Identity and Access Management in Multi-tier Cloud Infrastructure

by

MohammadSadegh Faraji

A thesis submitted in conformity with the requirements
for the degree of Master of Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

Abstract

Identity and Access Management in Multi-tier Cloud Infrastructure

MohammadSadegh Faraji
Master of Science
Graduate Department of Electrical and Computer Engineering
University of Toronto
2013

The SAVI IAM is an identity and access management system for the Multi-tier cloud infrastructure. The goal of the SAVI IAM is to provide a flexible system to enable applications to adopt the cloud rapidly rather than concentrating on a specific function such as federation. The SAVI IAM distinguishes itself from previous work in three aspects: comprehensiveness, stability, and technology independence.The SAVI IAM is a comprehensive solution for cloud providers. It uses two fine-grained access control model: constrained Role-based Access Control and Attribute-based access control. To address application requirement, it has implemented delegation and trust mechanism to enable administrators to delegate their authorities temporarily to applications.

The SAVI IAM is scalable in the sense than it can address huge number of requests by increasing the number of instances. On the other hand, the middleware component is able to cache local data in order to boost the performance of the the infrastructure. The SAVI IAM is built on top of Openstack Keystone v2.0, and supports Openstack, Amazon EC2, and SAVI APIs.

Dedication

I dedicate my thesis work to my family. A special feeling of gratitude to my loving parents whose words of encouragement and push for tenacity ring in my ears.

Contents

1 Introduction 1

Introduction 1

1.1 Identity and Access Management in Multi-tier Cloud . . . 1

1.2 Motivation . . . 3

1.3 Research Questions . . . 3

1.3.1 Challenges . . . 4

1.3.2 Research Barriers . . . 4

1.3.3 Scope of Research . . . 4

1.4 Methodology . . . 5

1.4.1 Development Phases . . . 5

1.5 Organization of thesis . . . 6

1.6 Contribution . . . 8

2 Background and Related works 9

Background and Related works 9

2.1 Cloud Computing . . . 9

2.1.1 Cloud Characteristics . . . 9

2.1.2 Cloud Service Model . . . 10

2.1.3 Deployment Model . . . 11

2.2 Cloud Security . . . 12

2.2.1 Identity and Access Management . . . 14

2.2.2 Traditional Identity Management Model . . . 16

2.2.3 Cloud Computing Identity Management Models . . . 17

2.3 Multi-tier Cloud . . . 20

2.3.1 Smart Application on Virtual Infrastructure (SAVI) . . . 21

2.3.2 The Global Environment for Network Innovations (GENI) . . . 25

2.3.3 Conclusion . . . 28

3 Threat Modelling 29

Threat Modelling 29

3.1 Introduction . . . 29

3.2 Threat Modelling Techniques . . . 30

3.3 Threat Modelling . . . 31
3.3.1 SAVI Characterization . . . 32
3.3.2 SAVI Asset . . . 33
3.3.3 SAVI Threats . . . 33
3.3.4 Attack-Asset-Entry Relationship . . . 36
3.4 Conclusion . . . 36

4 SAVI IAM **38**

SAVI IAM **38**
4.1 Introduction . . . 38
4.2 SAVI Security Architecture . . . 40
4.2.1 AAA . . . 41
4.2.2 Configuration . . . 42
4.2.3 Registry . . . 42
4.2.4 Incident Handling . . . 42
4.3 Identity and Access Management . . . 43
4.3.1 Requirements Analysis . . . 43
4.3.2 Proposed System Design . . . 45
4.3.3 Identity Manager . . . 47
4.3.4 Policy Management . . . 48
4.3.5 Token Management . . . 48
4.3.6 Authentication Component . . . 49
4.3.7 Middleware . . . 50
4.4 Implementation . . . 51
4.5 Conclusion . . . 55

5 Access Control **56**

Access Control **56**
5.1 Introduction . . . 56
5.2 Background . . . 57
5.3 Requirement Analysis . . . 58
5.4 The Proposed Design . . . 59
5.4.1 Role-Based Access Control . . . 60
5.4.2 Attribute-Based Access Control . . . 61
5.4.3 Delegation and Trust . . . 64
5.5 Conclusion . . . 65

6 Performance and Scalability **66**

Performance and Scalability **66**
6.1 Introduction . . . 66
6.2 Requirement Analysis . . . 66
6.2.1 Scalability Issues . . . 67

6.2.2 Scalability Strategies . . . 68
6.3 Proposed Design . . . 69
6.3.1 Caching Layer . . . 70
6.3.2 Middleware . . . 72
6.3.3 Load balancing . . . 73
6.4 Performance Evaluation . . . 73
6.4.1 Apache JMeter . . . 74
6.4.2 SAVI IAM Setup . . . 75
6.4.3 Test Scenarios . . . 77
6.5 Conclusion . . . 80

7 Conclusion and Future scope **82**

Conclusion and Future scope **82**
7.1 Future work . . . 82
7.2 Conclusion . . . 82

Bibliography **84**

List of Tables

3.1 Attack Asset Relationship 36

4.1 SAVI Resources 47

6.1 SAVI IAM functions traffic 69
6.2 SAVI IAM System Characteristics 74

List of Figures

1.1 Multi-tier cloud infrastructure 2
1.2 Research Structure 7

2.1 Cloud service model and deployment model 12
2.2 Identity Lifecycle Management [21] 15
2.3 Multi-tier architecture 21
2.4 SAVI architecture 22
2.5 SAVI Logical Structure 23
2.6 SAVI component diagram 24
2.7 GENI Architecture 26
2.8 Conceptual View of ExoGENI software stack 27

3.1 Operation ”Aurora” Hit Google (Mid. 2009 Dec. 2009) [68] 31
3.2 SAVI Trust Level 32

4.1 SAVI Testbed Main Entities and IAM 40
4.2 SAVI TB Clearinghouse internal components 41
4.3 IAM Architecture 46
4.4 Manifesting Management UML Diagram 47
4.5 Identity Management UML Diagram 48
4.6 An Authentication Request 50
4.7 IAM Middleware Architecture 50
4.8 Openstack Keystone v2.0 Essex Architecture 51
4.9 SAVI portal homepage 52
4.10 Project Management Page 53
4.11 Join Project Page 53
4.12 Switch between projects 54
4.13 Switch between regions 54

5.1 SAVI Authorization Architecture 60
5.2 Core RBAC Model 61

6.1 Single Process IAM 69
6.2 Multi-instances IAM 70
6.3 caching model in the IAM 71

6.4 Load balancing over the IAM instances 73
6.5 Openstack Keystone v2.0 78
6.6 Single Process IAM 78
6.7 Full-featured IAM 79
6.8 Comparison of three evaluated systems 80

Chapter 1

Introduction

1.1 Identity and Access Management in Multi-tier Cloud

Cloud Computing is a new business model that abstracts underlying resources to share them among multiple disjoint customers. Over the past few years, cloud computing has transitioned from supporting web-based applications in a highly programmable infrastructure, and is now widely used. Depending on the abstraction layer, the resources can be hardware, programming tools or software. Cloud computing is built on four pillars: on-demand self-service, broad network access and resource pooling, rapid elasticity, and measured service [53].

Cloud computing has enabled hosting and delivery of services over the Internet as well as moving computation and data from terminal devices or local servers to core data centres due to flexibility, scalability, and economic savings [3]. Most services have been supported by massive-scale distant datacenters located at sites of renewable or low cost energy. However, some services require low latency (e.g. dense small cells with radio over fiber, alarms in smart grids, safety application in transportation, monitoring in remote health, fire or emergency alarms in smart cities), the processing of large volume of local information (e.g. video capturing in lecture rooms), or high security provided by intelligent converged network and computing resources at the edge of the network, for example in the premises of traditional telecom service providers.

Due to diverse range of application requirements, we need to provide a multi-tier model for resources. Each tier provides a variety of resource types with different properties, for example, the edge tier may be located near wireless access points and provisions low latency resources while a core tier can be in a massive data centre with huge amount of resources, but it inflicts a higher delay on the application. This multi-tier infrastructure provides an agile and flexible platform to address the design of future applications. The Smart Applications on Virtual Infrastructure (SAVI) testbed is an example of a multi-tier infrastructure.

Smart Applications on Virtual Infrastructure (SAVI) has been established with a focus on future application platforms designed for applications enablement [35]. The objective of the SAVI is to address the design of future application platforms built on flexible, versatile and evolvable infrastructure that can be readily deploy, maintain, and retire the large-scale, possibly short-lived, distributed applications that will be typical in the future applications marketplace.

As shown in Figure 1.1, SAVI considers a multi-tier cloud infrastructure to include Smart Edge

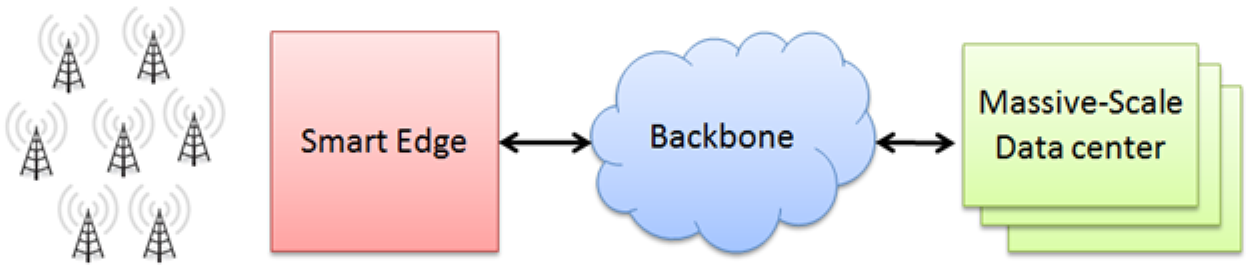


Figure 1.1: Multi-tier cloud infrastructure

where local players work together with remote massive-scale data centres to provide better services for Quality of Service (QoS) sensitive applications. SAVI investigates the hypothesis that all computing and networking resources can be virtualized and managed using Infrastructure-as-a-Service (IaaS). The Smart Edge should go beyond conventional cloud resources to address highly QoS demanding applications such as video distribution, fast and secure communication, wireless access controls, etc. In other words, the Smart Edge will be smaller-scale heterogeneous data centres including line rate processors, re-configurable hardware, graphical processors, specialized hardware accelerators and crucially future highly programmable networking equipment.

The Global Environment for Network Innovations (GENI) [20] is another multi-tier cloud infrastructure but with a different goal. Unlike SAVI which is looking for a unified management layer, GENI is looking for federating different testbeds or resource providers with different control and management plane. GENI provides a wrapper in front of a set of testbeds or resource aggregators so that it primarily maintains their independence, and secondarily provides a unified APIs for users. GENI focuses on handling user requests while SAVI is application-centric.

While multi-tier cloud computing addresses issues related to future application platforms, many research issues cut across such infrastructures. For example, infrastructures must support rapid application deployment; the overall control and management structure for such a cloud must be compatible with the control and management in the smart edge, and they must work together to support end-to-end application Quality of Experience (QoE); Adaptive resource management mechanisms must be designed so that the feedback loops they create remain stable; Pricing or other incentives must be built into resource allocation mechanisms to promote cooperation among different resource owners, for example service providers and application providers, virtual wireless operators and owners of access networks [73].

Along with these benefits and issues, security raises a severe concern in this setting. Moving an on-premise infrastructure to a remote location poses security risks to an organization data. Mather et al.(2009) list six primary concerns about security in cloud computing environment [44]: data-in-transit, data-at-rest, processing of data(including multi-tenancy), data lineage, data provenance, and data remanence (magnetization). We can protect data-in-transit through encryption and SSL/TLS; however, data at rest raises serious risks in case security is compromised. The first step to protect data at rest is to control access to it by both outsiders or insiders.

The Cloud Security Alliance (CSA) developed a list of most important security services in cloud computing environments and Identity and Access Management (IAM) is placed at the top [31] since many customers are wary of access control to their data in systems outside of their physical location. IAM establishes identity to help a resource provider to identify each user or application in the network, then it determines the identity of an individual or process (authentication), subsequently, it grants a correct level of access to it based on context such as user, targeted resource, and environmental attributes. Various models have been proposed to address identity management in cloud including central IAM, trusted third party, federation solutions etc. However, these are not effective for a multi-tier infrastructure where all resources are managed by applications. These prior architectures mainly focused on federation of cloud providers, and paid less or no attention to access management. Despite these models effectiveness for simple access management, such as an administrator delegating roles to users, they are not useful for complex situations in a multi-tier cloud (e.g. an application wants to acquire a resource on behalf of an administrator). Meanwhile, their heavy dependence on existing technology prevents deployment of new techniques, and as a result, their mechanisms are limited to the chosen technology at the design time.

1.2 Motivation

The motivation of the thesis is to propose an architecture to handle identity and access management in a multi-tier cloud computing. This architecture should be implementable on either private or public cloud, and independent of underlying technologies, geographical distance, and be interoperable with other infrastructure. Furthermore, it must maintain the positive features of cloud infrastructure such as elasticity. To future-proof the architecture, it should be open so that it can adopt new authentication and access management technologies.

1.3 Research Questions

Considering the motivation of this research and topics in background section, a research objective is defined. The research objective is to design and implement an architecture for identity and access management on Multi-tier cloud computing environments. This objective implies the main research question of this thesis:

What are the required elements of a scalable, flexible, and technology-independent IAM on a multi-tier cloud computing?

In order to answer the main research question, we pose multiple research questions:

- What are the various IAM architectures in traditional IT environments?
- What are the various IAM architectures in multi-tier cloud environments?
- What are the differences of the multi-tier cloud computing environments compared to existing IAM technologies?
- What are the essential elements of a suitable architecture?
- What are the risks of the proposed architecture?

The first research question requires an overview of traditional IAM architectures and the different technologies from the past. In the second question, we try to explain emerging technologies in identity and access management, and consider their pros and cons in cloud environments. The third questions explains our rationale to initiate this research, and identifies the deficiencies in existing solutions. When designing a new architecture, some risks are introduced to the whole infrastructure, such as performance overhead, bottlenecks, or new security risks. The last question explores these risks, and our solutions to deal with them. The answer to the main research question can be obtained by answering all of the above questions.

1.3.1 Challenges

The first challenge in designing this architecture is to keep components open to future technologies, this technology can be in the backend, such as database, memcache, or LDAP etc., or in processes such as authentication and authorization workflows. Decoupling backends from technologies, or even workflow from a particular technique needs a well-defined abstraction layer. Components can be located at distant locations and wrapped with web service APIs, or in the same node but with the access limited through defined interfaces. At the same time, each component must be coherent in the sense of having all the required functions to do its job. Performance and scalability considerations of the IAM bring about some issues regarding the degree to which components should be distributed and abstracted. If IAM is decentralized, we run into the challenge of data consistency and performance degradation, whereas a centralized IAM jeopardizes the whole infrastructure by making IAM a bottleneck.

1.3.2 Research Barriers

The lack of commercial open source IAM is the first challenge. To test other architectures thoroughly, we need to have access to their architecture or source code, and possible setup. Cloud providers and identity providers have little interest to disclose their security architecture information, although they provide general information about architecture or control processes. When a system is already implemented, there is no practical way to determine the efficiency of individual features as we do not have real access violation data. As a result, there is no accurate measurement to compare how much effective our architecture is to others.

The second challenge is the required effort of implementation and the required expertise. Because authentication and authorization is an essential element in all components in the cloud (e.g. computation, storage, and network etc.), any changes to this process need to make proper changes in corresponding components. Thus, developing IAM requires knowledge on the rest of the components as well, which makes developing and testing a time-consuming and complex job.

1.3.3 Scope of Research

Identity and access management and cloud environments are two broad topics, so, considering all details related to IAM is beyond the scope of this research. To complete the thesis and meet the research objective, we define the scope of this research as follows: There are three types of delivery models in cloud computing: Infrastructure as a Service (IAAS), Platform as a Service(PAAS), and Software as a Service (SAAS). IAAS enables users to work with virtual resources such as virtual machine, storage, and network directly while users can run their source code in PAAS, and SAAS allows them to use a prepared application with no worry about support-related issues. Our IAM aims to address identity and access management in a IAAS environment where all components serves users through web service technology. Meanwhile, developing the inner authentication and authorization mechanisms are not considered part of this research. In this research, we do not intend to develop a new algorithm for authentication or authorization, and we use backend technologies such as database and LDAP etc. in full.

We consider federation of cloud infrastructures in our design section; however, the implementation of such federation component to enable a cloud provider to be federated with other cloud providers will be future work. We implement our IAM system for one administrative domain and one cloud provider; however, we take federation into account in design section to allow IAM to be extended in the future. In the Mel and Grance model [47], we are concentrating on a privately owned cloud for deployment model and Infrastructure as a service for service model.

This research is taken from the point of view of a private cloud provider that wants to use an IAM solution to provide identity and management service throughout all its nodes across Canada. The requirements is gathered using literature review, and by discussing with SAVI design team.

1.4 Methodology

This research is based on the data gathered by literature review and identifying the new security risks posed by multi-tier cloud architecture and applications requirements. The literature review helped us to survey previous practices and theoretical background to recognize essential elements for our architecture and find right mechanisms that fit into our components. We examine the architecture of a multi-tier cloud infrastructure so that we can understand the components and their functions well. The second step involves recognizing the traditional IAM architectures and models. Subsequently, to create a solid theoretical framework, we perform a threat modelling to identify potential threats in this setting, and then list the mitigation.

After crafting a concrete theoretical background, we intend to design and implement IAM. We researched several methodologies that can be incorporated into our IAM development process. After an intensive literature review, we decided to proceed with a Spiral Model because:

- Short development cycle allows to quickly develop a prototype and test it on a real system
- Interfaces between parallel development in other components must be compatible. Because our testbed is based on service oriented architecture, failure in compatibility will result in system failure.
- Anchor points milestone - our testbed has a milestone for each release, therefore IAM along with other components must be evolved. To meet the milestones, we should use an iterative evolvable approach.
- Our requirements are not fully clear at the beginning, and the underlying technology also constantly changes.

Spiral model is a risk-driven software development and is based on the same premise of managing risks by expanding capabilities through increments in an evolutionary manner [5]. Our Spiral model has two distinguishing features, first it is a cyclic method for incrementally designing and implementing IAM, the other one is a set of anchor point milestones to make sure we address the requirements.

1.4.1 Development Phases

Our development comprises five phases: requirements, design, implementation, testing, and deployment. During requirements phase, the goal is to determine the design requirements of the IAM system.

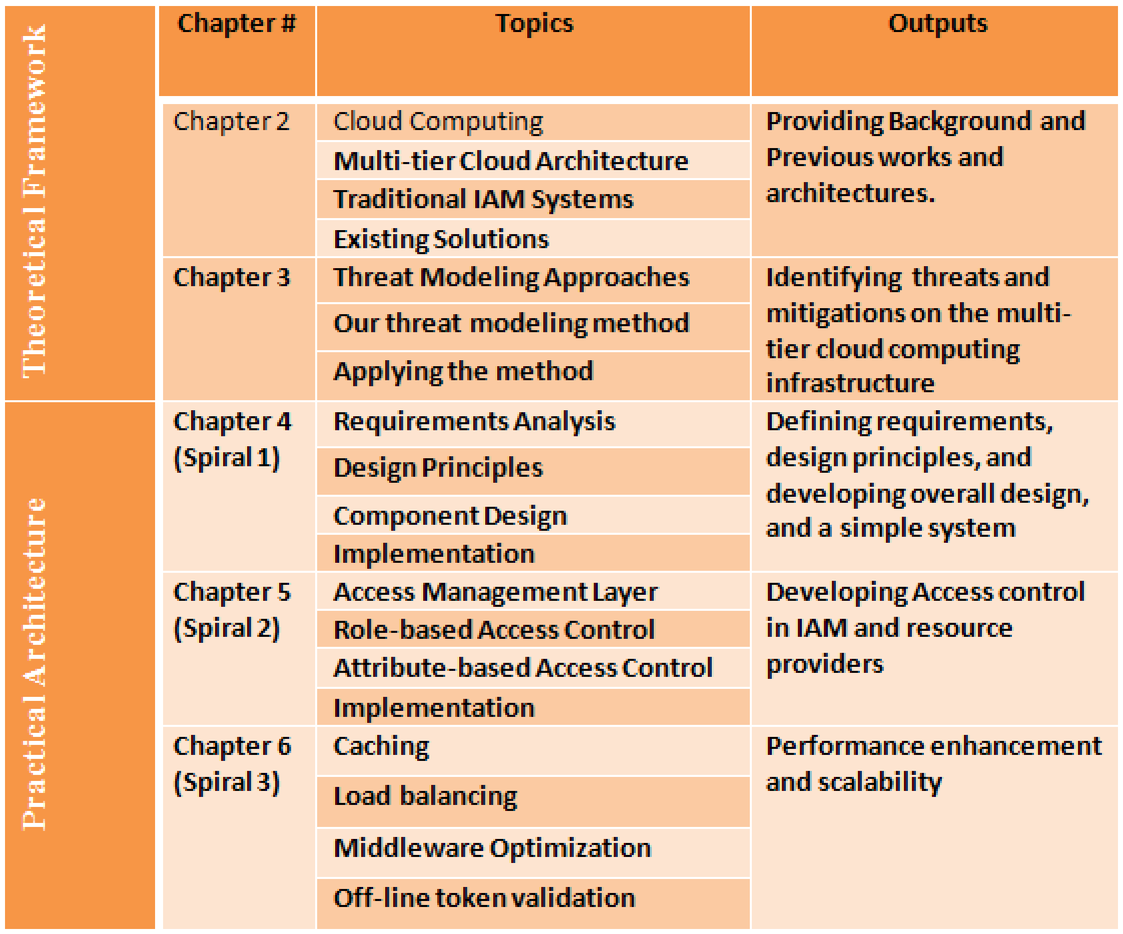
Requirements are the foundation to our system development. Vague, incorrect and incomplete requirements can jeopardize the project success. We receive requirements from several sources: previous IAM requirements, interviews of the development team, threat modelling, and industry standards [42]. In the design phase, we develop a conceptual architecture to address the requirements. Design provides a bridge between requirements and implementation, and it plays a major role in developing this system as most of security bugs find their origin in this phase [25]. Design is based on design principles, such as Least Privilege, Fail Safe, Minimizing Attack Surface as well as and design patterns such as Factory Class and Strategy etc. The output of the design phase identifies important components whose correct functionality is crucial for IAM, along with components properties and the interaction between them. This output gives an overall picture of IAM while ignoring detailed design and development. In the subsequent spirals if we identify new threats or change in priority of a threat which in turn necessitates changes in design.

In the implementation phase, we undertake to write a secure code to convert the design into a real system. Next the implementation is debugged. The development process requires constant testing to ensure that the new design does not break any functionality. We have two types of tests: security testing and functional testing. In security testing, testers leverage threat modelling data, and create some misuse cases to run on the software. Functional testing involves unit testing and integration testing where a component is tested to ensure it works and does not break its compatibility with other components. The final phase in our methodology is to deploy the IAM where the source code first goes through a security review to identify any remaining security flaws, and then it is deployed on the server.

1.5 Organization of thesis

This thesis is divided into two sections: theoretical framework and practical architecture. Theoretical framework creates a concrete mindset for our design decisions while the practical architecture deals with the system development. As Figure. 1.2 demonstrates Chapter 2 and 3 comprise the theoretical framework section. This section conveys the rationale of previous IAM designs and explores the architecture of two open multi-tier cloud infrastructures. A clear understanding of multi-tier cloud architecture is necessary to perform a comprehensive threat modelling in the next chapter. We survey the current threat modelling approach, and choose one of them. After applying some changes to fit into our requirements, we conduct threat modelling on the SAVI IAM. We identify potential threats, mitigation and attack surfaces, and classify them into groups. This chapter gives the reader the rationale behind some design decisions, where there is not well-known principle or design pattern in literature.

The second section designs the IAM architecture where each chapter maps to a spiral in the lifecycle of our software system development. In chapter 4 (spiral 1), we gather all requirements, design principles, and produce a preliminary design of our system. This design (as per Spiral methodology) is followed by implementation. We implement the architecture with the simplest mechanisms for components e.g. empty role in access management. Next we deploy and test the system on a real infrastructure. Although there is no explicit part for requirements gathering in the following chapter, it is carried out before each design phase. Chapter 5 concentrates on access management where we pursue an evolutionary approach starting from Role based access control (RBAC), and wind up to a high-end authorization method named Attribute Based Access Control (ABAC). In Chapter 6, we concentrate on scalability and performance. We introduce some techniques to boost performance and enable the IAM to scale up



	Chapter #	Topics	Outputs
Theoretical Framework	Chapter 2	Cloud Computing	Providing Background and Previous works and architectures.
		Multi-tier Cloud Architecture	
		Traditional IAM Systems	
		Existing Solutions	
	Chapter 3	Threat Modeling Approaches	Identifying threats and mitigations on the multi-tier cloud computing infrastructure
		Our threat modeling method	
		Applying the method	
Practical Architecture	Chapter 4 (Spiral 1)	Requirements Analysis	Defining requirements, design principles, and developing overall design, and a simple system
		Design Principles	
		Component Design	
		Implementation	
	Chapter 5 (Spiral 2)	Access Management Layer	Developing Access control in IAM and resource providers
		Role-based Access Control	
		Attribute-based Access Control	
		Implementation	
	Chapter 6 (Spiral 3)	Caching	Performance enhancement and scalability
		Load balancing	
		Middleware Optimization	
		Off-line token validation	

Figure 1.2: Research Structure

with the increasing number of the requests. We prepare the IAM to run on a production level environment such as SAVI. We discuss approaches to boost the performance, and we identity the bottlenecks for this architecture. We run performance measurement experiments to show our features have a reasonable impact on performance compare to similar cases in our baseline of implementation or other identity providers.

Future work deals with federation issue whose implementation is beyond the scope of this research. We perform requirement analysis and develop a rough design. This chapter manages federating with massive resource providers such as cloud providers (e.g. Amazon EC2 etc.) and other testbeds. We discuss authentication and authorization in order to prepare a plan for our future work.

1.6 Contribution

In summary, this research makes the following contributions:

- We design a comprehensive architecture for a centralized IAM in a multi-tier cloud infrastructure.
- We propose three performance enhancing techniques of the IAM for scalability: load balancing, caching, and middleware.
- We propose a fine-grained policy-based access control for trust-relationship management.
- To test our proposed IAM on the Canadian SAVI Testbed.
- Using the testbed, we have shown that the IAM outperforms the previously proposed IAM for cloud infrastructure in throughput and response time.

Chapter 2

Background and Related works

2.1 Cloud Computing

The term *cloud computing* first appeared nine years ago when Amazon web-service was introduced, but the idea of renting resources is not new; consequently, cloud computing has many antecedents. Various definitions of cloud computing and its related applications have appeared in both in scientific and business literature. The roots of cloud computing lay in the idea of computing as a utility (like water and gas), and are closely related to the development of Grid computing. Vaquero et al. [67] attempted to produce a standard definition of cloud computing:

> Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically recongured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay-per-use model in which guarantees are oered by the Infrastructure Provider by means of customized SLAs.

Cloud infrastructure consists of three essential elements: the client, grid computing, and utility computing. Grid computing incorporates multiple independent machines into a large network, allowing computer resources to be efficiently managed. Clients can connect to this grid through a public network such as the Internet. Utility computing is used to share resources between users and keep track of each users usage, enabling the cloud to charge users for resource use on a pay-as-you-go business model.

Organizations may use cloud computing resources to process data, store information, enhance productivity, and manage services such as accounting, communications, or customer service. The main draw of cloud computing for organizations is that it eliminates the need for them to have their own dedicated data centres. Instead, computing services can be provided on demand in a similar manner to traditional utilities such as water and gas. Organizations pay only for the services they use in a pay-as-you-go business model. For example, Amazon AWS clients are charged according to type of virtual machine used, time of usage, and storage space used.

2.1.1 Cloud Characteristics

As with the very definition of cloud computing, essential characteristics of the cloud network also vary from one provider to another. The National Institute of Standards and Technology (NIST) defines five essential characteristics of cloud computing system [48]:

- On-demand Self-service: A client should be able to acquire or release resources without requiring outside human interference.
- Broad Network Access: Resources should be available over the network, and a client should be able to access resources through standard mechanisms by using thin (e.g. Smartphones) or thick (e.g. PC) clients.
- Resource Pooling: Resources are pooled to serve disparate customers on the same or different physical machines. Resources can be dynamically assigned according to customer demands. Clients should not be aware of the source location of lower-level computing services, but should be permitted to specify higher-level locations (e.g. country of origin). Resources can include computation, storage, networking etc.
- Rapid Elasticity: Clients can acquire, release, and scale resources in an elastic manner, making the available resources appear unlimited from the clients point of view.
- Measured service: The cloud management layer constantly monitors, controls, and reports resource use to both the provider and client, providing a metering capability.

