read } z\ ,$$
$$A \text{ says}_\infty\ x \text{ can say}_\infty\ y \text{ can say}_0\ C \text{ can read } z$$

$$A \text{ says}_\infty\ C \text{ can read } z \leftarrow$$
$$x \text{ says}_0\ C \text{ can read } z\ ,$$
$$A \text{ says}_\infty\ x \text{ can say}_0\ C \text{ can read } z$$

SecPAL Assertion Safety

- Recall that the only requirement on the constraint domain is that the validity of a ground constraint must be decidable in polynomial time.
- The goal of SecPAL's assertion safety rules is to ensure that constraints are ground at runtime when they have to be evaluated.
- A ground constraint is simply equivalent to `true` or `false`.

SecPAL Assertion Safety

A fact that includes "can say" is *nested*; otherwise, it is *flat*.
An assertion A says : fact if $\mathit{fact}_1, \ldots, \mathit{fact}_n$ where c is safe if:

- the conditional facts $\mathit{fact}_1, \ldots, \mathit{fact}_n$ are flat
- all variables in c also occur somewhere else in the assertion
- if fact is flat, all variables in fact also occur in a conditional fact

Authorization Queries

- Upon receiving an access request, a service using SecPAL looks up an authorization query in an authorization query table and then executes this query against the local assertion context.
- The assertion context must include all credentials required to support the request (e.g., credentials submitted by the requester).
- The result of query evaluation is a set of substitutions that map variables in the query to constants.

Syntax of SecPAL Authorization Queries

$$
\begin{array}{lcll}
q & ::= & e \text{ says } \mathit{fact} & \text{(atomic query)} \\
 & | & q_1, q_2 & \text{(conjunction)} \\
 & | & q_1 \text{ or } q_2 & \text{(disjunction)} \\
 & | & \text{not}(q) & \text{(negation)} \\
 & | & c & \text{(constraint)} \\
 & | & \exists x(q) & \text{(existential quantification)}
\end{array}
$$

- Conjunctions, disjunctions, negations, constraints, and existential quantification are permitted.
- Discussion: what about universal quantification?

Authorization Query Evaluation

$$\begin{aligned}
AuthAns_{\mathcal{AC}}(e \text{ says } fact) &= Answers_{\mathcal{P}}(e \text{ says}_{\infty} fact,\ \emptyset) \\
AuthAns_{\mathcal{AC}}(q_1,\ q_2) &= \{\theta_1\theta_2 \mid \theta_1 \in AuthAns_{\mathcal{AC}}(q_1) \text{ and } \theta_2 \in AuthAns_{\mathcal{AC}}(q_2\theta_1)\} \\
AuthAns_{\mathcal{AC}}(q_1 \text{ or } q_2) &= AuthAns_{\mathcal{AC}}(q_1) \cup AuthAns_{\mathcal{AC}}(q_2) \\
AuthAns_{\mathcal{AC}}(\text{not}(q)) &= \begin{cases} \{\varepsilon\} & \text{if } vars(q) = \emptyset \text{ and } AuthAns_{\mathcal{AC}}(q) = \emptyset \\ \emptyset & \text{if } vars(q) = \emptyset \text{ and } AuthAns_{\mathcal{AC}}(q) \neq \emptyset \\ \text{undefined} & \text{otherwise} \end{cases} \\
AuthAns_{\mathcal{AC}}(c) &= \begin{cases} \{\varepsilon\} & \text{if } \models c \\ \emptyset & \text{if } vars(c) = \emptyset \text{ and } \not\models c \\ \text{undefined} & \text{otherwise} \end{cases} \\
AuthAns_{\mathcal{AC}}(\exists x(q)) &= \{\theta_{-x} \mid \theta \in AuthAns_{\mathcal{AC}}(q)\}
\end{aligned}$$

