CeNet— CAPABILITY ENABLED NETWORKING: TOWARDS LEAST-PRIVILEGED NETWORKING

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

In today's IP networks, any host can send packets to any other host irrespective of whether the recipient is interested in communicating with the sender or not. The downside of this openness is that every host is vulnerable to an attack by any other host. We observe that this unrestricted network access (network ambient authority) from compromised systems is also a main reason for data exfiltration attacks within corporate networks. We address this issue using the network version of capability based access control.

We bring the idea of *capabilities* and capability-based access control to the domain of networking.

CeNet provides policy driven, fine-grained network level access control enforced in the core of the network (and not at the end-hosts) thereby removing network ambient authority. Thus CeNet is able to limit the scope of spread of an attack from a compromised host to other hosts in the network.

We built a capability-enabled SDN network where communication privileges of an endpoint are limited according to its function in the network. Network capabilities can be passed between hosts, thereby allowing a delegation-oriented security policy to be realized. We believe that this base functionality can pave the way for the realization of sophisticated security policies within an enterprise network.

Further we built a policy manager that is able to realize Role-Based Access Control (RBAC) policy based network access control using capability operations. We also look at some of the results of formal analysis of capability propagation models in the context of networks.

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CHAPTER 1

INTRODUCTION

1.1 Thesis Statement

Our thesis is: A network version of capability-based access control can realize a more secure network by allowing only explicitly allowed communications, thereby removing the ambient authority present in the current network architecture. It further enables delegation oriented policies to be realized within an enterprise network.

We tested our thesis by building a capability enabled SDN network where the communication privileges of an endpoint are limited according to its function in the network. In pure capability mode, hosts interact with each other using the capability APIs and delegation model. On top of this pure capability mode, we built a policy manager that is able to translate a Role Based Access Control (RBAC) policy into capability operations, thereby realizing RBAC access control built into the network core. Rights propagate through a capability system through well-defined graph transformations, which gives us the ability to strongly reason about the correctness and security properties of the policy realized by that system.

1.2 Motivation

One fundamental cause for the increase in cybersecurity threats such as malware is the inability to secure modern operating systems and applications. Specifically, the traditional approach that security can be achieved by deploying up-to-date patches on the end host is no longer valid and cannot resist a well-sponsored, targeted attack. Attackers use a set of automatic bug-finding tools which have demonstrated the possibility of discovering zero-day vulnerabilities in every layer of computer system: web browsers, file systems, network protocol stacks, operating system call interface, hypervisors, firmware of network and graphic cards, trusted platform modules, and even System Management Mode (SMM

[1]) [1, 2, 3, 4, 5] of the processor. Despite continued advances in host and application defenses [6, 7, 8, 9], and in software testing and verification [10], the complexity of network stacks, operating system kernels, language runtimes, and user applications suggests that endpoint security vulnerabilities will continue to exist.

Once discovered, endpoint vulnerabilities can be exploited to compromise vulnerable systems through a variety of "distribution" mechanisms: spear phishing, social engineering, drive-by downloads, email attachments, etc. Once compromised, infected hosts install additional malware in the form of key loggers, back doors, and command-and-control software [11]. This malware in turn allows attackers to steal credentials and perform reconnaissance of the compromised host and its network environment, thus enabling lateral movement to other hosts within the organization [12]. This exploratory process might continue for an extended period of time, while "data of interest" is being exfiltrated by the attackers via the installed back doors [13]. For example, according to a 2013 data breach report by the Verizon RISK team [11], 62% of breaches remain undiscovered for several months, while in 36% of cases data ex-filtration occurs within hours of an initial compromise.

While endpoint vulnerability might be the beachhead for the common attack pattern described above [14, 15], we note that the network presents the second fundamental "enabler" exploited by attackers. First, the malware distribution mechanisms listed above by design circumvent network firewalls, which still represent the state-of-the-art network periphery protection, by delivering their malicious payload to an endpoint that is inside a trusted domain. (Note that this is true whether that be host-based firewalls or firewalls deployed at the edge of an enterprise or datacenter network.) Once executing on an endpoint inside the trusted domain, malware essentially has *unrestricted network access*: Firewall rules commonly allow connectivity to the outside world, thus allowing malware to create back doors and command-and-control channels to allow attackers to reach into the protected domain and export stolen data. Unrestricted access within the protected domain enables the discovery and exploitation of other vulnerable systems.

Based on the above observations, it is evident that operating system defenses alone

[1]SMM mode is intended for use only by system firmware, not by applications software or general-purpose systems software.

are fundamentally insufficient to address the cybersecurity problem. When host defenses are compromised (and history suggests it is a question of *when*, not *if*), the compromised host will have unfettered network access. We note that this unrestricted access represent a network version of *ambient authority* in operating systems [16] in which an application runs with all the authority of the invoking user.

This state of affairs suggests that current network defenses suffer from two fundamental deficiencies:

- The inability of the network to constrain network interaction based on policies that define acceptable patterns of communication.
- When communication is constrained, network mechanisms that enforce such constraints are coarse grained and divorced from the nuanced needs of network services and applications.

We argue that to address current cybersecurity concerns, what is called for is a network architecture that inherently supports three security related primitives:

- *Least privileged communication*, where the communication capabilities of an endpoint is limited according to its function in the network. In other words the network core enforces policy driven access control, thereby removing the ambient nature of network.
- To have these privileges be determined by *fine-grained application-driven policies*.
- *Strong isolation* between arbitrary and dynamically created groups of entities, where the communication within a group is governed by a common set of policies and the entities have a shared trust domain.

Note that we are not suggesting that network defenses by themselves will be sufficient to prevent cyber attacks. Indeed, *defense in depth* principles suggest that current best-practice host-based protection mechanisms, e.g., those based on lightweight virtual machine containers [7, 8, 17, 6], be used together with network-based defenses. We are, however, arguing that more sophisticated network defenses and network defenses that allow for more meaningful interaction between endpoints and the network are necessary to address the problem.

1.3 Our System

Towards this vision, this thesis presents our work on *Capability Enabled Networking* (CeNet). In CeNet the network-interaction between nodes are explicitly controlled via capabilities that allow network interactions to be governed by fine grained policies.

A key feature of CeNet is the clean separation of the specification and semantics of such policies and the enforcement thereof. CeNet assumes an underlying SDN fabric controlled by the CeNet capability system. The combination of CeNet capability system and SDN fabric removes network ambient authority by allowing only a policy driven *access* in the network. The policies based on which the network-core enforces access control are however determined by applications running on capability-enabled nodes (within the limits of their authority) that operate outside the network proper. This separation mirrors the same partitioning of functionality in capability-enabled operating systems where the kernel enforces capability restrictions, but the policies of collaboration are determined by applications [16].

While we envision our work to be more broadly applicable, for this thesis we specifically limit our focus to SDN substrates under single administrative control such as datacenters and enterprise networks.

We make the following contributions:

- We illustrate how the generic capability access control model applies to a principled approach to network security.

- We present the design of CeNet, a capability-enabled network architecture that enables strong isolation and least-privileged communication driven by fine-grained application policies.

- We demonstrate the practicality of our approach by showing how CeNet can seamlessly incorporate legacy nodes through capability-aware proxies.

- We present a prototype implementation and evaluation of the CeNet primitives.

- In search of more expressive policies, we explore the utility of combining other access control models with capability-based access control.

- We use the *take-grant(tg)* model used to formally analyze the propagation of rights in a capability system, and how formal models can be leveraged to strongly reason about the correctness of the security properties of the system in a network context.

1.4 Threat Model

CeNet is designed to operate in a modern datacenter or enterprise network environment. We assume that hosts can be attacked at any time, with and without cooperation of malicious users. The malicious code will try to use the compromised host for finding and exploiting remote vulnerabilities in all hosts reachable over the network. CeNet does not trust anything on the end hosts.

CeNet assumes that the SDN infrastructure—switches and the controller—is trusted. CeNet does not protect against attacks on the SDN infrastructure. In a virtual datacenter environment, CeNet extends its trust to include software SDN switches in the end hosts.

CeNet provides policy-driven, fine-grained network-level access control enforced in the core of the network (and not at the end-hosts), thereby removing network ambient authority. Thus CeNet limits the spread of an attack from a compromised host to other hosts in the network.

1.5 Assumptions and Context

CeNet assumes a fixed network where hosts are not mobile. This is a reasonable assumption in a network where security is an important goal.

The context of this thesis is to specifically address the ambient authority present in a single-prefix switched local network (consisting of only switches and hosts). Without CeNet these link-layer switches forward packets based on MAC addresses using their self learning capability - the downside of which is that it allows a host to send packets to any other host in the local network.

1.6 Thesis Structure

The following provides a brief outline of the general structure of the rest of this document:

In *Chapter 2*, we describe the idea and philosophy of the capability model. We touch upon the concepts of *ambient authority*, *principle of least authority (POLA)*, *object capa-*

bilities, sample systems, etc. Further, we give an outline of our interpretation of how this model translates to a network scenario.

In *Chapter 3*, We describe the core architecture of our SDN-based, capability-aware network. Further, we present the capability model based APIs to be used by the end hosts to interact with the controller to realize a network devoid of ambient authority, its bootstrapping, use cases, implementation, and evaluation.

In *Chapter 4*, we describe how our network is able to enforce access control according to a high-level policy by translating it into capability operations. We describe an example scenario, implementation, and evaluation of this.

In *Chapter 5*, we describe the *take-grant (tg) model* which is a classic model used to analyze the propagation of authority in a capability system. Further we present the major results from the formal analysis of this model. We present an example scenario on how rights propagate through a network capability system using well-defined graph transformations of the *tg* model. We conclude that this gives us the ability to strongly reason about the correctness and security properties of the policy realized.

The capability model has a rich history of research and in *Chapter 6* we summarize the relevant related works on which this thesis is built.

In *Chapter 7* we summarize our contributions and suggest possible extensions to this work.

CHAPTER 2

CAPABILITY PHILOSOPHY

In this chapter, we describe the principles and philosophy behind the capability model. We touch upon the concepts of *ambient authority*, *principle of least authority (POLA)*, *object capabilities*, etc. This is followed by a brief overview of a few systems making use of the aforementioned concepts from other domains like operating systems and programming languages. Further we give an outline of our interpretation of how this model translates to a network scenario.

2.1 Capability Model

Capabilities [18] are unforgeable authority-wielding references (tokens). In this thesis, we will use the word *authority* to mean the ability of a *subject* to access a *resource (object)*. Access to a resource by a subject in a capability system is allowed by virtue of that subject possessing the capability to that resource. In other words, access requests in a capability system can only be authorized by capability presentation. The total authority a subject has in a capability system is conveyed by the capabilities it holds and the transitive closure of what the possession of those capabilities permits. Subjects have no ambient authority. Capability systems restrict the authority of a subject by simply limiting the capabilities it holds. Isolation between two untrusted subjects may be achieved granting them non-overlapping capabilities.

Some salient features of capability model are described below:

- *No designation without authority*. Capabilities are a means of realizing *authorization-based access control*, which contrasts with the typical *identity-based access control*, which uses Access Control Lists (ACLs) to specify permissions. The ACL model presumes some namespace, such as the space of filenames, that subjects use to designate resources. This namespace must be separate from the representation of authority [19] in an ACL system. Miller claims that this separation (designation problem) [19] is arguably one of the deepest problems in computer security. Capabilities combine into one entity the name of the object they are referring to and the permissions required to access that object.

A *deputy* is an entity that must manage authority coming from various sources. A *confused deputy* can be tricked into wielding its authority inappropriately. Aforementioned atomicity (grouping the name of the referred object and the permissions required to access it) provides a strong tool for avoiding confused deputy problem [20] as it leaves no room for ambiguity about what authority is being exercised during a request to access a resource. Thus the Capability model simplifies the implementation of trusted systems by unifying addressing and protection mechanisms [21].

- *Principle of least privilege [22].* This principle states that every entity should operate using the minimal set of privileges necessary to complete its task. Delegation is a key idea in the capability model that facilitates this principle. A subject can easily delegate part of its authority to another subject by passing on a capability.

- *Only connectivity begets connectivity [23].* The only ways to get a capability in a capability system are by introduction, endowment (construction) or parenthood (creation).

A capability system as considered in this work can represent the computer system as a graph of subjects connected with edges that represent rights, or *capabilities*. The labels on the edges indicate the type of the capability (explained in the following chapter).

The object-capability model [24] replaces the traditional subject-object dichotomy with the notion of objects from programming languages that function as both subjects that initiate access and objects which are targets of action [25]. In such systems capabilities are references to objects. In such a system capabilities allow objects to interact with each other, e.g., invoke functions, send messages, and exchange rights.

In a capability system, the only way to access a resource is to invoke a capability, or a reference to a capability, that enables access to a particular object. In our context *invoking a capability* means invoking operations via our APIs (explained in the following chapter) with the capability (designating the resource) as an argument.

Multiple formulations of the capability model exist [18, 26, 27, 28, 29, 30]. At a high level, the capability model can be captured with three core operations: *create*, *grant*, and *revoke*. These operations provide rules for mutating the protection graph, i.e., creating new objects, adding new edges to the graph, and removing existing edges. The create operation allows any object (with appropriate capabilities) to create a new object. The new object is isolated by default. It can be accessed by its creator via a capability returned by the create operation. The grant operation enables transfer of rights from one object to another. The grant operation takes an existing capability as an argument and passes it to the grantee object. Naturally, the grant operation requires that the granter had a capability to access the grantee. Finally, the revoke operation removes the rights from the object.

Capabilities provide a foundation for both *discretionary* and *mandatory access control*. Capabilities travel only along the edges of the capability graph. By default, all subjects are created with no authority and receive all rights as capabilities from other subjects.

Capability access control [18, 26, 24] provides a foundation for constructing secure systems in the face of persistent exploitable vulnerabilities and untrusted components [31, 16]. In the face of exploitable and untrusted components, practical security can be achieved by partitioning a large, untrusted system into small pieces that have minimal rights. Capabilities are designed as a mechanism that

1. helps minimizing authority of individual applications in a complex environment with a large number of dynamic principals; and
2. provides a formal control model that defines interactions between untrusted components and outcomes of untrusted computations.

The rules of the capability system limit the exchange of capabilities (flow of rights) across objects. The capability models are shown to be *decidable*: by looking at the initial distribution of capabilities it is possible to decide the upper limit of authority for individual subjects in face of all possible transformations to the system and future exchanges of rights [26]. By controlling the initial distribution of capabilities, it is possible to ensure *confinement* [30]. Confinement in the context of capability systems can be stated as the ability of the system to limit the propagation of authority. This property can be used to create runtime compartments satisfying certain security properties as given in the EROS [30] work.

The capability model contrasts with Mandatory access control (MAC) in the following way [16]:

- *Interest of whom* - MAC caters to the interest of an administrator, whereas capabilities cater to the interest of the user or application.
- *Policy source* - MAC rules are specified in global policy files whereas policy is embedded in application code for capabilities (capabilities are quite good in allowing code to express policy)
- *Granularity* - MAC suffers from coarse granularity (due to broad sweeping policies). Consequently, it is very hard to isolate rights, whereas capabilities sometimes help in this scenario.

As observed by Miller in one of his talks, early system security research was focused only on the needs of individual corporations which had central control and which saw delegation and propagation of delegation as a problem. Today, decentralized cooperation between organizations and individuals is becoming increasingly prevalent, and delegation may be better suited to achieving this. But we should do delegation in ways of least authority. Literature about capabilities argues that the excessive authority implicitly granted by traditional access control mechanisms (which does not support least authority delegation) is the reason behind the massive prevalence of security vulnerabilities [32]. The object-capability paradigm, with its pervasive and extensible support for the principle of least authority, enables mutually suspicious interests to cooperate more intimately while being less vulnerable to each other [32].

2.2 Example of Capability Systems from Other Domains

Capability model has been used in multiple domains like operating systems and programming language :

- **Operating systems**: Many systems claim strong security benefits, just by removing ambient authority. In most cases this just means disallowing global name-spaces for user processes and allowing them to operate only on explicitly granted file descriptors (capabilities). Some examples are Polaris [33], Capsicum [34] and Plash [35].

Another system based on capability model, SEL4 [36] has formal proofs that it can correctly enforces high level security properties like integrity and authority confinement.

- **Programming languages**: Various object-capability languages like E, Joe-E, Emily, and W7 are used to create web mashups that use contents from untrusted third parties, while allowing rich interactions among the third party contents and also between embedding page and third party contents. The aforementioned object-capability languages are restricted (specialized) subsets of larger programming languages, intended to provide capability safety by eliminating language constructs (e.g., static variables) that could leak authority.
- **Networking**: Generic capability access control model has not been applied to network access control. **This thesis is the first work in this direction.**

2.3 Capability Principles Applied to Networks

The key principle enabling security in capability systems is the ability to construct small, isolated computations that operate on a minimal number of isolated resources. By minimizing the authority of individual computations, a capability system provides a guarantee that even if part of the computation is compromised, the possible impact is minimal and limited to the set of objects reachable through capabilities. (Note that the citations in the emphasized portion in this section are not capability systems, but systems with certain desirable security properties. The intention is to point out that a capability based network can realize those properties.)

- **Isolation by default.** Capability systems ensure that objects are isolated by default. Objects are created with no implicit rights to access any resource in the system.

  In a capability controlled network all communication is initially blocked [37]. Nodes receive individual capabilities to open network connections. This model encourages careful distribution of rights and significantly reduces the attack surface compared to traditionally "open by default" systems and networks.

- **Fine-grained computations and resources.** To ensure that authority of individual computations is minimal, capability systems rely on fine-grained isolation of computations and resources. The ability to create fine-grained computations is based on support from underlying hardware and software platforms.

In a networked system, isolation can be provided at the granularity of physical or virtual machines. Isolation at the level of individual physical machines, even though fairly coarse grained, is a big improvement over the traditional state of the art in network security—granularity of an entire network. Virtualization is a de facto part of the system stack in datacenter environments and is also increasingly being used for fine-grained isolation in end systems [7, 8, 17, 6]. As such it provides a lightweight, fine-grained, and practical mechanism for running computations and hosting data objects in isolation. Combined with fine-grained network isolation, virtualization becomes a foundation for least-privilege datacenter and enterprise environments.

- **Fine-grained delegation of rights.** The capability model is designed to extend fine-grained isolated environments with the flexible, dynamic, and fine-grained management of rights. In a capability system, delegation is a transfer of rights from one object to another. Being able to selectively grant subsets of their rights, applications naturally minimize the authority of individual computations. To isolate itself from potentially untrusted code, a capability-enabled application follows the following pattern: The application creates an isolated execution environment. This environment receives a minimal set of rights required to complete the computation. The result of the computation is obtained through a narrow, well-defined result protocol. Even if part of the computation is compromised, the effect of the compromise is confined by the capability system and underlying isolation mechanisms.

