A Logic-based Knowledge Representation for Authorization with Delegation
(Extended Abstract)*

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Abstract

We introduce Delegation Logic (DL), a logic-based knowledge representation (i.e., language) that deals with authorization in large-scale, open, distributed systems. Of central importance in any system for deciding whether requests should be authorized in such a system are delegation of authority, negation of authority, and conflicts between authorities. DL’s approach to these issues and to the interplay among them borrows from previous work on delegation and trust management in the computer-security literature and previous work on negation and conflict handling in the logic-programming and non-monotonic reasoning literature, but it departs from previous work in some crucial ways. In this introductory paper, we present the syntax and semantics of DL and explain our novel design choices. This first paper focuses on delegation, including explicit treatment of delegation depth and delegation to complex principals; a forthcoming companion paper focuses on negation.

Compared to previous logic-based approaches to authorization, DL provides a novel combination of features: it is based on logic programs, expresses delegation depth explicitly, and supports a wide variety of complex principals (including but not limited to k-out-of-n thresholds). Compared to previous approaches to trust management, DL provides another novel feature: a concept of proof-of-compliance that is not entirely ad-hoc and that is based on model-theoretic semantics (just as usual logic programs have a model-theoretic semantics). DL’s approach is also novel in that it combines the above features with smooth extensibility to non-monotonicity, negation, and prioritized conflict handling. This extensibility is accomplished by building on the well-understood foundation of DL’s logic-program knowledge representation.

Keywords: Authorization, delegation, trust management, security policy, non-monotonicity, conflict handling, knowledge representation, logic programs.

1 Introduction

In today’s Internet, there are a large and growing number of scenarios that require authorization decisions. By an authorization decision, we mean one in which one party submits a request, possibly supported by one or more credentials, that must comply with another party’s policy if it is to be granted. Scenarios that require authorization decisions

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Authorization is inadequate. Reasons include: 

Electronic commerce is one class of services in which authorization decisions play a prominent role. Merchants and customers both have valuable resources at risk and must have appropriate policies in place before authorizing access to these resources. An interesting aspect of e-commerce is that security policies and business policies are not always clearly separable. If a merchant requires that electronic checks for more than a certain amount be signed by at least two members of a set of trusted parties, is that a “security policy” or a “business policy”? It would be desirable for one authorization mechanism to be able to handle both.

Authorization in Internet services is significantly different from authorization in centralized systems or even in distributed systems that are closed or relatively small. In these older settings, authorization of a request is traditionally divided into two tasks: authentication and access control. Authentication answers the question “who made the request?” and access control answers the question “is the requester authorized to perform the requested action?” Following the “trust-management approach,” first put forth by Blaze et al. [4, 5], we argue that this traditional view of authorization is inadequate. Reasons include:

- **What to protect?**: In a traditional client/server computing environment, valuable resources usually belong to servers, and it is when a client requests access to a valuable resource that the server uses an authorization procedure to decide whether or not to trust the client. In today’s Internet (or any large, open, distributed system), users access many servers, make many different types of requests, and have valuable resources of their own (e.g., personal information, electronic cash); indeed “client” is no longer the right metaphor. Such a user cannot trust all of the servers it interacts with, and authorization mechanisms have to protect the users’ resources as well as those of the servers.

- **Whom to protect against?**: In a large, far-flung network, there are many more potential requesters than there are in a smaller, more homogeneous (albeit distributed) system. Some services, e.g., Internet merchants, cannot know in advance who the potential requesters are. Similarly, users cannot know in advance which services they will want to use and which requests they will make. Thus, authorization mechanisms must rely on delegation and on third-party credential-issuers more than ever before.

- **Who stores authorization information?**: Traditionally, authorization information, e.g., an access control list, is stored and managed by the service. Internet services evolve rapidly, and thus the set of potential actions and the users who may request them are not known in advance; this implies that authorization information will be created, stored, and managed in a dynamic, distributed fashion. Users are often expected to gather all credentials needed to authorize an action and present them along with the request. Since these credentials are not always under the control of the service that makes the authorization decision, there is a danger that they could be altered or stolen. Thus, public-key signatures (or, more generally, mechanisms for verifying the provenance of credentials) must be part of the authorization framework.

For these and other reasons, dividing authorization into authentication and access control is no longer appropriate. “Who made this request?” may not be a meaningful question – the authorizer may not even know the requester, and thus the identity or name of the requester may not help in the authorization decision. The goal of a growing body of work on trust management [4, 5, 9, 7, 3] is to find a more flexible, more “distributed” approach to authorization. The trust-management literature approaches the basic authorization question directly: “Does the set $C$ of credentials prove that the request $r$ complies with the set of local security policies $P$?” The trust-management engine is a separate system component that takes $(r, C, P)$ as input and outputs a decision whether compliance with policy has been proven.

Furthermore, trust-management adopts a “peer model” of authorization. Every entity can be both a requester and an authorizer. To be an authorizer, it maintains policies and is the ultimate source of authority for its authorization decisions. As a requester, it must maintain credentials (e.g., public-key certificates, credit card numbers, and membership certificates) or be prepared to retrieve or obtain them when it wants access to a protected resource. When submitting a request to an authorizer, the requester also submits a set of credentials that purport to justify that the requested action is permissible. An authorizer may directly authorize certain requesters to take certain actions (and may not even try to “authenticate” these requesters by resolving their “identities”), but more typically it will delegate this responsibility to credential issuers that it trusts to have the required domain expertise as well as relationships with potential requesters.

Basic issues that must be addressed in the design of a trust-management engine include the definition of “proof of compliance,” the extent to which policies and credentials should be programmable, and the language or notation in which they should be expressed.

In this paper, we propose the authorization language Delegation Logic (DL) as a trust-management engine. Its notable features include:
A definition of “proof of compliance” that is founded on well-understood principles of logic programming and knowledge representation. Specifically, DL starts with the notion of proof embodied in Datalog definite ordinary logic programs [17]. DL then extends this with several features tailored to authorization.

A rigorous and expressive treatment of delegation, including explicit linguistic support for delegation depth and for a wide variety of complex principals.

The ability to handle “non-monotonic” policies. These are policies that deal explicitly with “negative evidence” and specify types of requests that do not comply. Important examples include hot-lists of “revoked” credentials and resolution of conflicting advice from different, but apparently both trustworthy, sources.

“Non-monotonic” here means in the sense of logic-based knowledge representation (KR).