2.1.2 Cloud Service Model

Commercial cloud computing services are typically divided into three service models, distinguished by their level of resource abstraction [48]:

- **Infrastructure as a service (IaaS):** This model offers virtual resources to users. Users can directly connect to computation and storage and run their own software using these resources. In this model, the provider delivers the hardware (server, storage, and network), and associated software (Hypervisor, Operating system, or file system). This model is similar to traditional hosting services, but clients do not commit to any single resource, and can dynamically scale their resource use. To deploy their applications, customers move an operating system image to a virtual computing slice. In this model, customers often manage maintenance and patching themselves. Amazon EC2 and Google Compute Engine are two examples of this model.
- **Platform as a Service (PaaS):** The PaaS provider delivers a platform on which a customer can develop and deploy their codes. In this model, customers do not interact with virtual resources directly. This offloads the burden of maintaining, patching and managing the underlying infrastructure to the PaaS provider. PaaS mainly comprises infrastructure, development tools, databases, and some middleware. Scaling of applications is often carried out by the cloud provider, but in terms of complex backend development such as data lineage, this model is extremely limited. The two examples of PaaS are Google AppEngine and Herkou.
- **Software as a Service (SaaS):** SaaS the dominant cloud computing service model. In SaaS, applications are hosted remotely by a service or an application provider, and provide service on demand over the Internet. Clients share only their data with cloud provider. There are numerous examples of SaaS such as Gmail, Google Calendar etc.

2.1.3 Deployment Model

There are four basic deployment models for cloud computing computing:

- **Public Cloud:** The public cloud is the most well-known cloud model. In this system, clients use third-party resources in a fine-grained, self-service manner over the Internet. Resources are mainly accessible through web applications or command-line interfaces. The cloud provider periodically measures and bills used resources on a utility computing basis [57].

- **Private Cloud:** Private clouds provide organizations with their own dedicated data centres. The main driver for the adoption of private cloud computing is for organizations to maintain greater control of their data, an ability typically lacking in public cloud systems. However, this model requires a certain level of engagement and expertise to set up and maintain. There are two types of private clouds:

  - **On-premise:** This is a cloud system which has been integrated into an organizations IT process. An organization can use available software such as Openstack to run a cloud service on its own hardware. This model is also known as an internal cloud, and provides the greatest degree of control over a clients data. On-premise clouds are better suited for organizations which desire greater configurability and control over their data infrastructure [70].
  - **External Private Cloud:** In this model, a private cloud platform is hosted by an external cloud provider, but with the guarantee of privacy. There are two strategies for creating a private cloud on a third-party datacenter. The first is to create a separate zone with separate physical machines. Such isolated networks on Amazon EC2 allow US Federal Government agencies to move their sensitive data and computation to the cloud while maintaining compliance with their own internal standards and regulations [27]. This approach is not feasible for most private companies due high cost of setup. The second approach is to provide a bare metal service to clients, whereby physical hardware rather than virtual machines are allocated to customers [12].

- **Hybrid Cloud:** In this model, the cloud infrastructure consists of a combination of two clouds (private and public). The Hybrid deployment model enables organizations to retain the data in the private cloud while performing computation tasks on the public cloud. Therefore, the organization combines the privacy of the private cloud with the infinite resources of the public cloud. Cloud bursting is a common practice for expanding resources across multiple cloud or load balancing between independent infrastructures. Cloud bursting allows an application to run in a private cloud, but acquire additional resources from external clouds as needed. The advantage of cloud bursting is that organizations can perform the vast majority of their computing on their own private network, paying only for extra public cloud usage during peak hours [51].

- **Community Cloud:** In this model, the cloud infrastructure provides resources exclusively to organizations with similar cloud requirements in order for them to work together and achieve their business objectives. Such an arrangement might be managed by one of the member organizations or a third party.

Figure 2.1 illustrates the organizational distinctions between the four different cloud deployment models:

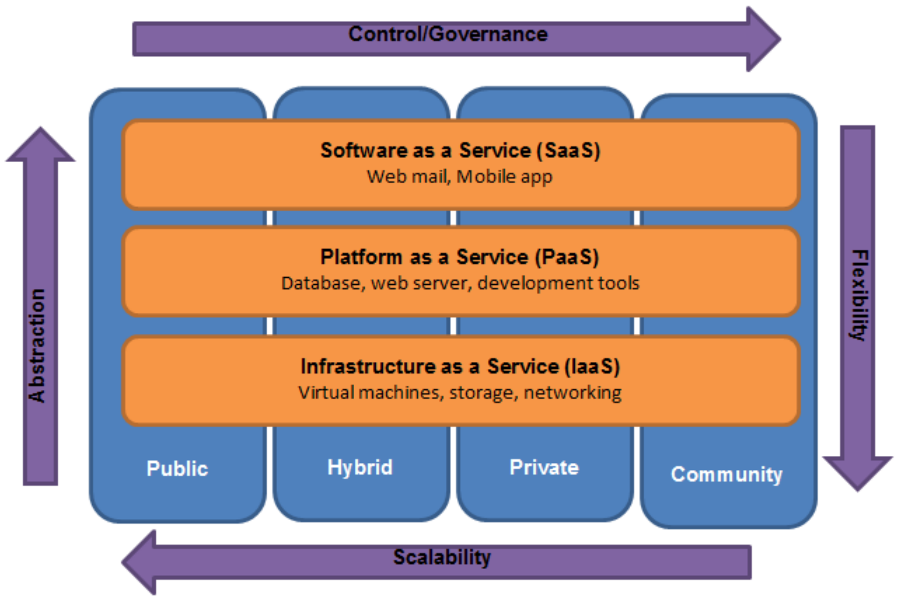

Control/Governance
Software as a Service (SaaS)
Web mail, Mobile app
Platform as a Service (PaaS)
Database, web server, development tools
Infrastructure as a Service (IaaS)
Virtual machines, storage, networking
Abstraction
Flexibility
Public
Hybrid
Private
Community
Scalability

Figure 2.1: Cloud service model and deployment model

2.2 Cloud Security

While cloud computing demonstrates clear advantages, migrating to a cloud-based system poses security risks to an organizations data. Kandukari et al. [34] consider seven cloud security issues that organizations should include in their Service Level Agreement:

- **Privileged user access:** Privileged user access ensures that only authorized users have access to an organizations data and resources
- **Data location:** Data location risk considers the comparative security risk of storing and processing data in one location (e.g. county) over another. The inherent level of uncertainty over where in the cloud data will be stored necessitates the encryption of data before its introduction into the cloud.
- **Data segregation:** Because of multi-tenancy nature of the cloud computing model, data from different users can be stored in the same location. This creates the risk of breaches to the isolation layer, which can compromise other users resources and data. There should thus exist a clear boundary at different abstraction layers to segregate each users data.
- **Data disposal:** Because the data is located outside of an organizations territory, data loss is always a risk. Therefore, cloud providers often keep multiple copies of data as backup. Data disposal considers the risk of data remaining in the cloud after a user leaves, and ensures that all unused data is wiped out.
- **Recovery:** Organizations must explicitly defines how data is recovered in the case of failure.
- **Investigation:** Investigation imposes contractual commitments on cloud providers to support measurements of services and used resources.

- **Long viability:** Long viability assures users that data is available even after the contract is broken.

Research challenges in cloud computing security can be divided into 6 categories [66]: Authentication and identity management, access control and accounting, trust management and policy integration, secure services, privacy and data protection, and organizational security management.

- Authentication and Identity Management concern the federation of cloud users identities, enhancing authentication, developing architectures, and the security of users identities. Data segregation should be applied to users identities and personal information as well.
- Access Control and Accounting researchers propose access control models to protect users data in the cloud. These models should be flexible enough to provide a fine level of access for users and applications and to enforce the principle least-privilege and separation of duties. Such access control must incorporate privacy-preserving requirements expressed through a set of rules. Some researchers propose a policy-neutral access control framework for proper interoperability. Cloud provider constantly perform accounting of users and applications to issue bills for them which should not violate the privacy of users. Therefore, privacy is a major concern in both Access Control and Accounting.
- Trust Management and Policy Integration address heterogeneity among the cloud provider policies and security frameworks. Applications might use multiple cloud providers to offer services; therefore, security measurement is required to to ensure such a dynamic collaboration is managed securely, and that security breaches are avoided during the interoperation process.
- Secure Service Management addresses quality of service, price, and service-level agreement in service search and composition.
- Privacy and data protection is the core challenge in the cloud computing. Mather et al. [45] list five main security risks to user data in the cloud: data-at-rest, data-in-transit, processing of data, data lineage, and data remanence (magnetization). According to this classification, a users data can be compromised in five different states: when data is in storage, traversing the cloud network, processing in virtual machines, remaining in cloud after the user is left. To protect stored data, users can use encryption algorithms. Users can use SSL/TLS to protect data-in-transit, and homomorphic algorithms for data-in-process. Cloud providers provide provenance records to track ownership and process history of data objects in the cloud [43] and ensure customers that data is processed correctly. Provenance of information can be used for traceback, auditing, and history-based access control [40, 72].
- Organization Security Management helps organizations to adopt cloud computing. When an organization moves to the cloud, new risks are introduced such as shared governance, availability and incident handling, data leakage, resiliency issue, and insider attacks. This category of research is mainly focused on developing life-cycle models, risk analysis and management processes, penetration testing [36], and service attestation [11].

The remainder of this chapter concentrates on Authentication and Identity Management research. In Identity Management, both traditional identity management models and existing solutions for cloud computing are explored. Next, the concept of multi-tier cloud computing and the prototypes such as Smart Application for Virtual Infrastructure (SAVI) and the Global Environment for Network and Innovation (GENI) are considered.

2.2.1 Identity and Access Management

Identity refers to a set of user attributes, an application, or a thread of executions that helps distinguish entities in the cloud from one another [1]. Identity management is a combination of processes and technologies used to manage and secure access to data and resources, and to protect user information. It is composed of two main processes: establishing an identity (which can be carried out during initial registration), and user authentication. Identity establishment is the process of associating a user, running process, or thread of execution with a legitimate cloud entity, and is the cornerstone of user access control policy. Managing identities is a challenging task in cloud security, as organizations tend to use multiple cloud providers for resource provisioning while maintaining a single identity in order to manage access to these resources. The four parties are involved in identity management process are as follows [7]:

- **Identity provider:** issues identities, and manage identities in subsequent operations
- **Service Provider:** provides the service or resource for which a user must be authenticated
- **Entity:** makes the claim about an identity
- **Identity verifier:** performs authentication to verify the claim of an entity

To authenticate a user, the identity verifier makes use of one or more following factors:

- Information that both parties know, such as a password
- A token that a party owns which can distinguish its identity such as One Time Password Kit (OTP).
- An attribute unique to the entity, such as biometrics (fingerprints, voice recognition etc.)

An identity manager should have the following capabilities in order to deliver identity services in cloud computing [9]:

- **Identity provisioning/deprovisioning:** An identity manager should be able to assign and revoke the identity of an entity in the cloud in a secure and just-in-time manner.
- **Authentication:** This is the process of determining the truth of a claim an entity makes about an identity.
- **Authorization and Entitlement:** Entitlements are a set of attributes which specify the access rights of an entity. Authorization uses these attributes to confirm or deny a request.

After identity is established, and procedures are defined, Identity Lifecycle Management should be specified. Identity Lifecycle Management is the process of managing accounts, policy changes, and entitlement, and tracking policy compliance. It includes the following features:

- **Workflow:** Steps in identity lifecycle management should be automated in order to decrease administrative efficiency and reduce security risks by reducing human interference.

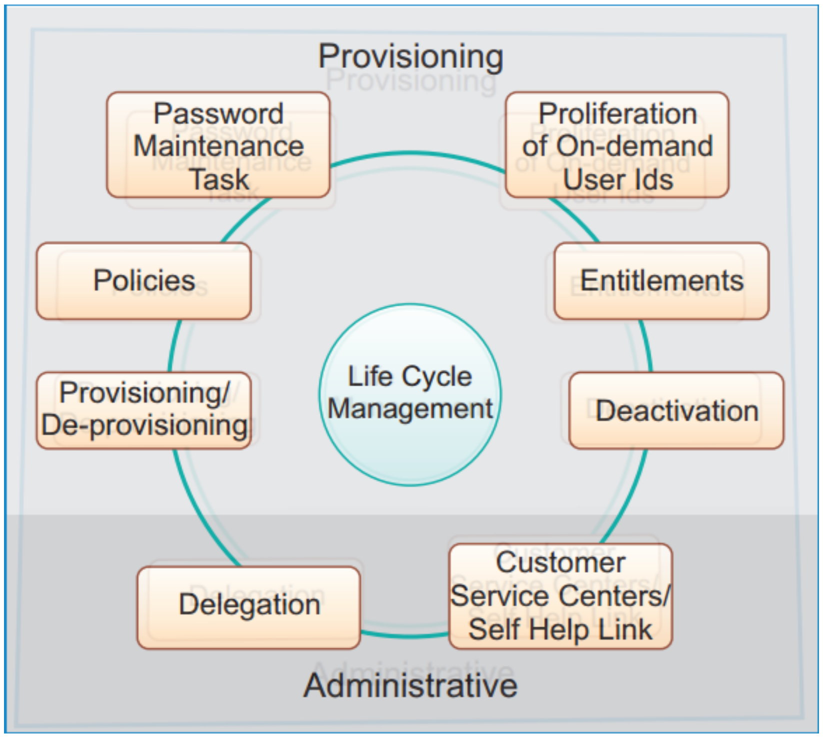

Provisioning
Password Maintenance Task
Proliferation of On-demand User Ids
Policies
Entitlements
Life Cycle Management
Provisioning/ De-provisioning
Deactivation
Delegation
Customer Service Centers/ Self Help Link
Administrative

Figure 2.2: Identity Lifecycle Management [21]

- **Delegation:** Delegation is the process of granting permission to an application or entity to carry out certain tasks in the future. Delegation is necessary in cloud as the majority of tasks and processes are volatile and short-lived.

- **Entitlement:** Access control attributes should be clearly defined. For example, in Role-Based Access Control (RBAC), roles must specified and the membership declared.

Figure 2.2 shows the lifecycle of identity management in a cloud computing environment. These tasks are performed by two basic components: provision and administration. Provision components manage identities and user profile information while administrative component mainly handles access management.

Proliferation of User ID occurs when a user has multiple identities in multiple services - a common occurrence on the Internet. Cloud federation refers to unionizing resources from different cloud providers aggregated in a single pool to enable users to receive three interoperability services from the providers: resource migration, resource redundancy and combination of complementary resources. Migration allows the relocation of resources, such as virtual machine images, data items, source code, etc. from one provider to another one. While redundancy allows concurrent usage of similar service features in different providers, combination of complementary resources and services allows combining different types to aggregated services. Federation plays an important role in deploying an application spreading across multiple cloud provider or an application that is the composition of independently administered services. There are two important barriers to effective federation: incompatible technology and trust issues. To overcome these issues, service providers connect standard protocols such as Service Markup Language (SAML) to create a complete trust model between the sender and receiver of an identity. To develop an identity and access-management system, an identity management lifecycle should initially be specified. Identity lifecycles are further discussed in Chapter 4. Although the SAVI identity lifecycle is similar to Figure 2, it has adjusted to fit into our architecture.

2.2.2 Traditional Identity Management Model

In order to better understand the metrics of identity management in clouds, as described in later sections, this section provides a detailed overview of traditional identity management models.

Isolated User Identity Model

In this model [32], the service provider issues identities to the customers and verifies the identity itself. Therefore, a user receives multiple credentials and access permissions across different service providers. The main advantage of this model is its simplicity for the service provider, while the main drawback is the difficulty of managing multiple identities faced by the user. This approach increases security risks, as users often choose the same password for all their accounts.

Federated User Identity Mode

To remove credential redundancy and prevent fragmented login, a new approach for federating identity management of service providers has been proposed. Identity federation involves establishing agreements between service providers to recognize each others identities in a federated domain. This agreement defines the mapping of a users identity when they transfer from one administrative domain to another. In this model, when a user is authenticated to access one service providers system, their identity is automatically confirmed on a Single-Sign-On (SSO) across multiple domains [19].

Centralized User Identity Models

The Centralized User Identity model defines an identity provider which stores all user identifiers and credentials. This identity provider is then used by multiple service providers to manage their users. There are several possible implementations for this model, but here only the most common implementations - the Meta-Identifier and Single Sign-On (SSO) models - will be examined.

The Common User Identity (CUI) model is the simplest way to implement a centralized model in which a central node is dedicated to providing user identity and credentials. In this model, a user can access all service provider resources using the same identifier and credentials. PKI is a typical implementation of this model. The main challenge in implementing CUI is selecting a unique identifier valid across all domains. Email addresses are a good example of such an identifier, but their security can easily be undermined by changing the address or registering under a fake address [33].

In the Meta-Identifier model, each service provider identifier is mapped to a unique meta identifier. Each identity provider issue its own identifier to users; however, credentials is shared between different providers. When a user wants to authenticate himself to an identity provider, the identity provider maps his identity to meta identifier. Then the identity provider checks the credential against the available credential. In this model, user credentials are identical across providers; only the identifiers are different. Users do not know about the meta identifier, which is an internal agreement between service providers. This model is useful for integrating legacy identity management systems in organizations, and is effective when all service providers are under the administration of one organization [13].

Single Sign-On (SSO) is an extension of previous models wherein a service provider delegates authentication to another provider, which serves as the identity provider. This provider takes the responsibility of issuing identities and credentials, and authenticating users. This model is similar to federation model except that there is no need for identity translation. In the federation model, users identities must be translated to an agreed-upon technology platform in order to be transferred to the second provider; however, there is no such requirement in the SSO system since the transfer is performed by a single entity [24].

User Centric User Identity Management

User-centric identity management offloads management of multiple credentials to the user side. It offers automation and system support of the identity management process to users so that they can manage various identifiers and credentials simultaneously. This model uses a Personal Authentication Device (PAD) to store all credentials and identities issued by service providers in a dedicated piece of hardware. A user must first authenticate themselves using a master set of credentials; the PAD then authenticates the user to access the service providers resources. This PAD can also be a piece of software; the Keyring application finds its origin in this model. Other devices (e.g. Smartphones, tablets) can incorporate PADs as a built-in feature [32].

2.2.3 Cloud Computing Identity Management Models

Identity Management (IDM) in web services is experiencing a paradigm shift from an organization-centric model to a trusted third-party model on the cloud. Third party identity providers allow both scalability and flexibility to users and applications over the Internet. Traditional identity management models are either user-centric or service-centric; however, these models cannot be used on a massive scale in the cloud. Recent work on cloud IDM has focused on the general concepts of IDM, federation and decentralization. Researchers have proposed various methods for addressing cloud-specific requirements such as anonymous authentication to prevent disclosing information before being authenticated. Federation has drawn more attention due to two main advantages: it enhances infrastructure usability for users, and it eliminates the necessity of developing a new API for each identity manager or service provider. There are three research challenges for federation: technical, informal (cultural), and formal (e.g. Legal) [23]. The last research challenge is designing a decentralized architecture for identity management. Researchers leverage two techniques to overcome this challenge: clustering identity-related activities and assigning each cluster to a decentralized components. In this section, we proposed models for Cloud computing IAM along with strategies to enhance IAM security and scalability.

Entity Centric Model

Angin et al. [2] propose an entity-centric approach for IDM in the cloud. The key elements in this model are Active Bundles. An active bundle includes payloads, privacy policies, integrity checks and virtual machines. Virtual machines is used to enforces policies. To make active bundle effective in cloud, this model has to incorporate anonymous authentication, which means authenticating users before disclosing the payload. It should also enable untrusted virtual machines to connect to IDM, and protect these machines from side-channel [58] and correlation attacks. Providing anonymous identification prevents a service provider from accessing to identity data before first identifying itself. This approach is independent of the trusted third-party, and preserves the privacy of entities from service providers. This model does not address the service registry and catalogue in an IAM service. The scalability of this model is questionable because intermediates systems cannot cache entity data to boost performance. This is a problem, since active bundles are large data packages. This model is comprehensive for the web applications as these applications need maximum flexibility, and ultimate portability. In the cloud, all service providers use standard APIs which makes flexibility in API definition useless. The second drawback of this architecture is performance that is an important requirement in IaaS.

Bhargava et al. [56] propose an approach for identity management which is independent of the trusted third party and has the ability to use identity data on untrusted hosts. The approach is based on the use of predicates over encrypted data and multi-party computing for negotiating a use of a cloud service. It uses active bundles, which are middleware agents that include personal information data, privacy policies, a virtual machine that enforces these policies, and a set of protection mechanisms. An active bundle interacts on behalf of a user to authenticate access to cloud services using a users privacy policies. The drawback of using active bundles for authentication is that the active bundle may not be executed at all on the hosted machine, resulting in a request denial. The users data, however, will always remain protected.

Federation Model

In [26], a model has been proposed to address multilateral federation among cloud services, in cloud applications and external services. This model proposes an identity federation broker that introduces a trusted third party as a trust broker to simplify the management of identity federation in a user centric manner. This federation broker enable transitive federation based on brokered trust model, and service provider only needs to register once to broker to support potential federation with external services and in-cloud apps. On the other hand, subscribers have full control over cross service access, which actually triggers configuration over transitive federation between services in a transparent way. Moreover, the solution can adopts different federation technologies (e.g. Shibboleth) and identity management systems for service providers. The broker is providing attributes to provide a cross service access for the users.

Stihler et al. propose a federated identity management approach to support multi-domain clients in a multi-provider environment [65]. This model integrates SaaS and IaaS layers while concealing the details of identity management in the IaaS layer. This integration enables SaaS application developers to track resource usage in a user-based fashion and apply security policies to individual users. This architecture uses OpenID for SaaS application and OpenSAML toolkit for federation.

Celesti et al. [8] propose a IdP/SP-based architecture to address the heterogeneity problem in Identity Management (IDM). The proposed distributed architecture consists of hundreds of IDPs interacting with clouds authentication module. It uses SAML to create a trust-relationship between IDPs with different security mechanisms. In this architecture, IDP in the service providers cloud acts as a third party, asserting a foreign cloud and a foreign cloud Identity Manager.

Identity Management Solutions

Rackspace is one the major cloud providers, a commercial deployment of Openstack using Keystone V2.0 for identity management. Keystone V2.0 is the baseline for our implementation as well. There are some differences between Rackspace Keystone and Openstack Keystone in their respective URLs, and request and response formatting. The Rackspace identity manager does not support policy management, and its authentication mechanisms are password and API key [29]. The second major cloud provider is Amazon. Amazon Web Service (AWS) Identity and Access Management (IAM) is a web service that allows organizations to unify users and their entitlements management. It eliminates the redundant burden of managing multiple users, and consolidates billing in Amazon. Applications can also obtain a temporary security credential to send requests to Amazon services. Amazon IAM supports Google, Amazon, and Facebook identity federation. Users can work with AWS IAM in four ways: Management Console to browse and manage IAM and AWS resources through the web; Command-Line interface; and AWS SDK to use the IAM programmatically in their applications; and Query API. The identity broker in Amazon IAM is a portal to bridge web sign-on with a key-based system. Administrators divide users into groups. Each group is associated with a policy file which defines the permissions. The policy file can also attach to a resource (e.g. Amazon S3) to specify who has access to the resource. To grant temporary access to users or services that normally don't have access to AWS resources, Amazon IAM supports role-based delegation, whereby one user can delegate access to AWS resources to another user using IAM roles [28].

OpenID is an open-source, decentralized, user-centric digital identity management solution for web services that provides seamless SSO that is compatible with existing internet technology (URL, HTTP, SSL, Diffie-Hellman). OpenID V1.0 supports only stateful authentication, and OpenID v2.0 supports both stateful and stateless authentication. OpenID can be integrated with cloud platforms (e.g. Openstack) to provide decentralized delegation for cloud services [**?**]. Users can keep their OpenID entity after the identity provider is gone, making OpenID a flexible solution for delegating authority to applications. However, OpenID is prone to phishing attacks, wherein users enter their credentials into webpage posing as an OpenID provider website. Attackers can easily transform existing URLs into an account which can be used at sites which support OpenID logins [60].

Shibboleth came out of the academic community through the Internet2, receiving much attention due to its claim of eliminating the need for universities to authenticate users for an array of web resources. It is an open-source implementation of Security Markup Language (SAML), which is used for federated identity management and cross-domain authentication and authorization. In Shibboleth, there are two entities: Identity Provider(IdP) and Service Provider (SP). These components are deployed separately, but work together to provide secure access to cloud resources. Shibboleth is useful for organizations and cloud providers for several reasons [52]: authentication is performed within the organization or cloud provider, and the organization can control attributes released to the remote service provider. IDP provides an identity for an entity which is used by SP to authorize a user. SP is a service or resource on the cloud. Once an entity is authenticated to the identity provider, the IDP issues an assertion that contains the entity attributes to present to the SP. This assertion shows that the entity is authenticated to IDP, and because of the trust relationship between IDP and SP, the entity is authenticated to SP as well. As a result, there is an identity federation between the identity provider and the service provider. Shibboleth 2.0 is based on OASIS SAML. SAML uses attributes to represent an entity identity. The only drawback to Shibboleth is its use of the same trust level for all services. Therefore, Shibboleth discloses the same attributes to all services while in a real world, service have different level of trust to know an entity attributes and secret information [49].

Privacy and Identity Management for Europe (PRIME) provides privacy-preserving authentication using anonymous credentials. It takes a highly interdisciplinary approach in order to produce solutions that are technically feasible, user-centric, socially acceptable, legally enforceable and commercially viable. PRIME provides a consistent user experience for identity-related interactions with service providers. The user-side component uses protocols for gaining third party (IDP) endorsement for claims to relying parties (RPs). PRIME provides anonymous credentials by using a identity mixer protocol to enable users to selectively disclose parts of their attributes in credentials obtained from IDP, without disclosing all the information. IDP signs credentials with its public key to preserve the integrity of the endorsement. A major limitation of PRIME is that it requires both user agents and SPs to implement the PRIME middleware, which hinders standardization [6].

Higgins is an open-source user-centric trust framework and collaborative project for providing a consistent user experience based on card icons for the management and release of identity data. As an interoperability framework, Higgins provides an API and data model to virtually integrate and federate identity and security information from various sources such as CardSpace, OpenID, and Liberty. Higgins has two major components [17]:

- Lower-level components for creating identity services such as attribute services, token services, and relying party Websites (i.e. service providers) and services.
- Upper-level components for creating user-centric applications which allow users to view, employ and manage various identities (i-cards). More specifically, Higgins upper-level components can be used to build identity agents which allow users to accept i-cards from card-issuing sites (i.e. identity providers). These agents can be used to create self-issued cards, manage a users set of cards, and to use these cards towards service providers (relying parties) or local applications.

2.3 Multi-tier Cloud

Multi-tier cloud architecture provides a model whereby cloud providers can provision flexible and reusable resources. By segregating a resource type into tiers, cloud providers gain the option of modifying or adding a specific resource rather than offering a resource from scratch. A two-tier architecture is typically composed of a management tier, and a data tier. Figure 2.3 shows the general layout of a three-layer cloud architecture:

The terms layer and tier are often used interchangeably, but in the literature layer refers to logical structuring while tier refers to the physical arrangement of the system infrastructure [5]. The topmost layer is a node layer, where each node can offer its own configuration and resources. For example, a cluster can offer NetFPGA while this resource is not available in another datacenter. The second layer is data layer which includes all resources shared between various nodes in a different datacenter such as computation, networking, storage, and images etc. This tier addresses general application requirements (e.g. processing and storage); application with special requirements are handled on the node tier. The last and lowest tier is the management tier, where measurement and management services are offered to applications and resources. Identity and Access management, resource and service registry, monitoring and measurement, and resource allocation are examples of services in this tier. The management Layer is the furthest tier from the client, while the node tier is the closest. This reference model has several advantages, including [35]:

- Resource can be load balanced separately.

