A Framework for Secure and Interoperable Cloud Computing with RBAC, MAC, and DAC

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Ph.D. Dissertation

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Cloud computing has emerged as a de facto approach throughout society, commercial and government sectors, and research/academic communities. In the last decade, many organizations have considered outsourcing their IT service to the cloud where the services would have better availability and quality. However, this requires mobile and desktop clients for different stakeholders, in a domain such as healthcare, to obtain information from multiple systems, that may be: operating with different paradigms (e.g., cloud services, programming services, web services); utilize alternate cloud service providers; and, employ diverse security/access control techniques. This raises two main problems: *services integration* and *security policies integration*. The *services integration problem* focuses on the difficulties that occur when a client is trying to access services that could be operating with different types of APIs. The *security policies integration problem* occurs since the alternate cloud service providers may have different access control capabilities, making it difficult for the client developer to realize a cohesive security solution. In order to address these two problems, this dissertation presents a *Framework for Secure and Interoperable Cloud Computing (FSICC)* that provides a set of global cloud services for use by clients and systems with access control provided by RBAC, MAC, and DAC. The work presented herein involves five research areas: *Architectural Blueprints for Supporting*

FSICC that contain options for connecting clients and systems with FSICC; *an Integrated RBAC, MAC, and DAC Model for Cloud Computing* via a Unified Cloud Computing Access Control Model (UCCACM) that contains a set of definitions necessary for supporting the work on FSICC; *Security Mapping/Enforcement Algorithms for Global Security Policy Generation and Global API Generation* which includes Security Policies and Services Registration, Global Services Generation, and Global Security Policy Generation; *a SOA-Based Security Engineering Process (SSEP) for FSICC* that is utilized to combine security policies from different systems into one global security policy in which SSEP also includes a process for security enforcement code generation; and, *Dynamic Enforcement via Intercepting Process* involves a set of programmatic mechanisms that are able to intercept a service call from a client to a FSICC global service to perform security enforcement checks.

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Chapter 1
Introduction

Cloud computing has emerged as a de facto approach throughout society, commercial and government sectors, and research/academic communities. In fact, the wide usage of mobile devices means that average users understand the storage and synching of photos, videos, email, contacts, files, etc., in the cloud. In the last decade, many organizations have considered outsourcing their IT service to the cloud where the services would have better availability and quality. However, this requires mobile and desktop clients for different stakeholders, in a domain such as healthcare, to obtain information from multiple systems, that may be: operating with different paradigms (e.g., cloud services, programming services, web services); utilize alternate cloud service providers; and, employ diverse security/access control techniques. This raises two main problems: *services integration* and *security policies integration*. The *services integration problem* focuses on the difficulties that occur when a client is trying to access services that could be operating with different types of application programmer interfaces (APIs). In this case, the developer of the client will need to work with different paradigms such as programming language APIs or web services that may be constantly changing and must also be integrated in order to be successfully utilized for the client. The *security policies integration problem* occurs since the different paradigms and alternate cloud service providers may all have different types of security and access control capabilities, making it very difficult for the developer of the client to realize a cohesive security solution.

Currently, there is no set of technologies and/or a framework that provides solutions for the service integration and security policy integration problems. The notion of having a unified set of global cloud services is one possible solution to the services integration problem. An approach that supports the combination of different security policies such as Role-Based Access Control (RBAC)

(Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), Mandatory Access Control (MAC) (Bell & La Padula, 1976), or Discretionary Access Control (DAC) (Dittrich, Härtig, & Pfefferle, 1988), from multiple sources into one global security policy is a possible solution to the security policies integration. For services integration at the system level, the HL7 Fast Healthcare Interoperability Resources (FHIR) (Health Level 7, Fast Health Interoperable Resources list, 2016) provides a service integration infrastructure that can be extended to support RBAC, MAC, and/or DAC models in which the infrastructure can serve as an initial solution for the two problems above (i.e., services integration and security policies integration).

The main objective of this dissertation is to provide a solution to the service integration and security policy integration problems that will allow clients and systems to interact with one another in a framework. Such a framework would provide the unification of services and security capabilities from different paradigms (e.g., cloud services, programming services, web services), alternate cloud service providers, and diverse security/access control (RBAC, MAC, and/or DAC); the main intent of the unification is to offer global services that can be available to clients and systems alike. Towards this main objective, this dissertation presents a *Framework for Secure and Interoperable Cloud Computing (FSICC)*, shown in Figure 1.1, that provides a set of global cloud services for use by clients and systems with access control provided by RBAC, MAC, and/or DAC.

To facilitate the discussion of Figure 1.1, we briefly review the following key terms: application programmer interface (API), web service, cloud service, system, client, and registry. An *API* is a general concept that creates a programming interface for a system that can be utilized by another system or application without disclosing the actual source code of that system. In this dissertation, API refers to the programming interface for legacy programming languages such as Java, C++, C, etc. A *web service* is a programming interface (such as REST and SOAP) that typically operates over the Hypertext Transfer Protocol (HTTP). A *cloud service* is a web service hosted in a cloud environment that makes a cloud service more available and accessible than a normal web service. A *system* is a type of software that provides services that can be API, web services, or cloud services, where the system is intending to publish its services to FSICC. A *client* is a desktop, web, or mobile application that is built using different sets of services (API, web services, or cloud services) provided by systems via FSICC. A *registry* is a special service of FSICC that enables a system to register and add its services to FSICC (System Registry), and, a client to utilize services of FSICC (System Registry).

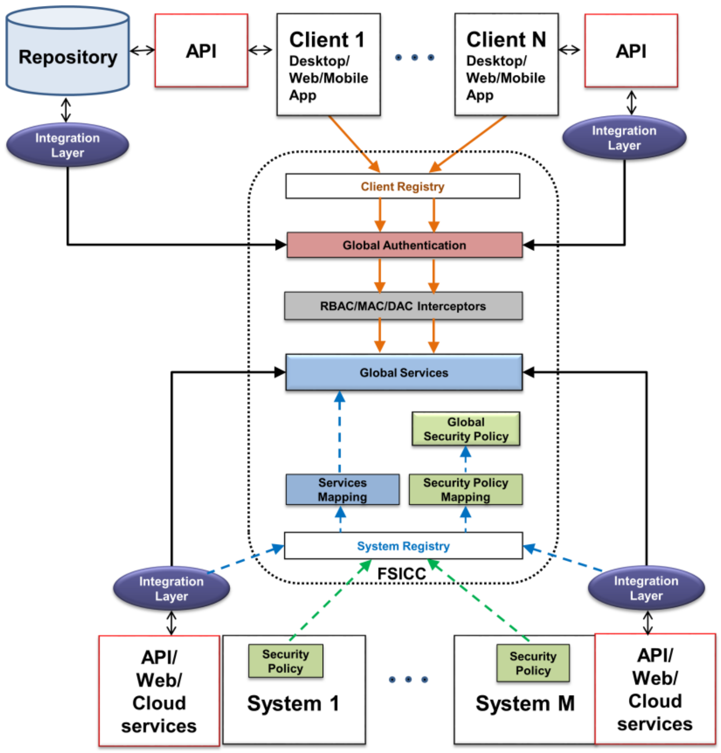


Figure 1.1. The Framework for Secure and Interoperable Cloud Computing (FSICC).

FSICC as presented in Figure 1.1 has two main actors that are interacting via FSICC to develop applications in the service-oriented architecture (SOA) manner (IBM, 2015). These actors are *Clients*, top of Figure 1.1, and *Systems*, bottom of Figure 1.1. From an overall viewpoint, each system builds and publishes their cloud, programmatic, or web services, as shown at the bottom of Figure 1.1. Then, a developer of a mobile or desktop client, at the top of Figure 1.1, discovers such services and utilizes them to develop the client application. The FSICC in the middle of Figure 1.1, augments SOA application development with two additional layers and their interactions: *Global Services* and *Global Security Policy* boxes. The interactions of clients and systems with FSICC occurs in a number of different ways. From a system perspective, each system creates an Integration Layer API in front of their API and modifies their Security Policy to be defined against the Integration Layer API. Each system then registers the system's name, the Integration Layer API, and the Security Policy into the FSICC using the Systems Registry box in the middle of Figure 1.1.

In support of systems, the security engineer of the FSICC creates a global resource that includes: a set of Global API (Services) based the integration layer APIs of each system utilizing the Services Mapping box; and, a Global Security Policy based on systems' Security Policies which utilizes the Security Policy Mapping box in the middle of Figure 1.1. From a client perspective, each client creates an Integration Layer API, top of Figure 1.1, in front of their API. Each client then registers the client's name into the FSICC, using the Clients Registry box and reconfigures the client Integration Layer API to call the Global API. In support of clients, the security engineer of the FSICC performs actions that: associates each registered client with one of the registered systems; and, defines a Global Security Policy that enables the authorized/authenticated clients, via the RBAC/MAC/DAC Interceptor and Global Authentication boxes in the middle of Figure 1.1, to access services of the appropriate system based on the client and system names. Note that in Figure 1.1, registered clients are first authenticated by the Global Authentication box and then authorized by the RBAC/MAC/DAC Interceptor box, before access to Global Services is allowed.

1.1 Motivation for Access Control for Cloud Computing

Cloud computing provides services in the cloud to be utilized by mobile applications/users and businesses. The Gartner group indicated that cloud computing represents the majority of IT funding by 2016 (Shetty, 2013). The International Data Corporation (Idc.com, 2015) reported that organizations and enterprises around the world spent approximately $70 billion to adopt cloud computing services in 2015 with the number of cloud-based services expected to triple by 2020. Cloud computing is provided by major corporations such as Amazon (Amazon.com, 2016), AT&T (AT&T, 2016), Dell (Dell.com, 2016), etc. Security breaches have come to the forefront (Kelion, 2014) especially in personal cloud storage (Wingfield, 2015). Outsourced data and services are located on servers that belong to security domains which are different from an organization's security domain, raising numerous security and privacy issues (Takabi, Joshi, & Ahn, 2010). Other efforts have included: a survey of the different data/network security, authentication, authorization, and confidentiality issues that impact cloud computing (Subashini & Kavitha, 2011); a review of the available cloud computing advances in concepts, functionalities, unique features, and technologies (Wang, Von Laszewski, Younge, He, & Kunze, 2010); and, the characterization of cloud computing as the likely dominant technology for computing on the Internet (Pallis, 2010).

Outsourcing services to the cloud has many advantages including (Skyhigh Networks., 2016): better availability, since most cloud providers ensure more that 90% uptime; better mobility where the hosted services are typically accessible from any place on earth as long as internet connection is available; and cost effective due to that fact that computing equipment are provided by the cloud provider. Such advantages attract governments and businesses to move their services to the cloud. However, the movement to the cloud has resulted in new attacks to illegally access a crucial and sensitive data, such as electronic health records of large number of patients. This is possible since these cloud services are typically designed to be utilized without any type of access control. There is an emergent need to control who can access which cloud services at which times and under which conditions. The publishing of services in the cloud leads to a large number of consumers of such services in which controlling access to which services each consumer can utilize is not supported in existing paradigms (e.g., cloud services, programming services, web services), and available cloud service providers. One approach is to have cloud services controlled using the three main aforementioned access control models, RBAC, MAC, and DAC, since they provide unique capabilities that can control how services are accessed by users, clients, and systems.

RBAC provides an efficient way to manage consumers by using the concept of role in which each role can be authorized to access a sub-set of the available cloud services and each consumer is assigned one or more suitable roles. When cloud services need to access very sensitive information such as patient data that needs to be more strongly controlled than other parts of the patient data, MAC can be employed to control access to services. In this case, MAC can be utilized to label cloud services and their consumers using sensitivity levels which are hierarchically ordered from most to least secure: Top Secret (TS) < Secret (S) < Confidential (C) < Unclassified (U). Using MAC, each cloud service can be assigned a sensitivity level known as a classification, and each consumer can be assigned a sensitivity level known as a clearance along with read and write properties. DAC can offer the ability of a consumer of the cloud services to enable another consumer to utilize all or a sub-set of its authorized cloud services (that are assigned based on a role or a clearance) through a delegation of authority. In this case, DAC can be utilized to keep a list of delegated services, along with authorized delegated users, where each consumer can delegate all or a subset of his/her authorized cloud services to another consumer anytime.

1.2 Motivation for Healthcare Systems and Applications

In this dissertation, we utilize healthcare as the primary vehicle to justify and explain our work since it represents as a critical emergent application for cloud computing. In the United States, the Center of Medicare and Medicaid Services released the Meaningful Use Stage 3 (Himss.org., 2016) guidelines that require all health information technology (HIT) systems to have cloud services to access, modify, and exchange health-related data. HIT systems include electronic health records (EHR) such as OpenEMR (OpenEMR, 2016), OpemMRS (OpenMRS Inc., 2016), and Drchrono EHR (Gibraltar Dr., 2016); and personal health records (PHR) such as Google Health (Google Inc., 2016), Microsoft HealthVault (Microsoft Inc., 2016), and WebMD (WebMD LLC., 2016). In support of the interoperability and exchange of healthcare data, the international Health Level 7 (HL7) (Health Level 7, Health Level Seven INTERNATIONAL, 2016) organization has taken a leadership role for standards to allow the integration, sharing, and exchange of electronic healthcare data, specifically: HL7 Version 2 (Health Level 7, HL7 Version 2, 2016), HL7 Version 3 (Health Level 7, HL7 Version 3, 2016), the Clinical Document Architecture (CDA) (Health Level 7, Clinical Document Architecture, 2016), and HL7 Fast Healthcare Interoperability Resources (HL7 FHIR) (Health Level 7, Fast Health Interoperable Resources, 2016).

In support of this dissertation, we strongly leverage the Healthcare Interoperability Resources (FHIR) which provides a RESTful Application Program Interface (API) to share data in a common format. FHIR conceptualizes and abstracts information for HL7 into 119 currently defined (and always increasing) Resources that effectively decompose HL7 into logical components to track a patient's clinical findings, problems, allergies, adverse events, history, suggested physician orders, care planning, etc. The intent is to allow a unified access to FHIR's RESTful health-related data sharing APIs so that applications can be easily built to uniformly utilize multiple HIT systems.

Concurrent with these activities has been an explosion of mobile health (mHealth) applications for both patients and medical providers (Aitken, 2013). These mHealth applications also require access to health data via cloud services from multiple HIT systems to ensure that all of the necessary information is collected for patient care. Each of these HIT systems may operate with different paradigms (e.g., cloud, API, web services) and employ different security/access control techniques. Thus, mHealth applications would need to work with a heterogeneous collection of paradigms and security protocols, with the strongly likelihood that set of information sources may grow or shrink over time. This makes it problematic to develop mHealth applications that are easily maintained and evolved.

The main issue for healthcare is to ensure that the available services of these HIT systems are carefully authorized to control which mHealth application can utilize which service at which time; this is specifically what FHIR has been defined to provide. For example, an HIT system for a pharmacy would have cloud services for: a physician to submit a prescription (R_x) electronically to the pharmacy (service S_1); a pharmacist to be able to fill the R_x and reduce the number of refills (service S_2); the pharmacist to send notification via text/phone to the patient that the R_x is available (service S_3); the insurance company to access the information on the R_x for approval and payment (service S_4); the physician to have the R_x inserted into his/her EHR (serviceS_5); the patient to access medications in the PHR (service S_6); and, so on. Access control for cloud services of an HIT system can ensure that the mHealth application and its authorized users are restricted to particular services.

The problem is that there is currently no solution that allows cloud services to be controlled on this basis, complicated by the fact that cloud services are available from different cloud suppliers that may not be compatible with one another. For example, the cloud services S_1 to S_6 listed above can be controlled by the three access control models, RBAC, MAC, and DAC. For RBAC, four roles can be created: *physician* (authorized to access services S_1 and S_5), *pharmacist* (authorized to access services S_2 and S_3), *insurance company* (authorized to access service S_4), and *patient* (authorized to access service S_6). In this case, a user that has been authorized to a given role would be limited to only invoke those Services of the role through the client application. For MAC, each cloud service can be assigned a classification level: (S_1, C); (S_2, S); (S_3, U); (S_4, S); (S_5, C); and (S_6, TS). In this case, the user that has been authorized to a clearance level, say, S, would be limited to invoke those services whose classification levels are less than or equal to the clearance of the user, namely S, C, and U. For DAC, each cloud service can be delegated from one consumer to another by delegating role or clearance that is authorized to each authorized cloud service.

1.3 Motivation of Security Requirements and Cloud Computing Capabilities for FSICC

As discussed in Section 1.2, the healthcare domain is an emergent application for cloud computing, in which the Meaningful Use Stage 3 guidelines recommend health information technology (HIT) systems to provide cloud services that enable health-related data owners to access, modify, and exchange data. This requires mobile and desktop applications for patients and medical providers to obtain healthcare data from multiple HITs, that may be operating with different paradigms (e.g., cloud services, programming services, web services), use different cloud service providers, and employ different security/access control techniques. To address these issues, we have identified four of security requirements and three cloud computing capabilities that will need to underlie and support FSICC. These four security requirements and three cloud computing capabilities for FSICC simplifies and enables client access via global resources using standardized system APIs.

The four security requirements of FSICC are: *Numerous and Varied Access Control Models, Control Access to Cloud Services Using RBAC, Support Delegation of Cloud Services Using DAC*, and *Control Access to Cloud Services Using MAC*; each are briefly reviewed. The *Numerous and Varied Access Control Models* security requirement is intended to support a wide range of access control such as RBAC (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), MAC (Bell & La Padula, 1976),   DAC (Dittrich, Härtig, & Pfefferle, 1988), Attribute-based Access Control (ABAC) (Yuan, E. & Tong, J. , 2005), Usage Access Control (UCON) (Sandhu, R. & Park, J. , 2003), etc.; this is since each system may utilize any access control model. The *Control Access to Cloud Services Using RBAC* security requirement dictates that access to cloud services will be realized by enhancing RBAC by extending permissions from objects to services. The *Control Access to Cloud Services Using MAC* security requirement dictates that access to cloud services will be realized by enhancing MAC by extending the labeling of objects with classifications to services with classifications. Lastly, the *Support Delegation of Cloud Services Using DAC* security requirement dictates that access to cloud services will be realized by enhancing DAC by providing the ability to delegate services on a user by user basis.

The three cloud computing capabilities of FSICC are: *Local Service Registration and Mapping to Global Services, Local Security Policies Registration to Yield Global Security Policy,* and *Global Registration, Authentication, Authorization, and Service Discovery for Consumers*; each are briefly reviewed. The *Local Service Registration and Mapping to Global Service* cloud computing capability is for systems to register their local services which are then mapped to a global set. The *Local Security Policies Registration to Yield Global Security Policy* cloud computing capability is for systems to register their local security policy that is utilized to generate a global security policy. The *Global Registration, Authentication, Authorization, and Service Discovery for Consumers* cloud computing capability is to support the process of a consumer (mobile, web, or desktop app) to register within FSICC to discover and be authenticated and then authorized to utilize services.

1.4 A High-Level View of Presented Approach

In this dissertation, the architecture view of our presented Framework of Secure and Interoperable Cloud Computing (FSICC) in Figure 1.1 can be complemented with a component view as given in Figure 1.2. Specifically, in Figure 1.2, there are six main components outlined boxes. The first component *Involved Parties*, topmost component in Figure 1.2, refers to clients and systems and their APIs previously shown in the top and bottom of Figure 1.1, and consists of: a Clients box that includes an API; and, multiple Systems boxes that includes an API and a security Policy. As the first step toward creating a global security policy and services, clients and systems may utilize two separate components: the *Security Policy Mapping* component which refers to the process and algorithms that can be utilized to generate the global security policy that was shown in the middle of Figure 1.1; and, the *Architectural Blueprint* component which refers to the process and steps that can be followed to create different integration layers for clients and systems.

An *integration layer* is a standard API (e.g., FHIR API for a healthcare case as discussed in Section 2.4 of Chapter 2) that converts the data format of a system or client from/to a common data format. Such a common data format can be utilized by other systems and clients, in addition to the FSICC, to easily exchange data. An integration layer exists with an integration framework (IFMWK) which is a set of standards and associated technologies that allow different systems to interact with one another utilizing one common data representation. The associated technologies allow integration servers to be designed and implemented to facilitate the exchange of information using the common data representation via a set of shared unified services via an integration layer. The FHIR standard is one example of an integration framework which has a set of resources in XML, JSON, RDF, and Turtle that are a common data representation with associated services for CRUD and searching.

In FSICC, all security policies (that can be any combination of RBAC, MAC, and/or DAC) of each system go through two main phases: the *Policies Combining phase* (RBAC integration, MAC integration, and DAC integration) that creates one set of policy (global security policy) that has all policies from different systems; and, the *Policies Updating phase* (only for RBAC and MAC) that is needed to update role names (for RBAC) and update global MAC with users and services form systems based on the global sensitivity levels (for MAC). In addition, there are a number of different *Application Integration Options* to allow an application to send/receive data with multiple mixed clients and pure or mixed systems, via FSICC, by the creation of an integration layer API in front of their API (services) by utilizing one of the *Architectural Blueprint* options. An *Architectural Blueprint* option is a guideline that defines the way of placing and creating an integration layer for a systems or client to allow such them to exchange data with other systems and clients in one common data format. There are three *Architectural Blueprints* options as shown in Figure 1.2: a *Basic Architecture* that includes an IFMWK server that works directly with the App repository and IFMWK servers of different HIT systems; an *Alternative Architecture* that includes a IFMWK server that works directly with the App RESTful API and IFMWK servers of different HIT systems; and, a *Radical Architecture* that removes the repository and has IFMWK servers for the App API and a number of HIT systems.

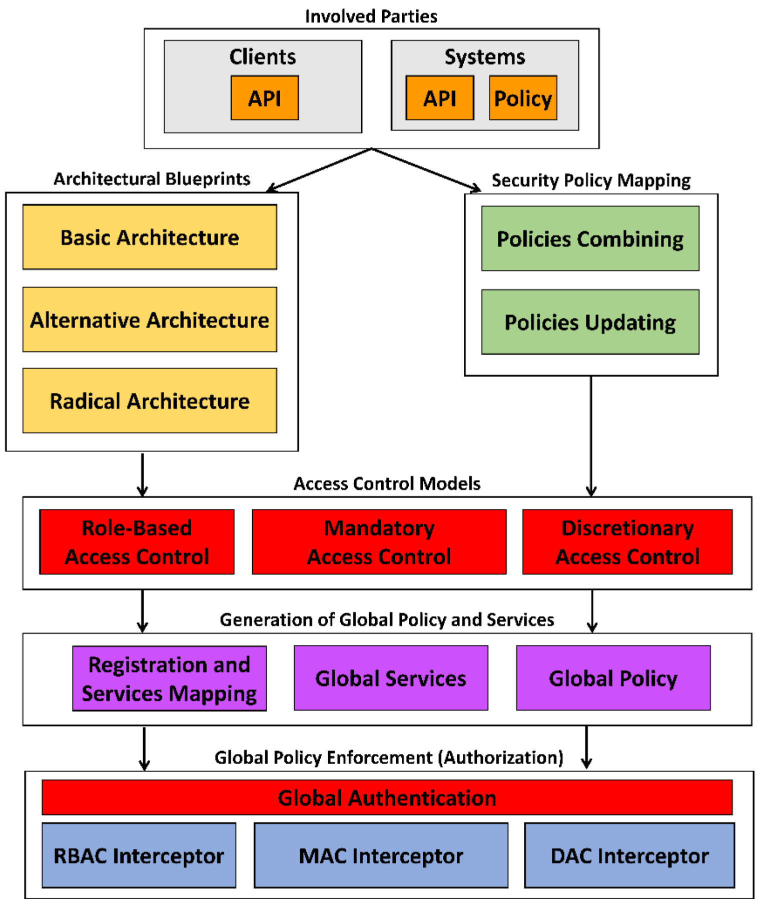


Figure 1.2. A Component-Level View of the presented FSICC.

The selection of an architectural blueprints option is determined based on four factors that describe the situation of a client or system: the *overall architecture* of the application (i.e., one-tier, two-tier, and three-tier architecture); the *involved technologies* that can be used to develop the application (i.e., RESTful APIs, programmatic APIs, database API); the *source code availability* of the application, APIs, server code, or database; and, the *allowable access to system* sources (RESTful APIs, programmatic APIs). Based on the output of the *Architectural Blueprints* component and after a system has registered at the Integration Layer, the security engineer of FSICC can establish the global API (services) in a two-step process. First, the security engineer creates a set of common services from the integration layer API, utilizing the *Services Mapping* process using the *Generation of Global Policy and Services* component in Figure 1.2, where each system in the global API is configured to send/receive requests to/from the integration layer API of the appropriate system. Second, each client can configure its integration layer API to send/receive requests to/from the Global API. Based on the output of the *Security Policy Mapping* component, the security engineer utilizes the *Access Control Models* component to define the security policies of systems that was shown at the bottom of Figure 1.1 and in the process to establish the global security policy that was shown in the middle of Figure 1.1. The security engineer can develop the global security policy by: creating global roles in which each global role can be authorized to a subset of the global services and creating new users (from clients) in which each global user can be assigned to one or more global roles (RBAC); assigning classification for each global service, and assigning clearance for each global user with read and write properties (MAC); and, enabling role or service delegation from one to another global users (DAC).

The resulting global services (API) and global security policy comprise the *Generation of Global Policy and Services* component, shown in the middle of Figure 1.2. After establishing the global security policy, a number of security interceptors can be created to enforce the global security policy on the users' access requests, after such users have been authenticated. A security interceptor can be defined as a programmatic mechanism that is able to intercept a service call from a client application to an API (service) in order to perform appropriate security enforcement checks. The *Global Policy Enforcement* component shown at the bottom of Figure 1.2 refers to the RBAC/MAC/DAC interceptors box that was shown in the middle of Figure 1.1, consists of four boxes. The *Global Authentication* box is utilized to verify the claimed credentials, ID and security token, that a user (client) provided is correct or not. The *RBAC Interceptor* box provides the ability to allow/deny a global user with a global role from accessing a specific global service. The *MAC Interceptor* box provides the ability to allow/deny a global user with a clearance from accessing a specific global *service*. The *DAC Interceptor* box provides the ability to allow/deny a global user (with a delegated global role, global service, or global clearance) from accessing a specific global service. Collectively, FSICC as presented in Figure 1.2, represents a set of interacting components that allows from a transition to isolated clients and systems being able to join and utilize a global environment that provides a single common way to access services.

1.5 Research Objectives and Expected Contribution

In this section, we discuss the research objectives and expected contributions of this dissertation. Since the component-level view of the presented FSICC in Figure 1.2 does not provide an adequate representation of the underlying models, concepts, and research of FSICC for the dissertation, we supplement Figure 1.2 with Figure 1.3 which provides a high-level view of the research of FSICC as discussed in Section 1.4, organizing and grouping the components of Figure 1.2 into a perspective that identifies the research areas and foci of the dissertation. Figure 1.3 has horizontal boxes that contain the main research foci of this dissertation and vertical boxes that span across multiple foci.

The five horizontal boxes are: *Architectural Blueprints* that contain the different options for architectural option for connecting clients and systems with FSICC that was shown in the upper left portion of Figure 1.2; *Unified Cloud Computing Access Control Model* with boxes for Schema Definitions, Enterprise Definitions, Policy Definitions, FSICC Definitions, and Intercepting Definitions; *Access Control Models* for the ability to control services via RBAC, MAC, and DAC as discussed for FSICC's security requirements in Section 1.3 and that was shown in the middle of Figure 1.2; *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* for generating the security policy from multiple systems to make global APIs available to clients what's showing in the lower portion of Figure 1.2; and, *Global Security Policy and Global API Utilization and Security Enforcement* that utilizes security interceptors that was shown in the bottom of Figure 1.2 to allow/deny clients from access global services of FSICC. The security requirements introduced in Section 1.3 are represented by the upper right vertical box SECURITY REQUIREMENTS in Figure 1.3 that spans two horizontal boxes: Unified Cloud Computing Access Control Model and Access Control Models. The cloud computing capabilities introduced in Section 1.3 are represented by the lower right vertical box CLOUD COMPUTING CAPABILITIES in Figure 1.3 that spans two horizontal boxes: Global Security Policy and Global API Generation and Global Security Policy and Global API Utilization and Security Enforcement.

From a research perspective, the presented Framework for Secure and Interoperable Cloud Computing that was shown in Figure 1.2 has the following four expected contributions (**EC-A, EC-B, EC-C,** and **EC-D**) which are presented and discussed using the security requirements and cloud computing capabilities of Section 1.3 and Figures 1.2 and 1.3. The expected contributions are also highlighted in the horizontal and vertical boxes of Figure 1.3.

EC-A: Architectural Blueprints for Supporting FSICC: This contribution facilitates the interoperability and information exchange of clients and systems and presents a collection of three architectural blueprints (i.e., Basic Architecture, Alternative Architecture, and Radical Architecture) for the design and development of integration framework (IFMWK) servers utilizing a standard integration framework (e.g., FHIR in the healthcare domain) that enable the integration between systems with applications. This was shown in the upper half (left) of Figure 1.2. The architectural blueprints are represented as the first horizontal box *Architectural Blueprints* in Figure 1.3 and includes three main boxes for: Interoperability Issues, Integration Options, and Integration Blueprints. Each blueprint is based on the location that IFMWK servers can be placed with respect to the components of the application (UI, API, Server) or a HIT system in order to define and design the necessary infrastructure to facilitate the exchange of information via IFMWK.

EC-B: An Integrated RBAC, MAC, and DAC Model for Cloud Computing: This contribution involves a Unified Cloud Computing Access Control model (UCCACM) for the FSICC that provides a single view of global services to applications (i.e., clients) and allows those global services to be authorized according to RBAC, MAC, and DAC policies. The UCCAC model is represented by the second horizontal box *Unified Cloud Computing Access Control Model* in Figure 1.3 that includes five main boxes for: Schema Definitions, Enterprise Definitions, Policy Definitions, FSICC Definitions, and Intercepting Definitions. The contribution will include a set of formal definitions for RBAC, MAC, and DAC access control models that specifies, in detail, the way that: each system can register its services and security policies; and, a security engineer can define a set of global RBAC, MAC, and/or DAC policies on a unified set of global cloud services. The UCCAC model basically provides formal definitions for the main components of Figure 1.2.

