Cedar: A New Language for Expressive, Fast, Safe, and Analyzable Authorization

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Cedar is a new authorization policy language designed to be ergonomic, fast, safe, and analyzable. Rather than embed authorization logic in an application’s code, developers can write that logic as Cedar policies and delegate access decisions to Cedar’s evaluation engine. Cedar’s simple and intuitive syntax supports common authorization use-cases with readable policies, naturally leveraging concepts from role-based, attribute-based, and relation-based access control models. Cedar’s policy structure enables access requests to be decided quickly. Cedar’s policy validator leverages optional typing to help policy writers avoid mistakes, but not get in their way. Cedar’s design has been finely balanced to allow for a sound and complete logical encoding, which enables precise policy analysis, e.g., to ensure that when refactoring a set of policies, the authorized permissions do not change. We have modeled Cedar in the Lean programming language, and used Lean’s proof assistant to prove important properties of Cedar’s design. We have implemented Cedar in Rust, and released it open-source. Comparing Cedar to two open-source languages, OpenFGA and Rego, we find (subjectively) that Cedar has equally or more readable policies, but (objectively) performs far better.

∗Work carried out while at Amazon Web Services

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INTRODUCTION

Authorization is the problem of deciding who has access to what in a multi-user system. Every cloud-based application has to solve this problem, from photo sharing to online banking to health care. A common solution is to embed access control logic in the application code, as shown in the get_list method for TinyTodo (Figure 1), a hypothetical application for managing todo lists.

This approach has three major drawbacks. First, it is hard to write correct permissions. The logic in get_list denies access if the requester is neither an admin, nor the list’s owner, nor a member of its readers or writers groups. It would be easy to mistakenly drop a not or improperly nest the conditions; such mistakes account for four of the top 25 security weaknesses in 2023 [34]. Second, embedded permissions are hard to understand and audit. An auditor needs to read the application’s code to check access invariants such as a list’s editors can perform all the same actions as the list’s readers. Finally, embedded permissions are hard to maintain. Changing authorization logic means changing the application code, so policy versioning is tantamount to code versioning. Adding crosscutting permissions (e.g., supporting a new user role) requires updates to code in multiple places, which offers more chances for mistakes.

Policies as code. A better alternative is to externalize access control rules into policies written in a domain-specific authorization language, and delegate decisions to the language’s authorization engine. This approach is called policies as code [54]. With policies as code, lines 2–6 of get_list become a single, unchanging call to the authorization engine, e.g., if not client.is_authorized(...):

return 'AccessDenied'. The authorization engine makes a decision by consulting the application’s policies, which are expressed separately from the application code, in a dedicated DSL. This makes access control rules easier to understand, audit, change, version, and share between applications.

But building a high-quality authorization language is a significant challenge that requires balancing four competing goals. In particular, the language should be expressive, so that application developers can grant access based on user and resource attributes, group membership, and session context [21, 26, 43]; performant, so that requests are decided quickly; safe, so that policy authoring mistakes are caught or avoided; and analyzable, so that policy analysis tools can reason precisely about important access invariants.

The first goal is in tension with the other three. A highly expressive language may have constructs that are slow to execute, hard to prove safe, and impossible to analyze precisely. A fast, safe, and...
analyzeable language, in contrast, may be too weak to express common authorization use-cases. To our knowledge (Section 6), no existing language finds the ideal balance of these four goals.

**Cedar: a novel authorization language.** This paper presents Cedar, a new authorization language that is simultaneously expressive, performant, safe, and analyzable. Cedar is used at scale in products and services from Amazon Web Services, and is open source.

Cedar’s vocabulary can naturally express who has access to what based on users’ roles and attributes of their environment. Most Cedar operators take constant time, and looping constructs are linear, ensuring fast policy evaluation times. While deciding a request considers all active policies, Cedar is able to quickly slice the full policy set to evaluate only those relevant to the request.

Cedar’s design creates a safe foundation for authoring policies. Policies have no side effects, and decisions are indifferent to the order that policies are considered. Cedar policies never authorize an action by default—it must be explicitly permitted. Cedar provides a policy validator, based on a novel type system leveraging singleton types [1] and static capabilities [12], that ensures policy evaluation will never error on a type mismatch, or a bogus attribute or role name.

Cedar’s design ensures that its policies are efficiently analyzable by reduction to SMT, so that access invariants can be proved automatically. We define a novel symbolic compiler that translates Cedar policies to SMT, producing a decidable, sound, and complete encoding of their semantics.

**Implementation and Evaluation.** We have formalized Cedar in Lean [35] and used Lean’s proof assistant to prove the properties mentioned above. We have implemented Cedar in Rust, and used extensive differential random testing to ensure that the implementation matches the model.

We conduct three sets of experiments to evaluate Cedar’s expressiveness, performance, and analyzability. First, we use Cedar to encode the authorization models for two example applications previously modeled in OpenFGA [40], a recently developed language for specifying relationship-based access control (ReBAC) [43] policies. We can express both of these OpenFGA models with validated Cedar policies. Next, we compare the performance of Cedar, OpenFGA, and Rego [36]—a popular authorization language based on Datalog—on three example applications: the two OpenFGA examples and an additional example described in Section 2. Comparing the performance of these three models on randomly generated inputs, we find that the Cedar authorizer is 28.7×-35.2× faster than OpenFGA and 42.8×-80.8× faster than Rego. We also evaluate the effectiveness of Cedar’s policy slicing, and find that authorization is 10.0×-18.0× faster on average, when using a Cedar templates-based encoding. Finally, we find that Cedar’s type system is powerful enough to validate all policies in our example models, and Cedar’s symbolic compiler reduces analysis questions about these policies into SMT-LIB formulas that take, on average, 75.1 ms to encode and solve.

In summary, this paper makes the following contributions:

- Design, implementation, and evaluation of Cedar, a new authorization language that balances expressiveness, safety, performance, and analyzability.
- A verified validator for Cedar, designed to accept safe policies that are translatable to SMT.
- A verified symbolic compiler for reducing Cedar to a decidable fragment of SMT.

Cedar’s code, documentation, and example apps can be found at [https://github.com/cedar-policy/](https://github.com/cedar-policy/).

2 **OVERVIEW**

We overview Cedar using TinyTodo, the application introduced in the prior section. We illustrate the structure and semantics of Cedar policies and its data model, how the Cedar validator typechecks Cedar policies to prevent run-time errors, and how the Cedar symbolic compiler allows us to reason about the meaning of Cedar policies.
Fig. 2. Cedar policies for TinyTodo

2.1 Basic TinyTodo policies: Creating and managing lists

TinyTodo allows individuals, called Users, and groups, called Teams, to organize, track, and share their todo Lists. We specify and enforce TinyTodo’s access rules using Cedar policies.

Consider the first two of TinyTodo’s policies shown in Figure 2. Policy 0 states that any principal (a TinyTodo User) can create a list or get a listing of their previously created lists. The resource Application::"TinyTodo" represents the TinyTodo application itself, which is a container for any created list. Policy 1 states that any principal can perform any action on a resource that is a List and whose owner attribute matches the requesting principal. TinyTodo always sets a List’s owner at the time it is created to the User that created it.

Suppose there is a TinyTodo user andrew who attempts to create a new todo list called "Create demo", add two tasks to that list, and then complete one of the tasks. Creating the list is authorized by Policy 0: Any user is allowed to create a List. The other three actions are authorized by Policy 1: since andrew is the owner of the List, he may carry out any action on it.

2.2 Cedar data model: Hierarchical entities

Principals, resources, and actions are represented by Cedar entities. Entities are collected in an entity store and referenced by a unique identifier consisting of two parts: the entity type and entity ID. Each entity is associated with zero or more attributes mapped to values, and zero or more parent entities. The parent relation on entities forms a directed acyclic graph (DAG), called the entity hierarchy.

Figure 3 illustrates the TinyTodo entities after carrying out the actions described above. On the left is the entity for the list andrew created, which has entity reference List::"0". We can see that the entity has five attributes, name, owner, readers, editors, and tasks. All entities of type List have these attributes. On the right of the figure we see four User-typed entities (along the bottom) and five Team-typed entities (along the top), which are arranged in a hierarchy; each arrow points to an entity’s immediate parent. TinyTodo set these attributes, and created Team::"1" and Team::"2", when it created the list, and updated tasks as tasks were added and completed.

An application might store its data in a SQL database or a key-value store in a format that best suits its purposes. When it goes to authorize a user request, it provides the Cedar authorizer
access to the necessary parts of that data, mapped to Cedar entities. It could do so by mapping its native-stored data to Cedar entities at the time of the request, or during the application’s operation.

2.3 Cedar policy structure: Supporting RBAC, ABAC, ReBAC

In general, Cedar policies have three components: the effect, the scope, and the conditions. The effect is either permit or forbid, indicating whether the policy is authorizing access or taking it away. The scope comes after the effect, constraining the principal, action, and resource components of requests that the policy applies to. The conditions are optional expressions that come last, adding further constraints, oftentimes based on attributes of request elements. Policies access request elements using the variables principal, action, resource, and context. The context record stores application-specific data about the request, such as current time or source IP address.