In combining both of these properties, DL departs sharply from earlier trust-management engines, some key points of which we now review. PolicyMaker, which was introduced in [4] and was the first system to call itself a “trust-management engine,” uses an ad-hoc (albeit rigorously analyzed [5]) notion of “proof of compliance” and handles only monotonic policies. KeyNote [3] is a second-generation system based on most, but not all, of the same design principles as PolicyMaker; in particular, KeyNote uses an ad-hoc notion of proof of compliance (derived from the one used in PolicyMaker), and it does not handle non-monotonic policies. Unlike PolicyMaker, KeyNote takes an integrated approach to the design of the compliance-checking algorithm and the design of the programming language in which credentials and policies are expressed. DL also takes an integrated approach to these two aspects of authorization. REFEREE [7] handles nomonotonic policies, but it uses an ad hoc proof system that was never rigorously analyzed. SPKI [9] handles limited forms of non-monotonicity, but the “proof of compliance” notion (to the extent that one is specified in [9]) is ad-hoc.

1 For review of standard concepts and results in logic programming, see [2]. For example, “Ordinary” logic programs (LP’s) correspond essentially to pure Prolog, but without the limitation to Prolog’s particular inferencing procedure. These are also known as “general” LP’s (a misleading name, since there are many further generalizations of them) and as “normal” LP’s. “Definite” means without negation. “Datalog” means without function symbols of more than zero arity. “Arity” means number of parameters.

2 A KR is (logically) monotonic when its entailment relationship (i.e., what it sanctions as conclusions) has the following property: if the set of premises (e.g., rules) \( P_2 \) is a superset of the set of premises \( P_1 \), then the set of conclusions entailed by \( P_2 \) according to \( K \) is a superset of the set of conclusions entailed by \( P_1 \). If a KR is not monotonic, it is called non-monotonic. Non-monotonicity means that adding premises can lead to retracting previously-sanctioned conclusions.

The outline of the rest of the paper is as follows. In section 2, we give an overview of DL. In section 3, we give the syntax and semantics of the monotonic case of DL, called D1LP. In section 4, we give an example of D1LP’s usage. In section 5, we give an overview of our expressive extension to handle negation and prioritized conflict, called D2LP. A forthcoming companion paper gives details about D2LP. In section 6, we briefly discuss related work and future work.

2 Overview of DL

Our use of a logic-program knowledge representation as the foundation of our authorization language (a.k.a. “trust-management engine”) offers several attractions: computational tractability, wide practical deployment, semantics shared with other practically important rule systems, relative algorithmic simplicity, yet considerable expressive power.

We chose Datalog definite ordinary logic programs (OLP’s) as the starting point for DL. (More generally, however, we could have started from other variants of logic-based knowledge representation, e.g., OLP’s without the Datalog restriction.) DL extends Datalog definite OLP’s along two dimensions that are crucial to authorization: delegation and non-monotonic reasoning. The resulting notion of “proof of compliance” is easier to justify than the ad-hoc notions used in PolicyMaker, KeyNote, REFEREE, and SPKI, because it is an extension of the well-studied, logic-programming framework.

As in much of the related literature, e.g., [1, 19, 25], we use the term principal to mean an “entity” or “party” to an authorization decision. For example, a principal may make a request, issue a credential, or make a decision. Each authorization decision must involve a distinguished principal that functions as the “trust root” of the decision; this principal is referred to as Local. DL supports the specification of sets of principals, via thresholds and lists, as well as dynamic sets of the form “all principals that satisfy the following predicate.” DL principals express beliefs by making direct statements and delegation statements.

The DL framework provides a uniform representation for requests, policies, and credentials. Information in DL is represented as rules and facts that are built out of statement formulas. A request in DL corresponds to a query. E.g., a simple query might be to ask whether the ground statement "Local says is key(12345, Bob)" is true. More generally, a request can be a complex expression of statements; these expressions are called statement formulas and

3 Under commonly met restrictions (e.g., no logical functions of non-zero arity, a bounded number of logical variables per rule), inferencing, i.e., rule-set execution, in LPs can be computed in worst-case polynomial-time. By contrast, classical logic (e.g., first-order logic), is NP-complete under these restrictions and semi-decidable without these restrictions.

4 Local plays the role that POLICY plays in PolicyMaker.
are defined in the next section. All of the policies and credentials that the receiving principal uses in evaluating the request form a DL program \( P \). The DL semantics defines a unique minimal model for \( P \), and the request is authorized if and only if it is in this model. The DL semantics provide the definition of “proof of compliance.” This use of model-theoretic semantics is a novel feature of DL and a clear departure from the approaches taken by other trust-management engines.

Delegation is one of the two major concepts with which we extended Datalog definite OLP’s to form DL, and it is the main technical focus of this paper. Distinguishing features of DL’s approach to delegation include:

- Delegations have arbitrary but specified depth. For example, by using a depth-2 delegation statement, a principal \( A \) may delegate trust about a certain class of actions to principal \( B \) and allow \( B \) to delegate to others but not allow these others to delegate further.

- Delegations to complex principal structures are allowed. For example, a principal \( A \) may delegate trust about a certain class of purchases to all principals that satisfy the predicate \text{GoodTaste}() \.

The other major concept that we added to Datalog definite OLP’s to form DL is non-monotonicity. DL uses explicit negation to allow a policy to say what is forbidden, negation-as-failure to allow a policy to draw conclusions when there is no information about something, and priorities to handle conflicts among policies.

We use DL to denote our general approach to trust management. The monotonic version of DL (i.e., Datalog definite OLP’s plus our delegation mechanism) is called D1LP, and the non-monotonic version (i.e., with negation and prioritized conflict handling) is called D2LP. This first paper focuses on D1LP, and only gives an overview of D2LP; a forthcoming companion paper focuses on D2LP.

Compared to previous logic-based approaches to authorization, DL provides a novel combination of features: it is based on logic programs, expresses delegation depth explicitly, and supports a wide variety of complex principals (including but not limited to \( k \)-out-of-\( n \) thresholds). Compared to previous approaches to trust management, DL provides another novel feature: a concept of proof-of-compliance that is not entirely ad-hoc and that is based on model-theoretic semantics (just as usual logic programs have a model-theoretic semantics). DL’s approach is also novel in that it combines the above features with smooth extensibility to non-monotonicity, negation, and prioritized conflict handling. This extensibility is accomplished by building on the well-understood foundation of DL’s logic-program knowledge representation.

3 Syntax and Semantics of D1LP

In this section, we formally define D1LP’s syntax and semantics.

3.1 Syntax

1. The alphabet of D1LP consists of three disjoint sets, the constants, the variables, and the predicate symbols.

2. A base atom is an expression of the form

\[
pred(t_1, \ldots, t_n)
\]

where \( pred \) is a predicate symbol and each \( t_i \) is a term.

3. A direct statement is an expression of the form

\[
X \text{ says } p
\]

where \( X \) is either a principal or a principal variable, “says” is a keyword, and \( p \) is a base atom. \( X \) is called the subject of this direct statement. A base atom encodes a trust belief or a security action, and a direct statement represents a belief of the subject.

