Exploiting KeyNote in WebCom: Architecture Neutral Glue for Trust Management

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July 28, 2000

Abstract

A practical trust management system for the WebCom distributed computing architecture is described. Public key credentials are used to determine the authorization of X509 authenticated SSL connections between peers. WebCom provides an architecture neutral meta-language (glue) for bringing together the components of a distributed application in such a way that the components need not concern themselves with synchronization or concurrency issues. This encourages a loose coupling between application components and trust management, which, in addition to supporting off the shelf application components, results in applications that are easier to develop, understand and maintain.

KEYWORDS: Trust Management; Authorization; Mobile Computation; Meta-Computing; Distributed System Security; Software Engineering; Condensed Graphs.

1 Introduction

Trust Management (TM) [4, 6, 19] is an approach to constructing and interpreting the trust relationships among public keys that are used to mediate security critical actions. Credentials are used to specify delegation of authority among public keys, and are used to determine if a signed request complies with a local authorization policy. KeyNote [3, 4] is an expressive and flexible trust management scheme that provides a simple credential notation for expressing both security policies and delegation. A standard API to KeyNote is used by an application to make queries about whether

requests (to the application) have authorization or not. The formulation and management of security policies and credentials are separate from the application, making it straight forward to support trust management policies across different applications. KeyNote has been used to provide trust management for a number of applications including active networks [7] and to control access to Web pages [1].

In this paper we describe the development of a KeyNote based trust management system for the WebCom [17, 14] distributed computing architecture. Applications in WebCom are programmed as hierarchical *Condensed Graphs* of mobile components. These components represent tasks, or graphs of sub-components, that are made available for execution across a network. Condensed Graphs provide for a complete separation between the implementation of its components and their synchronization and communication. It can be used as a meta-language for 'glueing' together new and existing off the shelf components.

This flexibility extends to trust management with the integration of KeyNote into WebCom. WebCom application components do not use the KeyNote API and, therefore, need not be aware, in a programmatical sense, of the trust management system. WebCom acts as a form of reference monitor, using the contextual information in the Condensed Graph of an application to construct KeyNote queries to determine the authorization for the application components. This loose coupling of functionality and trust management leads to applications that are easier to develop, understand and maintain.

The paper is organized as follows. Sections 2 and 3 outline the KeyNote and WebCom architectures, respectively. Sections 4, 5 and 6 describe how KeyNote is integrated into WebCom by using KeyNote credentials to determine the authorization of X509 authenticated SSL connections. Section 7 sketches the implementation issues.

2 Trust Management

When a request from an untrusted principle (key) is made to a networked application to execute a particular action, then, authentication notwithstanding, the application must determine whether the key(s) that made the request is authorized. Authorization comes in the form of digitally signed public key credentials that bind public keys to the authorization to perform various actions. For example, Alice may hold a credential, signed by her manager's private key, binding her public key to her authorization to place

orders up to a value of £100.00. Alice's public key signs an order request to the purchasing application; her credential provides proof of authorization.

In practice, authorization is achieved by a collection of credentials that exhibit the necessary trust relationships between their keys. For example, we may trust Alice's public key for orders up to £100.00, if her manager's public key is trusted to delegate orders up to £100.00 (or more), and so forth along a delegation chain that ends in a key that is known to be appropriately trusted. Given a policy (public keys, trusted in known ways), and a collection of credentials, a network application must determine whether a particular public key is authorized to request a particular operation. The application may use a trust management scheme such as KeyNote [4] to determine whether the request is authorized, without the application having to know about how that determination is made. The KeyNote trust management architecture is depicted in Figure 1. A Public Key Infrastructure (PKI) is used to manage the credentials.

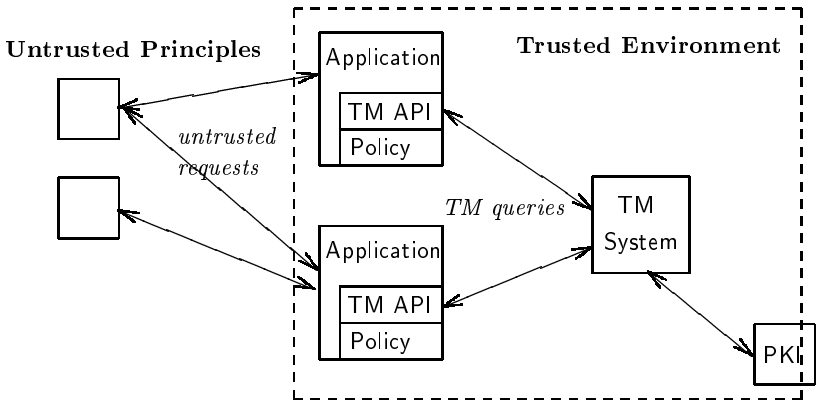


Figure 1: KeyNote Trust Management Architecture (From [3]).