EC-C: Security Mapping/Enforcement Algorithms and SSEP: The Security Mapping/Enforcement Algorithms aspect of this expected contribution is realized within the horizontal box near the bottom of Figure 1.3, labeled *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* which includes Security Policies and Services Registration, Global Services Generation, and Global Security Policy Generation. This SOA-based security engineering process (SSEP) aspect of this expected contribution for FSICC that can be utilized to combine security policies (that can be RBAC, MAC or DAC) from different systems into one global security policy, in which SSEP also includes a process for security enforcement code generation. This was shown in the upper right half of Figure 1.2. A portion of the SSEP is human assisted in order to reconcile naming issues of roles, mapping sensitivity levels, etc., that are integrated from multiple clients and systems. Once the policies are successfully mapped, all of the security enforcement code can be automatically generated by algorithms. The SSEP for FSICC is represented by the left vertical box *SOA-BASED SECURITY ENGINEERING* in Figure 1.3 that spans all of the five horizontal boxes: Architectural Blueprints, Unified Cloud Computing Access Control Model, Access Control Models, Global Security Policy and Global API Generation, and Global Security Policy and Global API Utilization and Security Enforcement.

EC-D: Dynamic Enforcement via Intercepting Process: This contribution involves a set of programmatic mechanisms that are able to intercept a service call from a client app to an API in order to perform appropriate security enforcement checks. This was shown in the bottom of Figure 1.2. In Figure 1.3, these security interceptors are represented within the last horizontal box *Global Security Policy and Global API Utilization and Security Enforcement* in Figure 1.3, and the Security Enforcement via Interceptors box in Figure 1.2. Interceptors include: a RBAC Interceptor that is able to determine at runtime if the requested API call on a global service can be executed for a specific user with a specific role; a MAC Interceptor that is able to determine at runtime if the requested API call on a global service can be executed for a user with a clearance and limited by if the services is read or write; and a DAC Interceptor that is able to determine at runtime if the requested API call on a global service can be executed for a specific user with a delegated role/service/clearance.

Throughout the remainder of the dissertation, these expected contributions (**EC-A, EC-B, EC-C,** and **EC-D**) will be high-lighted when relevant.

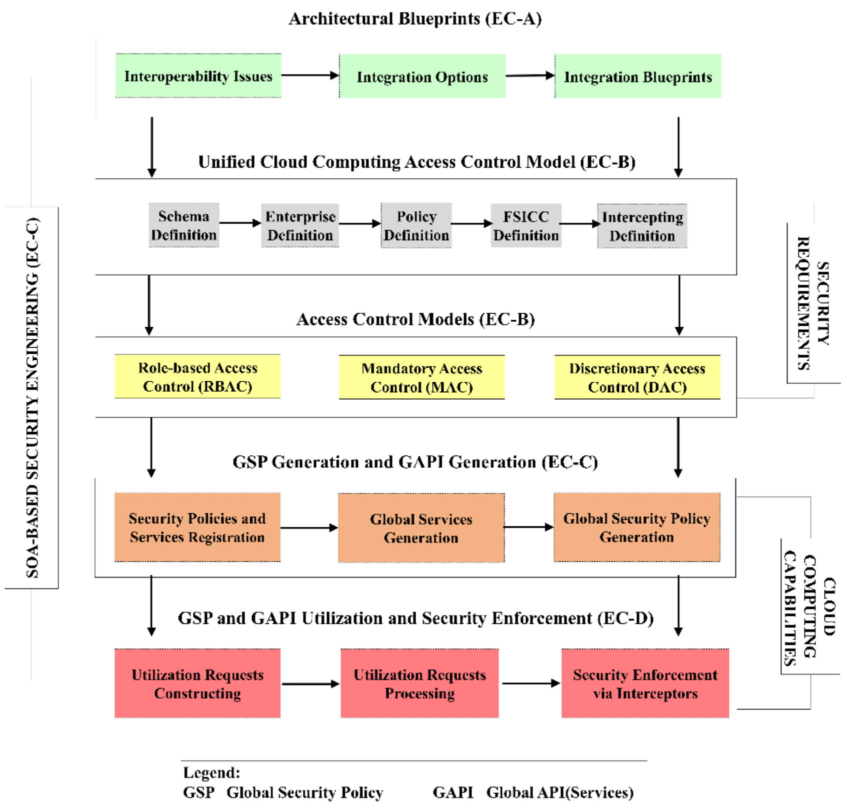

Architectural Blueprints (EC-A)
Interoperability Issues
Integration Options
Integration Blueprints
Unified Cloud Computing Access Control Model (EC-B)
Schema Definition
Enterprise Definition
Policy Definition
FSICC Definition
Intercepting Definition
Access Control Models (EC-B)
Role-based Access Control (RBAC)
Mandatory Access Control (MAC)
Discretionary Access Control (DAC)
GSP Generation and GAPI Generation (EC-C)
Security Policies and Services Registration
Global Services Generation
Global Security Policy Generation
GSP and GAPI Utilization and Security Enforcement (EC-D)
Utilization Requests Constructing
Utilization Requests Processing
Security Enforcement via Interceptors
SOA-BASED SECURITY ENGINEERING (EC-C)
SECURITY REQUIREMENTS
CLOUD COMPUTING CAPABILITIES
Legend:
GSP Global Security Policy
GAPI Global API(Services)

Figure 1.3. High-Level View of FSICC Research Areas and Foci.

1.6 Research Progress to Date

In support of the presented Framework for Secure and Interoperable Cloud Computing, a number of articles have been published:

- **Baihan, M.**, Sánchez, Y., Shao, X., Gilman, C., Demurjian, S., & Agresta, T. (2018). A Blueprint for Designing and Developing M-Health Applications for Diverse Stakeholders Utilizing FHIR. In R. Rajkumar (Ed.), *Contemporary Applications of Mobile Computing in Healthcare Settings* (pp. 85-124). Hershey, PA: IGI Global.
- **Baihan, M.**, and Demurjian, S. (2017). A Framework for Secure and Interoperable Cloud Computing. In *Research Advances in Cloud Computing*, S. Chaudhary (ed.), Springer.
- **Baihan, M.**, Demurjian, S., Rivera Sánchez, Y., Toris, A., Franzis, A., Onofrio, A., Cheng, B., and Agresta, T. (2017). Role-Based Access Control for Cloud Computing Realized within HAPI FHIR. *Proceedings of 16th International Conference on WWW/INTERNET 2017 (ICWI 2017)*, October 2017.

Other published or submitted articles:

- Rivera Sánchez, Y., Demurjian, S., and **Baihan, M.** (2017). Achieving RBAC & MAC on RESTful APIs for Mobile Apps using FHIR. In *The 5th IEEE International Conference on Mobile Cloud Computing, Services, and Engineering*.
- Ziminski, T. B., Demurjian, S. A., Sanzi, E., **Baihan, M.**, and Agresta, T. (2017). An Architectural Solution for Health Information Exchange. In *International Journal of User-Driven Healthcare (IJUDH)*, *6*(1), 65-103.
- Rivera Sánchez, Y., Demurjian, S., and **Baihan, M.** (2017). A Service-Based RBAC & MAC Approach Incorporated into the Fast Healthcare Interoperable Resources (FHIR) standard. Submitted to *The Digital Communications and Networks Journal, special issue on The Security, Privacy, and Digital Forensics of Mobile Networks and Mobile Cloud.*

1.7 Dissertation Outline

The remainder of the dissertation has seven chapters. In Chapter 2, we review background on: cloud computing and its main technologies; RBAC, MAC, and DAC models that are utilized to enforce authorization on cloud services; application programming interfaces (APIs); and, the Fast Health Interoperable Resources (FHIR) standard and its HAPI FHIR implementation. In Chapter 3, we present and explain four security requirements and three cloud computing capabilities for FSICC that both simplifies and enables client access via global resources via standardized system APIs. Chapter 4 defines a Unified Cloud Computing Access Control model (UCCACM) for RBAC, MAC, and DAC access control for a cloud setting; this addresses Contribution EC-B: An Integrated RBAC, MAC, and DAC Model for Cloud Computing. In Chapter 5, we present a set of blueprints for the design and development of IFMWK servers in which an application can interact with multiple HIT systems via IFMWK through the design, implementation, and usage of IFMWK servers. The architectural blueprints consist of three main architectural integration options: Basic Architecture, Alternative Architecture, and Radical Architecture; this addresses Contribution EC-A: Architectural Blueprints for Supporting FSICC. Chapter 6 has two main parts. The first part presents a set of algorithms for generating the global security policy of FSICC; this partially addresses Contribution EC-C: Security Mapping/Enforcement Algorithms and SSEP by focusing on Security Mapping/Enforcement Algorithms. The second part introduces and discusses three security interceptors for RBAC, MAC, and DAC via a number of checks and an algorithmic approach for each interceptor; this addresses Contribution EC-D: Dynamic Enforcement via Intercepting Process. Chapter 7 introduces and discusses an SOA-based security engineering process for FSICC that is intended to help security engineers of systems and clients, on one side, and the security engineer of FSICC, on the other side, to establish and maintain secure interoperable services via RBAC, MAC, and DAC; this partially addresses Contribution EC-C: Security Mapping/Enforcement Algorithms and SSEP by focusing on SSEP. Finally, Chapter 8 summarizes the contributions of the dissertation and discusses future work.

Chapter 2
Background

This chapter provides background material on the main concepts and topics that support the discussion and explanation in the remainder of this dissertation. Section 2.1 presents the cloud computing concept and underlying application programming interfaces (APIs), and discusses the main technologies behind cloud computing with an emphasis on the service-oriented architecture (SOA) technology that underlies the cloud service model. Section 2.2 reviews the three classic access control approaches: role-based access control (RBAC) (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), discretionary access control (DAC) (Dittrich, Härtig, & Pfefferle, 1988), and mandatory access control (MAC) (Bell & La Padula, 1976). Section 2.3 introduces and explains the Fast Health Interoperable Resources (FHIR) standard with an emphasis on the FHIR Resources and reviews the HL7 Application Programming Interface FHIR (HAPI-FHIR) which is one popular reference implementation of the FHIR standard. Section 2.4 introduces and presents a sample healthcare scenario utilized throughout this dissertation.

2.1 Cloud Computing and APIs

Cloud computing has emerged as a de facto approach throughout society, commercial, governmental sectors, and research/academic communities. The National Institute of Standards and Technology (NIST) (Mell & Grance, 2011) defines: "Cloud computing is a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction." Historically, cloud computing emerged from the evolution of existing technologies (Zhang, Cheng, & Boutaba, 2010), such as service-oriented architecture, that are combined in a certain way to provide a new business model. Service-oriented architecture (SOA) (IBM, 2015) is a model for designing systems in which the focus is around offering services for different consumers. An SOA implementation, such as the web services standard, could adopt the eXtensible Markup Language (XML) as an SOA approach that enables systems to provide and consume services in a common manner without the need to use a specific programming language or operating system.

This facilitates services integration. Service suppliers define and publish services for use by consumers. Cloud services are provided and delivered based on the cloud service model (Microsoft.com, 2016) by leveraging concepts from SOA. In the cloud service model in Figure 2.1, there are three main components: Cloud Service Registry, Cloud Service Supplier, and Cloud Service Consumer. The *Cloud Service Registry* component maintains information on available cloud services. The *Cloud Service Supplier* component publishes services to the Cloud Service Registry. The *Cloud Service Consumer* component discovers services from Cloud Service Registry and consumes them. Cloud services are the APIs that define the way that cloud consumers can access and utilize cloud-computing resources such as software.

Cloud computing utilizes an Application Programming Interface (API) to support the definition of services. An API requires a set of inputs via an HTTP request to generate a response in a specific format such as the Extensible Markup Language (XML), the JavaScript Object Notation (JSON), etc., based on the inputs. In cloud computing, the cloud services are the APIs that define the way that cloud consumers can access and utilize cloud-computing resources such as software. Some benefits of creating an API are: (1) data can be transferred from one system to another system easily and smoothly; (2) an API can be called and processed by almost any programming language that can be different from the programming language of the actual system implementation; and,

(3) an API can be utilized to encourage external developers to add new features or to enhance current features of a system. An API can be designed using web services such as: Representational State Transfer (REST) (Fielding, 2000), Simple Object Access Protocol (SOAP) (Microsoft Inc., 2016), etc. Any API designed based using the REST protocol is called a RESTful API, which is defined as a set of definitions for methods of the Back-end system. A RESTful API utilizes a Hypertext Transfer Protocol (HTTP) request to interact with the API consumers and the back-end system (Rouse, 2014). RESTful requests are frequently referred to as CRUD, which is short for Create, Read, Update, and Delete functions. CRUD operations from an HTTP perspective are typically defined as: GET to retrieves data; PUT or POST to insert data; POST, PUT, or PATCH to update data; and, DELETE to remove data. RESTful APIs have become a dominant choice for designing and implementing cloud services.

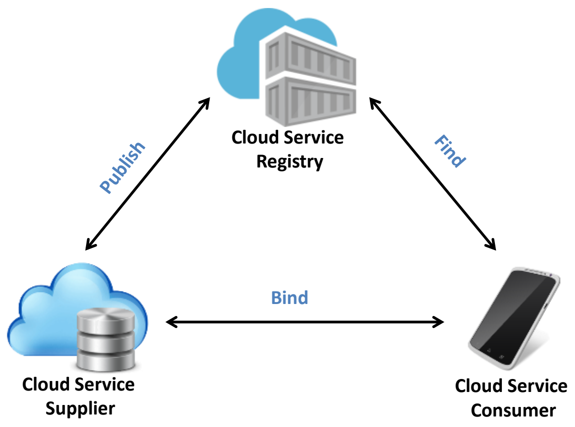


Figure 2.1. Cloud Service Model.

2.2 Access Control Models

Access control models have gained wide acceptance in computing, traditionally in controlling access to data in objects that are in a database or a repository. The three classic approaches are: role-based access control (RBAC) (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), discretionary access control (DAC) (Dittrich, Härtig, & Pfefferle, 1988), and mandatory access control (MAC) (Bell & La Padula, 1976). RBAC provides an efficient way to manage consumers, users of a system, by utilizing the concept of role in which each role can be authorized to access a sub-set of the available cloud services and each consumer is assigned one or more suitable roles. The RBAC model as shown in Figure 2.2 consists of three main components: *elements* that describe the different components; *constraints* that can be defined on the elements; and, *relations* that exist between the various elements.

There are five main elements in RBAC: *objects* that represent functionality for an application; *operations* that are defined on objects; *permissions* that are the allowed operations on the different objects; *roles* that represent a set of responsibilities for a user of the application to capture the defined permissions; and, *users* that are assigned to a role during a session of an application. RBAC supports a number of constraints that can be defined to restrict a user playing a specific role. Finally, RBAC elements can be organized into relations: a *role-user relation* to assign users to roles; a *role-permission relation* to assign permissions to roles; a *role-session relation* to assign sessions to roles; a *user-session relation* to assign users to sessions; an *operation-object relation* to assign objects to operations; and, a *role-role relation* to define a role hierarchy. Moreover, the role-role relations form a partial order and are represented using an *isa* role hierarchy based on generalization (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001). That is, any role that is located higher up in the hierarchy, is a more general role than roles lower in the role hierarchy. As a result, a non-root role inherits all of the permissions authorized to the roles above, namely, the ancestors. In addition, some roles in the role hierarchy are abstract roles in which no users will be assigned to such roles. For example, in healthcare, a physician role can be at a higher level than a private physician role, which inherits all of the permissions authorized to the physician role; in such a role hierarchy, the physician role is a more general role.

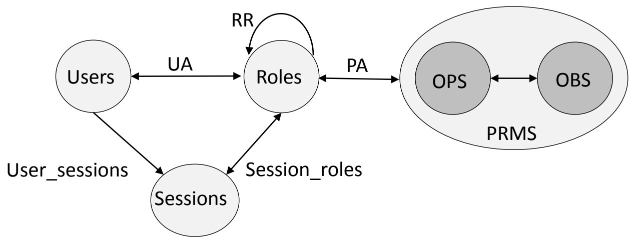


Figure 2.2. RBAC Model.

When cloud services need to access very sensitive information such as patient data that needs to be more strongly controlled than other parts of the patient data, MAC can be employed to control access to services using the concept of a sensitivity level, which is a security label that can be assigned to an object or a user to indicate the importance of such service or user. In MAC, sensitivity levels are assigned to subjects (clearance) and objects (classification) with the permissions for the subject to read and/or write an object dependent on the relationship between clearance (assigned to users) and classifications (assigned to objects). MAC typically is modeled using four sensitivity levels which are hierarchically ordered from most to least secure: Top Secret (TS) < Secret (S) < Confidential (C) < Unclassified (U); this is referred to as the multi-level security model (MLS). These terms are defined in the U.S. classification of information systems in a Presidential Executive Order (National Archives, 1982):

“(1) "Top Secret" shall be applied to information, the unauthorized disclosure of which reasonably could be expected to cause exceptionally grave damage to the national security.

(2) "Secret" shall be applied to information, the unauthorized disclosure of which reasonably could be expected to cause serious damage to the national security.

(3) "Confidential" shall be applied to information, the unauthorized disclosure of which reasonably could be expected to cause damage to the national security.”

In MAC, the central authority maintains a classification (CLS) for each object and a clearance (CLR) for each user in the system. The MAC model (Bell & La Padula, 1976) also has a set of properties, namely, *Simple Security (SS), Simple Integrity (SI), Liberal* (L*), and Strict* (S**) that has both Read and Write capabilities. Such properties are defined to determine under which conditions a user with a CLR level can read or write a given data item with a CLS level. First, the SS property (or read-down, no read-up) is the permission to read an object that has an equal or lower CLS level. That is, a user is allowed to read an object with a CLS level equal to or lower than their CLR level, but not those objects with a higher CLS level. Second, the SI property (or write-down, no write-up) is the permission to write an object that has an equal or lower CLS levels. That is, a user can write an object of equal or lower CLS level when compared to their CLR level, but not to those objects with a higher CLS levels. Third, the L* property (or write-up, no write-down) is the permission to write an object that has an equal or greater CLS level (the opposite of SI). Forth, S* Write property (or write equal) is the permission to write an object that only has an equal CLS level. Finally, the S* Read property (or read equal) is the permission to read an object that only has an equal CLS level. From a definition and management perspective, an Security engineer of a system would set the CLR level of users following the predefined sensitivity levels (e.g., TS, S, C, and U) to establish the levels for both users and objects. These levels are then augmented on a user-by-user basis by assigning the ability to read an object (via SS or S* Read properties) and the ability to write an object (via SI, L*, or S* Write properties).

To explain the read/write properties, assume that there is an object O_1 with a confidential classification; an object O_2 with a top secret classification; a user U_1 with a top secret clearance, with SS read property and SI write property chosen for that user. Assume another user U_2 with a secret clearance with SS read property and SI write property chosen for this user. In this setting, U_1 can read and write O_1 and O_2, while U_2 can only read and write O_1, as shown in Figure 2.3.

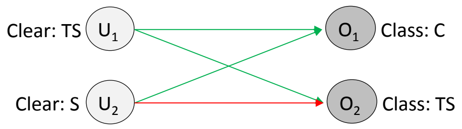
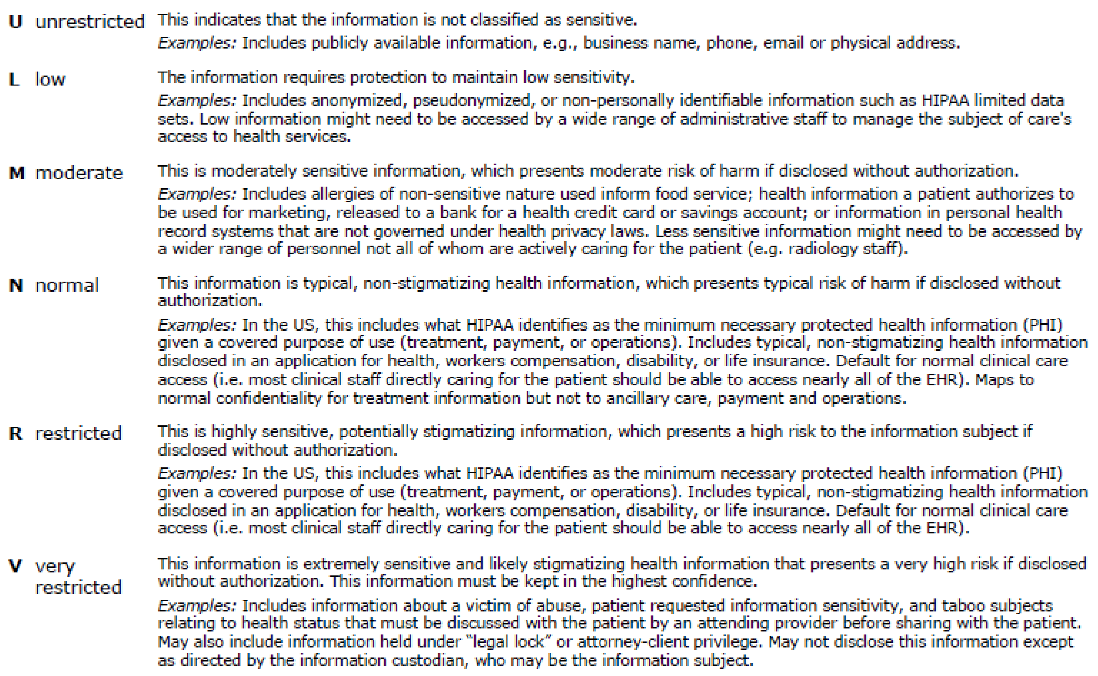


Figure 2.3. An Example of MAC.

However, the four sensitivity levels typically used in MAC are insufficient to classify data in some complex areas such as healthcare. For this reason, a number of healthcare-based sensitivity level sets have been proposed in the literature. Two main works are: the HL7 v3 standard confidentiality labels (Health Level 7., 2014); and a proposed healthcare multi-level security labeling system (Demurjian, Sanzi, Agresta, & Yasnoff, 2018). In the first work, the HL7 organization introduced the HL7 v3 standard which contains a definition for a set of confidentiality labels that is defined to accurately classify healthcare related data. Specifically, the HL7 v3 standard defines six confidentiality labels: U – unrestricted, L – low, M – moderate, N – normal, R – restricted, and V – very restricted; these six levels replace the four traditional sensitivity levels of MAC. Figure 2.4 presents the HL7 v3 confidentiality labels with a definition and examples for each confidentiality label, taken from (http://www.hl7.org/documentcenter/public_temp_DFF235EF-1C23-BA17-0CB382A77F4391FB/standards/vocabulary/vocabulary_tables/infrastructure/vocabulary/vs_Confidentiality.html). Note that these confidentiality labels indicate the type of healthcare related data that needs to be protected and are different from the typical four sensitivity levels of MAC.



U	unrestricted	This indicates that the information is not classified as sensitive. *Examples:* Includes publicly available information, e.g., business name, phone, email or physical address.
L	low	The information requires protection to maintain low sensitivity. *Examples:* Includes anonymized, pseudonymized, or non-personally identifiable information such as HIPAA limited data sets. Low information might need to be accessed by a wide range of administrative staff to manage the subject of care's access to health services.
M	moderate	This is moderately sensitive information, which presents moderate risk of harm if disclosed without authorization. *Examples:* Includes allergies of non-sensitive nature used inform food service; health information a patient authorizes to be used for marketing, released to a bank for a health credit card or savings account; or information in personal health record systems that are not governed under health privacy laws. Less sensitive information might need to be accessed by a wider range of personnel not all of whom are actively caring for the patient (e.g. radiology staff).
N	normal	This information is typical, non-stigmatizing health information, which presents typical risk of harm if disclosed without authorization. *Examples:* In the US, this includes what HIPAA identifies as the minimum necessary protected health information (PHI) given a covered purpose of use (treatment, payment, or operations). Includes typical, non-stigmatizing health information disclosed in an application for health, workers compensation, disability, or life insurance. Default for normal clinical care access (i.e. most clinical staff directly caring for the patient should be able to access nearly all of the EHR). Maps to normal confidentiality for treatment information but not to ancillary care, payment and operations.
R	restricted	This is highly sensitive, potentially stigmatizing information, which presents a high risk to the information subject if disclosed without authorization. *Examples:* In the US, this includes what HIPAA identifies as the minimum necessary protected health information (PHI) given a covered purpose of use (treatment, payment, or operations). Includes typical, non-stigmatizing health information disclosed in an application for health, workers compensation, disability, or life insurance. Default for normal clinical care access (i.e. most clinical staff directly caring for the patient should be able to access nearly all of the EHR).
V	very restricted	This information is extremely sensitive and likely stigmatizing health information that presents a very high risk if disclosed without authorization. This information must be kept in the highest confidence. *Examples:* Includes information about a victim of abuse, patient requested information sensitivity, and taboo subjects relating to health status that must be discussed with the patient by an attending provider before sharing with the patient. May also include information held under "legal lock" or attorney-client privilege. May not disclose this information except as directed by the information custodian, who may be the information subject.

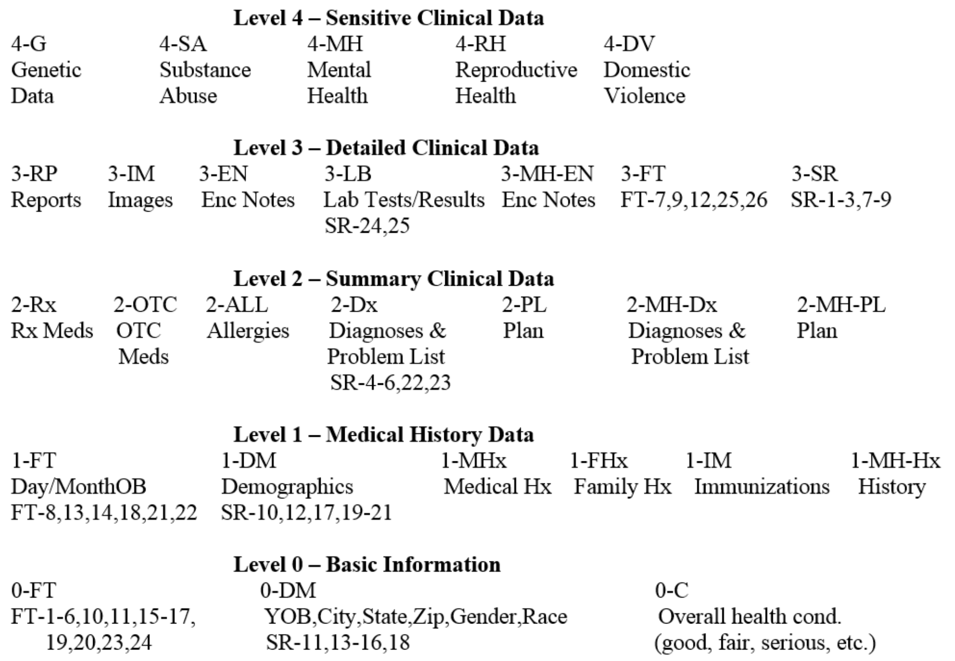
Figure 2.4. Confidentiality Labels from HL7 Release 3 Standard.

In the second work, Demurjian et al., (Demurjian, Sanzi, Agresta, & Yasnoff, 2018) proposed a multi-level security labeling system for healthcare domain which has five healthcare sensitivity levels (0-4) and within each level there are different categories of data that will be given to different users based on their need as Figure 2.5 shows, where Level 0 is the least secure, while Level 4 is the most secure. Specifically:

- Level 0 (*Basic Information*) is public data available to anyone without control in which data in this level can be categorized into: 0-DM for basic demographics such as city and state of residence, 0-C for general health condition, and 0-FT for information related to tracking fitness data.
- Level 1 (*Medical History Data*) contains data that has some restrictions in which data in this level can be categorized into: 1-DM for detailed demographic data, 1-MHx for history of the patient and his/her family, 1-FHx for more sensitive patient-collected

fitness data, 1-IM for immunizations, and 1-MH-Hx for mental health history of the patient.

- Level 2 (*Summary Clinical Data*) contains clinical data in which data in this level can be categorized into: 2-Rx for prescription, 2-OTC for over-the-counter medications, 2-ALL for allergies, 2-Dx for medical diagnoses and problem list, 2-PL for plan for treatment or other related instructions, 2-MH-Dx for mental health, separate medical diagnoses and problem list, and 2-MH-PL for plan for treatment or other related instructions.
- Level 3 (*Detailed Clinical Data*) is for use by medical providers in which data in this level can be categorized into: 3-RP for reports from imaging studies (CT Scans, MRIs, X-Rays, etc.), 3-IM for the images from the studies, 3-EN for detailed information on each medical visit, 3-LB for laboratory tests ordered, dates, and results including surveillance data, 3-MH-EN for information about mental health encounters, 3-SR for surveillance data, and 3-FT for clinical data from fitness devices.
- Level 4 (*Sensitive Clinical Data*) contains sensitive information on a patient that is used by medical specialists in which data in this level can be categorized into: 4-G for data on genetics, 4-SA for substance abuse, 4-MH for mental health psychotherapy notes, 4-RH for reproductive health, and 4-DV for domestic violence.