Cedar policies support role-based, attribute-based, and relation-based access control (RBAC, ABAC, and ReBAC, respectively). RBAC is possible because of Cedar’s support for a hierarchy of entities. For example, Policy 2 in Figure 2 is an RBAC-style policy, which states that any principal who is a member of the admin Team (such as User::"emma") can perform any action on a TinyTodo resource.

ABAC-style policies use policy conditions to reference attributes. For example, Policy 1 mentions resource.owner, where owner is a attribute of resource. As shown in Figure 3, attributes can be primitive-typed values (like a number or string), collections, records, or entity references.

ReBAC-style policies use attributes that reference entity groups to express relations between two entities. For example, Policy 3 is a ReBAC-style policy, which states that any principal can read the contents of a task list (Action::"GetList") if they are in either the list’s readers or editors groups. Here, principal in resource.readers and principal in resource.editors are expressions that can be viewed as querying whether principal is in the readers and editors relations with resource.

For our running example, suppose User::"andrew" shares List::"0" with the team interns as a reader (which he is allowed to do because of Policy 1). As a result, TinyTodo will update the hierarchy in Figure 3 to add a parent edge from Team::"interns" to Team::"1". Now if User::"aaron" attempts to read the contents of List::"0" he will be allowed to do so according to Policy 3: its condition principal in resource.readers is true since the readers attribute of List::"0" corresponds to Team::"1", which is an ancestor of User::"aaron" in the entity hierarchy.
entity Application;
entity Team, User in [Team, Application];
entity List in [Application] { readers: Team, editors: Team, owner: User };
action CreateList appliesTo { principal: [User], resource: [Application] };
action GetList appliesTo { principal: [User], resource: [List] };

Fig. 4. TinyTodo schema

2.4 Safety
Cedar has a design goal of creating a safe foundation for writing policies. One aspect of this goal is that Cedar’s authorizer denies by default: If no permit policy exists that authorizes a request, the request will be denied.

Another aspect is that forbid policies always override permit policies when making the final decision. For example, Policy 4 expresses that no intern is allowed to create a new task list (Action::"CreateList"). With this policy, if aaron tries to create a list, his request will be approved by Policy 0, but denied by Policy 4, with the final decision that the request is denied. This behavior allows forbid policies to act like guardrails that enforce universal non-access rules.

The third aspect of safety is that Cedar’s authorizer is deterministic: It is guaranteed to terminate and always produce the same authorization decision for a given request, hierarchy, and set of policies. Because Cedar policies are free of side effects and general loops, policy evaluation order doesn’t matter. Because Cedar’s algorithm for selecting the policies relevant to a request is sound, the authorizer will produce the same outcome as if had it considered all available policies.

2.5 Validating policies
A final aspect of safety is ensuring that Cedar policy evaluation will not result in an error, e.g., if the policy attempts to access a non-existent attribute. Policy writers can use the Cedar validator to ensure that policies are (mostly) error-free. To do so, they provide a schema that lists the names and the type structure of an application’s entities, as well as the application actions and the allowed shapes of requests that contain them.

A schema for TinyTodo is shown in Figure 4 (some actions and entity attributes are elided). The schema declares four entity types: Application, User, Team, and List. The Application entity type is the simplest possible: it has no associated attributes and has no parents in the entity hierarchy. The combined User and Team entity type declaration indicates that both can have Team entities as parents (as we see in Figure 3) as well as Application entities. A List entity can have Application-entity parents and must have the attributes owner, readers, and writers. The schema also declares two actions, CreateList and GetList, and specifies that they apply to specific principal and resource entity types—any request involving these actions must include principal and resource entities of these types. All of the policies in Figure 2 are valid with respect to this schema.

Policy validation works by typechecking the policy specialized to each of the allowed actions in the request environments (maps from variables like principal and resource to types) induced by those actions’ schemas. A policy is valid if it typechecks in every environment. The type system uses a novel combination of static capabilities [12] and boolean singleton types [1]. Capabilities ensure that a policy always checks the presence of an optional attribute before accessing it. Singleton types True and False are ascribed to expressions sure to evaluate to true and false, respectively. The type system uses them to type expressions like false && (1 == “hello”): since the first conjunct has type False the whole expression will—the erroring second conjunct will be short-circuited. Singleton types are also used to warn when a policy will evaluate to false (or true) in every environment, making it effectively useless (or over-influential).
Typechecking in each relevant environment, rather than a single generic environment, adds cost but avoids many false alarms. There are typically few principal types and a recommended best practice is to specialize each action to a resource type (e.g., Action::"GetList"), so validation time tends to be $O(na)$ where $n$ is the size of the policies and $a$ is the number of actions.

2.6 Analyzing policies

The validator can flag certain mistakes, but it cannot answer deeper questions about policy behavior. One such question is policy equivalence—do two (sets of) policies evaluate to true on the same set of requests? For that, we turn to Cedar’s symbolic compiler, which works by reducing policies to SMT formulas, and discharging questions about their behavior using an SMT solver.

To illustrate, suppose that we drop Policy 2 and replace Policy 0 in Figure 2 with Policy 0.1 shown to the right. Is the resulting policy set (Policy 0.1 together with Policies 1 and 3) equivalent to the original (Policies 0, 1, 3 and 4)? The answer is no: the new policy set accepts fewer requests than the original.

Equivalence analysis uses the symbolic compiler to generate an SMT formula that is satisfiable if some request is allowed by one policy set but not the other. If the solver finds a model for this formula, the analysis turns it into a concrete counterexample—a request and entity store—on which the two policy sets differ. In this case, given the entity store in Figure 3, the original policy set will let aaron perform the GetOwnedLists action but the new one will not. This is because Policy 0.1 prevents interns from performing either a CreateList or GetOwnedLists action. Adding && action == Action::"CreateList" to the condition of Policy 0.1 fixes the problem.

We designed Cedar specifically to support an SMT encoding that is sound, decidable, and complete; no prior authorization language enjoys such an encoding. To achieve it, we use a novel type-based translation that employs only decidable theories, and finite sets of ground well-formedness constraints (e.g., to ensure entity graphs are acyclic) rather than quantified constraints.

3 SYNTAX, SEMANTICS, AND TYPING

This section presents a partial formalization of the syntax of Cedar policies (Section 3.1), the semantics of Cedar expression evaluation (Section 3.2) and authorization (Section 3.3), and the semantics of policy validation (Section 3.4). We have proved several properties of Cedar’s design (Section 3.5) using a formalization in Lean [35]. Details about full Cedar are given in Section 3.6.

3.1 Syntax: Policies and expressions

The concrete syntax of Cedar policies follows the grammar at the top of Figure 5. Nonterminals are formatted in blue, terminals are in red, and grammatical elements are in black. We write \{a\} to indicate zero or more occurrences of a, and \[b\] to indicate zero or one occurrence of b.

The grammar references expressions $e$ and entity references $E::s$, whose abstract syntax is given at the bottom of Figure 5. The semantics of a policy $c$ is defined by conversion to an expression $e$, written as toexp($c$). This function conjoins the Principal, Action, and Resource components of $c$, using true is used if the component is just a variable, along with the conditions Cond: when expressions are used as given, and unless expressions are negated. For example, the conversion of Policy 3 from Figure 2 is $e_s$, && (principal in resource.readers || principal in resource.writers), where $e_s$ is the converted scope true && action == Action::"GetList" && true.
We formalize Cedar expression evaluation as a small-step operational semantics with the judgment
\[ \mu, \sigma \vdash e \rightarrow e' \] which states that under entity store \( \mu \) and authorization request \( \sigma \) the expression \( e \) reduces to expression \( e' \). The entity store \( \mu \) is a map from entity references \( E:s \) to pairs \( (v, h) \), where \( v \) is a record value and \( h \) is the set of the entity’s ancestors in the hierarchy. An authorization request \( \sigma \) is a map from variables \( x \) to values \( v \), where \( v \) is an entity reference when \( x \) is either principal, action, or resource, and \( v \) is a record when \( x \) is context. Stuck states in the semantics correspond to raised errors in the implementation.

Figure 6 shows a selection of expression evaluation rules. We do not show any congruence rules as they are straightforward—evaluation is call-by-value and proceeds left to right. (While Cedar supports neither I/O nor mutable state, evaluation order affects the occurrence of run-time errors.)

The first line of rules shows that projecting an attribute \( f \) from an entity reference requires looking up the entity reference in the store and projecting from the corresponding record. This will fail if the entity is not present in the store or if its record lacks the requested attribute. Rules for records are similar.

The first rule on the second line shows that values are considered equal if and only if they are syntactically identical. For entity references this amounts to nominal, rather than structural, equality since \( \mu, \sigma \vdash E_1:s_1 \rightarrow E_2:s_2 \rightarrow \text{false} \) even when \( \mu(E_1:s_1) = \mu(E_2:s_2) \). The second rule on that line shows that \( v_1 \) is \( E \) amounts to a dynamic check of whether \( v_1 \) has the type \( E \). The last rule handles request variable lookup.

The third line shows that membership in the entity hierarchy, \( E_1:s_1 \in E_2:s_2 \), evaluates to \text{true} if \( E_2:s_2 \) is \( E_1:s_1 \) or is a member of the ancestors of \( E_1:s_1 \). Otherwise, the result is \text{false}.