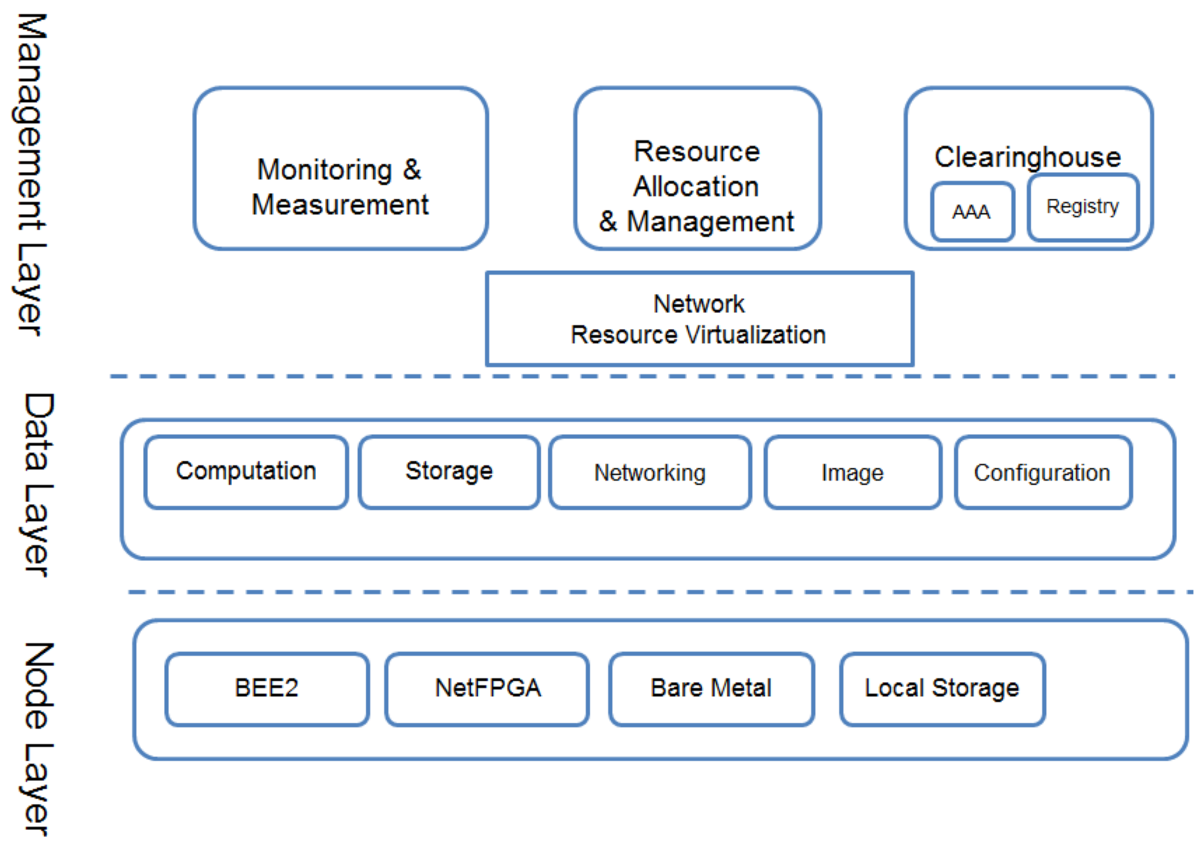


Figure 2.3: Multi-tier architecture

- Adding or modifying resources in nodes is independent of the rest of architecture.
- Deployment of new resources is faster and easier

The prominent characteristic of this reference model is asymmetry; each node can have its own set of resources. Each node can be a cloud provider, a cluster, or a set of servers. There are two implementations of this reference model: Smart Application for Virtual Infrastructure (SAVI) in Canada, and the Global Environment for Network Innovations (GENI) in US. In the rest of this chapter, the security architecture of this platform is examined.

2.3.1 Smart Application on Virtual Infrastructure (SAVI)

The SAVI Testbed is a platform for designing, prototyping, and demonstrating an application-platform testbed for experiments on Future Internet architectures, protocols, and applications. SAVI tries to build a large-scale nation-wide Canadian application platform testbed. As Figure 3 depicts, SAVI testbed consists of five major elements:

- **Core Nodes:** these provide resources for applications and are located in massive data centres. The Core Nodes are accommodated by conventional cloud computing resources (computing, storage, and basic networking), while Edge Nodes include more advanced resources such as re-configurable hardware.

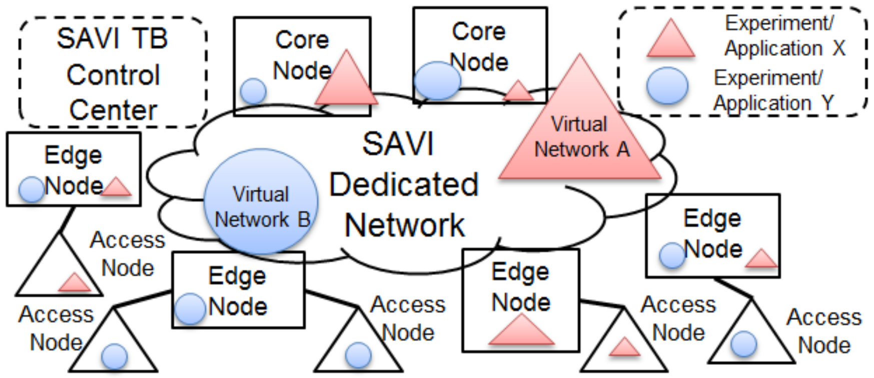


Figure 2.4: SAVI architecture

- **Smart Edge Nodes:** these provision resources for applications and are located near Access Nodes. Examples of these resources are computer, storage, network, optical access, wireless access, and re-configurable hardware resources (e.g. BEE4 and NetFPGA). Core and Smart Edge nodes together are referred to as the Extended Cloud in SAVI.

- **Access Nodes:** these enable users to connect to the SAVI network through wireless access points.

- **SAVI Network:** this connects Core Nodes and Edge Nodes together

- **TB Control Centre:** the management layer of SAVI.

In the current deployment of SAVI, Edge Nodes are deployed on sites in participating universities (e.g. University of Toronto, York University). Some universities also deploy an Access Node; therefore it is not necessary for them to have Edge Node as well.

As SAVI aims to be both a research testbed and a cloud provider, it supports both applications and experiments. In SAVI terminology, applications deliver a feature to end users and need to guarantee an agreed-upon level of service, while experiments are comparably short-lived, used by a researcher, and aimed at gathering measurement data or user feedback. In practice, however, both applications and experiments are treated equally in SAVI TB, and are used interchangeably in this document. To use the SAVI testbed, applications send a request for resource slices to the SAVI Control & Management plane, where this request is addressed by allocating a virtualized resource to the application. In addition to serving such requests, the SAVI Control Centre performs authentication, authorization, and accounting - all of which are bundled in the Clearinghouse component. Clearinghouse is a design principle borrowed from GENI and Amazon to make security-related tasks more effective and efficient.

Figure 2.4 shows the overall architecture of SAVI testbed, in which Edge and Core Nodes are dispersed in various geographical locations, and a SAVI dedicated network connects these elements together. Each edge node can have access points, and all nodes can use SAVI TB Control Centre services through the AVI network.

Figure 2.4 also shows how two sample applications (A & B) that run SAVI TB. These applications obtain a slice of Core Node, Edge Node, and Access Node resources. In this figure, application X, represented by a triangle, uses virtualized resources in all Core Nodes and Edge Nodes (except one

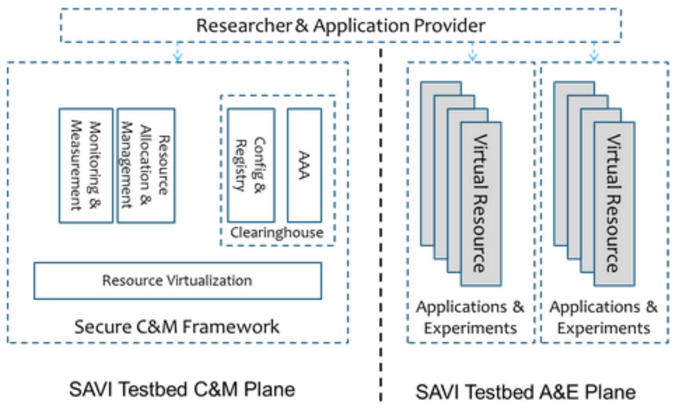


Figure 2.5: SAVI Logical Structure

Edge Node). The number of resources used by each Application is depicted by the size of triangle (for Application X). For instance, Application X uses more resources in one of the Core Nodes and Application Y (represented by circle) uses more virtualized resources in the other Core Node. SAVI nodes are also securely connected to the Internet to access outside resource. However, for simplicity these connections are not depicted in Figure 1. In the next section, we describe each of these components and their respective responsibilities.

The logical structure of SAVI consists of two tiers, as depicted in Figure 2.5. The C & M tier performs resource allocation and secures a slice of virtualized resources for the application. The application then runs in the A & E plane over the allocated virtual resources throughout SAVI TB, including any combination of Edge Nodes, Core Nodes, Access Nodes, and network resources. The SAVI-TB C & M plane is also responsible for traditional FCAPS management tasks (Fault, Configuration, Administration, Performance, and Security), as well as control related tasks such as on-demand allocation/de-allocation of virtualized resources to/from experiments and applications. The main advantage of having such a tiered structure is to enable applications to control their management tasks, including resource allocation. In SAVI, applications can run their own resource allocation algorithms in the management tiers where the algorithm can optimize allocated resources. Researchers can run their experiments or applications on the A& E plane, which is a set of allocated virtualized resources for that project (i.e.. applications or experiments). This plane allows applications to follow any desired architecture (e.g. P2P, Star topology) to address their design requirements. SAVI enforces the minimum constraints on the internal architecture of applications. To facilitate application development and expedite creation of cloud-based apps (particularly short-lived apps), SAVI provides certain software components that can be used by developers to rapidly deploy their applications.

SAVI deploys the above logical components in the following manner: node-level components are placed on their corresponding nodes while C&M components can be distributed throughout the testbed or centrally located at nodes.

Figure 2.6 shows the component diagram for SAVI TB, and how they are linked together. Users can use SAVI web portal or command-line clients to access SAVI resources. There is a Monitoring and Measurement component that provides a metering capability for SAVI resource status in real-time. This data is presented to both researchers and resource providers. This component operates in publish/subscribe mode, meaning that resource providers or researcher must subscribe for data,

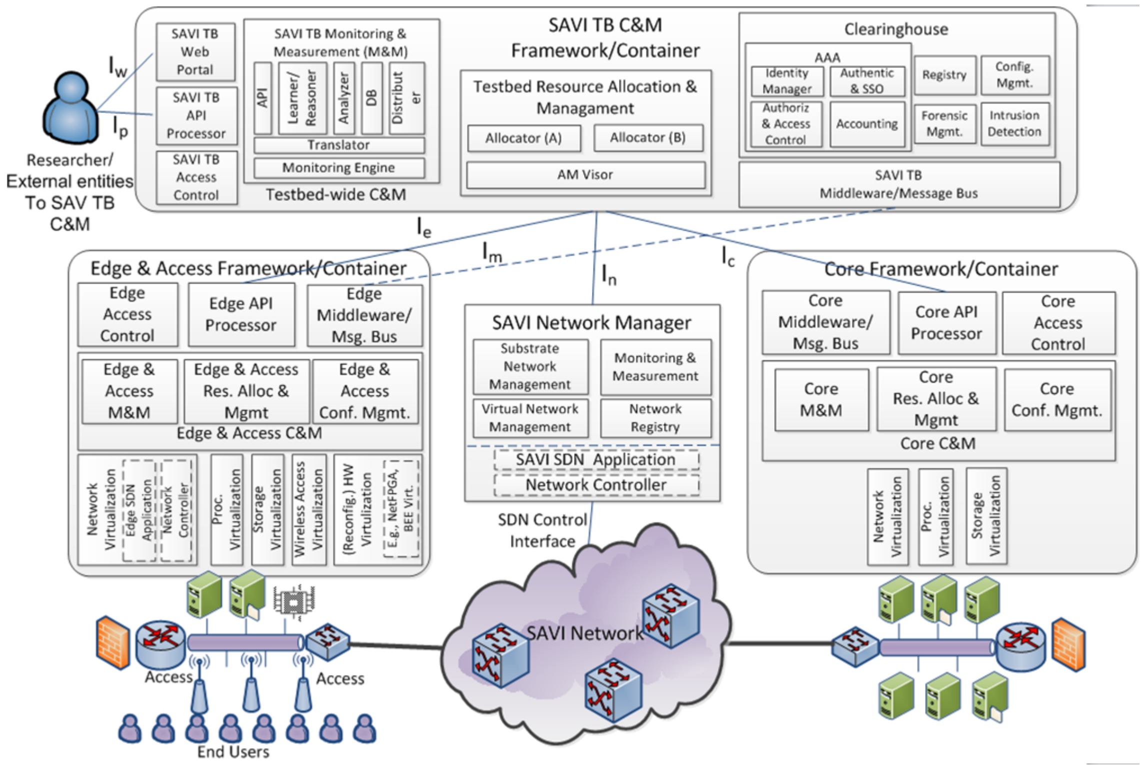


Figure 2.6: SAVI component diagram

which is sent to them when it becomes available. The Network Manager is responsible for managing virtual networks and external connectivity. A virtual network in SAVI TB is an isolated slice of the substrate network, which is allocated and configured as a part of the resource allocation process. The substrate network connects different campuses. Each zone is an OpenFlow-enabled network, operated using a logically-centralized controller. The SAVI Network Manager orchestrates these in-zone OpenFlow controllers to create a single logical network.

As shown in Figure 2.6, the SAVI framework and SAVI Clearinghouse are directly connected to security management in SAVI. In the rest of this section, these components are described in detail.

SAVI Secure Framework

The SAVI TB secure framework is responsible for providing the framework in which all SAVI TB components can operate and interact without any violations. It includes functionality that are required by all (or many) components such as middleware, as well as API and Web Portal processing. All SAVI TB components based on this framework run independently (i.e. are loose-coupled) and communicate with each other asynchronously. Researchers or other external entities can see a SAVI TB service list (an access control list of each service) via a web portal or application. The framework also acts as a distributed container that hosts different SAVI TB components and facilitates their communication through the middleware. This framework should be secured by a strict access control/authentication mechanism to deny access to SAVI TB components by malicious users, and by an optional encryption mechanism (e.g. a Secure Socket Layer (SSL)) to ensure confidentiality of communication with SAVI TB components. The framework should also provide a warning message to the researcher or other components and stop the experiment or application in the event of any operational or management problems with SAVI TB.

The SAVI C&M Web Portal provides a SAVI TB service list, control for the & management status of the SAVI TB, and an access control list. The SAVI C&M Application also provides the same functions as the SAVI C&M Web Portal using PC or smart devices. SAVI C&M API provides general interfaces for accessing SAVI TB C&M. An Access Control Manager manages subscribers and their access control list. This framework provides a message-oriented middleware for asynchronous communication between different components by handling both request-response and notification-type messages. A message bus is used to enable access to different SAVI TB components through various protocols such as ActiveMQ, XMPP, AMQP, Web Services, and Email. The enterprise service bus such as OpenESB, Apache ServiceMix, or Mule can be used on the SAVI C&M Container for designing and implementing interaction and communication between mutually-interacting software components in service-oriented architecture. All SAVI TB components can be easily enabled or disabled without any interruptions to the system at run-time.

2.3.2 The Global Environment for Network Innovations (GENI)

The Global Environment for Network Innovations (GENI) [20] is a testbed for prototyping and demonstrating virtualized network experimentation. Like SAVI, GENI has control framework to manage resource allocation, discovery and optimization. Unlike SAVI, however, which requires a unified management layer, GENI allows resources to have their own management layers even with different control frameworks. Protein [55] and Exigent [15] are two control frameworks proposed for GENI implementation. There are seven main requirements for GENI:

- **Generality:** GENI must place minimal constraints on researchers and developers in terms of data format, functionality, and paradigm. It should incorporate a broad range of networking protocols and technologies.
- **Slice ability:** As GENI is a cloud, it should support multi-tenancy solutions (supporting multiple applications or experiments in parallel); while also guaranteeing their isolation.
- **Fidelity:** GENI must offer different levels of abstraction, allowing researchers experiment and invent without having to build anything from scratch. GENI should also define topology in the nodes and spread them geographically to represent the size of a real-world environment and provide network-wide abstraction.
- **Real Users:** GENI aims to run real applications that serve real users, so it should encourage long-lived useful applications.
- **Research Support:** Developing tools to increase GENIs ease of use.
- **Observability:**GENI control framework observes and measures resources and activities
- **Sustainability:** developing new technologies for GENI partners and supporting technology rollover without disruption.

In Figure 2.7, a researcher can log into the system using credentials in one of the federated organizations with GENI. Then, the researcher can create a slice of resources in a desired physical location

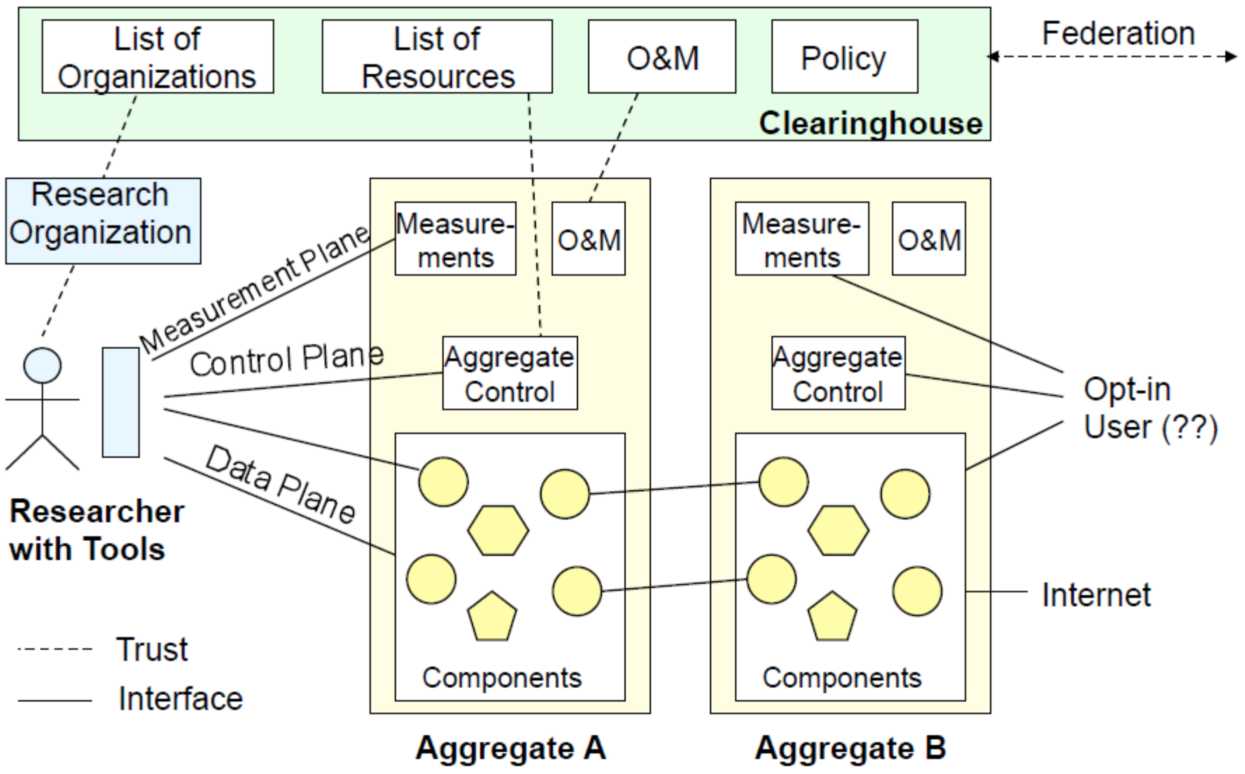


Figure 2.7: GENI Architecture

and run the experiment. One of the design principles of GENI is to keep the core (the fixed universal point for all the nodes) minimal. GENI defines federation as the interconnection of independently owned resources in order to enable researchers create and populate slices and run experiments on them. According to this definition, resources can be federated into the GENI framework in two ways: as an aggregate (shown in figure 8), or as a suite that is managed and administered independently.

ExoGENI is an implementation of the GENI control framework, which provides resources such as computation, storage, and networking to researchers [4]. ExoGENI uses OpenFlow-enabled hybrid Ethernet switches and cloud computing software such as Openstack. Figure 2.8 shows how ExoGENI combines off-the shelf components and services to provide resources for GENI users. GENI users can access the testbed through GENI API or ALT-G API. Open Resource Control Architecture (ORCA [?]) allocates and tracks resource slices by orchestrating the calls to a handler plugin. The handler plugin calls the appropriate APIs from the resources provider in the IaaS layer. GENI follows a multi-tier architecture in which the Testbed substrate provides the hardware used by the IaaS layer to provide services. Then, the GENI layer wraps all APIs into a unified set under the name of GENI APIs. A slice may span multiple ExoGENI, and the researchers can link them or other external resources via a service-level agreement. Each ExoGENI site is a small IBM cluster integrated with OpenFlow switches. Each rack in ExoGENI site runs a FlowVisor [63] that mediates access from the OpenFlow controller to the OpenFlow data plane. When a slice wishes to set up OpenFlow controller to manage traffic on its local data plane, ORCA calls FlowVisor to allow the controller to manage the traffic. User requests are sent to control resource allocation. As with SAVI, ExoGENI control nodes run on control servers,

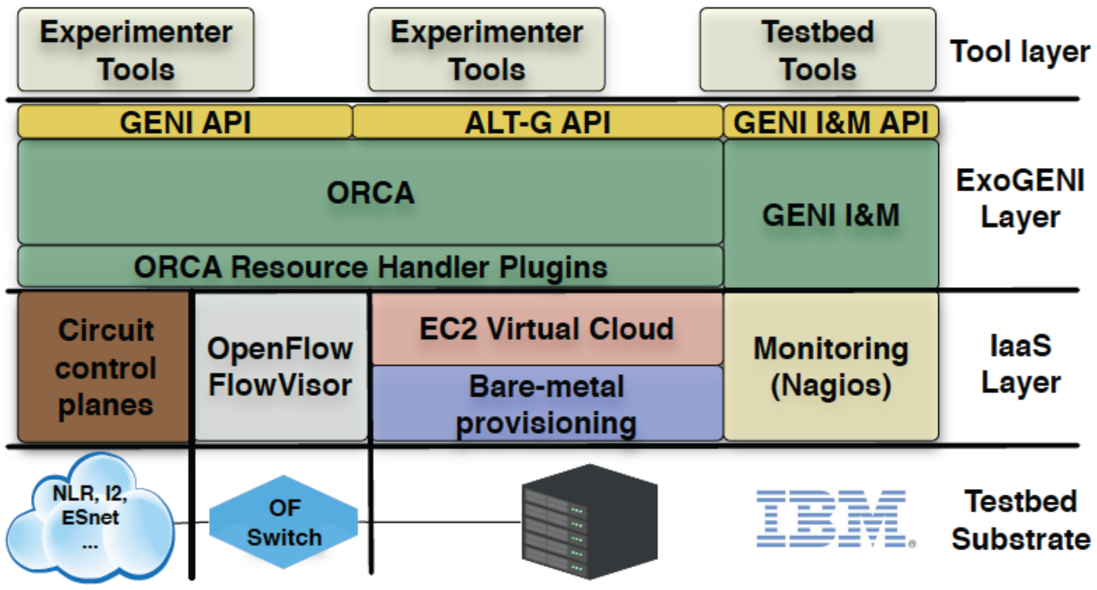


Figure 2.8: Conceptual View of ExoGENI software stack

and worker nodes are physically separated. Each computation slice can be a virtual machine provided by Openstack or a bare-metal system based on xCAT. After booting up an image, the researcher must give the URL of a shared repository accompanying the image hash to an ImageProxy server to validate and transfer the image to either a virtual or physical machine.

ExoGENI IAM

ExoGENI uses asymmetric cryptography to authenticate users and applications referred to a specific entity. Entities send requests over an authenticated transport (e.g. SSL/TLS or Signed requests) to enable the receiver to verify the senders public-key. Using keypairs to authenticate entities is a common practice in cloud computing to enable user tools to easily send requests to cloud resources outside of a browser session. ExoGENI RT/ABAC assign roles to entities to control their access to available resources. A role is a named property or predicate of an entity which helps the IAM to decouple access control from real-world identities. As ExoGENI is a community cloud, organizations can run their own identity provider using the same identities and roles as in ExoGENI. This set of identities is called an identity domain. To authenticate a user from an identity domain, the user can choose the home domain during the web single sign-on (SSO). The home domain issues a statement to assert the identity of a user to ExoGENI.

ExoGENI uses logic-based trust management to provide a fine-grained and powerful solutions for trust and authorization in the testbed. The ExoGENI trust-management framework is called Clearinghouse, and uses *libabac*, an open-source library, to implement Attribute-Based Access Control (ABAC) based on the RT family of role-based trust logic. ExoGENI includes a web-based IdP, Project Authority, and Slice Authority implemented as PHP scripts that invoke Java programs linked to LIBABC, and ORCA extension for RT/ABAC authorization policy in ORCA-based GENI aggregates. It delivers:

- Authorization based on user identity, group affiliations, specific action on a piece of resource (slice)

- Support for delegation permissions such as capability-based access control for slices
- Flexible declarative authorization policies and delegated policy evaluation

The trust logic provides a general language for constrained delegations of trust, and a logic-based policy framework for reasoning delegations and local policy rules. A logic is a combination of language and inference procedures used to express facts and rules that are applied to requests. In RT/ABAC, each resource has policies which control which users are authorized to perform certain actions. Each resource has a local inference engine to generate facts and rules. The resource grants trust to each entity if the inference engine authorizes the action based on the facts and policies. Slices of a resource is the granularity of authorization and accountability. If an entity is authorized to control a slice, it can control any virtual resource in the slice which removes the overhead of defining a separate policy for each virtual resource.

ExoGENI uses existing external identity services (e.g. Shibboleth) to provide a federated infrastructure with cloud systems to serve user communities spanning multiple campuses and across-organizations. Shibboleth and other SSO systems support federated identities in order to enable a cloud provider to locate an entity home domain and IDP, and establish trust relationships with IDPs that are verified by a federated identity root. For example, InCommon Federation in GENI endorses the IDPs of its members. The resource provider delegates trust to the InCommon federation root, and the resource provider can add a policy rule to accept credentials from any IDP endorsed by the root, even if the IdP is not known in advance.

2.3.3 Conclusion

Current approaches to cloud IAM focus on offering solutions for federation and access control. The lack of a comprehensive analysis - from conception to physical implementation - of the proposed solutions has resulted in impractical and fractured models. Meanwhile, some aspects of current access management problems are specific to advanced cloud platforms such as SAVI. For example, infrastructure users can acquire a set of virtual resources to run their applications, or an application can send requests for resources on behalf of users. A virtual resource can span multiple providers in different geographical locations or under another administration. This research focuses on designing and implementing a comprehensive architecture that meets multi-tier cloud requirements such as SAVI. The following features distinguish this work from previous works:

- SAVI IAM is used as a reference architecture to host a variety of mechanisms for authentication and authorization.
- The goal of SAVI IAM is not to define a new model of authentication or a novel access control; however, it use all the previous technologies to improve the security in the SAVI testbed.
- The IAM is technology-independent.
- SAVI IAM leverages the common management layer of SAVI to optimize the internal authentication process.
- The proposed architecture should not require any changes on the resource providers.

Chapter 3

Threat Modelling

3.1 Introduction

With fast pace advent of cloud computing and associated applications, security takes more and more attention. Any application needs a model of computation, a model of storage, and a model of communication, and a model of security. Multiplexing the virtual resources of disjoint users on the same physical hardware is necessary to achieve elasticity, and the illusion of innite capacity requires each of these resources to be virtualized to hide the implementation of how they are multiplexed and shared. It is conceivable that a users virtual resource could be co-located by its adversary which in turn engenders a new set of threats (e.g. side-channel [59]) and might violate customer security triad (Confidentiality, Integrity, Availability). When selecting security measures, the system designer must take the design of the entire system into account, and not incorporate security technologies at random, in other words, they should follow security engineering process.

Systems security engineering is concerned with identifying security risks, requirements and recovery strategies. It also involves a process through which security designers develop security mechanisms and it should be incorporated into system design process. Security Engineering has three main steps: modelling threats, gathering security requirements, and developing security mechanisms. Each stage of security engineering provides feedback to the previous stage and subsequently to all preceding stages. Threat modelling and security requirements are the fundamental building blocks to the rest of security system is built.

Identifying threats helps security designer to gather a proper security requirement list. This step is very important when the definition of security for a system is faulty. Threat modelling or threats identification tries to see the system from an adversary's perspective to protect system assets. Despite the critical of threat modelling in security design of a system, little effort has been dedicated to it comparing to other aspects of system security. There are several existing methodologies on threat modelling and many more on requirement engineering including: fault tree, attack net, attack trees, Microsoft's threat modelling, but most of them lack enough expressiveness and fail to embrace the new requirements and semantics of software defined infrastructure to enable reasoning about threats.

3.2 Threat Modelling Techniques

In order to model threats on Software defined Infrastructure we need to look at different threat modelling techniques. We use these models to provide a handle to create a more ideal solution. We will go through different techniques and explain their pros and cons.