4. A threshold structure takes one of the following forms:

\[
\text{threshold}(k, \{(A_1, w_1), \ldots, (A_n, w_n)\})
\]

where “threshold” is a keyword, \( k \) and the \( w_i \)'s are positive integers, the \( A_i \)'s are principals, and \( A_i \neq A_j \) for \( i \neq j \). The \( w_i \)'s are called weights. The set

\[
\{(A_1, w_1), \ldots, (A_n, w_n)\}
\]

is called a principal-weight pair set (abbreviated P-W set). If \( w_i = 1 \), then \( (A_i, w_j) \) can be written as \( A_i \). A threshold structure supports something if the sum of all the weights of those principals that support it is greater than or equal to \( k \).

\[
\text{threshold}(k, \text{Prin says } \text{pred/x})
\]

where “threshold” and \( k \) are the same

\footnote{In Prolog, variables can also start with upper-case letters, and all constants start with lower-case letters. We want to allow constants to start with upper-case letters, and we restrict variables to start with underscore.}
as above, \( \text{Prin} \) is a principal, \( \text{pred} \) is a predicate symbol, and \( x \) is the arity (number of parameters) of \( \text{pred} \). The arity \( x \) should be either 1 or 2. When \( x = 1 \), "\( \text{Prin} \) says \( \text{pred}(x) \)" defines a P-W set that gives weight 1 to all principals \( A \) such that "\( \text{Prin} \) says \( \text{pred}(A) \)" is true. When \( x = 2 \), "\( \text{Prin} \) says \( \text{pred}(A, x) \)" defines a P-W set, where the corresponding weight for any principal \( A \) is the greatest positive integer \( w \) such that "\( \text{Prin} \) says \( \text{pred}(A, w) \)" is true. These are called dynamic threshold structures.

5. A principal structure takes one of the following forms:

- \( A \) where \( A \) is a principal
- \( TS \) where \( TS \) is a threshold structure
- \( PS_1, PS_2 \) where \( PS_1 \) and \( PS_2 \) are principal structures. This is the conjunction of two principal structures. If both \( PS_1 \) and \( PS_2 \) support a base atom \( p \), then \( PS_1, PS_2 \) also supports \( p \).
- \( PS_1; PS_2 \) where \( PS_1 \) and \( PS_2 \) are principal structures. This is the disjunction of two principal structures. If either \( PS_1 \) or \( PS_2 \) supports a base atom \( p \), then \( PS_1; PS_2 \) also supports \( p \).
- \{ \( PS \) \} where \( PS \) is a principal structure

In a principal structure, conjunction (\( \cdot \)) takes precedence over disjunction (\( ; \)). A principal list is the special case of a principal structure that has the form \( \{ A_1, \ldots, A_n \} \), where each \( A_i \) is a principal. A principal set is the special case of a principal list in which there are no repetitions, i.e., in which \( A_i \neq A_j \) for \( i \neq j \).

6. A delegation statement takes the form

\[
X \text{ delegates } p^d \text{ to } PS
\]

where \( X \) is either a principal or a principal variable, \( \text{delegates and to are keywords, } p \) is a base atom, \( d \) is either a positive integer or the asterisk symbol \( * \), and \( PS \) is a principal structure. \( X \) is called the subject, \( d \) is called the delegation depth, and \( PS \) is called the delegatee. For example,

Alice delegates \( \text{is_key}(x) \cdot 2 \) to Bob is a delegation statement. Intuitively, it means:

Alice says \( \text{is_key}(\text{Key},X, X) \)

if Bob says \( \text{is_key}(\text{Key},X, X) \).

In this example, Alice trusts Bob in making direct statements about the predicate \( \text{is_key} \). Alice may also trust Bob in judging other people’s ability to make direct statements about \( \text{is_key} \), i.e., Alice trusts anyone Bob trusts. In this case, the delegation depth is 2. Similarly, delegation depth can also be greater than 2. A delegation depth \( * \) means unlimited depth.

7. A statement is either a direct statement or a delegation statement. In the semantics of D1LP, the role of “statement” is similar to the role of “atom” in ordinary LP's.

8. A statement formula takes one of the following forms:

- \( S \) where \( S \) is a statement.
- \( F_1, F_2 \) meaning \( (F_1 \text{ and } F_2) \), where \( F_1 \) and \( F_2 \) are statement formulas,
- \( F_1; F_2 \) meaning \( (F_1 \text{ or } F_2) \), where \( F_1 \) and \( F_2 \) are statement formulas,
- \( (F) \) where \( F \) is a statement formula.

In a statement formula, the operator \( \cdot \) (and) takes precedence over the operator \( ; \) (or).

9. A clause, also known as a rule, takes the form:

\[
S \text{ if } F.
\]

where \( S \) is a statement and \( F \) is a statement formula in which no dynamic threshold structures appear. \( S \) is called the head of the clause, and \( F \) is called the body of the clause. The body may be empty; if it is, the “if” part of the clause may be omitted. A clause with an empty body is also called a fact. Permitting dynamic threshold structures in the body in effect introduces logical non-monotonicity, which is why we prohibit it in D1LP. However, when we introduce negation-as-failure in D2LP, this restriction will be dropped.

There are two special principals that can be used in the body of a clause: “I” and “Local”. “I” refers to the subject of the head. It is the default subject for all statements in the body and may optionally be omitted. For example, when Alice believes

Bob says \( p \) if \( q \), I says \( r \).

this is shorthand for Alice believing

Bob says \( p \) if Bob says \( q \), Bob says \( r \).

"Local" refers to the principal that is using this statement and trying to make an authorization decision, i.e., the current trust root. For example, when Alice believes “Bob says \( p \) if Local says \( q \).”, and Alice believes (that Alice says) “q”, then Alice can conclude that “Bob says \( p \).”

Multi-agent logics of belief (or of knowledge) express beliefs from the viewpoints of multiple agents. DL can
be viewed as expressing beliefs from the viewpoints of multiple agents. However, in DL, there is a single, distinguished viewpoint: that of the principal Local. Every DL rule or statement is implicitly regarded as a belief of Local. In other words, DL is used from one principal’s viewpoint: i.e., Local’s. Let Local be the agent Alice. When Alice believes

Bob says is_key(Key[M, M])
if CA says is_key(Key[M, M]),
this means that “If I (Alice) believe that CA says is_key(Key[M, M]), then I (Alice) can believe that Bob says is_key(Key[M, M]).” The direct statements “CA says is_key(Key[M, M])” and “Bob says is_key(Key[M, M])” actually mean “Alice believes CA says is_key(Key[M, M])” and “Alice believes Bob says is_key(Key[M, M]).” It doesn’t matter whether “Bob says is_key(Key[M, M])” is believed by other principals, even Bob himself.

10. A program is a finite set of clauses. This is also known as a logic program (LP) or as a rule set.

As usual, an expression (e.g., term, base atom, statement, clause, or program) is called ground if it does not contain any variables.