The fourth line, the \text{in} operator with its RHS as a set of entities evaluates to \text{true} if the LHS is in at least one entity in the set (\text{false} otherwise). As usual, conditionals short-circuit; note they are not well-defined for non-boolean guards. Expressions \( e_1 | e_2 \) \&\& \( e_2 \) evaluate equivalently to if \( e_1 \) then \text{true} else (if \( e_2 \) then \text{true} else \text{false}) and if \( e_1 \) then (if \( e_2 \) then \text{true} else \text{false}) else \text{false}, respectively.
Boolean operations on sets include contains, which checks element membership, containsAny, which checks overlap, and containsAll, which checks containment. The like operator matches strings, interpreting * in the style of the Unix shell. Integers can be compared, added, subtracted, and multiplied by a constant.

Cedar’s semantics is generally forgiving for operations on entity references that do not exist in \( \mu \), to minimize the data required to decide a request. For example, == happily compares non-existent references, so operations like action == Action:"foo" can succeed even when \( \mu(\text{Action:"foo"}) \) is undefined. Evaluation will get stuck on a projection \( E::s.f \) when \( E::s \) does not exist, since it is unclear what value to return. We considered creating a null value, but decided to avoid repeating that "billion dollar mistake" [25]!

3.3 Authorization and slicing

Cedar’s authorization algorithm is given in the following pseudocode:

```plaintext
1 def authorize(\( \mu, C, \sigma \)) =
2     def evaluate(e) = v where \( \mu, \sigma \vdash e \rightarrow^* v \)
3     let \( C_S = \{ c \mid c \in \text{slice}(\sigma, C) \land \text{evaluate(toexp(c))} = \text{true} \} \)
4     if forbids(\( C_S \)) = \emptyset \land \text{permits}(\( C_S \)) \neq \emptyset then Allow else Deny
```

Procedure authorize() takes policies \( C \), a request \( \sigma \), and an entity store \( \mu \), and returns a decision Allow or Deny. Line 2 defines partial function evaluate(e) to return \( v \) if \( e \) evaluates to it via the transitive closure of the semantics \( \rightarrow^* \). Line 3 uses this function to evaluate the request. First, it slices out the policies in \( C \) that are relevant to deciding \( \sigma \) (more below). Then, each policy \( c \) in the slice is converted to an expression \( e_c \) and evaluated; those policies \( c \) which satisfy the request (i.e.,
for which $e_c$ evaluates to `true`) are collected in $C_S$. Finally, per line 4, the request is allowed if there are no satisfying `forbid` policies and at least one satisfying `permit` policy, else it is denied.\footnote{In the Cedar implementation, the `Allow/Deny` decision is coupled with extra diagnostics, which include the IDs of the `determining` policies—the `permit` policies that evaluated to `true` for `Allow`, or the `forbid` policies that did so for `Deny`—and any policies that exhibited errors when evaluated.}

Rather than evaluate $\sigma$ under every policy $c \in C$, authorize uses subroutine slice($C, \sigma$) to quickly select only the policies relevant to $\sigma$. Recall that the `Principal` and `Resource` parts of the policy scope optionally constrain the principal and resource, respectively, to be $==$ or $\in$ a particular entity. Let $pof(c)$ be the entity $E::s$ named in the `Principal` portion of policy $c$, or a special identifier `Any` if no entity is named. Let $rof(c)$ behave likewise for the `Resource` portion. Define the key for $c$ to be $\langle pof(c), rof(c) \rangle$. We can store the policies $C$ as a map $\Sigma$ from keys to sets of policies.

For a request $\sigma$ we construct a set of keys from the cross-product of the ancestors of $P$ and $R$ in $\mu$, where $P = \sigma(\text{principal})$ and $R = \sigma(\text{resource})$. That is, let $\mu(P) = (\_, h_P)$ and $\mu(R) = (\_, h_R)$, and let $K = (h_P \cup \{P, \text{Any}\}) \times (h_R \cup \{R, \text{Any}\})$. $K$ is the set of keys (each of which is a pair) arising from the cross product of $P, R$, and their ancestors or `Any`. The slice of relevant policies is then $\bigcup_{k \in K} \Sigma(k)$. Other schemes are possible too, e.g., which take into account the policy conditions. This scheme performs well when the policy store is large, but $P$ and $R$ have relatively few ancestors.

### 3.4 Policy validation

Users can optionally validate their Cedar policies prior to use, to ensure that certain run-time errors will not occur. Policies are validated against a schema, which is a pair $(M, S)$ where $M$ is the entity schema and $S$ is the action schema.

- $M$ maps entity types $E$ to pairs $(\tau, P)$ where $\tau$ is the (record) type of $E$’s attributes, and $H$ contains the types of entities that can be ancestors of entities of type $E$.
- $S$ maps action entities $A$ (of form `Action::s`) to triples $(A_p, A_r, A_x)$ that describe the allowable shape of requests involving $A$. In particular, $A_p$ is the set of principal entity types that can accompany $A$; $A_r$ is the set of resource entity types that can accompany $A$; and $A_x$ the type of context records that can accompany $A$.

Using the concrete syntax for schemas shown in Figure 4, $M$ is defined by the entity declarations, and $S$ is defined by the action declarations.

Validating a policy $c$ for a schema $(M, S)$ proceeds in three steps. First, for each action $A \in \text{dom}(S)$, we produce a set of request environments $A_\Gamma$, where request environment $\Gamma \in A_\Gamma$ is a map from variables $x$ to types $\tau$. $A_\Gamma$ is defined as $\{ \text{principal}: E_p, \text{resource}: E_r, \text{context}: A_x | E_p \in A_p, E_r \in A_r \}$. Second, we convert $c$ into an expression $e = \text{toexp}(c)$ (see Section 3.1), and replace all occurrences of variable action in $e$ with $A$; call the result $e_A$. Finally, we typecheck $e_A$ for each request environment $\Gamma \in A_\Gamma$. The expression typing judgment has form $\alpha; \Gamma \vdash e : \tau; \epsilon$, and is described next. Typechecking $e_A$ requires that there exists some $\epsilon$ such that $\emptyset; \Gamma \vdash e_A : \text{Bool}; \epsilon$.

The judgment $\alpha; \Gamma \vdash e : \tau; \epsilon$ states that under capability $\alpha$ and request environment $\Gamma$, expression $e$ has type $\tau$ and produces capability $\epsilon$ conditioned on $e$ evaluating to `true`. Selected type rules are given in Figure 7a. Types are defined at the bottom of Figure 5, and are notable for the use of singleton types `True` and `False`, and record types with optional attributes: a record attribute $\omega_f: \tau$ is optional when $\omega$ is `?`, otherwise it is required; we elide an optionality · when clear from context.

**Boolean singleton types.** Expressions that definitely evaluate to `true` and `false` may be given singleton types [1] `True` and `False`, respectively, which are subtypes (`<`) of `Bool`. To make the SMT encoding (Section 4) tractable, the subtyping rules, shown in Figure 7b, support `depth` subtyping but not `width` subtyping, and there is no subtyping among entity types.

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For $==$, rules on lines (1)-(2) of Figure 7a require that to be type-correct the equated expressions must be comparable, in the sense that their types have a shared supertype. The rules also leverage that two syntactically identical expressions always evaluate to equal values, whereas two entities with different types or identifiers are surely non-equal.

The last rule on line (2) typechecks $e \Is E$ with singleton types exclusively, since we know expression $e$’s precise type statically. Thus $\Is$ is (only) useful when some request environments $\Gamma \in A_T$, typecheck $e$ such that $E = E_1$, while others do not. For example, for TinyTodo Policy 1 (Figure 2), the use of $\Is$ is important because resource has type $\text{List}$ in some request environments and type Application in others.

For $\In$, the first rule on line (3) indicates that $e_1 \In e_2$ will have type $\text{False}$ if the entity type of $e_2$ is not the same as that of $e_1$, and is not among $e_1$’s type’s ancestors. The rules for expressions
if \( e_1 \) then \( e_2 \) else \( e_3 \) on line (4) leverage singleton types to ignore unreachable expressions. The first rule shows that for a \( True \) guard, the conditional will surely evaluate to \( e_2 \), so \( e_3 \) can be ignored; the second rule reasons similarly for a \( False \) guard.

Singleton types, and the rules for conditionals in particular, are important for avoiding false alarms when validating a policy. For example, consider Policy 3 from Figure 2, which converts to the following expression

\[
\text{true} \&\& (\text{action} == \text{Action::"CreateList"} \&\& (\text{true} \&\& \\
\text{(principal in resource.readers} \|\| \text{principal in resource.writers})))
\]

To validate the policy against a schema \((S, M)\) that corresponds to Figure 4, we first consider action \(\text{Action::"CreateList"}\). We substitute it for action in the above expression yielding

\[
\text{true} \&\& (\text{Action::"CreateList"} == \text{Action::"GetList"} \&\& (...))
\]

We then typecheck this expression under request environment \(\Gamma = \text{principal:User, resource: Application, context: \{\}}\). The subexpression \((\text{Action::"CreateList"} == \text{Action::"GetList"} \&\& (...))\) is equivalent to if \(\text{Action::"CreateList"} == \text{Action::"GetList"} \text{ then (...) else false}\). When typing this expression, the guard will have type \(False\) per the first rule on line (2) of Figure 7a. So, the second rule on line (4) ignores the expression (...), written \(e_2\) in the rule, giving the whole conditional the type of \(false\) expression, which is \(False\). Doing so is critical: The \text{resource.readers} part of (…) fails to typecheck, since \(\Gamma(\text{resource}) = \text{Application}\), which has no \text{readers} attribute.