  In a capability-enabled network, fine-grained delegation of rights guarantees that nodes receive minimal rights to access network resources, e.g., constrained to specific computational resources, or hosts servicing data objects, thus preventing access to other parts of the network and obstructing multistage attacks [38].

- **Local policy decisions.** In contrast to traditional mandatory access control models, capabilities do not rely on the notion of a centralized access control policy. Instead, capabilities enforce a hierarchy of access control restrictions. High-level policies define security guarantees and information flow across coarse-grained parts of the system. At the same time, applications have complete freedom to enforce their local access control decisions on the subset of resources they reach through capabilities. Applications are encouraged to combine the principle of fine-grained compartmentalization with their internal logic to minimize the authority of individual computations.

The hierarchical nature of capability access control ensures that in a capability-controlled network, it is possible to securely split resources across multiple tenants, but at the same time guarantee that each tenant has freedom to enforce local security policies inside its isolated compartment. Natural integration of access control decisions and application logic allows a maximal realization of the principle of least authority. The access control policy remains encoded inside the application logic, not at the level of system interface [39, 40]. Networked applications are free to make local policy decisions on a per-request basis — a degree of dynamism and granularity that is simply not available in traditional access control frameworks. Further, the ability to make local policy decisions solves many access control management problems inherent to the nonhierarchical access control models [39, 41].

- **Capability design patterns.** The basic capability model enables confinement by completely isolating parts of the protection graph [30]. Complete isolation is insufficient in a practical system. Parts of the system need to communicate. The true power of capabilities is revealed when the base capability model is extended with a small set of trusted objects that serve as security-enforcing abstractions [24]. Similar to design patterns in object-oriented languages, trusted capability objects implement *object capability patterns* [24]—composable access control abstractions. Object capability patterns are designed to enable security guarantees for mutually mistrusting components [24, 42]. A number of object capability patterns exists to implement a variety of access control patterns, e.g., one-way information flow (diode pattern [24]), revocable rights (caretaker pattern [24]), applying a specific policy to all capabilities reachable from the initial capability (membrane pattern [24]), and responsibility tracking (Horton protocol [42]).

  In a capability-controlled network, a set of well-designed access control patterns that have well-understood behavior and guarantees enable scaling of secure protocols in *the face of complex, mistrusting parties.*

2.4 Summary

In this chapter, we looked at the principles and philosophy behind capability model. Further we gave an overview of our interpretation of how this model would translate to a network scenario.

CHAPTER 3

CAPABILITY NETWORK ARCHITECTURE

In this chapter, we describe the core architecture of our SDN-based, capability-aware network. We present the capability model-based APIs to be used by end hosts to interact with the controller to realize a network devoid of ambient authority, its bootstrapping, use cases, implementation, and evaluation.

3.1 Our Approach

In CeNet we use the fundamental properties of capability systems, discussed in the previous chapter, as a foundation to realize strong network security. We think of *policy-driven access control* being built into the network so that only permitted interactions are allowed by the network core.

This contrasts with traditional network access control mechanisms in the following manner:

- Firewalls
  - Usually present only at the network periphery. Per host firewalls can provide fine grained access control within the local network, but they have certain limitations listed below.
  - High-level policy is interpreted by network admin and manually translated into firewall specifics. This limitation is applicable to both peripheral and per host firewalls.
  - For per-host firewalls — it is difficult to make changes to an implemented policy as ACLs are distributed at various places.
  - For per-host firewalls — it is difficult to reason about the type of access allowed by the network, since the policy is implemented in such an ad hoc and distributed fashion.

  - For per-host firewalls — if the OS on a host is compromised, it no longer has control over the attacker probing the internal network via arbitrary packets, whereas in our approach even if an end-host OS is totally compromised, networks still enforces access control.

- VLAN

  - Creates smaller ambient networks. The inherent ambient authority increases the potential attack surface for a host. It also increases the damage when things are compromised at a host.

We start by considering hosts in a network as fundamental objects and go on to identify other objects which signify ownership, reachability, and delegation to hosts in the network. We develop the model by identifying a set of operations (based on the capability model) that allow applications running on hosts to collaborate and utilize the network in a secure manner.

Our host side control path APIs provide the means for hosts to receive rights over other network objects. One particular type of right (called a flow capability) gives a host the permission to send data packets to another specific host. As a result of the control interactions by which a sender received a flow capability to a specific receiver, the network is programmed to steer data packets containing flow capabilities to the appropriate destination host.

Further, we have mechanisms to bootstrap hosts with initial capabilities. We have a bootstrap policy manager which helps to easily specify a coarse-grained network policy to start with.

We recognize the following benefits of the capability model in a network scenario:

- Allowing the network owner to specify a coarse grained policy at the top level.

- Allowing a level of dynamism, decentralization, and evolution of policies within the aforementioned protected domains via the concept of delegation. This can be done via our host side APIs, which interact with the capability system.

- The ability to reason about the protection state of the system.

3.2 CeNet Architecture

CeNet is an object capability [24] system that extends traditional networks with fine-grained access control, dynamic management of rights, and secure collaboration (Figure 3.1). CeNet treats the hosts of a traditional network as a collection of objects in the capability system. Network communication, host management (in this work this means ownership), and exchange of rights are mediated and controlled by the rules of the CeNet capability system. CeNet builds on two core principles: *strong isolation* and *controlled communication*. To ensure isolation, CeNet operates in the context of an environment where all hosts are connected to a software defined network (SDN). CeNet uses the underlying SDN substrate to prevent all communication until it is explicitly allowed. As shown in Figure 3.1, the CeNet capability system is implemented as an SDN controller application. In CeNet all network communication is controlled according to the rules of the capability

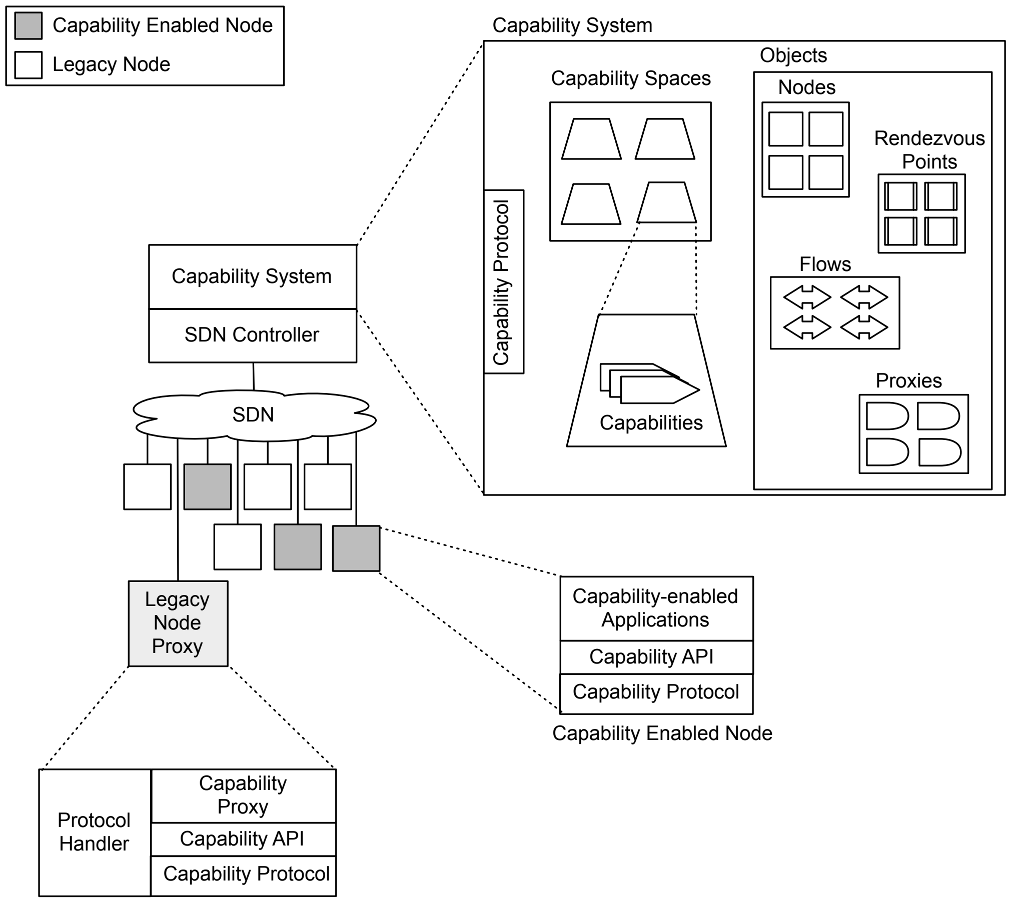


Figure 3.1. CeNet architecture

model. Network nodes can open network connections and communicate with each other if, and only if, they possess a capability for such a connection.

CeNet provides support for both pure capability-enabled and unmodified legacy nodes. This pragmatic approach eases adoption by being backwards compatible, while at the same time allowing new functionality to be realized. Capability-enabled nodes run a capability protocol that allows capability-enabled applications to interact with the capability system, e.g., exchange rights, establish network connections and specify access control policies.

Legacy nodes do not have any awareness of the capability system, but are seamlessly incorporated in CeNet through a mechanism of legacy node proxies. Legacy node proxies are special nodes designed to provide backward compatibility with legacy protocols in a capability network. Proxies intercept protocol interactions from legacy nodes and translate them into capability invocations. After the network flows are established with the help of proxies, legacy nodes directly use the network to interact with other legacy nodes or capability-enabled nodes.

CeNet provides a clean separation of the policy and mechanism for access control in computer networks. CeNet implements the mechanism—a clean, flexible layer of access control. The combination of CeNet capability system and SDN fabric removes network ambient authority by allowing only a policy driven *access* among hosts in the network. The policies based on which the network-core enforces access control are, however, determined by applications running on capability-enabled nodes (within the limits of authority granted to them) that operate outside the network proper.

The CeNet separation of policy and enforcement and the delegation of rights inherently enabled by capability systems provide for a powerful security primitive that cleanly maps onto existing communication models, while also enabling the realization of novel communication models.

For example, the degenerate case of a single (or replicated) capability-enabled node that runs a network management application mimics the prevalent "logically centralized" SDN control application approach [43, 44]. While such a system would not fully utilize CeNet features, it would still benefit from realizing higher-level policies in a capability system with clean delegation and revocation abstractions.

A more sophisticated use case might involve a multitenant datacenter environment where a subset of nodes and complete control of the policies associated with that subset might be delegated to each tenant. For this use case, the applications are essentially capability-enabled nodes that are allowed to manipulate the capability system (according to the rights delegated to them) and as a side effect create flows in the SDN substrate according to application-specific policies.

For both scenarios described above, capability manipulation is essentially limited to control-plane operations. However, as we describe below, the CeNet API also provides data send and receive functionality. This allows for complete end-to-end capability-enabled interaction between applications. For example, in such a scenario, all hosts in the system may be capability enabled, so that both control and data plane interaction between the nodes will require the use of capabilities.

In Section 3.2.1 below, we first consider the functionality of CeNet assuming a "pure capability" environment where all nodes are capability-enabled. In addition to simplifying the exposition, this represents a realistic scenario for networks with high security requirements. Later we describe how CeNet deals with legacy nodes.

Note that the terms *application/host/node* and *endpoint* are used interchangeably because in a security critical scenario, it is likely that an application would be running all by itself within a physical host, virtual machine, lightweight container, or would have a lightweight network stack linked directly into its address space [45, 46]. Our host-side APIs are geared more toward these single-function security use cases. In this initial version of our work, our APIs do not satisfactorily address the security requirements for a general-purpose network stack that must demultiplex the packets to various application processes.

3.2.1 CeNet Capability System

CeNet exposes the resources of a computer network through a capability interface. Capabilities mediate all network operations, e.g., the ability to open and accept new connections, the exchange of rights and the management of network hosts.

3.2.1.1 Capabilities

The core of CeNet is the capability system (Figure 3.2). Network hosts access resources of the network by invoking capabilities. Capabilities both name specific objects and provide authority to perform operations on them. Objects represent resources of the network.

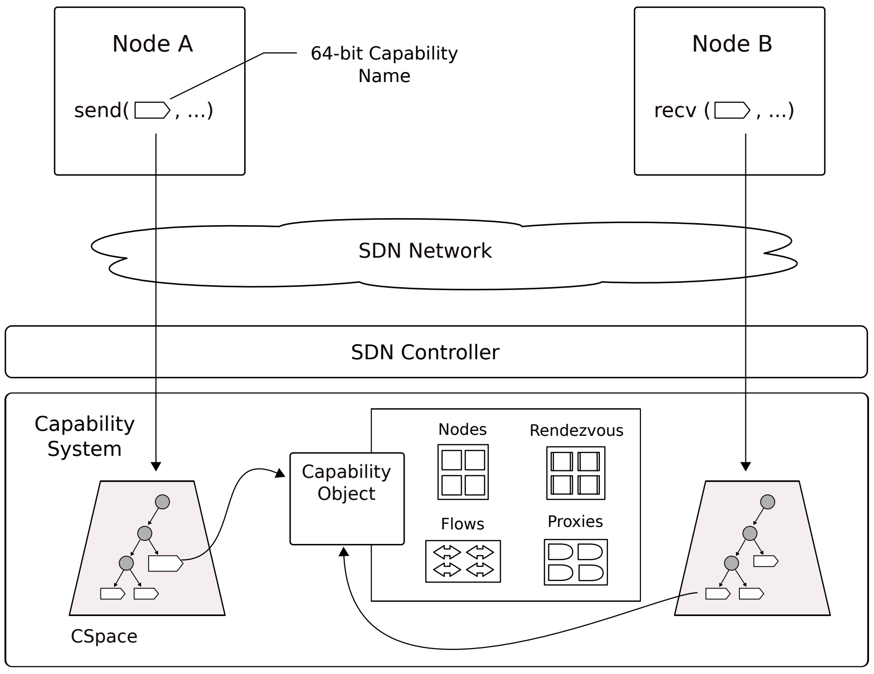


Figure 3.2. CeNet capability system

Possession of a capability allows a node to perform a specific operation on the object. However, hosts do not have any intrinsic authority beyond that accessible via capabilities.

Hosts refer to capabilities by their local names—64-bit capability identifiers that have no special meaning outside of the host. For each host the CeNet capability system maintains a *capability space* (or a CSpace), a datastructure that resolves local capability identifiers into capability references that contain specific rights to a specific object. The difference between capability identifier and capability reference is merely an implementation detail and the translations are handled automatically by the system. In the context of our system if we merely mention the term capability (without being specific of whether it is a capability identifier or reference), it usually means a local capability identifier in the context of a host, which is translated (by the capability system in the central SDN controller) to an object pointer (reference) referring to a unique object (Section 3.2.1.2 below provides a detailed description of object types supported by CeNet) in our system.

Hosts invoke capabilities via the CeNet capability application programming interface (API). The API maps onto a simple capability protocol that conveys API invocations to the CeNet controller. Each capability protocol message contains a capability identifier which designates a receiving object, an operation to perform on the object, and one or more arguments.

A host is identified by its location on the network. A location is the switch identifier and the port-number, through which the host attaches to the network. The unforgeable property of capability identifiers in our system is based on the fact that capability creation or transfer happens (via CeNet APIs) only with the knowledge of the capability system in the controller. Later, when a host presents a capability, for exercising its authority, the RPC messages are tagged with the originating switch and port identifier by the Openflow switches. The capability system can easily validate whether this token was indeed granted to this particular host. Since switch firmware is part of our Trusted Computing Base (TCB), it is impossible for a malicious host to exercise a nongranted capability token.

3.2.1.2 Objects

Objects encapsulate the logic of host management, connection establishment, and capability management operations. Objects provide the only interface for a CeNet application to interact with the environment of the network. For example, the invocation of a capability on a flow object allows a node to establish a unidirectional flow to the host pointed to by the flow object. State and code of the objects is part of the CeNet capability system. CeNet defines four object types:

- **Node:** Each physical or logical node (VM) in the system is represented by a node object. Node objects implement a management interface to the physical and logical hosts of the CeNet system. A capability to a node allows its owner to reclaim the node and reset it to a clean state by power cycling the node, controlling its boot protocol, and reseting its capability space. By controlling the distribution of node capabilities, CeNet enables flexible partitioning of the network resources. Control over any node can be delegated to any node within the system.

- **Rendezvous point:** A rendezvous point is a communication primitive that enables nodes to exchange capabilities via send and receive operations. A rendezvous point maintains a queue of messages from the sender. When the receiver invokes a receive, the capabilities are transferred to the receiver.

- **Flow:** A flow object enables establishing a unidirectional flow for data-path communication between nodes. Only the receiving end of the flow is fixed when the flow object is created. Like any capability, capability to a flow object can be passed around and invoked multiple times. Any node that possesses a capability to a flow object can open a network flow to the receiving end. CeNet relies on support from the underlying SDN to establish flows.

- **Proxy:** Proxy objects allow proxy nodes to proxy all the control plane traffic (DHCP, DNS and ARP) of a legacy node (to the proxy node) and translate them to capability operations, thereby mediating its exchange of rights. Thus CeNet uses proxy objects to allow legacy nodes to interact with the capability system in a transparent manner. The proxy object allows a node which holds a capability to the proxy to invoke capability exchange operations on behalf of the legacy node associated with the proxy object. When the proxy object capability is passed into a capability exchange operation, the operation is performed on the CSpace of the legacy node that is pointed to by the proxy object.

3.2.1.3 Operations

Capability operations define the rules for modifying the state of the protection graph of a capability system. CeNet implements a version of the *take-grant* capability model [26, 47]. The CeNet capability model allows the following operations:

- **Create.** The create operation creates a new object of a requested type. Create returns the capability pointing to the new object to its caller. Create operations can be used to create new RP and flow object types. Node and Proxy objects are not usually created (as semantically it doesn't make sense) by endhosts. They are created and their capabilities are received by admin and proxy hosts, respectively, during bootstrap.

- **Mint.** The Mint operation creates a new capability that points to an existing object. Mint is typically done before a grant (delegation) as it allows for the revocation of a minted capability by the minter at a later point of time (by passing the original capability to the revoke operation). This operation is object type agnostic.

- **Send and receive.** Nodes exchange capabilities by passing them into the *send* and *receive* operations. Send and receive operate on rendezvous objects. Any node which has a capability to a specific rendezvous point can send and receive messages to the RP.

- **Send and receive data.** Send and receive data operations allow nodes to use the CeNet API for data plane communication.
- **Revoke.** The revoke operation allows the invoking host to delete the object pointed to by the capability. This renders useless all the minted capabilities which it might have delegated to others. It is object type agnostic.
- **Reset.** The reset operation cleans the capability space of a node and resets it with a single rendezvous point available to the node through the well-known CAP0 capability identifier. The invoker should have a node capability to the target node for this operation to succeed.

3.2.2 CeNet Host-Side APIs

Capability operations are exposed to hosts via an API. The primary function of the capability API is to enable hosts to interact with the controller to manipulate the protection state of the system. The API can also be leveraged for datagram-based messaging functions.