Authorization Query Safety

$$\frac{\textit{fact} \text{ is flat}}{I \Vdash e \text{ says } \textit{fact} : \textit{vars}(e \text{ says } \textit{fact}) - I} \qquad \frac{\textit{vars}(c) \subseteq I}{I \Vdash c : \emptyset}$$

$$\frac{I \Vdash q_1 : O_1 \qquad I \Vdash q_2 : O_2}{I \Vdash q_1 \text{ or } q_2 : O_1 \cap O_2} \qquad \frac{I \Vdash q : O \qquad \textit{vars}(q) \subseteq I}{I \Vdash \text{not}(q) : \emptyset}$$

$$\frac{I \Vdash q_1 : O_1 \qquad I \cup O_1 \Vdash q_2 : O_2}{I \Vdash q_1, q_2 : O_1 \cup O_2} \qquad \frac{I \Vdash q : O \qquad x \notin I}{I \Vdash \exists x(q) : O - \{x\}}$$

- An authorization query q is safe if and only if there exists a set of variables O such that $\emptyset \Vdash q : O$.
- Note that only flat facts can occur in an authorization query, ensuring that “can say” goals are always ground at runtime.

Query Evaluation in Cassandra

$E_{loc} \Diamond \textsc{Resolve-Clause}(E_{req}, \mathsf{root}(P_0; c_0))$

foreach $R \equiv P_0 \leftarrow \vec{P}, c \in \mathcal{P}$ such that $c_0 \wedge c$ is satisfiable **do**

  if R is an aggregation rule **then**

    $E_{loc} \Diamond \textsc{Aggregate}(E_{req}, (P_0, c_0), R)$

  else if $E_{req} = E_{loc}$ **then**

    $E_{loc} \Diamond \textsc{Project}(E_{req}, \mathsf{body}((P_0, c_0); \vec{P}; c_0 \wedge c))$

  else

    $E_{loc} \Diamond \textsc{Project}(E_{req}, \mathsf{body}((P_0, c_0); [\mathsf{canReqCred}(E_{req}, P_0), \vec{P}]; c_0 \wedge c))$

Query Evaluation in Cassandra

$E_{loc} \Diamond \textsc{Project}(E_{req}, \mathsf{body}((P_0, c_0); \vec{P}, c_1))$

if $\vec{P} = []$ **then**

  foreach satisfiable $c \in \exists_{-P_0}(c_1)$ **do**

    $E_{req} \Diamond \textsc{Process-Answer}(\mathsf{ans}((P_0, c_0); c))$

else

  foreach satisfiable $c \in \exists_{-P_1}(c_1)$ **do**

    $E_{loc} \Diamond \textsc{Propagate-Answer}(E_{req}, \mathsf{goal}((P_0, c_0); (P_1, c); \vec{P}; c_1))$

Query Evaluation in Cassandra

$E_{loc}\Diamond\textsc{Process-Answer}(\mathsf{ans}(P_0, c_0), c)$

if c is not subsumed by a constraint in $E_{loc}\Diamond Ans(P_0, c_0)$ **then**

$\quad E_{loc}\Diamond Ans(P_0, c_0) := E_{loc}\Diamond Ans(P_0, c_0) \cup \{c\};$

$\quad$ **foreach** $(E_{req}, \mathsf{goal}((Q_0, d_0); (P_0, d); \vec{Q}; d_1)) \in E_{loc}\Diamond Wait(P_0, c_0)$

$\qquad\qquad$ such that $c \wedge d_1$ is satisfiable **do**

$\qquad E_{loc}\Diamond\textsc{Project}(E_{req}, \mathsf{body}((Q_0, d_0); \vec{Q}; c \wedge d_1)$

Query Evaluation in Cassandra

$E_{loc}\Diamond\text{PROPAGATE-ANSWER}(E_{req}, \mathsf{goal}((P_0, c_0); (P_1, d_0); \vec{P}; c_1))$

if there exists $(P_1, d_1) \in Dom(E_{loc}\Diamond Ans)$ such that $d_0 \Rightarrow d_1$ **then**

  $E_{loc}\Diamond Wait(P_1, d_1) :=$

    $E_{loc}\Diamond Wait(P_1, d_1) \cup (E_{req}, \mathsf{goal}((P_0, c_0); (P_1, d_0); \vec{P}; c_1));$

  foreach $a \in Ans(P_1, d_1)$ such that $a \wedge c_1$ is satisfiable **do**

   $E_{loc}\Diamond\text{PROJECT}(E_{req}, \mathsf{body}((P_0, c_0); \vec{P}; a \wedge c_1))$

else

  $E_{loc}\Diamond Ans(P_1, d_0) := \emptyset;$

  $E_{loc}\Diamond Wait(P_1, d_0) := \{(E_{req}, \mathsf{goal}((P_0, c_0); (P_1, d_0); \vec{P}; c_1))\};$