3.2 Semantics

In this subsection, we define the set of statements that are sanctioned as conclusions by a D1LP. Formally, this set of conclusions is defined as the minimal model of the D1LP. This model assigns a truth value (true or false) to each ground statement. The value true means that the statement is an entailed conclusion; false means that it is not an entailed conclusion. These conclusions represent the beliefs of the principal that is the trust root, i.e., Local.

Let \( \mathcal{P} \) be a given D1LP.

Our semantics is defined via a series of steps. First, we define a language \( \mathcal{LO}_\mathcal{P} \) that expresses definite OLP’s (definite logic programs [17]). By contrast, we write the original input (D1LP) language of \( \mathcal{P} \) as \( \mathcal{LI}_\mathcal{P} \). Second, we define a translation that maps \( \mathcal{P} \) to a ground definite OLP \( \mathcal{O} \) in \( \mathcal{LO}_\mathcal{P} \). Third, we define the minimal model of \( \mathcal{O} \) as the correspondent (under this translation) of \( \mathcal{P} \)’s minimal model in the usual OLP semantics [17].

We begin by defining \( \mathcal{LO}_\mathcal{P} \). Let \( N \) be the number of all principals in \( \mathcal{P} \), \( MaxDepth \) be the greatest integer used as a delegation depth in \( \mathcal{P} \), and \( MaxArity \) be the maximum arity of any predicate in \( \mathcal{P} \). The language \( \mathcal{LO}_\mathcal{P} \) has two important predicates: holds and delegates. The predicate holds takes four parameters:

\[
\text{holds} \left( \text{subject}, \text{pred}, [\text{params}], \text{length} \right)
\]

Here, the domain of subject is the set of all principals appearing in \( \mathcal{P} \), which we write as principals. The domain of pred is the set of all the predicate symbols appearing in \( \mathcal{P} \). The domain of [params] is all the length-1 lists of constants that appear in \( \mathcal{P} \), where \( 0 \leq l \leq MaxArity \). The domain of length is integers \([1..N]\).

A ground atom of the predicate holds represents a ground direct statement

\[
\text{subject says pred}([\text{params}])
\]

Intuitively, length represents the number of delegation steps that is enough to derive the corresponding direct statement. When length = 1, it means this direct statement can be derived directly without the use of delegation. We need not consider cases in which this length exceeds the number \( N \) of principals.

The predicate delegates takes six parameters:

\[
delegates \left( \text{subject}, \text{pred}, [\text{params}], \text{depth}, \text{delegatee}, \text{length} \right)
\]

Here, subject, pred, params, and length are as above. The domain of depth is \([1..MaxDepth]\cup\{\ast\}\). The domain of delegatee is the set of all principal sets, which we write as \( 2^{\text{principals}} \). Recall that there are \( N \) principals altogether, and thus \( 2^{\text{principals}} \) is finite. Notice that only principal sets, rather than more general principal structures, are permitted as delegatee here. The reason this suffices to represent \( \mathcal{P} \) will become clear soon.

A ground atom of the predicate delegates represents a delegation statement

\[
\text{subject delegates pred}([\text{params}]) \rightarrow \text{depth} \text{ to delegatee}
\]

We define \( \mathcal{LO}_\mathcal{P} \) to include (in addition to holds and delegates) several “built-in” predicates and functions, as follows. The predicates \( =, \leq, \geq, <, >, \) and the functions \( +, - , \) and \( \text{min} \), are defined on the domain \([1..\max(N, MaxDepth)]\cup\{\ast\}\). The predicates \( \subseteq \) and \( \geq \) are defined on the domain of principal sets \( 2^{\text{principals}} \). “Built-in” is used in the Prolog sense: the predicates and functions are interpreted in the semantics and in inferencing) as having pre-defined behavior. The behavior of “\( \ast \)” is similar to \( \infty \), e.g., for any integer \( l \) in \([1..\max(N, MaxDepth)]\) : \( l < \ast, \ast - l = \ast, \ast = \ast, \) and \( \min(\ast, l) = l \). Notice that, technically, \( \mathcal{LO}_\mathcal{P} \) is many-sorted, in that the domains of some parameters of the predicates (in particular, of holds and delegates) are typed. This also is a straightforward and commonly-made extension of the usual OLP formalism. See, for example, [17].

The Herbrand base of \( \mathcal{LO}_\mathcal{P} \) is the set of all ground atoms in \( \mathcal{LO}_\mathcal{P} \). Because all the domains used above are finite, the Herbrand base of \( \mathcal{LO}_\mathcal{P} \) is also finite. An interpretation of
$L_\mathcal{O}_P$ is an assignment of truth values (true and false) to the Herbrand base of $L_\mathcal{O}_P$. Such an interpretation can also be viewed as a set of true ground atoms, i.e., as a conclusion set.

Given an interpretation $I$ of $L_\mathcal{O}_P$ and a principal structure $PS$, we define $PS^I$, the normal form of a principal structure under (i.e., relative to) $I$, as follows. A principal structure $PS^I$ is in normal form when it is of the form: 

$$PS^I_1; PS^I_2; \ldots; PS^I_r$$

where each $PS^I_i$ is a principal set and, for any $i \neq j$, $PS^I_i \nsubseteq PS^I_j$. One can view $PS$ as a negation-free formula in propositional logic; $PS$’s normal form $PS^I$ is then the result of converting that propositional-logic formula into its reduced disjunctive normal form (DNF). Here, the reduced DNF is logically equivalent (in propositional logic) to $PS$ given $I$. “Reduced” means that there is no subsumption: neither within a conjunct (i.e., no repetitions of principals) nor between conjuncts (i.e., no conjunct is a subset of another conjunct). For dynamic threshold structures like “threshold($k$, $Prin$ says pred($x$))”, the interpretation $I$ determines the P-W set defined by $Prin$ and pred. A threshold structure

$$\text{threshold}(k, \{(A_1, w_1), (A_2, w_2), \ldots, (A_n, w_n)\})$$

is converted to the disjunction of all minimal subsets of \{A_1, \ldots, A_n\} whose corresponding weights sum to be greater than or equal to $k$. For example,

$$\text{threshold}(3, \{(A, 2), (B, 1), (C, 1), (D, 1)\})$$

is converted to

$$\{A, B\}; \{A, C\}; \{A, D\}; \{B, C, D\}.$$ 

After two principal structures have been transformed, their conjunction and disjunction are convertible to normal form using methods similar to the usual ones used in propositional logic.

Equipped with the definitions of $L_\mathcal{O}_P$ and $PS^I$, we are ready next to give the main definition of the translation. Given an interpretation $I$ of $L_\mathcal{O}_P$, the translation $Trans^I$ maps $P$ into a definite OLP $O^I$ in the language $L_\mathcal{O}_P$, i.e., $O^I = Trans^I(P)$. We define $Trans^I$ via four steps.