The KeyNote architecture provides a level of separation of security policy authorization and application functionality. As a software engineering paradigm, techniques that support separation of concerns for security [4, 8], synchronization [12], real-time constraints [2], and so forth are desirable since they lead to applications that are easier to develop, understand and maintain. While KeyNote provides this separation at a conceptual level, calls to the KeyNote API must still be coded as part of an application. For example,

```
// given request to carry out an action
PCV= kn_query(..,keys, action, policy, credentials);
if (PCV=="true")
  {do the requested action}
else
  {reject the requested action}
```

While ensuring cohesive applications, there remains a coupling within the application between the functional and security concerns, that is, we do not have complete separation of concerns at the code level, since calls to the trust management API are intertwined with the functionality.

3 The WebCom Distributed System

The WebCom system [17] uses a variant of the client/server paradigm to distribute operations for execution over a network. The system uses implicit program parallelism, separates the application program from the underlying computation engine and is efficient yet compact. The heart of the WebCom system is the Condensed Graphs computational model that it employs [15, 18]. Applications are coded as hierarchical graphs which provide a simple notation in which lazy, eager and imperative computation can be naturally expressed. There are two types of distributable operation: nodes that represent atomic tasks and condensed nodes that represent subtasks encapsulated as subgraphs.

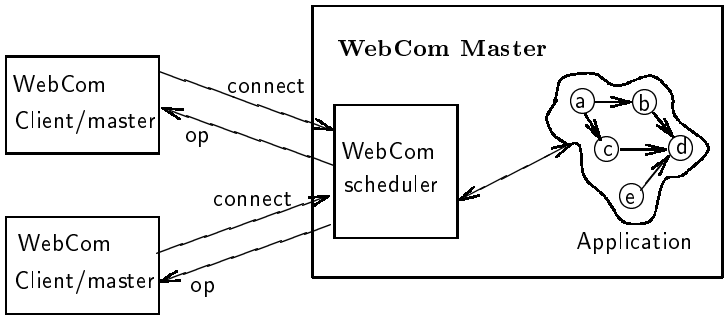


Figure 2: WebCom Architecture

The top-level architecture of WebCom, illustrated in Figure 2, consists of a master and an arbitrary number of clients. Clients connect to the master, which in turn assigns them operations for execution. Atomic operations may be scheduled to execute on any client. Condensed nodes (defining graphs)

may be scheduled to run on designated client-masters, which have the ability to schedule its component operations to further clients.

An advantage of developing distributed applications as Condensed Graphs is that their implementation (graph) can be coded independently of the underlying system and/or network architecture. Atomic operations are value-transforming actions and can be defined at any level of granularity, ranging from low-level machine instructions to mobile-code programs such as applets, COM objects or COTS components. Atomic operations need not address synchronization or concurrency concerns: such details are implicitly specified in the Condensed Graph and managed by WebCom. Therefore, WebCom provides for a separation of concerns at the code level, allowing a loose coupling between functionality and control.

EXAMPLE 1 (From [9]) Condensed Graphs are used to exploit parallelism in a computation and WebCom can schedule the computation across networks of workstations [17]. Figure 3 gives an example of a graph that schedules a distributed brute-force key search given known plain/cipher text. The key space is split into a series of intervals indexed as $0, 1, \ldots, maxindex$. Atomic operation

```
Int cr(Int interval);
```

searches a specified interval for the key. If found the key is returned, otherwise 0 is returned. Condensed node search is defined recursively and has a high degree of parallelism that can be exploited by WebCom which schedules its component cr operation to be executed on clients (and can schedule graph operation search to client-masters). Operation search is passed the initial value *maxindex*. By definition [15], the behavior of a condensed