Level 4 – Sensitive Clinical Data

4-G	4-SA	4-MH	4-RH	4-DV
Genetic Data	Substance Abuse	Mental Health	Reproductive Health	Domestic Violence

Level 3 – Detailed Clinical Data

3-RP	3-IM	3-EN	3-LB	3-MH-EN	3-FT	3-SR
Reports	Images	Enc Notes	Lab Tests/Results SR-24,25	Enc Notes	FT-7,9,12,25,26	SR-1-3,7-9

Level 2 – Summary Clinical Data

2-Rx	2-OTC	2-ALL	2-Dx	2-PL	2-MH-Dx	2-MH-PL
Rx Meds	OTC Meds	Allergies	Diagnoses & Problem List SR-4-6,22,23	Plan	Diagnoses & Problem List	Plan

Level 1 – Medical History Data

1-FT	1-DM	1-MHx	1-FHx	1-IM	1-MH-Hx
Day/MonthOB FT-8,13,14,18,21,22	Demographics SR-10,12,17,19-21	Medical Hx	Family Hx	Immunizations	History

Level 0 – Basic Information

0-FT	0-DM	0-C
FT-1-6,10,11,15-17, 19,20,23,24	YOB,City,State,Zip,Gender,Race SR-11,13-16,18	Overall health cond. (good, fair, serious, etc.)

Figure 2.5. A Multi-Level Healthcare Sensitivity Levels.

DAC can be defined as an access control mechanism that can restrict operations (e.g., read, write, execute) on objects (or services) based on the identity of subjects (users) and/or groups to which they belong, as shown in a Figure 2.6. The word "discretionary" in DAC indicates that a subject with a certain access permission is capable of passing that permission on to any other subject so that the delegated user may utilize the delegated permission. A subject is also called an *original user* which means that the user was assigned the role directly in the security definition process. A role that is assigned to an original user is referred to as an *original role*, in such an original role has *original role permissions.* An original user may also be assigned a clearance level if they are assigned mandatory access capabilities which is reference to as an *original clearance*. An original user may have delegation of authority which allows the original user to pass on the original role to a *delegated user* who acquires all of the capabilities of the original uses role. When the original role is passed to the delegated user, is it is referred to as the delegated role of that delegated user.

The delegated role in turn has delegated role permissions, and if the original user had an original clearance, it too could be passed to the delegated user as a delegated clearance. Two other important concepts for DAC are delegation authority and pass on delegation of authority. *Delegation authority* is the authority given to an original user that allows the original user to delegate his or her role to a delegated user. Pass-on delegation authority, PODA, is the authority given to an original user or delegated user that allows that user to delegate on a useful set of definitions and rules for delegation which underlie a proposed delegation language (Zhang, L., Ahn, J., & Chu, T., 2001).

In a cloud computing setting, DAC can offer the ability of a consumer of the cloud services to enable another consumer to utilize all or a sub-set of the consumer's authorized cloud services, that are assigned based a role or a clearance, through a delegation of authority. DAC, as shown in Figure 2.6, utilizes the concept of delegation to pass privileges among users to delegate both authority and permissions to another user. For example, in healthcare, a physician Charles that is leaving the office on the weekend could delegate his responsibilities (e.g., patients) to the on-call physician Lois who will be covering any queries from patients. Charles can delegate all of his permissions and also the ability to further delegate those permissions beyond the original scope. For example, if the on-call physician Lois has to attend to an emergency, she could then employ user-directed delegation to delegate the permissions passed to her by Charles to another user Thomas. Administrative-directed delegation has a security engineer to control delegation.

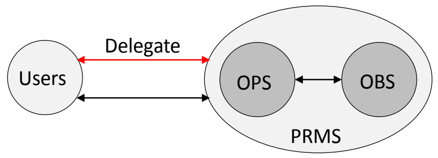


Figure 2.6. DAC Model.

Traditionally, RBAC, DAC, and MAC models define permissions over objects and operations of a system. However, the work in this dissertation is focused on a *Framework for Secure and*

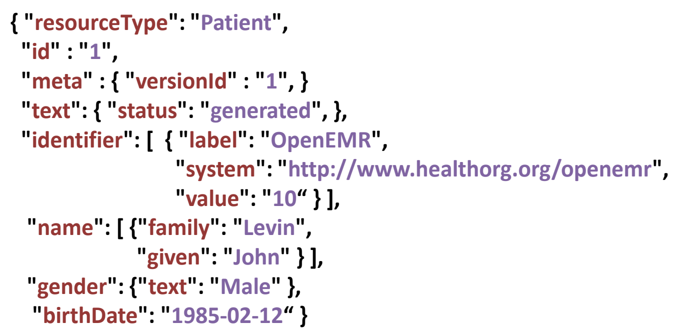
Interoperable Cloud Computing (FSICC) which involves the definition of Global Services and the need to define security policies that allow the ability to determine which user can access which service at which times. The work in this dissertation is very cloud-computing focused with an emphasis on services, and since we are interested in supporting Access Control in FSICC the RBAC, DAC, and MAC models need to be upgraded, extended, and modified so that permissions can be defined against cloud services. Such an extension to access control will provide us with the ability to: specify which role can access which cloud service at which time and under which situation thereby supporting RBAC; define a classification of each cloud service and a clearance for each user/client in order to control which Services can be accessed thereby supporting MAC; and, delegate a cloud service from one user to another user thereby supporting DAC. This allows the FSICC to authorize a mobile, web, and desktop applications, by roles/clearance, to access cloud services.

2.3 FHIR and HAPI FHIR

The Fast Health Interoperable Resources (FHIR) is a health integration standard developed by the Health Level Seven International (HL7) organization (Health Level 7, Fast Health Interoperable Resources, 2016). FHIR is primarily structured around the concept of FHIR resources (Health Level 7, Fast Health Interoperable Resources list, 2016) which are the data elements and associated RESTful APIs that can be leveraged for exchanging healthcare information, particularly between mobile applications and HIT systems.   FHIR Resources, the main building block in FHIR, can hold any type of information that FHIR deals with to be exchanged from one health information technology system to another via RESTful API services that utilize with an XML or JSON format. Resources are broadly classified into different categories: Clinical Findings; Patient Problems, Allergies, and Adverse Events; Patient History;

Suggested Physician Orders; and, Interdisciplinary Care Planning. To illustrate, sample FHIR resources from the 119 currently defined (and always increasing) are: the Practitioner resource to track medical providers (physicians, nurses, office staff, etc.); the Patient resource can track demographic data on patients; the RelatedPerson resource to track parents/guardians; the FamilyMemberHistory for basic information on a family medical history; the Condition resource to track the relevant medical conditions; the Observations resource to track symptoms, and other medical observations; and, the Encounter/EpisodeOfCare resources to track the different times that changes to patient data occur based on a visit (Encounter) or action at the visit (EpisodeofCare).

FHIR Resources can be utilized by HIT systems and applications for different purposes. For example, an mHealth application may use the Patient resource to store and exchange information about patients back and forth with different HIT systems. All FHIR resources have five main properties in common: a unique URL for identification purposes; common metadata; a human readable section; a number of predefined data elements; and, an extension element that enables a system to add new data elements. FHIR provides four main equivalent representation formats: the Unified Modeling Language (UML) format for a diagrammatic representation of the resource; an XML schema that is subset of the HL7 schema for the resource; a JSON representation to facilitate a programmatic exchange via a RESTful APP; and, a Turtle resource definition format (RDF) to assist the process of bridging between operational data exchange within formal knowledge processing systems. Figure 2.7 shows an example of a FHIR Patient resource represented in the JSON format. FHIR supports a number of REST API services to enable a system to retrieve and modify data in the Resources. The main five services are: *Create* to add a new instance of a resource; *Read* to retrieve an existing instance of a resource; *Update* to manipulate data in an existing instance of a resource; *Delete* to remove an existing instance of a resource; and, *Search* to retrieve all existing instances of a resource. The first four services are similar to CRUD, while the fifth service for search is intended to allow repositories to be accessed.



```
{ "resourceType": "Patient",
  "id" : "1",
  "meta" : { "versionId" : "1", }
  "text": { "status": "generated", },
  "identifier": [  { "label": "OpenEMR",
                     "system": "http://www.healthorg.org/openemr",
                     "value": "10“ } ],
   "name": [ {"family": "Levin",
                  "given": "John" } ],
   "gender": {"text": "Male" },
    "birthDate": "1985-02-12“ }
```

Figure 2.7. An Example of Patient Resource in JSON.

One popular reference implementation of the FHIR standard is the HL7 Application Programming Interface FHIR (HAPI-FHIR) (HAPI community, 2016) which is an open-source Java-based library of the FHIR standard. Following the FHIR standard, the HAPI-FHIR library provides a HAPI-FHIR server that can be used in front of a system. Figure 2.8 shows the HAPI-FHIR server architecture that consists of three components: HAPI ResfulServer, Resource Providers, and, the Back-end system. The HAPI ResfulServer is a Servlet that a developer utilizes to: create instances of user-defined resource providers; and, specify the Servlet path. A Resource Provider is a class that represents one FHIR resource (e.g., Patient) that has a number of empty annotated methods for CRUD verbs that a developer needs to implement. These empty annotated methods are utilized to to parse HTTP requests and convert the transferred data to/from FHIR format/Back-end System format, and to interact with the Back-end System. The Back-end System is a Health IT system (HIT) that handles the Resource Providers requests to retrieve or modify the actual Electronic Health Records (EHR).

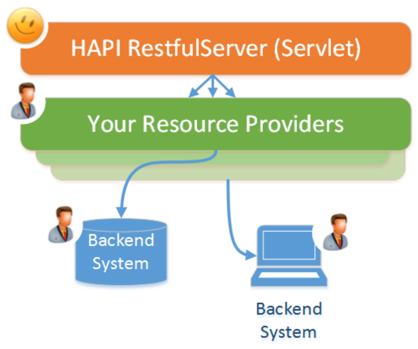


Figure 2.8. The HAPI-FHIR Server Architecture (HAPI community, 2016).

The HAPI-FHIR library also provides a general HAPI server interceptor (University Health Network, 2016) which is programmatic approach that allows a developer to examine each incoming HTTP request to add useful features to the HAPI ResfulServer such as authentication, authorization, auditing, logging, etc. The general HAPI interceptor, the InterceptorAdapter class, defines a number of methods that enable a developer to interact with the incoming HTTP requests at different points of the request lifetime. As Figure 2.9 shows, these methods are: incomingRequestPreProcessed that is invoked before performing any action to the request; incomingRequestPostProcessed that is invoked after determining the request type which classifying the request; incomingRequestPreHandled which is invoked before sending the request to the Resource provider; and, outgoingResponse which is invoked after the request is handled by the appropriate Resource provider. Each of these methods must returns either true, to continue processing the request, or false, to abort and reject the request. Moreover, a developer may extend the InterceptorAdapter class and implement the needed methods and register the extended class in the HAPI ResfulServer.

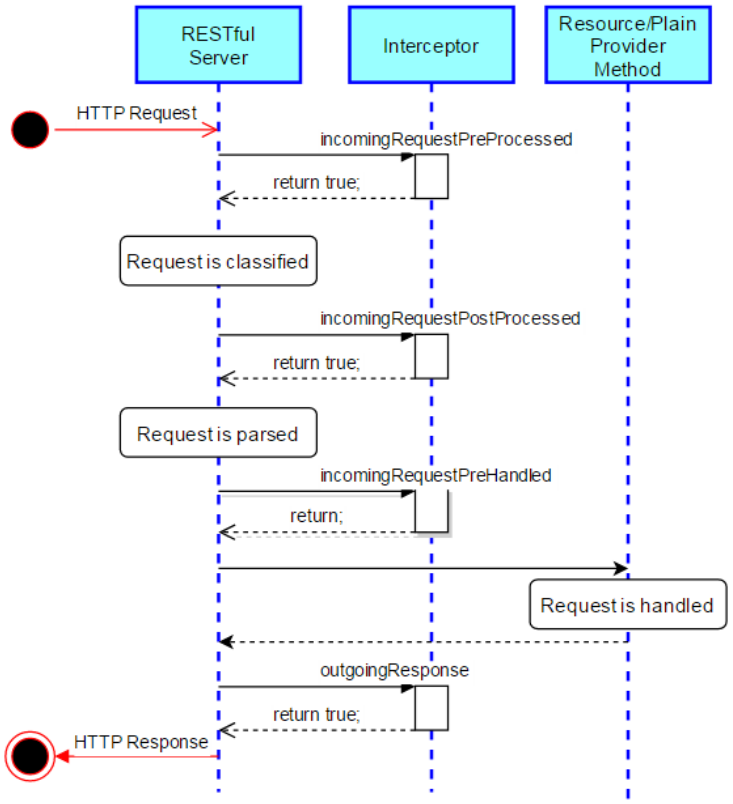
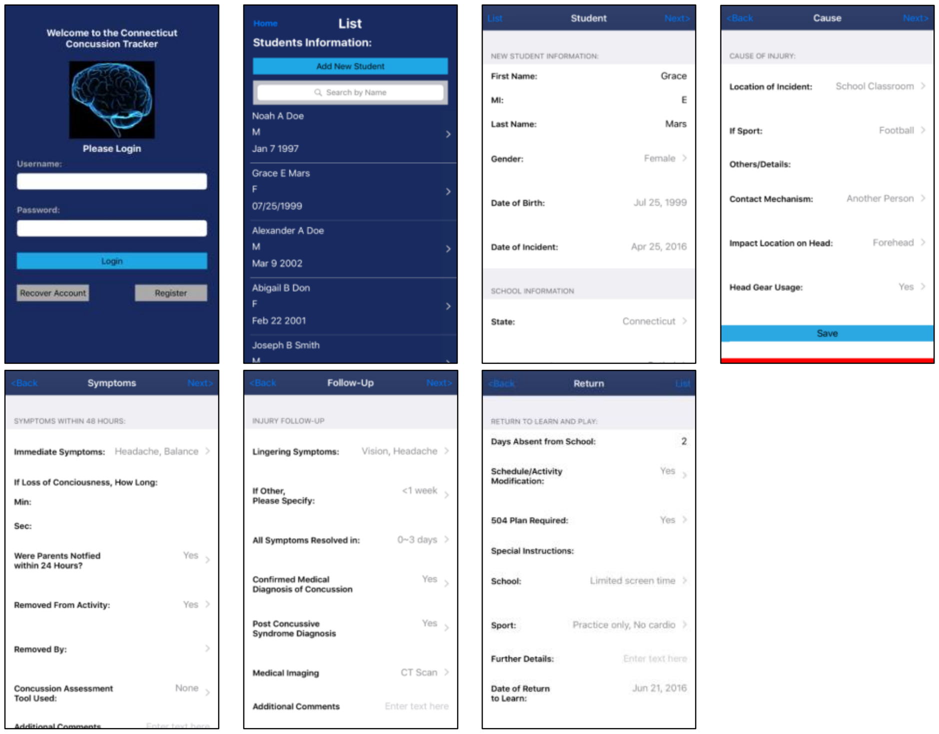


Figure 2.9. The Methods of HAPI Interceptor (University Health Network, 2016).

2.4 A Healthcare Scenario

To assist in explaining FSICC and all of its components and features in this dissertation, this section presents a healthcare scenario that has two mHealth client apps, the Connecticut Concussion Tracker (CT^2) and ShareMyHealth, and two HIT systems, the open electronic health record, OpenEMR (OpenEMR, 2016) and MyGoogle. To begin, CT^2 is a mHealth app, as shown in Figure 2.10 for Android and iOS devices, which is developed as a joint effort between the Departments of Physiology and Neurobiology, and Computer Science & Engineering at the University of Connecticut, in collaboration with faculty in the Schools of Nursing and Medicine. The CT^2 app allows the user (e.g., parent/guardian, coach, athletic trainer, school nurse) to report and manage the concussion incidents of students from kindergarten through high school. The CT^2 app uses an HIT system (i.e., OpenEMR) as a back-end system to maintain patients-related data.

The CT^2 contains seven tabs starting from the top left and continuing to the second row in Figure 2.10 ('Login', 'List', 'Student', 'Cause', 'Symptoms', 'Follow-up', and 'Return') where: the 'Login' tab allows the user to enter a concussion, to retrieve an open case, or to find a student by name; the 'List' tab which contains the list of students the user has permission to view and, for each student gives him/her the option to add a concussion or edit an existing one; the 'Student' tab allows the user to input the student's general information (e.g., name, birthdate, school, and the date of concussion); the 'Cause' tab allows the user to specify how and where the concussion occurred; the 'Symptoms' tab allows users to record the symptoms the student had within 48 hours and other pertinent data; the 'Follow-up' tab allows users to record the status of the student over time; and, the 'Return' tab allows users to specify when the student can return to school activities. Both versions (Android and iOS) of CT^2 utilize an API (services) to manage CT^2 data as given in Table 2.1. Services CT_1 and CT_2 are used to: add/modify a student concussion status, and, retrieve such status information, respectively. CT^2 utilizes CT_3 and CT_4 services to: retrieve all information about a student, and create/update new student information, respectively. Services CT_5 and CT_6 provide ways for the CT^2 to: create/update a student follow-up summary, and retrieve follow-up information, respectively. Finally, by calling services CT_7 and CT_8, CT^2 can: retrieve all information about a student concussion, and add/modify new student concussion information, respectively. CT^2 defines four roles (see Table 2.2): Coach, Nurse, Trainer, and Parent. All of the four roles can access: all GET services CT_2, CT_3, CT_6, and CT_7; and two PUT services CT_4, except Coach, and CT_8. Moreover, Trainer has an additional PUT service (CT_5) while Nurse has access to all PUT services.



Students Information:

Noah A Doe
M
Jan 7 1997

Grace E Mars
F
07/25/1999

Alexander A Doe
M
Mar 9 2002

Abigail B Don
F
Feb 22 2001

Joseph B Smith
M

NEW STUDENT INFORMATION:

First Name:	Grace
MI:	E
Last Name:	Mars
Gender:	Female
Date of Birth:	Jul 25, 1999
Date of Incident:	Apr 25, 2016

SCHOOL INFORMATION

State:	Connecticut

CAUSE OF INJURY:

Location of Incident:	School Classroom
If Sport:	Football
Others/Details:	
Contact Mechanism:	Another Person
Impact Location on Head:	Forehead
Head Gear Usage:	Yes

SYMPTOMS WITHIN 48 HOURS:

Immediate Symptoms:	Headache, Balance
If Loss of Conciousness, How Long:	
Min:	
Sec:	
Were Parents Notfied within 24 Hours?	Yes
Removed From Activity:	Yes
Removed By:	
Concussion Assessment Tool Used:	None
Additional Comments	Enter text here

INJURY FOLLOW-UP

Lingering Symptoms:	Vision, Headache
If Other, Please Specify:	<1 week
All Symptoms Resolved in:	0~3 days
Confirmed Medical Diagnosis of Concussion	Yes
Post Concussive Syndrome Diagnosis	Yes
Medical Imaging	CT Scan
Additional Comments	Enter text here

RETURN TO LEARN AND PLAY:

Days Absent from School:	2
Schedule/Activity Modification:	Yes
504 Plan Required:	Yes
Special Instructions:	
School:	Limited screen time
Sport:	Practice only, No cardio
Further Details:	Enter text here
Date of Return to Learn:	Jun 21, 2016

Figure 2.10. CT^2 Mobile Application - iOS Version Interceptor.

ShareMyHealth is an mHealth app as shown in Figure 2.11 developed by a team of undergraduate students at the University of Connecticut, for Android and iOS devices. ShareMyHealth provides patients with a means to manage and share their fitness data across multiple systems. Patients can gather data from multiple sources (e.g., MyGoogle, OpenEMR, etc.) that can then be made available to medical providers. The first row of Figure 2.11 contains four screens: *Welcome* for the initial opening of the app; *Sign In with Google* to authenticate the user credentials to access his/her fitness data, such as Google Fit API (via MyGoogle system); *Initial Access* for the user to define fitness data; and *Home* where the user sees their basic information and can access their "*Health*" and "*Settings*" pages. The second row of Figure 2.11 contains four screens: *Health View* for viewing information on steps, calories, weight, and height; and a *Settings* page to view setting such as name, gender, date of birth, etc.; and, a second setting page that to modify information. Pressing the "View Steps" button utilizes the user's Google API Token to pull their data from the Google Fit cloud (via MyGoogle system). When a user presses the "Sync Steps" button, the app packages the data into Google Fit via MyGoogle system which in turns sends the information into OpenEMR via OpenEMR API. Settings such as name, gender, etc., are updated by direct calls from ShareMyHealth to OpenEMR.

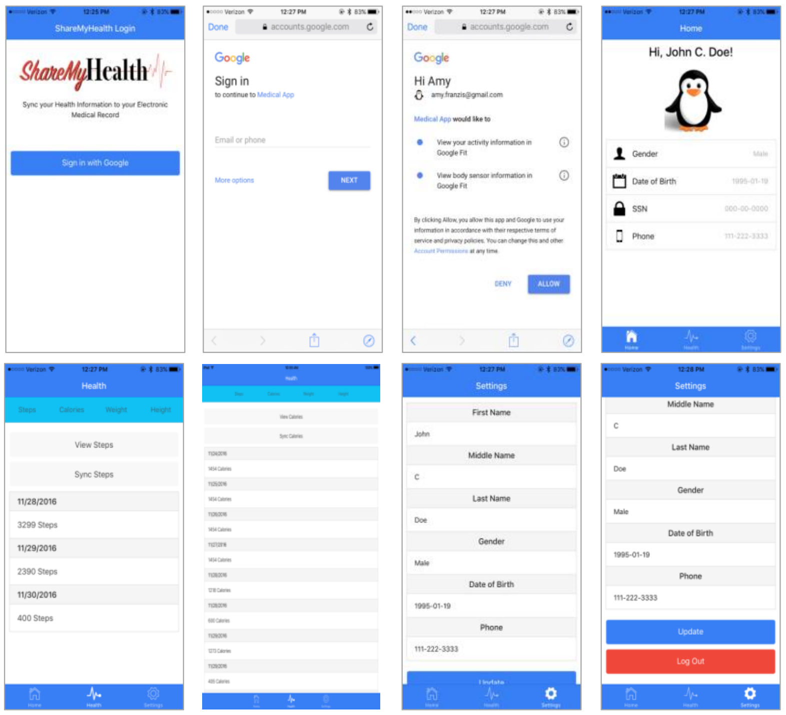


Figure 2.11. ShareMyHealth Mobile Application.

ShareMyHealth has access to a RESTful API (SMH_1 to SMH_5 services, see Table 2.3). Moreover, the ShareMyHealth API makes calls (via MyGoogle system) to: Google OAuth API that prompts the current user (patient) to allow ShareMyHealth access to the user's Google Fit data; Google REST Fit API to access measurement data (step, height, weight, and calorie); and OpenEMR API to read and update patient data. Specifically, ShareMyHealth utilizes services SMH_1 and SMH_2 to add/update and read a patient's measurements data, respectively. ShareMyHealth calls services SMH_3 and SMH_4 to add/update and read a patient's demographic information. In addition, service SMH_5 is used to grant ShareMyHealth app (using its Token) an access to the user (patient) fitness data. ShareMyHealth has two roles (see Table 2.4): Patient, that has access to all five services, and Physician, that has access to all services but SMH_1 and SMH_3.

Table 2.1. CT^2 Services.

Sid	Service Name
CT_1	PUT /CT2/concussion/status statusINFO
CT_2	GET /CT2/concussion/status statusID
CT_3	GET /CT2/student studentID
CT_4	PUT /CT2/student/add studentINFO
CT_5	PUT /CT2/followup/add followupINFO
CT_6	GET /CT2/followups followupID
CT_7	GET /CT2/concussion/student studentID
CT_8	PUT /CT2/concussions/add concussionsINFO

Table 2.2. CT^2 Roles.

Rid	Role	Service Name
CT_{R1}	Coach	CT_2, CT_3, $CT_6 – CT_8$
CT_{R2}	Nurse	$CT_1 – CT_8$
CT_{R3}	Parent	$CT_2 – CT_4$, $CT_6 – CT_8$
CT_{R4}	Trainer	$CT_2 – CT_8$

Table 2.3. ShareMyHealth Services.

Sid	Service Name
SMH_1	PUT /SMH/newMeasure/mID mINFO
SMH_2	GET /SMH/Measures/mID
SMH_3	PUT /SMH/newPatient/pID pINFO
SMH_4	GET /SMH/Patients/pID
SMH_5	PUT /SMH/Users/uID Token

Table 2.4. ShareMyHealth Roles.

Rid	Role	Service Name
SMH_{R1}	Patient	SMH_1 – SMH_5
SMH_{R2}	Physician	SMH_2, SMH_4, SMH_5

OpenEMR (OpenEMR, 2016) is an open source Electronic Health Record (EHR) system and a medical practice management app that can be utilized by any health/medical organization around the world. OpenEMR is a Meaningful Use Stage 2 certified (Himss.org., 2016) and is expected to be a Meaningful Use Stage 3 EHR certified soon (Himss.org., 2016). In addition to a web-based interface, OpenEMR has a RESTful API from which we have selected a subset of eight services as shown in Table 2.5. Services $OEMR_1$ and $OEMR_2$ enable an app (or a user via an app) to add/update a note about a patient, and, retrieve information about such a note, respectively. An app may utilize services $OEMR_3$ and $OEMR_4$ to: retrieve patient information, and, create/update new patient information, respectively. Services $OEMR_5$ and $OEMR_6$ provide ways for an app to: create/update a patient follow-up summary, and, retrieve information about such a follow-up, respectively.

Finally, by calling services $OEMR_7$ and $OEMR_8$, an app can: retrieve patient condition information, and, add/modify new patient condition information, respectively. Moreover, the OpenEMR system defines eight roles (see Table 2.6): Patient, Physician, Coach, Nurse, Trainer, Parent, CT^2, and MyGoogle in which the last two roles are designed for CT^2, and MyGoogle, respectively. The roles Nurse, Trainer, and Parent can access: all GET services $OEMR_2$, $OEMR_3$, $OEMR_6$, and $OEMR_7$; and two PUT services $OEMR_4$ and $OEMR_8$. Moreover, Trainer has an additional PUT service ($OEMR_5$) while Nurse and Physician roles have access to all PUT services. In addition, the Physician can only access $OEMR_2$ and $OEMR_4$ services, while the Patient role can access the services $OEMR_1$, $OEMR_2$, $OEMR_3$ and $OEMR_4$. The Coach role can access all services except $OEMR_1$, $OEMR_4$, and $OEMR_5$. Moreover, the MyGoogle role is restricted to access $OEMR_1$ and $OEMR_2$ services, while the CT^2 role can access all services.

Table 2.5. OpenEMR Services.

Sid	Service Name
$OEMR_1$	PUT /OpenEMR/updatepatientnotes noteINFO
$OEMR_2$	GET /OpenEMR/getnotes noteID
$OEMR_3$	GET /OpenEMR/getallpatients patientID
$OEMR_4$	PUT /OpenEMR/addpatient patientINFO
$OEMR_5$	PUT /OpenEMR/addvisit visitINFO
$OEMR_6$	GET /OpenEMR/getvisits visitID
$OEMR_7$	GET /OpenEMR/getlist conditionID
$OEMR_8$	PUT /OpenEMR/addlist conditionINFO

Table 2.6. OpenEMR Roles.

Rid	Role	Service Name
$OEMR_{R1}$	Physician	$OEMR_2$, $OEMR_4$
$OEMR_{R2}$	Patient	$OEMR_1$ – $OEMR_4$
$OEMR_{R3}$	Coach	$OEMR_2$, $OEMR_3$, $OEMR_6$ – $OEMR_8$
$OEMR_{R4}$	Nurse	$OEMR_1$ – $OEMR_8$
$OEMR_{R5}$	Parent	$OEMR_2$ – $OEMR_4$, $OEMR_6$ – $OEMR_8$
$OEMR_{R6}$	Trainer	$OEMR_2$ – $OEMR_8$
$OEMR_{R7}$	CT^2	$OEMR_1$ – $OEMR_8$
$OEMR_{R8}$	MyGoogle	$OEMR_1$, $OEMR_2$

Table 2.7. MyGoogle Services.

Sid	**Service Name**
MG_1	PUT /MyGoogle/fitness/dataSources/dsID dsINFO
MG_2	GET /MyGoogle/fitness/dataSources/dsID
MG_3	PUT /MyGoogle/newPatient/pID pINFO
MG_4	GET /MyGoogle/Patients/pID
MG_5	PUT /MyGoogle/Users/uID Token

Table 2.8. MyGoogle Roles.

Rid	**Role**	**Service Name**
MG_{R1}	SMH	MG_1 – MG_5

Finally, MyGoogle is a HIT that we developed to act as a middle layer between the ShareMyHealth app and the two HIT systems: OpenEMR and Google Fit (Google, 2017), which is an open HIT system for sharing and managing patient fitness data (e.g., step, height, weight, and calorie) that is maintained in the Google Fitness Store (in the cloud) that enables multiple apps to access such data via Google Fit APIs. Google Fit consists of two APIs: Fit REST API to add/update patient fitness data; and, Google OAuth API to authenticate apps to access users' fitness data. MyGoogle HIT has an API (Table 2.7) to access OpenEMR API and Google Fit APIs and acts on behalf of apps. The MyGoogle API consists of five services. MG_1 and MG_2 enable an app to add/modify and read users' fitness data from/into Google Fitness Store via Fit REST API, respectively. MG_3 and MG_4 add/update and read a patient's demographic information from/into OpenEMR via OpenEMR API, respectively. MG_5 utilizes Google OAuth API to authenticate an app (using its Token) to access a user' fitness data. In addition, MyGoogle defines one role, i.e., SMH, (see Table 2.8) which is designed to be assigned to ShareMyHealth app. The SMH role can access all MyGoogle API services.