Semantically, we treat a rule containing variables as shorthand for the set of all its ground instances. This is standard in the logic programming literature. We write $P^{\text{inst,d}}$ to stand for the LP that results when each rule $r$ in $P$ is replaced by the set of all its possible ground instantiations, i.e., by all of the ground clauses that can be obtained by replacing $r$’s variables with constants (or “instantiating” them).

The first step of $Trans^I$ is to replace $P$ by $P^{\text{inst,d}}$.

The second step of $Trans^I$ is to replace all the delegation statements in $P^{\text{inst,d}}$ by those that delegate to principal sets, as follows. Let $PS^I$ be written as $PS^I_1; PS^I_2; \ldots; PS^I_r$; each $PS^I_i$ is a principal set.

- Rewrite head delegation statements.
  Replace every clause of the form
  $$A \text{ delegates } s^d \to PS$$
  by the $r$ clauses:
  $$\{ A \text{ delegates } s^d \to PS^I_i \text{ if } F \} \text{ for } i = 1..r.$$ 

- Rewrite body delegation statements.
  Replace every delegation statement
  $$A \text{ delegates } s^d \to PS$$
  that occurs in the body of a clause, by the conjunction of the $r$ delegation statements:
  $$A \text{ delegates } s^d \to PS^I_1,$$
  $$A \text{ delegates } s^d \to PS^I_2,$$
  $$\ldots,$$
  $$A \text{ delegates } s^d \to PS^I_r.$$ 

Let $T^I_3$ denote the program after the above transformations.

The third step of $Trans^I$ takes $T^I_3$ as input and translates it to an OLP $T^I_4$ in the language $L_\mathcal{O}_P$, as follows.

- For any direct statement
  $$A \text{ says } pred(\text{params})$$
  in the body of a clause, change it to:
  $$\text{holds}(A, \text{pred}, [\text{params}], N).$$

- For any direct statement
  $$A \text{ says } pred(\text{params})$$
  in the head of a clause, change it to:
  $$\text{holds}(A, \text{pred}, [\text{params}], 1).$$

- For any delegation statement
  $$A \text{ delegates } pred(\text{params})^d \to PS$$
  in the body of a clause, change it to:
  $$\text{delegates}(A, \text{pred}, [\text{params}], d, PS, N)$$

- For any delegation statement
  $$A \text{ delegates } pred(\text{params})^d \to PS$$
  in the head of a clause, change it to:
  $$\text{delegates}(A, \text{pred}, [\text{params}], d, PS, 1).$$

Here, as before, $N$ is the number of principals in $P$. Intuitively, if a statement in the head is deduced, then it is deduced directly (length 1); if a statement can be deduced within any length, it is true.

The result of these changes is $T^I_4$.

The fourth step of $Trans^I$ is to add a further collection of clauses to $T^I_4$; the resulting OLP program is $O^I$ in the language $L_\mathcal{O}_P$. Intuitively, these additional clauses represent all instances of several meta-rules of deduction involving delegation. Because the relevant domains are finite, there are a finite number of such instances.

Let $A$ be a principal; $BS$ be a principal set \{B_1, \ldots, B_n\}; CS$ be another principal set; $d$ and $d_0$ be delegation depths (i.e., elements of $[1..\text{MaxDepth}] \cup \{*\}$); and, $l$ and $l_0$ be lengths (i.e., elements of $[1..N]$). Let $pred$
Every ground clause that has the form:
\[
\text{holds}(A, \text{pred}, [\text{params}], l) \\
\text{implies holds}(A, \text{pred}, [\text{params}], l_0), \\
l \geq l_0.
\]

Intuitively, this represents the deduction meta-rule that: If a direct statement is deducible within length \(l_0\), then the direct statement is deducible within any longer length \(l \geq l_0\).

Every ground clause that has the form:
\[
deploytates(A, \text{pred}, [\text{params}], d, \text{CS}, l) \\
\text{implies deploytates}(A, \text{pred}, [\text{params}], d_0, \text{BS}, l_0), \\
d_0 \leq d_0, l \geq l_0, \text{CS} \supseteq \text{BS}
\]

Intuitively, this represents the deduction meta-rule that: If a delegation statement is deducible, then any weaker delegation statement is deducible within any longer length. Smaller depth and larger conjunctive delegate set each weaken a delegation statement.

Every ground clause that has the form:
\[
\text{holds}(A, \text{pred}, [\text{params}], l_0 + 1) \\
\text{implies holds}(B_1, \text{pred}, [\text{params}], 1), \\
\text{holds}(B_2, \text{pred}, [\text{params}], 1), \\
\ldots, \\
\text{holds}(B_n, \text{pred}, [\text{params}], 1), \\
l_0 < N.
\]

Intuitively, this represents the deduction meta-rule that enforces the effect of depth-1 delegations.

Every ground clause that has the form:
\[
deploytates(A, \text{pred}, [\text{params}], \min(d, d_0 - l), \text{CS}, l_0 + l) \\
\text{implies deploytates}(A, \text{pred}, [\text{params}], d_0, \text{BS}, l_0), \\
deploytates(B_1, \text{pred}, [\text{params}], d, \text{CS}, l), \\
deploytates(B_2, \text{pred}, [\text{params}], d, \text{CS}, l), \\
\ldots, \\
deploytates(B_n, \text{pred}, [\text{params}], d, \text{CS}, l), \\
l < d_0, l \leq (N - l_0).
\]

Intuitively, this represents the deduction meta-rule that enforces the effect of chaining of delegations. The depth of the deduced (head) delegation of \(A\) is bounded both by the depth of the delegation from \(A\) to \(\text{BS}\) and by the depth of the delegations from \(B_i\)'s to \(\text{CS}\). The depth of the delegation from \(A\) to \(\text{BS}\) has to cover the path lengths that have already been used in deriving delegations from \(B_i\)'s to \(\text{CS}\).

The \(O^I\) that results (from adding these further clauses to \(T^I\))) is a ground definite OLP. It thus has one or more OLP-models, i.e., models in the usual OLP semantics [17]. In particular, it has a model \(\text{MinOLPModel}(O^I)\) that is minimal in the sense of the usual OLP semantics.

**Proposition 1** Given two interpretations \( I \subseteq J \) of \( \mathcal{L}_O \), if an interpretation \( K \) of \( \mathcal{L}_O \) is an OLP-model of \( O^I \), then \( K \) is also an OLP-model of \( O^J \).

**Proof.** See the expanded Research Report version for the full proof. **Overview:** Essentially, this is a logical-monotonicity property. The key observation is the following: The differences that may exist between \( O_J \) and \( O_I \) can only be caused by dynamic threshold structures, which are only allowed to appear in heads of clauses. Consider the normal forms of a dynamic threshold structure \( TS \) under \( I \) and \( J \), i.e., \( TS^I \) and \( TS^J \). If we view them as propositional formulas, then \( TS^I \) implies \( TS^J \), because \( I \subseteq J \). This makes \( O^J \) at least as strong (in deduction power) as \( O^I \). \( \blacksquare \)

**Definition 2** An interpretation \( I \) of \( \mathcal{L}_O \) is an O-model of a DILP program \( P \) if and only if \( I \) is an OLP-model of \( O^I = \text{Trans}^I(P) \).