3.2.3 Bootstrapping Capability-Enabled Nodes

In this section we first explain how nodes are bootstrapped into the capability system. We then consider how such a bootstrapped node can use the CeNet communication primitives to establish communication between nodes.

In any network administrative domain, enterprise, datacenter or cloud, there are certain high-level network management policies that govern the roles and functionalities of nodes in the system and effectively form the context within which any detailed policies are applied. For example, in a datacenter or enterprise environment, specific nodes would be designated to run “infrastructure services” like DHCP and DNS. Likewise, in the cloud infrastructure, specific nodes will be designated to run the “cloud control” software stack while other nodes will be designated as compute nodes.

Our goal with CeNet is to provide a generic framework that can accommodate and enhance the functionality of any of these scenarios (and indeed enable alternative scenarios). Without loss of generality, in our exposition below we assume that some higher level management function has designated a *master node* that has full control over a number of other nodes in the system. Because a master node can in turn dynamically delegate "submaster" capabilities to any of the nodes it controls, this setup applies to all of the scenarios mentioned above. For example, the master node might be the sole master node in a datacenter or enterprise environment, or it might be a master node for a subset of nodes belonging to a specific customer or department in a datacenter or cloud infrastructure.

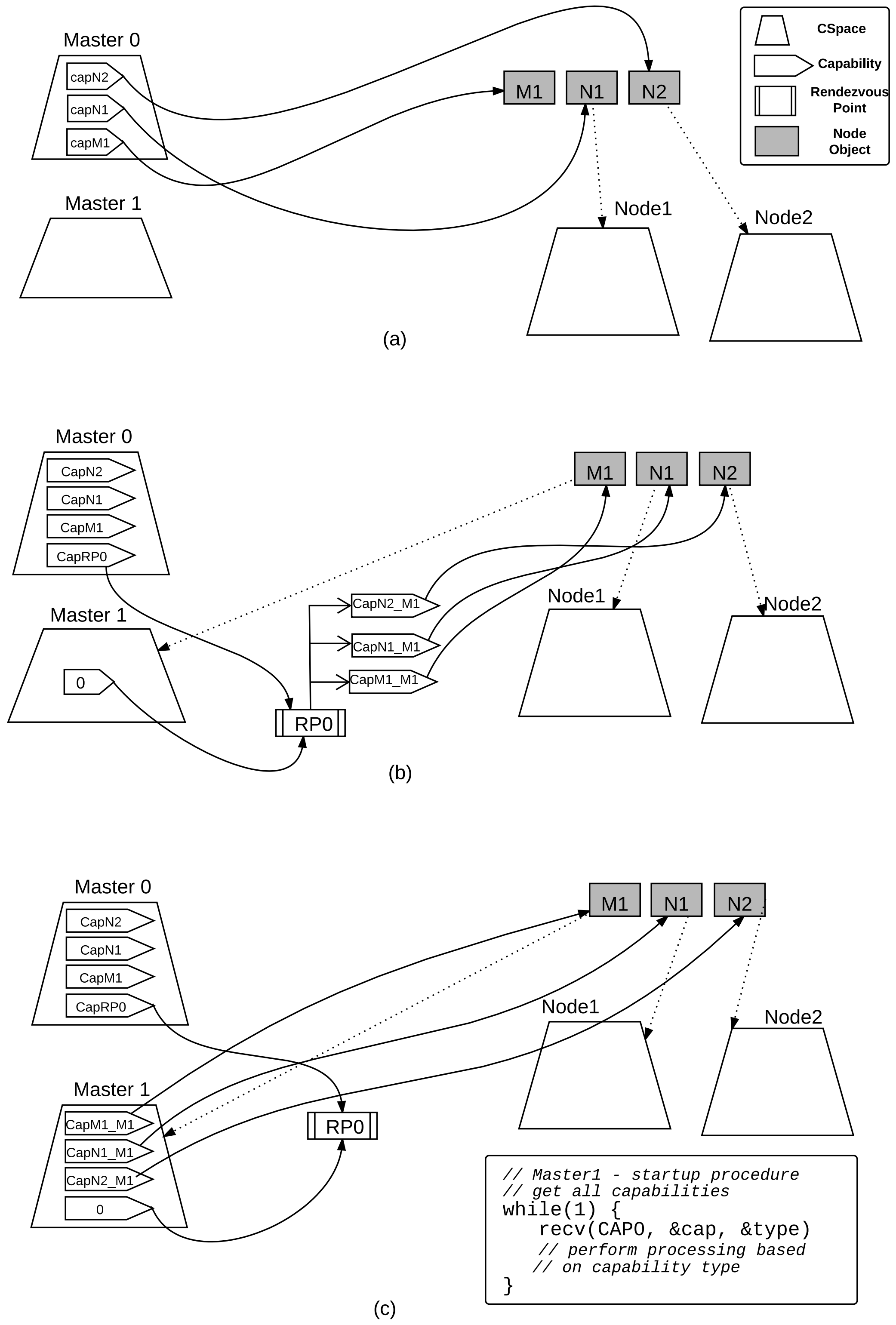
3.2.3.1 Bootstrapping Master Node

Figure 3.3 depicts the scenario in which *Master0*, a node which has control over three physical nodes, creates a new isolated network partition. *Master0* chooses one of the three nodes to become the master inside the partition (*Master1*). The master bootstrap protocol allows *Master0* to pass control over the partition to *Master1*. Figure 3.3 (a) shows the initial state of the capability system. *Master0* possesses capabilities to the three nodes. To start the master boot protocol, *Master0* invokes the following operations:

```
capRP0 = create (TYPE_RP)
reset (capM1, capRP0)
capM1_M1 = mint (capM1)
send (capRP0, capM1_M1)
capN1_M1 = mint (capN1)
send (capRP0, capN1_M1)
capN2_M1 = mint (capN2)
send (capRP0, capN2_M1)
```

Master0 creates a new rendezvous point *RP*0. It then invokes a *reset* operation on *Master1*. The reset operation performs two things. First, it cleans the capability space of the node. Second, it inserts the rendezvous object *RP*0 in the empty CSpace of the reset node (*Master1*). After reset, the node has no capabilities besides a capability to the rendezvous object. Similar to the UNIX environment, the rendezvous object serves as the "standard input" for *Master1*. It is used to exchange capabilities while performing the boot protocol. The reset operation arranges that the rendezvous object is available to the node through a capability with a well-known name, 0.

Master0 uses the *mint* operation to create copies of capabilities referring to three nodes and the *send* operation to send these capabilities to the rendezvous point *RP*0. The master mints capabilities, so it can revoke them later without losing its own control over the nodes,



```
// Master1 - startup procedure
// get all capabilities
while(1) {
    recv(CAP0, &cap, &type)
    // perform processing based
   // on capability type
}
```

Figure 3.3. Bootstrap master

which it has through capabilities *capM*1, *capN*1, and *capN*2.

Given this initial state, Figures 3.3 (b) and (c) depict the bootstrapping actions when the master node starts up. The master invokes the receive operation on its “standard input” capability “0” to receive the node capabilities waiting in the rendezvous queue. Figure 3.3 (c) shows how this results in the enqueued capabilities being imported into the capability space of *Master1*. Note that the manipulation of the capability space shown in these figures occurs in the data structures of the capability system (associated with the SDN controller), as a result of invocations via the CeNet API (shown in Figure 3.2).

3.2.3.2 Bootstrapping Other Nodes

The above bootstrap protocol is followed to bootstrap any capability-enabled node into the system. For example, to bootstrap *Node1*, the *Master1* executes the following commands:

```
capM1_N1RP0 = create (TYPE_RP)
reset (capN1, capM1_N1RP0)
capN1_N1 = mint (capN1)
send (capM1_N1RP0, capN1_N1)
```

The master node creates a new rendezvous object *capM1_N1RP0*. The master then invokes the *reset*() operation on the node referred by the *capN*1 capability, and passing the *capM*1_*N*1*RP*0 rendezvous capability as an argument, thus establishing *Node1’s RP0*. The master mints the capability to the node and sends it to the rendezvous object. Figure 3.4 shows that *Node*1 follows the same startup procedure (i.e., performing a receive operation on the capability “0”). After receive, *Node*1 is fully bootstrapped into the capability system. It has a capability to itself, which allows it to create new objects, e.g., rendezvous points and

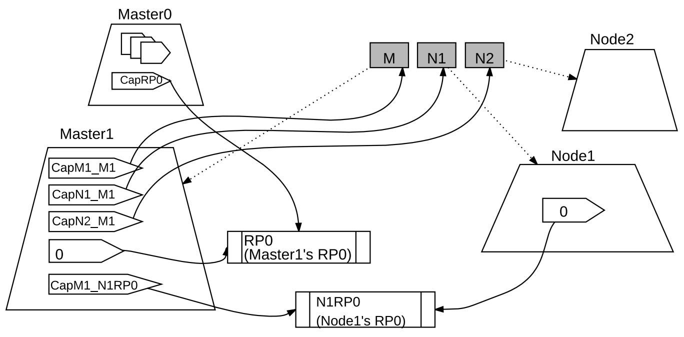


Figure 3.4. Bootstrap node into capability system

flows, and to receive more capabilities from the master through its standard input capability zero.

3.2.3.3 Allowing Nodes to Exchange Capabilities

Once nodes are bootstrapped into the capability system, the master node (or any node with appropriate capabilities) can create a rendezvous point to allow nodes to exchange capabilities directly. Figure 3.5 presents an example of three nodes, in which a new communication channel is set up between the two nodes $Node1$ and $Node2$. Master1 can exchange capabilities with $Node1$ and $Node2$ through the existing rendezvous objects $N1RP0$ and $N2RP0$ (from the bootstrap of those nodes). *Master1* executes the following commands to create a new rendezvous point and share it with both nodes:

```
capN1N2RP = create (TYPE_RP)
capN1_RP_N2 = mint (capN1N2RP)
send (capM1_N1RP0, capN1_RP_N2)
capN2_RP_N1 = mint (capN1N2RP)
send (capM1_N2RP0, capN2_RP_N1)
```

The master creates a new rendezvous object. The master then mints two new capabilities from the rendezvous point capability and sends these capabilities to $Node1$ and $Node2$ via the rendezvous points they share with the master ($N1RP0$ and $N2RP0$). Both nodes receive capabilities to the new rendezvous object with the receive operation. The receive operation imports the appropriate capabilities into the capability space of the receiver. The end state, with the new rendezvous point shared between $Node1$ and $Node2$ is depicted in Figure 3.5. (To simplify the figure we show only the relevant CSpaces and objects.)

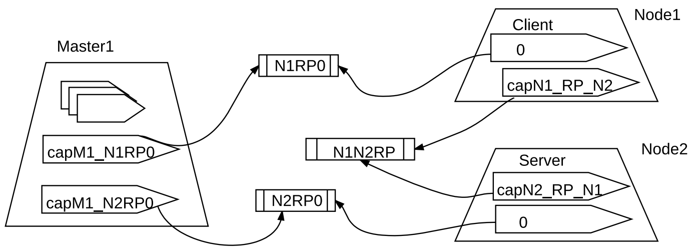


Figure 3.5. Allow nodes to exchange capabilities

3.2.3.4 Communication Primitives

With the ability to exchange capabilities in place, nodes in a CeNet system can create communication-related objects (flow objects) and exchange the associated capabilities to enable communication. Again, the semantics associated with such communication will be application-specific, according to the delegation of capabilities amongst participating applications, while the enforcement of the policies will lie with the capability-driven SDN infrastructure. For example, to realize the common "logically centralized" policy manager approach, a centralized master node can create flow objects on behalf of nodes under its control and pass the capabilities associated with these objects to the nodes in question (via shared rendezvous points). Nodes receiving these capabilities will thus be enabled to communicate according to the policies enacted by the master node.

CeNet's ability to delegate capabilities, however, also enables the realization of fine-grained, distributed policies. For example, Figure 3.6 depicts the scenario where a client and a server are explicitly enabled to exchange capabilities (as illustrated in Figure 3.5) and use this ability to create flow objects and exchange the associated capabilities to enable client/server communication.

With reference to Figure 3.6, $Node2$, acting as a server and wanting to enable communication with a client ($Node1$), will perform the following invocations via the CeNet API:

```
capInUFlow = create (capN2, TYPE_UFLOW, flow_spec)
send (capN2_RP_N1, capInUFlow)
...
recv (capN2_RP_N1, &capOutUFlow)
```

Figure 3.6 (a) shows the result of these invocations. The server creates a new flow object and shares it with the client through a rendezvous point they share. The flow is of type, $TYPE\_UFLOW$, indicating that it is a unidirectional flow towards the server and with a optional flow specification. *flow_spec* can be used to demux packets at the receiving host to multiple applications if required (somewhat like port numbers). Note that at this point, the flow object only exists in the capability system; no flow has actually been realized in the SDN substrate. CeNet can also proactively push flow specification to the substrate if

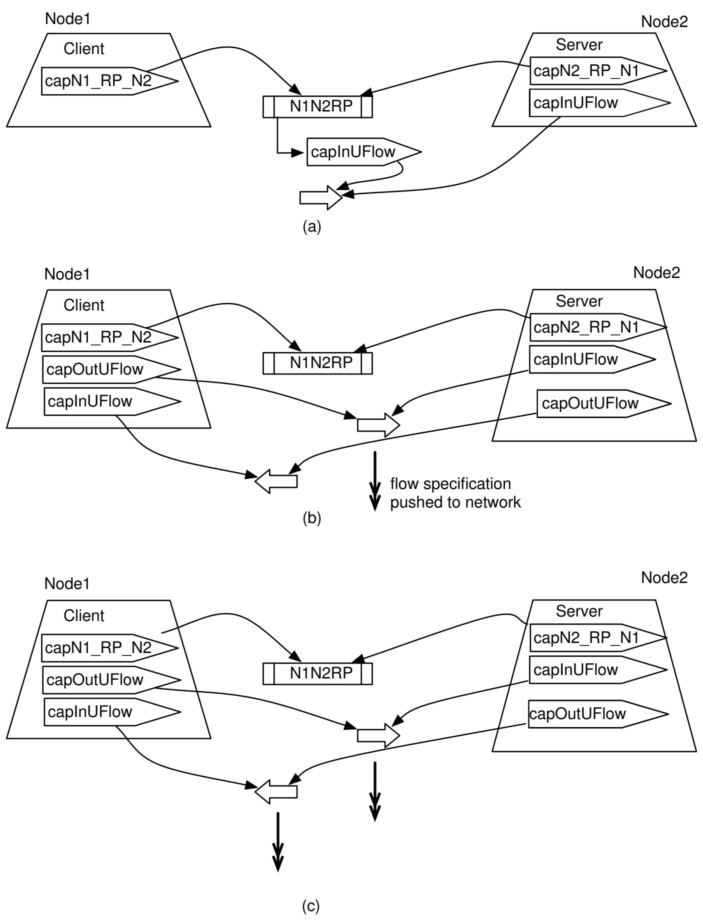


Figure 3.6. Unidirectional flows

the flow-type is specified as $TYPE\_UFLOW\_PUSH$.

The client, $Node1$, will receive the unidirectional flow object. The client then creates a flow pointing in the other direction as follows:

```
recv (capN1_RP_N2, &capOutUFlow, &type)
capInUFlow = create (capN1, TYPE_UFLOW, flow_spec)
send (capN1_RP_N2, capInUFlow)
senddata (capOutUFlow, data)
```

The client API invocations essentially mirror that of the server in terms of creating a unidirectional flow object towards the client and sharing it with the server via the rendezvous point. The client then starts sending on the flow capability it received from the server. As shown in Figure 3.6 (b), receiving data on the flow capability will result in the flow specification being pushed into the SDN substrate so that subsequent interaction will not involve the controller. In a similar fashion, once the server has performed a receive to import a flow capability generated by the client, $capOutUFlow$, the server can use $senddata()$ with the capability to send data to the client. Again, this flow of data will serve as a trigger to push the flow specification into the SDN substrate as depicted in Figure 3.6 (c).

A key property of the take-grant capability system is the transitive, reflexive, and symmetric closure over all Grant connections (discussed in more detail in Chapter 5). This closure provides an authority bound which is invariant over system execution. Our bootstrap protocol is based on this. In other words, any amount of capability transfer from the initial bootstrapped state cannot introduce a new connection between two objects that were not already connected by some path in the closure.

3.2.4 Dealing with Legacy Nodes

We envision that complete autonomous environments, e.g., high security datacenters, could run the CeNet system and protocols. However, to ease adoption, backwards compatibility with legacy nodes is an important requirement. As described earlier, CeNet deals with legacy nodes by delegating control of such nodes to proxy nodes capable of interacting with both the legacy nodes (via legacy protocol handlers) and with the capability system through the CeNet API (and protocol).

Two scenarios are of interest. The first is a domain consisting of only legacy nodes. With appropriate higher-level policies driving the CeNet capability system and with delegation to different master nodes, this scenario still benefits from CeNet's least-privileged communication and strong isolation primitives.

In the second scenario, legacy nodes are integrated into a CeNet environment and allowed to seamlessly communicate with capability-enabled nodes. For example, in such a mixed-node deployment, a capability-enabled server could grant or deny access to clients based on fine-grained application-level policies and have those policies be enforced by the SDN infrastructure.

The mechanisms involved with both scenarios are essentially the same. Without loss of generality we consider the mixed deployment scenario below in more detail.

3.2.4.1 Bootstrapping Proxy and Legacy Node

Our approach to integrating legacy nodes into CeNet builds on two insights. First, most protocols used by legacy nodes are of a request/response nature. These protocols readily map onto the send and receive functions exposed by the CeNet API to share capabilities and import them into a node's capability space. Below we consider one possible mapping making use of DHCP, DNS, and ARP protocols.

Second, since the capability identifiers used by hosts for invocations across the CeNet API have local significance only, the proxy can maintain a mapping between capability identifiers and legacy "protocol identifiers." For example, the IP and MAC layer addresses used by legacy protocols in effect become "proxy capability identifiers."

Figure 3.7 illustrates this scenario. *Node2* is a capability-enabled server. *Node1* is a legacy client. The *Master* node sets up a system in which nodes *Node1* and *Node2* are allowed to communicate. The master designates a *Proxy* node to act on behalf of *Node1*. Proxy node is responsible for performing capability operations on behalf of a legacy node, so as to seamlessly integrate the legacy node into the capability-enabled network. The master then creates a proxy object. Note that this instance of *create()* invocation takes a capability to the legacy node as the first argument. The create operation associates the proxy object with the legacy node. The master shares the proxy capability with the proxy node:

```
// On Master
capP = create (capN1, TYPE_PROXY) //CapP points to ProxyN1 object in figure
capP_N1 = mint (capP) //CapP, CapN1 in master's CSPace are not shown
send (capM_RP_P, capP_N1)

// On Proxy
recv (capP_RP_M, &capProxy_N1, &type)
```

When the proxy node receives the proxy capability, the CeNet capability system configures the SDN substrate in such a way that all control plane traffic, e.g., DHCP, DNS and ARP, from the legacy node is routed to the proxy node.