  $Loc(P_1, d_0)\Diamond\text{RESOLVE-CLAUSE}(E_{loc}, \mathsf{root}(P_1; d_0))$

Atomic Query Evaluation in SecPAL

RESOLVE-CLAUSE($\langle P \rangle$)
  $Ans(P) := \emptyset$;
  foreach $(Q \leftarrow \vec{Q}, c) \in \mathcal{P}$ **do**
    if $nd = resolve(\langle P; Q :: \vec{Q}; c; Q; [\,]; Cl \rangle, P)$
      exists **then**
      PROCESS-NODE(nd)

PROCESS-ANSWER(nd)
  match nd **with** $\langle P; [\,]; c; \_; \_; \_ \rangle$ **in**
   if $nd \notin Ans(P)$ **then**
    $Ans(P) := Ans(P) \cup \{nd\}$;
   foreach $nd' \in Wait(P)$ **do**
    if $nd'' = resolve(nd', nd)$ exists **then**
      PROCESS-NODE(nd'')

Atomic Query Evaluation in SecPAL

PROCESS-NODE(nd)
 match nd **with** $\langle P; \vec{Q}; c; \_; \_; \_\rangle$ **in**
  if $\vec{Q} = [\,]$ **then**
   PROCESS-ANSWER(nd)
  else match $\vec{Q}$ **with** $Q_0 :: \_$ **in**
   if there exists $Q_0' \in dom(Ans)$
     such that $Q_0 \preccurlyeq Q_0'$ **then**
    $Wait(Q_0') := Wait(Q_0') \cup \{nd\}$;
    foreach $nd' \in Ans(Q_0')$ **do**
     if $nd'' = resolve(nd, nd')$ exists **then**
      PROCESS-NODE(nd'')
   else
    $Wait(Q_0) := \{nd\}$;
    RESOLVE-CLAUSE($\langle Q_0\rangle$)

Understanding Atomic Query Evaluation

$$(\{\langle P\rangle\} \uplus Nodes, \mathtt{Ans}, \mathtt{Wait}) \xrightarrow{ResolveClause} (Nodes \cup Nodes', \mathtt{Ans}[P \mapsto \emptyset], \mathtt{Wait})$$

$$\text{if} \quad Nodes' = \{nd \;:\; Cl \equiv Q \leftarrow \vec{Q}.c \in \mathcal{P},$$

$$nd = resolve(\langle P; Q :: \vec{Q}; c; Q; [\,]; Cl\rangle, P) \text{ exists }\}$$

$$(\{nd\} \uplus Nodes, \mathtt{Ans}, \mathtt{Wait}) \xrightarrow{PropagateAnswer} (Nodes \cup Nodes', \mathtt{Ans}[P \mapsto \mathtt{Ans}(P) \cup \{nd\}], \mathtt{Wait})$$

$$\text{if} \quad nd \equiv \langle P; [\,]; \mathtt{True}; \_; \_; \_\rangle$$

$$nd \notin \mathtt{Ans}(P)$$

$$Nodes' = \{nd'' \;:\; nd' \in \mathtt{Wait}(P),\ nd'' = resolve(nd', nd) \text{ exists}\}$$

$$(\{nd\} \uplus Nodes, \mathtt{Ans}, \mathtt{Wait}) \xrightarrow{RecycleAnswers} (Nodes \cup Nodes', \mathtt{Ans}, \mathtt{Wait}[Q' \mapsto \mathtt{Wait}(Q') \cup \{nd\}])$$

$$\text{if} \quad nd \equiv \langle \_; Q :: \_; \_; \_; \_; \_\rangle$$

$$\exists\, Q' \in dom(\mathtt{Ans}) \;:\; Q \preccurlyeq Q'$$

$$Nodes' = \{nd'' \;:\; nd' \in \mathtt{Ans}(Q'),\ nd'' = resolve(nd, nd') \text{ exists}\}$$