Fault Tree

Fault tree is the graphical representation of failure analysis which leverages Boolean logic to show the interconnection of a series of low-level events to undesired states of the system. A node in this tree represents an event and trajectories are casual relationship of events stated in Boolean logic. Leaf nodes are system events while intermediate nodes are hazards where the reliability and availability is required. Each node can have OR or AND connection to the previous node in the hierarchy which can be translated to the requirement of co-occurrence of two events if they want to succeed. For example, if you want to run a virtual machine you should be authenticated and authorized to boot up a virtual resource. In OR connection, event success is independent of individual success while depends on both failure.

Attack Tree

The term Attack Tree was introduced by Schneier [62], and in theory, is very close to Threat Tree and Fault Tree. Attack Tree is a directed graph that describes how a system can be compromised. Each node represents a goal, and root is the overall goal. An attacker should achieve the intermediate goal in order to accomplish the higher goal while leaf nodes represents atoms of an attack. Figure 3.1 shows the partial attack tree for Aurora Operation [69] which was a cyberattack conducted by an Advanced Persistent Threat (APT) in China with ties to People's Liberation Army. Each path maps to an attack strategy, the dotted line in Figure 3.1 shows IE vulnerability attack where user download a rootkit malware that leverages IE zero-day vulnerability to infect the machine, then the malware is able to crack administrator password, and by elevating the privilege, it can access to valuable information which is the ultimate goal of attackers.

Fault Tree, attack tree, and threat tree lacks adequate semantics to express reasoning about threats such as Trust. They can not express attacks as they are unable to capture atomic details about APIs, and shared resources. They do not indicate internal attack structure, events impact, or how attribute can be synthesized.

Ptri Net

McDermott [46] tried to describe an attack using the strength of Ptri Net by separating data and processes. In this approach, he defined attack as a Petri Net with a set P, P=p_1,p_2,p_3,...,p_n as Places, and a set T, T=t_1,t_2,t_3,...,t_n as transitions. Each place represent a state of knowledge base, and each transition is an event or action. Places are connected to transitions through unidirectional arcs which represents their relationships.Each attack net is represented by a set of tokens S which can move from one place to another place along an arc which can be translated to the progress of attack.

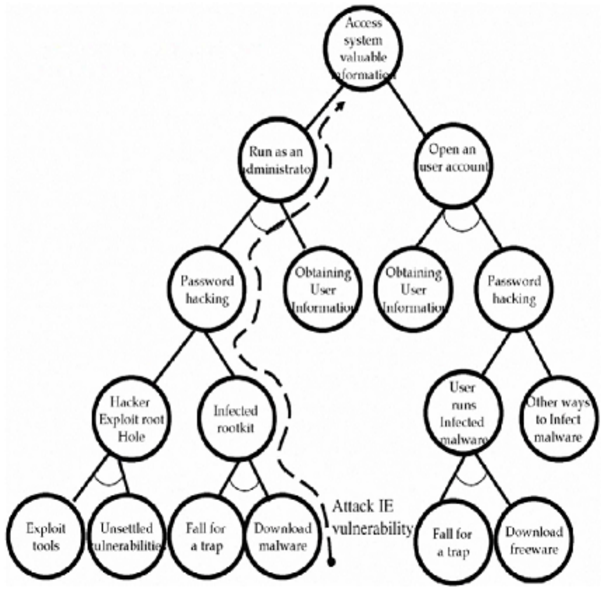


Figure 3.1: Operation "Aurora" Hit Google (Mid. 2009 Dec. 2009) [68]

3.3 Threat Modelling

SAVI is currently designing a national testbed for creating and delivering future internet applications. This testbed will provide a flexible, virtualized, and converged infrastructure to support experimental research in application-oriented networking, cloud computing, integrated wireless/optical access networks, and future internet architectures. This diversity of facilities make the testbed an enticing target for attackers; therefore, careful attention must be paid to design in order to ensure security. Due to its similarities to GENI, the SAVI threat model is not substantially different from GENI in the abstract viewpoint. However, specific implementation strategies and different components goals, and their security requirements expose the architecture to several challenges. To model potential threats, the trust level to each group of users - and corresponding attack types - must be defined.

Figure 3.2 - rings of threats to the SAVI architecture. At the centre is the infrastructure with the greatest privileges. Outer rings represent progressively less-privileged users: SAVI researchers, opt-in users using SAVI resources, and outsiders, respectively.

As relates to threat modelling, SAVI infrastructure comprises of four main components: Control & Management, Core Framework/Container, Smart Edge, and the SAVI Network Manager. These four main components are identified as privileged components which can interact with various components in SAVI. Any software running on top of these components - excluding researchers applications - fall into this class of threats. Moving outward, resources allocated to researchers, currently-running experiments, and usage behaviours of allocated resources are taken into account. In perfect isolation, a threat in this class results in less serious consequences than a threat at infrastructure level because the threat is alive as long as the resources are not deallocated. The next layer belongs to opt-in users who hold less privileges and, consequently, pose fewer risks to the SAVI TB. User network traffic and software fall in this class.

A user may run an application on-premise and wield the application with a researchers application on SAVI TB. Finally, as SAVI tends to connect to current internet architecture, it is susceptible to endemic

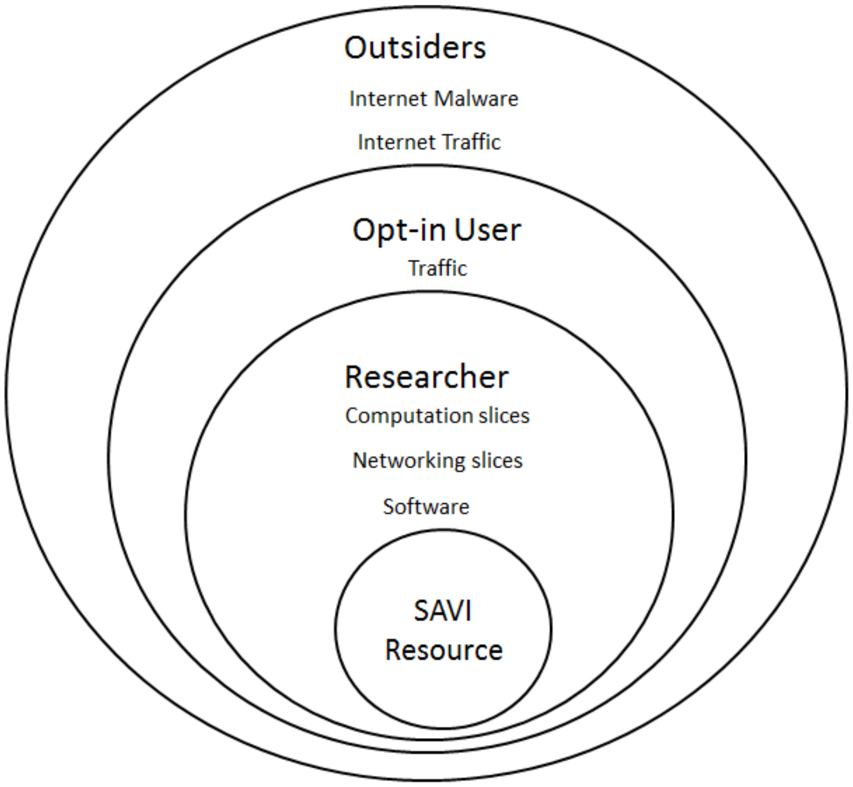


Figure 3.2: SAVI Trust Level

internet Malware. Threat modelling was conducted using the same process suggested by Suvda Myagmar et al. [50], which consists of the following three high-level steps: characterizing the system, identifying the assets and access points, and discovering threats. Although the same process was employed, the sequence of execution is different.

3.3.1 SAVI Characterization

We characterize SAVI with the following features:

- **Point of Entries:** Users can interact with from three point of entries: admin, internal, and public. Admin entry is connected to the management network, and only top administrators and topmost trustworthy components can connect to this network. Any breach to this network results in SAVI testbed crash. The second entry is internal network which can be accessed by virtual resources in the same node or other SAVI nodes. This network has the medium level of trust because identity of users have been verified. The last one is public entry which is connected to the Internet. People who interacts with this entry may not have any identity. Therefore this entry brings about the most risks to SAVI.

- **Access Points:** Regardless of resources functionality, their interfaces are protected by the IAM middleware. Users can not bypass the middleware unless the resource defines an object Public. Access policies are defined by administrators at the IAM. There is always the risk of unauthorized access to resources due to poor policy definition by administrators, or misconfigured resources.

3.3.2 SAVI Asset

Assets in SAVI can be divided into three classes based on the owner of the asset:

- **User Asset:** Users have two set of assets on SAVI: data and resource. Users stores their credentials in the IAM, files in the storage. Their data in process can also be in risk if an attacker can get into their virtual machines. The second users asset is their resources that they pay for them. An attacker can compromise users resources to launch an attack against an internal target or external target.

- **System Asset:** There are plenty of resources on SAVI testbed that have not allocated to any users yet. These resources are considered as system asset. These resources are always enticing targets for an attacker. To gain the control of these resources, attackers need to access the management network. Attackers can escalate their privilege to the SAVI administrator through the management network. Therefore, the management network is considered as the most important asset for SAVI.

3.3.3 SAVI Threats

There are two main classes of attacks which must be addressed by the SAVI security framework. The first class consists of attacks that abuse SAVI resources to perform malicious activities against resources or principals outside the SAVI cloud. Although these attacks are difficult to launch, their severity justifies their classification in a separate category. Denial of Service (DoS) attacks [30], spamming [41], botnets [16], and Malware injection (e.g. BluePil [54] and Subvirt [39]) are typical examples in this category. It is often difficult to detect such attacks, as distinguishing these anomalies from normal system behaviour is not always feasible. The second category includes attacks conducted on SAVI resources and applications to gain control of the SAVI network or disrupt the functionality of an application. These attacks can be initiated by a rogue experiment or a malicious attacker. Cloud computing is intrinsically an adversarial environment, thus a deciency in the virtualization layer may result in a breach in the isolation boundary. For example, an attacker can place his virtual machine on the same physical machine as the target virtual machine [11], and open a side channel to perform a timing analysis on the SSH keystroke [12]. Thus, the attack is conducted from one virtual machine upon another without the direct intervention of hackers. Another attack type is one which compromises a user assets security triad (Condentiality, Integrity, Availability). User assets include user meta data information (e.g. credentials [13]), intellectual property (e.g. data and software [11]), and resources (e.g. computation, storage, and network). Therefore, a level of isolation between applications is required.

The following section lists specific threats that SAVI clearinghouse must address. This list was compiled by studying the literature and estimating the likelihood of each potential occurrence. For example, user account hijacking (i.e. session riding) is a likely incident in SAVI testbed because SAVI researchers often do not properly protect their credentials. Determined attacks against SAVI components are less frequent. The list of likely threats includes both attacks which can be launched exclusively or in concert with other threats as part of a larger systematic attack. The SAVI testbed should continue to function even while countering such attacks. Therefore, like GENI, SAVI requires a kill switch to quickly and completely suspend a misbehaving application or experiment to prevent a single disruption from spreading throughout the system. For example, if spammers were to subvert SAVI, causing Spamhaus to blacklist one of the SAVI IP addresses and cause a major service disruptions, the SAVI administrator can use the switch to suspend the testbed and allow the rest of the system to proceed unimpeded. A constant auditing feature should be incorporated into SAVI in order to monitor the components; if the activities of a specific component cannot be sufficiently monitored, the administrator should then be able to restrict the activities to that component. For example, if there is a unauthorized access to a component in the management network - especially components invisible to the monitoring and auditing plane - the administrator should constrain communication between this component and the Internet. The following list outlines the main security challenges currently faced by SAVI:

- **Shared Technology Issues:** applications and experiments may escape isolation boundaries in order to disrupt the execution of other applications within SAVI or obtain information about other applications or experiments. Because clouds implement a multi-tenancy model, it is likely that an application is co-located by an adversary. To clear a boundary between virtual resources, a virtualization hypervisor mediates access between them. However, even hypervisors exhibit flaws that can enable virtual machines to gain inappropriate levels of control or influence on the co-located virtual machines. Such a flaw [59] exposed a vulnerability in Amazon EC2 that allows an attacker to place a virtual machine (VM) on the same physical machine as a targeted VM and construct a side channel between two VMs on the same physical machine, enabling a SSH keystroke timing attack [64].

- **Account Hijacking:** An attacker can hijack a users account in three ways: stealing user credentials, session hijacking, and session riding. It is common within the security community for users to be careless with their credentials, allowing them to be easily stolen via social engineering tactics. Session hijacking refers to the use of a users session key to gain unauthorized access to the information within the cloud, while session riding involves hackers sending commands to a cloud service on behalf of the targeted researcher by sending the user an email or tricking the user into visiting a specially crafted website. Attack methods such as phishing, fraud, and exploitation of software vulnerabilities fall into this class of threat.

- **Escalation of Privilege:** This threat concerns attackers taking advantage of flaws in software to grant themselves elevated access to the cloud and its associated data and applications. Because SAVI is an on-demand resource-provisioning infrastructure, it provides some interfaces to users and application to acquire or release resources, and some other management interfaces in management plane to configure this resources. An attacker can escape the users trust boundary and gain unauthorized access to these interfaces. The likelihood of such attacks is greater for SAVI than for traditional systems, where these interfaces are available to administrators. Attackers can use their privilege to disrupt other applications or experiments, or evade metering and billing.

- **Vulnerability of SAVI Software Stacks or Procedure:** The first challenge to maintain the SAVI testbed is software patch management. A major vulnerability of SAVI lies in its software patch management. SAVI uses Openstack to provide virtual resources to users. Openstack components are under constant development, with the source code changing daily. When a vulnerability is discovered in these components, it should be fixed immediately; otherwise, it might be exploited by attackers. One important step is to actively manage all SAVI nodes i.e. proactively keeping all software stacks up to date with known security patches. The SAVI components should also be configured with the minimum number of open ports. In addition, an intrusion-detection system is also necessary for the continuous monitoring of anomalous nodes by the SAVI Clearinghouse. Internet protocol vulnerabilitiessuch as those which permit man-in-the-middle attacksare therefore also relevant to SAVI security. Another major vulnerability lies in poor key-management procedures. As noted in a European Network and Information Security Agency study, users use keypairs to strengthen their account authentication, and encrypt the data in the cloud with their Public/Private keys. Therefore, cloud computing infrastructures require the management and storage of many different kinds of keys. Finally, advances in cryptoanalysis can render any cryptographic mechanism or algorithm insecure as novel methods of breaking them are discovered. This can result in massive data leakage.

- **Rogue Experiment:** a runaway experiment can cause unwanted traffic on the Internet and cause an entity to trigger a true or false alarm in other parts of the Internet. Attackers can leverage cloud resources to host malicious code for spamming, web fraud, personal information theft, and other nefarious activities. Cloud resources can also be hijacked to crack passwords and keys, launch DDOS attacks, launch dynamic attack points, host malicious data, control bonets, build rainbow tables, and create CAPTCHA solving farms. A highly relevant set of computational resource vulnerabilities concerns the handling of virtual machine images; an attacker can provide or place a faulty virtual machine image on a users resource in order to provide back-door-access.

- **Denial of Service (DoS):** When an application notices a high volume of traffic and workloads on its services, it acquires more resources to cope with the additional workload; this way, the illusion of infinite resources is created for the user. This function, however, can be exploited by an attacker to create the maximum amount of damage by flooding the system with data, causing it to become overwhelmed and shut down. A side-effect of flooding applications on the cloud is that other applications on the same physical machine may also be affected by the flood attack. Once resources on a physical node are exhausted, other applications on the same hardware are no longer able to function. A Denial of Service attack on an application is thus an attack on all applications on the same physical machine. Depending on the level of the attack sophistication, a distributed DoS can cause the SAVI control centre to shift affected applications to other systems, result in the flood attack spreading to the whole SAVI testbed.

- **Direct Attacks Against Vulnerabilities in the SAVI Control Centre:** The components that make up the SAVI Control Centre are the most central and important in the system; any attacks against these components will affect the entire testbed. For example, if the number of requests on the SAVI IAM passes a certain threshold, the IAM slows down, affecting the performance of the entire testbed. Such components are thus vulnerable to DoS attacks, as sending them a large number of requests can paralyze the whole testbed. The first step to countering this threat is to define a trust relationship model between the control centre and the rest of the components in order to prevent malicious calls from being exchanged. The second step involves adopting a well-defined software development process for these components. This process should include a Security Development Lifecycle(SDL) in order to eliminate, to the greatest extent practicable, any vulnerabilities (e.g. buffer overflow and format-string vulnerabilities). If off-the-shelf components are to be used, standard practices such as software verification tools, test suites, and penetration testing can be applied to reduce the likelihood of vulnerabilities.

The above threats are general cases; each individual component is vulnerable to its own unique set of threats. Building a threat model for each individual component, however, is beyond the scope of this research. Therefore, this paper will focus on threats specific to the Access Management system, specifically:

- **Denial of Service (DoS):** as described above, DoS attacks can target all components within the SAVI system, particularly the SAVI Control Centre. However, DoS by account lockout can only be performed on the IAM. Several operations performed by the IAM (e.g. Authentication and Account Lockout) require considerable amounts of resource to respond, while attackers do not require any resources to create the triggering request.
- **Weak Credentials-Reset Mechanisms:** attackers can leverage a weak credentials-reset mechanism to steal a users credentials. This occurs when cloud providers manage user credentials themselves instead of using federated authentication.
- **Faulty Authorization Check:** when administrators prepare policies to authorize users, loopholes in policy files can grant attackers access to certain resources. Authorization logic might also become faulty under certain circumstances, making the SAVI services vulnerable to insufficient or faulty authorization checks. For example, the root cause of URL guessing attacks is faulty authorization checks.
- **Coarse-Grained Access Control:** If the IAM offers a coarse-grained access control model, which does not address the least-privilege and separation-of-duties principles, then administrators cannot provide users with only those privileges they strictly require to perform their tasks.
- **Insufficient Auditing:** The auditing logs are the main input through which intrusion detection systems detect attacks. The logs can be used for the future references.

3.3.4 Attack-Asset-Entry Relationship

Table 3.3.3 shows how attacks can compromise system and user's asset in SAVI:

Table 3.1: Attack Asset Relationship

Threat	Point of Entry	Target
Shared Technology Issues	All	User Asset
hline Account Hijacking	All	User Asset
hline Escalation of Privilege	Admin	System Asset
hline Vulnerability of SAVI Software Stacks or Procedure	Internal	System and User Asset
hline Rogue Experiment	Internal	System Asset
hline Denial of Service (DoS)	All	Both
hline Attacks Against Vulnerabilities in the SAVI Control Centre	Public and Internal	System resource

3.4 Conclusion

This chapter discusses about the threats on the SAVI testbed. An attack can launch from three types of interfaces on SAVI: admin network, internal network, and public network. The target of an attack can be a user's asset which can be the data or the acquired resources, or system resources. An attacker can abuse the existing vulnerabilities on software or hardware components to escalate his privilege, compromise an experiment, or launch attack against a target outside of SAVI. In the next chapter, we design and implement SAVI IAM.

Chapter 4

SAVI IAM

4.1 Introduction

Chapter 2 explored different cloud security frameworks and current research on identity and access management. Chapter 3 outlined various threats and vulnerabilities that face multi-tier cloud systems, defining the various assets that characterize such systems and the specific attack types associated with each asset. These definitions are necessary to lay the groundwork for the proposed SAVI IAM outlined in this thesis. As outlined in Chapter 2, current research on identity and access management can be divided into 3 main categories:

- Federation and cross-domain interaction
- Access control in the cloud
- New architectures for identity management in the cloud

The current research falls into the last category. Other researchers in the field have mainly concentrated on developing new architecture for federation using existing technologies (e.g. SAML), building distributed architectures in order to make the cloud scalable. Although authentication and authorization are standard requirements for any identity management system, many others are required to successfully implement IAM. Furthermore, other researchers have largely overlooked the intimate relationship between authentication and authorization. The proposed architecture outlined in this thesis distinguishes itself from previous approaches via the following design features:

- **Comprehensive:** The architecture includes all features defined by Cloud Security Alliance as the standard for IAM. It does not focus on authentication feature, but also places consider the whole requirements for a comprehensive IAM. The SAVI IAM is an Identity and Access Management solution for the cloud that encompasses all features (manifesting, authentication, and authorization etc.).
- **Practical:** Unlike previous approaches, which implemented as software code to measure the performance metrics of the proposed architecture, the architecture outlined in this thesis can be used in a production level-environment. The IAM runs on a SAVI testbed, which can host both experiments and commercial applications. In this environment, the two main considerations are stability and the use of standard protocols.

- **Technology Independent:** The original purpose of this work is to be technology- independent so that other researchers can improve upon the architectures methods and mechanisms later. This independence can be seen in the internal design of the IAM components. Components invoke each other through standard APIs, therefore; any changes to a single component have the minimal impact on other components. Furthermore, changing the internal technology does require any modifications to resources using the IAM.

- **Application Orientated:** Unlike previous approaches, which only considered real users, this architecture also considers applications as important entities in multi-tier cloud infrastructures. There are two major differences between applications and real users. First, applications can go rogue when compromised, and therefore cannot be granted absolute trust. Secondly, unlike users, applications are very conservative in their adoption of new methods, particularly in legacy software systems. Therefore, multi-tier cloud infrastructures should incorporate a collection of methods to authenticate and authorize entities.

The distinguishing feature of the proposed architecture is its objective to provide an IAM solution for application enablement. IAM for multi-tier clouds requires speed, flexibility, and the ability of the IAM to act as an application enabler rather than a specific operational function. Along this objective, we choose a well-known software development methodologyThe methodology of this research was based on a spiral model, in which a design is constructed iteratively based on an increasingly-refined set of system requirements.

The chapter is organized as follows:

- The Introduction outlines the goals of this research, and the specific design requirements considered.

- The Requirement Analysis section analyzes in more detail the system requirements and components that must be refined to successfully implement the proposed architecture.

- The Proposed Design section outlines the solutions created to satisfy the design requirements, and provides an overview of the proposed architecture.

The following standard terminology will be used in subsequent sections:

- **Entity/Subject:** Both applications and users require digital representation within the SAVI TB. Applications or users which run actions and create flow of information in SAVI are called Subjects. The IAM verifies the identity of subjects to ensure that incoming requests are initiated from the source they claim to be. Each subject is required to go through a startup login process in order to receive a token, which can then be used by the the subject in all subsequent actions. Subjects can use tokens to acquire computation, storage, and network resources.

- **Credential:** A credential is data used to verify the truth of an identity claim. IAM uses credentials to authenticate subjects. Credentials can include various attributes of a subject, such as OTP, a password, a public key, or a fingerprint.

- **Authentication:** It is the process of verifying the identity of a subject or the truth of a claim. The identity manager confirms that incoming requests are being made by the user who claims to be making the call by validating a set of claims. These claims primarily take the form of explicit credential requests. Once identity has been authenticated, the identity manager grants a token to the subject, which is used for identity authorization in all subsequent requests.

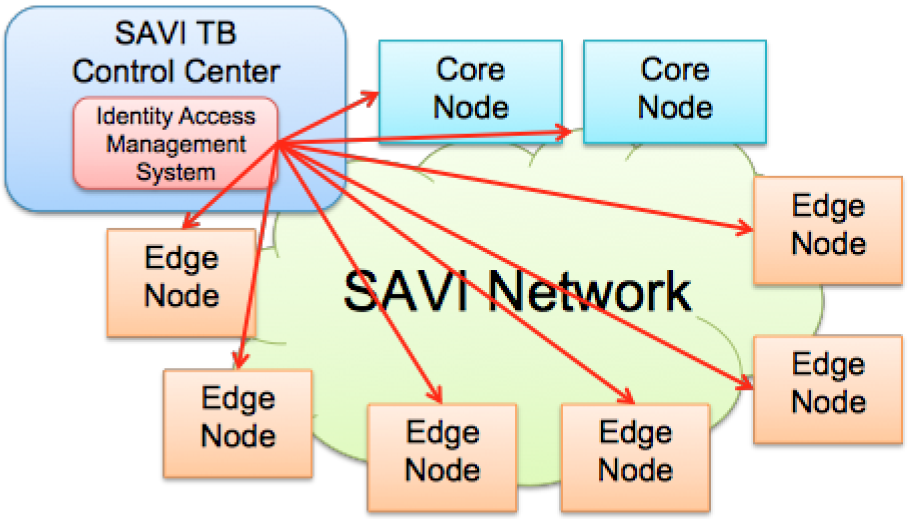


Figure 4.1: SAVI Testbed Main Entities and IAM

- **Tokens:** They are a series of numbers and letters granted to a subject following authentication to allow it to use resources on infrastructure. Each token is valid for a certain period of time, which can be defined for each specific context. The context can determine the scope of operations such as the available resources or number of accesses. If a token is not associated with a context, it known as an unscoped token. Tokens should be used in concert with authentication protocols (e.g. Kerberos, GSSAPI, and OAUTH) to be effective.

- **Role:** A personality that a subject assumes when performing a specific set of operations. A role includes a set of right and privileges. A subject assuming a specific role inherits its rights and privileges.

The rest of this chapter briefly outlines the SAVI security architecture, followed by the IAM requirements and design.

4.2 SAVI Security Architecture

SAVI is a testbed for the future application enablement. Figure 4.1 shows a high level view of the main SAVI Testbed entities, including the SAVI TB Control Centre, Core Nodes, Edge Nodes, and a SAVI network. Core and Edge nodes contain resources used for creating applications. The SAVI TB Control Centre hosts SAVI control and management functions, including resource allocation, clearinghouse, monitoring, and measurement. The SAVI IAM system located in the SAVI Control Centre is responsible for clearinghouse functions. The SAVI IAM asserts information about users, applications, or thread of executions, defined collectively as entities.

A Clearinghouse is a system within SAVI (consisting of software, operations, and policies) that brokers trust between the C & M plane and resources. It is the only component that every entity in SAVI TB fully trusts. The Clearinghouse component makes the various elements in SAVI TB interoperable and interfaces out-of-zone trust and security management systems. The SAVI TB Clearinghouse is composed

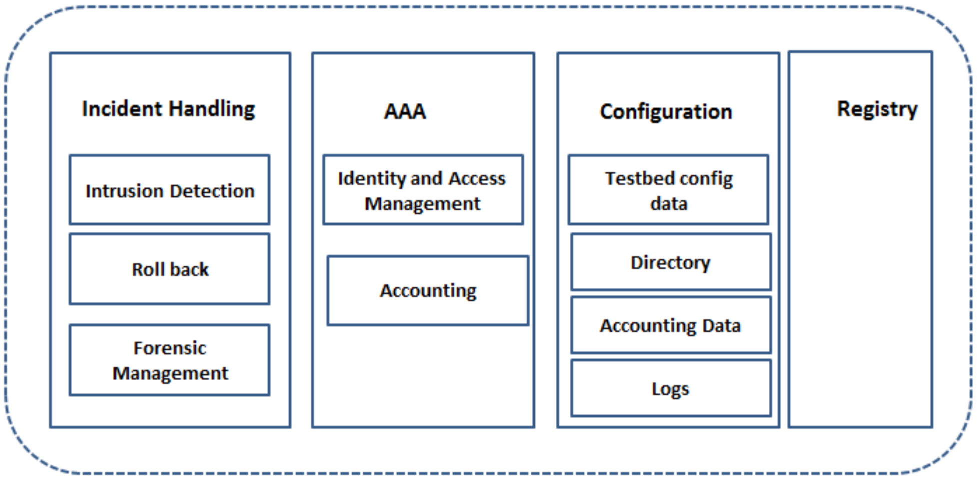


Figure 4.2: SAVI TB Clearinghouse internal components

of the following sub-components:

- **Authentication/Authorization/Accounting (AAA)**), responsible for implementation of Identity Lifecycle Management.
- A **Configuration Manager**, which stores all SAVI TB configuration data alongside credentials, access control policies, and resource usage logs.
- A **Registry** for all entities (e.g. resources, users, services).
- An **Incident Handling System**, responsible for reducing the impact of attacks on the SAVI TB.

These components are described in greater detail below.

4.2.1 AAA

Authentication-Authorization-Accounting (AAA) is in charge of managing the Identity Life Cycle in SAVI TB. It grants tokens to entities, manages the entitlement, and finally revokes the token when a subject leaves the system. Figure 6 illustrates the internal architecture of the SAVI TB AAA. In this architecture, the Identity Manager is responsible for handling the identities of users. Identities in SAVI TB are mainstream attributes (e.g. public keys, passwords, biometrics). Establishing and managing identities is a complicated process in large-scale systems. Therefore, SAVI TB Identity Management is cache-coherent. Caching allows lookups to be localized and accelerated without compromising system semantics. The Authentication and Single Sign On (SSO) sub-component verifies the identity of users as defined by the Identity Manager system. The authentication process in SAVI TB supports multi-factor authentication, wherein the identity of subject is verified through more than one credential (e.g. Password, Biometrics, and Public keys). Single Sign-On (SSO) is another essential element of authentication wherein entities are only allowed to use resources after a successful initial authentication. SSO attempts to minimize the number of credential requests from researchers while simultaneously preserving the privacy of subjects. Authorization and Access Control defines which resources a researcher has access to. The SAVI TB AAA implements fine-grained access control wherein an administrator-level researcher can assign granular permissions to other researchers. The final component is the Accounting system, which tracks researchers usage of SAVI TB resources. This accounting data can be used to bill researchers or their corresponding institutes. It is also a precious resource for forensic management purposes.