It turns out that every DILP program \( P \) has at least one O-model, as we will show below in Theorem 7.

**Theorem 3** The intersection of any two O-models of \( P \) is also an O-model of \( P \).

**Proof.** Given two O-models \( I \) and \( J \) of \( P \), one can conclude by the definition of O-models that \( I \) is an OLP-model of \( O^I \) and that \( J \) is an OLP-model of \( O^J \). Let \( K = I \cap J \). Because \( K \subseteq I \) and \( K \subseteq J \), Proposition 1 implies that \( I \) and \( J \) are both OLP-models of \( O^K \). Because definite ordinary logic programs have the property that two models’ intersection is still a model [17], \( K \) is an OLP-model of \( O^K \). By the definition of O-models, \( K \) is thus an O-model of \( P \). \( \blacksquare \)

**Definition 4** The minimal O-model of \( P \) is the intersection of all of its O-models. We write this as \( \text{MinOModel}(P) \).

It turns out that every DILP \( P \) has a minimal O-model; below, in Theorem 7, we show how to construct it.

Ultimately, we are interested in models expressed in \( \mathcal{L}_P \), the original DILP language of \( P \). We define a simple reverse translation \( \text{ReverseTrans} \) that maps each O-model \( I \) of \( P \) to its corresponding DILP-model in \( \mathcal{L}_P \), as follows.

- For each O-conclusion of the form
  \[
  \text{holds}(A, \text{pred}, [\text{params}], \text{length}),
  \]
  include the DILP-conclusion
  \[
  A \text{ says } \text{pred}(\text{params}).
  \]
For each O-conclusion of the form
\[ A \text{ delegates}(P, \text{pred}, [\text{params}], \text{depth}, \text{Delegate}, \text{length}) \],
include the D1LP-conclusion
\[ A \text{ delegates pred}(\text{params}) \wedge \text{depth} \rightarrow \text{Delegate} \].

Notice here that (delegation path) length is ignored after the OLP conclusions are drawn.

We define the \textit{Herbrand base} of \( \mathcal{P} \), in \( \mathcal{L}_I \), as the set of all ground statements of \( \mathcal{P} \), restricted to require that every principal structure be a principal set. We define an \textit{interpretation} of \( \mathcal{P} \) to be an assignment of truth values (true and false) to the Herbrand base of \( \mathcal{P} \). Such an interpretation can also be viewed as a set of true ground statements, i.e., as a conclusion set.

\textbf{Definition 5} An interpretation \( M \) of \( \mathcal{L}_P \) is a model of a D1LP program \( \mathcal{P} \) if and only if \( M = \text{ReverseTrans}(I) \) and \( I \) is an O-model of \( \mathcal{P} \). The \textit{minimal model} of \( \mathcal{P} \) is \( \text{ReverseTrans}(\text{MinOLPModel}(P)) \). We write this as \( \text{MinOLPModel}(P) \).

Next, we define \( \text{MinOLPModel}(P) \) and thus its corresponding \( \text{MinOLPModel}(\mathcal{P}) \) actually exist, by showing how to construct \( \text{MinOLPModel}(\mathcal{P}) \).

\textbf{Definition 6} Given \( \mathcal{P} \), we define an operator \( \Psi_{\mathcal{P}} \) that takes an interpretation \( I \) of \( \mathcal{L}_O \) and returns another one: \( \Psi_{\mathcal{P}}(I) = \text{MinOLPModel}(O^I) \), where \( \text{MinOLPModel} \) is the standard minimal model operator for OLP.

\textbf{Theorem 7 (Construct Minimal Model)} \( \text{MinOLPModel}(P) \) is the least fixpoint of \( \Psi_{\mathcal{P}} \). This fixpoint is obtained by iterating \( \Psi_{\mathcal{P}} \) a finite number of times, starting from \( \emptyset \). \( \text{MinOLPModel}(P) \) thus exists, for every D1LP \( \mathcal{P} \).

\textbf{Proof.} See the expanded Research Report version for the full proof. \textbf{Overview:} One key observation is that \( \Psi_{\mathcal{P}} \) is a monotone operator, due to the monotonicity properties of Proposition 1 and of definite OLP’s. Another key observation is that the domain of this operator, i.e., the space of interpretations, is finite due to the finite Herbrand base (largely because of the Datalog restriction).

\textbf{Inferencing:} Because of the finiteness properties mentioned above, computing \( \text{MinOLPModel}(P) \) is decidable. Given the minimal model \( \text{MinOLPModel}(P) \), queries in D1LP can be translated as we did for the body of a clause, then answered using the model. We have a current implementation of restricted D1LP. It is written in Prolog and uses a top-down query-answering method.

\section{Use of D1LP}

In this section, we use the public-key infrastructure problem to demonstrate the use of D1LP. The trust-management approach views the PKI problem from one user’s point of view. The user has trust beliefs and certificates from other principals, and it needs to decide whether a particular binding is valid according to its information. All of these beliefs, certificates, and decisions can be represented uniformly in D1LP.

D1LP can also be used to represent authorizations. Authorizing a principal to do something can be represented as a delegation to that principal. Whether to allow this principal to further grant this authorization to other principals can be controlled by delegation depth. An authorization request can be answered by deciding whether a delegation statement is true or false. Moreover, separation of duty [8] can be achieved by delegations to threshold structures.

We first show how certificates from different PKI proposals can be represented in D1LP. Pretty Good Privacy (PGP)’s certificates only establish key bindings; they have no delegation semantics. The delegations in PGP are expressed by trust degrees that are stored in local key rings. They all have depth 1. In PGP, a user can also specify threshold values for accepting a key binding. In D1LP, this can be achieved through dynamic threshold structures. One way is to use several predicates to denote different trust levels, for example, \texttt{fully_trusted} and \texttt{partly_trusted}. A user Alice may have the following policies:

\begin{itemize}
  \item Alice says \texttt{fully_trusted}(Bob).
  \item Alice says \texttt{fully_trusted}(Sue).
  \item Alice says \texttt{partly_trusted}(Carl).
  \item Alice says \texttt{partly_trusted}(Joe).
  \item Alice says \texttt{partly_trusted}(Peg).
  \item Alice delegates \texttt{is_key}(_Key, _User) \wedge 1 to threshold(1, \texttt{fully_trusted}/1).
  \item Alice delegates \texttt{is_key}(_Key, _User) \wedge 1 to threshold(2, \texttt{partly_trusted}/1).
\end{itemize}

Of course, one can also use \textit{weighted} dynamic threshold structures.