Capabilities for accessing optional attributes. The expression \(e\) has \(f\) checks whether attribute \(f\) is present in a record/entity \(e\), and the type system records the effect of this check using capabilities [12]. In judgment \(\alpha; \Gamma \vdash e : \tau; e\), the \(\alpha\) represents the set of optional attributes definitely available when \(e\) is evaluated, and \(\varepsilon\) is the set of attributes \(e\) proves to be available if it evaluates to \(true\).

The first rule on line (6) of Figure 7a types \(e\) has \(f\), producing capability \(\varepsilon = \{e.f\}\) when \(e\)'s type has an optional attribute \(f\).

The second rule on line (6) types expression \(e.f\): If \(f\) is an optional attribute (i.e., \(\omega = ?\)) then \(e.f\) must be in the capability \(\alpha\). The way it gets there is via the rules for conditionals on lines (4)-(5). The first rules on lines (4) and (5) take capability \(\varepsilon_1\) proved for the guard \(e_1\) and add it to \(\alpha\) when typing \(e_2\). This makes sense because \(e_2\) is only evaluated when \(e_1\) evaluates to \(true\). Putting it all together, when typing expression if \(e\) has \(f\) then \(e.f\) else false the guard has type \(Bool\) and capability \(\{e.f\}\), so the rule on line (5) types then-expression \(e.f\) under capability \(\alpha \cup \{e.f\}\), ensuring the second rule on line (6) applies.

The rules for conditionals on lines (4) and (5) prove the available capability \(\varepsilon\) by leveraging the presence of singleton types. The first rule on line (4) says that when \(e_1\) has type \(True\) we know that \(e_2\) will be evaluated, so the capability of the entire conditional is \(\varepsilon_1 \cup \varepsilon_2\). The second rule says that when \(e_1\) has type \(False\) we know that \(e_3\) will be evaluated. The final capability in this case is \(\varepsilon_3\) and not \(\varepsilon_1 \cup \varepsilon_3\) because attributes in \(\varepsilon_1\) are only available if \(e_1\) evaluates to \(true\), which we know it does not. The first rule on line (5) combines the reasoning of these two. Since the guard has type \(Bool\) we cannot be sure which branch will be evaluated, so we merge the capabilities of \(True\) and \(False\) cases using intersection, i.e., \((\varepsilon_1 \cup \varepsilon_2) \cap \varepsilon_3\).

In general, per rules on lines (1)–(3), we can give an expression \(e\) of type \(False\) an arbitrary capability set \(\varepsilon\) because doing so is vacuously sound: \(\varepsilon\) contains the available attributes only if \(e\) evaluates to \(true\), which we know it does not. Such rules add very useful precision, especially when handling \&\& and \(\|\) expressions.

---

2Two other rules, not shown, give this expression type \(True\) when \(e\)'s type definitely has attribute \(f\), and type \(False\) when it definitely does not, both producing an empty capability \(\emptyset\).
3.5 Properties

Since the authorizer is part of an application’s security trusted computing base (TCB), we take extra steps to confirm its design and implementation are correct. We formalize Cedar in Lean [35] and use it to prove the following properties:

- **Forbid trumps permit**: If any forbid policy evaluates to true, the request is denied.
- **Default deny**: If no permit policy evaluates to true, the request is denied.
- **Explicit allow**: If a request is allowed, some permit policy evaluated to true.
- **Sound slicing**: $\forall c \in C. c \notin \text{slice}(C, \sigma)$ implies $c$ cannot satisfy request $\sigma$.
- **Validation soundness**: Given a policy $c$ and request $\sigma$, let $e_A = \text{toexp}(c)[\text{action} \mapsto A]$, where $A = \sigma(\text{action})$, and let $\Gamma_A$ be a request environment conforming to $\sigma$. If $\emptyset, \Gamma_A \vdash e_A : \text{Bool}, e$ under entity type map $M$, then $\mu, \sigma \vdash e_A \rightarrow^* \nu$ for all entity stores $\mu$ conforming to $M$, and for which entity references in $c$ and $\sigma$ are defined.

Carrying out these proofs, and in particular the proof of validation soundness, revealed several bugs. Moreover, writing down a formal spec forced us to think deeply about corner cases, and the process revealed other subtle bugs in our semantics. We also use the Lean spec for testing our implementation, written in Rust, as described below in Section 3.6.

3.6 Full Cedar

For simplicity, this section has omitted discussion of three of Cedar’s features: templates, extension types, and action groups; all three are modeled in the full Lean formalization.

Templates are policies with one or more named slots. A template is similar in spirit to a SQL prepared statement, and can be linked into a complete Cedar policy by filling each slot with a Cedar value. At present, Cedar supports only two named slots, ?principal and ?resource, which may appear only in the Principal and Resource parts of the grammar in lieu of specific entities $E::s$. This restriction makes it easy to typecheck unlinked templates, and to index template-linked policies.

Extension types provide a uniform mechanism for extending the language. Cedar currently supports IP addresses and decimal numbers with this mechanism. Extension-typed values are created with function calls, e.g., `ip("1.2.3.4")` and `decimal("138.22")`, and operated on with method calls, e.g., `resource.amt.lessThan(context.amt) and context.addr.isInRange(principal.net)`. The Cedar evaluator implementation provides a plugin mechanism for new extension types.

Cedar actions are entities, so they can also be arranged hierarchically into groups. Action group memberships are specified in the schema so they can be leveraged during validation.

The Lean model is executable by compilation to native code, so we use extensive differential random testing [32, 55] to confirm that our Rust code and Lean model agree. We write input generators (for policies, entity stores, and requests) in the style of Palka et al. [42], and use the cargo fuzz framework [9] to test that equal inputs map to equal outputs. We also use cargo fuzz to test properties directly on the Rust code, e.g., the “round trip” property that a pretty-printed Cedar abstract syntax tree parses back to itself. This testing regime has been fruitful, uncovering nearly two dozen bugs since the project’s inception, and forcing us (via CI) to keep the Lean spec and proofs up to date.

4 SYMBOLIC COMPILATION

This section presents the Cedar symbolic compiler. The compiler works in three stages. First, it encodes Cedar types, entity stores, and requests as SMT types and variables (Section 4.1). Next, it uses this mapping to reduce well-typed Cedar expressions to well-typed SMT terms (Section 4.2). Finally, it constrains the SMT representation of the entity hierarchy to be sufficiently well-formed (Section 4.3), using only ground constraints (i.e., those without quantifiers). The compiler’s encoding
\( T(\text{Bool}) := \text{Bool} \quad T(\text{Long}) := \langle _\text{BitVec} 64 \rangle \quad T(\text{String}) := \text{String} \quad T(\text{Set } \tau) := \langle \text{Set } T(\tau) \rangle \)

\[ T(E) := i(E) \quad \text{where } E \text{ is an entity type} \]

\[ T(R) := i(R) \quad \text{where } R = \{ \omega_1 f_1 : \tau_1, \ldots, \omega_n f_n : \tau_n \} \]

\[ T_D(E) := (\text{declare-datatype } i(E) \ (i(E) \ (\text{eid } \text{String})))) \]

\[ T_D(R) := (\text{declare-datatype } i(R) \ (i(R) \ T_D(R, f_1) \ldots T_D(R, f_n))))) \]

\[ T_D(R, f_i) := (i(R, f_i) \ T(\tau_i)) \quad \text{where } R = \{ \ldots, f_i : \tau_i, \ldots \} \]

\[ T_D(R, f_i) := (i(R, f_i) \ (\text{Option } T(\tau_i))) \quad \text{where } R = \{ \ldots, f_i : \tau_i, \ldots \} \]

Fig. 8. Translating a Cedar type to an SMT type. The function \( T \) takes as input a Cedar type and returns the corresponding SMT type expression. The function \( T_D \) generates SMT type declarations. SMT syntax is rendered in code font, and \( i \) maps its arguments to unique SMT identifiers.

is decidable, sound, and complete (Section 4.4). This result, the first of its kind for a non-trivial policy language, is made possible by Cedar’s controls on expressiveness, and by leveraging invariants ensured by Cedar’s policy validator.

### 4.1 Encoding types, entity stores, and requests

Cedar’s types are designed to enable a direct translation to SMT types, as shown in Figure 8. Primitives and sets are encoded as built-in SMT types (as well as CVC5’s theory of sets which is not standardized [6]), and entities and records as SMT algebraic datatypes. An entity type becomes a datatpye with a string field \( \text{euid} \) that represents the entity ID. A record type becomes a datatype that encodes a required attribute of type \( \tau \) as a field of type \( T(\tau) \), and an optional attribute as a field of type \( \langle \text{Option } T(\tau) \rangle \). The translation uses the function \( i \) to ensure that all occurrences of a given Cedar type map to the same SMT type.