Chapter 3
Security Requirements and Cloud Computing Capabilities for FSICC

As we discussed earlier in Section 1.2, the healthcare domain is an emergent application for cloud computing, in which the Meaningful Use Stage 3 guidelines recommend health information technology (HIT) systems to provide cloud services that enable health-related data owners to access, modify, and exchange data. This requires that mobile and desktop applications for patients and medical providers obtain healthcare data from multiple HITs, which may be operating with different paradigms (e.g., cloud services, programming services, web services), use different cloud service providers, and employ different security/access control techniques. To address these issues, this chapter presents the four *Security Requirements* and the three *Cloud Computing Capabilities* that underlie and support FSICC. These four security requirements and three cloud computing capabilities for FSICC simplifies and enables client access via global resources using standardized system APIs. A security requirement represents what we consider to be the key security features for supporting security in FSICC. The four security requirements are: *Numerous and Varied Access Control Models, Control Access to Cloud Services Using RBAC, Support Delegation of Cloud Services Using DAC,* and *Control Access to Cloud Services Using MAC*. A cloud computing capability represents what we consider to be the critical characteristics for supporting cloud computing in FSICC. The three cloud computing capabilities of FSICC are: *Local Service Registration and Mapping to Global Services, Local Security Policies Registration to Yield Global Security Policy,* and *Global Registration, Authentication, Authorization, and Service Discovery for Consumers*. To understand the role of security requirements and cloud computing capabilities for

FSICC, we reexamine Figures 1.1 to 1.3 which also provides a more complete discussion of FSICC and its functionality.

To begin, recall that Figure 1.1 from Chapter 1 presented the architecture of FSICC. The top of Figure 1.1, had client Applications (Web, Mobile, and Desktop) which corresponds to the Clients box in the *Involved Parties* component that was at the top of Figure 1.2 from Chapter 1. These client applications are interested in utilizing a subset of the available global services and global security policies of FSICC. FSICC was shown in the middle of Figure 1.1 and had eight boxes that interact with one another. The Clients Registry box, at the top of FSICC, is for clients to register themselves into the FSICC. The next lower box is the Global Authentication box that is responsible for verifying clients' identities before allowing them to be authorized to access global services of FSICC. The next box down is the RBAC/MAC/DAC interceptors box that is in charge of allowing/denying clients requests to access global services of FSICC based on roles/clearances. The Clients Registry, the Global Authentication, and the RBAC/MAC/DAC interceptors boxes refer to the Global Policy Enforcement component that was shown in Figure 1.2. The Global Services box, in the middle of FSICC, is the set of global services that mirror services of registered systems and are available to interested clients to utilize.

The next lower box is the Global Security Policy box which has the global security policy that defines what set of global services each client can access based on RBAC, MAC, and DAC models. The two next boxes are: the Security Policy Mapping box that is responsible for combining a set of security policies from different systems and generating the global security policy; and, the Services Mapping box which combines a set of services from systems into one set of global services. The System Registry, at the bottom of FSICC, enables systems to provide their services and security policies. The System Registry, the Services Mapping, the Global Security Policy, and the Global

Services boxes refer to the Generation of Global Policy and Services component that was shown in Figure 1.2. The Security Policy Mapping box refers to Security Policy Mapping component that was shown in Figure 1.2. The bottom of Figure 1.1 had Web, Programming, and Cloud Applications, which corresponds to the Systems box in the *Involved Parties* component at the top of Figure 1.2, that are willing to provide their services and security policies into the FSICC. Security requirements have influence on security policy and mapping boxes as well as the RBAC, MAC, and DAC models and interceptors. Cloud computing capabilities have influence on the services, service mapping, and system registry boxes.

In addition, FSICC that was given in Figure 1.2 is an infrastructure for cloud computing that provides a global policy authorization and enforcement mechanism and is capable of supporting different access control models such as RBAC, DAC, and MAC in the *Access Control Models* component in the middle of the figure. This is the main component where security requirements have an impact. FSICC organizes and globally manages the cloud services, APIs, and web services from multiple service suppliers (systems) via the Systems box in the *Involved Parties* component at the top of Figure 1.1 into a set of global services in the Global Services box in the *Generation of Global Policy and Services* component in Figure 1.2. These are the main components where cloud computing capabilities have an impact. This allows the mobile, web, and desktop applications clients in the Clients box in the *Involved Parties* component at the top of Figure 1.2 to be used to easily discover and utilize them in order to interact with multiple constituent systems with a common interface. Representative technologies to support the implementation of FSICC include: the HAPI FHIR reference model (Health Level 7, Fast Health Interoperable Resources, 2016) from Section 2.3; the DIRECT project (The Direct Project, 2016) that allows for the sharing of information with best practices that have trust and privacy considerations; and, the HEART WG project (OpenID, 2016) that provides privacy and security specifications for authorization and access to health-related RESTful APIs.

Furthermore, Figure 1.3 from Chapter 1 presented a high-level view of the FSICC's main aspects. Figure 1.3 has five horizontal boxes for each main aspect of FSICC and vertical boxes that span across the horizontal boxes. The five horizontal boxes are: *Architectural Blueprints* box that contain the different options for architectural option for connecting clients and systems with FSICC; *Unified Cloud Computing Access Control Model* box with boxes for Schema Definitions, Enterprise Definitions, Policy Definitions, FSICC Definitions, and Intercepting Definitions; *Access Control Models* box for the ability to control services via RBAC, MAC, and DAC; *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* box for generating the security policy from multiple systems to make global APIs available to clients; and, *Global Security Policy and Global API Utilization and Security Enforcement* box that utilizes security interceptors to allow/deny clients from access global services of FSICC. Moreover, the security requirements for FSICC, which will be described in this chapter, are represented in Figure 1.3 by the upper right vertical box SECURITY REQUIREMENTS that spans two horizontal boxes: Unified Cloud Computing Access Control Model and Access Control Models. The three cloud computing capabilities, which will be described in this chapter, are represented in Figure 1.3 by the lower right vertical box CLOUD COMPUTING CAPABILITIES that spans two horizontal boxes: Global Security Policy and Global API Generation, and Global Security Policy and Global API Utilization and Security Enforcement.

The presentation in the remainder of this chapter is in four parts. Section 3.1 defines and explains the four security requirements for FSICC: *Numerous and Varied Access Control Models*, *Control Access to Cloud Services Using RBAC*, *Support Delegation of Cloud Services Using DAC*, and

Control Access to Cloud Services Using MAC. Section 3.2 details the three cloud computing capabilities with associated components of the FSICC: *Local Service Registration and Mapping to Global Services*; *Local Security Policies Registration to Yield Global Security Policy*; and, *Global Registration, Authentication, Authorization, and Service Discover for Consumers*. Section 3.3 discusses related research in cloud computing as compared with FSICC. Note that the work in this chapter has been published in (Baihan, M. & Demurjian, S., 2017).

3.1 FSICC Security Requirements

This section discusses four security requirements for FSICC, exploring the impact of the SECURITY REQUIREMENTS vertical box in Figure 1.3. A security requirement represents what we consider to be the key security features for supporting security in FSICC. To facilitate this discussion, there must be a shift in focus on the concept of RBAC, DAC, and MAC permissions on objects and operations to one that assigns permissions to individual cloud services. For RBAC, this corresponds to the global services being assigned to different users by role. For MAC, global services are assigned classifications (TS, S, C, U) with a user having a clearance and performing domination checks on classification vs. clearance for every service invocation. For DAC, this corresponds to the ability to delegate services from user to user by role and potentially limited by classification/clearance checks if MAC has defined. The remainder of this section presents and discusses the four security requirements: *Numerous and Varied Access Control Models, Control Access to Cloud Services Using RBAC, Support Delegation of Cloud Services Using DAC,* and *Control Access to Cloud Services Using MAC.*

Security Requirement 1 - Numerous and Varied Access Control Models. The first security requirement acknowledges that the constituent systems (i.e., service suppliers) that wish to publish access to cloud, API, or web services may have access control and security protocols that are varied. Thus, FSICC must be capable of supporting a wide range of access control models such as Role-based Access Control (RBAC) (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), Mandatory Access Control (MAC) (Bell & La Padula, 1976), Discretionary Access Control (DAC) (Dittrich, Härtig, & Pfefferle, 1988), Attribute-based Access Control (ABAC) (Yuan, E. & Tong, J. , 2005), Usage Access Control (UCON) (Sandhu, R. & Park, J. , 2003), etc. This leads to *Security Requirement 1 - Numerous and Varied Access Control Models* and is represented in the Access Control Models horizontal box in Figure 1.3.

From the healthcare scenario of Section 2.4, we know that each HIT (MyGoogle and OpenEMR) supports RBAC as illustrated in Tables 2.6 and 2.8. These systems also support DAC to allow permissions (services) to be delegated from a physician Charles (user) to the on-call physician Lois (user) after hours and weekends. FSICC, as was shown in Figure 1.1, enables these systems to register their security policies (as shown for MyGoogle and OpenEMR in Tables 2.6 and 2.8) into FSICC via the System Registry box in Figure 1.1. This is the Registration and Services Mapping box of the Generation of Global Policy and Services component in Figure 1.2, in which security policies are combined via the Security Policy Mapping box in Figure 1.1, Security Policy Mapping component in Figure 1.2, to generate the global security policy via the Global Security Policy box in Figure 1.1, Global Policy box of the Generation of Global Policy and Services component in Figure 1.2. Specifically, the global security policy should define, for each role, the global services assigned by role. This was accomplished as discussed by mapping permissions to call systems' services (cloud, web, and API) from Table 2.5 and 2.7 into permissions to call global cloud services.

Security Requirement 2 - Control Access to Cloud Services Using RBAC. The second security requirement involves the large number of services that are published in the cloud by multiple systems which are to utilized by numerous consumers, meaning that the usage of such services is expected to be high, which needs to be controlled so that only certain consumers at different times can have access to specific services. Thus, when all of the system services are collected into a set of global cloud services, the resulting set can be controlled based on roles, as shown in the RBAC box of the Access Control Models horizontal box in Figure 1.3, in which each role can be assigned on a consumer-by-consumer basis. This leads to *Security Requirement 2-Control Access to Cloud Services Using RBAC* where global services can be assigned by role, see the Role-based Access Control box of the Access Control Models component in Figure 1.2.

To illustrate, the global security policy may define nine global roles: GPhysician (global physician), GPatient (global patient), GCoach (global coach), GNurse (global nurse), GParent (global parent), and GTrainer (global trainer) would be assigned to individuals that are utilizing applications, while GCT^2 (global CT^2), GMyGoogle (global MyGoogle), and GSMH (global SMH) represent the roles of the systems and applications that may need to utilize services. The GPhysician role is used by a doctor to access his/her patients' electric information and to provide better healthcare services for his/her patients. The GPatient role is used by a patient to access his/her digital information and to request different healthcare services. The GCoach role is used by a coach to report a health incident (e.g., concussion) at an athletic event with very limited information on the patient. The GNurse role is used by a nurse to manage a patient's health incident from its occurrence to its resolution. The GParent role is used by a parent to both report a health incident on his/her child while attending the athletic event or to track the current status of his/her children that have health incidents. The GTrainer role is used by a trainer to do a limited preliminary assessment if a health incident occurs at a training event. Moreover, The GCT^2 application role is used by a CT^2 application to gather information related to patients' concussion incidents. The GMyGoogle system role is used by the MyGoogle system to gather medical and fitness information of patients. Finally, The GSMH application role is used by the ShareMyHealth application to retrieve/add fitness information of patients. In addition, there is also a need to work on the ability to constrain the invocation of a service based on values.

Security Requirement 3 - Support Delegation of Cloud Services Using DAC. Users of applications, which consume services, may need: to collaborate with other users to accomplish a better job; and/or to have other users to perform some of their tasks on behalf of them in case of emergency. This leads to *Security Requirement 3 - Support Delegation of Cloud Services Using DAC* where FSICC supports the ability to delegate cloud services from one user to another, see the Discretionary Access Control box of the Access Control Models component in Figure 1.2 and the DAC box of the Access Control Models horizontal box in Figure 1.3. For example, consider a user Charles with a GPhysician role is leaving the office for the day or the weekend and is interested in delegating his/her authority to access the services for his patient to the on-call physician Lois who will be covering night and weekend inquiries from patients. In this case, Lois will then be utilizing a mobile application to access patient data that is available via OpenEMR services (see Section 2.4). Charles could delegate all or some of his OpenEMR services to Lois. For example, Charles may delegate global services that involve patient data. If the delegation for Charles to Lois is during the week (Monday to Thursday) it could go into effect at 5pm (close of business) and be revoked at 9am (start of business). For weekend calls the delegation would go from Friday at 5pm to Monday at 1am.

Security Requirement 4 - Control Access to Cloud Services Using MAC. Many services may access very sensitive information such as patient data that needs to be more strongly controlled than other parts of the patient data. For example, mental health data is limited to a psychiatrist or psychologist and not available to a family medical provider. This leads to *Security Requirement 4 - Control Access to Cloud Services Using MAC* as shown in the Mandatory access control (MAC) box of the Access Control Models horizontal box in Figure 1.3. This supports the definitions and usage of classifications (for services) and clearances (for users) which are instrumental in controlling access to a service and the data passed by a service. Thus, to further restrict access to cloud services, FSICC supports MAC in addition to RBAC and DAC, has shown in the Mandatory Access Control box of the Access Control Models component in Figure 1.2. That is, all of the global services may be labeled with classification levels, and all users may be labeled with clearance levels. Specifically, each of the global cloud services in FSICC can all be labeled with a classification level (i.e., TS, S, C, or U).

3.2 FSICC Cloud Computing Capabilities

The set of security requirements in Section 3.1 leads to the definitions of a set of three FSICC cloud computing capabilities, as shown in the CLOUD COMPUTING CAPABILITIES vertical box in Figure 1.3, that bring together all of the concept and focus on the process and components of FSICC. Cloud Computing Capability 1, *Local Service Registration and Mapping to Global Services*, is for systems to register local services which are then mapped to a global set. Cloud Computing Capability 2, *Local Security Policies Registration to Yield Global Security Policy,* is for systems to register their local security policy which is utilized to generate a global security policy. Cloud Computing Capability 3, *Global Registration, Authentication, Authorization, and Service Discover for Consumers*, is to support the process of a consumer's (mobile, web, or desktop app) registration to discover and be authenticated and then authorized to utilize services. The remainder of this section discusses these three cloud computing capabilities using the healthcare scenario of Section 2.4.

Cloud Computing Capability 1 - Local Service Registration and Mapping to Global Services. This cloud computing capability of FSICC enables a service supplier (system) to register its cloud, programming, and/or web services as indicated by the arrows at the bottom of Figure 1.1, as shown in the Security Policies and Services Registration and Global Services Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3. Referring to column 2 in Tables 2.5 and 2.7, OpenEMR registers the cloud services $OEMR_1$ to $OEMR_8$ and MyGoogle registers its services MG_1 to MG_5. For eexampl, OpenEMR registers $OEMR_1$ with name OpenEMR, URI (/OpenEMR/updatepatientnotes), PUT CRUD method, and input variable noteINFO; MyGoogle registers MG_1 with name MyGoogle, URI (/MyGoogle/fitness/datasource/dsID), PUT CRUD method, and input variable dsINFO.

The end result of the registration is that all of the cloud services, API calls, and web services of systems are transitioned to a set of equivalent global services. For each registered cloud, API, or web service, a global cloud service is created with appropriate components that mirror the signature of the system service named as a new global cloud service, which was represented in Figure 1.1 by the Services Mapping and Global Services boxes that car spawns to the Generation of Global Policy and Services component in Figure 1.2. For example, the service $OEMR_1$ can be mapped to a new global service in FSICC. Note that the existence of $OEMR_1$ is no longer visible to the mobile, cloud or web application; this is true for all of the converted services/API calls. The end result is a unified set of global cloud services to be presented to the mobile, web, or desktop applications as supported by the *Services Mapping* box of FSICC as was shown in Figure 1.1, which maintains a mapping list of system to global cloud services.

Cloud Computing Capability 2 - Local Security Policies Registration to Yield Global Security Policy. This cloud computing capability allows HIT systems to register their local security policies (roles and permissions to APIs) that can then be combined to yield a global security policy, as shown in the Security Policies and Services Registration and Global Security Policy Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3. The local policy registration process of this cloud computing capability enables a service supplier (system) to specify the security requirements or policy to access its services (cloud, web, and API) as indicated by the arrows at the bottom of Figure 1.1. After the systems register the local services, as given in Tables 2.5 and 2.7, they can then register the local security policies that are available in their systems as given in Tables 2.6 and 2.8. This includes for a particular HIT system: the defined roles, the permissions that are defined on each local service, the permissions authorized to each role, the classifications for each service, and the allowable delegations.

As local security policies are registered over time, a security administrator or policy engineer is responsible to design and evolve an appropriate global security policy that would encompass all of the local security requirements (from all different access control models) and provides a unified, global view for the applications. This is supported in FSICC as shown in Figure 1.1 by the Security Policy Mapping and Global Security Policy boxes, which correspond to the Security Policy Mapping component and the Generation of Global Policy and Services component, respectively, in Figure 1.2. The security engineer defines a global security policy over global cloud services based on defined local roles and associated permissions in the bottom of Figure 1.1 to define a set of global roles and their permissions. This is accomplished by: defining global roles, assigning global permissions to global cloud services, authorizing global roles to global permissions, and defining constraints over these assignments. In the healthcare scenario, the global roles can be defined and evolved over time by considering and unifying all of the particular roles of the originally registered HIT systems (such as MyGoogle and OpenEMR) and new systems that are added over time.

Specifically, for the healthcare scenario from Section 2.4, the RBAC permissions as given by the roles and API services in Tables 2.6 and 2.8 are mapped to a global set of roles and the global API services, respectively. For example, for the patient role in Table 2.6, the permissions to the OpenEMR services $OEMR_1$-$OEMR_5$ are mapped into the permissions to equivalent global cloud services that are the authorized global services to the global patient role GPatient. Similarly, for the SMH role in Table 2.8, the permissions to the MyGoogle services MG_1-MG_5 are mapped into the permissions to equivalent global cloud services that are the authorized global services to the global SMH role GSMH. Essentially, at a high-level, the authorized permissions of the Patient role of OpenEMR and the SMH role of MyGoogle are mapped into new global roles GPatient (global patient) and GSMH (global SMH), respectively. The security engineer needs to make similar mapping and define new global roles (GPhysician, GCoach, GNurse, GParent, and GTrainer) for the other local roles and the other systems that are also functioning as roles (GCT^2 and GMyGoogle). These processes are supported by the *Security Policy Mapping* box of FSICC as was hownn in Figure 1.1. A mapping list of local to global security policies is maintained by the *Global Security Policy* box of FSICC.

Cloud Computing Capability 3 - Global Registration, Authentication, Authorization, and Service Discover for Consumers. This cloud computing capability enables services consumers (mobile, web, or desktop app) to register themselves, which then allows application users to discover and be authenticated and then authorized to utilize services by role, as shown in the GSP and GAPI Utilization and Security Enforcement horizontal box in Figure 1.3. The intent is to provide access for application users to the global roles and the authorized global services. The global registration activity of this cloud computing capability is supported by the Client Registry box of FSICC as shown in Figure 1.1, which corresponds to the Registration and Services Mapping box of the Generation of Global Policy and Services component in Figure 1.2. The global authentication activity of this cloud computing capability is supported by the Global Authentication box of FSICC as was shown in Figure 1.1, which corresponds to the Global Authentication box of the Global Policy Enforcement component in Figure 1.2. The global authorization activity of this cloud computing capability is supported by the RBAC/MAC/DAC Interceptors box of FSICC as shown in Figure 1.1, which corresponds to the RBAC Interceptor, MAC Interceptor, and DAC Interceptor boxes of the Global Policy Enforcement component in Figure 1.2. The service discovery activity of this cloud computing capability is supported by the Global Services box of FSICC as was shown in Figure 1.1, which corresponds to the Global Services box of the Generation of Global Policy and Services component in Figure 1.2. Note that we distinguish between consumers that are designing and deploying new mobile, web or desktop applications vs. ones that are retrofitting an existing mobile, web, or desktop application that may have its own access control (RBAC, DAC, and/or MAC) and cloud/web/programming APIs.

For consumers designing and deploying a new application, we can extend the healthcare scenario of Section 2.4 with a mobile application for the patient and a desktop EHR application for the physician, where all of these applications have been developed using the global cloud services. To accomplish this development, each application must register with FSICC in order to gain the relevant global roles to be authorized to each application user. A user of the mobile application for the patient would be authorized to the GPatient global role and limited to the services authorized to GPatient. The physician using the EHR desktop application would be authorized to the GPhysician global role and limited to the services authorized to GPhysician. For the HIT systems, MyGoogle would have the GMyGoogle global role with its authorized global services. Note that OpenEMR services are not called by the consumers' applications instead MyGoogle services utilize OpenEMR services to store/retrieve patient demographic data (see the healthcare scenario of Section 2.4).

Cloud Computing Capability 3 is also utilized to allow a consumer of a new application to discover global cloud services for the healthcare scenario. This is accomplished by utilizing a service discovery request to the Global Services box of FSICC as seen in Figure 1.1. The discovery request returns a list of all available services by GSid, name, and description. Upon successful discovery, the service consumer (application) can then submit a request to utilize one or more discovered services. The application can send a list of the global services requested and its identification information to the Global Authentication box of FSICC which authenticates the application. Then, the RBAC/MAC/DAC Interceptors box of FSICC authorizes the appropriate global user role associated with the requested services, and then forwards the service access request along with the application's global role to the Global Security Policy box of FSICC. The Global Security Policy box then authorizes the requested global services only if the application's global role is authorized to access such a service. As a result of calling a global cloud service, the mapped local service or API call of a local HIT system is invoked. Note that the HIT system allows the call only as long as the application's global role is mapped to an equivalent local role that is authorized to access such a system service.

For example, suppose that the mobile application for the patient sends a service discovery request to the Global Services box of FSICC to find a service to return the demographic information for a patient. The discovery sends back the id of the required global service, name (e.g., GET /FSICC/Patient/id), and a description such as calls the $OEMR_3$ of the OpenEMR system. Based on this, the patient mobile application can send a global service access request along with the application identification information to the Global Authentication box. This box can then authenticate the application and forward the request to the RBAC/MAC/DAC Interceptors box that can authorize the application to utilize the GPatient role and forward the global service access request along with the GPatient role to the Global Security Policy box. The Global Security Policy box enables the patient mobile application to access the requested global service, since the GPatient global role can access that global service. Then, the Global Security Policy box retrieves the patient role, of OpenEMR system, which is mapped to the GPatient global role. As a result of calling the authorized global service, an access request to the mapped system service $OEMR_3$ along with the patient local role is sent to the OpenEMR system. The OpenEMR system allows the patient mobile application to access the service $OEMR_3$ since the patient local role is authorized to access $OEMR_3$.

For consumers retrofitting an existing mobile, web, or desktop application, there is an extra layer (i.e., the integration layer) of functionality that must be considered. Recall the CT^2 and ShareMyHealth mHealth (SMH) applications from the healthcare example in Section 2.4. Each of these applications has its own API to access its database. Suppose that the developer of SMH needs to expand SMH capabilities in order to store/retrieve patients' fitness and demographic information from MyGoogle and OpenEMR (via MyGoogle) systems, respectively. Suppose also that the SMH has already defined roles for patient and physician that impact the way that the app works for different users in terms of the fitness and demographic data collected can be entered, viewed, and/or edited. In order to make use of the global roles and services of FSICC, the existing SMH app needs to be able to map its own app roles to appropriate global roles, and, programmatically link its API so that it will be able to call the appropriate global services of MyGoogle. In order to support this programmatic link, the SMH app may also operate in the role of a provider per cloud computing capability 1 to define and register a new set of services for the SMH app that link its current API services to the global services. This requires a similar process as described above to map from the local SMH roles to the global roles.

3.3 Related Work in Cloud Computing

In this section, we present a number of related efforts in cloud computing, from both academic and industrial communities, that are solving similar problems to FSICC, comparing and contrasting their work to FSICC. The first effort (Buyya, Ranjan, & Calheiros, 2010) proposed a framework named InterCloud for federating cloud services to manage the services of multiple cloud service providers in which the framework allocates cloud services to the cloud consumers based on quality of service (QoS) needs of the consumer. To accomplish this, the Cloud Broker, which is a component of their framework, determines the most suitable cloud service provider based on the cloud services preferences through the Cloud Exchange, which is another component of InterCloud. Our use of global services in FSICC provides a one-stop shopping location for consumers which is similar to InterCloud since both frameworks remove the consumers' needs to search through many cloud providers. Further, our work utilizes the global roles (and their assigned services by RBAC, DAC, and MAC) in order to control which services each consumer is allowed to perform which is different from their work that does not provide any security features to control access to the cloud services.

A second effort (Nair, Porwal, Dimitrakos, Ferrer, & Tordsson, 2010) introduced a framework design for cloud services that supports features including: data confidentiality and integrity for cloud service consumers; enable cloud service providers to publish cloud services that are unified to the cloud service consumers; and, manage the published cloud services. Their framework allows the cloud service providers to receive access requests from the framework without the knowledge of the actual service consumer requesting such an access, and enforces access control over the published cloud services. Their approach contrasts with our approach, particularly for the healthcare domain, where the knowing of the identity of the consumer by the provider is vital to restrict access to protected health information (PHI). Moreover, the main common features between our framework and their framework are: unifying multiple services from different providers to the consumers side, and controlling the unified services using access control means.

A third effort in (Tordsson, Montero, Moreno-Vozmediano, & Llor, 2012) proposed a cloud broker that enables a heterogeneous set of cloud service providers, in which each provider may require a different infrastructure to operate, to integrate with the cloud broker. Such a cloud broker is capable of: optimizing placement of virtual infrastructures across variant clouds; and, hiding the processes of deploying and managing the cloud services of the cloud providers. The proposed broker utilizes a scheduling algorithm that manages the processes of cloud services deployment. Our work on FSICC is similar to their effort, since our global roles and services effectively hide the location of the local services providers which is similar to the cloud broker approach in hiding the processes of deploying and managing the cloud services. Our work utilizes RBAC, DAC, and MAC access control models to control which services each consumer can access which is different from their work that does not provide any security features to control access to cloud services.

The fourth effort (Vordel, 2016), the Vordel Cloud Service Broker, supports integrating local on-site applications with offsite cloud services via the Multi-Domain Registry, one main component of Vordel. Vordel also provides monitoring, and management services. Vordel is located between the cloud service providers and the cloud consumers referred to as organizations. An organization may utilize Vordel broker to introduce a level of trust within the cloud application of such an organization. The work on Vordel is similar to our efforts in FSICC since they map the services of cloud providers to organizations' applications via a Multi-Domain Registry and we map local roles/services to global roles/services that offer RBAC, DAC, and MAC security. The main difference between our and theirs is that they do not clearly explain the way the integrated services in the Multi-Domain Registry are controlled in term of what cloud services each consumer is restricted to access.

A fifth effort (Jamcracker, 2016), the JamCracker platform, unifies the processes of cloud management and governance. Specifically, JamCracker provides a number of services including: risk and policy compliance management; operation management; and, create, deliver, and multi-cloud services management. JamCracker also allows cloud service providers to unify delivery and management of private and public cloud application/services and distribute them to cloud service consumers. JamCracker enables cloud service providers to publish their services and virtualized applications along with security policies (only RBAC is supported) to control their services and applications via the JamCracker Connect, one main component of the JamCracker platform. The main similarities between our work on FSICCC and the JamCracker are both frameworks that unify multiple services from different providers to the consumers side, and control the unified services using access control means. However, while our framework supports controlling access to the unified services using RBAC, MAC, and DAC, JamCracker only supports RBAC as an access control mechanism.

A final effort (Amato, Di Martino, & Venticinque, 2012) proposed a cloud broker that acts as a component that: manages the use, performance, and delivery of cloud services; and, mediates the process of enabling cloud service consumers to access cloud services of service providers. This is achieved by the proposed cloud broker utilizing an agent that dynamically identifies a set of cloud services from various providers based on the service consumer requirements. The architecture of the cloud broker agent is presented along with its implementation in (Amato & Venticinque, Multi-objective decision support for bro-kering of cloud sla, 2013). Their effort is similar to our work on FSICC since both works remove the consumers’ needs to search through many cloud providers. However, their effort utilizes an agent-based approach to find one cloud provider that most suit the needs of the cloud consumer, while FSICC unifies many services from multiple cloud providers to be used by the cloud consumers. Moreover, while our framework supports controlling access to the unified services using RBAC, MAC, and DAC, their effort does not provide any security features to control access the cloud services.

The major difference between our work in FSICC and the aforementioned efforts is that their focus is on solving portions of the problems that we are attempting to address in FSICC; none of these efforts provides a comprehensive solution to the problem of securing and integrating cloud and none-cloud services provided from different service provides.

Chapter 4
A Unified Cloud Computing Access Control Model (UCCACM) for RBAC, MAC, and DAC

This chapter defines and explains a *Unified Cloud Computing Access Control Model (UCCACM) for RBAC, MAC, and DAC* that is intended to upgrade these existing access control models so that they are capable of defining permissions based on services. The model has been motivated and influenced by the four main security requirements of FSICC as presented in Section 3.1. The first requirement, *Numerous and Varied Access Control Models* acknowledges that the systems providing services to FSICC may have access control and security protocols that are varied (i.e., RBAC, MAC, DAC, ABAC, etc.), which would require UCCACM to have broad access control abilities. The second requirement, *Control Access to Cloud Services Using RBAC*, offers one possible way to the availability of services to users by assigning roles that authorize to access a sub-set of the available cloud services on a role by role basis. The third requirement, *Support Delegation of Cloud Services Using DAC*, offers the ability for users of cloud services to enable other consumers to utilize all or a sub-set of the user's authorized cloud services in which DAC can be utilized to keep a list of delegated services, along with authorized delegated users, in which each user can delegate all or a sub-set of his/her authorized cloud services to another consumer anytime. Finally, the fourth requirement, *Control Access to Cloud Services Using MAC*, provides the ability users that need access to sensitive information in certain secure cloud services to utilize MAC to label cloud services with sensitivity levels called classifications (e.g., Top Secret (TS) < Secret (S) < Confidential (C) < Unclassified (U)) which can be made available to users that are assigned clearances under appropriate with read and write properties as described in Section

2.3 of Chapter 2. These last three security requirements for RBAC, MAC, and DAC, are the foundational capabilities that need to underlie UCCACM.