Figure 3.7 (a) depicts the result of *Master* resetting the legacy node *Node1* for bootstrapping it into the capability-enabled network. The rendezvous point $N1RP$ becomes the standard input for *Node1*. Another rendezvous point is created for communication between *Node1* and *Node2* ($N1N2RP$). The master has sent associated capabilities to appropriate rendezvous points. Note that from *Master* perspective these operations are exactly the same as the actions it took to bootstrap a capability enabled node as described in Section 3.2.3.

The legacy node bootstrap continues when *Node1* initializes its network interface, e.g., after reboot. At this point the legacy node issues a DHCP request. DHCP traffic from the legacy node is routed to the proxy. The proxy node receives and parses the DHCP request from the legacy node. The proxy realizes that the legacy node is ready to join the network. The proxy performs the node part of the bootstrap protocol on behalf of the legacy node. The receive operation below imports capabilities from the rendezvous point *N*1*RP* into the capability space of the legacy node *Node1*. (The result of these operations is shown in Figure 3.7 (b)):

```
// On Proxy
while (recv(capProxy_N1, 0, &cap, &type)) {
   //capability specific processing
}
```

Although the receive invocation is invoked by the proxy node, the receive operation is performed on the CSpace of the legacy node, i.e., the node pointed by the *capProxy_N*1

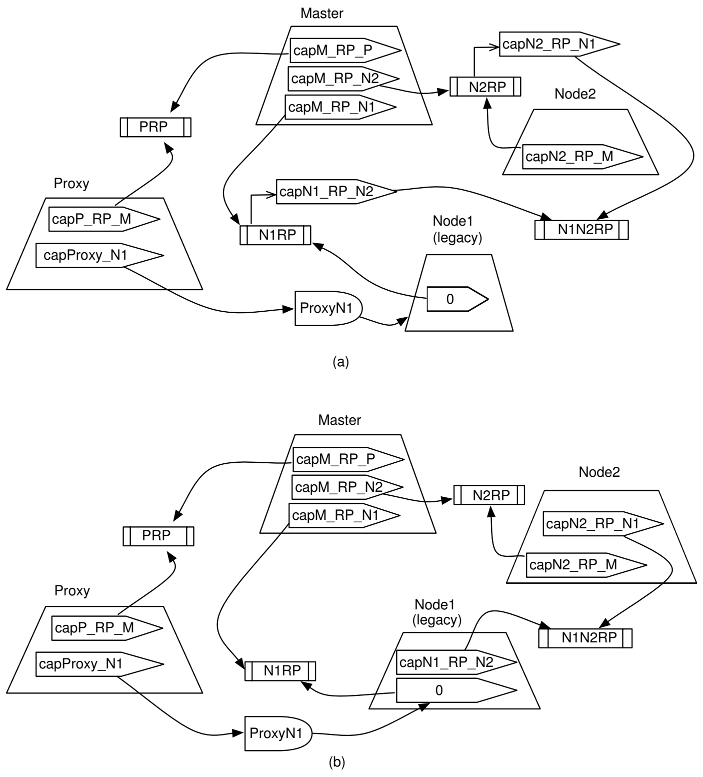


Figure 3.7. Bootstrap legacy proxy node and and legacy node

capability. The capability which points to the RP "0" is also taken from the CSpace of the legacy node. On successful invocation of the functions above, the proxy protocol handler performs regular DHCP functions based on the received request. It returns a DHCP response and maintains the mapping between the DHCP parameters and capability identifiers it received on behalf of the legacy node. (For example the proxy can maintain a mapping between the IP it issued in response to Node1's DHCP request, the proxy capability id corresponding to Node1 and list of Node1 local capability identifiers like capN1_RP_N2, received as a result of the recv in the previous snippet.)

In the code sequence above, the receive operation is used with an additional argument—a capability to the proxy object.

Once the legacy node and the proxy node are bootstrapped in this manner, the same protocol is followed for setting up data flows. (The exchange of rights for setting up a CeNet flow is shown in Figure 3.6.) The proxy intercepts regular protocol exchanges from the legacy node and translates them into capability operations. Specifically, the capability-enabled server ($Node2$) will invoke the exact same capability operations to create a unidirectional flow object towards itself (Figure 3.6 and Section 3.2.3.4).

To realize the flow in the other direction, i.e., from the legacy client ($Node1$), the legacy node issues a DNS request to resolve the server hostname to an IP address. This request is directed to the proxy node. Based on the information that the request came from $Node1$ the proxy node uses the proxy capability associated with $Node1$ ($capProxy\_N1$) to invoke the receive operation:

```
// On Proxy
recv (capProxy_N1, capN1_RP_N2, &capOutFlow, &type)
```

On success, the proxy again proceeds with regular protocol processing, i.e., constructing a DNS response message and responding to the client.

On initiating communication with the server, the client issues an ARP request to resolve the MAC address of the server. Again this message is intercepted and parsed by the proxy. The proxy then proceeds to create a flow from the client to the server:

```
// On Proxy
capInFlow = create(capProxy_N1, TYPE_UFLOW, spec)
send(capProxy_N1, capN1_RP_N2, capInFlow)
```

At this point the capability space is in the same state as at the equivalent point in Figure 3.6 and IP based flow table entries can be pushed proactively to route the packets between the two hosts (on the intermediate switches connecting them), thus allowing the two hosts to communicate.

3.2.4.2 Hybrid Nodes

In Sections 3.2.1 and 3.2.3 we assumed that capability-enabled nodes would use the messaging functionality of the CeNet API for any node-to-node communication (Figure 3.8 (a)). This functionality is not practical for communication between capability-enabled nodes and legacy nodes. Instead, we make a reasonable assumption that for this type of interaction, the capability-enabled node would make use of a regular (legacy) network stack for "data path" interaction with the legacy node, but use the CeNet API for the "control plane" interaction with the capability system (Figure 3.8 (b)).

3.3 Use Case - Preventing Data Exfiltration

To illustrate the utility of our approach, we consider how the CeNet capability system can prevent data exfiltration in an enterprise network setting. The requirement here is to create enterprise network functionality, where different parties need to get their work done, but at the same time limit the damage and loss of data in the event of a security compromise at any of the hosts.

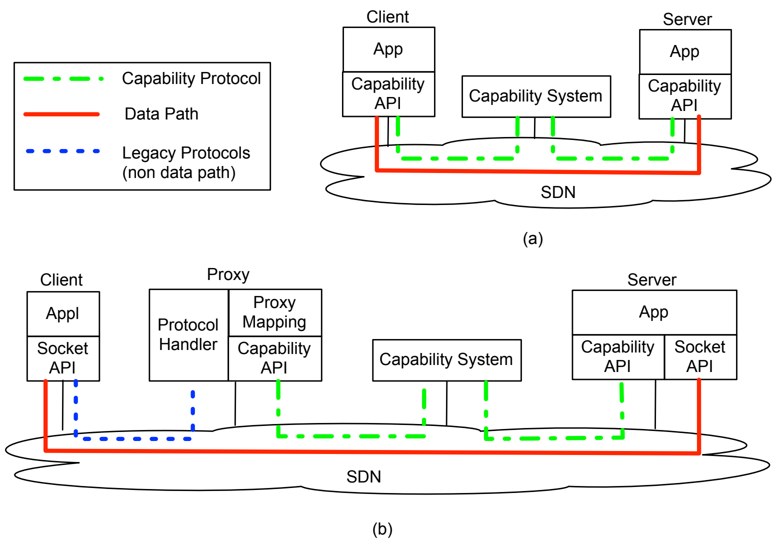


Figure 3.8. CeNet protocol view

In our example scenario shown in Figure 3.9, the network needs to allow the following interactions:

- a host with sensitive data needs to be accessed by a data scientist
- a group of three employees working on a project needs to collaborate
- the company needs to serve web pages showing the current inventory status, which is available on the database hosted on a different machine.

The fine-grained network access control (provided by capabilities) can alleviate the spread of a malware (e.g., exploiting a zero-day vulnerability, and all hosts are unpatched). This in turn can reduce the scope of data exfiltration in such a corporate network.

During the bootstrap, the master entrusts each host with only the capabilities it requires to perform its task.

Here the webserver serves webpages to the external world, so during bootstrap, the master gives it only the capabilities (flow capabilities) required to interact with the database server and vice versa. In the event of some security loophole in one of the scripts executed by the webserver, or some zero-day vulnerability in the web server code or host networking

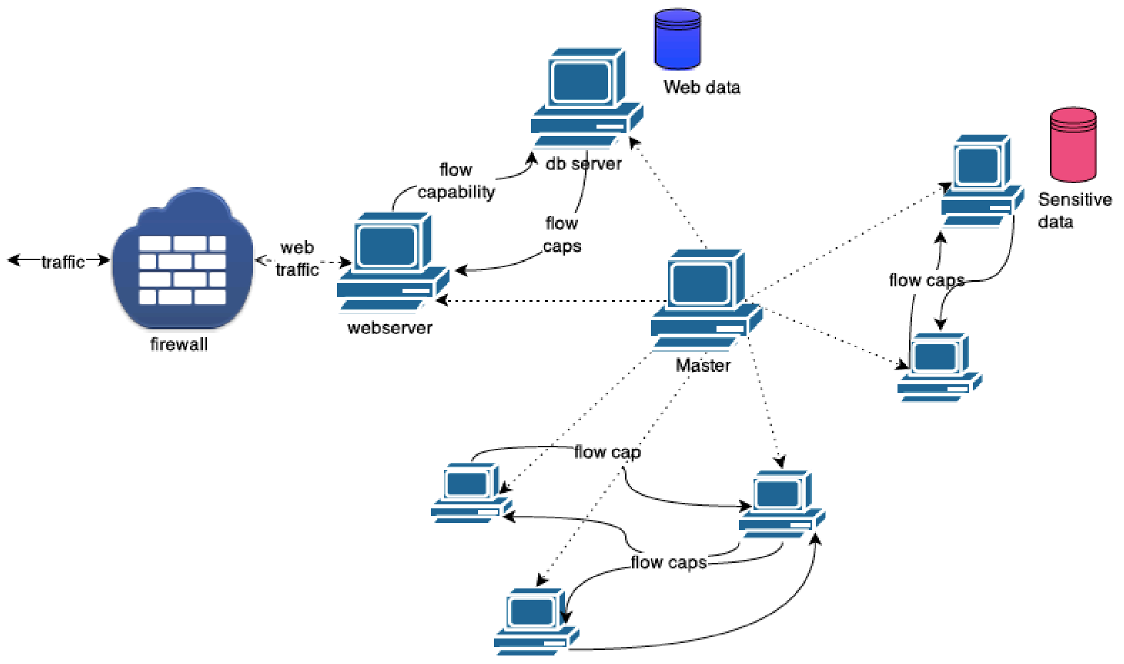


Figure 3.9. Data exfiltration

stack code, the attacker (even with root privileges of the webserver) can only reach the database server, thereby leaving other parts of the network safe from attacks. In this scenario, the attacker might be able to exfiltrate the webdata, *but the network would not provide him a chance to attack and exfiltrate the sensitive data*.

Similarly the master establishes a rendezvous point, which allows the data scientist and the system hosting the sensitive data to exchange flows that would enable them to communicate.

In the case of three employees needing to collaborate, the master need not get into the specifics of their collaboration. The system allows the nature of collaboration of these three host, to be decided by one of them (submaster). To achieve this, master delegates the ownership of those three nodes to one among them (say the host designated for the project manager). Now the project manager can decide the actual nature of collaboration among the three. By carefully granting just the three node capabilities to the project manager, the master can accomplish two goals: flexible collaboration and isolation of the three from the rest of the network. The protection state of the whole system could continue to evolve based on how the project manager host allows the remaining two to collaborate among themselves and with him. But no sequence of operations (capability-graph mutations) would enable these hosts to get a capability to other hosts in the network.

Why capabilities? Functionally this achieves security guarantees similar to running firewalls on every individual host, but the existing method of placing ad hoc firewall rules on endhosts leaves many opportunities for misconfiguration (if users are allowed to change the endhost firewall rules) and is difficult to reason about the overall security state of the network, as there is no explicit way of tracking rule changes. This level of fine grained security can be realized more easily in traditional SDN systems (like Ethane [43]). However, the policies are dictated by a single policy file without any scope of delegation, dynamism or evolution.

The capability model permits a level of evolvability from the bootstrapped protection policy of the system. End hosts can determine the policies based on delegated capabilities, thereby allowing a level of decentralization. However, the nature of evolution of protection state is using well defined graph transformations and consequently it is possible to reason about the protection state at any point in time or the possible upper bound of authority propagation.

To summarize, the following are the key advantages of CeNet system:

- policy-driven access control by the network core
- delegation of authority with the ability to revoke
- dynamic changes
- reason about the access allowed

3.4 Implementation

To verify the feasibility of our approach, we realized a prototype implementation of the CeNet architecture. The main components are the capability system, the capability API, and a bootstrap protocol.

3.4.1 Capability System

The CeNet capability system is implemented as an application in the POX SDN controller. POX is an extendable SDN controller implemented in Python. CeNet relies on POX functionality for all network management operations, e.g., maintaining a centralized view of the network, creating network flows, etc. The CeNet capability protocol, objects, and operations directly extend the functionality of the POX controller application.

Capabilities are implemented as Python objects within the controller process. A rendezvous point is a producer-consumer buffer that allows nodes to exchange capabilities. The buffer preserves the order in which messages were received. A flow object has the source and destination host information (source information is populated when the flow object is received by the senders). Based on these the path between the given hosts can be calculated based on the network topology. At the time when a flow is pushed into the SDN substrate, the CeNet system computes the route as a list of switch and input-output port combinations of intermediate switches. It also has methods to proactively push flows (both forward and reverse) in all the switches. In our current implementation we are giving the network topology and paths (between host pairs) as an input to the system, but it should be possible to hook into the network topology discovery module of POX to automatically compute the path.

The capability class maintains a reference to one of the capability objects and some logic for generating unique capability identifiers. Capabilities are associated with specific hosts. CeNet relies on a pair of *switch identifier* and *port number* to uniquely identify a host for each capability invocation. The CeNet system keeps track of capabilities for each node in a capability space, or CSpace, data structure. We use a simplified implementation of the CSpace—a list. This works well for the small number of capabilities, but does not scale. In other systems, capabilities are kept in radix trees with guards [48, 10]. Capability spaces for all nodes are kept in a Python dictionary—a key-value data structure indexed by a pair *(switch id , port number)* that uniquely identifies each host.

While we have implemented the logic associated with the reset operation as far as the capability space is concerned, we have not implemented the external mechanisms that might be associated with this operation to physically reset nodes.

3.4.2 Capability API and Protocol

CeNet implements the capability API that can be directly utilized by capability-aware applications. The API provides capability applications with remote access to interact with the capability system. Remote invocation of the capability operations is built on the capability protocol. Our realization of this protocol is implemented as a simple request / response protocol on top of UDP. The payload of each capability protocol message contains the capability operation to be performed, as well as the capability identifier needed for that operation. Each message also contains any additional parameters associated with the specific operation.

3.4.3 Data-path APIs

Our current implementation of data-path APIs *Send / receive data* overloads the VLAN field to carry the flow capability (token) and we route based on this capability. We use rawsockets to construct the packets.

3.4.4 Limitations

The limitations of our implementation include the following:

1. The data APIs currently support only UDP messaging. Connection oriented semantics need to be implemented over this.

2. Realizing traditional ambient networks (where every host needs access to every other host) using flow capabilities may create pressure on SDN flow table entries. In our model, the same destination would be identified by different flow capabilities in the context of different hosts. While this is a desirable security property, it limits scope of flow aggregation (to the same destination).

3.5 Performance Evaluation

We did a basic performance evaluation of our primitives. Our evaluation focuses on an end-to-end evaluation of CeNet, the scalability of the capability system itself, and the functionality of the legacy node proxy. We evaluated our prototype implementation in a Mininet network emulation environment controlled by a POX-based SDN controller with the CeNet capability system and executing on a 2.1 GHz Intel Xeon system running Ubuntu Linux.

3.5.1 End-to-end Evaluation

Once the appropriate capability operations have been performed to realize flows, CeNet uses the SDN network directly and there is no further overhead due to capabilities. Our evaluation therefore focuses on an end-to-end measurement of the overhead introduced by the CeNet capability system.

Typically, the capability-related overhead would come in two scenarios: (i) the additional overhead to bootstrap new nodes into the capability system or handing over additional capabilities to existing nodes and (ii) the additional overhead introduced in setting up flows between two hosts interested in communicating. The first operation happens when a master at a particular level delegate authority of a subset of nodes to a master at a lower level in the delegation tree. As such this operation is not in the communication critical path. The second operation introduces some overhead as a flow object needs to be created and the associated capability passed to the other end of the communication.

We evaluated this overhead by instrumenting our implementation to determine the breakdown of time within end-to-end API invocations for CeNet capability operations. These results were obtained with the capability system preloaded with 840 nodes and with the CSpace of each node populated with 1,000 capabilities.

Our results are shown in Figure 3.10. The bars show the average total time for each

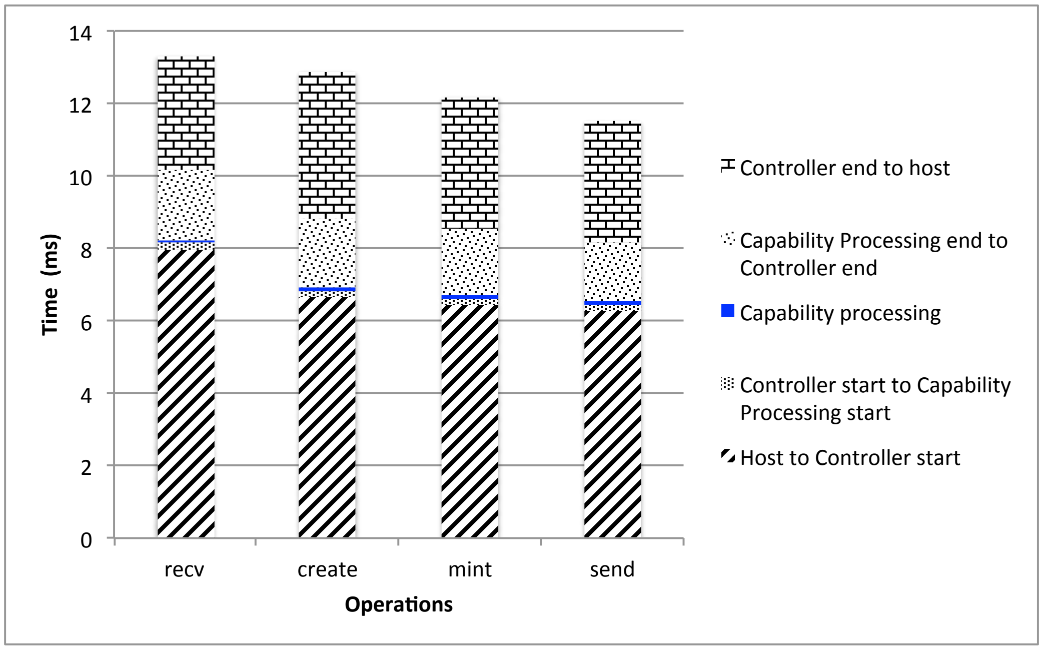


Figure 3.10. End-to-end time split

CeNet operation. Our first observation is that the operations introduce fairly modest overhead, somewhere between 11 and 13 ms, depending on the operation. Each bar is divided to show the relative contributions of different components in an end-to-end invocation. The bottom component ("Host to Controller start") and top component ("Controller end to host") represent the overhead of the capability protocol to get the request from the invoking host to the capability system. The request/response nature of our capability protocol is evident, and since this is a remote invocation, these two measures make the largest contribution to the end-to-end delay.