The symbolic compiler leverages this type mapping to represent the request and entity store as a set of \emph{uninterpreted functions and constants}. Figure 9 shows how to generate this representation for a request environment \( \Gamma \) and entity schema \( M \) (see Section 3.4). The function \( V_P(\Gamma) \) encodes each variable \( x \in \Gamma \) as an uninterpreted constant of type \( T(\Gamma(x)) \). The function \( F_D(M) \) encodes the attributes and ancestors of each entity type \( E \in M \) as uninterpreted functions: \( F_D(E, R) \) maps entities of type \( T(E) \) to their attributes, while \( F_D(E, E') \) maps entities to their ancestors of type \( T(E') \). Together, these functions and constants represent the set of all possible concrete stores and requests that conform to \( M \) and \( \Gamma \). We refer to them respectively as the \emph{symbolic store} for \( M \) and \emph{symbolic request} for \( \Gamma \).

**Example 4.1.** Consider the entity schema \( M \) for the \textit{TinyTodo} schema in Figure 4, and the request environment \( \Gamma \) for the action \texttt{Action::"GetList"}. The symbolic store and request for \( M \) and \( \Gamma \) are defined as follows, with parts of the encoding omitted for brevity, and names prettified for readability:

```plaintext
(declare-datatype User ((User ( eid String)))) ; Entity types
(declare-datatype Team ((Team ( eid String))))
(declare-datatype List ((List ( eid String)))) ; Record types
(declare-datatype ListRecord ((ListRecord ( readers Team) (editors Team) (owner User))))
(declare-fun listAttrs (ListRecord) ListRecord) ; Attribute functions
(declare-fun userInTeam (User) (Set Team)) ; Ancestor functions
(declare-fun teamInTeam (Team) (Set Team))
(declare-const principal User) ; principal constant
(declare-const resource List) ; resource constant
```

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The compiler uses the rules in Figure 10 to reduce a Cedar expression \( e \) to an SMT term \( \hat{e} \) under a given symbolic store and request. This reduction is formalized using a big-step operational semantics: the judgement \( M, \Gamma \vdash e \downarrow \hat{e} \) states that under the symbolic entity store for \( M \) and symbolic request for \( \Gamma \), \( e \) reduces to \( \hat{e} \). The rules assume \( e \) is well-typed, and define a total function from well-typed expressions to well-typed terms. If \( e \) has type \( \tau \) under \( M \) and \( \Gamma \), then \( M, \Gamma \vdash e \downarrow \hat{e} \) holds, and \( \hat{e} \) is a well-typed term of type \( (\text{Option } T(\tau)) \) (Theorem 4.1). We use the \text{Option} type to encode errors: the term \( \hat{e} \) evaluates to \text{none} on an error not ruled out by the validator (Section 3.5).

**Theorem 4.1.** Let \( e, \Gamma, \) and \( M \) be an expression, environment, and entity schema such that \((\alpha; \Gamma) \vdash e : \tau, e \) for some \( \alpha \). Then, there is a well-typed SMT term \( \hat{e} \) of type \((\text{Option } T(\tau))\) such that \( M, \Gamma \vdash e \downarrow \hat{e} \).

Figure 10 shows a selection of symbolic compilation rules. Omitted rules are defined straightforwardly in terms of the corresponding SMT operators. For example, Cedar equality \( = \) reduces to SMT equality \( = \) (not shown).

The rules on line 1 handle variables and entity references, translating them to terms of the form \((\text{declare-const } \iota(x, \tau) T(\tau))\). A variable \( x \) translates to the uninterpreted constant \( \mathcal{V}(x, \tau) := \iota(x, \tau) \). The rules on line 2 translate attribute operations to terms of the form \((\text{declare-fun } \iota(E, R)(T(E)) T(R))\). The resulting terms encode error propagation by evaluating to \text{none} if \( e \) errors. For an optional attribute \( f \), the expression \( e.f \) translates to \( \overline{f} \), which retrieves the optional value of \( f \) from the record or entity \( \text{val}(\hat{e}) \). The expression \( e \) has \( f \) translates to a term \( \overline{b} \) that evaluates to \text{true} only if \( \overline{f} \) is a \text{some} value. Required attributes are handled analogously.

The rule on line 3 translates the hierarchy membership test \( e_1 \in e_2 \) on entities. The generated term evaluates to \text{true} when \( \hat{e}_1 \) and \( \hat{e}_2 \) evaluate to entity terms \( \hat{e}_1 \) and \( \hat{e}_2 \) satisfying one of two conditions: \( \hat{e}_1 \) equals \( \hat{e}_2 \), or \( \hat{e}_1 \) has ancestors of type \( E_2 \) that include \( \hat{e}_2 \). This encodes a strongly typed version of the dynamic in semantics given on line 4 of Figure 6.

Finally, the rules on lines 4 and 5 handle conditional expressions \( \text{if } e_1 \text{ then } e_2 \text{ else } e_3 \). This follows a standard symbolic semantics with merging [44]. If \( \hat{e}_1 \) reduces to \((\text{some true})\) or \((\text{some false})\), the conditional translates to \( \hat{e}_2 \) or \( \hat{e}_3 \), respectively. Otherwise, it translates to an \text{ite} term that selects \( \hat{e}_2 \) or \( \hat{e}_3 \) based on the value of \( \hat{e}_1 \), or errors if \( \hat{e}_1 \) is \text{none}. 

Fig. 9. Representing entity stores and requests as uninterpreted functions and constants. \( \mathcal{V}_D(\Gamma) \) introduces an uninterpreted constant for each variable in the request environment; \( \mathcal{F}_D(M) \) introduces a set of uninterpreted functions for each entity type \( E \). \( M(E) = (R, P) \) gives the record and set of ancestor entity types for \( E \).
The rules in Figure 10 encode expression semantics for an arbitrary entity store that conforms to the Cedar semantics to the term $(\text{some (set.member (readers (listAttrs resource)) (userInTeam principal))})$.

**Example 4.2.** Consider the symbolic store and request from Example 4.1, and the expression principal in resource.readers from Policy 3 in Figure 4. The symbolic compiler translates this expression to the term $(\text{some (set.member (readers (listAttrs resource)) (userInTeam principal))})$.

### 4.3 Sufficiently well-formed hierarchies

The rules in Figure 10 encode expression semantics for an arbitrary entity store that conforms to the entity schema $M$. But not all such stores are well-formed under Cedar’s semantics, which expects the entity hierarchy to be a DAG. This requires the ancestor functions $F(E,E')$ to collectively define an acyclic, transitive relation on entities. Leaving these functions unconstrained leads to incompleteness, as shown in Example 4.3.
Example 4.3. Consider the expression Team::"A" in Team::"B" & Team::"B" in Team::"A". This expression can never evaluate to true given a well-formed entity hierarchy (a DAG). But its encoding with respect to the symbolic store from Example 4.1 has a model:

```plaintext
(define-fun teamInTeam ((t Team)) (Set Team) ; maps A -> B and B -> A
  (ite (= t (Team "A")) (set.singleton (Team "B")) (set.singleton (Team "A"))))
```

This model does not correspond to any well-formed hierarchy because it contains a cycle between Team::"A" and Team::"B". As such, it represents a spurious counterexample (a false alarm) to the assertion that the example expression is always false.

One solution is to encode acyclicity and transitivity constraints on the ancestor functions directly using quantified formulas. For example, the following formulas assert well-formedness for the function teamInTeam from Example 4.1:

```plaintext
(assert ; acyclicity: ∀t. t ∉ teamInTeam(t) (forall ((t Team)) (not (set.member t (teamInTeam t))))
(assert ; transitivity: ∀t1,t2,t3 ∈ teamInTeam(t1) → teamInTeam(t2) ⊆ teamInTeam(t1) (forall ((t1 Team) (t2 Team)) (=> (set.member t2 (teamInTeam t1)) (set.subset (teamInTeam t2) (teamInTeam t1))))
```

However, the quantifiers make the encoding undecidable, causing timeouts or unknown results.

We address this by grounding the well-formedness constraints based on the following observation: a Cedar expression e accesses only a finite set of entities from the store. It is sufficient for the store to be well-formed on just this set. We can over-approximate this set, called the footprint of e, by collecting all subexpressions of e with an entity type. For example, the expression in Example 4.3 has footprint {Team::"A", Team::"B"}, and the expression in Example 4.2 has footprint {principal, resource, resource.readers}. Grounding the constraints relative to the footprint maintains decidability while ensuring completeness (Section 4.4).

Figure 11 shows the grounding function \( wf(e, \Gamma, M) \). The function emits a transitivity constraint for every pair of footprint expressions of type \( E_1 \) and \( E_2 \) that may be transitively connected via an entity of type \( E_3 \). It emits an acyclicity constraint for every footprint expression of type \( E_1 \) that may have an ancestor of the same type. Together, these two constraints force the relation defined by the ancestor functions to be the transitive closure of an underlying DAG.