In support of these requirements, this chapter presents a Unified Cloud Computing Access Control Model (UCCACM) for the FSICC in which UCCACM provides a set of details definitions to cover all aspect of the four requirements above along with examples for each definition. UCCACM also provides a single view of global services to applications and allows those global services to be authorized according to RBAC (FSICC's security requirement 2), MAC (FSICC's security requirement 4), and DAC (FSICC's security requirement 3) policies; this supports expected contribution EC-B: an Integrated RBAC, MAC, and DAC Model for Cloud Computing from Section 1.5. Moreover, UCCACM is an access control model that utilizes three main access control models (RBAC, MAC, and DAC) to define and enforce security policies for both: clients/systems, and global resources. That is, each client/system defines RBAC, MAC, and/or DAC security policies against its objects. Moreover, the security policies for the global resources of FSICC are defined and enforced against global cloud services of such global resources. UCCACM has a critical placement as a layer in the High-Level View of FSICC Research Areas and Foci of Figure 1.3, that provides of capabilities and functionalities that are necessary to support the Access Control Models in the next layer. These two adjacent layers are influenced by the four security requirements.

The rest of this chapter provides formal definitions of UCCACM in eight sections. Section 4.1 presents a set of core definitions on schemas to support authorizing users to a set of schemas based on roles and/or sensitivity levels. Section 4.2 provides core definitions on enterprise application that include definitions for clients, systems, and types of clients and systems as part of the enterprise application. Section 4.3 discusses core definitions on RBAC, MAC, and DAC models that describe the way that such access control models can be modified to support the four security requirements of FSICC. Section 4.4 describes advanced definitions on enterprise applications in which the security aspects of RBAC, MAC, and DAC models are introduced into clients and systems of any enterprise application. Section 4.5 has core definitions on global resources and permissions by API in which definitions that describe what are global services and the way that such global services are controlled via means of RBAC, MAC, and DAC are provided. Section 4.6 presents advanced definitions on FSICC that describe the way that services and security policies of different systems are mapped. Section 4.7 discusses core definitions on security interceptors for RBAC, MAC, and DAC along with enforcement checks that each security interceptor utilizes. Section 4.8 presents related work on access control for cloud computing. Throughout the entire presentation of UCCACM, detailed examples will be provided utilizing the healthcare scenario of section 2.4 Chapter 2. Note that the work in this chapter has been published in (Baihan, M., et al., 2017).

4.1 Core Definitions on Schemas

To begin, Definitions 1 to 4 are adopted from work on adding RBAC, MAC, and DAC to XML schemas (De La Rosa Algarin A. , 2014) (De La Rosa Algarin, Ziminski, Demurjian, & Rivera Sánchez, 2014) that allowed XML schemas to be customized based on role and classifications to customize what each user is authorized to see from instances of the schema.

Defn. 1: An *element* $e = < e_{ID}, e_{NAME} >$ is defined as two-tuple that represents a single piece of a data abstraction that describes one aspect of a data structure, where e_{ID} is the element's unique identifier, and e_{NAME} is an element name.

Defn. 2: A *schema* (SC) is a data abstraction that represents the structure of a particular kind of information, and is defined as a three-tuple $SC =< SC_{ID}, SC_{NAME}, SC_E >$ where SC_{ID} is a schema's unique identifier, SC_{NAME} is a schema name, and SC_E is a set of elements (as defined in Defn. 1) that represent the schema.

Defn. 3: Each schema, SC_j, has a set of j$_n$ schema instances, $SCI_j =< sci_1, sci_2, ..., sci_{j_n} >$, where $sci_i =< sci_{ID}, sci_V >$ in which sci_V is an element-value set of a schema for all elements in each schema.

Defn. 4: Let *o={read, insert, update, delete},* be the set of operations that can be performed against an element (e) of a schema.

Example 4.1: A schema for the Patient resource can be represented as $SC_1 =< 1, Patient, Paient_E >$ where $Paient_E = \{< 1, id >, < 2, name >, < 3, gender >, < 4, birthDate >\}$. A schema instance of SC_1 can be represented as $sci_1 =< 1, sci_{1_V} >$ where $sci_{1_V} = \{< id, 7 >, < name, Ali >, < gender, male >,$ $< birthDate, 2005 - 8 - 7 >\}$.

4.2 Core Definitions on Enterprise Application

After establishing definitions for schemas and schemas' elements that describe the way that data in FSICC is organized to be exchanged from system to system or from system to client via FSICC, in this section, we provide core definitions on main actors of FCISS that provide, consume, and/or maintain such data using the defined schemas and schemas' elements. These actors form a concept of an enterprise application that includes clients, systems, and types of clients and systems as part of the enterprise application. The next set of definitions, Definitions 5 to 8, are associated with a large-scale enterprise application that is comprised of clients and systems. Specifically, the definition for enterprise application explains the Involved Parties component of Figure 1.2. Furthermore, the definitions for clients and systems describe that contents and types of Clients and Systems boxes of the Involved Parties component of Figure 1.2.

Defn. 5: An *Enterprise Application,* $EA = < EA_{ID}, EA_{NAME}, EA_{CS}, EA_{SS}, EA_{SCS} >$, has a unique identifier (EA_{ID}), name (EA_{NAME}), sets of client applications (EA_{CS}) and systems (EA_{SS}), and a set of schemas (EA_{SCS}). EA, via FSICC, allows multiple clients (mobile, web, desktop) to interact with multiple systems via APIs (cloud, web, programmatic).

Example 4.2: An enterprise application for health information exchange (EA_{HIE}) would allow applications for patients, family members, medical providers, insurance companies, etc. (e.g., CT^2 and ShareMyHealth from Section 2.4), to interact with OpenEMR and MyGoogle (from Section 2.4) via cloud, web, or programmatic APIs. These HITs utilize FHIR Resources, the integration layer in Figure 1.1 from Chapter 1, (Health Level 7, Fast Health Interoperable Resources list, 2016) which include schema representations in both XML and JSON. The schemas defined in EA_{SCS} are used by each HIT system.

The inclusion of schemas as part of an EA allows for the modeling of the information utilized in a cloud computing application to be represented. Many cloud computing applications utilize cloud computing services that send/receive XML or JSON objects, which in turn based on underlying schemas; this is true with FHIR and the API reference implementation. Thus, an EA with schemas provides an actual link from the type of information and the APIs. Given example 4.2, definitions for client and system can be provided.

Defn. 6: A *client* in an EA is a mobile, web, or desktop application, top of Figure 1.1 from Chapter 1, that includes, as part of its functionality, cloud-based services, web services, or a programming API of services, and is interested in utilizing a subset of EA_{SCS} via available cloud computing services. A client can be characterized based on the degree that it is a consumer and/or a provider in a cloud, web, or programming service-based setting. There are two different types of clients:

i. A Pure Client is only a consumer of services.

ii. A Mixed Client is primarily a consumer of services and is also a provider of a small number of services.

Defn. 7: A *system*, bottom of Figure 1.1 from Chapter 1, in an EA provides functionality for use by clients via cloud-based services, web services, or a programming API, and is interested in providing access to a subset of EA_{SCS} via its services or API. A system can be characterized based on the degree that it is a consumer and/or a provider in a cloud, web, or programming service-based setting. There are two different types of systems:

i. A Pure System is only a provider of services.

ii. A Mixed System is primarily a provider of services and is also a consumer of a small number of services.

Example 4.3: Recall the healthcare scenario from Section 2.4 and let us assume that the CT^2 client does not provide services. Based on this assumption we can categorize the ShareMyHealth and CT^2 client Apps; and OpenEMR and MyGoogle systems as follows:

- CT^2 client App is a *pure client*, since it only utilizes services from OpenEMR system
- ShareMyHealth client App is a *mixed client*, since it utilizes services from MyGoogle system and provides a number of services
- OpenEMR system is a *pure system*, since it only provides services
- MyGoogle system is a *mixed system*, since it provides services and utilizes services from OpenEMR

4.3 Core Definitions on RBAC, MAC, and DAC for Roles/Users

After providing definitions on enterprise applications, clients, and systems, in this section, we transition to describe the way that three main access control models RBAC, MAC, and DAC, see RBAC, MAC, and DAC boxes of the Access Control Models component in Figure 1.2, can be modified to enable the clients and systems in an enterprise application to utilize such access control models to protect their services from unauthorized access. The next set of definitions, Definitions 8 to 30, discuss the way that the FSICC security requirements in Section 3.1 from Chapter 3 are supported in our work. Specifically, providing RBAC features for systems and clients supports the security requirement 2 of FSICC: Control Access to Cloud Services Using RBAC. Moreover, providing MAC features for systems and clients supports the security requirement 4 of FSICC: Control Access to Cloud Services Using MAC. Finally, providing DAC features for systems and clients supports the security requirement 3 of FSICC: Support Delegation of Cloud Services Using DAC.

Defn. 8: A *role, r,* is defined as a two-tuple $r = < r_{ID}, r_{NAME} >$ where r_{ID} is a role unique identifier and r_{NAME} is a role name.

Defn. 9: Let $R_{C/S} = \{r_1, r_2, ..., r_j\}$ be defined as the set of j roles for a given client/system where $r_j \in R_{C/S}$ and $r_j = < r_{ID_j}, r_{NAME_j} >$.

Defn. 10: In support of mandatory access control (FSICC's security requirement 4), we define a linearly-ordered set of sensitivity levels (U-unclassified < C-confidential < S-secret < TS-top secret) with the ability to assign levels of clearances (CLR) to users/clients and classifications (CLS) to schemas' elements and services.

In support of mandatory access control, Definitions 1 and 2 are revised in order to define the classification on each schema and each element of a schema.

Defn. 1: (V2) An *element* $e = < e_{ID}, e_{NAME}, e_{CLS} >$ is defined as three-tuple element that represents a single piece of a data abstraction that describes one aspect of a data structure, where e_{ID} is the element's unique identifier, e_{NAME} is an element name, and e_{CLS} is the element classification, as described in Defn. 10.

Defn. 2: (V2) A *schema* (SC) is a data abstraction that represents the structure of a particular kind of information, and is defined as a four-tuple $SC = < SC_{ID}, SC_{NAME}, SC_E, SC_{CLS} >$ where SC_{ID} is a schema's unique identifier, SC_{NAME} is a schema name, SC_E is a set of elements (as defined in Defn. 1v2) that represent the schema, and SC_{CLS} is the schema classification that is equal to the least secure of all of its constituent elements.

Given the V2 revised Defns. 1 and 2, the corresponding permissions can be defined for RBAC and MAC on roles and users with Definitions 11 to 19 to present: the concept of a permission, the way that permissions are associated with roles, the way that a user is defined with a clearance, the way that a user assigned a role, and the way that different roles are related.

Defn. 11: A permission, *p*, is defined as a three-tuple $p = < p_{ID}, p_{SC_{ID}}, p_O >$ where p_{ID} is a permission unique identifier, $p_{SC_{ID}}$ is ID of the involved schema (Defn. 2v2), and p_0 is the operation (Defn. 4).

Defn. 12: A role permission, *rp*, is defined as a three-tuple $rp = < rp_{ID}, p_{ID}, r_{ID} >$ where p_{ID}, r_{ID} are the IDs of the involved permission (Defn. 11) and role (Defn. 8), respectively.

Defn. 13: Each role *r* has a *role-permission set (RPS)* $RPS_r = \{rp_1, rp_2, ..., rp_k\}$ of role permissions (Defn. 12).

Defn. 14: A *user, u,* is defined as three-tuple $u = < u_{ID}, u_{NAME}, u_{CLR} >$, where u_{ID} is a user unique identifier, u_{NAME} is a user name, and u_{CLR} is a user clearance (Defn. 10).

Defn. 15: Let $U_{C/S} = \{u_1, u_2, ..., u_j\}$ be defined as the set of j users for a given client/system, where $u_j \in U_{C/S}$ and $u_j = < u_{ID_j}, u_{NAME_j}, u_{CLR_j} >$.

Defn. 16: Each *user* $u_i \in U_{C/S}$ can be assigned a role $r_j \in R_{C/S}$ for a *user role assignment (ura),* $ura_k = < u_i, r_j >$, that signifies that a user is limited to playing that role and the authorized permissions. Note that a user can be assigned multiple roles but only plays one role in any session with a client/system.

Defn. 17: The *user-role-assignment set* *(URAS$_{C/S}$)* for a client/system, $URAS_{C/S} = \{ura_1, ura_2, ..., ura_k\}$ is the set of all *k* user role assignments (Defn. 16), that contains an entry for relevant user/role combinations that are applicable for RBAC in support of any client/system.

Defn. 18: Each role r has a *role-role set (RRS)* $RRS_{r^i} = \{r_1, r_1, .., r_k\}$ based on the *isa* role hierarchy as described in Section 2.2.

Defn. 19: The *role hierarchy (RH_{C/S})* for a client/system, $RH_{C/S} = \{RRS_{r^1}, RRS_{r^2}, .., RRS_{r^k}\}$ is the set of all k role-role sets (Defn. 18).

In support of discretionary access control (FSICC's security requirement 3) and based on the DAC concepts that were introduced in Section 2.2, we provide definitions 20 to 30 that distinguish between the user who performs the delegation act referred to as an original user and the user who acquires additional permissions based on a delegation act referred to as a delegated user. These definitions also present the way that an original user is supported with different options to perform the delegation (i.e., delegate role, delegate role permission, and delegate clearance).

Defn. 20: An *original role,* or, is a system or client role that is delegable.

Defn. 21: An *original role permission,* orp, is in the role-permission set (RPS) of a specific original role or.

Defn. 22: An *original clearance,* oc, is a clearance (Defn. 10) in a system or client that is delegable.

Defn. 23: An *original user,* ou, is a system or client user who assigned: an original role or, in which ou is illegable to delegate or or orp to another original user ou; and/or an original clearance oc with read/write properties, in which ou is illegable to delegate oc to another original user ou.

Defn. 24: A *delegated clearance,* dc, is a clearance (Defn. 10) that is delegated to a user.

Defn. 25: A *delegated role*, dr, is a role that is delegated to a user.

Defn. 26: A *delegated role permission*, drp, is a role permission that is delegated to a user.

Defn. 27: A *delegated user*, du, is a user to whom a delegated role dr, delegated role permission drp, or delegated clearance dc will be delegated.

Defn. 28: *Delegation Authority (DA)*: A Security engineer determines which users in a system or client can delegate their roles/role permissions/clearance to other users in that system or client.

Defn. 29: *Pass On Delegation Authority (PODA)* is a Boolean value assigned to a user which determines if he/she can delegate his/her roles/role permissions/clearance to another user (*poda=true*) or not (*poda=false*).

Defn. 30: A *Delegation Set (DS)* for a system or client is a set of active role/role permission/clearance delegations $DS_{C/S} = \{ d_1, d_2, \ldots, d_n \}$ in which each active delegation $d_i = \{ ou, du, dr / drp / dc \}$ has three parts: original user (ou), delegated user (du), and a delegated role (dr), a delegated role permission (drp), or a delegated clearance (dc).

4.4 Advanced Definitions on Enterprise Applications

As previously discussed in Section 3.2, we presented three main cloud computing capabilities for FSICC with the associated components. These cloud computing capabilities were: Local Service Registration and Mapping to Global Services, see the Security Policies and Services Registration and Global Services Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3; Local Security Policies Registration to Yield Global Security Policy, see the Security Policies and Services Registration and Global Security Policy Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3; and, Global Registration, Authentication, Authorization, and Service Discover for Consumers, see the GSP and GAPI Utilization and Security Enforcement horizontal box in Figure 1.3. Based on this, this section provides a set of definitions, Definitions 31 to 33, that support the three aforementioned cloud computing capabilities of FSICC. Also, a number of definitions from Sections 4.1, 4.2, and 4.3 are redefined as version 2. To start, the three new definitions are for systems and clients with RBAC/MAC/DAC.

Defn. 31: A cloud, web, or programming service of a client or system, denoted σ , is defined as $\sigma =< \sigma_{ID}, \sigma_{NAME}, \sigma_{SIG}, \sigma_{Type} >$ with unique ID, name, signature, and type for each service. A signature σ_{SIG} is further defined in two different ways based on the technology used to create a service as following:

i. Web/cloud: $\sigma_{SIG} =< \sigma_{METHOD\_TYPE}, \sigma_{URI}, \sigma_{INPUT\_VARIABLE} >$ where $\sigma_{METHOD\_TYPE} \in \{Create, \mathrm{Re}ad\ , Update, Delete, GET, POST, PUT, DELETE\}$ is the type of CRUD method, σ_{URI} a unified resource identifier URI, and $\sigma_{INPUT\_VARIABLE}$ is the input variable.

ii. Program: $\sigma_{SIG} =< \sigma_{METHOD\_NAME}, \sigma_{RETURN\_TYPE}, \sigma_{PARAMETERS} >$ where σ_{METHOD_NAME} in the call name, σ_{RETURN_TYPE} is the return type, and $\sigma_{PARAMETERS}$ are the parameter names/types.

A service type σ_{Type} of a web/cloud-based service can be: (read) if σ_{METHOD_TYPE} is Read/GET; or (write) if σ_{METHOD_TYPE} is Create/Update/Delete/POST/PUT/DELETE. A service type σ_{Type} of a program-based service can be: (read) indicating that values of all service parameters $\sigma_{PARAMETERS}$will not be modified after the service call, (write) indicating that values of all service parameters $\sigma_{PARAMETERS}$can be modified after the service call, or (read/write) indicating that values of some service parameters $\sigma_{PARAMETERS}$can be modified after the service call while values of other parameters will not.

Defn. 32: A *system*, $S^i =< S^i_{ID}, S^i_{NAME}, S^i_{API}, S^i_{SC_S}, S^i_{R_S}, S^i_{RPS_S}, S^i_{RH_S}, S^i_{U_S}, S^i_{URAS_S}, S^i_{DS_S} >$, $S^i \in EA_{SS}$ is identified by a unique identifier, name, and cloud, web, or programmatic API of a system, respectively, where a given S^i_{API} is comprised of a set of i$_j$ API services $S^i_{API} = \{\sigma^i_1, \sigma^i_2, \sigma^i_3, ..., \sigma^i_j\}$ with each σ_j as given in Defn. 31 along with a schema subset $S^i_{SC_S}$, sets of roles $S^i_{R_S}$, role permission sets $S^i_{RPS_S}$, role hierarchy $S^i_{RH_S}$, users $S^i_{U_S}$, user-role assignment set $S^i_{URAS_S}$, and system delegation set $S^i_{DS_S}$ (Definitions 2v2, 9, 13, 19, 15, 17 and 30 respectively).

Example 4.4: MyGoogle and OpenEMR (from Section 2.4) are two systems in *EA$_{SS}$* where there are RESTful cloud services for MyGoogle, and RESTful web services for OpenEMR. Figures 4.1 and 4.2 define MyGoogle and OpenEMR systems, respectively, with the signature σ_{SIG} as a placeholder for readability.

S^1=<s₁, **MyGoogle**, S^1_{API}, $S^1_{SC_ς}$, $S^1_{R_ς}$, $S^1_{RH_ς}$, $S^1_{RPS_ς}$, $S^1_{U_ς}$, $S^1_{URAS_ς}$, $S^1_{DS_ς}$ >, where

$S^1_{API}=\{\sigma_1^{S^1},\sigma_2^{S^1},\sigma_3^{S^1},\sigma_4^{S^1},\sigma_5^{S^1}\}$ where $\sigma_1^{S^1}$ =<MG₁, NewDataSource, σ_{SIG}^{MG1} >,

$\sigma_2^{S^1}$ = <MG₂, ReadDataSource, σ_{SIG}^{MG2} >, $\sigma_3^{S^1}$ =<MG₃, NewPatient, σ_{SIG}^{MG3} >,

$\sigma_4^{S^1}$ =<MG₄, ReadPatient, σ_{SIG}^{MG4} >, $\sigma_5^{S^1}$ =<MG₅, AppAuth, σ_{SIG}^{MG5} >

to show the contents of a service's signature, we present the signature for $\sigma_1^{S^1}$:

σ_{SIG}^{MG1} = <PUT, /MyGoogle/fitness/dataSources/dsID, dsINFO>

$S^1_{SC_ς}=\{sc_1^{S^1},sc_2^{S^1},sc_3^{S^1}\}$ in which

$sc_1^{S^1}$ =<1,Observation,{<1,id,BSI>, <2,subject,SIS>, <3,status,BSI>, <4,performer,SIS>},BSI>

$sc_2^{S^1}$ =<2,Patient,{<1,id,BSI>, <2,name,BSI>, <3,gender,BSI>, <4,birthDate,SIS>},BSI>

$sc_3^{S^1}$ =<3,Person,{<1,id,BSI>, <2,name,BSI>, <3,Token,SIS>},BSI>

$S^1_{R_ς}=\{r_1^{S^1}\}$ in which $r_1^{S^1}$ =<MG$_{R1}$,SMH>

$S^1_{RH_ς}=\{\phi\}$

$S^1_{RPS_ς}=\{rp_1^{S^1}, rp_2^{S^1}, rp_3^{S^1}, rp_4^{S^1}, rp_5^{S^1}\}$ in which $rp_1^{S^1}$ = <p_1, $r_1^{S^1}$, $sc_1^{S^1}$,insert>,

$rp_2^{S^1}$ = <p_2, $r_1^{S^1}$, $sc_1^{S^1}$,read >, $rp_3^{S^1}$ = <p_3, $r_1^{S^1}$, $sc_2^{S^1}$,insert >,

$rp_4^{S^1}$ = <p_4, $r_1^{S^1}$, $sc_2^{S^1}$,read >, $rp_5^{S^1}$ = <p_5, $r_1^{S^1}$, $sc_3^{S^1}$,insert >}

$S^1_{U_ς}=\{u_1^{S^1}\}$ with $u_1^{S^1}$ =<1,ShareMyHealth,VSI,SS,L*>

$S^1_{URAS_ς}=\{ura_1^{S^1}\}$ with $ura_1^{S^1}$ =< $u_1^{S^1}$, $r_1^{S^1}$ >

$S^1_{DS_ς}=\{\phi\}$

Figure 4.1. MyGoogle Notation for Example 4.4.

S^2=<s₂, **OpenEMR**, S^2_{API}, $S^2_{SC_ς}$, $S^2_{R_ς}$, $S^2_{RH_ς}$, $S^2_{RPS_ς}$, $S^2_{U_ς}$, $S^2_{URAS_ς}$, $S^2_{DS_ς}$ >, where

$S^2_{API}=\{\sigma_1^{S^2},\sigma_2^{S^2},\sigma_3^{S^2},\sigma_4^{S^2},\sigma_5^{S^2},\sigma_6^{S^2},\sigma_7^{S^2},\sigma_8^{S^2}\}$ in which $\sigma_1^{S^2}$ =<OEMR₁, updatepatientnotes, σ_{SIG}^{OEMR1} >,

σ_2^{S2} = <OEMR₂, getnotes, σ_{SIG}^{OEMR2} >, $\sigma_3^{S^2}$ =< OEMR₃, getallpatients, σ_{SIG}^{OEMR3} >,

$\sigma_4^{S^2}$ =< OEMR₄, addpatient, σ_{SIG}^{OEMR4} >, $\sigma_5^{S^2}$ =< OEMR₅, addvisit, σ_{SIG}^{OEMR5} >,

$\sigma_6^{S^2}$ =<OEMR₆, getvisits, σ_{SIG}^{OEMR6} >, $\sigma_7^{S^2}$ =< OEMR₇, getlist, σ_{SIG}^{OEMR7} >,

$\sigma_8^{S^2}$ =< OEMR₈, addlist, σ_{SIG}^{OEMR8} >

to show the contents of a service's signature, we present the signature for $\sigma_1^{S^2}$:

σ_{SIG}^{OEMR1} = <PUT, /OpenEMR/updatepatientnotes, noteINFO>

$S^2_{SC_ς}=\{sc_1^{S^2},sc_2^{S^2},sc_3^{S^2},sc_4^{S^2}\}$ in which

$sc_1^{S^2}$ =<1,Observation,{<1,id,BSI>, <2,subject,BSI>, <3,status,BSI>, <4,performer,level_2>},BSI>

$sc_2^{S^2}$ =<2,Patient,{<1,id,BSI>, <2,name,BSI>, <3,gender,BSI>, <4,birthDate,SIS>},BSI>

$sc_3^{S^2}$ =<3,Encounter,{<1,id,BSI>, <2,subject,SIS>, <3,status,BSI>, <4,appointment,BSI>},BSI>

$sc_4^{S^2}$ =<4,Condition,{<1,id,BSI>, <2,subject,SIS>, <3,clinicalStatus,BSI>, <4,assertedDate,SIS>},BSI>

$S^2_{R_ς}=\{r_1^{S^2},r_2^{S^2},r_3^{S^2},r_4^{S^2},r_5^{S^2},r_6^{S^2},r_7^{S^2},r_8^{S^2}\}$ in which $r_1^{S^2}$ =<OEMR$_{R1}$,Physicion>,

$r_2^{S^2}$ =<OEMR$_{R2}$,Patient>, $r_3^{S^2}$ =<OEMR$_{R3}$,Coach>, $r_4^{S^2}$ =<OEMR$_{R4}$,Nurse>,

$r_5^{S^2}$ =<OEMR$_{R5}$,Parent>, $r_6^{S^2}$ =<OEMR$_{R6}$,Trainer>, $r_7^{S^2}$ =<OEMR$_{R7}$,CT^2>,

$r_8^{S^2}$ =<OEMR$_{R8}$,MyGoogle>

$S^2_{RH_ς}=\{rh_1^{S^2}\}$ with $rh_1^{S^2}=\{r_2^{S^2},r_1^{S^2}\}$

$S^2_{RPS_ς}=\{rp_1^{S^2},rp_2^{S^2},rp_3^{S^2},rp_4^{S^2},rp_5^{S^2},rp_6^{S^2}\}$ with $rp_1^{S^2}$ =<p_1, $r_1^{S^2}$, $sc_1^{S^2}$, read>,

$rp_2^{S^2}$ =<p_2, $r_1^{S^2}$, $sc_2^{S^2}$, insert>, $rp_3^{S^2}$ =<p_3, $r_2^{S^2}$, $sc_1^{S^2}$, insert >,

$rp_4^{S^2}$ =<p_4, $r_2^{S^2}$, $sc_1^{S^2}$, read >, $rp_5^{S^2}$ =<p_5, $r_2^{S^2}$, $sc_2^{S^2}$, insert >,

$rp_6^{S^2}$ =<p_6, $r_2^{S^2}$, $sc_2^{S^2}$, read>

$S^2_{U_ς}=\{u_1^{S^2},u_2^{S^2}\}$ with $u_1^{S^2}$ =<1,John,SID,SS,SI>, $u_2^{S^2}$ =<2,Sara,SIS,SS,SI>

$S^1_{URAS_ς}=\{ura_1^{S^2},ura_2^{S^2}\}$ with $ura_1^{S^2}$ =< $u_1^{S^2}$, $r_1^{S^2}$ >, $ura_2^{S^2}$ =< $u_2^{S^2}$, $r_2^{S^2}$ >

$S^2_{DS_ς}=\{d_1^{S^2}, d_2^{S^2}\}$ with $d_1^{S^2}$ =< $u_2^{S^2}$, $u_1^{S^2}$, $r_2^{S^2}$ >, $d_2^{S^2}$ =< $u_1^{S^2}$, $u_2^{S^2}$, SID >

Figure 4.2. OpenEMR Notation for Example 4.4.

Defn. 33: A *client application,* $C^i \in EA_{CS}$ is defined as $C^i =< C^i_{ID}, C^i_{NAME}, C^i_{API}, C^i_{SC_C}, C^i_{R_C}, C^i_{RPS_C}, C^i_{RH_C}, C^i_{U_C}, C^i_{URAS_C}, C^i_{DS_C} >$ with unique identifier, name, C^i_{API} the set of i*j* API services $C^i_{API} = \{\sigma^i_1, \sigma^i_2, \sigma^i_3, ..., \sigma^i_j\}$ with each σ_j as given in Defn. 31, and, a schema subset $C^i_{SC_C}$, sets of roles $C^i_{R_C}$, role permission sets $C^i_{RPS_C}$, role hierarchy $C^i_{RH_C}$, users $C^i_{U_C}$, user-role assignment set $C^i_{URAS_C}$, and client delegation set $C^i_{DS_C}$ (Definitions 2v2, 9, 13, 19, 15, 17 and 30 respectively).

Example 4.5: In Section 2.4 we have two clients: ShareMyHealth with RESTful cloud services; and CT^2 with RESTful web services, which are in EA_{CS}. Figures 4.3 and 4.4 define ShareMyHealth and CT^2 clients with the signature σ_{SIG} as a placeholder for readability.