The three components in the middle of each bar represent the SDN controller receive processing ("Controller start to Capability Processing start"), the actual capability processing ("Capability processing"), and the SDN controller send processing ("Capability Processing end to Controller end"). Interestingly, the actual capability processing makes the smallest contribution, with controller-related processing dominating.

3.5.2 Capability System

To get a sense of its scalability, we evaluated our capability system in isolation. Figure 3.11 shows the capability-related overhead of the receive operation and how this overhead varies according to the number of capabilities in the CSpace. The shape of the graph

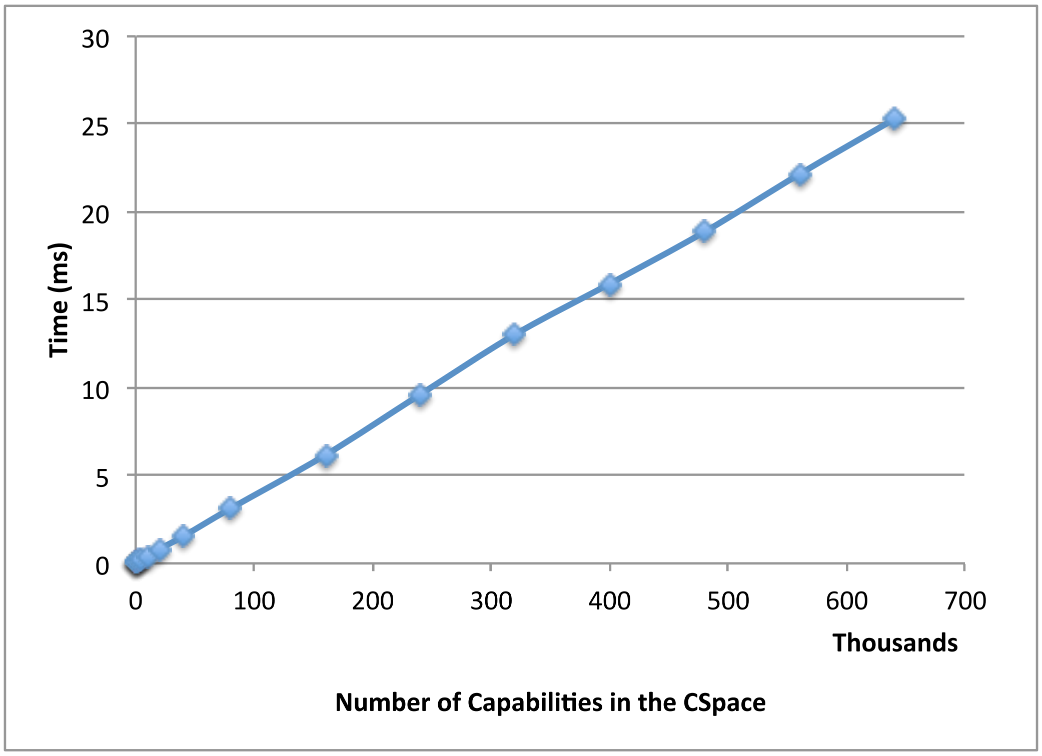


Figure 3.11. Capability processing time in controller

is in line with our list-based implementation, i.e., O(N) complexity where N is the number of capabilities in the CSpace. Even with this naive solution the performance is reasonable, e.g., for a reasonable number of around 1000 capabilities per CSpace, the overhead is around 0.07 ms. Even in a scenario where there are more than 600,000 capabilities in the CSpace the capability processing overhead is a tolerable 25 ms.

During node boot up, the controller must create objects and their corresponding capabilities and populate the necessary data structures. We measured the time taken to perform these operations as a function of the total number of capabilities in the system. Specifically, the time was measured while performing these operations in a tight loop, so that the number of capabilities effectively increased with each operation. The results for this experiment are shown in Figure 3.12. While we do not have a good sense of the total number of capabilities that would be needed in a realistic system, we note that the time for a system with a 100,000 capabilities is less than a second, and for a 500,000 capabilities it is less than 5 seconds. This appears to be a reasonable overhead for an operation that is only performed once when a node starts up.

For our next experiment we created a setup with 850 nodes each having 1,000 capabili-

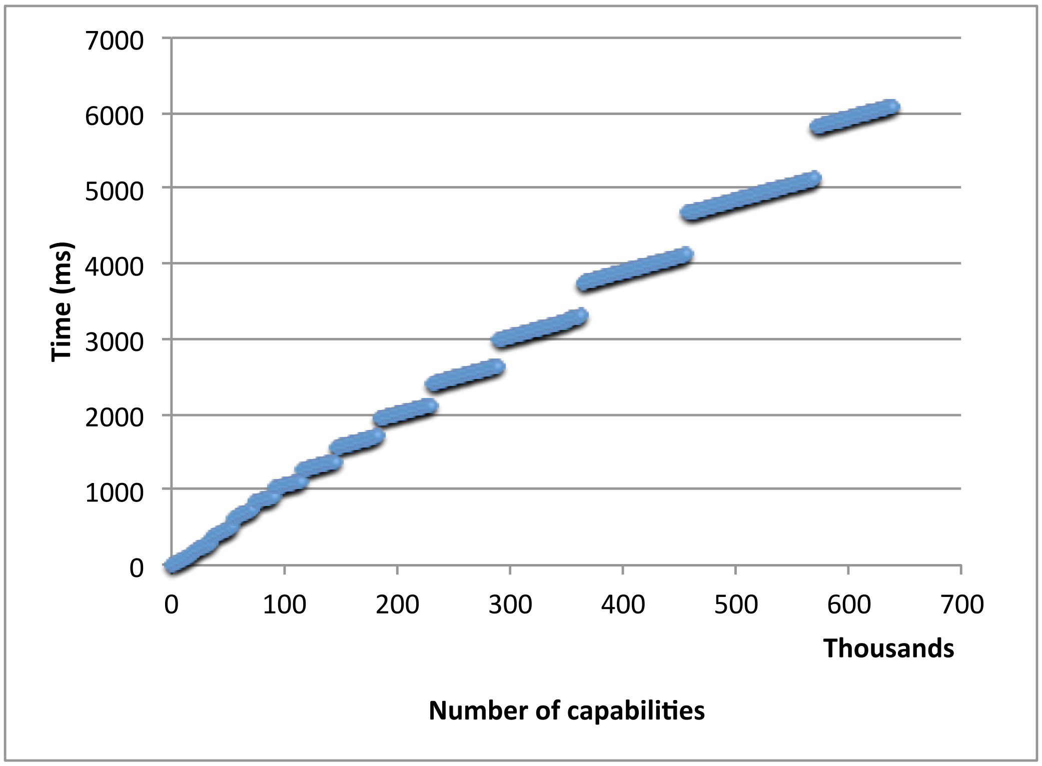


Figure 3.12. Controller bootstrap overhead due to capabilities

ties in their CSpace. Figure 3.13 shows the capability-processing overhead in the controller for a randomly chosen set of 250 hosts from this setup. The graph shows that, since the first-level indexing is hash based, the capability-related overhead for an operation is more or less the same irrespective of the host. The graph also shows that the capability processing is quite stable: the average time for all 850 nodes was 0.07 ms with a standard deviation of 0.01.

Legacy proxy node. We performed a functional evaluation of our proxy node implementation. Specifically, within our Mininet environment we created the setup depicted in Figure 3.8 (b). In this experiment the capability-enabled server node invoked appropriate capability operations to create a flow in the SDN substrate towards itself. We then manually performed a DHCP request from the legacy node to trigger the client-side operation. On receiving a successful DHCP response from the proxy node, we manually performed a *ping <hostname>* on the legacy node. This first triggered a DNS request to resolve the hostname and then a subsequent ARP request to resolve the server's MAC address. We captured the network interaction for this experiment via tcpdump in the Mininet setup.

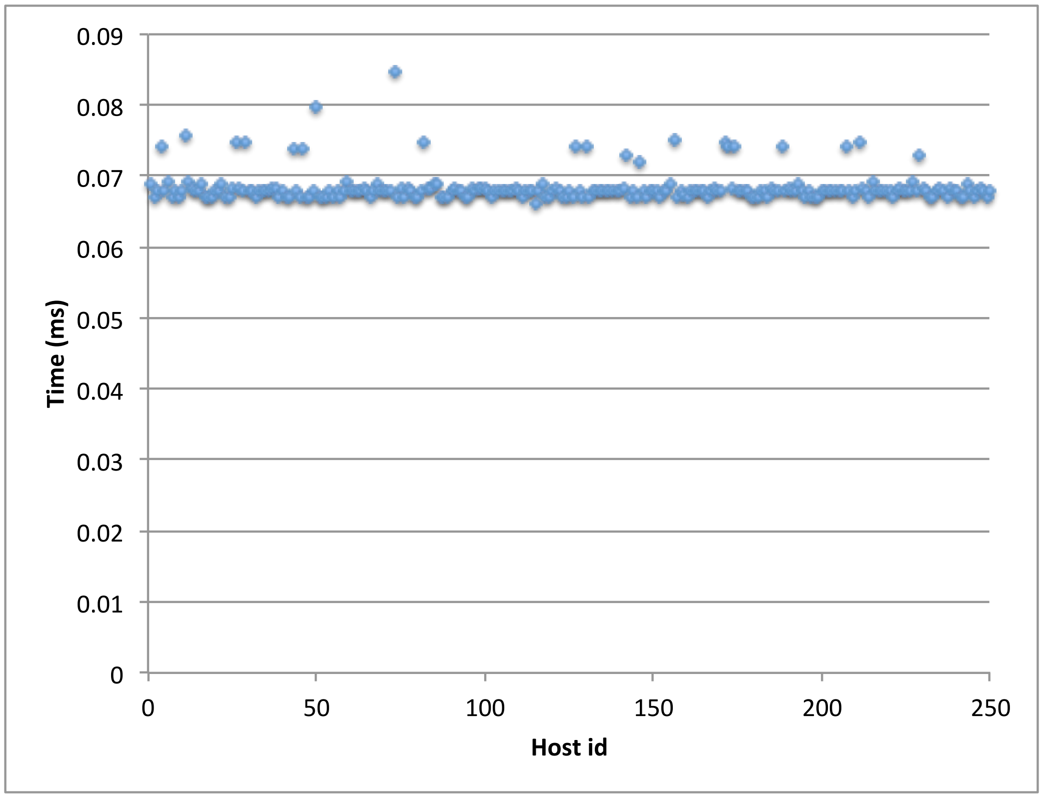


Figure 3.13. Capability access time for different hosts

Figure 3.14 shows an annotated time series of the interactions between the components in this setup.

3.6 Summary

In this chapter we talked about a mechanism for providing practical security, fine-grained access control, and least privilege in traditionally open networks. Based on principles of capability access control, we develop a powerful access control model which fits the needs of a modern data center or enterprise network. Capabilities enable fine-grained isolation and delegation of rights in a hierarchical, dynamic, multitenant environment, with a large number of mistrusting principals. While ensuring global security properties, CeNet allows individual hosts to make application-specific decisions. This natural integration of the application logic and access control enables construction of true least privileged environments.

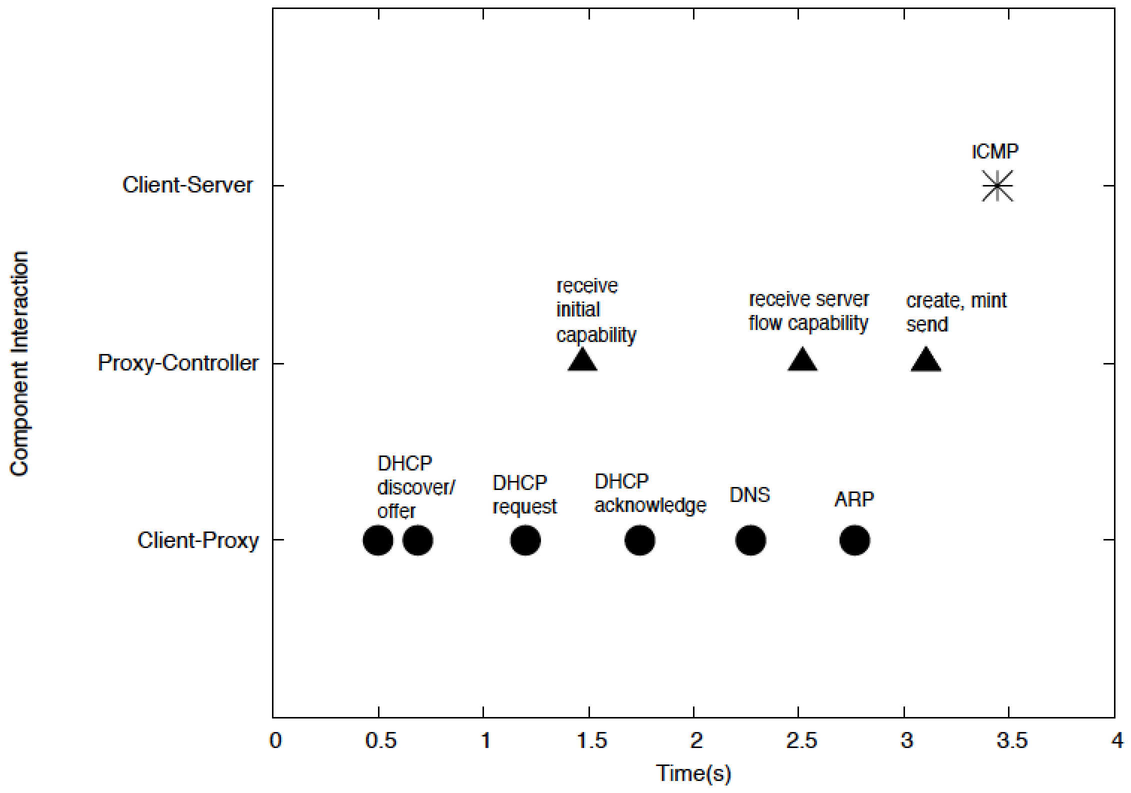


Figure 3.14. Capability-enabled and legacy node interaction

CHAPTER 4

HIGH-LEVEL POLICIES

In this chapter, we describe how our network is able to enforce access control according to a high-level policy by translating it into capability operations. We describe an example scenario, implementation, and evaluation of this.

We refer to the component that does the aforementioned translation as a *policy manager*. It sits above the capability system in the SDN controller as shown in Figure 4.1 and translates a high-level policy into a set of capabilities and hands them over to the relevant CSpaces using capability operations. The CSpaces now mirror that policy and our capability-based SDN controller enforces it over the network. This essentially bootstraps the network with an initial coarse grained policy.

The primary advantage of the network enforcing policy-based access control (versus an ambient network) is that this approach of least privileged networking reduces the potential attack surface for a host (in a network). It also reduces damage (to other hosts in the network) when the integrity of a host (in a network) is compromised.

We have experimented with the following two policies: sandbox master policy and Role-Based Access Control (RBAC).

4.1 Sandbox Master Policy

This policy mirrors what we called *Master0* in the previous chapter. This allows specifying the master which has full control over a number of other nodes in the system. The policy manager grants the relevant capabilities (node capabilities to hosts in the sandbox) to the master.

The sandbox master, during its bootstrap, receives the capabilities granted as per the network bootstrap policy and now using the capability APIs it can decide on the nature of fine-grained collaboration among the other nodes in the sandbox. Thus the system allows policy evolution.

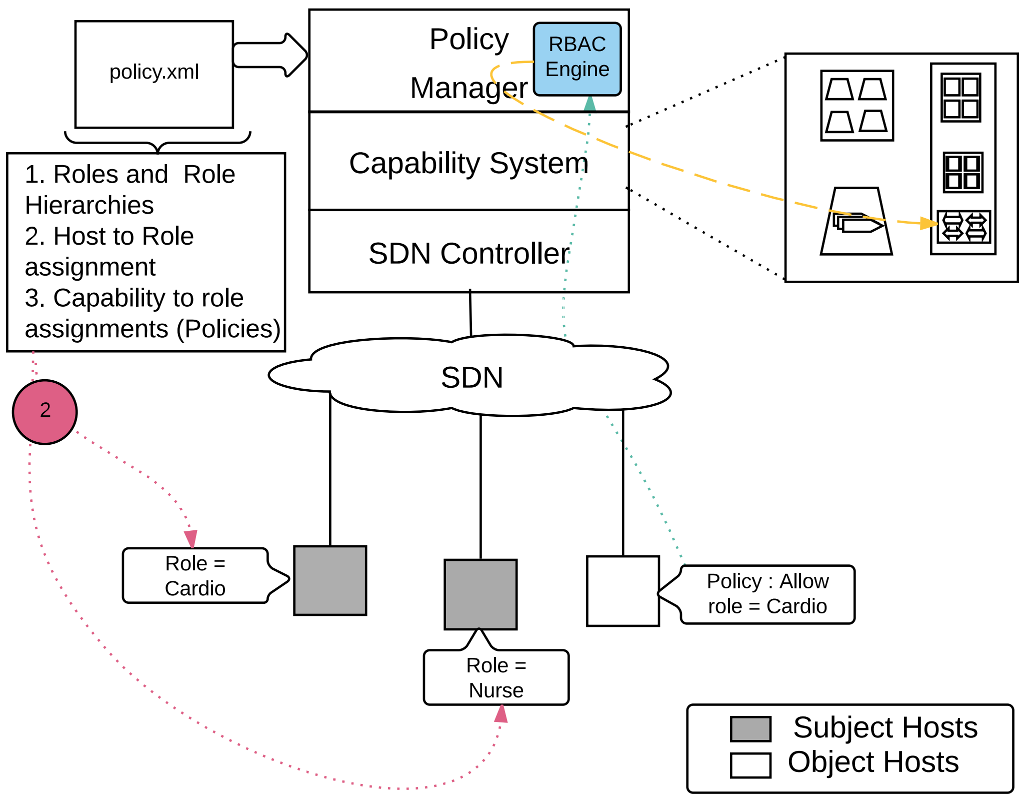

policy.xml
Policy Manager
RBAC Engine
Capability System
SDN Controller
1. Roles and Role Hierarchies
2. Host to Role assignment
3. Capability to role assignments (Policies)
SDN
2
Role = Cardio
Role = Nurse
Policy : Allow role = Cardio
Subject Hosts
Object Hosts

Figure 4.1. CeNet Policy manager and RBAC engine

Except for some implementation details later on, we do not discuss this further in this chapter as this corresponds to *Master0* bootstrapping *Master1* from the previous chapter.