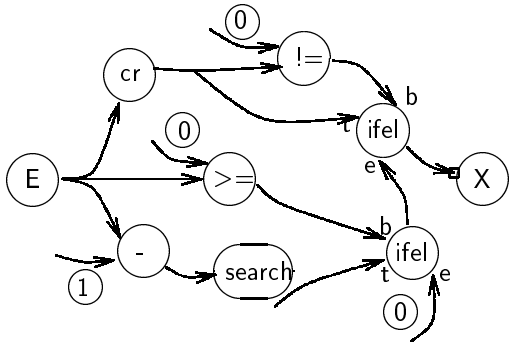
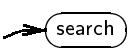


Figure 3: Recursive Definition of Condensed Node 

node such as search is constructed as a Condensed Graph with a single entry

node (E) and single exit node (X). Node ifel is an if-then-else operation, with boolean condition b and then and else clauses t and b, respectively. △

EXAMPLE 2 Condensed Graphs may also be used as a distributed job control language to describe application system scheduling requirements, such as work-flow. A clerk performs a prop operation to complete a purchase order and a manager executes an auth operation to inspect and authorize the order. The scheduling of this system is described by the condensed node order defined in Figure 4. A WebCom master schedules atomic actions

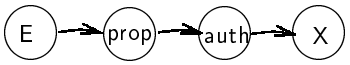
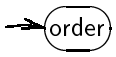


Figure 4: Definition of Condensed Node 

prop and auth to appropriate connected clients. For example, [13] shows how such operations can be implemented as Microsoft COM objects that are scheduled by WebCom according to the graph order. In this system, connecting clients specify the operations that they wish, or are willing, to have scheduled to them. In the next section we will describe how such clients may be authenticated and their authorization determined. △

4 Integrating KeyNote into WebCom

Figure 5 illustrates how the KeyNote trust management scheme (Figure 1) is integrated into WebCom by regarding WebCom as an application. The

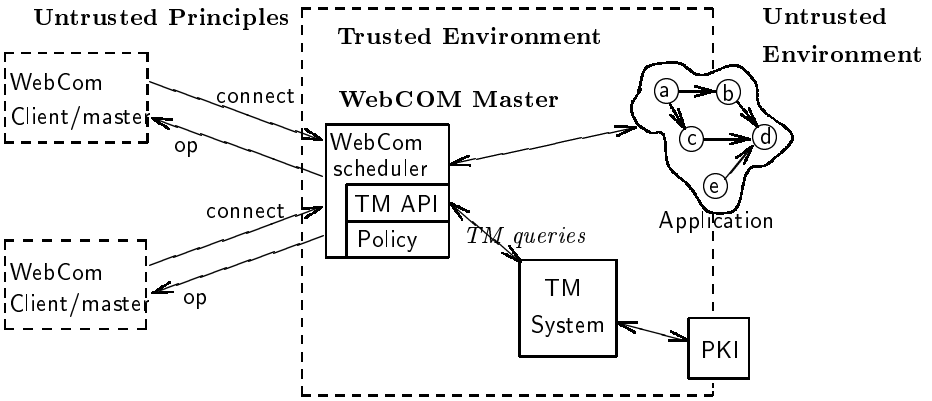


Figure 5: WebCOM-KeyNote Architecture

WebCom master authenticates its clients and uses their credentials to determine what operations it may schedule to them. Each WebCom client has a trust management architecture that is similar to the KeyNote architecture in Figure 1, authenticating the master and using the master's credentials to determine whether it is authorized to schedule the operation. We selected KeyNote because of its simplicity and expressiveness. KeyNote provides a simple notation for specifying both local security policies and credentials that can be sent over untrusted networks.

EXAMPLE 3 For this presentation we assume that there is just one root public key Kwebcom that is trusted to delegate authority related to the WebCom application. This is specified by the following KeyNote trusted policy credential.

```
KeyNote-Version: 2
Comment: Unconditionally delegate trust for the
         WebCom application to the key Kwebcom
Authorizer: POLICY
licensees: "Kwebcom"
Conditions: app_domain=="WebCom";
```

Note that for the purposes of illustration in this paper we use short simple names to represent public keys rather than encoding them as proper cryptographic keys. It is assumed that the Internet Assigned Numbers Authority (or some other suitable authority) will provide a registry of reserved app_domain names that provide the name of the application domain for which the credential is defined [4]. △

5 WebCom Master Authorization

WebCom masters schedule operations to be executed by WebCom clients. Some of these operations may access local resources on the client and therefore the WebCom master must prove that it has the authority to do so by furnishing the appropriate credentials to the client. Figure 6 illustrates how, in the current prototype, X509 certificates are used for authentication and KeyNote credentials are used for authorization:

1. The connecting WebCom client establishes an SSL connection with the master, and in the process, the master presents an appropriate X509 certificate chain to its public key K_{master}. If the protocol run is successful then the client knows that it is communicating with K_{master}.