C^1=<c$_1$, **ShareMyHealth**, C^1_{API}, $C^1_{SC_C}$, $C^1_{R_C}$, $C^1_{RH_C}$, $C^1_{RPS_C}$, $C^1_{U_C}$, $C^1_{URAS_C}$, $C^1_{DS_C}$ >, where

C^1_{API}={ $\sigma^{C^1}_1$, $\sigma^{C^1}_2$, $\sigma^{C^1}_3$, $\sigma^{C^1}_4$, $\sigma^{C^1}_5$ } with $\sigma^{C^1}_1$ =<SMH$_1$, NewMeasure, σ^{SMH1}_{SIG}>,

$\sigma^{C^1}_2$ =<SMH$_2$, ReadMeasure, σ^{SMH2}_{SIG}>, $\sigma^{C^1}_3$ =<SMH$_3$, NewPatient, σ^{SMH3}_{SIG}>,

$\sigma^{C^1}_4$ =<SMH$_4$, ReadPatient, σ^{SMH4}_{SIG}> , $\sigma^{C^1}_5$ =<SMH$_5$, AppAuth, σ^{SMH5}_{SIG}>

to show the contents of a service's signature, we present the signature for $\sigma^{C^1}_1$:

σ^{SMH1}_{SIG} =<PUT, /SMH/newMeasure/mID, mINFO>

$C^1_{SC_C}$ ={ $sc^{C^1}_1$, $sc^{C^1}_2$, $sc^{C^1}_3$ } in which

$sc^{C^1}_1$ =<1,Observation,{<1,id,BSI>, <2,subject,SIS>, <3,status,BSI>, <4,performer,SIS>},BSI>

$sc^{C^1}_2$ =<2,Patient,{<1,id,BSI>, <2,name,BSI>, <3,gender,BSI>, <4,birthDate,SIS>},BSI>

$sc^{C^1}_3$ =<3,Person,{<1,id,BSI>, <2,name,BSI>, <3,Token,SIS>},BSI>

$C^1_{R_C}$ ={ $r^{C^1}_1$, $r^{C^1}_2$ } with $r^{C^1}_1$ =<SMH$_{R1}$,Patient>, $r^{C^1}_2$ =<SMH$_{R2}$,Physician>

$C^1_{RH_C}$ = { $rh^{C^1}_1$ } with $rh^{S^2}_1$ = {$r^{C^1}_1$, $r^{C^1}_2$ }

$C^1_{RPS_C}$ ={ $rp^{C^1}_1$, $rp^{C^1}_2$, $rp^{C^1}_3$, $rp^{C^1}_4$, $rp^{C^1}_5$ } where $rp^{C^1}_1$ =<p_1, $r^{C^1}_1$, $sc^{C^1}_1$, insert>,

$rp^{C^1}_2$ =<p_2, $r^{C^1}_1$, $sc^{C^1}_2$, insert >, $rp^{C^1}_3$ =<p_3, $r^{C^1}_1$, $sc^{C^1}_3$, insert >,

$rp^{C^1}_4$ =<p_4, $r^{C^1}_2$, $sc^{C^1}_1$, read >, $rp^{C^1}_5$ =<p_5, $r^{C^1}_2$, $sc^{C^1}_2$, read >

$C^1_{U_C}$ ={ $u^{C^1}_1$, $u^{C^1}_2$ } in which $u^{C^1}_1$ =<1,Sarah,VSI,SS,SI>, $u^{C^1}_2$ =<2,Nasser,SIS,SS,L*>

$C^1_{URAS_C}$ ={ $ura^{C^1}_1$, $ura^{C^1}_2$ } with $ura^{C^1}_1$ =< $u^{C^1}_1$, $r^{C^1}_1$ >, $ura^{C^1}_2$ =< $u^{C^1}_2$, $r^{C^1}_2$ >

$C^1_{DS_C}$ ={ $d^{C^1}_1$ } with $d^{C^1}_1$ =< $u^{C^1}_1$, $u^{C^1}_2$, $r^{C^1}_1$ >

Figure 4.3. ShareMyHealth Notation for Example 4.5.

C^2=<c$_2$, **CT²**, C^2_{API}, $C^2_{SC_C}$, $C^2_{R_C}$, $C^2_{RPS_C}$, $C^2_{U_C}$, $C^2_{URAS_C}$, $C^2_{DS_C}$ >, where

C^2_{API}={ $\sigma_1^{C^2}, \sigma_2^{C^2}, \sigma_3^{C^2}, \sigma_4^{C^2}, \sigma_5^{C^2}, \sigma_6^{C^2}, \sigma_7^{C^2}, \sigma_8^{C^2}$ } with $\sigma_1^{C^2}$ =<CT$_1$, NewStatus, σ_{SIG}^{CT1} >,

$\sigma_2^{C^2}$ =<CT$_2$, ReadStatus, σ_{SIG}^{CT2} >, $\sigma_3^{C^2}$ =<CT$_3$, ReadStudent, σ_{SIG}^{CT3} >,

$\sigma_4^{C^2}$ =<CT$_4$, NewStudent, σ_{SIG}^{CT4} >, $\sigma_5^{C^2}$ =<CT$_5$, NewFollowup, σ_{SIG}^{CT5} >,

$\sigma_6^{C^2}$ =<CT$_6$, ReadFollowup, σ_{SIG}^{CT6} >, $\sigma_7^{C^2}$ =<CT$_7$, ReadConcussion, σ_{SIG}^{CT7} >,

$\sigma_8^{C^2}$ =<CT$_8$, NewConcussion, σ_{SIG}^{CT8} >

to show the contents of a service's signature, we present the signature for $\sigma_1^{C^2}$:

σ_{SIG}^{CT1} =<PUT, /CT2/concussion/status, statusINFO>

$C^2_{SC_C}$ ={ $sc_1^{C^2}, sc_2^{C^2}, sc_3^{C^2}, sc_4^{C^2}$ } in which

$sc_1^{C^2}$ =<1,Observation,{<1,id,BSI>, <2,subject,SIS>, <3,status,BSI>, <4,performer,SIS>},BSI>

$sc_2^{C^2}$ =<2,Patient,{<1,id,BSI>, <2,name,BSI>, <3,gender,BSI>, <4,birthDate,SIS>},BSI>

$sc_3^{C^2}$ =<3,Encounter,{<1,id,BSI>, <2,subject,SIS>, <3,status,BSI>, <4,appointment,BSI>},BSI>

$sc_4^{C^2}$ =<4,Condition,{<1,id,BSI>, <2,subject,SIS>, <3,clinicalStatus,BSI>, <4,assertedDate,S>},BSI>

$C^2_{R_C}$ ={ $r_1^{C^2}, r_2^{C^2}, r_3^{C^2}, r_4^{C^2}$ } with $r_1^{C^2}$ =<CT$_{R1}$,Coach>, $r_2^{C^2}$ =<CT$_{R2}$,Nurse>,

$r_3^{C^2}$ =<CT$_{R3}$,Parent>, $r_4^{C^2}$ =<CT$_{R4}$,Trainer>

$C^2_{RPS_C}$ ={ $rp_1^{C^2}, rp_2^{C^2}, rp_3^{C^2}, rp_4^{C^2}, rp_5^{C^2}, rp_6^{C^2}, rp_7^{C^2}, rp_8^{C^2}, rp_9^{C^2}, rp_{10}^{C^2}, rp_{11}^{C^2}$ } with $rp_1^{C^2}$ =<p_1, $r_1^{C^2}$, $sc_1^{C^2}$, read>,

$rp_1^{C^2}$ =<p_2, $r_1^{C^2}$, $sc_2^{C^2}$, read >, $rp_1^{C^2}$ =<p_3, $r_1^{C^2}$, $sc_3^{C^2}$, read >, $rp_1^{C^2}$ =<p_4, $r_1^{C^2}$, $sc_4^{C^2}$, read >,

$rp_1^{C^2}$ =<p_5, $r_1^{C^2}$, $sc_4^{C^2}$, insert >, $rp_1^{C^2}$ =<p_6, $r_3^{C^2}$, $sc_1^{C^2}$, read >, $rp_1^{C^2}$ =<p_7, $r_3^{C^2}$, $sc_2^{C^2}$, read >,

$rp_1^{C^2}$ =<p_8, $r_3^{C^2}$, $sc_2^{C^2}$, insert >, $rp_1^{C^2}$ =<p_9, $r_3^{C^2}$, $sc_3^{C^2}$, read >, $rp_1^{C^2}$ =<p_{10}, $r_3^{C^2}$, $sc_4^{C^2}$, read >,

$rp_1^{C^2}$ =<p_{11}, $r_3^{C^2}$, $sc_4^{C^2}$, insert >

$C^2_{U_C}$ ={ $u_1^{C^2}, u_2^{C^2}$ } in which $u_1^{C^2}$ =<1,Sarah,S>, $u_1^{C^2}$ =<2,Alic,C>

$C^2_{URAS_C}$ ={ $ura_1^{C^2}, ura_2^{C^2}$ } with $ura_1^{C^2}$ =< $u_1^{C^2}$, $r_1^{C^2}$ >, $ura_2^{C^2}$ =< $u_2^{C^2}$, $r_3^{C^2}$ >

$C^2_{DS_C}$ ={ $d_1^{C^2}$ } with $d_1^{C^2}$ =< $u_2^{C^2}$, $u_1^{C^2}$, $r_3^{C^2}$ >

Figure 4.4. CT^2 Notation for Example 4.5.

UCCACM for cloud computing, that supports the FSICC's security requirements (see Section 3.1), also provides the means to represent a unified set of global services encapsulated into one Global Resource for a given EA and its systems. This allows the clients to be able to utilize a set of shared global services rather than specific services for each system that may be in different formats (e.g., cloud services, web services, programmatic API services in different languages, etc.). This is basically meant to support the FSICC's cloud computing capabilities (see Section 3.2). Although, grouping multiple systems services attracts app developers, in a domain such as healthcare, there is a need to create useful and rich apps (i.e., apps with many features) in an easy and efficient way (i.e., avoid effort duplication). This need must be balanced against the potential to create one great target that attackers can utilize to illegally access a large set of crucial and sensitive data (see Security Risks of adopting FSICC in Section 3.3), through services, such as electronic health records of large number of patients. Thus, an access control mechanism should be developed and utilized to restrict services access only to the authorized users and their Apps.

Moreover, since there is a demonstrated need to protect such global services we make two major observations: (1) there must be a shift in focus on the concept of RBAC permissions from objects and operations (in the traditional RBAC model) to permissions that define individual global services that are authorized by role to make invocations (calls) on objects; and (2) there is a need to utilize a larger set of the four sensitivity levels of MAC such that the set of sensitivity levels can adequately classify sensitive data in complex areas such as healthcare, note that the healthcare-based security level approaches discussed in Section 2.2 are too focused on the healthcare domain. In this dissertation, we present an access control mechanism, i.e., UCCACM, that provides solutions for observations 1 and 2. Regarding the first major observation, Figure 4.5 shows the UCCACM for RBAC part that consists of four elements: Roles; Users; Sessions; and Permissions (i.e., the defined service calls on objects), and five relations: User-Role (i.e., which user assigned to which role); Role-Permission (i.e., which role authorized to which service in which each service calls a specific object); User-Session (i.e., which user is active in the current session); Role-Session (i.e., which role of the current user is active in the current session); and Role-Role (i.e., which role, or set of roles, is the parent of the active role based on the *isa* role hierarchy).

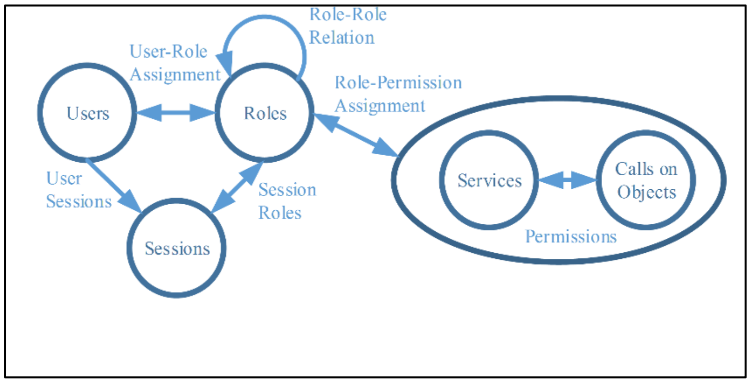


Figure 4.5. The UCCACM for RBAC Part.

In the case of the second major observation, recall the work presented in Section 2.2 and Figure 2.5. In Section 2.2, we reviewed the different HL7 confidentiality levels: U – unrestricted, L – low, M – moderate, N – normal, R – restricted, and V – very restricted (Health Level 7., 2014). In Section 2.2, we also reviewed the work on the lattice-based categories and subcategories of sensitivities for healthcare that defined five main healthcare sensitivity levels: 0 – Basic Information, 1 – Medical History Data, 2 – Summary Clinical Data, 3 – Detailed Clinical Data, 4 – Sensitive Clinical Data (Demurjian, Sanzi, Agresta, & Yasnoff, 2018) in Figure 2.5. Using that work as a basis, for the second major observation, we present a set of five sensitivity levels (0-4) that can be utilized to classify data of any complex domain such as healthcare, but not limited to the healthcare domain as follows:

Level 0: *Public Information (PI)* contains data that is freely available to anyone. Examples for data at this level are: basic demographics such as city and state of residence; and general personal information such as bachelor graduation year and university name.

Level 1: *Basic Sensitive Information (BSI)* contains data that has some restrictions. Examples for data at this level are: detailed demographic data such as the patient name, full address, and date of birth.

Level 2: *Sensitive Information Summary (SIS)* contains data that groups or summaries a set of data that is classified as Basic Sensitive Information. Examples for data at this level are: clinical data including prescription and over-the-counter medications; and key data of a student's academic record such as GPA.

Level 3: *Sensitive Information Details (SID)* contains data that elaborates and provides more information about data that is classified as Basic Sensitive Information. Examples for data at this level are: reports from imaging studies (CT Scans, MRIs, X-Rays); and detailed academic information such as a report on a student academic record.

Level 4: *Very Sensitive Information (VSI)* contains very sensitive information about people or organizations. Examples for data at this level are: sensitive information on a patient that is used by medical specialists including data on genetics, substance abuse, mental health psychotherapy notes; and sensitive employees' information such as social security number.

In the examples from this point forward, we refer to Level 0 to Level 4, respectively, by the acronyms: PI, BIS, SIS, SID, and VSI.

Given Figure 4.5, we revise the Definitions 9, 15, 16, 17, and 30 to version 2 (v2) that includes G (for global) as an option for a role set, user set, user role assignment, user-role assignment set, and delegation set.

Defn. 9: (v2) Let $R_{C/S/G} = \{r_1, r_2, ..., r_j\}$ be defined as the set of j roles for a given client/system/Global Resource where $r_j \in R_{C/S/G}$ and $r_j = < r_{ID_j}, r_{NAME_j} >$.

Defn. 15: (v2) Let $U_{C/S/G} = \{u_1, u_2, ..., u_j\}$ be defined as the set of j users for a given client/system/Global Resource, where $u_j \in U_{C/S/G}$ and $u_j = < u_{ID_j}, u_{NAME_j}, u_{CLR_j} >$.

Defn. 16: (v2) Each *user* $u_i \in U_{C/S/G}$ can be assigned a role $r_j \in R_{C/S/G}$ for a *user role assignment (ura),* $ura_k = < u_i, r_j >$, that signifies that a user is limited to playing that role and the authorized permissions. Note that a user can be assigned multiple roles but only play one role in any session with a client/system/Global Resource.

Defn. 17: (v2) The *user-role-assignment set (URAS$_{C/S/G}$)* for a client/system/Global Resource, $URAS_{C/S/G} = \{ura_1, ura_2, ..., ura_k\}$ is the set of all *k* user role assignments (Defn. 16v2), that contains an entry for relevant user/role combinations that are applicable for role-based access control in support of any client/system/Global Resource.

Defn. 30: (v2) *Delegation Set (DS)* for a client/system/Global Resource is a set of active role/role permission delegations $DS_{C/S/G} = \{ d_1, d_2, \ldots, d_n \}$ in which each active delegation $d_i = \{ou, du, dr / drp / dc\}$ has three parts: original user (ou), delegated user (du), and a delegated role (dr), a delegated role permission (drp), or a delegated clearance (dc).

To complete the changes, based on the presented sensitivity levels above we revise the Defn. 10 to version 2 (v2) to include the five sensitivity levels.

Defn. 10: (v2) In support of mandatory access control (FSICC's security requirement 4), we define a linearly-ordered set of sensitivity levels (0-PI < 1-BSI < 2-SIS < 3-SID < 4-VID) with the ability to assign levels of clearances (CLR) to users/clients and classifications (CLS) to schemas' elements and services.

4.5 Core Definitions on Global Resources and Permissions by API

As we introduced RBAC, MAC, and DAC into definitions for systems and clients in Section 4.3 and revised in Section 4.4, in this section, we present a set of definitions (Definitions 34 to 39) that focus on the higher-level needs of UCCACM within FSICC. Specifically, UCCACM provides a unified set of global services encapsulated into a number of Global Resources. This supports FSICC's cloud computing capability 1 in Section 3.2, see the Security Policies and Services Registration and Global Services Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3. This set of global services belongs to a given enterprise application and its systems in which interested clients are able to utilize authorized services from this set of shared global services. This is to remove the need for clients to utilize multiple and possibly heterogeneous services from each system, separately, that may be in different formats (e.g., cloud services, web services, programmatic API services in different languages, etc.). Moreover, the FSICC's global services are controlled using RBAC, MAC, and/or DAC which supports FSICC's cloud computing capability 2 in Section 3.2 as was shown in the GSP Generation and GAPI Generation horizontal box in Figure 1.3.

Defn. 34: A *global service* of a global resource, denoted β, is defined as $\beta = <\beta_{ID}, \beta_{NAME}, \beta_{SIG}, \beta_{CLS}>$ with unique ID, name, signature (similar to σ_{SIG} in Defn. 31), and a classification (Defn. 10) for each service.

Defn. 35: A *global resource, G^i* represents a set of global services that are intended to map to services from different Clients/Systems.

Defn. 36: For a global resource, G^i, a *global service permission,* $\beta^i_{gp} = < r^i_{ID_k}, \beta^i_{ID_j} >$, binds a jth global service β^i_j of G^i_{API} by identifier, $\beta^i_{ID_j}$, to a role $r^i_k \in G^i_{R_G}$ by identifier, $r^i_{ID_j}$.

Defn. 37: For a global resource, G^i, and a role $r^i_k \in G^i_{R_G}$, a *role permissions set,* $RPS_{r^i_k}$ = $\{\beta^i_{gp_1}, \beta^i_{gp_2}, ..., \beta^i_{gp_n}\}$ contains all of the *n* global service permissions $\beta^i_{gp_j}$ associated with a role.

Defn. 38: For a global resource, G^i, the *resource role permissions set,* $G^i_{RRPS_G}$ =\{ $RPS_{r^i_1}$, $RPS_{r^i_2}$, …, $RPS_{r^i_m}$ \} contains all of the role permission sets for the *m* roles in $G^i_{R_G}$.

Defn. 39: A *global resource,* G^i can be represented as $G^i = < G^i_{ID}, G^i_{NAME}, G^i_{API}, G^i_{R_G}, G^i_{U_G}, G^i_{URAS_G}, G^i_{RRPS_G}, G^i_{DS_G} >$, is identified by a unique identifier, name, and cloud API, respectively, where a given G^i_{API} is comprised of a set of i_j API services $G^i_{API} = \{\beta_{i_1}, \beta_{i_2}, \beta_{i_3}, ..., \beta_{i_j}\}$ with each β_j as given in Defn. 34 along with sets of roles $G^i_{R_G}$, users $G^i_{U_G}$, user-role assignment sets $G^i_{URAS_G}$ (Definitions 9v2, 15v2, and 17v2 respectively), a resource role permission set, $G^i_{RRPS_G}$ (Defn. 38), and a resource delegation set $G^i_{DS_G}$ (Defn. 30v2).

Example 4.6: Figure 4.6 defines the Global Resource G^1 with the signature σ_{SIG} as a placeholder for readability. The global services (see Table 4.1) are organized into one Global Resource G^1 with global roles (Table 4.2).

G^1=<g$_1$,**EA$_{HIT}$FSICC**, G^1_{API}, $G^1_{R_G}$, $G^1_{U_G}$, $G^1_{URAS_G}$, $G^1_{RRPS_G}$, $G^1_{DS_G}$ >, where

G^1_{API}={ $\beta_1^{G^1}, \beta_2^{G^1}, \beta_3^{G^1}, \beta_4^{G^1}, \beta_5^{G^1}, \beta_6^{G^1}, \beta_7^{G^1}, \beta_8^{G^1}, \beta_9^{G^1}$ } in which $\beta_1^{G^1}$ =<gs$_1$, NewObservation, β_{SIG}^{gs1} , S>,

$\beta_2^{G^1}$ =<gs$_2$, ReadObservation, β_{SIG}^{gs2} , S >, $\beta_3^{G^1}$ =<gs$_3$, NewPatient, β_{SIG}^{gs3} , C >,

$\beta_4^{G^1}$ =<gs$_4$, ReadPatient, β_{SIG}^{gs4} , S >, $\beta_5^{G^1}$ =<gs$_5$, NewUser, β_{SIG}^{gs5} , S >,

$\beta_6^{G^1}$ =<gs$_6$, NewEncounter, β_{SIG}^{gs6} , U >, $\beta_7^{G^1}$ =<gs$_7$, ReadEncounter, β_{SIG}^{gs7} , U >,

$\beta_8^{G^1}$ =<gs$_8$, NewCondition, β_{SIG}^{gs8} , C >, $\beta_9^{G^1}$ =<gs$_9$, ReadCondition, β_{SIG}^{gs9} , C >

to show the contents of a service's signature, we present the signature for $\beta_1^{G^1}$:

β_{SIG}^{gs1} =<PUT, /FSICC/Observation/id, obINFO>

$G^1_{R_G}$ ={ $r_1^{G^1}, r_2^{G^1}, r_3^{G^1}, r_4^{G^1}, r_5^{G^1}, r_6^{G^1}, r_7^{G^1}, r_8^{G^1}, r_9^{G^1}$ } with $r_1^{G^1}$ =<G$_{R1}$,GPhysician>,

$r_2^{G^1}$ =<G$_{R2}$,GPatient>, $r_3^{G^1}$ =<G$_{R3}$,GCoach>, $r_4^{G^1}$ =<G$_{R4}$,GNurse>, $r_5^{G^1}$ =<G$_{R5}$,GParent>,

$r_6^{G^1}$ =<G$_{R6}$,GTrainer>, $r_7^{G^1}$ =<G$_{R7}$,GCT^2>, $r_8^{G^1}$ =<G$_{R8}$,GMyGoogle>, $r_9^{G^1}$ =<G$_{R9}$,GSMH>

$G^1_{U_G}$ ={ $u_1^{G^1}, u_2^{G^1}$ } with $u_1^{G^1}$ =<1,John,VSI>, $u_2^{G^1}$ =<2,Ali,BSI>

$G^1_{URAS_G}$ ={ $ura_1^{G^1}, ura_2^{G^1}$ } with $ura_1^{G^1} = < u_1^{G^1}, r_1^{G^1} >$, $ura_2^{G^1} = < u_2^{G^1}, r_2^{G^1} >$

$G^1_{RRPS_G}$ = { $rp_1^{G^1}, rp_2^{G^1}$,} where $rp_1^{G^1}$ ={ $\beta_{gp_1}^{G^1}, \beta_{gp_2}^{G^1}, \beta_{gp_3}^{G^1}$ }, $rp_1^{G^1}$ ={ $\beta_{gp4}^{G^1}, \beta_{gp_5}^{G^1}, \beta_{gp_6}^{G^1}, \beta_{gp_7}^{G^1}, \beta_{gp_8}^{G^1}$ } with

$\beta_{gp_1}^{G^1} = < r_1^{G^1}, \beta_2^{G^1} >$, $\beta_{gp_2}^{G^1} = < r_1^{G^1}, \beta_4^{G^1} >$, $\beta_{gp_3}^{G^1} = < r_1^{G^1}, \beta_5^{G^1} >$, $\beta_{gp_4}^{G^1} = < r_2^{G^1}, \beta_1^{G^1} >$,

$\beta_{gp_5}^{G^1} = < r_2^{G^1}, \beta_2^{G^1} >$, $\beta_{gp_6}^{G^1} = < r_2^{G^1}, \beta_3^{G^1} >$, $\beta_{gp_7}^{G^1} = < r_2^{G^1}, \beta_4^{G^1} >$, $\beta_{gp_8}^{G^1} = < r_2^{G^1}, \beta_5^{G^1} >$

$G^1_{DS_G}$ ={ $d_1^{G^1}$ } with $d_1^{G^1} = < u_2^{G^1}, u_1^{G^1}, r_2^{G^1} >$

Figure 4.6. Global Resource G^1 Notation for Example 4.6.

Table 4.1. FSICC Global Services for Global Resource G^1

Gid	Service Name
gs$_1$	PUT /FSICC/Observation/id obINFO
gs$_2$	GET /FSICC/Observation/id
gs$_3$	PUT /FSICC/Patient/id ptINFO
gs$_4$	GET /FSICC/Patient/id
gs$_5$	PUT /FSICC/User/id usINFO, Token
gs$_6$	PUT /FSICC/Encounter/id enINFO
gs$_7$	GET /FSICC/Encounter/id
gs$_8$	PUT /FSICC/Condition/id cnINFO
gs$_9$	GET /FSICC/Condition/id

Table 4.2. FSICC Global Roles for Global Resource G^1

Rid	Role	FSICC Services
G_{R1}	GPhysician	gs_2, gs_4, gs_5
G_{R2}	GPatient	$gs_1 - gs_5$
G_{R3}	GCoach	gs_2, gs_3, $gs_7 - gs_9$
G_{R4}	GNurse	$gs_1 - gs_4$, $gs_6 - gs_9$
G_{R5}	GParent	$gs_2 - gs_4$, $gs_7 - gs_9$
G_{R6}	GTrainer	$gs_2 - gs_4$, $gs_6 - gs_9$
G_{R7}	GCT^2	$gs_1 - gs_4$, $gs_6 - gs_9$
G_{R8}	GMyGoogle	gs_1, gs_2
G_{R9}	GSMH	$gs_1 - gs_5$

4.6 Advanced Definitions on FSICC

After presenting a set of definitions that describes the unified set of global services of FCISS, this section continues and provides a set of Definitions 40 to 48 that explains the way that services and security policies of different systems are mapped to generate global services and global security policy for FSICC. Specifically, this section defines the main components of the FSICC and the way that such components are generated from the separate mapping involving clients and systems. The first mapping is from clients (which have services to register) and Systems to Global resources. The second mapping is from Client/System roles to Global roles which is FSICC's cloud computing capability 2 in Section 3.2 and the Security Policies and Services Registration and Global Security Policy Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3. The third mapping is from Clients/Systems API services to Global API services which is FSICC's cloud computing capability 1 in Section 3.2 and the Security Policies and

Services Registration and Global Services Generation boxes of the GSP Generation and GAPI Generation horizontal box in Figure 1.3.

Defn. 40: The Framework for Secure and Interoperable Cloud Computing (FSICC) can be represented as $FSICC = <G, R, U, URAS, RRPS>$ where G = {G^i | *all i resources}* is a set of all of the global resources in which each G^i as given in Defn. 39, $R = \{G^i_{R_G} |_{all i}\}$ of all role sets from all *i* global resources, $U = \{G^i_{U_G} |_{all i}\}$ of all user sets from all *i* global resources, $URAS = \{G^i_{URAS_G} |_{all i}\}$ of all user role assignment sets from *i* the global resources, and $RRPS = \{G^i_{RRPS_G} |_{all i}\}$ of all resource role permission sets from all *i* global resources.

Defn. 41: Client/System to Global Mapping $CSGM_{FSICC_i} =< C^{ID} / S^{ID}, G^{ID} >$ where each C^i / S^i is mapped to one $G^i \in G$.

Defn. 42: Client/System to Global Mapping Set: $CSGMS_{FSICC} =< CSGM_{FSICC_1}, CSGM_{FSICC_2}, \ldots, CSGM_{FSICC_j} >$, where $CSGM_{FSICC_j}$ is as defined in Defn. 41.

Defn. 43: Client/System API to Global API Mapping $CSAGAM_{FSICC_i} =< C^{ID}_{API} / S^{ID}_{API}, G^{ID}_{API} >$ where each C^i_{API} / S^i_{API} is mapped to G^i_{API}.

Defn. 44: Client/System API to Global API Mapping Set $CSAGAMS_{FSICC} =< CSAGAM_{FSICC_1}, CSAGAM_{FSICC_2}, ..., CSAGAM_{FSICC_j} >$, where $CSAGAM_{FSICC_j}$ is as defined in Defn. 43.

Defn. 45: Client/System Roles to Global Roles Mapping $CSRGRM_{FSICC_i} =< C_{R_C}^{ID} / S_{R_S}^{ID}, G_{R_G}^{ID} >$ where $C_{R_C}^{i} / S_{R_S}^{i}$ are mapped to $G_{R_G}^{i}$.

Defn. 46: Client/System Roles to Global Roles Mapping Set $CSRGRMS_{FSICC} =< CSRGRM_{FSICC_1}, CSRGRM_{FSICC_2}, ..., CSRGRM_{FSICC_j} >$, where $CSRGRM_{FSICC_j}$ is as defined in Defn. 45.

Defn. 47: Client/System Users to Global Users Mapping $CSUGUM_{FSICC_i} =< C_{U_C}^{ID} / S_{U_S}^{ID}, G_{U_G}^{ID} >$ where $C_{U_C}^{i} / S_{U_S}^{i}$ are mapped to $G_{U_G}^{i}$.

Defn. 48: Client/System Users to Global Users Mapping Set $CSUGUMS_{FSICC} =< CSUGUM_{FSICC_1}, CSUGUM_{FSICC_2}, ..., CSUGUM_{FSICC_j} >$, where $CSUGUM_{FSICC_j}$ is as defined in Defn. 47.

Note that the mappings in Definitions 41-48 are performed by a FSICC security engineer in regards to reconciling roles and APIs as part of the mapping process. Part of this process is performed utilizing a set of algorithms for global RBAC policy generation, global MAC policy generation and global DAC policy generation; this will be explored in detail in Section 6.3 of Chapter 6.

Example 4.7: Table 4.3 contains the mappings of services and roles of MyGoogle, OpenEMR, CT^2, and ShareMyHealth (see Section 2.4). This is basically, the result of utilizing FSICC's cloud computing capability 1: local service registration and mapping to global services; and cloud computing capability 2: local security policies registration to yield global security policy (see Section 3.2). Table 4.3a is for the role mapping where the client role and system role could map to the same global role, as shown for the first six rows, e.g., SMH_{R1} and $OEMR_{R2}$ rows are the Patient role for Client/System, respectively, that maps to the global Patient role G_{R2}. Tables 4.3b to 4.3e map CT^2, ShareMyHealth, MyGoogle, and OpenEMR services, respectively, to global services.

Table 4.3. Mapping Tables to Global Services.

a. Mapping Client/System to Global Roles.