4.2 Role-Based Access Control (RBAC)

Role-Based Access Control (RBAC) [49] is used for protection of resources in structured organizations like hospitals, universities and companies [50]. RBAC regulates access to resources based on the roles of individual users within an enterprise.

In addition to reducing the attack surface, introducing RBAC in our system simplifies the task of bootstrapping a large network with the correct access control policy. We observe that while the bootstrapping procedure as mentioned in the last chapter works well for a small network (providing fine-grained control), it might be overwhelming to specify it in the same fine-grained fashion for a large network. With RBAC, we do not assign capabilities directly to hosts (users); instead, we use RBAC to manage what capabilities a host gets. RBAC introduces the role concept; capabilities are assigned to roles, and roles are assigned to hosts.

RBAC Parameters and Policies: Consider a simplified hospital network scenario as given in Figure 4.2. We have hosts belonging to doctors (with varied specializations like cardiologist, physician etc.), nurses, and file servers (hosting medical records, payroll records etc). To simplify the policy specification, we choose to classify the hosts in the network as *subject hosts and object hosts*, where object hosts are data repositories like file servers and subject hosts are client devices from which those data may be accessed.

The following RBAC functionalities are supported by our system:

- Creating/specifying *roles* in the system. Some examples of roles from the aforementioned scenario are cardiologist, nurse, etc.
- *Host* to *role* assignment. Again in the context of our example scenario, this means, *host N1* belongs to a *physician* and *host n4* belongs to a *nurse*.
- Permission (*capability to a host*) to role assignment. Reachability (*flow*) to a particular host would naturally be the fundamental permission (*capability*) in our system. It is possible to augment this with other types of capabilities like admin (*node capability*), delegation (*rendezvous point capability*) rights, etc.

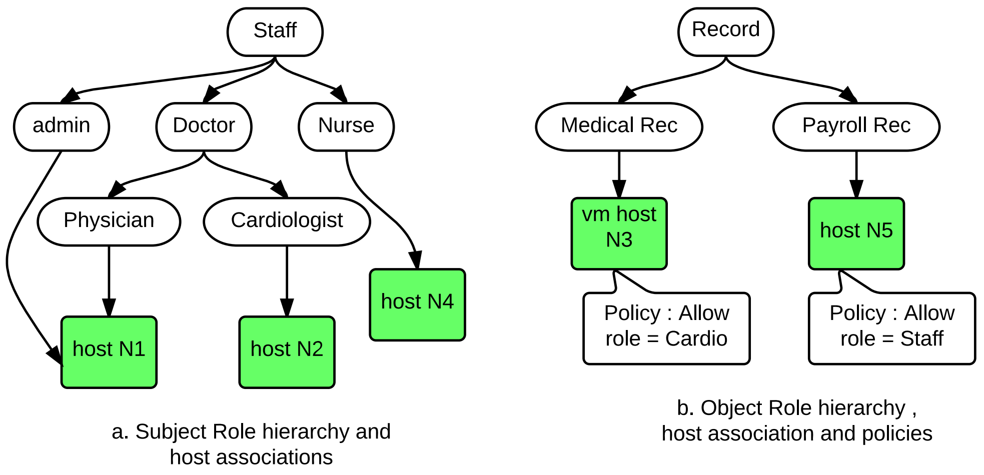

Staff
admin
Doctor
Nurse
Physician
Cardiologist
host N1
host N2
host N4
a. Subject Role hierarchy and host associations
Record
Medical Rec
Payroll Rec
vm host N3
host N5
Policy : Allow role = Cardio
Policy : Allow role = Staff
b. Object Role hierarchy , host association and policies

Figure 4.2. CeNet RBAC roles and polices in a hospital network

To be more precise the assignment of permissions to roles can be represented as a tuple:

$$(subj\_role \times capability\_type(FL) \times object\_role) \tag{4.1}$$

Note that for convenience our system allows to specify an *obj_host* instead of an *obj_role* as the third parameter in the above equation. An example of this from our sample scenario is $(doctor \times flow\_capability \times host\_N3)$ which allows connectivity between hosts that are assigned doctor roles and the object host *N3*. We synonymously call this association a policy. (Again, to be more correct, the whole policy of the network would be comprised of many such individual policy items.)

- Role hierarchies - RBAC has the concept of a role hierarchy, which is a natural means for structuring roles to reflect the lines of authority and responsibility in an organization. Figure 4.2 shows the hierarchy of roles in our hospital network scenario. We show general roles towards the top of the tree and specific roles toward the bottom.

  There is a natural concept of delegation (along the lines of organizational authority and responsibility) embedded in this role hierarchy tree. This allows us to obtain the desired policy granularity by specifying the policy in terms of roles at any level of the tree. Say for example, with reference to Figure 4.2, if a policy specifies $allow < staff > access\ to < hostN5 >$, this is enough to allow the cardiologist role to access *N5*, by virtue of being a more specialized version of the *doctor role*, which is a specialized version of the *staff role*. This further simplifies policy specification.

4.3 Realizing RBAC Policies Through Capability Operations

Assume the aforementioned four parameters — *roles, host to role assignments, permissions to role assignments, and role hierarchies* — are provided for an enterprise network. It is then possible to evaluate which hosts are entitled to receive which capabilities. This allows us to populate the CSpaces of our subject hosts, thereby enabling us to easily bootstrap the capability systems for our network.

Our policy manager in a sense precalculates the closure over all allowed connectivity between hosts based on the role-hierarchy tree and a given policy. Then it invokes the CeNet API to instantiate the lower-level polices in the appropriate CSpaces (thereby freeing us of the burden of invoking the capability APIs manually to realize a policy). This translation (closure calculation) is straightforward and more details are present in the implementation section.

4.4 Sample Use Case Scenario

Our system allows us to specify network access control in the form of a high-level RBAC policy. The policy manager consults an input file to gather *roles, host to role assignments, role hierarchies, and policies*, which are the basic parameters of an RBAC system.

Coming back to our hospital network scenario in Figure 4.2, one of the policy items specified is $(role\_cardiologist \times flow\_capability \times role\_med\_rec)$. During bootstrap the RBAC policy manager, based on the aforementioned RBAC parameters in the policy file, would identify the hosts between which the network should allow connectivity based on this policy. Based on this, it would invoke the CeNet API to instantiate the lower-level polices in the appropriate CSpaces.

For this simple case and policy, we have only one subject host with the role *cardiologist (host N2)* and only one object host with the role *medical record (VM host N3)*. As per the policy, the network would allow this interaction. The *cardiologist host (host N2)* can use the *flow capability* (endowed by the policy manager as a result of composing this policy) and data-path APIs to interact with the medical record host (VM host N3). Simultaneously, the switches would be programmed to recognize this flow capability and would route them to the relevant output port, which ultimately leads to the destination.

This system is sufficiently higher-level than the pure capability system, as the RBAC policy specified can be at a high level (based on coarse/fine roles), and the policy manager realizes the corresponding network access control using CeNet APIs. Mostly the end-hosts need to be only aware of the capability-aware data-path APIs. The creation and delegation of capabilities mirroring the high level policies are handled by the policy manager.

Discussion. It is possible to achieve RBAC and similar levels of delegation at a higher level (e.g., at the level of files) using capability-based authentication services (at the application layer) running over a traditional ambient network. But if the integrity of a host OS is compromised, these higher level protection schemes fail to be of much use in constraining the attacker from targeting other vulnerable hosts in the network.

The difference in our approach is that we are implementing security at a lower layer. This gives us the advantage that even when a host OS is compromised, policy-driven access control enforced by the network provides a layer of protection.

For example, in the event that a nurse's host is compromised, the attacker can only reach (attack) hosts that the nurse had reachability to. In a traditional network, assuming all hosts had some zero-day vulnerability in their network stack, the attacker would be able to target every host once it gains a foothold on the nurse's host.

4.5 Rich Sharing

Until now we have considered flow capabilities, which deal with subject to object host connectivity, and this is enough to realize a basic RBAC system. The policies are specified with respect to object hosts (object roles). Once bootstrapped, the policies are static in this basic RBAC system.

CeNet allows for a more dynamic approach by factoring in other types of capabilities like *node capability, RP capability etc*. CeNet allows delegation of flow capabilities at run time between permitted subject roles that are in unrelated branches of the subject role hierarchy tree. The policies that allow such delegation can be specified in terms of roles in the subject role-hierarchy tree. The format of such a policy would look like:

$$(subj\_role1 \times capability\_type(RP) \times subj\_role2) \tag{4.2}$$

A specific example of the above policy is ($role\_doctor \times RP \times role\_nurse$), which would create RPs between doctor hosts and nurse hosts (during bootstrap), thereby allowing a doctor to delegate a flow capability (to a patient medical record) temporarily to a nurse, if the need arises. This delegation can be done through capability APIs via the aforementioned RP.

The primary difference between this policy 4.2 and the former one 4.1 is that, here the policy involves two subject roles, whereas in the former the policy was between a subject role and an object role. This allows fine-grained delegation thereby allowing dynamism and policy evolution.

Use case: To appreciate the utility of fine-grained policies and delegation, it is necessary to consider a system with a large number of hosts, where each requires different policies. Assume a hospital stores medical records in a virtualized (cloud) environment where it would be possible to realize fine-grained, isolated access to such data. For example, as an extreme design point, each medical record might be made available via its own light-weight VM and virtualized network environment, so that CeNet network-level policies can be applied. For this part of our work we assume such an environment.

Assume that the RBAC *host to role* associations are as shown in the Figure 4.3 — i.e., hosts *h1, h2, h3* are *subject hosts* with roles of *admin, cardiologist*, and *nurse*, respectively. *lvm1* is an object host with the role *medical record container*. Assume that the *role-hierarchy tree* for this scenario corresponds to that of Figure 4.2. The following are the high-level policies specified:

$$(role\_cardiologist \times FL \times role\_medical\_rec) \tag{4.3}$$

$$(role\_doctor \times RP \times role\_nurse) \tag{4.4}$$

Based on the first policy item above, the *cardiologist host h2* would have access to medical record VMs. It is possible that many medical records match the object role of *role_medical_rec* and that the cardiologists would have access to all of them (as shown in Figure 4.3). Further, the second policy item would allow the *cardiologist host h2* to *delegate* the *flow capability* of a specific patient's medical record to his *nurse host h3* for some temporary purpose and later take the delegation back when desired. This shows the flexibility and granularity achieved by our approach of augmenting RBAC with capabilities and delegation. This achieves the flexibility of allowing an authorized nurse to access the medical record even though the pure RBAC policy (Equation 4.3 alone) does not allow this access. Conventional systems would require an administrator to set up an adhoc policy to allow nurse access or would require the doctor to hand over his credentials.

The following steps lists a workflow which demonstrates the utility of rich sharing:

1. During bootstrap the policy manager looks at the policy in Equation 4.4. The policy manager recognizes this as a *delegation* policy and identifies the matching hosts between whom RPs have to be created to enable controlled delegation. In this

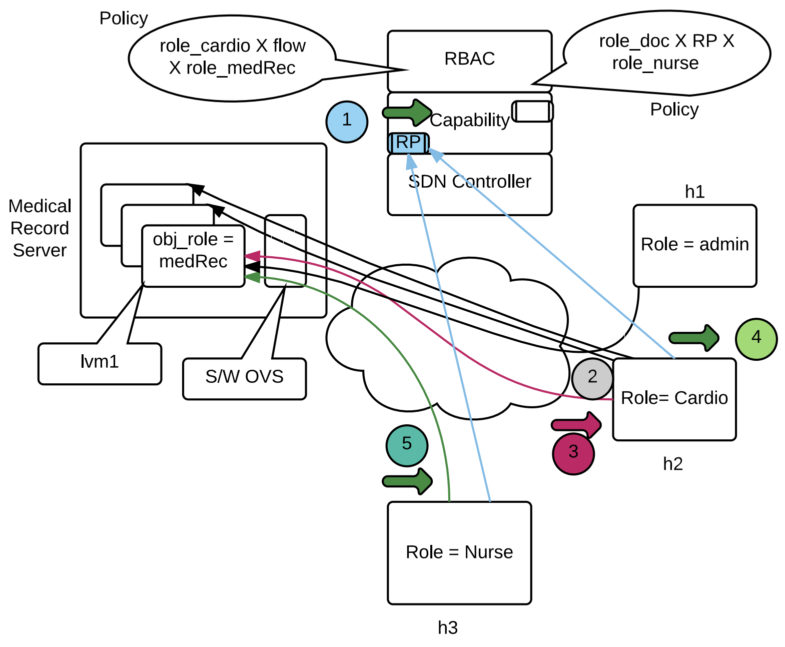


Figure 4.3. CeNet rich sharing scenario

scenario, it creates an RP between the cardiologist (h2) and nurse (h3), updates their CSpaces, and queues the capability to this new RP in their RP0s.

2. The policy manager consults the policy in Equation 4.3 and recognizes it as a *flow* policy. Based on this, it creates flow capabilies to the three medical records matching *obj_role* = *role_med_rec* and gives them to the only subject host matching the role *cardiologist* (*i.e., host h2*).

3. Using one of the above granted capabilities for (*lvm1*), *cardiologist's host h2* can access the medical record *lvm1*.

4. The cardiologist wants his nurse to update a patient's medical record. For this he delegates the flow capability of that patient's medical record to a nurse via the shared RP.

5. The nurse can access the patient's medical record via the flow capability received as a part of the above delegation.

6. The doctor can later revoke the previously granted flow.

4.6 Implementation

The policy manager sits above the capability framework on the SDN controller. Figure 4.1 shows the relative position of the policy manager with respect to the capability system and the SDN controller. The policy manager invokes the CeNet capability API directly as a function call (and not RPC - as is the case when hosts invoke it) to realize a policy. The policy manager consults a *policy.xml* file to input the bootstrap policy.

The policy manager currently supports two policies:

The **Sandbox Master** policy specifies the master host and its slaves. The policy realization in this scenario involves creating *RP0s* for all the hosts. In addition, *node capabilities* to all the slave nodes are queued up in the *master's RP0*. On booting up, the master can use the authority of these granted capabilities to write a control-path application (next level policy manager) using the CeNet APIs to realize a desired pattern of collaboration among the slave nodes, or designate a submaster and so on.

```
<sandbox>sandbox1<name> sbox1</name>
    <master>(2,1)</master>
    <node>(2,2)</node>
    <node>(3,1)</node>
    <node>(3,2)</node>
    <node>(3,3)</node>
</sandbox>
```

The above snippet shows a policy specification designating a master and its slaves. Note that the *tuple (x,y)* in the snippet uniquely identifies the host attached to *switch x's port y* in the *mininet* environment.

For the **RBAC** policy, the parameters mentioned in Section 4.2 need to be provided as input in the *policy.xml* file. A simple RBAC policy snippet related to our running example is given below, followed by an explanation of the tags.

```
<rbac>
    <SubjRole_Hierarchy>[("staff", "none") , ("doc", ["staff"]),
        ("nurse", ["staff"]), ("cardio", ["doc"]),
        ("physician", ["doc"])]</SubjRole_Hierarchy>

    <SubjRole_Assocn>[((2,1), ["cardio"]),
        ((2,2), ["nurse"]),
        ((3,2), ["physician"])]</SubjRole_Assocn>

    <ResourceRole_Hierarchy>[("record", "none"),("med_rec",["record"]),
        ("payroll_rec", ["record"])]</ResourceRole_Hierarchy>

    <!-- Jithu's medical record lies in (3,1)-->
    <RsrcRole_Assocn>[(((3,1),"jithu"), ["med_rec"])]</RsrcRole_Assocn>

    <policies>[("allow" , ("doc", "flow" ,((3,1),"jithu")))]</policies>
</rbac>
```

- Roles and role hierarchies are specified using tags $< SubjRole\_Hierarchy >$ and $< RsrcRole\_Hierarchy >$. Note that the contents of these tags loosely encode the hierarchy given in Figure 4.2.

- Host to role assignments are specified using tags $< SubjRole\_Assocn >$ and $< RsrcRole\_Assocn >$

- Policies and permissions to role assignments are specified using tag $< policies >$. Note that loosely encodes the relation $(role\_doctor \times FL \times host\_(3,1))$. Here, the third parameter in this policy is very specific (i.e., it specifies a host) and not a *role* like *med_rec* as in Equation 4.3. The policy manager is flexible enough to allow specifying either a role or a host as the third parameter of this policy.

The policy rules are composed in conjunction with the role hierarchies and role associations specified in the policy input file. The RBAC engine is based on a *simple-rbac* Python library. During the policy composing and capability translation phase, for every *object host* matching *parameter 3* of a given policy, the above module identifies the list of matching *subject hosts*. The policy manager uses this knowledge to create appropriate capabilities (*flow caps* in this scenario - illustrated in Figure 4.1) to the object hosts and queue them to the subject hosts RP0 using the capability operations discussed in the previous chapter. In addition, the policy manager creates RP0 to all hosts.

```
//In the Doctor host
cap_fl,cap_type = cap.rpc_recv(cap_rp0)
```

```
cap.send_data_udp(cap_fl, "GET medical record")
```

Those matched subject hosts can now operate using those capabilities as shown above. In this particular scenario of flow capabilities, the network switches would be configured to route data packets carrying flow capabilities to the corresponding object hosts.

4.6.1 Evaluation

4.6.1.1 Security Properties

The network is in an *off-by-default* state. As explained in the RBAC policy translation section, policy rules are composed in conjunction with role hierarchies and role associations specified. Only explicitly allowed hosts satisfying the policy are granted flow capabilities (allowed data path access to an object host) or given permission to delegate (by establishing RP between hosts matching policies) to another subject host.

In addition, since all policies are translated to capability operations, at any point looking at the CSpaces within the controller, we would be able to answer any reachability queries at present or a later point in time.

It should be possible to identify and explore a suitable metric which can quantify the security property better.

4.6.1.2 Ease of Use

The policy manager automates the task of realizing certain useful network access control properties as compared to the manual bootstrapping procedure. Also, as explained in the rich sharing section, the concept of delegation allows evolution from the initial state within the authority bounds.

Clearly we are not in a position to quantify this. It would be worthwhile to explore a suitable metric which can quantify this property better.