$$(\{nd\} \uplus Nodes, \mathtt{Ans}, \mathtt{Wait}) \xrightarrow{SpawnRoot} (Nodes \cup \{\langle Q\rangle\}, \mathtt{Ans}[Q \mapsto \emptyset], \mathtt{Wait}[Q \mapsto \{nd\}])$$

$$\text{if} \quad nd \equiv \langle \_; Q :: \_; \_; \_; \_; \_\rangle$$

$$\forall\, Q' \in dom(\mathtt{Ans}) \;:\; Q \not\preccurlyeq Q'$$

Understanding Atomic Query Evaluation

Lemma A.11. (answer groundness) If $(Nodes, Ans, Wait)$ is reachable from some initial state and $\langle P;[\,];c;S;\vec{nd};Cl\rangle \in Nodes$ then S and c are ground and c is valid.

Lemma A.12. (node invariant) We write $\bigcup Ans$ as short hand for $\bigcup_{P\in dom(Ans)} Ans(P)$. If $(Nodes, Ans, Wait)$ is reachable from some initial state and $\langle P;\vec{Q};c;S;\vec{nd};Cl\rangle \in Nodes$ with $Cl = R \leftarrow \vec{R}, d$, then:

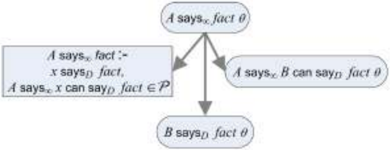
1. $S \preccurlyeq P$;
2. $Cl \in \mathcal{P}$;
3. $\vec{nd} \subseteq \bigcup Ans$;
4. there is some θ such that $R\theta = S$, and $\vec{R}\theta = \vec{Q}'@\vec{Q}$ (where $\vec{Q}'$ are the answers in $\vec{nd}$), and $d\theta$ is equivalent to c.

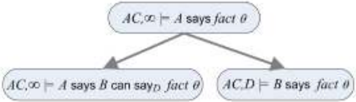
Strengths of SecPAL

- The SecPAL language was designed from the beginning to be easy to read and understand for users unfamiliar with formal logic.
- Usability is a critical part of security: a trust management system can be considered a security weakness if policy authors are not able to correctly express their intentions in the policy language.

Strengths of SecPAL

- SecPAL's evaluation algorithm builds a proof tree for each answer to a query, helping users and administrators understand why an answer was returned.
- The Datalog proof graph is easily converted into a SecPAL proof graph whose semantics may be more accessible.





Strengths of SecPAL

- SecPAL's simplicity was made possible by the insight that authorization queries can have a more expressive syntax than policy assertions without affecting the evaluation of atomic queries.
- Since authorization queries can include negation and existential quantification, policy idioms like separation of duties can be written naturally when the underlying evaluation model is just Datalog.

Limitations of SecPAL

- SecPAL has no support for automated credential retrieval, and there is no way for a user to learn what set of credentials must be submitted along with a request without knowing the details of the service's policy.
- See Moritz Y. Becker, Jason F. Mackay, and Blair Dillaway, "Abductive Authorization Credential Gathering," IEEE International Symposium on Policies for Distributed Systems and Networks, July 2009.

Limitations of SecPAL

- SecPAL has no explicit support for the role activations and deactivations that are central to Cassandra policies. DynPAL: Moritz Y. Becker, "Specification and Analysis of Dynamic Authorisation Policies," 22nd IEEE Computer Security Foundations Symposium, July 2009.
- SecPAL's query evaluation algorithm may not work well in a distributed setting. In particular, the left-to-right tabling resolution may exhibit poor performance if answers from remote locations have to be waited for.

Summary

- The SecPAL language combines a readable, English-like syntax and intuitive semantic rules with a translation into Datalog with constraints for evaluation.
- Safety conditions on policy assertions and authorization queries guarantee that query evaluation remains decidable without restricting the choice of the constraint domain.
- Authorization queries are syntactically distinct from policy assertions. Conjunctions, disjunctions, negations, constraints, and existential quantification are supported without compromising the tractability of the language.

Questions/Comments