Client Rid	Client Role Name	System Rid	System Role Name	Global Rid	Global Role Name
CT_{R1}	Coach	$OEMR_{R3}$	Coach	G_{R3}	GCoach
CT_{R2}	Nurse	$OEMR_{R4}$	Nurse	G_{R4}	GNurse
CT_{R3}	Parent	$OEMR_{R5}$	Parent	G_{R5}	GParent
CT_{R4}	Trainer	$OEMR_{R6}$	Trainer	G_{R6}	GTrainer
SMH_{R1}	Patient	$OEMR_{R2}$	Patient	G_{R2}	GPatient
SMH_{R2}	Physician	$OEMR_{R1}$	Physician	G_{R1}	GPhysician
		$OEMR_{R7}$	CT^2	G_{R7}	GCT^2
		$OEMR_{R8}$	MyGoogle	G_{R8}	GMyGoogle
		MG_{R1}	SMH	G_{R9}	GSMH

b. Mapping of CT^2 Services to Global Services.

Sid	Service Name	Gid	FHIR CRUD/Resource
CT_1	PUT /CT2/concussion/status statusINFO	G_1	PUT Observation
CT_2	GET /CT2/concussion/status statusID	G_2	GET Observation
CT_3	GET /CT2/student studentID	G_4	GET Patient

CT_4	PUT /CT2/student/add studentINFO	G_3	PUT Patient
CT_5	PUT /CT2/followup/add followupINFO	G_7	PUT Encounter
CT_6	GET /CT2/followups followupID	G_8	GET Encounter
CT_7	GET /CT2/concussion/student studentID	G_{10}	GET Condition
CT_8	PUT /CT2/concussions/add concussionsINFO	G_9	PUT Condition

c. Mapping of ShareMyHealth Services to Global Services.

Sid	Service Name	Gid	FHIR CRUD/Resource
SMH_1	PUT /SMH/newMeasure/mID mINFO	G_1	PUT Observation
SMH_2	GET /SMH/Measures/mID	G_2	GET Observation
SMH_3	PUT /SMH/newPatient/pID pINFO	G_4	GET Patient
SMH_4	GET /SMH/Patients/pID	G_3	PUT Patient
SMH_5	PUT /SMH/Users/uID Token	G_5	PUT User

d. Mapping of MyGoogle Services to Global Services.

Sid	Service Name	Gid	FHIR CRUD/Resource
MG_1	PUT /MyGoogle/fitness/dataSources/dsID dsINFO	G_1	PUT Observation
MG_2	GET /MyGoogle/fitness/dataSources/dsID	G_2	GET Observation
MG_3	PUT /MyGoogle/newPatient/pID pINFO	G_4	GET Patient
MG_4	GET /MyGoogle/Patients/pID	G_3	PUT Patient
MG_5	PUT /MyGoogle/Users/uID Token	G_5	PUT User

e. Mapping of OpenEMR Services to Global Services.

Sid	Service Name	Gid	FHIR CRUD/Resource
$OEMR_1$	PUT /OpenEMR/updatepatientnotes noteINFO	G_1	PUT Observation
$OEMR_2$	GET /OpenEMR/getnotes noteID	G_2	GET Observation

$OEMR_3$	GET /OpenEMR/getallpatients patientID	G_4	GET Patient
$OEMR_4$	PUT /OpenEMR/addpatient patientINFO	G_3	PUT Patient
$OEMR_5$	PUT /OpenEMR/addvisit visitINFO	G_7	PUT Encounter
$OEMR_6$	GET /OpenEMR/getvisits visitID	G_8	GET Encounter
$OEMR_7$	GET /OpenEMR/getlist conditionID	G_{10}	GET Condition
$OEMR_8$	PUT /OpenEMR/addlist conditionINFO	G_9	PUT Condition

4.7 Core Definitions on Interceptors

As we described earlier in Section 3.2 of Chapter 3, the global security policy of FSICC is generated by the cloud computing capability 2 of FSICC, i.e., local security policies registration to yield global security policy, that utilizes two components of FSICC: Security Policy Mapping box of FSICC in Figure 1.1 and Global Security Policy box of FSICC in Figure 1.1. To enforce the FSICC's global policy defined on global resources with the allowed API service calls controlled by RBAC (FSICC's security requirement 2), MAC (FSICC's security requirement 4), and DAC (FSICC's security requirement 3) permissions, this section introduces a set of definitions for security Interceptor that is able to intercept API calls to global services in order to perform appropriate RBAC, MAC, and DAC security enforcement checks. To begin, we define an interceptor as follows:

Defn. 49: A Security Interceptor is defined as a programmatic mechanism that is able to intercept a service call from a client application to an API in order to perform appropriate security enforcement checks.

The remainder of this chapter reviews the interceptors for RBAC, MAC, and DAC. Section 4.7.1 provides a set of definitions that explains the way that the global RBAC policy are enforced using the RBAC interceptor. Section 4.7.2 discusses a set of definitions that explains the way that the global MAC policy is enforced using the MAC interceptor. Section 4.7.3 provides a set of definitions explains the way that the global DAC policy are enforced using the DAC interceptor. Note that at the end of each subsection, we provide an example for the respective definitions.

4.7.1 Definitions on RBAC Interceptor

In support of the FSICC's security requirement 2 (see Section 3.1), this section presents definitions for the RBAC interceptor. Definitions 50 to 52 provide two enforcement checks that the RBAC interceptor utilizes to enforce the global RBAC policy.

Defn. 50: User-Role Enforcement Check: For a global resource, G^i, a user $u^{ID} \in G^i_{UG}$ can utilize a role $r^{ID} \in G^i_{RG}$ iff the entry $<u^{ID}, r^{ID}>$ exists in the User-Role set G^i_{URASG}.

Defn. 51: Role-Service Enforcement Check: For a global resource, G^i, a user with a role $r^{ID} \in G^i_{RG}$ can access a global service $\sigma^i_{ID} \in G^i_{API}$ iff the entry $<r^{ID}, \sigma^i_{ID}>$ exists in the role permissions set $\text{RPS}_{rid} \in G^i_{RRPSG}$.

Defn. 52: The RBAC Interceptor of FSICC is a programmatic security enforcement check utilizing Definitions 50 and 51 that is able to determine at runtime if the requested API call on a global service can be executed for a user u^{ID} (Defn. 15v2) with a role r^{ID} (Defn. 9v2).

Example 4.8: Consider a Global Resource G^1 that has: a user $u_1^{G^1} = <1, John>$; and a role $r_1^{G^1} = <1, GPhysician>$ in which $r_1^{G^1}$ is authorized to access global services $\{\beta_1^{G^1}, \beta_2^{G^1}, \beta_3^{G^1}\}$; and suppose that the user-role assignment $ura_1^{G^1} = < u_1^{G^1}, r_1^{G^1} >$ is established, then the user $u_1^{G^1}$ can invoke all the three global services $\{\beta_1^{G^1}, \beta_2^{G^1}, \beta_3^{G^1}\}$.

4.7.2 Definitions on MAC Interceptor

In order to support the FSICC's security requirement 4 (see Section 3.1) and the MAC Interceptor, we first define the level of security enforcement checks that are required for MAC. The MAC model (Bell & La Padula, 1976) has a set of properties, namely, *Simple Security (SS), Simple Integrity (SI), Liberal* (L*), and Strict* (S**) that has both Read and Write capabilities. Such properties are defined to determine under which conditions a user with a CLR level can read or write a given data item with a CLS level. For the purposes of FSICC, this is focused on whether a user with a CLR level can invoke a write service (i.e., Create, Update, or Delete) or a read service (i.e., Read) with a CLS level that is part of a global service permission. Now we explain the way that MAC properties are used in FSICC. First, SS property (or read-down, no read-up) is the permission to invoke a read service that has an equal or lower CLS level. That is, a user is allowed to invoke a Read service with a CLS level equal to or lower than their CLR level, but not those Read services with a higher CLS level. Second, SI property (or write-down, no write-up) is the permission to invoke a write service that has an equal or lower CLS levels.

That is, a user can invoke a Create, Update, or Delete service of equal or lower CLS level when compared to their CLR level, but not to those Create, Update, or Delete services with a higher CLS levels. Third, L* property (or write-up, no write-down) is the permission to invoke a write service that has an equal or greater CLS level (the opposite of SI). Forth, S* Write property (or write equal) is the permission to invoke a write service that only has an equal CLS level. Finally, S* Read property (or read equal) is the permission to invoke a read service that only has an equal CLS level. From a definition and management perspective, an Security engineer of FSICC would set the

CLR level of users following the predefined sensitivity levels (e.g., TS, S, C, and U - see Defn. 10) to establish the levels for both users and services. These levels are then augmented on a user-by-user basis by assigning the ability to invoke a read service (via SS or S* Read properties) and the ability to invoke a write service (via SI, L*, or S* Write properties).

In support of the FSICC's security requirement 4 (see Section 3.1), this section presents definitions for the MAC interceptor. Definitions 53 to 56 introduce concepts on MAC read/write properties and an enforcement check that the MAC interceptor utilizes to enforce the global MAC policy.

Defn. 53: Available MAC properties: There are four properties: Simple Security (SS), Simple Integrity (SI), Liberal* (L*), Strict* (S*) that has both Read and Write capabilities. The SS property allows a user to invoke a read service iff the user's CLR is equal or higher than the CLS of the read service. The SI property allows a user to invoke a write service iff the user's CLR is equal or higher than the CLS of such a service. The L* property allows a user to invoke a write service iff the user's CLR is equal or below the CLS of such a service. The S* Write property allows a user to invoke a write service iff the user's CLR is equal to the CLS of such a service. The S* Read property allows a user to invoke a read service iff the user's CLR is equal to the CLS of such a service.

Defn. 54: User Assigned MAC Properties: The Security engineer is responsible for assigning each user one read property (SS or S* Read) and one write property (SI, L*, or S* Write).

Defn. 55: MAC Enforcement Check: For a global resource, G^i, a user $u \in G^i_{U_G}$ can invoke a Read, Create, Update, or Delete global service $\beta_i^{G^i}$ iff the CLR of *u* satisfies established MAC properties (Definitions 53 and 54).

Given Definitions 53 and 54, we revise Defn. 15v2 as below:

Defn. 15: (v3) A *user, u,* is defined as five-tuple $u = < u_{ID}, u_{NAME}, u_{CLR}, u_{MACRD}, u_{MACWR} >$, where u_{MACRD} is SS or S* Read and u_{MACWR} is SI, L*, or S* Write (Defn. 53).

Example 4.9: Consider a Global Resource G^1 that has a user $u_1^{G^1} = <1, John, TS>$ and three global services: a Create service $\beta_1^{G^1} = < gs^{11}, NewRx, \beta_{SIG}^{gs11}, S >$, a Read service $\beta_2^{G^1} = < gs^{12}, AllRx, \beta_{SIG}^{gs12}, S >$, and a Read service $\beta_3^{G^1} = < gs^{13}, CanRefill, \beta_{SIG}^{gs13}, C >$, and suppose that the Security engineer established two MAC properties (SS, SI) on $u_1^{G^1}$, then the user $u_1^{G^1}$ can invoke all the three global services, since the CLR level (TS) of $u_1^{G^1}$ is greater than all CLS levels (S, S, and C) of services ($\beta_1^{G^1}$, $\beta_2^{G^1}$, and $\beta_3^{G^1}$), respectively.

Defn. 56: The MAC Interceptor of FSICC is a programmatic security enforcement check utilizing Definitions (53, 54 and 55) that is able to determine at runtime if the requested API call on a global service can be executed for a user with a CLR (Defn. 15v3) and limited by a Read/Write properties combination (Defn. 54).

4.7.3 Definitions on DAC Interceptor

In support of the FSICC's security requirement 3 (see Section 3.1), this section presents definitions for the DAC interceptor. Definitions 57 to 60 provide three enforcement checks that the DAC interceptor utilizes to enforce the global DAC policy.

Defn. 57: Delegated User-Delegated Role Enforcement Check: For a global resource, G^i, a delegated user $du^{ID} \in G^i_{UG}$ can utilize a delegated role $dr^{ID} \in G^i_{RG}$ iff the entry $< ou^{ID}, du^{ID}, dr^{ID}>$ exists in the Delegation Set G^i_{DSG}.

Defn. 58: Delegated User-Delegated Role Permission Enforcement Check: For a global resource, G^i, a delegated user $du^{ID} \in G^i_{UG}$ can utilize a delegated role permission drp^{ID} iff the entry $< ou^{ID}, du^{ID}, drp^{ID}>$ exists in the Delegation Set G^i_{DSG}.

Defn. 59: Delegated User- Delegated Clearance Enforcement Check: For a global resource, G^i, a delegated user $du^{ID} \in G^i_{UG}$ can utilize a delegated clearance $dc^{ID} \in G^i_{RG}$ along with the associated read/write properties iff the entry $< ou^{ID}, du^{ID}, dc^{ID}>$ exists in the Delegation Set G^i_{DSG}.

Defn. 60: The DAC Interceptor of FSICC is a programmatic security enforcement check utilizing Definitions 57-59 that is able to determine at runtime if the requested API call on a global service can be executed for a delegated user du^{ID}.

Example 4.10: Consider a Global Resource G^1 that has: two users $u_1^{G^1} = <1, John>$ and $u_2^{G^1} = <2, Ali>$; and a role $r_1^{G^1} = <1, GPhysician>$ in which the resource delegation set $G^1_{DS_C}$ has an entry $\{ d_1^{G^1} \}$ with $d_1^{G^1} = < u_1^{G^1}, u_2^{G^1}, r_1^{G^1} >$, then the user $u_2^{G^1}$ can utilized all the global permissions that are authorized to $r_1^{G^1}$.

4.8 Related Work on Access Control for Cloud Computing

In this section, we review a number of related works on access control for cloud computing, comparing and contrasting their work to our approach in this chapter. We classify these related efforts into two main groups: the first group of three efforts involves data-based RBAC in a cloud setting while the second group of three efforts involves RBAC in a cloud setting at an API level.

The first effort (Tang, Wei, Sallam, Li, & Li, 2012) proposed an RBAC model with an owner role to enable the data owner to grant a user access to their data and to update the owner data in cloud, with a user role. Our work on UCCACM is similar to this effort since both works involve definitions for RBAC and DAC that can be utilized to restrict users access in the cloud. However, while our UCCACM provides MAC based capabilities to secure sensitive services, their effort does not consider the need for controlling users access based on sensitivity levels (MAC).

The second effort (Wang Z. , 2011) proposed a cloud-based RBAC that authorizes permissions to data in cloud with roles that assigned to cloud users. This is accomplished by two main algorithms: the User Role Assignment and the Role Permissions Assignment. To further control sensitive data, this effort enables a cloud user to disable/enable roles that are authorized to such sensitive data. The main common aspect between this effort and our work on UCCACM is that both works utilize RBAC to control user access in the cloud. However, regarding more sensitive data/services, their effort utilizes it approach that disable/enable roles while in UCCACM we utilize a more advanced technique with sensitivity levels (MAC).

The third effort (Takabi, Joshi, & Ahn, 2010) proposed a security framework for cloud computing environments that has an access control module that protects a provider's data in cloud using classic RBAC. Our work on UCCACM is similar to this effort since both works involve definitions for RBAC that can be used to restrict users access in the cloud. However, while our

UCCACM provides MAC and DAC based capabilities to secure sensitive services, their effort does not consider the need for controlling users access based on sensitivity levels (MAC) and delegation (DAC).

The fourth effort (Sirisha & Kumari, 2010) proposed an API-based RBAC model for cloud services that defines permissions against cloud services where permissions are authorized to roles that are assigned to users. This effort is similar to our work on UCCACM since both works define permissions against cloud API (cloud services). However, our UCCACM is more fine-grained since permissions are assigned to different CRUD methods of cloud services, while their effort allows/denies access to all CRUD methods.

The fifth effort (Wonohoesodo & Tari, 2004) proposed a Web Service (SOAP)-based RBAC model in which a role assigned to a service consumer is authorized to both a SOAP service and a parameter of a SOAP service with an access mode (e.g., read, write, execute, modify, and delete). The main common aspect between this effort and our work on UCCACM is that both works utilize RBAC to restrict the way that users can access services. However, while their effort is dedicated to SOAP-based services, the permissions in UCCACM can be defined and enforced on any type of cloud or web services such as SOAP and REST.

The last effort (Feng, Guoyan, Hao, & Li, 2004) also proposed a Service (SOAP)-Oriented RBAC model that authorizes SOAP services to roles that can be assigned to users, where when a user activates a role, an Actor is created that enables the user to access SOAP services authorized to the role. Although this effort introduced the role activation by users, this effort basically is similar to our work on UCCACM since both works utilize RBAC to restrict access to services. However, their effort is more focused on SOAP-based services, while in UCCACM the permissions can be defined and enforced on any type of cloud or web services such as SOAP and REST.

Overall, our work on UCCACM contrasts with the three first efforts by focusing on defining permissions against cloud services as opposed to data. Regarding the last three efforts, their work differs from UCCACM since none of these efforts utilizes sensitivity levels (MAC) or delegations (DAC) to restrict access to the services.

Chapter 5
Architectural Blueprints to Facilitate Interoperability and Information Exchange of Clients and Systems

As presented in Section 1.4 of Chapter 1, an *integration layer* was defined as a standard API that converts data from a system or client into a common data format to facilitate information exchange. Such a common data format can be utilized by other systems and clients, within a framework like FSICC, to easily exchange data. An integration layer exists with an *integration framework (IFMWK)* which is a set of standards and associated technologies that allow different systems to interact with one another utilizing one common data format. The associated technologies allow integration servers to be designed and implemented to facilitate the exchange of information using the common data format via a set of shared services via an integration layer. The integration framework facilitates the interactions of clients and systems with one another in FSICC by providing a common layer to allow clients and systems to interact with one another. The common layer of IFMWK can be used to map to and from cloud, programming, or web services. To accomplish this mapping, we assume that the integration framework IFMWK has an available implementation that can be utilized to generate dedicated IFMWK servers for two-way mapping and exchange as needed. The FHIR standard presented in Section 2.3 of Chapter 2 and its HAPI FHIR reference implementation, which has a set of resources in XML, JSON, RDF, and Turtle that are a common data representation with associated services for CRUD and searching, is an example of an integration framework (FHIR) and its implementation (HAPI).

As described in Chapter 1, the interactions and integration of clients and systems with the Framework for Secure and Interoperable Cloud Computing (FSICC), as shown in Figure 1.1, can be defined from a client perspective and from a system perspective. From a system perspective, each system, which corresponds to the Systems box in the Involved Parties component at the topmost of Figure 1.2 from Chapter 1, needs to create an integration layer API in front of their API, and modifies their security policy to be defined against the integration layer API. This integration layer corresponds to the Architectural Blueprints in Figure 1.3. *Architectural Blueprints,* the main focus of this chapter, are guidelines that define the way of placing and creating an integration layer for a systems or client to allow such them to exchange data with other systems and clients in one common data format. There are three *Architectural Blueprints* options as shown in Figure 1.2: a *Basic Architecture* option that includes a IFMWK server that works directly with the App repository and IFMWK servers of other systems; an *Alternative Architecture* option that includes a IFMWK server that works directly with the App RESTful API and IFMWK servers of other systems; and, a *Radical Architecture* option that removes the repository and has IFMWK servers for the App API and the other systems. Once a blueprint option has been chosen and applied, each system is able to register: the system's name, the integration layer API, and the security policy into FSICC. This is done using the Systems Registry box in the middle of Figure 1.1, which corresponds to the Registration and Services Mapping box of the Generation of Global Policy and Services component in Figure 1.2. Based on the integration layer of registered systems, the security engineer of the FSICC creates a global API. This corresponds to the Global Services box of the Generation of Global Policy and Services component in Figure 1.2, which is an integration layer in which clients may utilize such a global API via FSICC. Each of the different alternatives of the architectural blueprints process the means to integrate the services of a system so that can easily map to/from the global services.

From a client perspective, each client, which corresponds to the Clients box in the Involved Parties component at the topmost of Figure 1.2, creates an integration layer API at the top of Figure

1.1 in front of its API. Clients, like systems, may require an architectural blueprint option to integrate with FSICC, particularly in the case where it is a mixed client, see Defn. 6 in Section 4.2 of Chapter 4. With or without a blueprint, each client is able to register: the client's name into the FSICC, using the Clients Registry box, and reconfigure the client integration layer API to call the global API of FSICC, see Figure 1.1. The integration layer that can be created by systems, clients, and FSICC is the technology that facilitates the bi-directional mapping and exchange of information: between clients' applications and global services of FSICC; and, between systems' services and global services of FSICC.

The architectural blueprints presented in this chapter have a strong interaction with UCCACM as was shown in the top portion of Figure 1.3 from Chapter 1. UCCACM has four definitions that are directly related to architectural blueprints. Definitions 41 to 44 involve, respectively: the mapping of clients and systems that provide services to global resources in FSICC in Defn. 41; the set of all of the global resources that were mapped from clients and systems in Defn. 42; the mapping of the services of the APIs from clients and systems to the global services APIs of FSICC in Defn. 43; and, the set of all of the global APIs for all clients and systems in Defn. 44. The architectural blueprints that enable clients and systems to provide an API that is conducive to being integrated via UCCACM into FSICC which is facilitated using the mappings of Definitions 41 to 44. This chapter explores and examines three architectural blueprints options, Basic Architecture, Alternative Architecture, and Radical Architecture, for design and development processes that can be followed to integrate an mHealth, web, or desktop application utilizing FHIR to multiple HIT systems via FSICC. The work in this chapter supports expected contribution EC-A: Architectural Blueprints for Supporting FSICC from Section 1.5, this is represented by the Architectural Blueprints box at the top of Figure 1.3.

The remainder of this chapter is organized into a five-part discussion. In Section 5.1, we explore four issues that must be understood for an application of FSICC to support a discussion of the architectural blueprint options: the *overall architecture* of the application; the *involved technologies* that can be used to develop the application; the *source code availability* of the application, APIs, server code, or database; and, the *allowable access to system* sources. In Section 5.2, we examine the three different Architectural Blueprint options, namely, Basic, Alternative, and Radical, for integrating an application to multiple HIT systems via FSICC, utilizing an integration framework, IFMWK, with examples provided using FHIR. In Section 5.3, we present Architectural Blueprints for each of the three options that illustrates the way that the options can be realized using IFMWK, including the various phases and steps that are required. In Section 5.4, we explore a complex example that utilizes the Alternative and Radical Architectural Blueprint options prototype applied to the healthcare scenario from Section 2.4 of Chapter 2 via FHIR as an IFMWK and HAPI as a server. In Section 5.5, we discuss two related works in the literature that explain alternative ways that FHIR can be implemented to integrate healthcare systems and/or applications in different settings. Note that the work in this chapter has been published in (Baihan, M., et al., 2018) (Ziminski, T., Demurjian, S., Sanzi, E., Baihan, M., & Agresta, T., 2017).

5.1 Issues that Impact Interoperability

In this section, we explore the different characteristics and components of an application and its interaction with multiple mixed clients and pure or mixed systems via FSICC and as a result define for issues that impact interoperability. The four issues are: the *overall architecture* of the application with respect to tiers of functionality of mixed clients and pure or mixed systems such as one-tier, two-tier, and three-tier architectures, etc.; the *involved technologies* that are utilized by different mixed clients and pure or mixed systems such as RESTful APIs, programmatic APIs, database API, etc.; the *source code availability* of the mixed clients and pure or mixed systems such as the app, APIs, server code, or database; and, the *allowable access* to the mixed clients and pure or mixed systems via RESTful APIs, programmatic APIs, etc. Each is discussed in turn.

The first issue that impacts interoperability choices is the *overall architecture* of the application with respect to tiers of functionality of mixed clients and pure or mixed systems such as one-tier, two-tier, and three-tier architecture, etc. That is, in order to integrate a mixed client or pure or mixed system, via FSICC, one must understand its architecture. In general, there are three different architectures: one-tier, two-tier, and three-tier. In a one-tier architecture, the client/system would contain all of the components of the client/system including: user interface (the presentation layer); user request processing (the business layer); and the repository (the data layer). In a two-tier architecture, the client/system would have the user interface (the presentation layer) while user request processing (the business layer) and the repository (the data layer) are hosted in a separate server. In a three-tier architecture, the client/system would only have the user interface (the presentation layer) with the user request processing (the business layer) hosted by a separate server through an API and the repository (the data layer) hosted in another separate (third) server. Note that the repository in all three cases may in turn interact with another layer but from the perspective of the architectural blueprints options, this will be hidden. Also note that for the two and three tier architectures, the middle request processing layer might involve access to multiple separate APIs. For the purposes of this dissertation, the mixed clients and pure or mixed systems are client mHealth apps or system HITs. The second issue that impacts the choice of an integration option is the *involved technologies* that are utilized by different mixed clients and pure or mixed systems such as RESTful APIs, programmatic APIs, database API, etc. These technologies can be utilized by a mixed client or pure or mixed system to make external integration with FSICC possible. The programmatic API of a client/system is a set of definitions for functions or methods of that application, where an external application may call an API to perform an application's method without the knowledge of the actual code of such a method. A repository API is similar to the programmatic API, however, the functions or methods of such API perform operations over repository items that may be in a database or some other option. A RESTful API is a set of definitions for methods of an application. Such an API is designed based on the REST architecture (Fielding, 2000) which utilizes Hypertext Transfer Protocol (HTTP) requests to interact with the data of a client/system. Cloud services are the APIs that define the way that cloud consumers can access and utilize cloud computing resources such as software. These cloud services can be designed using web services such as Representational State Transfer (REST), Simple Object Access Protocol (SOAP), etc.

The third issue that impacts the choice of an integration option is the *source code availability* of the mixed clients and pure or mixed systems such as the app, APIs, server code, or database. Since a client/system can be developed based on different architectures (as described in issue 1), it is crucial to consider the availability of source code of components such as the app, APIs, server, or repository. Specifically, the source code of the client/system is the code that is used to implement: the user interface component and the methods that interacting with any external servers. The API's source code is the code that is utilized to map the application's methods to an abstract set of calls that an external source can invoke. The server code is the code that is used to implement the business logic of the application. The repository source code is the source file or database schema and any code that is used to access data in such a repository. Some of the architectural blueprint options require access to source code in order to make limited programmatic changes to support the integration. The intent is to try to minimize these changes when attempting to integrate an app with multiple mixed clients and pure or mixed systems via FSICC, in order to have little or no impact on existing code.

The fourth and final issue that impacts the choice of an integration option is the *allowable access* to the mixed clients and pure or mixed systems via RESTful APIs, programmatic APIs, etc. This enables external applications to be integrated with such mixed clients and pure or mixed systems. The ability to integrate these various API and services seamlessly with an integration framework such as HAPI FHIR is critical to support the different integrations options presented in this chapter. Recall in the introduction to this chapter, we defined an *integration framework*, *IFMWK*, as a set of standards and associated technologies that allow different systems to interact with one another utilizing one common data representation. The associated technologies allow integration servers to be designed and implemented to facilitate the exchange of information using the common data representation via a set of shared unified services. The FHIR standard is one example of an integration framework which has a set of resources in XML, JSON, RDF, and Turtle that are a common data representation with associated services for CRUD and searching. The HAPI FHIR reference implementation is the associated technology that implements the FHIR framework that uses CRUD services; as a result, it is possible to develop a FHIR server as a means to support integration. In summary, the exact configuration of each of the four aforementioned issues (*overall architecture*, *involved technologies, source code availability*, and *allowable access to* mixed clients and pure or mixed systems) has a direct impact on the different available options that can be utilized via an integration framework such as HAPI FHIR to integrate a particular application architecture and multiple mixed clients and pure or mixed systems via FSICC.

5.2 Application Integration Options

In this section, we enumerate a number of different *Application Integration Options* to allow an application to send/receive data with multiple mixed clients and pure or mixed systems, via FSICC, by the creation of integration servers. To begin, Figure 5.1 contains an architecture of an App (a client/system), its RESTful API, and its repository along with three systems (OpenEMR, OpenMRS, and a PHR such as MTBC (MTBC, 2016)). Note that while we use health information technology (HIT) in the example, the integration options and blueprints work for any IT system from any domain. The different components in Figure 5.1 define three architectural blueprint options that illustrate the alternate ways that the App can be integrated with the systems, via FSICC, based on the four issues previously discussed in Section 5.1 (*overall architecture, involved technologies*, *source code availability*, and *allowable access to client/system*). In order to facilitate the integration of multiple systems with one another, we utilize the previously integration framework, IFMWK, to accomplish this mapping, we assume that the integration framework IFMWK has an available implementation that can be utilized to generate dedicated IFMWK servers as needed. Note that the aforementioned FHIR standard and its HAPI FHIR reference implementation correspond to the sample of an integration framework and its implementation. Using this discussion as a basis, in this section, we present three architectural blueprint options: a *Basic Architecture* option that includes an IFMWK server that works directly with the App repository and IFMWK servers for OpenEMR, OpenMRS, and PHR; an *Alternative Architecture* option that includes an IFMWK server that works directly with the App RESTful API and IFMWK servers for OpenEMR, OpenMRS, and PHR; and, a *Radical Architecture* option that removes the repository and has IFMWK servers for the App API, OpenEMR, OpenMRS, and PHR. Note that the HITs that are shown (OpenEMR, OpenMRS, and PHR) are illustrative and in practice, a generalized version could have one or more systems via FSICC, but for explanation purposes we utilize   three HIT systems. Note that in the rest of this chapter, we use the term HIT systems as follows. HIT is referring to health information technology such as EMRs and PHRs, and systems is referring to pure or mixed systems as discussed in Defn. 7 of Section 4.2.

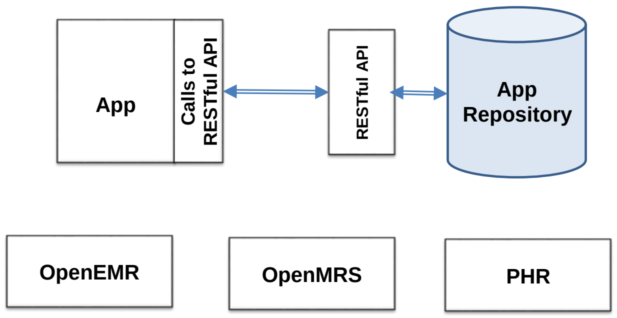


Figure 5.1. App and HIT Systems.