4.6.1.3 Scalability

The policy manager consults the policy file, instantiates the RBAC library with the parameters given in the input file, and identifies the matching flows and RPs to be created to enforce the policy. This is a one-time initial overhead and is not on any critical path.

The time taken by the RBAC library to identify the matching flows and RPs based on the policy can vary based on the number of hosts, roles, and shape of the role-hierarchy tree. A small issue we faced with the library was that, while it had an interface that was able to tell whether a given host matches a specific policy, it didn't have an interface that directly provided a list of all matching subject hosts (given a policy). Consequently we had to iterate over all the subject hosts, with the first interface to obtain the desired answer.

This makes the task of identifying if a given host matches a specified policy a critical one. Figure 4.4 shows the result of our analysis of the time taken by *simple-rbac* to determine if a subject host matches a given policy or not. The time increases as we increase the number of roles in the system.

We evaluated the worst-case time for this operation for a balanced binary tree host/role subject hierarchy layout (with host numbers in power of 2, with upto 16,384 hosts implying a depth of upto 14 role levels) keeping the object hierarchy tree constant. We observe that there is a slight increase in the worst-case time to complete this operation as we increase the number of hosts. However, for practical numbers the time per operation seems to be well within a reasonable limit. This overhead is incurred during the bootstrap phase, not on the critical path. It should be possible to write our own simple RBAC implementation, which provides our required interfaces and which should be able to answer this query in near-constant time.

The policy translation and realization involves the following additional overheads:

1. Creating flow capabilities for the matching hosts.

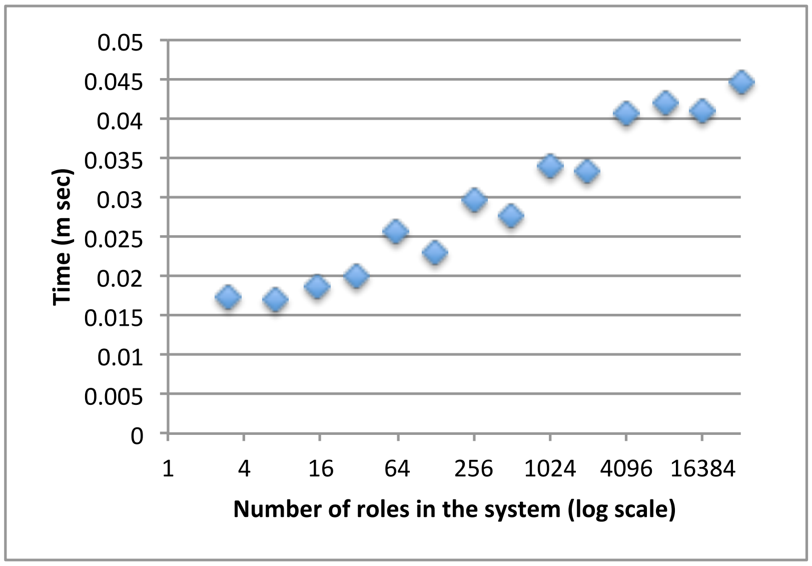


Figure 4.4. RBAC overhead

2. RPC overheads from object hosts to receive flow capabilities and invoke data transfers.

RPC overhead has been studied in the end-to-end analysis (previous chapter) and provides an idea of (2). Since the RBAC engine, policy manager, and capability system are within the SDN controller's address space, the overhead of (1) is negligible (much less than RPC overheads, as they are local function calls).

4.7 Summary

In this chapter we looked at how our network is able to enforce access control according to high-level policies by translating it into capability operations. Specifically we looked at RBAC policy in the context of a hospital network and augmenting RBAC model with the concept of delegation using capabilities.

The primary advantage of *network enforcing* policy-based access control (vs. ambient network) is that this approach reduces the potential attack surface for a host. It also reduces damage when a host is compromised.

CHAPTER 5

FORMAL REASONING

Capability systems allow formal reasoning about the access control allowed in a system. In this chapter we consider how such formal reasoning would apply in the CeNet system.

Specifically, we describe the *take-grant (tg) model* which is a classic model used to analyze the propagation of authority in a capability system. We capture the major results from a formal analysis of this model. We then discuss an example scenario about how rights propagate through a network capability system using well-defined graph transformations of the *tg* model. We conclude by saying how systems based on tg model and formal analysis give us the ability to reason about the correctness and security properties of the policy realized.

5.1 Formal Models and Security

In “Formal Models of Capability-Based Protection Systems” [51], Snyder states that protection systems are usually described informally with implementation details dominating the majority of discussions. Snyder further claims that the following pertinent questions cannot be answered merely based on implementation details or by looking at the code.

1. Does the system actually limit access to information to those users designated by the owner?
2. Can common sharing relationships actually be established with the given rules?
3. Under what circumstances can information be disseminated within the system?
4. What protection policy does the system implement?

A “model” favors an abstract formulation where questions similar to the above can be precisely stated and answered. In this chapter we attempt to deviate a bit from the hitherto implementation specific discussions and try to develop a minimal, intuitive study that aims to precisely state relevant questions and hopefully answer them in the context of network access control.

5.2 Take-Grant Model

tg protection model represents a system as a labeled directed graph whose nodes correspond to entities of the protection system. The directed edge from *subject s* to *entity e* denotes that s has α rights over e. Active entities are called subjects, passive entities (resources) are called objects and entity means either a subject or object.

$$\text{ⓢ} \xrightarrow{\alpha} \text{ⓔ}$$

Two special rights *take (t)* and *grant (g)* characterize this model. The meaning of these rights are:

- *Take* If Subject s has take right to an entity e then it can assume any right that e has to other entities in the system.
- *Grant* If Subject s has grant right to an entity e then it can transfer any right it has for other entities to e.

The dynamic state of the system moves from one protection state to another only using a fixed set of graph rewriting rules R. These rules transform the protection state of the system along a sequence of graphs $G_0, G_1, ..., G_n$ such that G_i follows from G_{i-1} by some rule in R. The analysis of the model focuses on answering if G_n has some particular property (like the undesirable propagation of an access rights implying a security violation). Typically the graph rewriting rules (governing transfer of rights) comprises of take, grant, create and remove. Additional system specific access rights like *read, right, etc.,* can be present. Invoking regular access rights (like read , write) do not transform the protection graph.

5.3 Modeling CeNet System

A capability grants some *right* to an *object or subject* (network host in our context of network) to its *owner* (another network host). This can be represented as a directed graph:

$$\text{Ⓐ} \xrightarrow{\alpha} \text{Ⓑ}$$

This can be interpreted as A has a capability to B with α rights. α can be a set with one or more rights. (The single edge represents multiple capabilities if $|\alpha| > 1$). For modeling our system, three rights are used: $R = \{flow, grant, take\}$. The *flow* right gives the ability for data transfer (A sending packets to B, through which attacker on A can try to compromise B), while the other two rights (*grant, take*) are control-plane operations — explained below — aiding in controlled sharing. Consequently, in our system, $\alpha \subseteq R$ for any edge. The protection state of our overall system captures all relationships concerned with information sharing within the network, and can be represented as a directed graph over all hosts in our network.

To make things concrete, let us take the example of the protection state of a simplified hospital network shown in Figure 5.1. The aim is to apply the *take-grant* model of rights propagation and view the results of a formal analysis of the model in the context of network access control. This example scenario is analogous to the computer science department example scenario from Snyder [51], which was in the context of access to files in a computer (with a different set of rights).

In our example scenario, the circles represent network hosts. We have the hosts of a medical professor, student resident, radiologist, medical researcher and a Head of Depart-

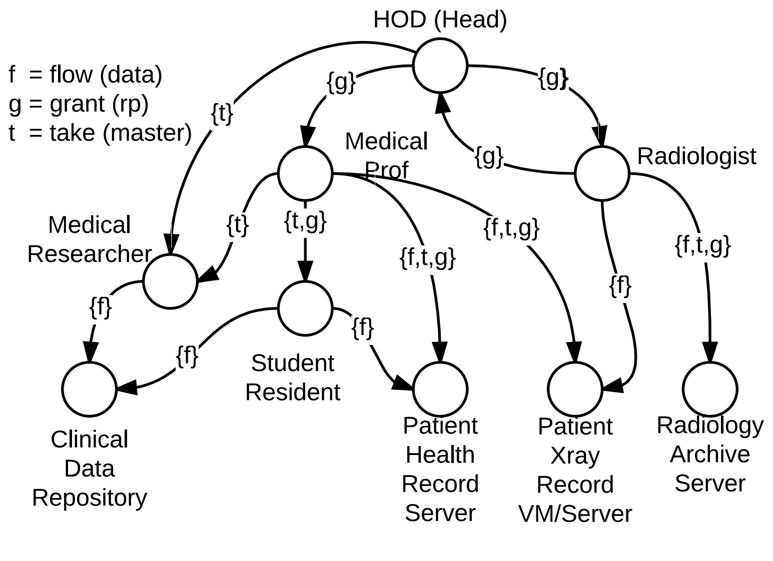


Figure 5.1. Protection graph of a simplified hospital network scenario

ment (HOD). In addition there are a few hosts serving data like a radiology archive server, an X-Ray record VM server, a clinical data server, etc.

The labels indicate the rights. Note that the radiology archive host is owned by the Radiologist and the access to this server is not shared with anyone (though rights may be granted to the HOD). The medical prof has access to a patient's X-ray record on an instantiated file server/VM, which he later intends to share with his student resident. The access to the X-ray record is shared with the radiologist and nobody else. The student resident has two roles. One role is of assisting the medical professor during patient consultation (consequently he has access to the patient health server) and the other role is that of an RA for a research project.

The protection graph abstracts the relationship among hosts at a point in time (say, the initial state). To answer the questions listed above, we must define the graph transformation rules. We closely model our graph-rewriting rules along the lines of the take-grant model. Let us look at the graph-rewriting rules allowed by our system:

- Grant: In our implementation, we call the exchange mechanism which facilitates the grant operation the rendezvous point.

  An application of the *grant* rule to the protection graph of Figure 5.1 would result in a graph transformation as shown in Figure 5.2. This transformation can be interpreted as "the medical professor grants (flow to the Xray record) to student resident." The effect of this operation is to establish a new sharing relationship that permits the student resident to have data path access (flow capability) to X-Ray record VM, so that he can do some analysis on the prof's behalf.

- Create: An application of the *create* rule to the protection graph that results from the above (grant) operation is given in Figure 5.3. This can be interpreted as "the student resident creates/instantiates a new object/VM containing his analysis of X-Ray report to which he has flow access."

- Take: This operation can be invoked by a host which possesses ownership over another host in the protection graph (in our implementation this loosely corresponds to a *node capability*). An application of the *take* rule to the protection graph from the above (create) operation can be considered next. This can be interpreted as "the

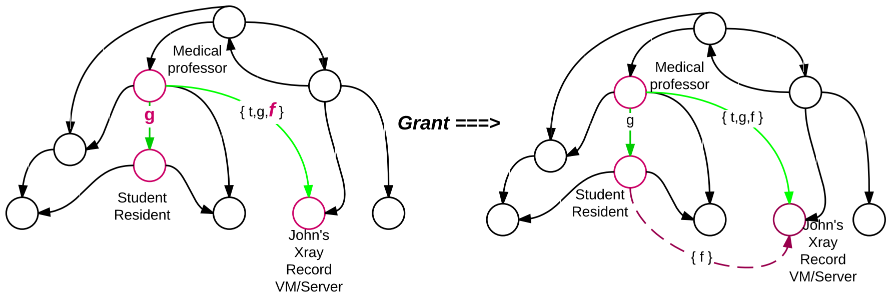


Figure 5.2. Grant rule applied to G0 [G0 is the Figure 5.1]. "The medical professor grants (flow to Xray record VM) to student resident."

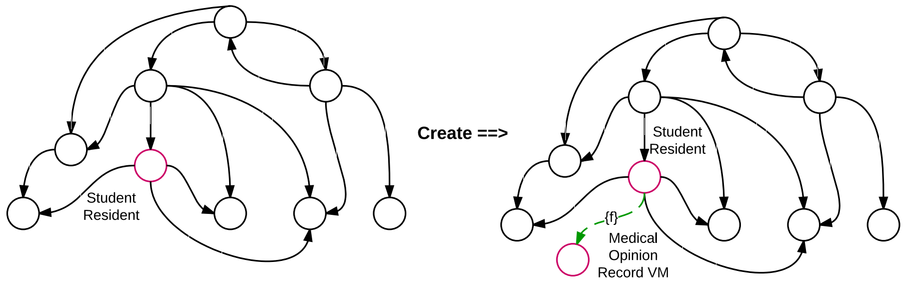


Figure 5.3. Create rule applied to G1 [Figure 5.2]. "The student resident creates/instantiates a new VM containing his analysis of X-Ray record to which he has flow access."

medical professor takes (flow to analysis) VM from student resident to whom he had 'ownership'." This is given in Figure 5.4.

- Remove: This operation can remove any subset of rights from an edge on the graph. This transformation can be initiated by node from which the edge originates.

Due to the similarities of our system with Snyder's take-grant model, in the following sections we attempt to summarize the main results and formal analysis of the model on his work (but adapted to fit our network model). We treat every host in the network as a subject and thereby effectively restricting *G* to a single colored graph (equivalent of saying every host can invoke take/grant, i.e., control path APIs) whereas in their formal model they

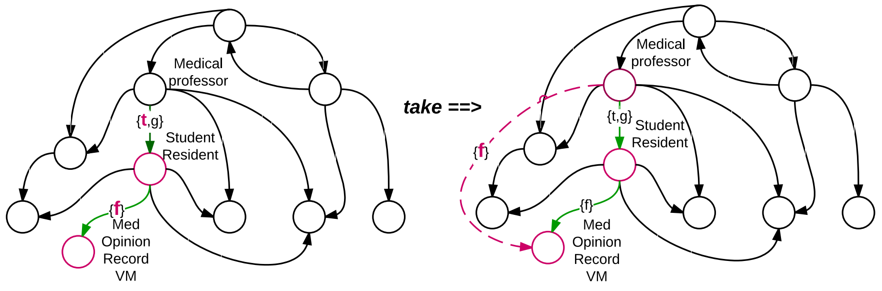


Figure 5.4. Take rule applied to G2 [Figure 5.3]. "The medical professor takes (flow to analysis) VM from student resident (over whom he has ownership rights)."

consider two colored graphs for modeling subject and object vertices distinctively (only subject hosts invoke take/grant operations). The results of two colored analyses would equally hold well in our case if we were keen on having a set of hosts that are not allowed to invoke control path APIs.

5.3.1 What Are the Questions ?

A relevant question for the professor would be

Can the X-ray record be stolen? (q.1)

The question *(q.1)* is a bit imprecise and we can make it more clear by asking:

"Can any host other than the medical professor or radiologist acquire a flow right to Y's X-ray record VM, without the professor or radiologist explicitly granting the right?" (q.2)

(q.2) puts the question in the perspective of our system and it clarifies *"stolen"* to mean that another host acquires *flow* rights (to Y's X-Ray record VM/server) without explicitly receiving it from either the *medical professor* or the *radiologist* who possess that in the original system.

We can express this more formally as: If there exists a sequence of rule applications $G_0 \vdash_{\rho_1} G_1 \vdash_{\rho_2} G2 \ldots \vdash_{\rho_n} G_n$ such that there is no rule $\rho_i (1 \leq i \leq n)$ where the *medical professor* or *radiologist* grants (flow to *X-Ray report*) to y for any y, and for which there is a vertex z in G_n (other than the radiologist or professor) with an edge from z to *medical-record VM/server* labeled f(flow), then *X-ray record* can be stolen.

Note that *take* and *create* make this question particularly challenging. For this particular case the answer is *no*. This is because no amount of allowed rule applications can result in another vertex (other than *medical prof* or *radiologist*) having an edge labeled *flow* to *X-ray record VM*. But if the *HOD* is permitted to *take* information from the *radiologist* (Figure 5.5) (may be intended to access some data from Radiology archive server) then Y's X-ray record can be stolen. A sequence of steps resulting in this is given towards the end of section 5.3.2.

The question can be generalized as given below

$$can.steal(\alpha, p, q, G)$$

The analogy to our example:

- $\alpha \implies$ the right being stolen (flow)
- $p \implies$ the recipient of the right (the student resident, the question is: is it possible for him to steal Y's X-ray record)
- $q \implies$ the right to whom is being stolen (X-ray record VM)

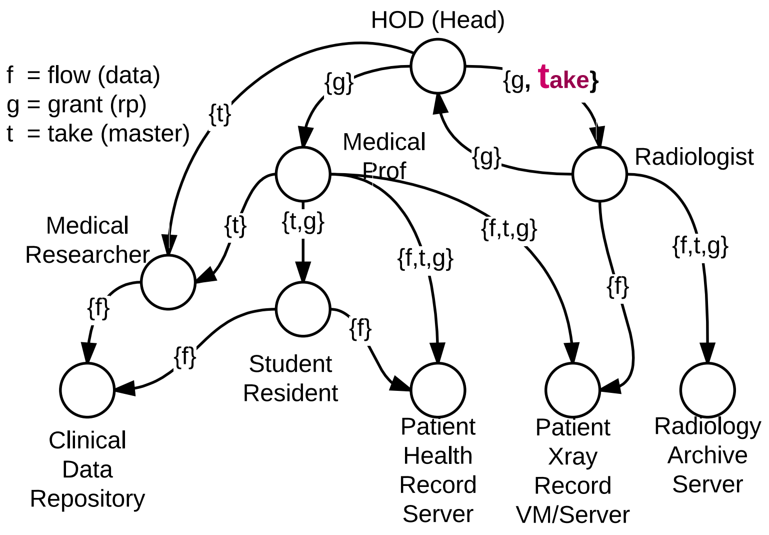


Figure 5.5. Protection graph in which the X-Ray record can be stolen

- $G \implies$ the original graph (G_0 from Figure 5.1)

We want to know the conditions which can result in *can.steal* being true for a particular graph G. This is crucial in answering our original questions regarding the model.

The condition of stealing is formally expressed with the help of another term *can.share*. In the following section 5.3.2, we define this term, then we express the conditions which can result in *can.share* being true. And finally we define *can.steal* formally and express the conditions which *can.steal* can be true in terms of *can.share*.

5.3.2 Sharing and Stealing

To share some right, the recipient host first needs to acquire relevant rights to the target host. As per our model this means that an edge from the recipient to the target must be added to the protection graph based on a valid sequence of graph transformations.

This can be written formally as below:

$can.share(\alpha, p, q, G_0)$. p can share (α rights to q) with someother host if and only if there are graphs $G_1, ..., G_n$ such that

$$G_0 \underset{\rho_1}{\vdash} G_1 \underset{\rho_2}{\vdash} G_2 ... \underset{\rho_n}{\vdash} G_n$$

and $p \xrightarrow[G_n]{\alpha} q$, which means that there is an edge from vertex p to vertex q labeled β and $\alpha \subseteq \beta$

We should appreciate the distinction between *take* and *grant* rights and *flow* rights in our system. *take* and *grant* rights have the ability to transform the protection state of the system (by applying the rules), whereas the flow right is of passive in nature and aids only in data path access to a host.