4.2.2 Configuration

The Configuration Manager subcomponent is a data store that holds all configuration data for establishing and maintaining the consistency of SAVI TB operations. This data includes platform-wide configurations; a list of Edge, Access, and Core nodes; SAVI network configurations and resources; experiment and user subscription configurations; and SAVI TB policies. It also stores all credentials, permissions, and access controls related to security management, as well as all data generated by other C & M components such as allocation, management, and registration. The Configuration manager should be reliable, high-performance, and immune to data leakage. All administrator-level users or components with valid access privileges can edit this data.

The Configuration Manager handles the following operations:

- **Configuration Identification:** the process of identifying the attributes that define every aspect of a configuration item.
- **Configuration Change Control:** a set of processes and approval stages required to change and re-baseline a configuration items attributes.
- **Configuration Status Accounting:** the ability to record and report on the configuration baselines associated with each configuration item at any point in time.
- **Configuration Audits:** This component is broken into functional and physical configuration audits.

4.2.3 Registry

A Registry stores all system resource registrations and makes them available to researchers or other SAVI TB components. The registry stores resource IDs, descriptions, capabilities, and capacities, and offers search functionality for finding registered services and resources. When researchers or other components wish to access a resource in SAVI TB, the request is sent to the Configuration Manager, which retrieves the requested service from the Registry. For efficient Registry service operation, a unique identification method for resources is required.

4.2.4 Incident Handling

The goal of the Incident Handling system in the SAVI TB Clearinghouse is to identify violations and minimize the impact of security attacks on the system. This module comprises three main sub-components (see Figure 4.2):

- An **Intrusion Detection System** passively intercepts traffic and detects anomalies in the SAVI TB. Intrusion Detection in SAVI TB is implemented in a distributed fashion, with agents running on all components.

- A **Rollback System** incorporates mechanisms that return a compromised system to its trusted state. Rolling back software, restoring configuration, and repairing bugs are examples of strategies that can be developed in this module.
- A **Forensic Management System** uses logs and accounting data to compile evidence that can be used to incriminate an attacker on the SAVI TB. Forensic management is a complicated job, and highly dependent on regulation, standards, and compliance of the country that a data centre located in. Due to reliance of compliance on geographical location, the effectiveness of forensic management depends greatly on location.

As discussed earlier, Authentication-Authorization-Accounting (AAA) consists of the IAM and the Accounting component; however, IAM is the most important component in the SAVI clearinghouse. The rest of this chapter concentrates on the design and implementation of the SAVI IAM.

4.3 Identity and Access Management

This section outlines a proposed architecture that improves the security of a multi-tier cloud. Both application-centric and user-centric security requirements are considered, with greater emphasis placed on applications The SAVI IAM adopts the "IdP/SP model", which incorporates four logical components: the *end-user* (a user, application, or a thread of execution that assumes an identity to interact with the available resources), the *user-agent* (software that allows the end-user to interact with the system), the *service provider* (SP) (a relying party that provides requested resources), and the *identity provider* (or asserting party, which asserts the identity of an end-user.) In the multi-tier cloud orchestration, the resources are the service providers and the IdP is the SAVI IAM system. The main challenge in implementing the IdP/SP model is scalability; the proposed solution extends the model to incorporate middleware that assumes some of the IAM responsibilities.

4.3.1 Requirements Analysis

There are three categories of requirements for an IAM in the multi-tier cloud infrastructure: 1) identity management, 2) access management, and 3) performance and scalability. When an application runs in the cloud, it initially identifies itself to the IAM in order to receive a list of available resources and slices of said resources. The behaviour of the applications is audited for future reference or for rolling back the system to a stable state in case of a crash.

subsubsectionIdentity Management Requirements:

- **Authentication:** This is the process of verifying an entitys identity to ensure that the entity has enough permissions to access its requested resources. The IAM should support several authentication methods, particularly well-known traditional methods (e.g. Passwords and Public Keys), to enable applications to rapidly adapt to the cloud. The IAM should also provide multi-factor authentication for accounts with high level security (such as administrators). Multi-factor authentication is the process of combining two or more types of authentication methods. Authentication should adapt to the risk level of the testbed. Risk-based authentication is an assessment of the risk involved in trusting the agent requesting a transaction, based on an assessment of behavioural, geographic, timing, and other factors. Single Sign-On (SSO) is the functionality that allows an entity to be authenticated once and maintain valid credentials for the duration of a session within one administrative domain.

- **Identity Federation:** This process allows an organization to extend entity access to other organizations. The IAM should support federation to allow entities to use different platforms. Single Sign-On is an essential feature of identity federation, allowing an entity to be authenticated internally and relay its authenticated identity to another cloud provider. This helps the cloud provider maintain the authentication process, and preserves the privacy of users. To effectively achieve cross-domain federation, the IAM must support a standardized entity authentication process, such as the Security Assertion Markup Language 2 (SAML2). Applications may use different authentication mechanisms to identify themselves to the IAM. In order for the IAM to support all authentication mechanisms, it is necessary to separate the authentication logic from the credential format.

- **Centralized Directory Service:** The directory service is a central component in cloud computing security, providing information about users, identities, projects, roles, etc. The directory service is heavily used by the authentication and access management components to store and retrieve identities and information.

- **Provisioning/Deprovisioning:** Provisioning is the process of allowing a user or application to use the infrastructure resources by granting appropriate credentials. Deprovisioning blocks further access to resources (e.g. in the case of an entity leaving on the cloud, transferring to another project, changing their meta information, etc.) by revoking granted permissions.

- **Manifesting:** The IAM is considered the point of entry for a user, and should provide sufficient information to allow the user to proceed with connection (e.g. endpoints to reach resources, their geographical locations etc.).

- **Revocation:** Keys, passwords, and systems are all capable of being compromised. Therefore, the SAVI IAM should be able to quickly revoke and replace keys and passwords, and suspend all permissions.

- **Auditability:** Since the IAM middleware intercepts all requests, it is able to track and furnish data for all basic audit requirements, as well as identify access violations or attacks and quantify risks and threats. It is necessary to know which project is responsible for each data packet, and to determine the entire chain of responsibility that resulted in unauthorized access. All activities, including authentications and access attempts, must be logged.

- **Usability:** Modelling users as part of security architecture is a key requirement for SAVI. Users tend to evade and ignore any system that is hard to use. It should be easy for users, particularly administrators, to create roles, constrain access etc.

Access Management

Access management involves two main operations: authorization and access policy management. Authorization ensures that users possess the correct level of access to a service or resource. Access management enables administrators to control entity access to resources and services by creating, updating, and deleting policies. Although access control has been extensively studied in the literature, the cloud requires its own access control management paradigm. The main goal of cloud infrastructures is to provide a highly-programmable platform, so the use of simple coarse-grained access control would be overly constraining to users and applications. Furthermore, since the rate of resource allocation and deallocation can be very high in application-oriented infrastructures, the authorization layer should not inflict a considerable performance overhead on resource providers. The authorization layer must obey the least-privilege and separation-of-duties design principles in order to ensure that entities have the minimum permissions needed to perform their duties, and that resource collusion is reduced (by distributing privileges among multiple entities). One final requirement if for delegation of authority, which enables an application or experiment to complete a task even after the initiator has left the infrastructure. This requirement is further explored in Chapter 5.

Performance and Scalability

The performance overhead for providing security must be modest, or the resource provider and users may be tempted to disable the security system. If the performance of the IAM is reduced, the effect cascades through the rest of the infrastructure. Resource providers are heavily dependent on the IAM for authentication and authorization, so any considerable performance overhead can result in a system crash. To avoid such crashes, the IAM should be designed and implemented with performance in mind. Moreover, the IAM should be able to scale itself in response to increased request volumes during peak hours.

4.3.2 Proposed System Design

The proposed SAVI IAM has been implemented to address the requirements outlined in the previous section. The SAVI IAM is a central identity manager with a distributed middleware based on the IdP/SP model. The proposed architecture is shown on Figure 4.3, and is composed of 6 basic components: Manifesting Management, Identity Management, Policy Management, Token Management, Authentication Management, and Middleware.

IAM requests originate from two sources: external entities and the middleware. External entities perform authentication and administrative operations:

- Creating, updating, listing, and deleting users
- Creating, updating, listing, and deleting projects
- Creating, updating, listing, and deleting roles
- Creating, updating, listing, and deleting policies
- Creating, updating, listing, and deleting endpoints
- Creating, updating, listing, and deleting service
- Assigning user roles
- Assigning user project membership

The second source of requests is the middleware, which requires the IAM to validate tokens and retrieve access information. The middleware reduces the IAM workload and increases its performance by caching identities offloading authorization responsibility.

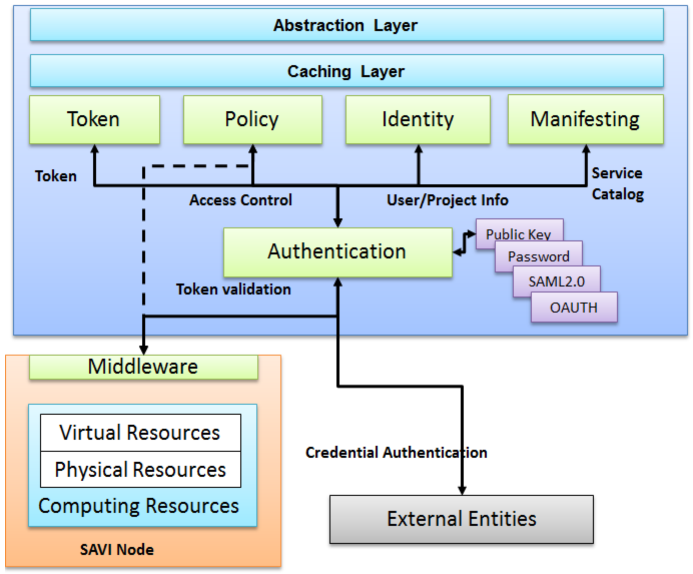


Figure 4.3: IAM Architecture

Manifesting Management

To access a resource, an entity requires the requested resources URL-named endpoint. Endpoints, together with associated resource attributes such as geographical locations, quotas, service level agreements, service types etc, are enclosed in a data structure called an endpoint record. Each endpoint record contains three types of endpoints: Public, Admin, and Internal. Public endpoints handle external access to the resource, Admin endpoints handle administrative tasks bound to a management network, and Internal endpoints handle inner component invocations. Each endpoint record has an edge node label. The list of endpoint records (the service catalogue) directs entities toward a resource or resource configurations and ensures entity alignment with governance standards. The service catalogue can be updated, retrieved, and created through the Manifesting Management component. The service catalogue is divided into regions corresponding to edge nodes within SAVI. Each edge node is independent of other nodes in terms of provisioned resources.

SAVI Edge Nodes are dispersed over various geographical locations throughout Canada. Each Edge node can be treated as an autonomous system, since all control and management components are duplicated except for the clearinghouse. Each SAVI installation has its own set of endpoints, each labelled by a region name. To run instances across sites, users have to explicitly select a region. Each Edge node corresponds to a specific region, and has its own set of resources; for example an edge node may possess non-conventional computing resources such as FPGA or NetFPGA, while another edge node may not.

Figure 4.4 illustrates the UML diagram for the Manifesting Management component. Each endpoint is associated with a service, which corresponds to available resources on the system. Currently, 8 services are available on the SAVI TB.

The "extra" resource attribute is intended to allow for additional tags or attributes associated with the endpoint. It allows implementations to map regionality or location if its appropriate for their environment. Name attribute in the above model can have three values: Admin, Public, and Internal.

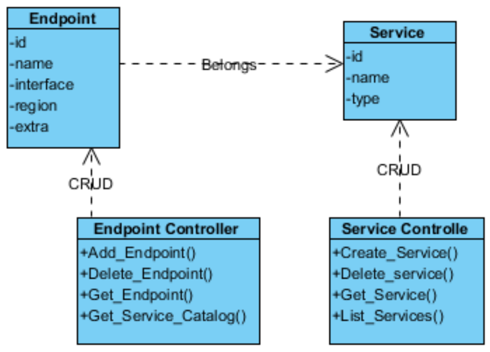


Figure 4.4: Manifesting Management UML Diagram

Table 4.1: SAVI Resources

Service Name	Service Type	Description
Nova	Computation	Provides virtual, bare metal, GPU, and atom machines.
Swift	Object Store	Allocates storage to users and applications.
IAM	Identity	Provides identity and access management.
Quantum	Networking	Provides networking as a service between interface devices (e.g. vNICs) managed by other SAVI services (e.g. Nova)
Whale	Configuration	Provides testbed configuration, log, and topology information.
Janus	Management	Provides a software-defined network manager.
Cinder	Volume	Provides an infrastructure for managing volumes in the SAVI testbed.
Glance	Image	Provides services for discovering, registering, and retrieving virtual machine images.

4.3.3 Identity Manager

The Identity Manager component is a central directory which stores users, projects, and relationship information. When a user joins the SAVI testbed, their identity goes through the following lifecycle:

1. An entity is created for the user.

2. The administrator grants a role to a user entity within a project. If the requested project does not exist, the administrator creates a new project.

3. The user sets their environmental variables, and sends a request for the desired resource.

4. When the task is complete, the user either manually revokes the toke or lets it expire.

Figure 4.5 shows the UML diagram for the identity component:
As Figure 4.5 illustrates,

- A user associated with no projects is useless from the perspective of SAVI testbed and should not be authenticated for any resources. Users can be associated with one or more projects, and therefore can also occupy one or more domains. A *project_id* label on a user resource represents a 'default' project, which is used in authorization and validation calls. If no *project_id* label is provided for such calls, the user's *"project_id"* is used as a default.

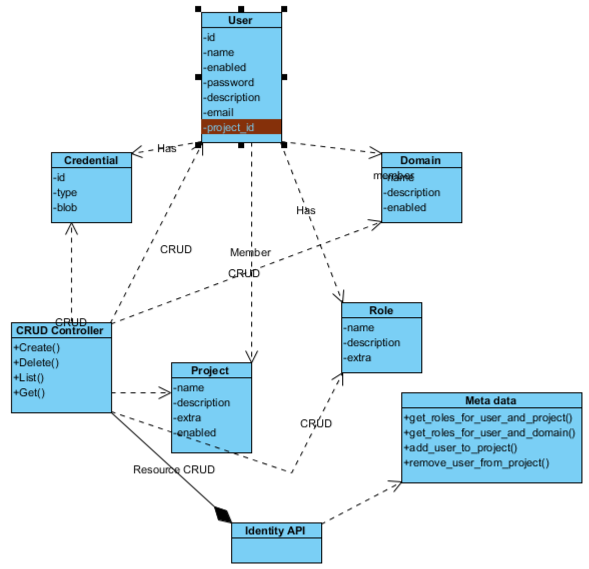


Figure 4.5: Identity Management UML Diagram

- Credentials can have any format as long as they are serializable and associated with a user. However, a user can have multiple credentials. Type is a string attribute in the credential model is that indicates how the blob should be interpreted, and can be ec2 and public key.
- Projects are the base units of ”ownership” in SAVI. Projects can have one or more users, but are always associated with a single domain. Users are assigned to roles in the context of a project.
- Domains are collection of projects, which have their own standards, governance, and compliance.

4.3.4 Policy Management

The Policy Management component is a central repository for storing access policies. Administrators can create, retrieve, update, and delete policies via this component. When the middleware wants to authorize a request, it fetches access policies from the IAM by calling the Policy Management component. Each access policy is associated with a service type, which enables administrators to define a separate policy for each resource type. The Policy Management component has the following attributes:

- id
- endpoint_id
- blob
- type

4.3.5 Token Management

The Token Management component is responsible for generating tokens for entities following the authentication process, and associating tokens with security meta-data. For example, when the IAM receives an incoming list of users requesting access to a project, it extracts the users tokens and asks the Token Management component to provide the necessary token authentication information. Token Management component has the following attributes:

- id
- expires (iso8601 timestamp)
- user (full resource description, see User resource above)
- project (full resource description, see project resource above)
- catalogue (full description of all endpoints available to/for the token)

The Token Management component can generate two types of token formats:

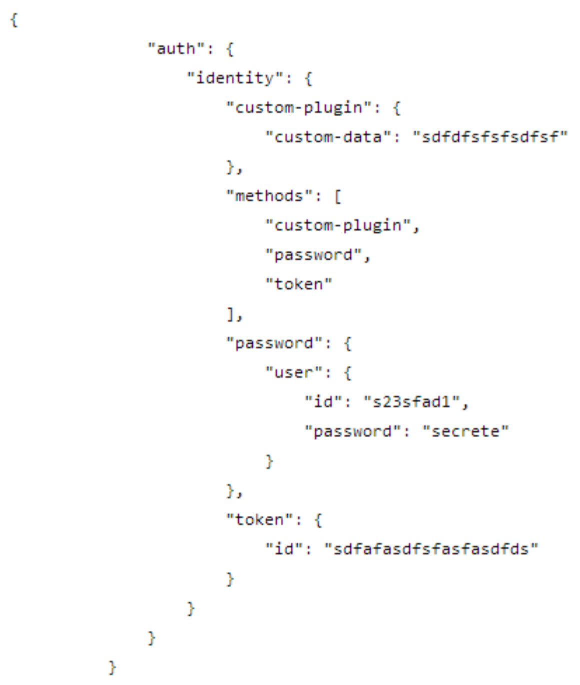
- **Universally Unique Identifier (UUID):** The UUID is a series of letters and numbers to maintain the session of a user or application. When an entity sends a request with a UUID token, the middleware connects to IAM to validate the token. The token management maintains the associated information with UUID tokens. For example, each token is associated with a project in which the token is valid. To get the project from the token, the token management component needs to be invoked. The token management component stores the project and the user of each token. If other components need more than project and user id, they can invoke the identity management component.

- **Public Key Infrastructure (PKI):** The IAM generates a PKI certificate for the entity and signs it with its own Public Key; in this arrangement the authentication middleware does not need to refer to the IAM to validate the token. PKI tokens enclose all information required to authorize and authenticate a user. The IAM does not store any PKI token data.

4.3.6 Authentication Component

The Authentication component, when used in concert with the Token Management component, is the cornerstone of the authentication process. The authentication module supports multiple authentication mechanisms; it fetches a users attributes and project information via the identity module to validate a users credentials. Separating logic from storage enables the IAM to support different authentication methods independently of the Identity Management component, allowing for flexible authentication. The IAM Authentication component determines the method of authentication in runtime. The following snippet shows a typical authentication request:

As the above code shows an identity is a list of methods and corresponding data to authenticate the identity with each method. For example, this request uses password based, token, and a custom plugin authentication method to verify the identity of entities. It is possible to combine two or more methods for the sake of strong authentication. For each method, the authentication component invokes the appropriate plugin to authenticate the data, then aggregates the result of each plugin. There is a type of authentication called re-scoping which means changing the security context. In re-scoping authentication, entity does not want to authenticate itself, but it needs to change the associated information with a token. For example, an entity needs to change the project to access another project files. If the authentication is for re-scoping, entity must append the previous method names into ”method_names”.



```
{
              "auth": {
                  "identity": {
                      "custom-plugin": {
                          "custom-data": "sdfdfsfsfsdfsf"
                      },
                      "methods": [
                          "custom-plugin",
                          "password",
                          "token"
                      ],
                      "password": {
                          "user": {
                              "id": "s23sfad1",
                              "password": "secrete"
                          }
                      },
                      "token": {
                          "id": "sdfafasdfsfasfasdfds"
                      }
                  }
              }
          }
```

Figure 4.6: An Authentication Request

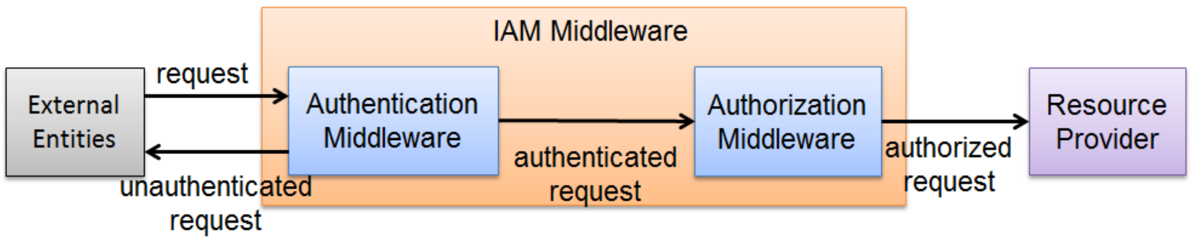


Figure 4.7: IAM Middleware Architecture

For each credential authentication request, there is an identity-type field that defines the appropriate method for validating the credential. Users can choose between different authentication methods (e.g. Public Key, Password, OAUTH, or SAML v2.0) or even token formats.

4.3.7 Middleware

The middleware resides in front of a resource provider, allowing it to intercept requests. After a request is authenticated and authorized, it is handed over to the service provider; otherwise, the request is directly rejected. As shown in Figure 4.7, the proposed IAM incorporates two middlewares, for authentication and authorization, respectively. The authentication middleware validates a token by sending it to the IAM system, while the authorization middleware builds a security context from a request and maintains a local version of access control policy synced with the IAM. To improve performance, authentication is maintained within the IAM, while authorization is delegated to the resource provider.

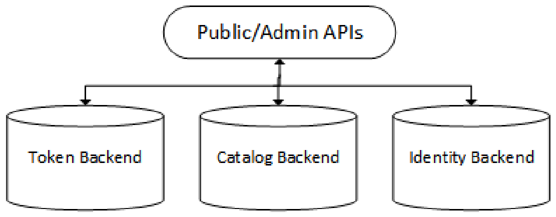


Figure 4.8: Openstack Keystone v2.0 Essex Architecture

4.4 Implementation

This section describes the detail of implementation for the SAVI IAM.

Openstack Keystone

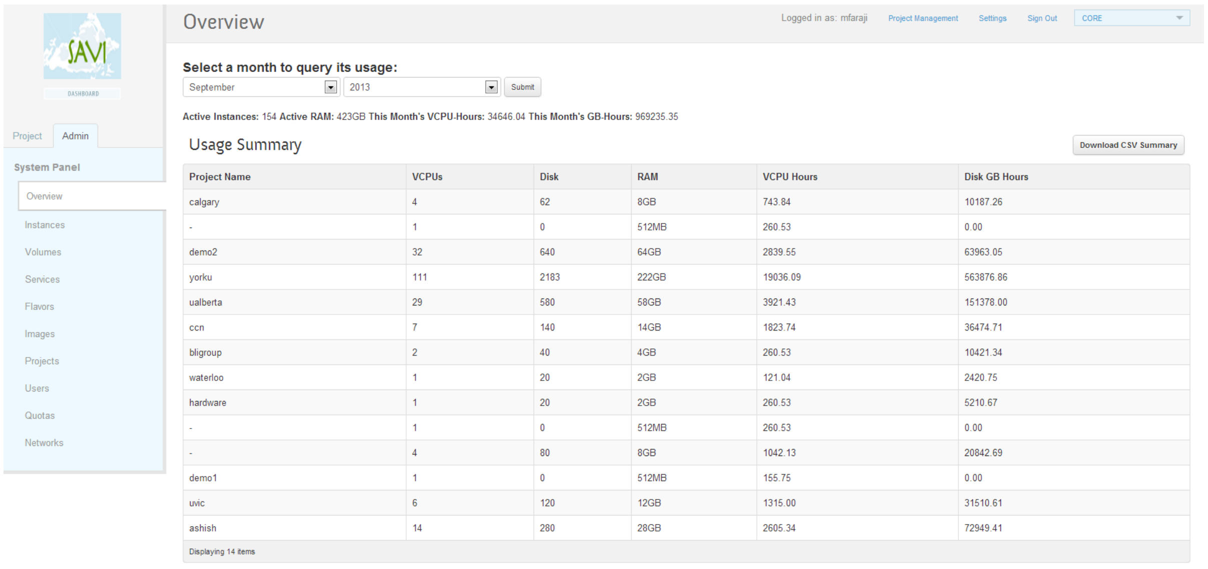
SAVI IAM is built on top of Openstack Keystone V2.0 [ref]. Keystone is Openstack identity manager. It has three basic components: Catalogue, Identity, and Token. Service catalogue stores a list of endpoints, and identity backend verifies tokens and credentials and handle CRUD operations on users meta-data, token backend generates tokens, and policy component manages policy operations. Keystone v2 does not support policy CRUD operations and there is no PKI support at the moment. Figure 4.8, shows the overall architecture of Keystone.

Keystone supports a well-defined format for credentials, and can generate tokens in Openstack and EC2 format. Keystone has two kinds of APIs which serve different types of users: Administrative operations can be performed through adminAPI; and regular queries go through Public API. It has an authentication middleware that sits on in the front line of each resource on the cloud, this middleware authenticate users tokens through Keystone. We choose Keystone v2.0 to build the SAVI IAM on top of that because:

- SAVI testbed is based on Openstack. Therefore, Keystone v2.0 reduce the burden of developing all Openstack identity APIs from beginning.
- The basic components (e.g. WSGI server, Paste, etc.) has already been implemented in Keystone v2.0. It save the implementation time dramatically.
- Openstack Keystone v2.0 has an active community of development, therefore we can actively receive a feedback about the SAVI IAM by comparing it with Openstack Keystone.

Access Control

Openstack Keystone has gone through 4 releases so far: Diablo, Essex, Folsom, and Grizzly. The SAVI IAM is built on top of Essex version which has been released in 2012. In Essex version, access control has been implemented very naively in which Keystone acts as a central directory. The access policy was kept in local file systems in on resource providers. Because each service has a different interpretation for each role, there has been a lot of inconsistency between privileges. For example, an admin role can list objects in one resource, while in another resource, he may not. This access control model was used as a foundation to develop the SAVI access management component.



Overview

Select a month to query its usage:
September | 2013

Active Instances: 154 **Active RAM:** 423GB **This Month's VCPU-Hours:** 34646.04 **This Month's GB-Hours:** 969235.35

Usage Summary

Project Name	VCPUs	Disk	RAM	VCPU Hours	Disk GB Hours
calgary	4	62	8GB	743.84	10187.26
-	1	0	512MB	260.53	0.00
demo2	32	640	64GB	2839.55	63963.05
yorku	111	2183	222GB	19036.09	563876.86
ualberta	29	580	58GB	3921.43	151378.00
ccn	7	140	14GB	1823.74	36474.71
bligroup	2	40	4GB	260.53	10421.34
waterloo	1	20	2GB	121.04	2420.75
hardware	1	20	2GB	260.53	5210.67
-	1	0	512MB	260.53	0.00
-	4	80	8GB	1042.13	20842.69
demo1	1	0	512MB	155.75	0.00
uvic	6	120	12GB	1315.00	31510.61
ashish	14	280	28GB	2605.34	72949.41

Displaying 14 items

Figure 4.9: SAVI portal homepage

Web Portal

To provide a more intuitive interface to users, SAVI uses a Web UI portal based on Openstack Horizon. Like other Openstack projects, Horizon is written in the Python programming language and uses a Django web framework. Users can issue commands through either a Web UI portal or a command line interface. In the proposed architecture, Openstack Horizon has been expanded to support central Keystone. Consequently users can now easily switch between SAVI nodes and acquire or release their resources. The main challenge in applying this expansion is in implementing region support in Openstack clients such as Nova (Openstack computation component) clients, as the portal uses these clients to interact with other Openstack components. The SAVI portal enables users to dynamically join, leave, or create projects. The difference between a portal and a CLI is that users are able to issue the same commands with fewer options through the web UI.