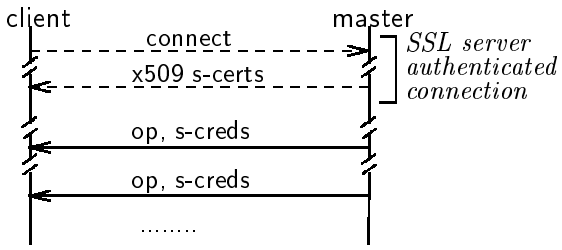


Figure 6: Master Authentication Message Sequence

2. The master schedules operation `op` to the client over the SSL connection and sends the necessary credentials that prove that K_{master} is authorized to schedule `op`. The WebCom client uses KeyNote to determine if the schedule is authorized, given the credentials of the master.

When a WebCom client uses KeyNote to determine whether it is safe to execute a scheduled operation or action, it must specify the circumstances of the query. These circumstances are described as the *action attribute set* of the query. This is a list of attribute names and value pairs that are agreed between the application writers and the writers of the related credentials. In addition to the existing attribute `app_domain`, two action attributes identify the circumstances of a WebCom KeyNote query:

- Attribute name `ROLE`, which can have, for example, values `schedule` or `execute`, indicating whether the principle is authorized to schedule or execute.
- Attribute name `NODE`, which can have values identified by the operations that can be scheduled/executed.

Note that a code-signing approach such as that used by Java [10], would not provide sufficient security infrastructure support for WebCom. A WebCom master schedules more than just code: it schedules mobile computations that are comprised of tasks and their inputs. A client must determine whether it should trust the master for the task it schedules along with the inputs to the task that the master provides and the subsequent output that is returned to the master.

EXAMPLE 4 Consider again Example 1. Assume a WebCom master owns public key Kmike and has been given the following KeyNote credential, signed by (the private key of) Kwebcom:

```
KeyNote-Version: 2
Comment: Kwebcom delegates scheduling authority to Kmike
Authorizer: "Kwebcom"
licensees:  "Kmike"
Conditions: app_domain=="WebCom" && ROLE=="schedule"
            && (NODE=="cr" || NODE=="search");
Signature: ..<signed by private key of "Kwebcom">..
```

This credential authorizes `Kmike` to carry out an operation if the C-like expression in the `condition` evaluates to true, given the attribute values as defined in the action attribute set of the operation requested.

We assume that a suitable X509 certificate for Kmike is also available. When operation `cr` is scheduled to a client, by an authenticated `Kmike`, the client queries KeyNote, with action attribute set

$$\begin{aligned} \texttt{app_domain} &\leftarrow \texttt{"WebCom"} \\ \texttt{ROLE} &\leftarrow \texttt{"schedule"} \\ \texttt{NODE} &\leftarrow \texttt{"cr"} \end{aligned}$$

and action authorizer `Kmike`. Given the above credential and the policy credential from Example 3, KeyNote returns `true` and the WebCom client executes the operation.

KeyNote can support delegation chains and sophisticated trust relationships. For example, `Kmike` can delegate the authority to schedule to `Kmaude` only `cr` operations, but not to to delegate this authority any further.

```
...
Authorizer: "Kmike"
licensees:  "Kmaude"
Conditions: NODE=="cr" && _ACTION_AUTHORISER=="Kmaude";
...
```

The KeyNote reserved attribute `_ACTION_AUTHORIZERS` a pre-defined attribute of the action attribute set, defining the names of principles directly authorizing an operation [4]. The credential above uses this attribute to prevent further delegation.