We say two vertices are *tg-connected* if, ignoring the directionality of edges, there is a path between them such that each edge on the path is labeled with t or g or both.

Theorem 1: $can.share(\alpha, p, q, G_0)$ is true if and only if the following two conditions hold true [26]:

Condition 1: There exist vertices $s_1, ..., s_u$ such that for each i, $1 \leq i \leq u$

$$s_i \xrightarrow[G_0]{\gamma_i} q \quad \text{and} \quad \alpha = \gamma_1 \cup ... \cup \gamma_u$$

Condition 2: p is tg-connected to $s_1, ..., s_u$

Intuitively, condition 1 states that some vertex (combination of vertices) in G_0 must possess the rights to the target. Condition 2 requires the existence of paths along which rights can be transferred from those vertices to the recipient p.

In our particular example, since the question is just about data path access to *X-Ray record VM*, a single right $\alpha = flow$ would suffice. However for a more general case, in our system α can be $\{take, grant, flow\}$

Discussion: In the formulation of *can.share*, complete cooperation from all relevant hosts in the protection graph was assumed. But in formulating the *can.steal* predicate, we assume that those possessing the rights will not cooperate in transmitting it, since otherwise "*steal*" does not make sense. In other words, an owner cannot claim a capability was stolen when he has aided in the dissemination of it [51].

$can.steal(\alpha, p, q, G_0)$ is true if and only if $!p \xrightarrow[G_0]{\alpha} q$ and there exist protection graphs $G_1, ..., G_n$ such that:

1. $G_0 \vdash_{\rho_1} G_1 \vdash_{\rho_2} G_2 ... \vdash_{\rho_n} G_n$
2. $p \xrightarrow[G_n]{\alpha} q$
3. if $s \xrightarrow[G_0]{\alpha} q$, then no ρ_i has the form s *grants* (α to q) *to* x for any $x \in G_{i-1}$

Informally it means that one cannot steal a right one already owns, nor can a theft occur if someone having the right in the initial graph *grant*s it away.

The condition under which rights can be stolen in a protection graph can be formally stated as:

Theorem 2: For vertices p and q in a protection graph G_0 and right α, $can.steal(\alpha, p, q, G_0)$ is true if and only if [52]:

1. $!p \xrightarrow[G_0]{\alpha} q$
2. there is a subject p' such that $p = p'$ or there is a tg-path between p and p'
3. there is a vertex s such that $s \xrightarrow[G_0]{\alpha} q$ and $can.share(t, p', s, G_0)$ is true (note that *can.share* talks about t and not α)

The theorem states that the right must be stolen directly from someone possessing it. The importance as per Snyder is that it is the *only* means of stealing the right.

The following sequence of steps tells how Y's X-Ray record may be stolen by the student resident in Figure 5.5.

The aim of the following sequence of operations is to set up a mail box between student resident and medical researcher — an innocuous activity from the professor's point of view.

1. Medical researcher creates a new object VM *m* (with $\{t,g\}$ rights).
2. Professor takes *(t to m)* from research assistant.
3. Professor grants *(t to m)* to student resident.
   comment- "steal" Y's X-ray record.
4. HOD takes *(g to m)* from Medical researcher.
5. HOD takes *(f to Y's X-ray record)* from radiologist.
6. HOD grants *(f to Y's X-ray record)* to m.
7. Student resident takes *(f to Y's X-ray record)* from m.

Discussion: From the definition of stealing, it seems the model is interested in finding out if anyone can get rights without the owners explicitly *granting* the right. And from the last theorem it looks like *take/create* is the path through which an unintended (nongranted) subject is able to steal a capability. The importance as per Snyder is that it is the only means of stealing the right. The intuitive interpretation of this theorem in a network context can imply that a rogue admin (admin can be modeled with take) is the path through which rights can be stolen.

The implications in network access control scenario are the following. Looking at the SDN controller capability datastructures (the current state of protection graph), it is possible to answer whether the network allows access between any given hosts. Further, the model is not very rigid and allows reasonable evolution from the initial state. Again, looking at the current state of the datastructures, the model would be able to answer whether any transformation can ultimately result in the network allowing access between a given pair of hosts (similar to the questions in Section 5.3.1). The model is decidable meaning it is possible to answer these questions in finite time.

Further, as shown in [52], it is possible to synthesize specific systems based on the analysis. The analysis enables us to make an informed choice as to which initial configurations to bootstrap the system into and it helps us determine what sharing can be achieved.

5.4 Conclusion

In summary we can say that a key property of take-grant capability system is the transitive, reflexive, and symmetric closure over all Grant connections. This closure provides an authority bound which is invariant over system execution. Our bootstrap protocol is designed based on this fact.

The theorems summarized with respect to classic TG model, especially the conditions for $can.steal(\alpha, p, q, G_0)$ have guided our model to be slightly different from the classic TG model. Similar to SEl4's modified TG system, we do not have the take-rule. This has the advantage of giving each subject control over the distribution of its authority at the source and we have this notion of reset operation. Removing the take rule and the addition of reset operation/node capability (which may be interpreted as a much lighter version of take) doesn't invalidate the desirable properties of TG model and a strong formal analysis would be able to provide tighter theorems in our case. We could come up with other predicates like *can.reach()* which might make more sense in a network scenario.

CHAPTER 6

RELATED WORK

6.1 Capability Architectures

Initially formulated by Dennis and Van Horn [18], capability systems became a popular mechanism for constructing secure, least-privilege environments in the areas of operating systems [10, 48, 53, 54, 55] and languages [24, 56]. For many years, capability access control was a target of misinterpretations [57, 58, 59]. The development of the object capability model [24] revived capabilities as a viable security abstraction for constructing least-privilege security environments [10, 16]. Miller et al. [19], and later Watson et al. [16], provide a good discussion of the advantages of the capability model for constructing practical security environments. The CeNet capability model builds on the design principles developed by the systems research community [53, 48, 47, 60]. Similar to seL4 [47], CeNet uses send and receive [61] to model the grant operation. Barrelfish extends the seL4 with support for scalable capability data structures [60]. The work on capability design patterns extends the basic capability model with the design principles for constructing secure systems in the face of mutually mistrusting principals and diverse security requirements [24].

Murray [62] provides an interesting discussion on principle of least authority (POLA) versus mandatory access control (MAC) and talks about a system called PULSE - Pluggable User-space Linux Security Environment, which implements a MAC-enforced, dynamic, user-level POLA implementation.

6.1.1 Take-Grant Model

The need for access control management arose in the 1970s and the notion of an access control matrix was introduced to keep track of which subjects have what types of access to which objects. The Harrison, Russo, and Ulmann (HRU) model [63] showed in 1976 that security is inherently undecidable in a conventional access control matrix. Specifically, for the HRU model, the question of whether a given right can reach a given subject, for a given set of macro commands, was undecidable. The underlying reason for their conclusion is the fact that users can give away access rights on their own initiative and without constraints.

To study under what conditions it was decidable, Jones, Lipton, and Snyder developed a model of protection called the take-grant protection model [26] in which questions of security were not only decidable, but decidable in time linear with the number of objects and rights [64]. Information and authority flow in the take-grant model is elegantly modeled using directed graphs and can be viewed as a generalization of the transitive closure problems [65]. The formal analysis of the TG model was studied by Snyder [51], who tries to answer questions as done in the previous chapter of this thesis.

Initially the tg model was used to analyze the transfer of authority (rights) through the repeated application of *de jure rules - take, grant, create , and remove*. These rules were useful in studying the case where the subject acquires direct rights (authority) to access the object (information). In 1979, Bishop and Snyder [27] added the notion of information (versus authority) transfer to the take-grant model by creating a set of rules called *de facto rules - post, pass, spy and find* rule. *De facto* rules are useful in studying the situation where the subject acquires the information without necessarily being able to get direct authority to access the information (e.g., by accessing a copy of the information with the assistance of others). These rules represent possible information flow paths in the graph using a new type of edge called *implicit edge*. Similar to *can.steal* and *can.share* from the formal analysis of classic tg model, here we have other predicates like *can.know* which can reason about flow of information. This might be a potential future exploration path in the network context for a network with even more stringent security guarantees.

The notion of theft of rights was introduced in 1981 [66], and described how one vertex acquires rights over another without cooperation of any owner of those rights. This was generalized to cover the theft of information [67], and was applied to the take-grant model to analyze a theft of information over a network [68]. This work came up with the predicates alluded to earlier like *can.steal* and *can.know* which can be useful in our network context as explained in the previous chapter.

Based on the TG model Shahriari [69] provides an approach to analyze network vulnerabilities and reason about the consequences of exploiting those vulnerabilities. Their approach of using the take rule to model a vulnerability is quite interesting and we can use a similar approach to model the effect of our administrative capability (node capability and reset operation) and understand the security implications in the presence a rogue admin.

Australian Governments Defense Science and Technology Organization's Annex [21] system's security and network architecture geared towards providing a Network Centric Warfare (NCW) platform — that can facilitate autonomous, mutually suspicious organizations to collaborate — is built on top of a distributed object-capability system. Annex claims tight integration of their very strong security architecture with next generation networking technologies as a unique contribution of their work. Their capability system's TCB seems to have a trusted component in both the device and the network. While the actual utility of their system was not very clear from the publication, their high level goals seemed to be in the direction of allowing a number of mutually suspicious, autonomous participants with differing security policies and interests to allow access to and sharing of networked resources within a Global Information Grid. In the face of their goals, it looks like the capability model is an apt framework for allowing collaboration among multiple parties with different goals, and CeNet was started with the observation that capability model can provide such similar goals (thus facilitating various interesting usecases) in a multitenant cloud provider network. While we haven't reached this end goal yet, this thesis takes the first step of replacing an ambient network with a network capable of enforcing dynamic policy driven access control (based on capability model).

6.1.1.1 Capability/Security Systems Based on the TG Model / Formal Reasoning

Summarized below are some popular systems which claim formal security as their advantage and which frequently comes up in capability and security communities.

The Security Enhanced L4 (SEL4) model is based on capabilities and modified take-grant model. Elkaduwe [70] prove that it is feasible to implement isolated subsystems using seL4 mechanisms, where an isolated subsystem can be viewed as a collection of processes or entities encapsulated in such a way that authority can neither get in nor out.

SEL4 model is slightly different from the classic TG model in that it is aimed at reasoning over the distribution and control of physical resources like memory. They do not use the take-rule in SEL4. This has the advantage of giving each subject control over the distribution of its authority at the source, and they have a more complex create rule.

Their proof shows that the desirable properties of TG still hold and can be generalized to a statement on full subsystems. They use Annabelle/HOL theorem prover which they claim is better than graph transformation.

Boyton [71] extends the aforementioned formalization by Elkaduwe with nondeterminism, explicit sharing of capability storage, and a delete operation for entities. He formally proves that this new high-level access control model of the SEL4 microkernel can enforce system-global security policies as well as authority confinement.

Sewell [36] proves that seL4 correctly enforces two high level security properties namely integrity and authority confinement. These properties are defined with reference to a user-supplied security policy, which specifies the maximum authority a system component may have. The integrity property gives useful guarantee conditions for components (e.g, a Linux guest operating system with millions of lines of code) without the need to consult their code. Based on these guarantees we can safely and formally compose such parts with the rest of the system.

EROS is a fast capability system for commodity processors whose higher-level security properties are based on the diminish-take [72] model, which is a variant of TG. Several design patterns in EROS, including confinement, protected subsystems, and user-supplied memory managers, are formally reasoned [72] using the formal analysis of this model.

The above two works indicate that systems based on the capability model provide much stronger security properties and much of their security claims has been formally verified. This was a motivation for exploring this security model in the context of network access control.

6.1.1.2 Capability/Security Systems Based on POLA

Many systems claim strong security benefits, just by removing ambient authority. In most cases this just means disallowing global name-spaces for user processes and allowing them to operate only on explicitly granted file descriptors (capabilities).

Plash (the Principle of Least Authority shell) [35] uses chroot() to take authority away from a process thereby preventing it from directly accessing the normal file-system. File descriptors to only the relevant files are then granted (like capabilities) to give only the required limited authority back to the process. This is achieved by linking applications to modified version of libc so that file open() operations are mediated by a trusted server that performs the open operation on behalf of application as per the policy. In default mode of operation to maintain compatibility with legacy apps, POLA is applied to files in the user's home directory.

CeNet proxy approach (Section 3.2.4) of seamlessly integrating legacy hosts into the CeNet syetm is quite similar to the approach taken by plash. The proxy intercepting protocol messages from the legacy client in CeNet system is quite analogous to the trusted server intercepting and mediating the open syscall in plash.

By adding capability primitives to standard UNIX APIs, Capsicum [34] gives application authors a means to realize least-privilege operation. Capsicum introduces capabilities and a capability mode that help in compartmentalization. Capsicum capabilities are an extension of UNIX file descriptors, and reflect rights on specific objects, such as files or sockets. Processes in capability mode are denied access to global name-spaces such as the file-system and PID name-spaces.

Polaris [33] is a package for Windows XP that allows users to configure the applications they launch with only the rights they need to do the job the user wants done. A polaris constrained application is launched in a restricted user account with few permissions (whereas the usual approach is to start an application using the user's account). Authority to access system libraries is provided to an application on startup. Also, when the the user chooses to open a specific file, the dynamic authority to that file is provided to the application.

6.1.1.3 Access Control Policy Systems

Few systems attempt to integrate capability-based access control mechanism with other access control models, with the aim of realizing flexible delegation and reduced administration cost. This motivation is quite similar to the utility of *rich sharing* scenario we explained in 4.5.

Capability-role-based access control (CRBAC) [50] model integrates capability-based access control mechanism into the RBAC model. It supports delegation of permissions and roles by capability transfer, said to be useful in clinical information systems scenario. One particular advantage they claim by basing their approach on capability model is that cross-domain delegation can be achieved without any authentication or administrator involvement. They claim that this makes flexible and smooth user-to-user delegation possible even in unusual situations such as an emergency in clinical systems.

While the motivation of *rich sharing* scenario we explained in 4.5 is similar to CRBAC above, the key difference is that we enforce access control in the network level and not in an application context as done in CRBAC.This gives us the security advantage that even when a host OS is compromised, the access control enforced by the network can play a key role in preventing the attacker from targeting other hosts in the network.

6.2 Networks and Capabilities

Capability concepts have been applied to networking in previous works, mostly in the context of denial-of-service (DoS) attacks. For example, capability tokens have been applied to the data path as a means to prevent DoS attacks [73]. In that work, senders were required to obtain tokens (capabilities) from potential receivers, and routers in the network were equipped to check the validity of the tokens. The capability mechanisms used in this earlier work are quite different from the classic capability access control model which forms the basis of our work. More recent work also proposed to deal with unwanted traffic through capability mechanisms, but instead of issuing capabilities, proposed to use dynamically changing IP addresses *as* the capabilities [74]. Superficially, this work is related to our approach of mapping legacy protocols to capability operations in a CeNet proxy.

In CeNet, no network communication is possible, unless explicitly allowed by a capability. As such our work is related to an earlier "off by default" approach [37]. This work explored the feasibility of an Internet-scale reachability protocol whereby a host could explicitly signal to the network its willingness to communicate with other hosts. Our work in CeNet is more pragmatic in that we limit our focus to SDN networks under a single administrative control.

The CloudPolice work [75] takes an approach that is philosophically different from our own. For access control in cloud environments they argue that the network should not be involved in this task at all, and that access control should be handled through hypervisor-based mechanisms. We argue that the CeNet approach, with the network enforcing policies, while the semantics of the policies are determined from capability enabled hosts, provides for a partitioning of functionality that allows a unique balance of flexibility and security.

CeNet utilizes an SDN substrate and as such is related to a variety SDN related works [43, 76, 77, 44, 78, 79]. The participatory networking work [79], allows control of an SDN network to be delegated to applications. This is somewhat similar to capability delegation in CeNet. However, the PANE work is about safely delegating network control, whereas CeNet delegates capabilities associated with network security access control.

CHAPTER 7

CONCLUSION AND FUTURE WORK

CeNet provides policy driven, fine-grained network level access control enforced in the core of the network (and not at the end-hosts) thereby removing network ambient authority. Thus CeNet limits the scope of spread of an attack from a compromised host to other hosts in the network.

We built a capability enabled SDN network where communication privileges of an endpoint are limited according to their function in the network. In pure capability mode hosts exchange rights, establish network connections and specify access control policies using the capability APIs which are mediated and controlled by the rules of the CeNet capability system. Rights propagate in a capability system through well defined graph transformations which gives us the ability to strongly reason about the correctness and security properties of the policy realized. Further, we built a policy manager which is able to realize a RBAC policy based network access control using capability operations. Finally we looked at some of the results of formal analysis of capability propagation models in the context of networks.

Thus we have proved our thesis statement "A network version of capability-based access control can realize a more secure network by allowing only explicitly allowed communications, and thereby removing the ambient authority present in current network architecture. It further enables delegation oriented policies to be realized within an enterprise network" to be true.

7.1 Future Work

- Basic networking capability: IP address and port have no relevance in a pure capability sense (and one can argue that they resemble the shared namespace which capability literature mentions as an attack vector). It is possible to eliminate IP and port from the packet structure and route the packet based on a flow capability which would encode both the destination host and the process / socket buffer.

Our current implementation of data-path APIs *send and receive data* achieves this by overloading the VLAN field to implement the flow capability, and we solely route based on this capability. This implementation in its current form does not consider multiprocess scenarios. One could implement a capability aware host-side networking stack capable of demuxing the packets into multiple socket buffers based on capabilities.

- High level policy: We explored the approach of realizing a high-level RBAC policy based network access control, by translating it into CeNet API operations. It is possible that other useful, high-level, policy-based network access control may be realized via this approach of translating to this intermediate point of capability API. Further, one could explore whether it is feasible to automate this translation from any high level policy to capability operations. One could also look into the usability versus security trade-off involved in manually hand-coding policy via capability API versus using high level-policy (and translating into a capability API).

- Formal models: We can use the guarantees provided by a capability based approach to develop tools that can answer practical questions about the guarantees of policies in real systems.

  Further, in our chapter on formal reasoning, we looked into the main results of capability systems based on the flow of rights (de jure rules). A more stringent system is possible based on flow of information (de facto rules). We need to understand the utility of reasoning based on information flow in the context of networks to understand if it makes sense in our setting. Pointers to the relevant related works were mentioned in the previous chapter [[27] , [67]].

- Use cases: We believe that the full blown utility of capability model is in multi-party scenarios, for example, a cloud provider setup where multiple isolated tenants share the cloud infrastructure, while making their own local policy decisions and co-operating (with other untrusted tenants) in a secure manner.

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