Example 4.4. To illustrate grounding, consider again the expression \( e \) from Example 4.3, along with \( \Gamma \) and \( M \) from Example 4.1. The compiler uses \( wf(e, \Gamma, M) \) to generate the following ground well-formedness assertions:

```plaintext
(assert (not (set.member (Team "A") (teamInTeam (Team "A")))))
(assert (not (set.member (Team "B") (teamInTeam (Team "B")))))
(assert (=> (set.member (Team "B") (teamInTeam (Team "A"))))
  (set.subset (teamInTeam (Team "B") (teamInTeam (Team "A")))))
(assert (=> (set.member (Team "A") (teamInTeam (Team "B"))))
  (set.subset (teamInTeam (Team "A") (teamInTeam (Team "B")))))
```

4.4 Soundness and completeness

The Cedar symbolic encoding is sound and complete for standard policy analyses, such as equivalence or subsumption [5]. Theorem 4.2 states the soundness and completeness result for the equivalence analysis. The proof of the theorem relies on a more general lemma, which we omit for brevity. The general lemma states that the encoding itself is sound and complete with respect to the concrete semantics of Cedar, following prior work [44]. This lemma can be used to show that other analyses based on the encoding are also sound and complete. We have proved soundness and completeness of the encoding on paper. We have also implemented the symbolic encoder in Lean, and proofs of soundness and completeness using the Lean encoder are underway, as of this writing.
We use the following examples to compare Cedar, OpenFGA, and Rego. Full authorization models
are evaluated by comparing Cedar against two prominent open-source, general-purpose authoriza-
tion frameworks: Cedar, OpenFGA, and Rego. In this application, Users are organized into Groups, and Documents are organized
to denote that e₁ is a subexpression of e with type E₁, i.e., α; Γ ⊢ e₁ : E₁, ε for some α and ε.

Theorem 4.2. Let e₁ and e₂ be well-typed boolean expressions under environment Γ and entity
schema M. Let t₁ and t₂ be their encodings where M, Γ ⊢ e₁ ↓ t₁ and M, Γ ⊢ e₂ ↓ t₂. Let φ be the term
(\text{isTrue}(\hat{t}_1) \text{isTrue}(\hat{t}_2)), where \text{isTrue}(\hat{t}) := (\text{some true} \hat{t}). Then, the assertions
wf(\phi, Γ, M) \cup \{\text{not} \phi\} are unsatisfiable if and only if e₁ and e₂ are both true or both false on all
well-formed inputs conforming to Γ and M.

5 Evaluation

We evaluate Cedar by comparing it against two prominent open-source, general-purpose authoriza-
tion languages, OpenFGA [40] and Rego [36], on three example sets of policies. We briefly discuss
how these examples are encoded in each language (Section 5.1), and we compare the performance in
terms of evaluation time for authorization requests (Section 5.2). We also examine the performance
impact of policy slicing (Section 5.3) and the performance of our SMT encoding (Section 5.4). The
code and data used for evaluation is available at https://github.com/cedar-policy/.

5.1 Example applications

We use the following examples to compare Cedar, OpenFGA, and Rego. Full authorization models
for each of these examples are given in the appendix of an extended version of this paper [13].

5.1.1 gdrive example. The gdrive example [39] comes from OpenFGA; we reimplemented it in
Cedar and Rego. In this application, Users are organized into Groups, and Documents are organized
into Folders. Users may own Documents and Folders, and Users and Groups can be granted view
access to Documents and Folders. View access is transitive for both Folders and Groups: view
access to a Folder entails view access to any sub-Folders and contained Documents; and likewise,
Users inherit view access from their Group parents. Other permissions are not transitive: a Folder’s
owner(s) can create new Documents inside the Folder, but owner(s) of the Folder’s parent Folder(s)
do not inherit this permission. Ownership also comes with implied permissions: a Document’s

\[ \text{wf}(e, \Gamma, M) := \text{let } e = \{\langle \hat{e}_1, E_1, i \rangle | \text{subExpr}(e_i, E_i, e) \land (\text{not}, P_i) = M(E_i) \land M, \Gamma \vdash e_i \downarrow e_1\} \in \{\text{wfa}(\hat{e}_1, E_1) | \langle \hat{e}_1, E_1, P_i \rangle \in e \land E_1 \in P_i \} \cup \{\text{wft}(\hat{e}_1, \hat{e}_2, E_1, E_2, E_3) | \langle \hat{e}_1, E_1, P_i \rangle \in e \land \langle \hat{e}_2, E_2, P_2 \rangle \in e \land E_2 \in P_1 \land E_3 \in P_1 \land P_2\} \]

\text{wfa}(\hat{e}_1, E_1) := \text{let } \hat{e}_1 = \text{val}(\hat{e}_1) \text{ in}
\text{implies(isSome}(\hat{e}_1), (\text{not} (\text{set.member } \hat{e}_1 (\text{F}(E_1, E_1) \hat{e}_1))))
\text{wft}(\hat{e}_1, \hat{e}_2, E_1, E_2, E_3) := \text{let } \hat{e}_1 = \text{val}(\hat{e}_1), \hat{e}_2 = \text{val}(\hat{e}_2), \hat{b} = \text{and}(\text{isSome}(\hat{e}_1), \text{isSome}(\hat{e}_2)) \text{ in}
\text{implies(\text{and}(\hat{b}, (\text{set.member } \hat{e}_2 (\text{F}(E_1, E_2) \hat{e}_1))),
(\text{set.subset } \langle \text{F}(E_2, E_3) \hat{e}_2 \rangle \langle \text{F}(E_1, E_3) \hat{e}_1)\rangle))
\text{implies}(\hat{b}_1, \hat{b}_2) := \text{if } \hat{b}_1 = \text{true then } \hat{b}_2 \text{ else if } \hat{b}_1 = \text{false then true else } (\Rightarrow \hat{b}_1 \hat{b}_2)
\text{and}(\hat{b}_1, \hat{b}_2) := \text{if } \hat{b}_1 = \text{true then } \hat{b}_2 \text{ else if } \hat{b}_1 = \text{false then false else } (\text{and } \hat{b}_1 \hat{b}_2)

Fig. 11. Generating ground well-formedness constraints for e, \Gamma, and M. We use \text{subExpr}(e_i, E_i, e) to denote

We report the results of some small experiments comparing Cedar’s expressiveness and performance against cloud service
providers’ purpose-built policy languages in Section 6.
owner or owners of the Document’s parent Folder(s) can view, share, or write to the Document.⁴ Finally, Documents may be marked as “public” in which case any User has view access.

OpenFGA encodes these permissions partly in the *authorization model* and partly in the *tuples* representing relationships between specific entities. This is somewhat analogous to how Cedar has both *policies* and *entity data* respectively. For example, the OpenFGA declaration of the `doc` type in Figure 12(a) indicates that owners of a document, or owners of the document’s parent folder, can write to and share the document. In Cedar, we express this permission using the policy in Figure 12(b).

There are many ways to encode the `gdrive` authorization model in Cedar; we implemented two. The first encoding uses static policies over entity data that embody specific permissions, such as a User being granted view access to a Document. The second one uses Cedar templates to express these permissions; the application would grant view access to a new User or Group by linking a Cedar template. These encodings represent different tradeoffs in the design space. We discuss these tradeoffs, including the impact on performance, in Section 5.3.

The encodings of the `gdrive` and `github` examples in Rego are similar to the one for TinyTodo, discussed below:

5.1.2 `github` example. OpenFGA also provides a `github` example [38] which we reimplemented in Cedar and Rego. In this application, Users and Repositories are organized into Teams and Organizations. Users and Teams may be granted read/triage/write/maintain/admin privileges on Repositories, and Users or Organizations may be granted read/write/admin privileges on Organizations. Repositories inherit the permissions of their (Organization) owners.

As in the `gdrive` example, these permissions are encoded partly in policies and partly in entity data. For Cedar, we make one simplification over OpenFGA’s encoding: whereas OpenFGA supports multiple Repository owners of type User or Organization, we require that repositories have a single Organization owner. As we did for `gdrive`, for `github` we implemented two different Cedar encodings: one using only static policies, and another using Cedar templates.

5.1.3 TinyTodo example. We also reimplemented the TinyTodo example application (Section 2) in OpenFGA and Rego. The OpenFGA translation was straightforward; the most important part is the definition of the `list` type, shown in Figure 13a. This defines the hierarchy wherein all owners of a list are also editors and readers, and all editors are also readers.

---

⁴OpenFGA’s provided authorization model does not consider owners of transitive parent Folder(s) for write and share, but we modified the example to consider transitive parents (in both OpenFGA and Cedar), which is in line with the semantics of Google Drive permissions. Figure 12(a) shows the original OpenFGA declaration for clarity, rather than our modification.
type list
relations
define owner: [user]
define editor: [user,team#member] or owner
define reader: [user,team#member, user:*] or owner or editor
define get_list: reader
define update_list: editor
define create_task: editor
define update_task: editor
define delete_task: editor
define edit_shares: owner
define delete_list: owner

(a) OpenFGA TinyTodo list type declaration

public_actions :=
["Action::"CreateList"",
"Action::"GetLists""
]

allow = true {
  input.Request.Action in public_actions
}

allow = true {
  input.Request.Resource.Owner ==
  input.Request.Principal
}

(b) Rego TinyTodo policy fragment equivalent to
Cedar policies 0 and 1 in Section 2

allow = true {
  some group in input.Request.Resource.Writers
  group in graph.reachable(input.Data.Groups, [input.Request.Principal])
}

(c) Rego TinyTodo policy fragment for computing membership transitively

Fig. 13. OpenFGA and Rego code for TinyTodo

Most of the Rego translation was also straightforward, resulting in Rego code like in Figure 13b. We encoded the graph of team membership using a series of JSON objects with super and users attributes. Unlike Cedar and OpenFGA, Rego does not have any built in notion of a transitive relation. This can be encoded by either using Rego’s standard library graph algorithms, or pre-computing transitive closure over all input data to Rego, moving a substantial chunk of authorization logic out of Rego and into the application. We encode the transitivity within the policy, using graph reachability as in Figure 13c.