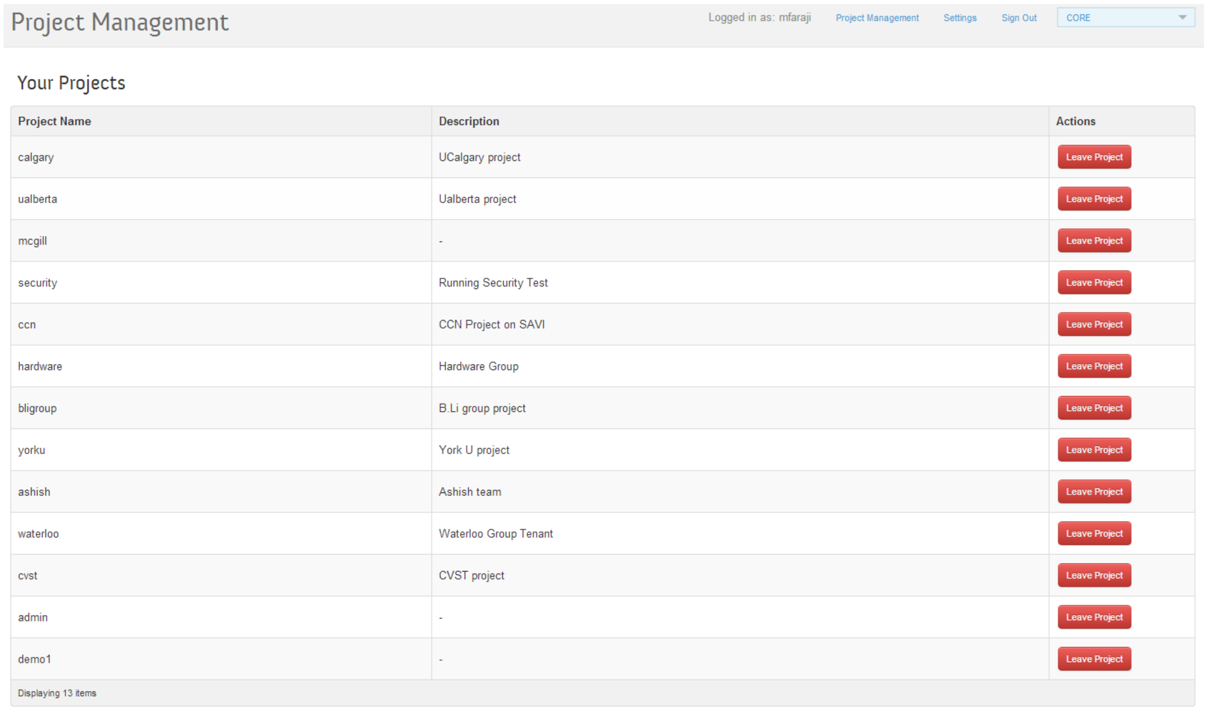
Figure 4.9 shows the homepage of the SAVI portal.

The side panel on the left enables users to interact visually with the Openstack components. Table in Figure 4.9 shows the statistics of the infrastructure. To leave a project, the user clicks on the Project Management.

Figure 4.10 shows a list of projects to which a user belongs. User can leave a project simply by clicking on the Leave Project button. Projects can be joined or created in the same manner.

As Figure 4.11 shows, users can join available and publicly visible projects, or they can ask for a new project. To switch between projects, users can click on the sidebar slider to choose the appropriate project (Figure 4.12).

To switch between regions, users can simply click on the top rightmost menu (Figure 4.13).

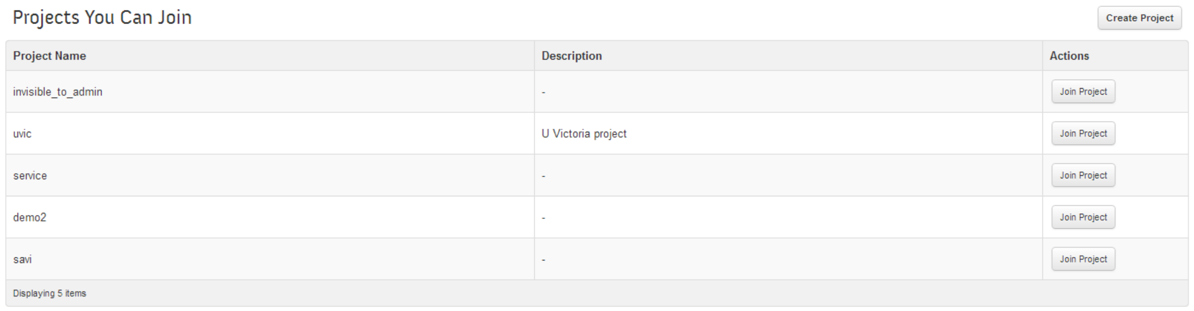


Your Projects

Project Name	Description	Actions
calgary	UCalgary project	Leave Project
ualberta	Ualberta project	Leave Project
mcgill	-	Leave Project
security	Running Security Test	Leave Project
ccn	CCN Project on SAVI	Leave Project
hardware	Hardware Group	Leave Project
bligroup	B.Li group project	Leave Project
yorku	York U project	Leave Project
ashish	Ashish team	Leave Project
waterloo	Waterloo Group Tenant	Leave Project
cvst	CVST project	Leave Project
admin	-	Leave Project
demo1	-	Leave Project

Displaying 13 items

Figure 4.10: Project Management Page

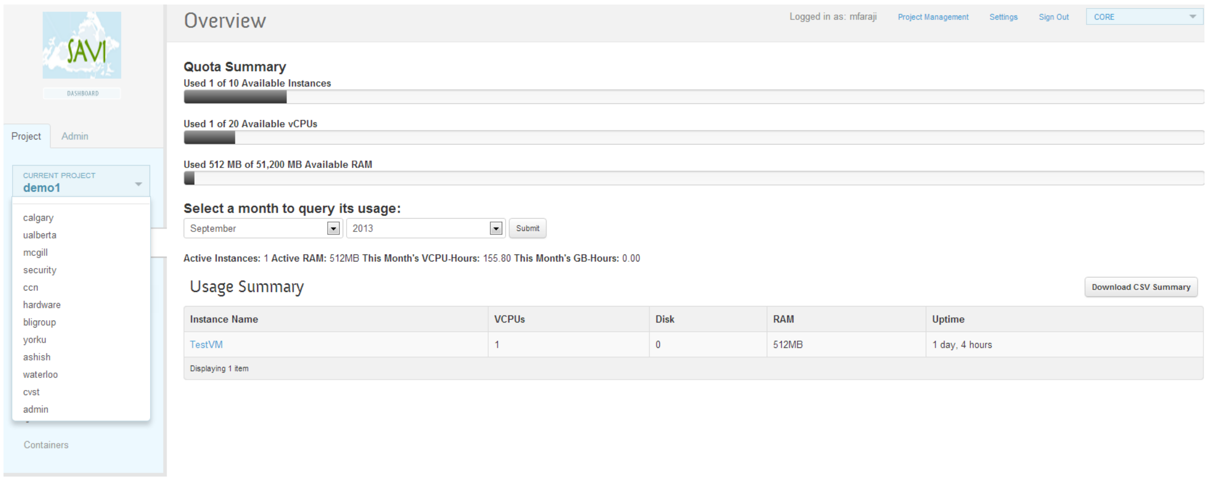


Projects You Can Join

Project Name	Description	Actions
invisible_to_admin	-	Join Project
uvic	U Victoria project	Join Project
service	-	Join Project
demo2	-	Join Project
savi	-	Join Project

Displaying 5 items

Figure 4.11: Join Project Page



Overview

Quota Summary

Used 1 of 10 Available Instances

Used 1 of 20 Available vCPUs

Used 512 MB of 51,200 MB Available RAM

Select a month to query its usage:

Active Instances: 1 Active RAM: 512MB This Month's VCPU-Hours: 155.80 This Month's GB-Hours: 0.00

Usage Summary

Instance Name	VCPUs	Disk	RAM	Uptime
TestVM	1	0	512MB	1 day, 4 hours

Displaying 1 item

Figure 4.12: Switch between projects

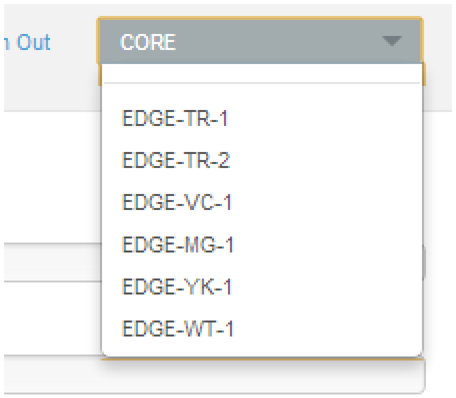


Figure 4.13: Switch between regions

4.5 Conclusion

This chapter discusses about the proposed architecture for the IAM in the multi-tier cloud infrastructure. The SAVI IAM distinguished itself from the works in the literature in terms of comprehensiveness, practicality, and technology independence. The SAVI IAM addresses three classes of requirements for the multi-tier cloud IAM: Identity Management, Access Control, and Scalability/Performance. The SAVI IAM is composed of 6 basic components. Among these components, the middleware is located on the resource provider. The middleware captures requests on the resource provider, and send them to IAM for authentication. Authorization is performed on in the middleware itself. One of the advantages of SAVI over previous works is flexibility in authentication. SAVI supports a wide range of authentication methods in its authentication component, and in return, it generates both UUID and PKI token. The SAVI IAM is built on top of Openstack Keystone v2.0 which is the identity manager for Openstack infrastructure. Using Keystone saves the time of developing Openstack Identity APIs as the SAVI testbed is using Openstack projects. Users of SAVI can interact with SAVI components through command-line and web UI. In the next chapter, we focus on developing a fine-grained access control for SAVI.

Chapter 5

Access Control

5.1 Introduction

The core task of the IAM in the SAVI testbed is to control users and applications access to available system resources. In security parlance, Access Control is the enforcement of a predefined access policy on resources in order to confine the actions of an entity to only those requests and resources to which it is entitled. The purpose of applying an Access Control policy is to reach a yes-no decision to accept or reject a request to perform an action. Access Control should provide administrators a fine level of control over access to their administrative domain. A fine-grained Access Control system provides control over methods, resources, and collections of resources. If the enforcement point is incapable of binding action requests to authenticated subjects with a sufficiently fine level of control, the access policy can easily be subverted. Such binding is called Secure Association. In a safe access-control policy, there is no access leakage to unauthorized users - directly or indirectly - at any level of the underlying cloud system. Traditional Access Control mechanisms cannot satisfy the multi-tier cloud infrastructure without modification. The multi-tier cloud infrastructure is more dynamic and distributed than traditional systems, and security for such an environment poses unique challenges.

In the multi-tier cloud, users and applications occupy a variety of domains; therefore, the Access Control system must cross the borders of administrative domains in order to function with heterogeneous systems. In multi-tier clouds, both IAM services and resources should be protected from unauthorized access. Therefore, the Access Control system for the cloud must enforce fine-grained access control at both the function and object level to ensures that users with permission to call a function also have appropriate access to target objects required to successfully perform a particular task. Access Control needs more than an identity to make this decision, so the traditional identity-based access control models - wherein entities and objects are managed via their identities - are insufficient. Such systems are susceptible to such problems as role explosion and information leakage [37]. To overcome these problems, the Access Control system should include the access context. In this application, Context is defined as the sum of all characterizing information relevant to the implementation of Access Control, including entity and resource attributes. Context enables Access Control to make an authorization decisions based on specific attributes of the user and target object rather than their identities.

The most important concept in Access Control is Access Policy. A policy is a collection of assertions that represent an entitys requirements, capabilities, preferences, and other properties that must be satisfied in order to gain access to the system. An Access Policy should be resource-independent and based on industry standards, specifying which entity may use which resource under which conditions. The Access Control Policy should not, however, be global, as each administrator should be able to define their own custom policies.

5.2 Background

One way of understanding the proposed approach to Access Control is by summarizing existing mechanisms for restricting access to resources. It is worth pointing out that these mechanisms generally fall under one or a combination of two forms:

- **Discretionary Access Control (DAC):** DAC is method of restricting access to an object based on the entitys identity (e.g. user, process, and group). This type of Access Control is called discretionary because the entity with a certain privilege is capable of passing its privileges or security attributes to another entity. DAC is widely used in many networks and operating systems.

- **Mandatory Access Control (MAC):** MAC is a method of constraining an entity from accessing or performing operations on a resource, based on predefined security attributes or labels assigned to the entity and the target object. This kind of access control was originally introduced by Bell and LaPadula [14]. The term mandatory refers to the fact that the system enforces Access Control, and that users or program cannot override it. MAC Access Controls are mandated by government order, and are thus more restrictive than in most commercial systems. A label on an object/resource is called a security classification, while a label on the entity is called a security clearance. These labels, along with the Access Policies, are processed by an engine in order to make authorization decisions.

There are many access control models implementing DAC and/or MAC. The following section outlines the 4 most common models:

- **Identity-Based Access Control (IBAC):** In this model, permissions are granted to entities based only their identities (e.g. usernames). Access Control List (ACL) is a typical example of this model, wherein an entity is allowed to access an application only if that users ID is on a list of authorized users (whitelist). This model is either all-in or all-out. It is extremely coarse-grained in the sense that it only considers one dimension (the user), ignoring resources, actions, and context. The main drawback of IBAC is identity-object-association explosion, which occurs when the number of identifiers in the ACL increases.

- **Role-Based Access Control (RBAC):** RBAC restricts access of entities to resources based on assigned roles. Each role is associated with a set of permissions. When an entity is authenticated, it is assigned a role; the entity can then be authorized based on its associated permissions. Compared to IBAC, RBAC add a layer of abstraction between the entity and its permissions. RBAC and IBAC fall under the category of DAC mechanisms, and are appropriate for addressing MAC requirements. To implement MAC with RBAC, a unique role must be created for each combination of security labels, which is not feasible in practice.

- **Lattice-Based Access Control (LBAC):** In LBAC, an ordered set of security labels is combined with a set of categories to form a lattice. The lattice adds levels of indirection between security labels and security classes. LBAC is effective when the system has a limited number of security labels and categories. It provides a coarse-grained access control without scalability and flexibility.

- **Attribute-Based Access Control (ABAC):** In the ABAC model, all entity, resource, and environmental attributes are considered in authorization decisions. The logic for decision-making is written in a policy file. ABAC provides a flexible MAC mechanism in which administrators can use all attributes (e.g. role, datetime, project etc.) to create a flexible authorization mechanism.

5.3 Requirement Analysis

In the section below, as in the previous chapter, the requirements for a SAVI testbed Access Control system are outlined, followed with the proposed system design. In the previous chapter, an empty role model was proposed for Access Management, in which the IAM stores only roles without permissions. In other words, the IAM was the only Role Authority. Resources apply locally-stored policy files on the entity roles in order to authorize each request. This chapter outlines the necessary Access Management architecture to satisfy the following requirements:

- **Central Policies Repository:** A major design decision concerned where the access control policies should be placed for use in access authorization. Traditionally, placing policies in a separate access authorization service was rejected for performance reasons. For simplicity, the same approach outlined in the previous chapter was followed. Locally-stored policy files lead to inconsistency problem when a role is granted a permission in one resource, but it is granted the same permission in another, similar resource.

- **Least Privilege:** The Access Control system should implement the least-privilege principle. Least-privilege is an important principle in computer security, wherein an entity is required to receive exactly the permissions it needs to perform its tasks. For example, most web servers do not need to open connections to arbitrary addresses to order to perform their tasks. The absence of this practice allows attackers to easily spread worms. Least privilege can protect the SAVI nodes against accidental violations, Malware, and malicious applications.

- **Explicit Trust:** The intended Access Control system should provide flexible mechanisms to define trust relationship, and delegate trust to another entity. One important aspect of trust relationships is delegation of authority, in which an entity gives its attributes (e.g. role) for a specific duration to another entity to perform a task. The delegation of the authority should be both flexible and manageable in the sense that the authority should be allowed to delegate any subset of permissions to subordinates, and the authority should have the capability of specifying what subordinates can do.

- **Separation of Duties (SoD):** The Access Control system must support Separation of Duty, a security principle used to distribute authority among multiple persons in order to complete a task. The purpose of this principle is to prevent fraud by spreading the responsibilities and authorities for an action.

5.4 The Proposed Design

As mentioned earlier, the Access Control model determines who can access which resources on the cloud infrastructure. Generally, Access Control models assume that the access permissions are known in advance and that access rules have been correctly set up. This assumption is not always accurate in practice, and administrators must to change the configurations (e.g. role, policy etc.) later. Therefore, the configurations for each administrator should be isolated from each other. SAVI uses an isolation-enabled Access Control model to provide flexible, adaptable, fine-grained access management. Isolation provides a method of addressing the problem of containment for compromised applications [ref], and has been used to add flexibility to role-based access control [22]. Isolation allows administrators to define authorization parameters (e.g. roles) in an isolation scope; each isolation scope can have its own policy. The isolation scope defines the granularity of isolation and can be a project, administrative domain, or physical node. The authorization layer fetches the security context and policies for each isolation scope separately. The proposed authorization architecture is illustrated in Figure 5.1. The architecture incorporates the following logical components:

- **Policy Enforcement Point (PEP):** PEP receives a request, forwards it to PDP (see below), and returns a decision from PDP to an external entity. In essence, it is the point of presence for Access Control, and must be able to intercept requests between users, applications, and requested resources. The PEP must be designed in such a way that entities can not bypass it to invoke protected resources.

- **Policy Decision Point (PDP):** PDP makes the authorization decision by evaluating an entitys attributes, resource attributes, and environment attributes against the applicable policies. Policy Decision Point is the policy execution engine, and contains the logic of authorization. The evaluation of policy rules may be boiled down to the evaluation of First Order Logic expressions, (i.e. Description Logic, or Horn Logic).

- **Attribute Authority (AA):** AA provides the required attributes to the PDP in order to make an authorization decision. Depending on the PDP logic, it may provide entity, target object, or situational attributes.

- **Policy Management Point (PMP):** PMP provides the policy information for the PDP. It is a set of RESTful API that enables PDP to access the latest versions of policies. It also enables administrators to create, modify, and delete policies. Policies consist of decision rules, conditions, and other constraints for accessing resources.

PEP and PDP have been implemented in the authorization middleware, with the PMP as the policy management component within the IAM. The Attribute Assertion component is composed of two parts: Subject Attribute Authority (SAA) and Resource Attribute Authority (RAA). SAA is part of the middleware, and extracts entity attributes after authentication. RAA is implemented by the specified resource, and provides the required entity attributes on-demand. The proposed design implements two Access Control models: Role-based Access Control (RBAC) and Attribute-Based Access Control (ABAC).

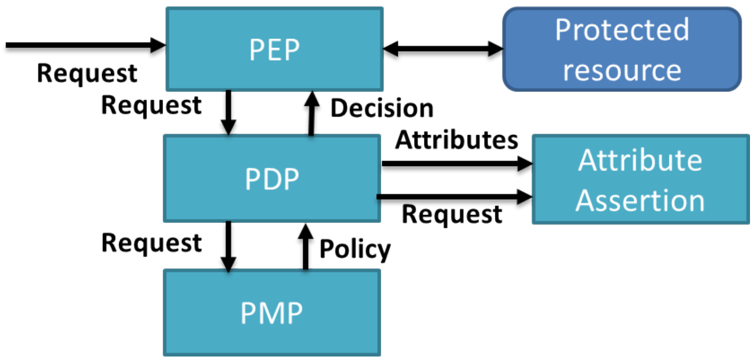


Figure 5.1: SAVI Authorization Architecture

5.4.1 Role-Based Access Control

Role-based Access Control (RBAC) is very useful Access Control model for cloud computing. Although its benets are fundamentally limited to entity attributes, it simplies the management of permissions. The main function of RBAC is the granting of permissions to users according to the assigned roles. Therefore, roles furnish a layer of abstraction between users and permissions. Administrators assign roles to users, and these roles incorporate new permissions as applications and systems join to them. There are three operations in RBAC: role assignment, request authorization, and role-permission association. RBAC has gone through the three main development stages - RBAC96, RBAC97, and RBAC02 - before becoming industry standard.

- **RBAC96:** It is the based of implementation in SAVI. RBAC96 supports role-permission, role hierarchy, and role constraints [61].
- **Distributed RBAC (dRBAC):** This system is not widely used; however, it is considered standard due to its being based on existing standard network protocols. dRBAC enables organizations to implement their own RBAC system and issue certificates for their internal users to use the organizations infrastructure. This certificate is signed by the home organizations public key, and contains issuer, domain name, and user ID. The permissions and privileges of each role are confined to the issuer domain (which is in the certificate) [18].
- **RBAC02:** In this system, users are not required to provide their identity to the resource provider; instead, the service receives authorization from the policy engine. The user presents their identity to the policy engine, receives authorizations, and presents these authorizations to the appropriate service. RBAC02 has several advantages, including: easy delegation, simple system upgrades, privacy preservation, and scalability [37].

Figure 5.2 illustrates the core RBAC model employed in SAVI testbed:

In Figure 5.2, each entity is assigned a role, which incorporates a set of permissions. Permissions are a combination of actions and resources. For example, the combination of the action *boot_vm* and a computation resource constitute a permission. An administrator can assign permissions to roles in an isolation scope. The SAVI RBAC is implemented at the API level. The required attributes to complete authorization in SAVI RBAC are the list of user roles, user projects, and identity statuses. Authorization

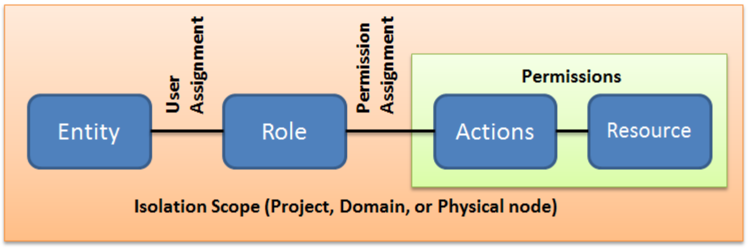


Figure 5.2: Core RBAC Model

is performed by checking the attributes against the policy. SAVI accepts policy in JavaScript Object Notation (JSON). The grammar for defining a policy is as follows:

```
"service/resource:action":[["role:role_name"]]
```

The service/resource can be a service or resource on the SAVI testbed or a component inside a resource. For example, a computation resource is composed of several components such as networking management subcomponent. An administrator can define the policy at the resource level or the component level. Action is an defined action inside the resource or component. Role is the policy predicate, which allows an action to be performed on a resource if the role of an entity is equal to *role_name*. This model has been extended to accept project as predicate, as in the below example:

```
"compute_network:create_network":[["role:admin"], ["project: sample"]
```

This policy states that an entity can create a network in networking subcomponent of computation resource if the role of entity is *admin* and the entity is a member of *sample* project. Although RBAC provides two level of control (resource and component), it lacks flexibility in policy definition. Additionally, there are three further drawbacks with RBAC: 1) substantial effort is required to define and assign roles to users, 2) administrator must introduce new roles to cover discrepancies, leading to role-explosion problems [38], and 3) RBAC is not suitable for cross-domain access management because reaching agreement as to what permissions are associated with a role is difficult [10]. Due to these barriers and to provide a finer level of access control, many service-oriented platforms have shifted to attribute based access control.

5.4.2 Attribute-Based Access Control

Unlike RBAC, the Attribute-Based Access Control (ABAC) [71] model can grant permissions based on security contexts known as attributes. An attribute is a named property or predicate of an entity (e.g. role, project) that can be matched to a specific value. By considering role and identity as attributes of an entity, ABAC combines the functions of both the IBAC and RBAC approaches. Therefore, ABAC is the converged technology of all previous access control models, and surpasses them in functionality. ABAC allows for semantically-richer and more expressive policy representation. As a result, it provides flexible access management by providing a logic that is more discriminating and fine-grained. For Access Control purposes, three main classes of attributes were considered:

- **Subject Attributes:** A subject is the same as an entity. As defined above, an entity is a user, application, or a thread of executions that acquires resources to perform a task. Each entity is associated with a set of characteristics. Such characteristics include the identifier, project, role, administrative domain, group membership, etc.
- **Resource Attributes:** A resource is a target object (e.g. file, virtual machine, or process) for a request. As with subjects, resources are associated with a set of attributes that can be used to make Access Control decisions. Resource attributes can be retrieved from a meta data service or facility. There are a variety of meta attributes relevant to Access Control, including ownership, service taxonomy, and Quality of Service (QoS).
- **Environmental Attributes:** These attributes describe the operational, technical, and even situational environment or context in which the request is sent. These attributes, which have been ignored by traditional access control models, include current date and time, the service risk level, and the network security level.

ABAC Policy Formulation

Here, we formally define the ABAC policy model in SAVI:

1. S, R, and E are subject, resource, and environment, respectively;
2. SA_k (1 $\leq$ k $\leq$ K), RA_m (1 $\leq$ m $\leq$ M), and EA_n (1 $\leq$ n $\leq$ N) are predefined attributes for subjects, resource, and increment, respectively;
3. ATTR(s), ATTR(r), and ATTR(e) are *attribute assignment* relations function of subject s, resource r, and environment e, respectively;

   ATTR(s) $\subseteq SA_1 \times ... \times SA_k$
   ATTR(r) $\subseteq RA_1 \times ... \times RA_k$
   ATTR(e) $\subseteq EA_1 \times ... \times EA_k$
4. In most general form, a Policy Rule that decides on whether a subject s can access a resource r in a particular environment e, is a Boolean function of s, r, and e's attributes: f(ATTR(s), ATTR(r), ATTR(e))

   Given all attributes assignment of s, r, and e, if the function's evaluation is true, then the access to the resource is granted; otherwise the access is denied.
5. A Policy rule base or Policy Store may consist of a number of policy rules, covering many subjects and resources within a security domain. The access control decision process in essence amounts to the evaluation of application policy rules in the policy store.

The relationship between these attributes is expressed with a predefined grammar in policy. In order to achieve backwards-compatibility, the same notations as in RBAC were employed. Three predicates can be defined in a policy declaration:

- **Rule:** This provides modularity and reusability. A policy can be defined as rule in order to assign it to several permissions. For example *admin_required* is a well-known policy in SAVI which declares that a user can perform an action if their role is admin, and they are part of the admin project.

This policy is used to protect administrative APIs. Because there are several administrative API, instead of writing this policy multiple times, it can be defined as a rule.

- **Security Context Attribute:** Security context attributes contain the entity attributes. Security context contains the entity ID, list of roles, project, and domain. These attributes are used in the same manner as RBAC in the sense that role: admin means that the role of the entity should posses an admin role. However, regular expression can be defined which means the value of an attribute can be determined at the run-time. For example, a project:

- **Field:** Fields contain the set of object attributes. A policy can allow an action to be performed if the target object has certain attributes. For example, a field:file:owner:public policy allows actions to be performed on any public files. Field attributes grant policies the ability to make authorization decisions based on the individual attributes of the target object. The advantage of field operation is that it allows actions based on arguments of the called function. For example, to connect a virtual machine to a virtual network, the virtual machine project can be retrieved using *"%(project)"*. To retrieve the project of the virtual network, we can use *"Field:network:project"*.

A sample policy for creating a virtual machine is as follows:

```
"compute: create-vm":[["rule:owner_required"]["rule:savi_admin_required"]]
"owner_required":[["role:admin"] and ["project:\%(project)"]]
```

Compute is the resource or a component in the resource, and create-vm is the name of action followed by the policy.

The security context attributes are standard, and identical from one resource to another. However, to keep the field definition flexible, the IAM allows each component to defines its own attributes inside a data structure called a resource map. The Resource Map is dictionary that guides the authorization middleware in extracting attributes. The authorization middleware can recognize a field so long as it knows how to fetch the associated attributes and check them against policy. Attribute Authority uses the resource map to extract attributes and provide them to the authorization middleware. The attribute authority module varies from one resource to another, and is invoked by the authorization middleware during access time. The second requirement for a newly introduced attribute is checker function, which is called by the middleware to validate an attribute. The checker function directs the middleware in interpreting an attribute. The middleware passes the value of the attribute along with the policy as an argument to the checker, and the function returns a Boolean value to indicate approval or denial.

The middleware can apply policies for two reasons: to protect a function, or filter its output. When policy is applied to protect a function, it intercepts a request before calling the function. If the request is authorized, the middleware calls the function on its behalf; otherwise, it is denied by the middleware. Protection can be considered as a binary function that either accepts or denies a request. When applied to filtering, policy removes the unauthorized output of a function. To filter the output, the middleware calls the function and removes unauthorized attributes of the returned values. Policy parsing is a time-consuming and complex job, involving the use of a greedy reduction algorithm to reduce a sequence of tokens into a single terminal. The value of this terminal forms the root of the Decision making tree, wherein each token maps to a checker function.

5.4.3 Delegation and Trust

Delegation of duty allows a task to be performed even when the initially-assigned user is not available. This is accomplished by granting an entity (user or process) the ability to perform an action temporarily. Delegation is useful when an administrator wishes to authorize an application or user at setup time to perform errands in the future, long after a token is expired. There are two types of delegation:

- **Dynamic Delegation of Authority (DelAuth):** DelAuth grants all or part of a users authority (delegator) to another user (delegatee) to perform a task.

- **Dynamic Delegation of Action (DelAct):** DelAct grants a user the required permissions because the request is part of an authorized process.

There are three main situations where a delegation is required:

- **Role Backup:** When the authority is not available to complete a task, an administrator can delegate privileges to another entity to perform the task on the first entitys behalf. The Failover application is an example of applications that need delegation of authority to recover the system on behalf of administrator when they are unavailable.