In X.509 [6], certification authorities (CAs)’ certificates are chained together to establish a key binding. For such delegation chains to be really meaningful, the certificates on such chains must also imply delegations. Since there is no limit on the length of delegation chains, all such delegations have depth ‘s’. Privacy Enhanced Mail (PEM) uses X.509’s certificates but limits the CA hierarchy to three levels: IPRA, PCAs, and CAs. Thus PEM’s trust model requires that every user give a depth-three delegation to IPRA.

A SPKI certificate does not establish key binding; it is a delegation from the issuer to the subject of the certificate.
It has one field that controls whether a delegation can be further delegated or not; this means that every delegation has depth 1 or ‘*’.

There are other proposals to use lengths of delegation paths as a metric for public-key bindings. The difference between these path lengths and our delegation depths is that, in the former, there is only one length, and it is specified by the trust root. However, every DL delegation statement can have a delegation depth limit. This has the effect of allowing every principal on the delegation path to specify how much further this path can go. Together, the set of delegation depths along the path determine whether the path is invalidly deep.

Next, we give an extended example of public key authorization with delegation. Consider a user Alice who wants to decide whether a public key $M_{\text{Key}}$ is web site $M_{\text{Site}}$’s public key. There are many certification systems that may be relevant. In particular, Alice trusts three of them: systems $X$, $Y$, and $Z$. System $X$ has three levels: $XRCA$, $XP\bar{C}A$, and $XCA$, where $XRCA$ is the root, $XCA$’s are CAs that certify users’ public keys directly, and $XP\bar{C}A$’s certify $XCA$’s public keys and are in turn certified by $XRCA$. System $Y$ has two levels: $YRCA$ and $YCA$’s. System $Z$ has only one level: $ZRCA$, which certifies users’ keys directly. Alice first translates (i.e., represents) certificates of these systems into statements using the predicates $\text{Xcertificate}(...)$, $\text{Ycertificate}(...)$, $\text{Zcertificate}(...)$.

Then Alice asserts some rules that translate these into statements of a common certificate predicate, say, $\text{is\_site\_key}(_\text{Key},_\text{Site})$. For example:

$$_\text{Issuer} \text{ says } \text{is\_site\_key}(_\text{Key},_\text{Site})$$

if $\text{Xcertificate}(\text{signature\_key},_\text{subject}, ...)$.

Next, Alice specifies the sense in which she trusts the three systems, by asserting the rule:

$$\text{Alice delegates } \text{is\_site\_key}(_\text{Key},_\text{Site})^{*} \text{ to } (XCA, (YRCA;ZRCA)).$$

This means that Alice requires system $X$ and one of systems $Y$ and $Z$ to certify a website public key. She does this with delegation depth 3 because she knows that 3 is the maximum number of levels in those certification systems. (Note that, for other purposes, Alice can use predicates other than $\text{is\_site\_key}$ and trust these systems differently.) Suppose that $M_{\text{Key}}$ is certified by both system $Y$ and system $Z$, i.e., there are certificates that translate into:

$$\text{YRCA delegates } \text{is\_site\_key}(_\text{Key},_\text{Site})^{*} \text{ to YCA}.$$

$$\text{YCA says } \text{is\_site\_key}(M_{\text{Key}},M_{\text{Site}}).$$

$$\text{ZRCA says } \text{is\_site\_key}(M_{\text{Key}},M_{\text{Site}}).$$

Then the given information is not enough to deduce (i.e., entail) that “Alice says $\text{is\_key}(M_{\text{Key}},M_{\text{Site}})$”.

Now suppose that, in addition to these systems above, Alice has a friend Bob. For whatever reasons, Alice trusts Bob unconditionally to certify websites’ public keys, i.e.,

$$\text{Alice delegates } \text{is\_site\_key}(_\text{K},_\text{S})^{*} \text{ to Bob.}$$

Bob thinks that certification by system $Z$ is itself enough for those sites that belong to association $\text{assoc}$, and he trusts $\text{ASSOC}$ in deciding which sites belong to $\text{assoc}$, i.e.,

$$\text{Bob delegates } \text{is\_site\_key}(_\text{K},_\text{S})^{1} \text{ to ZRCA}$$

if $\text{I says belongs\_to}(\text{S},_\text{assoc}).$

Bob delegates $\text{belongs\_to}(\text{S},_\text{assoc})^{1}$ to $\text{ASSOC}$.
policies is classical negation (a.k.a. explicit negation or strong negation), which allows policies that explicitly forbid something. Classical negation in rules, especially in the consequents (heads) of rules, enables one to specify both the positive and negative sides of a policy, (i.e., both permission and prohibition) using the expressive power of rules, e.g., using inferential chaining. As argued in [14, 15], this allows more flexible security policies. Classical negation is particularly desirable for authorization in Internet scenarios, where the number of potential requesters is huge. For low-value transactions, users sometimes have security policies that give access to all except a few requesters. Without negations, it would be effectively impossible to do this.

Introducing classical negation leads to the potential for conflict: Two rules for opposing sides may both apply to a given situation. Care must be taken to avoid producing inconsistency. Priorities, which specify that one rule overrides another, are an important tool for specifying how to handle such conflict. E.g., a known revocation overrides a general rule to presume trustworthiness. E.g., one principal overrides another’s decision/recommendation. Some form of prioritization is generally present in many rule-based systems; prioritization has also received a great deal of attention in the non-monotonic reasoning literature (see, e.g., [12] for some literature review and pointers).

Prioritization information is naturally available. One common basis for prioritization is specificity: Often it is desirable to specify that more specific-case rules should override more general-case rules. Another basis is recency, in which more recent rules override less recent rules. A third common basis is relative authority, in which rules from a more authoritative source override rules from a less authoritative one. For example, a superior legal/bureaucratic/organizational jurisdiction or a more knowledgeable/expert source may be given higher priority. It is often useful to reason about prioritization, e.g., to reason from organization roles or timestamps to deduce priorities. Reasoning about prioritization may itself involve conflict, e.g., a less recent rule may be more specific or more authoritative.

To allow users to express non-monotonic policies in a natural and powerful fashion, we define D2LP, which stands for version 2 of Delegation Logic Programs. D2LP is (logically) non-monotonic. D2LP expressively extends D1LP to include negation-as-failure, classical negation, and partially-ordered priorities. Just as D1LP bases its syntax and semantics on definite ordinary LP’s, D2LP bases its syntax and semantics on Courteous LP’s. The version of Courteous LP’s we use is expressively generalized as compared to the previous version in [12, 13].

In the rest of this section, we give an overview of D2LP. Full details will be given in a forthcoming companion paper.