5.2 Performance evaluation

We compare the authorization performance of Cedar, Rego, and OpenFGA on each of the application examples just presented. We consider the time it takes to authorize a request when all policies and entity data are available in memory. We thus factor out any time taken to retrieve policies and data from stable storage (if kept there) to focus our comparison on language-level evaluation time.

For each of the application examples, we implemented a random generator that produces entity and request data in the appropriate format, complying with each application’s assumed invariants. Our random generators produce edges in the entity graph (e.g., user-in-group relations,folder-viewable-by-user relations, etc.) in proportion to the number of possible edges in the graph, so the number of edges increases superlinearly as more entities are added. As we conduct performance testing, we ensure that the responses (allow/deny) returned by each of the authorization engines agree for each request; this confirms that the translation is correct and the respective implementations are solving the same underlying authorization problems.

5.2.1 Experimental setup. We conducted performance tests on an Amazon EC2 m5.4xlarge instance running Amazon Linux 2. We used Cedar version 3.0.1, Rego version 0.61.0, and OpenFGA commit
Fig. 14. Performance results for Cedar, OpenFGA, and Rego on the gdrive, github, and TinyTodo examples.

For each datapoint in the graphs in Figure 14, we generated 200 separate datastores, and 500 random \texttt{is\textunderscore authorized()} requests for each, for a total of 100,000 requests. We time the execution of the core \texttt{is\textunderscore authorized()} operation in Cedar, OpenFGA, and Rego, not including the time required to (for instance) initialize the entity data, parse the OpenFGA authorization model or Cedar/Rego policies, or perform HTTP-related processing. We report the median and p99 (99th percentile) execution times across these 100,000 requests.

5.2.2 Results. Averaged across all tested input sizes, and considering the median performance, Cedar is $28.7 \times$, $34.4 \times$, or $35.2 \times$ faster than OpenFGA (for gdrive, github, and TinyTodo respectively). By the same measure, Cedar is $60.4 \times$, $80.8 \times$, or $42.8 \times$ faster than Rego, respectively.

Drilling down further, we also see a marked difference in scaling behavior. In the gdrive case, Rego’s performance deteriorates from median 76\,µs with 5 Users/Groups/Documents/Folders, to median 676\,µs with 50 Users/Groups/Documents/Folders. Similarly, at p99, Rego’s performance deteriorates from 391\,µs to 1933\,µs. Rego’s scaling behavior on github shows similar trends. Meanwhile, OpenFGA scales well in the median case, with only a modest increase from 89\,µs to 219\,µs for gdrive as the number of entities increases, or 235\,µs to 746\,µs for github. Interestingly, increasing the input size affects OpenFGA’s p99 performance more strongly, with the gdrive p99 increasing from 283\,µs to 3012\,µs as the number of entities increases. In contrast to both Rego and OpenFGA, Cedar scales well (with our default, non-templates-based encoding): it handles gdrive authorization requests in a median 4.0\,µs with 5 Users/Groups/Documents/Folders, increasing only to 5.0\,µs with 50 Users/Groups/Documents/Folders. Likewise, its github performance is around median 11.0\,µs across this entire input range. Cedar’s p99 performance is also strong and consistent, under 10\,µs (gdrive) or 20\,µs (github) for all tested input sizes.

The gdrive, github, and TinyTodo examples rely on transitive relations in the authorization logic. Since Cedar and OpenFGA provide primitives for reasoning about transitive relationships, they are better equipped to handle these policies. In Rego, the user has to encode the transitivity of rules within the policy, resulting in both a reduction of clarity and increased running time. A user of Rego could instead opt to maintain the transitive closure as an invariant on the inputs to Rego, but this comes at the cost of moving a chunk of the authorization logic outside of the authorization policy language. Doing this improves the scaling behavior of Rego a great deal. For these three examples, Rego policies are hard to read and do not scale as the other two solutions.

Based on communication with the OpenFGA developers, the OpenFGA in-memory datastore is intended mainly for debugging and is not optimized, but obviously it is a fairer comparison than would be OpenFGA’s persistent-database-backed datastore.
5.3 Policy slicing

The sound policy slicing scheme presented in Section 3.3 does not benefit our Cedar gdrive and github examples because their policies do not have scope-level constraints on principal and resource. However, policy slicing does benefit the template-based encodings of these examples discussed in Section 5.1. (We name these variants gdrive-templates and github-templates, respectively.) This is because linked templates have principal or resource constraints in the policy scope, which serve as policy indexing keys.

gdrive-templates contains 4 static policies and 1 template whereas github-templates contains 3 static policies and 5 templates. We use templates to grant specific permissions to individual principals. For instance, we write the following template to grant a certain User, Team, or Organization write access to a repository.

\[
\text{permit (principal in ?principal, action in Action::"writeRepository", resource == ?resource);}\]

We implement the policy slicing algorithm in Section 3.3 and evaluate its performance by randomly generating template links and requests. For each possible pair of principal and resource entities, we generate a template link for that pair with probability 0.05. So, the expected number of template-linked policies is quadratic in the number of entities per entity type. We use the same experimental setup as described in Section 5.2.1.

We evaluate policy slicing by comparing our default Cedar encodings with no templates (“Cedar”), our template-based Cedar encodings without policy slicing (“Cedar (Templates)”), and our template-based Cedar encodings with policy slicing enabled (“Cedar (Policy Slicing)”). The results are shown in Figure 15. With templates but without policy slicing, Cedar’s performance is much poorer: there are many more policies to evaluate, and this more than offsets the performance benefit from the template encodings’ slightly less complex policies and slightly less entity data. With policy slicing enabled, most of the policies are excluded from the slice, and overall performance returns to comparable to our default Cedar encoding without templates—averaged across all tested input sizes, the Cedar (Policy Slicing) median is about 18% faster than the Cedar median for github, but about 94% slower than Cedar for gdrive.

5.4 SMT encoding

The Cedar symbolic compiler can be used to implement many different SMT-based analyses. One particularly useful analysis is checking that refactorings are done correctly. This requires analyzing


```plaintext
(a) Original policies

permit(
    principal,
    action == Action::"writeRepository",
    resource)
when { principal in resource.owner.writers };

permit(
    principal,
    action == Action::"triageRepository",
    resource)
when { principal in resource.owner.writers };

(b) Refactored policy

permit(
    principal,
    action in
    [Action::"writeRepository",
     Action::"triageRepository"],
    resource)
when { principal in resource.owner.writers };
```

Fig. 16. Analysis example: Equivalence after a refactoring of github policies

the whole policy set, and is thus a good way to evaluate the scalability of our encoding. To perform this evaluation, we consider a refactoring operation on each example application.

We illustrate the refactoring using the github model discussed in Section 5.1.2. Suppose we started with the two policies in Figure 16a and wanted to replace them with the policy in Figure 16b. This refactoring is correct: it doesn’t change the set of requests that satisfy the policy set under the given schema. The refactoring may seem obvious, but it is only correct because none of the actions listed have children in the schema. If we modify the schema to add a child action, the refactoring is no longer valid, because of the semantics of in on sets (see line 4 in Figure 6):

```plaintext
action "bug_inducing" in ["writeRepository"]
    appliesTo { principal: [User], resource: [Repository] }
```

We perform this same refactoring (expanding policies with lists of actions into multiple policies comparing actions using ==) to all of the policies in each of our applications. The overall timing results and times spent in the SMT solver are given in Table 1.

<table>
<thead>
<tr>
<th>Refactoring</th>
<th>github (ms)</th>
<th>gdrive (ms)</th>
<th>TinyTodo (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>27.1+33.8</td>
<td>16.4+28.9</td>
<td>52.2+67.4</td>
</tr>
<tr>
<td>Buggy</td>
<td>29.9+40.9</td>
<td>19.6+34.9</td>
<td>56.2+77.3</td>
</tr>
</tbody>
</table>

All experiments are run 50 times on a Intel(R) Xeon(R) Platinum 8124M CPU @ 3.00GHz. We use CVC5 [6] version 1.0.5 as our solver. Note that the invalid refactorings generally take longer to solve because we invoke the solver once for each action and the invalid cases have the additional action, bug_inducing.