- **Decentralization of authority:** Delegation helps distribute functions in a group, satisfying the separation-of-duties principle.

- **Collaboration of works:** When two parties work on the same resource for a period of time, both must be granted access to that resource.

The SAVI IAM supports the Permission-based Delegation Model (PBDM) [74], an RBAC96-based model. In this system, a user can delegate privileges by delegating a role associated with a permission to one or more other users and confining that permission to a project. There are two types of roles in SAVI: regular roles and delegation roles. When a user delegates a permission, a delegation role associated with the permission is created and assigned to another user. In SAVI, the unit of delegation is the permission that corresponds to a delegation role. Users can also assign regular roles, which contain a set of permissions. Administrators can delegate roles and permissions by default, but members require explicit authorization to delegate their roles. Delegation roles are created by administrators; therefore, administrators can control the permission flow by mapping permissions to delegations roles.

As delegation is a temporary privilege granted to an entity. Entities can obtain a delegation role during the access time once they have been authenticated. Delegation is an internal IAM process, isolated from protected services and middleware. This isolation it is useful when an administrator wishes to set up automated tasks. For example, when an application needs to scale up, the administrator can issue a delegation which authorizes the application to create more virtual instances of itself. In SAVI, a delegation privilege is a combination of project and delegated roles. An entity can be granted roles only within the scope of a designated project, and users cannot delegate whole roles to other users. Administrators can define more conditions for delegation (such as endpoints) to which an application can send requests. Delegated permissions can be recursively delegated to another user through a delegation chain.

5.5 Conclusion

Access Control decisions play an important role in any system that implements a multi-tenancy model. For cloud computing - a large scale-implementation of a shared model - access decisions must be more flexible and scalable than in standard models. This chapter defined the requirements for achieving fine-grained access control in a multi-tier cloud, and detailed the features of different access control models. A proposed design was outlined for an access model diagnostic authorization architecture, which implements two popular access models: RBAC and ABAC. At the end of the chapter, the function of delegation and trust in SAVI was described. Delegation and trust are essential features in application-oriented infrastructure, allowing applications to perform tasks on behalf of different users. The advantages of SAVI access management are threefold. First, it is independent of the specific Logic implemented; second, it provides authorization for any fine level of control; and finally, it supports delegation of authority to applications wherein an administrator can give a permission to an application at some point in the future.

Chapter 6

Performance and Scalability

6.1 Introduction

The multi-tier cloud infrastructure must be capable of scaling to accommodate billions of transactions for millions of users and application identities. In such infrastructures, a bottleneck occurs at the identity manager. If the IAM slows down, the effect cascades to other resource providers in the cloud. According to the Open Cloud Manifesto, a cloud infrastructure should dynamically scale itself so no single entity can hoard resources during peak hours. CRUD (Create, Retrieve, Update, Delete) operations, flexible authentication, and attribute-based authorization features in previous chapters degrade system performance, preventing the SAVI IAM from operating in a product-level environment. To prepare the system for installation in the SAVI testbed, performance must be boosted and the system made scalable in order to handle large request volumes without serious performance degradation.

The central issue concerning the scalability of the IAM is the systems ability to support both growing numbers of concurrent requests and different operation types. The following section focuses on important design considerations required to support scalability in different contexts. The most important consideration is the fact that the overall number of entities being concurrently used is not predictable and varies over time. It is therefore proposed to use a loosely coupled network of IAM instances with a standardized load balancer in the front end and coherent caching layer on the back end. Since each IAM instance manages a collection of requests, the load balancer serves to distribute requests among the various instances. Thus, two requests from the same user can be served by different instances. To enable the IAM instances to serve each others requests, each requests security data is decoupled from the serving instance. An instance can thus control the workload in a manageable manner in a similar manner to the middle-tier within a multi-tier client-server architecture.

6.2 Requirement Analysis

To better understand the requirements for achieving scalability, it is necessary to examine the relationship between architectural decisions and scalability issues. Only then can strategies for improving the scalability and performance of IAM be determined.

6.2.1 Scalability Issues

Scalability issues can arise from the very architecture of the IAM or the inherent nature of the SAVI testbed. The following specific issues were identified in the system studied:

- The SAVI IAM uses a RESTful design to address incoming requests. The RESTful design provides a standardized method for building an API using the HTTP protocol, and uses standard HTTP methods and return codes. This differs from RPC protocols like SOAP, in which HTTP merely acts as the envelope for RPC data and most information, including the method, is contained inside the XML payload. Each service defines a new vocabulary. The main drawback of the REST design is that its performance degrades when handling large volumes of responses. Because each request/response represents a single operation, the IAM incorporates all required data within each response. This approach works well for short responses, but degrades performance when handling large data packets.

- The RESTful APIs are implemented with Greenthread. The difference between Greenthread and native thread is that Greenthread employs a single thread of execution to serve the requests. Greenthread uses an event-based programming paradigm, in which the flow of the program is determined by specific events (e.g. IO complete). It is implemented by Coroutines, which is useful when a process must wait for a user input for long periods. This approach is common in Service-Oriented Architectures. In addition to the IAM, other components in SAVI (e.g. computation control) serve users via synchronous RESTful APIs implemented by Greenthread. The main difficulty regarding performance is that when the IAM handles concurrent GET or POST requests from very fast clients, it can starve other connected clients. The Greenthread responsible for serving fast clients tend to hoard processor power and only rarely yield to other Greenthread. Under regular workloads this is not a major problem, as the Greenthread serving fast clients often faces a full socket buffer and yield control to another Greenthread, preventing client starvation. When reading a large volume of data from disk (e.g. the Service Catalogue), however, the reading process is slower than writing to the network, and a full socket buffer is not encountered; the processor thus does not context switch. Under such circumstances, clients may end up timed out of the system.

- The SAVI components in the SAVI nodes require the SAVI IAM to authenticate and authorize requests. As the SAVI nodes are spread throughout Canada, the authentication and authorization requests are subject to network latency. Because the number of such requests is extremely high, this network latency can cause service disruption. From an attackers perspective, this latency can serve as an attack surface from which to launch a DoS attack against the remote SAVI nodes. For example, sending a large amount of data over the SAVI network can have collateral effects on other experiments running on the same network. An attacker can also send too many requests in order to swamp the network and prevent applications distributed across multiple SAVI nodes from communicating properly.

- As mentioned in Chapter 2, GENI is a federation of independently administered cloud providers which provision resources to users under the GENI unified API. In GENI orchestration, the trust boundary of each provider is limited to the administration domain. However, because of a unified management layer in SAVI, the trust boundary can be network-wide (i.e. the SAVI components occupy a single trust circle). Consequently, if the computation and networking components are authenticated to the SAVI testbed, the computation does not need to authenticate the network for each request. To enhance security, request authentication has traditionally been a built-in feature within the SAVI testbed. In the proposed IAM design, however, internal authentication between the SAVI components is no longer required due to the unified management layer.

6.2.2 Scalability Strategies

The most important scalability concern encountered during the design phase was the distribution of functions between the IAM and the resources providers, as both authentication and authorization are time-consuming and resource-intensive jobs. Consequently, authorization was delegated to middleware on the resource provider, while we maintained the authentication in the centralized IAM. This has the following advantages:

- By keeping authentication in the IAM, the users privacy is preserved.
- Because authorization policies are rarely changed, they can be locally cached on the resource provider.
- The authorization logic is lighter in terms of implementation, making the middleware source code more efficient.
- Because authorization is dependent on the resources attributes as well, certain aspects should be implemented by the resource provider.

As mentioned earlier, a slow central IAM can inflict delays on the whole testbed operation. Therefore, a scalable IAM should be capable of returning responses in a reasonable time, and coping with a large volume of requests without considerable throughput reduction. Among IAM functions, token authentication is the most frequent operation, followed by credential authentication. Policy management is a comparatively fairly rare operation. User, tenant, and role-membership are conducted at roughly similar rates, but still less frequently than authentication. Finally, authorization of resources is performed, and is therefore irrelevant to the operation of the IAM.

Two strategies were implemented to boost performance and make the IAM scalable:

1. Optimizing IAM response time and increasing throughput
2. Decreasing the number of calls to the IAM

Optimization is useful for handling requests which take a long time to respond, such as data querying and formatting. Table 6.2.2 tabulates average response size with likelihood of occurrence. The logs of the operational IAM were collected for a duration of two weeks, and the response sizes measured and averaged. The last column shows the contribution of each operation to the generated traffic by the IAM. The likelihood of occurrence is driven by dividing the number of calls for an operation by the total number of calls.

The response time is proportional to the generated traffic as all the data should be retrieved from the data store and formatted. Although policy management requires greater packet sizes than authentication, due to its rarer occurrence the generated traffic is fairly low. Therefore, any optimization of the authentication operation can considerably increase overall performance.

Table 6.1: SAVI IAM functions traffic

Operation	Likelihood	Response size	Average Traffic
Authentication	0.76	200KB	152 KB
hline Policy Management	0.001	250KB	0.25KB
hline User, Role, Project CRUD	0.1	10KB	1KB

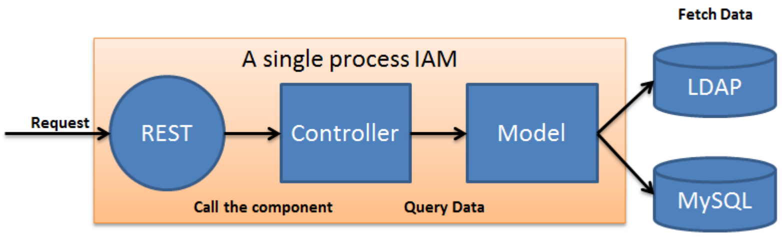


Figure 6.1: Single Process IAM

Two processes are required to build a response to an authentication request: the retrieval of credential info and the formatting of the service catalogue. The service catalogue is a large chunk of data, as it lists all available resources and associated attributes on the cloud. Since the service catalogue is dependent on user information (e.g. Project ID), it must be separately formatted for each request. The service catalogue cannot be partitioned because it is required in its entirety by the user. The formatted data, however, can be cached for each individual user. In the proposed design, a caching layer is implemented to take over this responsibility.

To decrease the number of calls to the IAM, some data must be cached in the middleware. An examination of the authentication middleware workflow reveals that it is not necessary to authenticate each token for every incoming IAM request, as the tokens remain valid for a long period of time. Instead, it is possible to update the validity status of a series of tokens. This authentication must be cache-coherent, meaning it should be performed locally without violating the semantics of the operation. Using these strategies as a guideline, an architecture was developed employing middleware caching and offline token validation to boost performance. We have implemented the IAM with Greenthread to conserve the system resources. To enhance the scalability, we create several instance of the IAM process, and do load balancing over them. Each instance of IAM is a Greenthread to conserve the system resources (e.g., Memory and Processing).

6.3 Proposed Design

The SAVI IAM follows a Model-View-Controller (MVC) architecture. MVC divides the IAM into three basic layers. The View Layer is the REST API that users and applications receive services from. The Controller Layer is logic of the IAM; authentication, policy management, and user management are examples of typical logics. The Model Layer permanently stores applications, abstracting the underlying storage system (e.g. SQL DB, LDAP, etc.). Figure 6.1 illustrates the MVC architecture for each IAM component:

The Abstraction Layer is a an abstract class that loads the appropriate drivers and corresponding configurations during the run-time. When a request arrives, the REST determines the proper controller

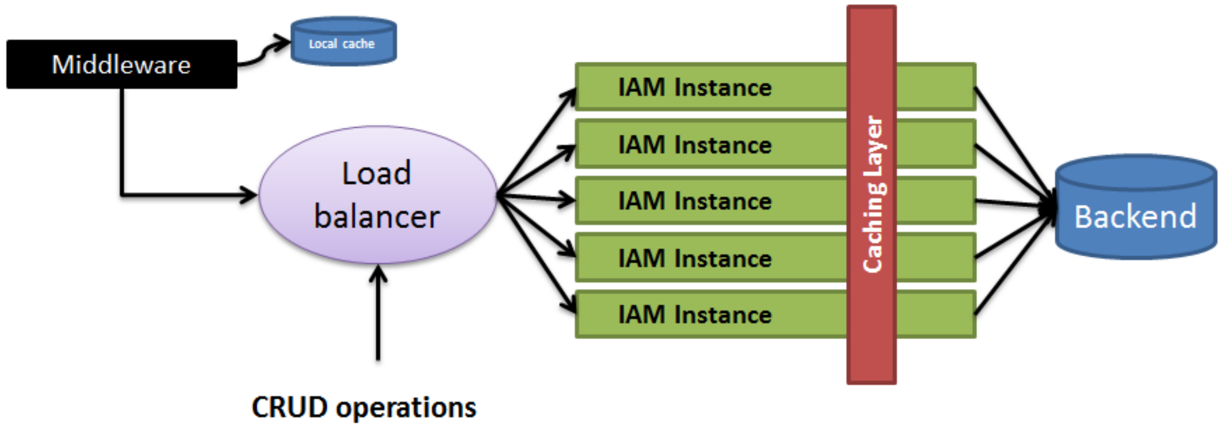


Figure 6.2: Multi-instances IAM

to call by analyzing the URL in the header. The controller then receives the request and, after processing the body, retrieves the data from the Model Layer to build the response. The Model Layer is an Object-Relational Mapping (ORM) that converts the raw data to objects before sending it to the controller. All these components can run within a single process in the system. Each process has one Greenthread to use the system resources efficiently. Each process is referred to as an IAM instance. The proposed architecture is composed of multiple instances of IAM, and a load balancer to distribute requests among the instances.

As shown in Figure 6.2, the load balancer distributes requests from both the middleware and directly from users among the IAM instances. The IAM instances have a caching layer to cache security information (e.g. the Service Catalogue), or share sensitive information (e.g. token data). These layers return the response directly to the client or middleware in order to decrease the load of the load balancer. The middleware also has a local cache to cache user data - including tokens. This architecture solves the problem of handling large data volumes by deploying multiple instances of the IAM. When an instance is busy, the load balancer sends the request to another instance. Furthermore, because the requests are distributed uniformly, they do not accumulated on one instance and cause timeout issues. The Caching Layer reduces response time by saving formatting and query data for each instance. The middleware is also capable of storing data in the local cache, which improves provider performance since the middleware does not need to contact the IAM for the consecutive requests from the same entity. This also decreases the traffic through the SAVI network, as resource providers need the IAM to periodically update their local caches. The remainder of this section outlines the challenges encountered in designing and implementing the architecture shown in Figure 6.2.

6.3.1 Caching Layer

The Caching layer is effective at improving SAVI IAM performance, and can also improve resource provider responsiveness. For the data cache, a major consideration is what data in the IAM should be cached and how this data should be cached. The main design features of the Caching Layer are as follows:

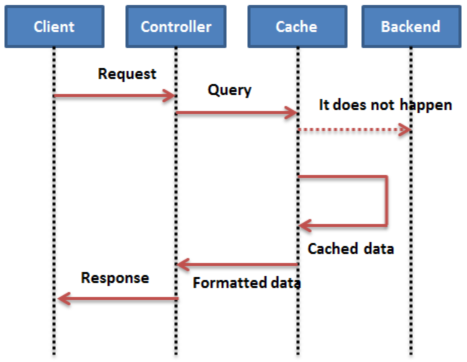


Figure 6.3: caching model in the IAM

- Frequently-retrieved data is cached in order to remove formatting time, which can in turn greatly improve performance and provide instant access to said data.

- Read-only reference data is also cached, as it is independent of each request.

- Caching of highly-volatile data is minimized.

Caching prevents redundant access to the database and unnecessary data formatting. The Caching Layer is located between the Model Layer and the Controller Layer, and catches invocations for the querying of data. Data is cached transparently after formatting, but this can result in data inconsistency when modification of data by other components leaves stale data in the cache. The Caching Layer places the output of each model in a distinct namespace. Namespace is caching memory space to which the Caching Layer dedicates a piece of data. The Caching Layer keeps track of cached data in the namespace. A caching namespace has three elements: a name, a list of keys, and cached blobs. For example, the largest data packet handled by the Caching Layer is the Service Catalogue, whose namespace name is catalogue. The list of keys is stored in the Caching Layer to facilitate the removal of stale cached blobs. A caching blob is composed of an access key, a cached value, and an expiration time. Figure 6.3 shows the sequence diagram of for caching in the SAVI IAM.

The Caching Layer validates the data to ensures it has not been expired. To manage cached data programmatically, the Caching Layer provides handlers, which enable other functions or components to remove cached data from the caching layer selectively and overcome inconsistency issues. These handlers indicate to the caching layer that the cached data is no longer valid. For example, the Service Catalogue is cached under the name "catalogue". When an administrator adds a new endpoint, the Caching Layer removes the cached Service Catalogues for all users. The *endpoint_add* function invokes the *revoke_all* handler to instruct the Caching Layer to revoke all Service Catalogues. The SAVI IAM can use caching and handlers by using decorators. For example, to cache the output of the *resource_list* function, the decorator is placed before the function, as follows:

```
@cached.cache(catalogue, project_id)
def resource_list(self, project_id):
    .
```

The code snippet caches the output of *resource_list* function in the 'catalogue' namespace; the key to retrieve the cached data is a combination of namespace name, (in this case, 'catalogue'), and 'project_id0,0' which is an argument to this function. Handlers are used as follows:

```
@cached.revokeall(catalogue)
def resource_add(new_resource):
        .
```

The *revoke_all* function has the namespace in its argument, and deletes the whole namespace data.

6.3.2 Middleware

The middleware has a great impact on the performance of the resource provider. In the proposed architecture, three features were added to the middleware in order to make it scalable:

- **Bulk Token Validation:** To validate tokens from regular entities, the middleware connects to the IAM and obtains privileged token with which to verify the users token. This task costs three network calls for the middleware. As tokens are valid for a specific duration, the middleware can store a token until it expires or is revoked by the IAM. When a request arrives, the middleware attempts to find its token in the local cache. If the token is found, the middleware allows the request to go through; otherwise, the request must be validated by the IAM. After validation, the token is cached in the local token lists. The middleware periodically updates the list of revoked tokens to remain consistent with the IAM. Local caching reduces the overhead of connection establishment. The middleware stores the token with the expiration date-time in the cache. For each request, the middleware first goes to cache to find the token. If the token is found, the middleware lets the request go through. Otherwise, it sends a request to IAM to update the tokens list. Performing periodic burst updates removes the overhead of connection establishment and increases performance dramatically.

- **Remote Address Authentication:** The performance overhead for internal authentication is substantial during peak usage because in multi-tier cloud infrastructures, resources need to call other resource providers to perform their tasks. Computation resources must connect to networking components in order to create a network, consequently resulting in a large number of unnecessary authentications that can considerably slow down the system. To overcome this issue, the concept of trusted parties was introduced, wherein agents or trusted components are introduced to the middleware of a resource, allowing the resource to pass through without validation. A trusted party is identified by its IP address and API keys. API key is long-term token granted by the IAM to a service.

- **Offline Token Validation:** When the IAM issues a PKI token, it signs the token with its Public Key. Each PKI token has an expiration date to indicate how long it will remain valid. The middleware does not need the IAM to verify a PKI token. The PKI tokens are issued to components or application that need to use a resource for a certain period of time. As the IAM can not revoke the PKI tokens, it does not issue them for users. This method is called off-line token validation. Below is a sample PKI token that can be validated without involving the IAM:

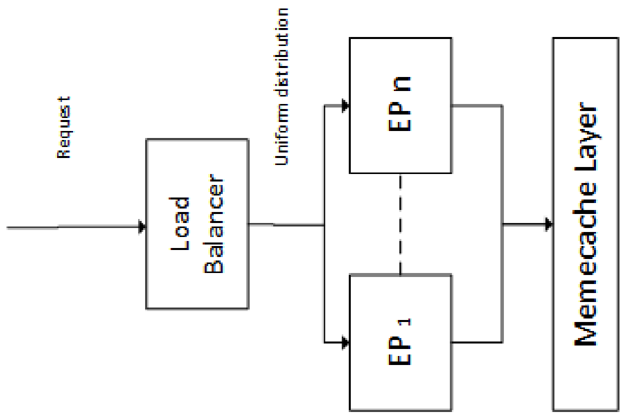


Figure 6.4: Load balancing over the IAM instances

```
{"auth":{"identity":"pki", "credential":{"username":"Bob","project":"demo",
"expires":"05092013","roles":["admin","saviAdmin"]}}
```

Because most tokens are from regular entities, they are valid for long periods of time; in the short term, however, they can be cached in the middleware. Meanwhile, internal components are already within the trust circle, and do not need authentication.

6.3.3 Load balancing

It is required that the SAVI IAM maintain the same performance level even when the number of users is increased dramatically. In the proposed architecture, load balancing is used to disperse requests between IAM instances. However, different data processes do not have access to each others memory space; consequently, they may be unable to find request states (such as tokens), causing entities to receive constant Unauthorized errors. To deal with this issue, IAM places tokens and security data on memcache under the same namespace. Through a system-wide caching layer, different instances can access security information by leveraging namespace and encryption parameters in order to secure cached data. A load balancer uniformly distributes requests among the instances, and creates more instances when the number of requests for each instance exceeds a certain threshold. As a result, the IAM system is able to dynamically scale itself by increasing the number of backend processes.

Figure 6.4 shows the workflow for a load-balanced IAM. A request enters the load balancer and is served by one of the Event-based processes. The load balancer forwards requests to one of the IAM processes (EP1 to EPn). The IAM keeps the state out of each process memory so that other event-based processes can access it. There is a memcache layer on the back of each process which stores the states of requests so that processes can serve each others requests.

6.4 Performance Evaluation

In this section, the performance of the proposed IAM using the SAVI Testbed is evaluated. The equipment setup will first be described, followed by results of the experiment.

6.4.1 Apache JMeter

Apache JMeter is an open-source Java desktop application designed to carry out performance analysis on a variety of applications, including HTTP(S), SOAP (Simple Object Access Protocol), JMS, JDBC (Java Database Connectivity), LDAP (Lightweight Directory Access Protocol), POP3 (Post Office Protocol), and IMAP (Internet Message Access Protocol). It performs load and robustness testing to analyze and measure the functional behavior of an application under different load types. JMeter has a decent UI, but can also be run from the command line if necessary. As JMeter runs on a Java Virtual machine, it can be run on a variety of operating systems and has native support for multithreading (i.e. scenarios where simulating concurrent users is desired). It has a fully configurable, pluggable, and scriptable (e.g. using BeanShell1) test architecture, so all types of performance tests can be run with it. In addition, multiple test iterations (runs), input parameterization, loops, assertions and timers are supported out-of-the-box.

Thread groups are used to specify the number of running threads and the ramp-up period. Each thread simulates a concurrent user, and the ramp-up period specifies the time required to create all the threads. For example with 5 threads and 5 seconds of ramp-up time, a thread is created every second. The loop count defines the running time for a thread. The scheduler also allows the start and end of the run time to be specified.

Pluggable samplers allow for a number of metrics to be recorded at test run-time. Basic test data analysis and reporting facilities are also included; these can be extended by installing appropriate plug-ins. JMeter uses a proprietary XML format to store both test plans (steps) and test result data. RESTFUL can be tested in JMeter using the ”RestSampler” sampler.

Listeners are used to post-process request data. For example, data can be saved to a file or be displayed using a chart. At the moment, the JMeter chart does not provide many configuration options; however, it is extensible. It is thus always possible to add an extra visualization or Graph result listener to allow result to be viewed as a graph; for example, the Spline Visualizer listener allows the result to be displayed as a smooth curve.

Experimental Setup To run these SAVI IAM, we used a XEON machine on SAVI testbed. Table 6.4.1 shows the system of characteristics of the machine running IAM:

Table 6.2: SAVI IAM System Characteristics

Number of Processors	12
Memory	32GB
Operating Systems	Ubuntu64
JDK	Oracle 7
Python	2.7

To evaluate the performance, we conducted a distributed testing on IAM because a single client machine is unable, performance-wise, to simulate enough users to stress IAM. Therefore a master machine can control multiple, remote JMeter engines from a single JMeter GUI client. Each engine is an Xeon system with 4 processors 4 GB memory on SAVI. The master is a large virtual machine with 4 processors and 8 GB memory. To configure distributed testing, a JMeter server should be running on each slave, and a GUI client on master machine. To run JMeter server in remote node, start the JMeter server component on all slaves by running the apache-jmeter/bin/jmeter-server. Now, the properties file on the controlling JMeter machine should be edited so it has the remote slaves. In /bin/jmeter.properties, in front of property, ”remote_hosts”, and list of remote slaves must be added. Multiple such slaves can be added via comma-delimited.

6.4.2 SAVI IAM Setup

To install SAVI IAM on Ubuntu 12.04, the system should have the following tools:

- Python 2.7
- git
- setuptools (Python library)
- pip

To install these tools run the following command in terminal:

```
# sudo apt-get install git-core python-pip
# sudo pip install setuptools
```

Then we make a clone of the code from the repository

```
# git clone https://github.com/mfaraji/keystone
# cd keystone
# git checkout -b silver remotes/origin/silver
```

Then we need to install dependencies:

```
# sudo apt-get install python-dev libxml2-dev libxslt1-dev libsasl2-dev libmysqld-dev
# sudo pip install -r tools/pip-requires
```

In our setup, we use mysql and memcached as our backend. Thus, we need to install these backends as well:

```
# sudo apt-get install mysql-server memcached
```

We are using haproxy for load balancing the load between IAM instances. To install haproxy:

```
# sudo apt-get install haproxy
```

To activate haproxy, we need to add it to system services:

```
# sudo vim /etc/default/haproxy
```

Then change ENABLED from 0 to 1. Then restart the service:

```
# sudo service haproxy restart
```

In the load balancer experiment, we explain how to configure load balancer to work with IAM instances. Now, we addresses all requirements to run SAVI IAM on our system. Now, we need to configure the backends:

1. Create keystone config folder:

   ```
   # sudo mkdir /etc/keystone
   ```

2. Copy configuration the following configuration files from keystone folder to /etc/keystone folder:

   - keystone.conf
   - logging.conf
   - policy.json

3. Now configure database credentials:

   ```
   # sudo vim /etc/keystone/keystone.conf
   ```

4. If memcache is not on the same machine, we need to modify the address and port in keystone.conf

To create the corresponding tables, we need to create to database first:

```
# mysql -u<username> -p<password>
mysql> create database keystone
```

To create tables: navigate to the root of the keystone folder, and run:

```
# bin/keystone-manage --config-file /etc/keystone/keystone.conf db_sync
```

To run the service:

```
# bin/keystone-all --config-file /etc/keystone/keystone.conf --debug
```

To interact with the SAVI IAM, Keystone client should be installed. To install Keystone client:

```
# git clone https://github.com/m/python-keystoneclient
# cd keystone
# git checkout -b silver remotes/origin/silver
```

The navigate to the repository to install the client:

```
# cd python-keystoneclient
# sudo python setup.py install
```

Next, the environment variables should be set. To set the variables, run the following commands:

```
# export OS_USERNAME=<user-name>
# export OS_TENANT_NAME=<tenant-name>
# export OS_REGION_NAME=<region-name>
# export OS_PASSWORD=<password>
# export OS_AUTH_URL=<url-to-openstack-identity>
```

(run "env — grep OS" command to make sure values are set correctly) he first argument is username, the second is tenant, the third is name of region, and the last is the URL of Keystone. At the end the following environment variables need to be set properly before any interaction with SAVI TB.

The region parameter is the name of the SAVI TB name. For now, it could be any of the following nodes: CORE (UofT), EDGE-TR-1 (Edge at UofT), EDGE-WT-1 (Edge at UWaterloo), EDGE-MG-1 (Edge at McGill). By choosing this parameter, you can specify on what Edge/Core node you want to get resource.

Now run the following command to see the list of endpoints:

```
# keystone endpoint-list
```

6.4.3 Test Scenarios

This section explains the different experimental scenarios used during testing and the specific metrics measured. In these test scenarios, the following parameters were measured in each authentication operation:

- **Throughput:** the number of requests processed per minute by the IAM or middleware.
- **Average:** the total running time divided by number of requests sent to the IAM or Middleware.
- **Median:** the component response time value where half of the response times are lower and half are higher.
- **Deviation:** the measure of how widely the component response time varies i.e. how dispersed the data is.

Evaluations were performed on three different systems:

1. The baseline system (Keystone v2.0. 2), against which the proposed system was compared.
2. A single instance of the SAVI IAM with Caching-Layer enabled 3).
3. A multi-instance, full-featured SAVI IAM (Caching-Layer enabled) .

In all experiments, the system was divided into 300 projects and 10 regions (SAVI nodes); each region contains 10 endpoints for a total of 100 endpoints. The system performance is measured while the number of concurrent fast clients is varied from 1 to 256. Fast clients are dumb processes which do not process responses, but continuously send requests to the SAVI IAM.