Syntactically, each D2LP rule (clause) is generalized to permit each statement to be negated in two ways: by classical negation $\neg$ and/or by negation-as-failure (NAF) $\sim$. Each rule also is generalized to permit an optional rule label, which is a handle for specifying priority. Prioritization is specified via the predicate overrides. overrides(label$_1$, label$_2$) means that every rule having rule label label$_1$ has strictly higher priority than every rule having rule label label$_2$. overrides is treated specially in the semantics to generate the prioritization used by all rules. Otherwise, however, overrides is treated as an ordinary predicate.

A D2LP direct statement has the form:

$$A \text{ says } [\sim] [\neg] p$$

A D2LP delegation statement has the form:

$$A \ [\sim] [\neg] \text{ delegates } p^d \text{ to } PS$$

Here, as when we described D1LP, $A$ is a principal, $p$ is a base atom, $d$ is a depth, and $PS$ is a principal structure. Square brackets (“...”) indicate the optionality of what they enclose. $\sim$ stands for classical negation and is read in English as “not”. $\sim$ stands for negation-as-failure and is read in English as “fail”.

When a statement does not contain $\sim$, we say it is classical; when it contains neither $\sim$ nor $\neg$, we say it is atomic.

Semantically, the negations’ scope can be viewed as applying to the whole statement. Intuitively, $\sim s$ means that $s$ is believed to be false. By contrast, $\sim cs$ means that $cs$ is not believed to be true, i.e., either $cs$ is believed to be false, or $cs$ is unknown. “Unknown” here means in the sense that there is no belief one way or the other about whether $cs$ is true versus false.

A D2LP statement formula is defined as the result of conjunctions and disjunctions applied to D2LP statements, similarly to the way in which a D1LP statement formula is defined as the result of conjunctions and disjunctions applied to D1LP statements (i.e., atomic statements). A D2LP rule (clause) is defined as:

$$<lab> \ S \ if \ F$$

Here, $S$ is a classical statement. $F$ is a statement formula. The rule label $lab$ is an ordinary logical term (e.g., the constant frau below) in the D2LP language. The rule label may optionally be omitted. Note that D2LP relaxes the D1LP prohibition on dynamic threshold structures in the body. Syntactically, a D1LP rule is a special case of a D2LP rule.

Next, we give a simple example that illustrates the use of classical negation and priorities. Let D2LP program $R_1$ be the following set of rules:

$$<cred> \ A \ say诚实(X)$$
$$\text{ if } B \ say信用评级(X, good).$$
$$<frau> \ A \ say非诚实(X)$$
$$\text{ if } C \ say欺诈(X),$$
\[ D \text{ says fraudExpert(C)}. \]
\[ A \text{ says overrides(fraud, cred)}. \]
\[ B \text{ says creditRating(Joe, good)}. \]
\[ D \text{ says fraudExpert(C)}. \]

\( R_1 \) entails the conclusion: \( A \text{ says honest(Joe)}. \)

Continuing the example, suppose the following statement is added to \( R_1 \) to form \( R_2 \).
\[ C \text{ says fraudulent(Joe)}. \]
\( R_2 \) instead entails the conclusion:
\[ A \text{ says } \neg \text{honest(Joe)}. \]

The semantics of a D2LP are defined via a translation \( Trans_2 \) to a ground courteous LP that is roughly similar to D1LP’s translation \( Trans \) to a ground OLP. Courteous LP’s expressively extend OLP’s to include \( \neg \) and \( \sim \), as well as prioritization represented via an \( overrides \) predicate on rule labels.

We impose some further expressive restrictions in D2LP, related especially to cyclicity of dependency between predicates, to ensure D2LP’s well-behavior semantically and computationally. (Limited space prevents us from detailing these restrictions here.) The generalized version of Courteous LP’s relies on the well-founded semantics [10], which is computationally tractable (worst-case polynomial-time) for the ground case.

Courteous LP’s semantic well-behavior includes having a unique (minimal) model that is \( \text{consistent} \) (\( s \) and \( \sim s \) are never both sanctioned as conclusions). D2LP inherits this same well-behavior. D2LP inferencing remains decidable; its finiteness properties are similar to those of D1LP.

In a forthcoming paper, we cover DL’s treatment of negation in detail, as we have covered delegation in detail in this paper.

6 Discussion and Future Work

As explained in previous sections, our design of DL was primarily influenced by earlier work on trust management and on logic programming and knowledge representation. There is other, more tenuously related work in the computer security literature, and we briefly discuss some of it in this Extended Abstract. A longer discussion appears in the expanded, Technical Report version of this paper.

In [1, 19, 25], Abadi, Burrows, Lampson, Wobber, and Plotkin developed a logic for authentication in distributed systems. The central notion in their logic is delegation, which they express via the “speaks for” relation. They develop a system of reasoning about which principals speak for which other principals. But they didn’t consider delegation-depth limits and threshold structures. In this sense, DL’s treatment of delegation is more powerful.

Maurer [21] modelled public-key infrastructure via recommendations with levels and confidence values. Delegation in DL is very similar to recommendation in [21], but there are several differences. One is that Maurer’s model supports direct statements and delegation statements but not clauses (rules). A second is that Maurer’s model supports reasoning about the delegations and beliefs of what DL calls “Local,” but it does not allow, say, Local A to reason about the beliefs of B (e.g., about whether, in A’s view, B delegates to C or B believes a particular statement). Thus, one cannot express, in Maurer’s model, that “A says X if B says Y.” This restriction permits delegation chaining to be much simpler than it is in DL and eliminates the need to maintain “lengths.” Thirdly, Maurer’s model does not support delegation to lists, threshold structures, etc.. Finally, DL does not use confidence values.

Neither Abadi \textit{et al.} nor Maurer consider negations and non-monotonicity. However, there is also previous work on authorization languages that consider negations. But these work is different from DL in that it does not consider delegation. The way these work handles negation is also different from D2LP. One well-known example is the language of Woo and Lam [26], which is based on Default Logic [22]. Woo and Lam do not guarantee that every program (or, in their terms, every “policy base”) has a model; furthermore, when a model exists, it might not have a meaningful interpretation, because of potential inconsistency. Well-founded semantics and prioritized conflict handling allow D2LP to support a more expressive set of non-monotonic policies and give a unique and meaningful model to every program.

Jajodia \textit{et al.} [14, 15] proposed a logical authorization language that is based on Datalog extended with two negations. They have only limited support for non-monotonic policies, however, via syntactic restrictions that ensure that policies are conflict-free and stratified. By contrast, D2LP is more expressive, via well-founded semantics and conflict handling. Programs written in Jajodia \textit{et al.}’s language are syntactically restricted and delegation-free special cases of D2LP, and D2LP would give the same model for them.

Future work will address the computational complexity of compliance checking in DL, syntactically restricted classes of DL programs for which compliance can be checked very efficiently, implementation of the DL interpreter (for which we now have only a preliminary version for restricted D1LP), and deployment of DL in an e-commerce platform.

References