6 RELATED WORK

Authorization policy languages have been studied extensively over the last few decades. Table 2 presents a qualitative comparison of Cedar to closely related prior languages. The comparison is along six axes: (1) Expressiveness considers support for common access control models, forbid policies, and search and string matching operations; (2) Syntax considers the readability of the language syntax; (3) Performance considers support for policy indexing and the running time of a policy in terms of policy and input size, both typical and worst cases; (4) Formal considers whether the language has a formal semantics and metatheory for security-relevant properties; (5) Validation considers support for policy validation, ranging from linting to sound type checking;

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Table 2. Qualitative comparison with prior authorization languages

<table>
<thead>
<tr>
<th>Language</th>
<th>RBAC</th>
<th>ABAC</th>
<th>ReBAC</th>
<th>forbid</th>
<th>search</th>
<th>Syntax</th>
<th>Performance</th>
<th>Formal</th>
<th>Validation</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cedar</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>yes</td>
<td>poly (lin)</td>
<td>yes</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>XACML</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>partial</td>
<td>poly</td>
<td>±</td>
<td>○</td>
</tr>
<tr>
<td>OPA/Rego</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>partial</td>
<td>exp (poly)</td>
<td>±</td>
<td>±</td>
</tr>
<tr>
<td>Zanzibar</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>yes</td>
<td>lin</td>
<td>±</td>
<td>±</td>
</tr>
<tr>
<td>Ponder</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>yes</td>
<td>exp (poly)</td>
<td>±</td>
<td>±</td>
</tr>
<tr>
<td>Cassandra</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>no</td>
<td>±</td>
<td>±</td>
<td>±</td>
</tr>
<tr>
<td>SecureUML</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>yes</td>
<td>poly</td>
<td>±</td>
<td>±</td>
</tr>
</tbody>
</table>

- ●: full, native support
- ●: partial support, or full support with encoding
- ●: minimal support
- -: no support
- e: support via extension
- ±: possible support, none now, and unlikely to be full support

and (6) **Analysis** considers whether the language supports semantic policy analysis. Elements of this characterization are necessarily subjective, and complete information was not always available.

Cedar natively supports RBAC and ABAC, can encode ReBAC, and supports forbid policies. Cedar has rudimentary string matching, and limits searching to membership in sets and the entity hierarchy. Cedar’s syntax directly expresses authorization concepts in simple terms. Cedar policies generally have linear-time performance; set containment operations can make running times quadratic in the worst case. Cedar has a formal semantics, with metatheory proved in Lean. It offers a sound schema-based policy validator, as well as a sound and complete encoding for the full language to a decidable fragment of SMT-LIB.

**XACML** [50] is an open source declarative policy language. XACML provides native support for ABAC and forbid (called *deny*) rules; RBAC can be encoded, but it is unclear how to encode ReBAC. XACML provides slightly more general search and string-matching combinators compared to Cedar. XACML’s syntax is XML-based, which can be hard to read; ALFA [52] defines a more readable syntax for XACML. XACML policies are labeled with an explicit set of *target* conditions that form the basis of policy indexing, analogously to Cedar policies’ scope. XACML has typed operators, but no schema-style validator (that we could find). Several prior works developed analyses for XACML policies, leading to partial formalizations of the language [10]. Fisler et al. [22] developed Margrave, which uses multi-terminal binary decision diagrams to provide sound satisfiability and change impact analysis for a limited subset of XACML. Hughes and Bultan [27] analyze a different subset of XACML by translation to SAT. Their encoding is neither sound nor complete.

**Open Policy Agent** (OPA) [36] is an open source authorization system that uses a Datalog-based language called Rego. Rego, like other Datalog-based languages (some are discussed below), is more expressive than Cedar, allowing users to define their own notions of evidence prioritization and combination, and data hierarchy. Rego naturally supports permit-style ABAC policies, and is powerful enough to encode RBAC, ReBAC, and forbid policies. Rego supports expressive string matching and search via recursive rules. Rego’s added expressiveness is a blessing but also a curse. It provides no built-in authorization concepts such as ‘allow’ or ‘deny’, leaving policy authors to make their own choices to encode these concepts, which later policy readers may find difficult to understand (especially if they are not experts). Rego’s evaluation performance can also be hard to anticipate. While typical uses for authorization should be polynomial [31], worst-case performance is exponential [16]. Datalog’s resolution algorithm is behind the scenes, so small policy differences can potentially lead to performance surprises [48, 53]. The Rego documentation suggests policy writers limit themselves to a "linear fragment," though it is not precise about what that fragment is [37]. OPA supports indexing but rules must adhere to certain restrictions [47]. Rego provides a policy validator that leverages JSON schema [46], but it is neither specified carefully nor proved sound. Producing an analyzer would be difficult, as Datalog program equivalence is undecidable [49].
Zanzibar [43] is a highly scalable, relationship-based access control (ReBAC) system that Google uses to manage permissions for its cloud products. The system defines authorization in terms of relationships between users and resources. Zanzibar’s implementation is proprietary, but there are several open source clones, such as Ory Keto [41], AuthZed SpiceDB [2], and Auth0 Fine Grained Authorization (FGA) [40]. Zanzibar supports RBAC and ReBAC with a natural syntax, and with policy validation. It does not support ABAC, string matching, or search. forbid-style policies are supported by expressing one relationship in terms of non-membership in some other relation. Zanzibar can load authorization models lazily, providing a kind of indexing [43]. Our experiments show that OpenFGA’s performance is roughly linear in the number of tuples involved in relevant relationships. Zanzibar provides no deep policy analysis now, but it might be possible, e.g., by using the SMT theory of relations [33].

Ponder [14] is a declarative object-oriented policy specification language for writing access control policies, with a readable syntax. It has direct support for ABAC, RBAC, ReBAC, and forbid policies. Ponder policy constraints are specified in a subset of the Object Constraint Language [51], which is typed, has no side effects, supports string matching, and provides a variety of higher-order operators that enable sophisticated searches. Ponder deployments support resource-based policy indexes [17], and while Ponder’s powerful operators could result in exponential worst-case performance, typical policies should be polynomial. Ponder has no formal semantics, but offers some degree of typechecking. We are not aware of automated analyses for Ponder policies, but there have been analyses developed for OCL via encoding to formal logic for use by SMT solvers [11, 15]. These encodings leave out some OCL features, and are otherwise incomplete due to the use of quantifiers.

SecureUML [30] specifies access rules via UML, in an approach called model driven security [7]. RBAC-style rules can be refined by conditions over attributes, which are specified in OCL. Rules are attached to UML actions, supporting a kind of indexing, and OCL conditions generally encourage polynomial-time performance. Analysis for SecureUML leverages analysis for OCL constraints, which has the limitations discussed above.

Cassandra is a Datalog-based authorization language parametrized by a choice of constraint domain to support arithmetic operations, set operations, and others. Cassandra can express a variety of access control models and support powerful search and string matching operations, but at the cost of exponential worst-case performance and even greater challenges in building analysis tools. Cassandra focuses on permit policies; it is unclear how forbid policies could be supported. Cassandra is a trust management [8] system, which handles decentralized authorization by potentially consulting (or receiving signed certificates from) multiple policy stores instead of a single, centralized policy store. Other similar works (also based on Datalog) include RTx [29], the Query Certificate Manager (QCM) [24], and Secure Dynamically Distributed Datalog (SD3) [28]. It would be interesting to explore extensions to Cedar to support the decentralized approach.

Cloud service authorization policy languages are purpose-built to protect resources managed by cloud services, including those from Google Cloud [23], Microsoft Azure [4], and Amazon Web Services (AWS) [3]. Cedar is primarily different in that it is general-purpose: policies can be customized to meet an application’s needs via Cedar’s user-defined principal, resource, and action types; custom entity hierarchies; and arbitrary entity relationships. Nevertheless, Cedar has features that are similar to those in cloud-service authorization languages, and supports some of the same patterns. For example, AWS IAM and Azure policies are also structured around principals/actions/resources, and they support service-specific attributes and roles. While a full translator is outside of the scope of this work, as a simple exercise we closely examined a subset of the AWS IAM policies in the benchmark collected by Eiers et al. [20] (specifically, the policies under the “samples/iam” folder in their repository [45]). We found that we could hand-translate
each of these policies to Cedar fairly directly. Authorization times on the translated policies were, averaged over 300 runs with 950 entities, 14μs with random queries and 15μs with well-formed queries. These times are in line with those of our experiments in Section 5.2.

Cedar’s symbolic compiler (described in Section 4) likewise bears similarities to previous work on symbolic analysis of cloud-based authorization languages. Backes et al. [5] present the first symbolic analysis of AWS IAM policies, with the aim of detecting policy misconfigurations. Eiers et al. perform symbolic analysis of AWS IAM and Microsoft Azure policies, using model counting to quantify permissiveness [19], compare policies’ permissiveness [20], or perform policy repair [18]. Our symbolic compiler for Cedar differs from these in that its encoding is both sound and complete, which is made possible by Cedar’s careful language design. This encoding can be a building block for follow-on analyses; for instance, it would be interesting to build analogues of the policy-misconfiguration or model-counting analyses from these previous works on top of our Cedar encoding.

7 CONCLUSION

This paper has presented Cedar, a new authorization policy language whose design carefully balances expressiveness, safety, performance, and analyzability. Cedar is used at scale in products and services from Amazon Web Services, and is open source. All code, documentation, and example applications can be found at https://github.com/cedar-policy/.

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