Any client will execute `cr` operations scheduled by `Kmaude`, but will not accept `search` operations. Given a collection of credentials, the keynote query searches the credential delegation graph for the appropriate paths that connect the trusted keys (policy) to the action authorizer (requesting key), and whose conditions are satisfied according to the action attribute set. The reader is referred to [4] for further details on how to specify KeyNote credentials. △

6 WebCom Client Authorization

WebCom client authorization is done by the master to determine whether the client has the necessary authorization to execute certain operations whose inputs or outputs may be security critical. The trust architecture for the WebCom master is given in Figure 5. Figure 7 illustrates how, in the current prototype, X509 certificates are used for client authentication and KeyNote credentials are used for authorization. Master certificates and

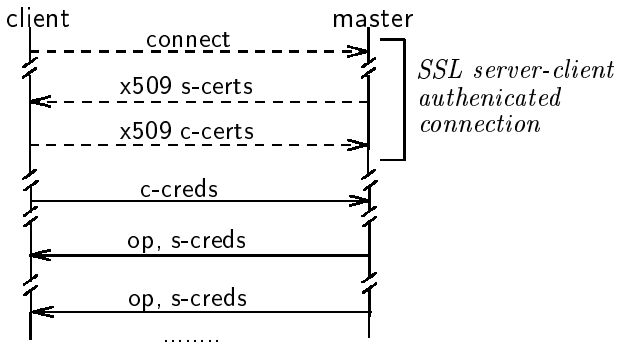


Figure 7: Master and Client Authentication Message Sequence

credentials are used as in the previous section. However, clients must now present their credentials when the secure connection is first established if they wish to have operations scheduled to them.

A WebCom master maintains a list of clients that are currently connected and available to be scheduled operations. Before scheduling an operation to a client, the master must determine if the client is authorized to execute the operation. This can done by the master making a query to KeyNote with an action attribute set based on attributes `ROLE` and `NODE`, and by the action authorizer which is the client key. If the client is not authorized to execute any of the operations scheduled by the master then the SSL connection can be terminated.

Connecting WebCom clients declare themselves available to execute a range of possible scheduled operations. The WebCom master uses KeyNote to *search* the database of the credentials of all connected and available clients for an action authorizer (client key) that has the authorization to execute the particular operation (as specified by the action attribute set). This search operation is an extension to the standard KeyNote API.

Example 5 Continuing Example 1, suppose that there are two WebCom

clients, identified by public keys `Kcharles` and `Kclare`. `Kcharles` is authorized to execute `cr` operations.

```
...
Authorizer: "Kwebcom"
licensees:  "Kcharles"
Conditions: app_domain=="WebCom"
            && ROLE=="execute" && NODE=="cr";
...
```

`Kclare` is authorized to execute or schedule `cr` and `search` operations, that is, she has the authority to operate as a client-master.

```
...
Authorizer: "Kwebcom"
licensees:  "Kclare"
Conditions: app_domain=="WebCom"
            && _ACTION_AUTHORISER=="Kclare"
            && (ROLE=="schedule" || ROLE=="execute")
            && (NODE=="cr" || NODE=="search");
...
```

We assume that appropriate X509 certificates for these keys are available for authentication purposes.

When the clients connect (and are authenticated), the WebCom master adds their credentials to its client credential database. When the master is ready to schedule operation `cr`, it sends a search query to KeyNote, given action attribute set `(ROLE←"execute"; NODE←"op")`. This new KeyNote search function searches the client credential database for action authorizers (keys) that are authorized, and in this case could return either `Kcharles` or `Kclare`. If the operation `search` is to be scheduled, then only `Kclare` could be returned by the KeyNote search. △

Example 6 A WebCom master (`Kserver`) running on a trusted server is authorized to execute an `order` operation and schedule its components (Example 2). We assume that the `order` operation may have been scheduled to `Kserver` from some other WebCom master.

```
...
Authorizer: "Kwebcom"
licensees:  "Kserver"
Conditions: app_domain=="WebCom"
            && _ACTION_AUTHORISER=="Kserver"
            && ((ROLE=="execute" && NODE=="order")
              ||(ROLE=="schedule"
                  && (NODE=="prop" || NODE=="auth")));
...
```

WebCom clients Alice (`Kalice`) and (`Kbob`) are authorized to execute `prop` and `order` operations, respectively.

```
...
Authorizer: "Kwebcom"
licensees:  "Kalice"
Conditions: app_domain=="WebCom"
            && ROLE=="execute" && NODE=="prop";
...
```

```
...
Authorizer: "Kwebcom"
licensees:  "Kbob"
Conditions: app_domain=="WebCom"
            && ROLE=="execute" && NODE=="auth";
...
```

When `Kalice` connects, requesting `prop` operations, she presents her credential(s). Her authorization is validated and the master schedules the execution of `prop` on her client system. Note that in this example, `Kalice` neither offers, nor has the authority, to execute `auth`. Similarly, Bob connects, offering to execute `auth`, which is scheduled. The WebCom master uses the same SSL secured connection to send operations to execute, and receive results from, the WebCom clients.