Figure 6.5 shows the experimental results for the baseline (Keystone v2.0) system. As can be seen, system performance degrades significantly as the number of users increases. This is seen as a rapid degradation of throughput (measured in requests served per second) on right-hand y-axis, and a large increase in response time (measured in milliseconds) on the x-axis. When the number of concurrent fast clients passes 128, the number of successful requests decreases sharply due to user timeout.

As shown in Figure 6.5, request response time increases with the number of concurrent users. The response times are concentrated around the average values, and are independent of the total number of the requests. This results from all requests being treated identically due to the lack of caching in the tested system.

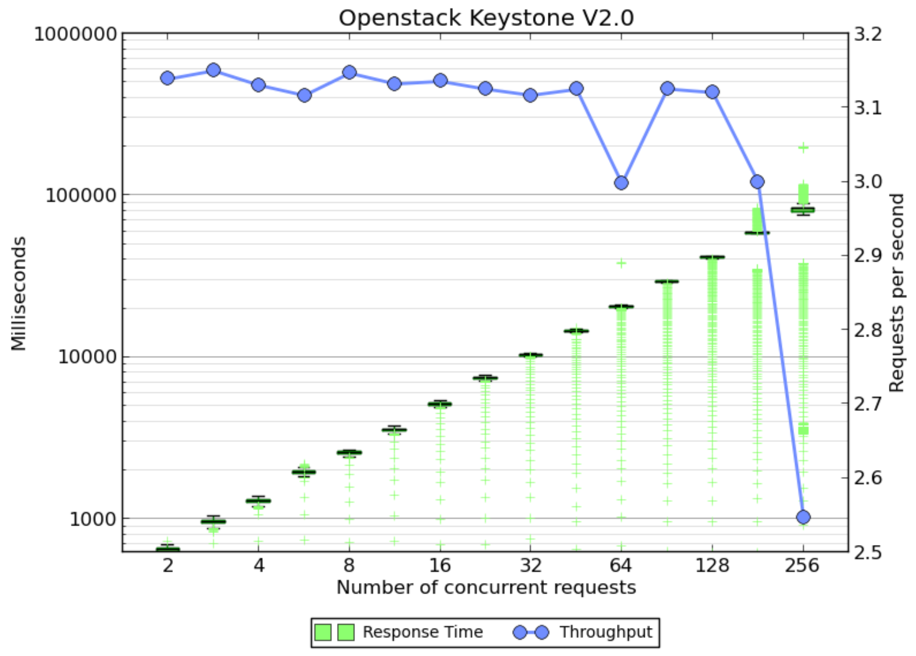


Figure 6.5: Openstack Keystone v2.0

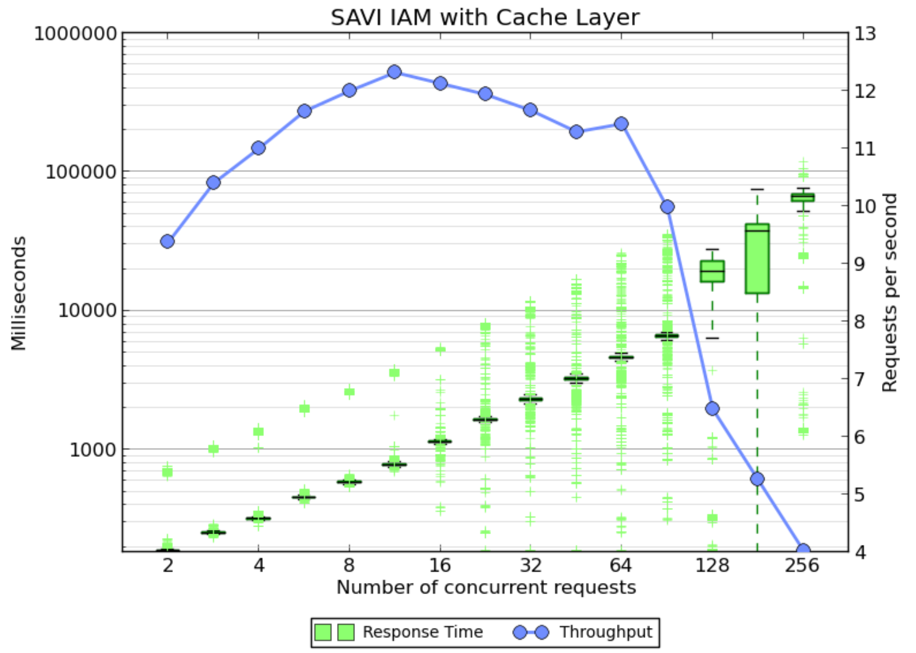


Figure 6.6: Single Process IAM

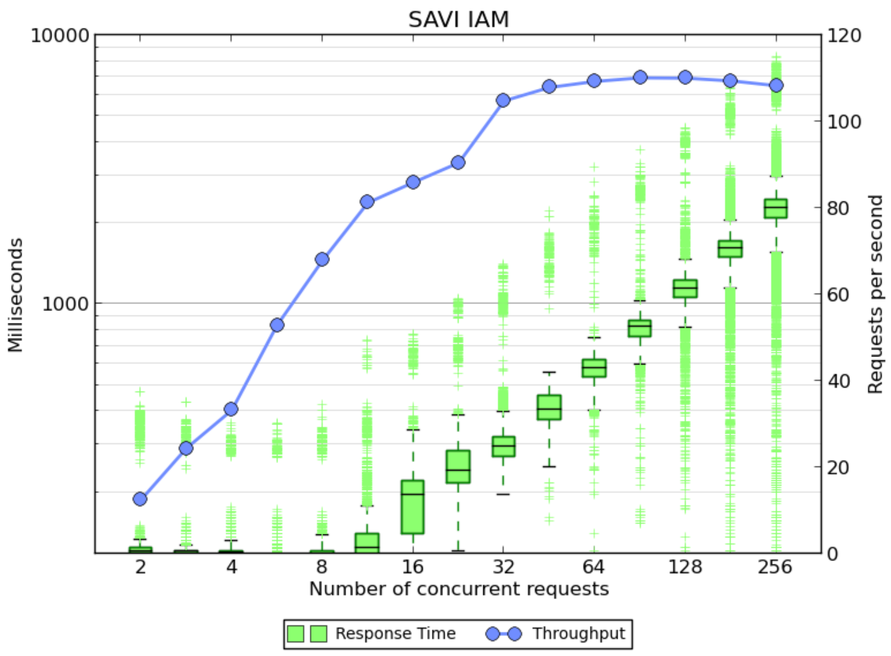
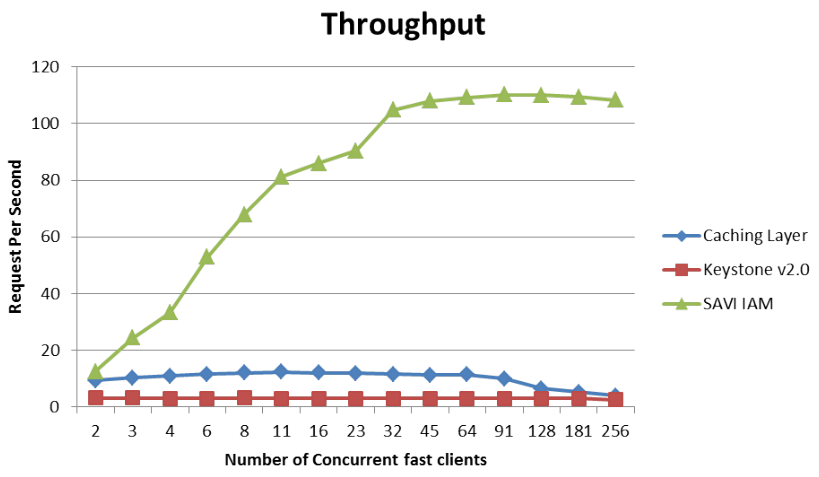


Figure 6.7: Full-featured IAM

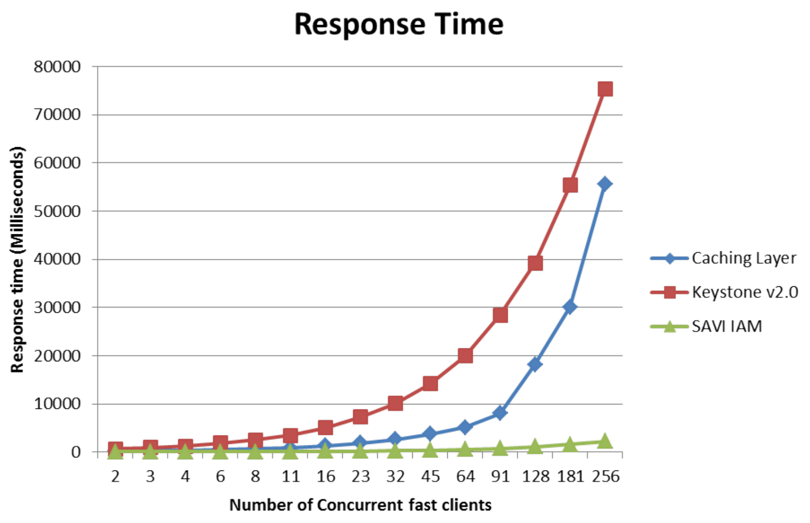
Figure 6.6 shows the experimental results for a single-instance implementation of SAVI IAM with Caching-Layer enabled. As described before, the Caching Layer performs transparent caching of data for request responses. As shown in Figure 6, the response time begins to vary once the number of concurrent requests passes 32 due to request repetition. Despite the caching, timeout occurs when the concurrent request volume reaches 256 - just as with the baseline Keystone v2.0 system. The throughput of the SAVI IAM, however, is higher than the baseline system at high concurrent-user volumes. At lower volumes, Keystone v2.0 slightly outperforms SAVI IAM since SAVI IAM places a version of each response in a cache as well. As the number of requests increases, the caching boosts the throughput because there is no need to repeatedly query and format the data for each request. For request volumes in the range of 64, the throughput of the SAVI IAM system is 4 times higher than that of Keystone v2.0. The response time for the SAVI IAM is also lower because fetching data from the cache is faster than querying storage and formatting the data.

Figure 6.7 shows the experimental results for the full-featured SAVI IAM with load balancer and 10 instances of SAVI IAM processes - including the Caching Layer. As can be seen, the SAVI IAM significantly outperforms the baseline systems in terms of both throughput and response time - especially in high loads. Also, a comparison of Figures 6.6 and 6.7 shows that the throughput is increased by a factor of 9 when 10 IAM instances are used. Moreover, the service time is decreased by a factor of 10 at the higher request rates.

Figure 1.8(a,b) compares the throughput and average response time for all three evaluated systems. This figure clearly shows that SAVI IAM is capable of handling high request rates while maintaining low responses time, and can scale itself as needed to handle higher concurrent user volumes.



(a) Throughput



(b) Response Time

Figure 6.8: Comparison of three evaluated systems

6.5 Conclusion

A cloud IAM should be scale up to address billions of transactions from users and applications. Scalability and performance of the cloud IAM plays a major role in the performance of the infrastructure. To achieve scalability in the SAVI IAM, we had two strategies: optimizing the IAM, and decreasing the number of invocations. The SAVI IAM has a caching layer to cache the responses partially. Caching saves query time and formatting time for the IAM. The middleware in SAVI has a local cache to store the valid tokens. Therefore, it places a token in the cache at the first time, and periodically update the cache in a bulk manner. There a concept of trust circle in the middleware which avoids the authentication of SAVI components, thereby the performance increased by 5 factors. On the other hand, local caching on the middleware drops the number of authentication requests by 10 which is along the second strategy. To make the SAVI IAM scalable, we run several instance of the IAM , and perform load balancing over them. This method is very flexible because the IAM can be scaled up and down when the number of requests changes. The advantages of the SAVI IAM over Openstack Keystone are threefold. The throughput is 10 times higher in large number of requests. It can be is flexibly scale up and down. It is more robust when in peak usage.

Chapter 7

Conclusion and Future scope

7.1 Future work

Our Future work mainly focus on federation of users. We intend to to be federated with other cloud providers (e.g., Amazon EC2) and other testbeds (e.g., GENI). We have two technical issues down the road: Authentication and Authorization. Format of identities are different among different providers, therefore, we need to either conform to the target provider format or we can use a standard solution such as Shibboleth. The second problem is authorization, and how to reach a unique interpretation from access policies. There are several standards for cross-domain access policy interoperation such as eXtensible Access Control Markup Language (XACML) which can be used to be federated in authorization as well.

The second part of our Future work focuses on new methods of Authentication such as QR-Code, and biometrics. We are very interested to incorporate new methods of authentication to improve the security of testbed.

7.2 Conclusion

This thesis presents a novel architecture to perform identity and access management(IAM) in a Multi-tier cloud infrastructure.Multi-tier cloud is the next generation of the cloud computing concentrating on the future applications requirements, and integrated the computing and communication. In the Multi-tier cloud, service providers can offer different resources in different nodes, and these services are supported by massive-scale data centers over the Internet. Multi-tier cloud infrastructure borrowed tier-based model from Software Engineering to provide resources in different layers. In this research, we focus on design and implementation of a flexible centralized identity and access management system for the multi-tier cloud infrastructure. We use spiral software development methodology for developing the IAM. Each spiral collects and analyzes a set of requirements, followed by a design to address these requirements. This thesis conducted three level of analysis on the IAM including: identity management, access control, and scalability. Identity management focuses on general concept of IAM and authentication. Access management provides a fine-grained access control in order to preserve the flexibility and programmability of the infrastructure while improving the security. As an essential requirement of a large-scale system, scalability enables the IAM to handle the large number of requests coming from the cloud. In terms of throughput, the SAVI IAM outperforms Openstack Keystone v2.0 by a factor of 10 in high volume of requests, and it shows more stability too.

Bibliography

[1] Hasan Ibne Akram and Mario Hoffmann. User-centric identity management in ambient environments. *International Journal On Advances in Intelligent Systems*, 2(1):254–267, 2009.

[2] P. Angin, B. Bhargava, R. Ranchal, N. Singh, M. Linderman, L.B. Othmane, and L. Lilien. An entity-centric approach for privacy and identity management in cloud computing. In *Reliable Distributed Systems, 2010 29th IEEE Symposium on*, pages 177–183, 2010.

[3] Michael Armbrust, Armando Fox, Rean Griffith, Anthony D. Joseph, Randy Katz, Andy Konwinski, Gunho Lee, David Patterson, Ariel Rabkin, Ion Stoica, and Matei Zaharia. A view of cloud computing. *Commun. ACM*, 53(4):50–58, April 2010.

[4] Ilia Baldine, Yufeng Xin, Anirban Mandal, Paul Ruth, Chris Heermann, and Jeff Chase. Exogeni: A multi-domain infrastructure-as-a-service testbed. In Thanasis Korakis, Michael Zink, and Maximilian Ott, editors, *TRIDENTCOM*, volume 44 of *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 97–113. Springer, 2012.

[5] Barry W. Boehm. Software risk management: Principles and practices. *IEEE Softw.*, 8(1):32–41, January 1991.

[6] Jan Camenisch, Ronald Leenes, and Dieter Sommer, editors. *Digital Privacy - PRIME - Privacy and Identity Management for Europe*, volume 6545 of *Lecture Notes in Computer Science*. Springer, 2011.

[7] Kim Cameron and Michael B Jones. Design rationale behind the identity metasystem architecture. In *ISSE/SECURE 2007 Securing Electronic Business Processes*, pages 117–129. Springer, 2007.

[8] A. Celesti, F. Tusa, M. Villari, and A. Puliafito. Security and cloud computing: Intercloud identity management infrastructure. In *Enabling Technologies: Infrastructures for Collaborative Enterprises (WETICE), 2010 19th IEEE International Workshop on*, pages 263–265, 2010.

[9] Antonio Celesti, Francesco Tusa, Massimo Villari, and Antonio Puliafito. Three-phase cross-cloud federation model: The cloud sso authentication. In *Advances in Future Internet (AFIN), 2010 Second International Conference on*, pages 94–101. IEEE, 2010.

[10] Ni Dan, Shi Hua-Ji, Chen Yuan, and Guo Jia-Hu. Attribute based access control (abac)-based cross-domain access control in service-oriented architecture (soa). In *Computer Science Service System (CSSS), 2012 International Conference on*, pages 1405–1408, 2012.

[11] Juan Du, N. Shah, and Xiaohui Gu. Adaptive data-driven service integrity attestation for multi-tenant cloud systems. In *Quality of Service (IWQoS), 2011 IEEE 19th International Workshop on*, pages 1–9, 2011.

[12] Jaliya Ekanayake and Geoffrey Fox. High performance parallel computing with clouds and cloud technologies. In *Cloud Computing*, pages 20–38. Springer, 2010.

[13] Tewfiq El Maliki and Jean-Marc Seigneur. User-centric mobile identity management services. In *SECURWARE International Conference*, 2007.

[14] November An Electronic, Len Lapadula, The Original, D. Elliott Bell, and Leonard J. Lapadula. Secure computer systems: Mathematical foundations.

[15] ExoGENI. Exogeni, 2013.

[16] M. C. Ferrer. Zeus in the cloud, December 2009.

[17] Eclipse Foundation. Higgins: Personal data service, 2013.

[18] Eric Freudenthal, Tracy Pesin, Lawrence Port, Edward Keenan, and Vijay Karamcheti. drbac: Distributed role-based access control for dynamic coalition environments. In *ICDCS*, pages 411–420, 2002.

[19] Martin Gaedke, Johannes Meinecke, and Martin Nussbaumer. A modeling approach to federated identity and access management. In *Special interest tracks and posters of the 14th international conference on World Wide Web*, WWW '05, pages 1156–1157, New York, NY, USA, 2005. ACM.

[20] GENI. Geni wiki, 2013.

[21] Anu Gopalakrishnan. Cloud Computing Identity Management. *SETLabs Briefings*, 7(7):45, 2009.

[22] Nagajyothi Gunti, Weiqing Sun, and Mohammed Y. Niamat. I-rbac: Isolation enabled role-based access control. In *PST*, pages 79–86. IEEE, 2011.

[23] A. Hayat. *A Pan European Interoperable Electronic Identity.* PhD thesis, Graz University of Technology, Austria, 2007.

[24] Markus Hillenbrand, Joachim Götze, Jochen Müller, and Paul Müller. A single sign-on framework for web-services-based distributed applications. In *Proceedings of the 8th International Conference on Telecommunications ConTEL (Zagreb, Croatia)*, volume 6, 2005.

[25] Michael Howard and David Leblanc. *Writing Secure Code.* Microsoft Press, Redmond, WA, USA, 2001.

[26] He Yuan Huang, Bin Wang, Xiao Xi Liu, and Jing Min Xu. Identity federation broker for service cloud. In *Proceedings of the 2010 International Conference on Service Sciences*, ICSS '10, pages 115–120, Washington, DC, USA, 2010. IEEE Computer Society.

[27] Amazon Inc. Aws govcloud (us) region government cloud computing, 2013.

[28] Amazon Inc. Aws identity and access management (iam), 2013.

[29] Rackspace Inc. Rackspace identity api, 2013.

[30] M. Jensen, N. Gruschka, and N. Luttenberger. The impact of flooding attacks on network-based services. In *Availability, Reliability and Security, 2008. ARES 08. Third International Conference on*, pages 509–513, 2008.

[31] Jerry Archer, Alan Boehme, Dave Cullinane, Nils Puhlmann, Paul Kurtz, Jim Reavis. CLOUD SECURITY ALLIANCE SecaaS DEFINED CATEGORIES OF SERVICE, 2011.

[32] Audun Jøsang and Simon Pope. User centric identity management. In *AusCERT Asia Pacific Information Technology Security Conference*, page 77. Citeseer, 2005.

[33] Audun Jøsang, Muhammed Al Zomai, and Suriadi Suriadi. Usability and privacy in identity management architectures. In *Proceedings of the fifth Australasian symposium on ACSW frontiers - Volume 68*, ACSW '07, pages 143–152, Darlinghurst, Australia, Australia, 2007. Australian Computer Society, Inc.

[34] B.R. Kandukuri, V.R. Paturi, and A. Rakshit. Cloud security issues. In *Services Computing, 2009. SCC '09. IEEE International Conference on*, pages 517–520, 2009.

[35] Joon-Myung Kang, Hadi Bannazadeh, and Alberto Leon-Garcia. Savi testbed: Control and management of converged virtual ict resources. In *Integrated Network Management (IM 2013), 2013 IFIP/IEEE International Symposium on*, pages 664–667, 2013.

[36] K. Karnad and S. Nagenthram. Cloud security: Can the cloud be secured? In *Internet Technology And Secured Transactions, 2012 International Conferece For*, pages 208–210, 2012.

[37] A.H. Karp. Authorization-based access control for the services oriented architecture. In *Creating, Connecting and Collaborating through Computing, 2006. C5 '06. The Fourth International Conference on*, pages 160–167, 2006.

[38] Alan H. Karp, Harry Haury, and Michael H. Davis. From abac to zbac: The evolution of access control models. Technical report, Hewlett-Packard laboratories, 2009.

[39] Samuel T King and Peter M Chen. Subvirt: Implementing malware with virtual machines. In *Security and Privacy, 2006 IEEE Symposium on*, pages 14–pp. IEEE, 2006.

[40] H. Koshutanski, F. Martinelli, P. Mori, and A. Vaccarelli. Fine-grained and history-based access control with trust management for autonomic grid services. In *Autonomic and Autonomous Systems, 2006. ICAS '06. 2006 International Conference on*, pages 34–34, 2006.

[41] Brian Krebs. Amazon: Hey spammers, get off my cloud. *Washington Post (July 2008)*, 2008.

[42] Steve Lipner. The trustworthy computing security development lifecycle. In *Proceedings of the 20th Annual Computer Security Applications Conference*, ACSAC '04, pages 2–13, Washington, DC, USA, 2004. IEEE Computer Society.

[43] Rongxing Lu, Xiaodong Lin, Xiaohui Liang, and Xuemin (Sherman) Shen. Secure provenance: the essential of bread and butter of data forensics in cloud computing. In *Proceedings of the 5th ACM Symposium on Information, Computer and Communications Security*, ASIACCS '10, pages 282–292, New York, NY, USA, 2010. ACM.

[44] Tim Mather, Subra Kumaraswamy, and Shahed Latif. *Cloud security and privacy.* Theory in practice. O'Reilly, Beijing, Cambridge, Mass., 2009.

[45] Tim Mather, Subra Kumaraswamy, and Shahed Latif. *Cloud Security and Privacy: An Enterprise Perspective on Risks and Compliance.* O'Reilly Media, Inc., 2009.

[46] J. P. McDermott. Attack net penetration testing. In *Proceedings of the 2000 workshop on New security paradigms*, NSPW '00, pages 15–21, New York, NY, USA, 2000. ACM.

[47] Peter Mell and Tim Grance. Effectively and Securely Using the Cloud Computing Paradigm, May 2009.

[48] Peter Mell and Timothy Grance. The nist definition of cloud computing (draft). *NIST special publication*, 800(145):7, 2011.

[49] R. L. Morgan, Scott Cantor, Steven Carmody, Walter Hoehn, and Ken Klingenstein. Federated Security: The Shibboleth Approach. *EDUCAUSE Quarterly*, 27(4):12–17, 2004.

[50] Suvda Myagmar, Adam J Lee, and William Yurcik. Threat modeling as a basis for security requirements. In *Symposium on Requirements Engineering for Information Security (SREIS)*, 2005.

[51] Srijith K Nair, Sakshi Porwal, Theo Dimitrakos, Ana Juan Ferrer, Johan Tordsson, Tabassum Sharif, Craig Sheridan, Muttukrishnan Rajarajan, and Afnan Ullah Khan. Towards secure cloud bursting, brokerage and aggregation. In *Web Services (ECOWS), 2010 IEEE 8th European Conference on*, pages 189–196. IEEE, 2010.

[52] Mark Needleman. The shibboleth authentication/authorization system. *Serials Review*, 30(3):252 – 253, 2004.

[53] Peter Mell and Tim Grance. The NIST Definition of Cloud Computing, 2009.

[54] Michael Price. The paradox of security in virtual environments. *Computer*, 41(11):22–28, 2008.

[55] ProtoGENI. Protogeni, 2013.

[56] R. Ranchal, B. Bhargava, L.B. Othmane, L. Lilien, Anya Kim, Myong Kang, and M. Linderman. Protection of identity information in cloud computing without trusted third party. In *Reliable Distributed Systems, 2010 29th IEEE Symposium on*, pages 368–372, 2010.

[57] Kui Ren, Cong Wang, and Qian Wang. Toward secure and effective data utilization in public cloud. *Network, IEEE*, 26(6):69–74, 2012.

[58] Thomas Ristenpart, Eran Tromer, Hovav Shacham, and Stefan Savage. Hey, you, get off of my cloud: exploring information leakage in third-party compute clouds. In *Proceedings of the 16th ACM conference on Computer and communications security*, pages 199–212. ACM, 2009.

[59] Thomas Ristenpart, Eran Tromer, Hovav Shacham, and Stefan Savage. Hey, you, get off of my cloud: exploring information leakage in third-party compute clouds. In *Proceedings of the 16th ACM conference on Computer and communications security*, CCS '09, pages 199–212, New York, NY, USA, 2009. ACM.

[60] C. Sample and D. Kelley. Cloud computing security: Routing and dns security threats, 2013.

[61] Ravi S. Sandhu, Edward J. Coyne, Hal L. Feinstein, and Charles E. Youman. Role-based access control models. *Computer*, 29(2):38–47, February 1996.

[62] Bruce Schneier. Attack Trees: Modeling Security Threats. *Dr. Dobb's Journal*, December 1999.

[63] Rob Sherwood, Glen Gibb, Kok-Kiong Yap, Guido Appenzeller, Martin Casado, Nick McKeown, and Guru Parulkar. Can the production network be the testbed? In *Proceedings of the 9th USENIX conference on Operating systems design and implementation*, OSDI'10, pages 1–6, Berkeley, CA, USA, 2010. USENIX Association.

[64] Dawn Xiaodong Song, David Wagner, and Xuqing Tian. Timing analysis of keystrokes and timing attacks on ssh. In *Proceedings of the 10th conference on USENIX Security Symposium - Volume 10*, SSYM'01, pages 25–25, Berkeley, CA, USA, 2001. USENIX Association.

[65] Maicon Stihler, Altair Olivo Santin, Arlindo L. Marcon Jr., and Joni da Silva Fraga. In Albert Levi, Mohamad Badra, Matteo Cesana, Mona Ghassemian, zgr Grbz, Nafa Jabeur, Marek Klonowski, Antonio Maa, Susana Sargento, and Sherali Zeadally, editors, *NTMS*.

[66] H. Takabi, J.B.D. Joshi, and Gail-Joon Ahn. Security and privacy challenges in cloud computing environments. *Security Privacy, IEEE*, 8(6):24–31, 2010.

[67] Luis M. Vaquero, Luis Rodero-Merino, Juan Caceres, and Maik Lindner. A break in the clouds: towards a cloud definition. *SIGCOMM Comput. Commun. Rev.*, 39(1):50–55, December 2008.

[68] Ping Wang, Wen-Hui Lin, Pu-Tsun Kuo, Hui-Tang Lin, and Tzu Chia Wang. Threat risk analysis for cloud security based on attack-defense trees. In *Computing Technology and Information Management (ICCM), 2012 8th International Conference on*, volume 1, pages 106–111. IEEE, 2012.

[69] Ping Wang, Wen-Hui Lin, Pu-Tsun Kuo, Hui-Tang Lin, and Tzu Chia Wang. Threat risk analysis for cloud security based on attack-defense trees. In *Computing Technology and Information Management (ICCM), 2012 8th International Conference on*, volume 1, pages 106–111, 2012.

[70] Aaron Weiss. Computing in the clouds. *netWorker*, 11(4):16–25, December 2007.

[71] E. Yuan and J. Tong. Attributed based access control (abac) for web services. In *Web Services, 2005. ICWS 2005. Proceedings. 2005 IEEE International Conference on*, pages –569, 2005.

[72] Olive Qing Zhang, Markus Kirchberg, Ryan K. L. Ko, and Bu-Sung Lee. How to track your data: The case for cloud computing provenance. In Costas Lambrinoudakis, Panagiotis Rizomiliotis, and Tomasz Wiktor Wlodarczyk, editors, *CloudCom*, pages 446–453. IEEE, 2011.

[73] Qi Zhang, Lu Cheng, and Raouf Boutaba. Cloud computing: state-of-the-art and research challenges. *J. Internet Services and Applications*, 1(1):7–18, 2010.

[74] Xinwen Zhang, Sejong Oh, and Ravi Sandhu. Pbdm: a flexible delegation model in rbac. In *Proceedings of the eighth ACM symposium on Access control models and technologies*, pages 149–157. ACM, 2003.