This is a example of a simple static separation of duty policy, provided by a combination of credentials and Condensed Graphs. We are currently exploring how dynamic separation of duty KeyNote support for credentials specifying threshold signatures might be transparently supported within our framework. △

7 Implementation

A number of working prototypes that use Condensed Graphs have been developed, demonstrating it usefulness as a general model of computation. Prototypes include a sequential Condensed Graph interpreter [15]; a PVM application programming interface for a cluster [16]; WebCom [17] referred to in this paper, and a specialization of WebCom that supports Microsoft COM objects [13].

To date, we have integrated the trust management support scheme described by this paper into the existing Java-based WebCom system described in [17]. The integration was straightforward and the current prototype uses existing packages where possible:

- The JCSI [11] package provides cryptographic, X509 certificate and SSL support. KeyNote credentials are constructed using the keys extracted from their corresponding X509 certificates.
- The existing KeyNote API was extended by the addition of a search query function, as outlined in Section 6.
- The current reference implementation for KeyNote is implemented in C. Java Native Interface is currently used to provide a Java API to KeyNote. It is planned to eventually replace this with a Java implementation of the Keynote Interpreter.

8 Discussion and Conclusion

KeyNote credentials are used to determine the authorization of X509 authenticated SSL connections between WebCom masters and clients. Client credentials are used by WebCom masters to determine what operations the client is authorized to execute; WebCom master credentials are used by clients to determine if the master had the authorization to schedule (trusted) the mobile-computation that the client is about execute; this authorization covers not just the scheduled code, but also its input data and output.

The relationship between the WebCom trust management system and local operation system protection mechanisms is not addressed in this paper. For example, in what protection domain should a client execute an operation that has been scheduled by an authorized master? In [9] we propose an abstract protection model for Condensed Graphs; our integration of KeyNote into WebCom can be regarded as one step towards implementing this protection model.

We use KeyNote to provide trust management for WebCom because of its ability to support expressive and fine-grained authorization and delegation policies. KeyNote Credentials are typically short, yet expressive, and are, therefore, not expected to contribute significantly to the communication overhead between clients and masters. For the purposes of illustration, only simple examples are presented in this paper. The reader is referred to [5] for a discussion of the expressiveness of KeyNote.

The KeyNote support in WebCom provides enhanced separation of concerns between the security, functionality and synchronization of applications. In addition to KeyNote providing separation between trust management and functionality at the conceptual level, we also have complete separation at the code level. Functional components such as `prop` and `auth` (Example 2)

can be coded independently of security concerns; security concerns are expressed independently in terms of a credential based policy, and the Condensed Graph specifies the synchronization and control concerns between these components. Only operation identifiers couple these concerns. Thus, trust management in WebCom acts as a wrapper for operations implying that operations may, if desired, be treated as untrusted since we do not require the application programmer to make explicit calls to KeyNote. We think of this as an architecture neutral glue for trust management.

The implementation described in this paper expresses security at the granularity of operation identifiers such as `prop`, `order`, and so forth. However, we expect that it will be straight forward to generalize this to include reference to the attributes used to pass input and output to and from these operations. During execution, the nodes in a Condensed Graph are represented as a triple: input parameter bindings, output binding and the operation applied [15]. These attributes can be referred to within credentials and form part of the action attribute set during a KeyNote query or search. With such an extension, Example 2 could be generalized to support credentials that authorize Bob to validate orders up to some limit. This is a topic for future research.

WebCom masters may promote clients to become client-masters by passing condensed nodes (for example `search` from Example 1), the components of which are subsequently scheduled by clients of the promoted client [14]. We are currently extending the WebCom trust management architecture to exploit promotion. This uses credentials to control whether masters have the authority to promote clients, and whether clients, in turn, have the authority to be promoted. Writing credentials that specify this is straightforward, and can be done by enlarging the domain of attribute `ROLE` to include values `promoter` and `promotee`. In addition to promoting a client, the master must write the necessary credentials to delegate to the promoted client the authority to schedule the operations it will be managing.

We are also currently porting our implementation to the existing WebCom application that supports Microsoft COM objects [13]. This would be particularly useful since it will provide the basis of a trust management glue for existing COTS components, such as spreadsheets, databases, word-processors, and so forth.

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