The *Basic Architecture* option is shown in Figure 5.2a, where the assumption is made that: direct access to the app repository is available; and, the source codes of app, RESTful API, OpenEMR and OpenMRS HIT systems and their APIs are available. In Figure 5.2a, at the bottom, there are IFMWK servers, see the ovals in Figure 5.2a, to load/store data from OpenEMR, OpenMRS and PHR (named OpenEMR.IFMWK, OpenMRS.IFMWK, and PHR.IFMWK) using their APIs (a third tier) into selected IFMWK resources; and an App.IFMWK server to load/store data from the App repository, at the top of Figure 5.2a. Basically, each HIT systems requires an IFMWK server (e.g., OpenEMR.IFMWK) to extract data to/from HIT via IFMWK resources that in turn interacts with the App.IFMWK server of the App repository. Interactions from the App via its RESTful API are not impacted; also, the App RESTful API to the App repository. However, to enable the App to take advantage of the HIT systems, two new IFMWK services App.IFMWK.LOAD and App.IFMWK.STORE are defined. The App.IFMWK.LOAD service retrieves all of the data from either OpenEMR, OpenMRS, or the PHR in the IFMWK format. This App.IFMWK.LOAD service takes the JSON IFMWK from the HIT.IFMWK (e.g., OpenEMR.IFMWK) server and add them into the App repository via an App IFMWK service, which converts the IFMWK format into App repository format. This allows all of the App RESTful API calls to use this temporary data. The App.IFMWK.STORE service extracts data from the App repository, via an App IFMWK service, which coverts App repository format into IFMWK format and adds them into the OpenEMR, OpenMRS, or the PHR repository. The App.IFMWK.LOAD and App.IFMWK.STORE services require source code availability of the repository in order to make the needed calls to stage data back and forth from HIT sources. Note that the App.IFMWK.LOAD and App.IFMWK.STORE services may also be periodically called to ensure that the repositories at both sides are updated. In this way, the App, API, and repository are not modified. Figure 5.2b presents a customized Basic Architecture applied to the healthcare domain where the FHIR framework is used as an example of an integration framework for healthcare, where all IFMWKs in Figure 5.2a is replaced by FHIR in Figure 5.2b.

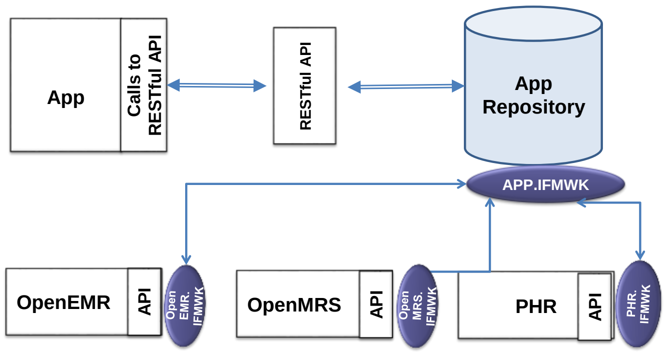


Figure 5.2a. Basic Architecture with Direct Database Access using IFMWK.

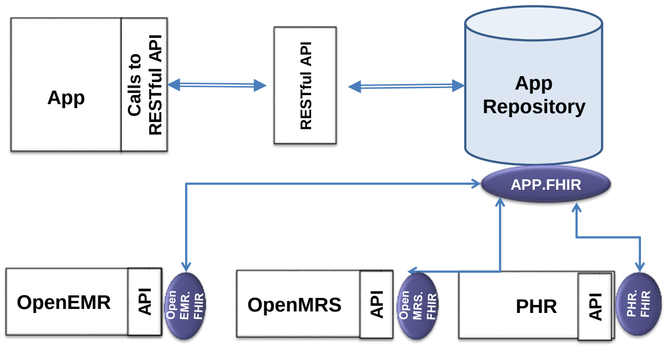


Figure 5.2b. Basic Architecture customized with FHIR for IFMWK.

In the second option, shown in Figure 5.3a, the situation is similar to the basic option in Figure 5.2a, except that there is no direct access to the app repository. Thus, the App.IFMWK server on the App side is moved in order to directly interact with the App RESTful API. There are still the HIT.IFMWK servers for OpenEMR/OpenMRS/PHR as in Figure 5.3a. In this option, the App continues to use the App RESTful API without change. However, the App.IFMWK.LOAD and App.IFMWK.STORE services transition to become part of the App RESTful API. That is, each App.IFMWK.READ service of the App RESTful API first calls the App.IFMWK.LOAD service, which takes an id of the queried instance and: retrieves the related data from OpenEMR, OpenMRS, or PHR via their IFMWK server. The second call adds retrieved data into the App repository via another App IFMWK API service using the App.IFMWK.CREATE service. This requires slight programmatic changes and source code availability (third issue of Section 5.1). The next step in the process calls the App.IFMWK.READ service of the App RESTful API which retrieves the related data from the App repository (which is updated with the new data from the HIT system). Similarly, each App.IFMWK.CREATE service of the App RESTful API first adds the related data into the App repository. Then, the App.IFMWK.CREATE service of the App RESTful API calls the STORE service, which takes the newly added data from the App repository via another App.IFMWK API service (i.e., a App.IFMWK.READ service) and adds them into the OpenEMR, OpenMRS, or the PHR database, via their IFMWK service. Note that, in this way, while the App and its calls to the App.IFMWK.RESTful API are not modified, there is a single call is added to either the App.IFMWK.LOAD or App.IFMWK.STORE services RESTful API. This requires source code availability of the RESTful API. Figure 5.3b presents a customized Alternative Architecture applied to the healthcare domain where the FHIR framework is used as an example of an integration framework for healthcare, with all of the IFMWKs in Figure 5.3a is replaced by FHIR in Figure 5.3b.

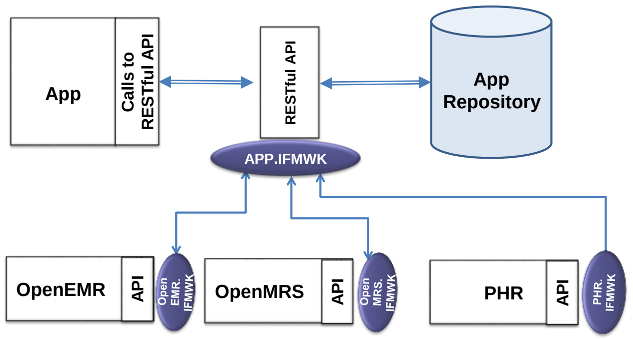


Figure 5.3a. Alternative Architecture with App RESTful API Access using IFMWK.

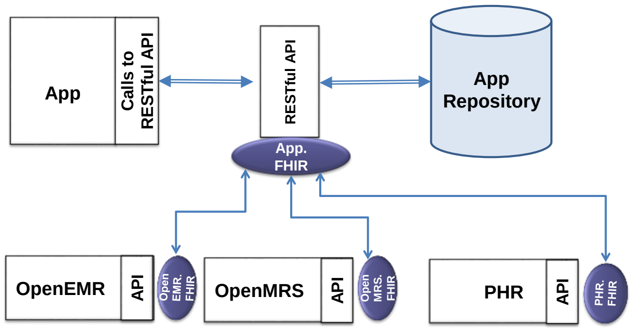


Figure 5.3b. Alternative Architecture customized with FHIR for IFMWK.

In the *Radical Architecture*, shown in Figure 5.4a, the situation is the same as the alternative option of Figure 5.3a, but alters the tiers by removing the repository (database). As a result, this option is a more drastic and involves replacing the App repository and so that it now totally relies on the HIT systems. This option would move and reconfigure all of the App data under the control of the HIT system to store and manage all data. This requires a total rewrite of the code for the App RESTful API with the strong requirement that all service signatures remain unchanged so as not to impact the App. In this case, every rewritten App RESTful API service implements a App.IFMWK service to directly call OpenEMR.IFMWK, OpenMRS.IFMWK, or PHR.IFMWK as required to load/store data as needed. In the Radical Architecture, the services defined are: App.IFMWK.CREATE, App.IFMWK.READ, App.IFMWK.UPDATE, and App.IFMWK.DELETE. Source code availability and changing the APIs may be required. This approach is clearly time and effort prohibitive. Figure 5.4b presents a customized Radical Architecture applied to the healthcare domain, where the FHIR framework is used as an example of an integration framework for healthcare, with all of the IFMWKs in Figure 5.4a is replaced by FHIR in Figure 5.4b.

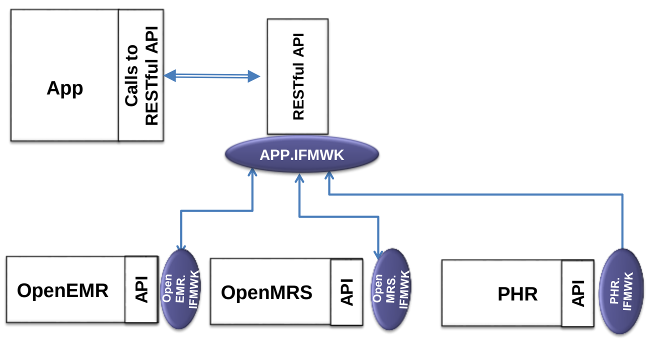


Figure 5.4a. Radical Architecture without a Database using IFMWK.

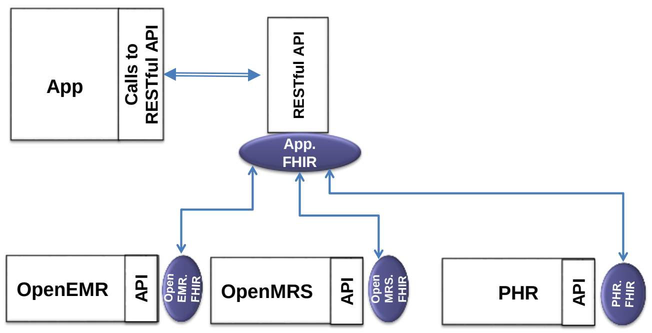


Figure 5.4b. Radical Architecture customized with FHIR for IFMWK.

5.3 Integration Steps and Processes of Architectural Blueprints

This section presents a discussion of the steps and processes that are necessary to develop the various IFMWK servers illustrated in Figures 5.2a, 5.3a, and 5.4a for the Basic, Alternative, and Radical options. The end result is set of guidelines for the architectural blueprints for the integration of an App application, via a App.IFMWK server that integrates with the App RESTful API, with multiple HIT systems, via FSICC, and a HIT.IFMWK server that integrates with the APIs of OpenEMR, OpenMRS, and PHR. The guidelines presented in this section provides stakeholders with a process to integrate an App with multiple HIT systems via FSICC using IFMWK servers. This section details the blueprints for the Basic, Figure 5.2.a, Alternative, Figure 5.3.a, and Radical, Figure 5.4.a, architectures. All three of these architectures blueprints share the common HIT.IFMWK blueprint which involves defining the HIT system data items to be sent/received and designing a HIT.IFMWK server to facilitate the exchange. The three architectures have their own specific needs, namely, the App.IFMWK server required at the App side Repository in Figure 5.2.a, the App.IFMWK server in Figure 5.3.a, and rewriting the App RESTful API in Figure 5.4.a with a App.IFMWK server. Note that while we are using an HIT system and the health care domain, this is generalizable to any IT system and associated domain.

To begin, the common *HIT IFMWK Blueprint* involves defining the HIT system data items to be sent/received back and forth via a set of Identified IFMWK Resources to another IFMWK server or client, and designing a HIT IFMWK server (HIT.IFMWK) with a RESTful API to facilitate the exchange. The processes of each step that are the guidelines are as:

1. Define the HIT system data items (i.e., for the HIT repositories in Figures 5.2.a, 5.3.a, and 5.4.a) that are needed to be exchanged to/from the App. This step consists of four sub-steps:
   a. Identify each single candidate data item (e.g., “patient name” table field) in the HIT repository that are accessible via an HIT API.
   b. For each candidate data item:
      - Provide a short and clear item name: by reviewing the IFMWK resources, identify a IFMWK resource, and mapping the candidate data item to the most comparable data item of the identified IFMWK Resource.
      - For the candidate data item, if there is no similar item’s name for the identified IFMWK resource, identify an item of a IFMWK resource that has the same datatype as the candidate data item.

        - Provide a brief description that explains the mapping for the case where there is a comparable IFMWK data item and more importantly, the case where there is only a comparable IFMWK data type.

    c. Group multiple related HIT system data items (e.g., patient name and patient gender) into a separate and distinct data abstraction (e.g., patient entity). This would make mapping to an Identified IFMWK Resource clearer by finding the most similar IFMWK resource's name.
    d. End Result: A set of *Identified IFMWK Resources* that map to the HIT data entities and items.

2. Design an HIT.IFMWK server in front of the HIT system API in two sub-steps:
    a. A HIT.IFMWK server is designed for all of the Identified IFMWK Resources in Step 1d that defines a IFMWK API that has CRUD operations for all of the Identified IFMWK Resources and interacts with the HIT API.
    b. Create Classes and CRUD services for all of the Identified IFMWK Resources for the HIT.
        - Create an HIT.IFMWK.Controller class that receives requests from the App (or any other system) and forwards each request to the appropriate Identified IFMWK Resource class based on the universally unique identifier (UUID) of an Identified IFMWK Resource.
        - Create a class for each Identified IFMWK Resource that receives requests from the IFMWK controller class and performs the requested CRUD service. This class is defined for each Identified IFMWK Resource as HIT.IFMWK.IFRCName where IFCRName is the Identified IFMWK Resource Class name. This class implements four main CRUD services:

- A HIT.IFMWK.IFRCName.Create service that stores an instance of a IFMWK resource from an external call from another IFMWK server to create and store new data into the HIT repository. This service takes the data in as a IFMWK Resource and then converts the data into a format that can be stored in the HIT repository via a call to one or more HIT API services. This effectively stores IFMWK Resource data into the HIT repository. For example, OpenEMR.IFMWK.Patient (the Patient IFMWK Resource) would call the service of an OpenEMR API that stores the data into the Patient_data table of OpenEMR's MySQL database.
- A HIT.IFMWK.IFRCName.Read service that is a request for an instance of a IFMWK resource from an external call from another IFMWK server that to read existing data from the HIT repository. This service takes the request for a IFMWK Resource that requires a call to one or more HIT API services to retrieve the data from the HIT and create an instance of an Identified IFMWK Resource to send back. For example, OpenEMR.IFMWK.Patient (the Patient IFMWK Resource) would call the service of an OpenEMR API that reads the data from the Patient_data table and perhaps other tables of OpenEMR's MySQL database and creates a FHIR Patient instance.
- An HIT.IFMWK.IFRCName.Update service that receives an instance of a IFMWK resource from an external call from another IFMWK server to update existing data into the HIT repository. This service takes the data in as a IFMWK Resource and then converts the data into a format that can be

stored in the HIT repository via a call to one or more HIT API services that update an existing instance.

- A HIT.IFMWK.IFRCName.Delete service that receives a request to remove one or more instances (based on the parameters in the request) of a IFMWK resource from an external call from another IFMWK server to delete existing data from the HIT repository. This service takes the request for a IFMWK Resource and interprets the request to call one or more HIT API services to delete instance(s).

Note that for healthcare and similar domains in practice, there may be a desire to not implement either HIT.IFMWK.IFRCName.Update or HIT.IFMWK.IFRCName.Delete services since in electronical medical records, incorrect data is not deleted, but is marked as incorrect. For example, an incorrect laboratory test result assigned to the wrong patient can be marked as not valid.

The *Basic Architecture Blueprint*, Figure 5.2.a, allows information from the App repository to be sent/received back and forth via a set of Identified IFMWK Resources to another IFMWK server or client by designing an App IFMWK server (App.IFMWK) with a RESTful API to facilitate the exchange. There are three main steps to the guideline: define the App data items, design the App IFMWK server with the LOAD and STORE services, and reuse the HIT IFMWK guideline:

1. Define the App data items (i.e., App repository tables' fields in Figure 5.2.a) needed to be exchanged with an HIT system. This step consists of four sub-steps in which the first three processes are identical to the processes of Step 1 of the HIT IFMWK Blueprint with the data

items now referring to the App data items as opposed to the HIT data items. End Result: A set of *Identified IFMWK Resources* that map to the App data items.

2. Design the App IFMWK server which consists of the App.IFMWK.LOAD and App.IFMWK.STORE services. This step has two sub-steps.
    a. A App.IFMWK.LOAD service that calls “read” services of an HIT.IFMWK to retrieve (in IFMWK format) all of the new added data from the HIT repository. Then, the App.IFMWK.LOAD service converts the retrieved IFMWK resources into a format that can be stored into App repository via App repository API. This read occurs upon startup to initialize the App repository with information from HITs.
    b. A App.IFMWK.STORE service that calls App repository API to retrieve all of the new added data in App repository and converts into the IFMWK format. Then, the App.IFMWK.STORE service simply forwards the converted data to appropriate HIT.IFMWK.CREATE services which add the new data into the HIT repository. This store occurs when the mobile app closes to update the HIT repository with information from App repository.
3. Employ the HIT IFMWK Blueprint.

Recall that the Basic Architecture has access to the source code of the repository. There may be more than one way to access the repository via Web/cloud services, an API (as with OpenEMR), or by direct programmatic access to the repository (e.g., a MySQL database). As a result, App.IFMWK.LOAD and App.IFMWK.STORE services would utilize one of these access modes in conjunction with calls to HIT.IFMWK CRUD services (e.g., OpenEMR.IFMWK.Patient.Read) and take the result of these calls for the identified IFMWK resources, and parse and put this information to/from App repository.

The *Alternative Architecture Blueprint*, Figure 5.3.a, also communicates with the common HIT IFMWK Blueprint as previously described in the last step of the Alternative Architecture blueprint. There are four main steps to the Alternative Architecture guideline: define the App data items and design the App IFMWK server (similar to the one in the Basic Architecture Blueprint), design the LOAD and STORE services, and reuse the HIT IFMWK Blueprint. The processes of each step are similar to the ones of the Basic Architecture guideline of Figure 5.2.a:

1. Define the App data items (i.e., App repository tables' fields in Figure 5.3.a) that are needed to be exchanged with an HIT system. This step consists of four main processes in which the first three processes are identical to the processes of Step 1 of the HIT IFMWK Blueprint with the data items now referring to the App data items as opposed to the HIT data items. End Result: A set of *Identified IFMWK Resources* that map to the App data items.
2. Design an App.IFMWK server in front of the App RESTful API in two sub-steps:
    a. A App.IFMWK server is designed for all of the Identified IFMWK Resources in Step 1d that defines a IFMWK API that has CRUD operations for all of the Identified IFMWK Resources and interacts with the HIT.IFMWK server.
    b. Create Classes and CRUD services for all of the Identified IFMWK Resources for the App repository.
        - A App.IFMWK.IFRCName.Create service that stores an instance of a IFMWK resource from an external call from another IFMWK server to create and store new data into the App repository. This takes the data in as a IFMWK Resource and then converts the data into a format that can be stored in the App repository via a call to one or more App RESTful API services. This effectively stores IFMWK Resource

data into the App repository. This would be similar to the OpenEMR example for the HIT.IFMWK server.

- A App.IFMWK.IFRCName.Read service that is a request for an instance of a IFMWK resource from an external call from another IFMWK server that to read existing data from the App repository. This takes the request for a IFMWK Resource that requires a call to one or more App RESTful API services to retrieve the data from the App repository and create an instance of an Identified IFMWK Resource to send back. This would be similar to the OpenEMR example for the HIT.IFMWK server.
- An App.IFMWK.IFRCName.Update service that receives an instance of a IFMWK resource from an external call from another IFMWK server to update existing data into the App repository. This takes the data in as a IFMWK Resource and then converts the data into a format that can be stored in the App repository via a call to one or more App RESTful API services, updating an existing instance.
- A App.IFMWK.IFRCName.Delete service that receives a request to remove one or more instances (based on the parameters in the request) of a IFMWK resource from an external call from another IFMWK server to delete existing data from the App repository. This takes the request for a IFMWK Resource and interprets the request to call one or more App RESTful API services to delete instance(s).

These App.IFMWK CRUD services are called by the App API in order to send information back and forth in a IFMWK format that can then be shifted to the HITs via the App.IFMWK.LOAD and App.IFMWK.STORE operations defined in Step 3.

3. Design the App.IFMWK.LOAD and App.IFMWK.STORE services. These two services are located between the App.IFMWK server and any HIT system IFMWK server and have sub-steps. The HIT.IFMWK CRUD services are used to support these functions.
    a. A App.IFMWK.LOAD service that calls "read" services of an HIT.IFMWK to retrieve (in IFMWK format) the new added data into HIT system. Then, the App.IFMWK.LOAD service simply forwards the retrieved data to "create" services of App.IFMWK which adds the new data into the App repository. This read occurs when the App.IFMWK.IFRCName.Read is called to update the App repository with information from HITs.
    b. A App.IFMWK.STORE service that calls "read" services of the App.IFMWK to retrieve (in IFMWK format) the new added data in App repository. Then, the App.IFMWK.STORE service simply forwards the retrieved data to "create" services of HIT.IFMWK which adds the new data into the HIT repository . This store occurs after the App.IFMWK.IFRCName.Create is called to update the HIT repository with information from App repository.
4. Employ the HIT IFMWK Blueprint.

Note that in practice, there may be a desire to not implement either App.IFMWK.IFRCName.Update or App.IFMWK.IFRCName.Delete since in electronical medical records, incorrect data is not deleted, but is marked as incorrect. In this case, we may not want the App to propagate incorrect data into the HIT systems.

Finally, the *Radical Architecture Blueprint*, Figure 5.4.a, has three main steps: define the App data items, redesign the App RESTful API, and communicate the IFMWK HIT Blueprint. The processes of these steps in this guideline are:

1. Define the App data items, see Figure 5.4.a, that are needed to be exchanged with an HIT system. This step consists of four main processes in which the first three processes are identical to the processes of Step 1 of the HIT IFMWK guideline with the data items now referring to the App data items as opposed to the HIT data items.
   End Result: A set of *Identified IFMWK Resources* that map to the App data items.
2. Redesign the App RESTful API to implement App.IFMWK server in two sub-steps:
   a. App.IFMWK server is designed for all of the Identified IFMWK Resources in Step 1d that defines a IFMWK API that has CRUD operations for all of the Identified IFMWK Resources and interacts with the HIT.IFMWK.
   b. Create Classes and CRUD services for all of the Identified IFMWK Resources for the App.
      - A App.IFMWK.IFRCName.Create service that receives the new data from the App, converts it into a format that can be assigned to a IFMWK resource, creates an instance of the IFMWK resource, and populates the IFMWK resource with the converted data. After that, this service calls the HIT.IFMWK.IFRCName.Create service with the IFMWK resource as a parameter.
      - A App.IFMWK.IFRCName.Read service that receives the id of a IFMWK resource from the App, invokes the HIT.IFMWK.IFRCName.Read service with the id as a parameter. After receiving the result in IFMWK format, this service converts the result into a format that can be used by the App and sends it to the App.
      - An App.IFMWK.IFRCName.Update service that is similar to the App.IFMWK.IFRCName.Create service, however, this service updates the existing data.

- A App.IFMWK.IFRCName.Delete service that receives the id of a IFMWK resource from the App, calls the HIT.IFMWK.IFRCName.Delete service.

3. Employ the HIT IFMWK Blueprint.

Note that for healthcare and similar domains in practice, there may be a desire to not invoke either App.IFMWK.IFRCName.Update or App.IFMWK.IFRCName.Delete services for the same issue discussed above. Also note that there is no need for LOAD and STORE in this Radical option since there is no repository remaining on the App side of Figure 5.4.a.

In summary, there are a number of observations to make regarding the IFMWK CRUD, LOAD, and STORE services. The CRUD services are defined to manipulate a single IFMWK resource that interacts with either the App Repository or the HIT system in order to take information in IFMWK format and convert it back and forth into the format of the data items in the Repository/HIT. This requires creating, reading, updating or deleting to/from the Repository/HIT using the respective API. For the read service on a particular resource, the information is retrieved using services of the API in the native format of the Repository/HIT and converted to the common format of the IFMWK resource so that it can be delivered through the IFMWK.READ service. For the update service on a particular resource, the resource comes in the common format and the update service would extract out the data items so that they can be assembled to call the appropriate Repository/HIT API services. The create and delete services would work in a similar fashion. The LOAD and STORE services differ in that they deal with multiple IFMWK resources. For STORE, a set of IFMWK resources is passed in via a common format and these resources are extracted and assembled to allow multiple API services to be called to store the information in the destination format of the Repository or HIT system. For LOAD, multiple API services from the repository/HIT are called to gather information that is then converted and assembled into the appropriate IFMWK resources. The resource concept of IFMWK facilitates information exchange. However, there is still extraction/conversion required to transition the data from the source to the sharable IFMWK format.

5.4 Blueprint Prototype Applied to the Healthcare Scenario

This section presents a proof-of-concept prototype that demonstrates the ability of a select subset of the Blueprints from Sections 5.2 and the usage of the corresponding guidelines in Section 5.3, that can be applied to the healthcare scenario from Section 2.4. This is by applying the blueprint process on two integration cases: (case 1) integrate the CT^2 mHelth app into the OpenEMR HIT system via FSICC (Chapter 3); and (case 2) integrate the ShareMyHealth mHelth app into the MyGoogle HIT system via FSICC (Chapter 3). In the process, we fully illustrate the application of two of the three architectures blueprints (Basic, Alternative, Radical) and the HIT IFMWK blueprint to the two integration cases above. The end result of this process is that the CT^2 and ShareMyHealth client Apps are able to utilize the services of the OpenEMR and MyGoogle systems, respectively, via the global services of the FSICC. The remainder of this section is organized into two parts. In Section 5.4.1, we detail the rational of the chosen architectural options for integrating the two mHelth apps into the two HIT systems (cases 1 and 2) using: the Alternative architecture to integrate CT^2 app into OpenEMR, see Figure 5.3b in Section 5.2; and the Basic architecture to integrate ShareMyHealth app into MyGoogle, see Figure 5.2b in Section 5.2. Then, in Section 5.4.2, we apply the three architectural options and associated guidelines of Section 5.3 to describe the integration steps and processes for integration cases 1 and 2.

5.4.1 Integrating Architectural Options for CT^2 and ShareMyHealth

This section explains the rationale that influenced the selection of the most suitable integration option for the two mHealth apps/clients CT^2 and ShareMyHealth and two HIT systems OpenEMR and MyGoogle for the three architecture options, Basic Figure 5.2, Alternative Figure 5.3, Radical Figure 5.4, discussed in Section 5.2. Note that we made an assumption that the FSICC has already been built and published its own IFMWK server (FSICC.FHIR) so that different apps and systems can integrate via the FSICC FHIR server. To begin, for the CT^2 mHealth app (case 1), the Alternative architecture was chosen and reconfigured, as shown in Figure 5.5, based on a number of reasons. First, we had significant human knowledge of the CT^2 mHealth app and RESTful API and maintain the MySQL database. Second, we had the source code available for: the App, the RESTful API, and the MySQL database. This meant that we had the ability to do any of the three architectural options, but we chose the Alternative architecture we were able to maintain the processing and flow of the CT^2 app through the RESTful API to the database. To apply the Alternative architecture, two FHIR servers, as shown in Figure 5.5, are created: one for the CT^2 RESTful API (CT^2.FHIR) and another one for the OpenEMR API (OpenEMR.FHIR). These two FHIR servers are utilized for exchanging data between CT^2 and OpenEMR via FSICC. Moreover, from the CT^2 App's perspective, the signatures of the services of the CT^2 RESTful APIs remained unchanged, while from the CT^2 API's perspective, the interaction with the app and the database remained unchanged. For example, when a user interacts with the CT^2 App to view and modify a concussion incident for a student, the process transitions from the user request to an API call to a database access to a returned concussion incident. The only change in the process is at the start when a user requests a concussion incident for the student and at the end when a user stores the modified concussion incident for a student. In both situations, the FHIR server of the CT^2 RESTful API intercepts and retrieves/stores the concussion incident to OpenEMR via FSICC.

When the incident is loaded from OpenEMR.FHIR via FSICC.FHIR, a temporary copy is made in the CT^2 database and all of the changes that occur via the RESTful API are made to the database on that temporary copy. The final store sends the temporary copy through the CT^2.FHIR and FSICC.FHIR servers to OpenEMR.FHIR. We decided against the Radical Architecture since we didn't want to make the substantial changes that would be required to migrate all of the information in the CT^2 database to OpenEMR. This would have included registration information, permissions (who can see/modify which concussion incidents), etc., that would have been difficult to directly store in OpenEMR.

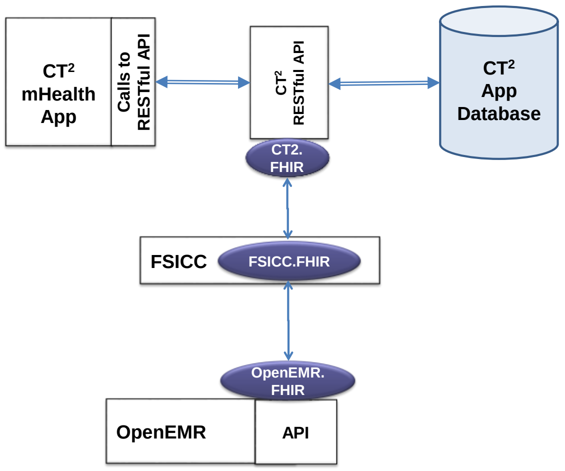


Figure 5.5. Alternative Architecture for Integrating CT^2 into OpenEMR via FSICC.

For case 2, the Basic architecture was chosen and reconfigured for the ShareMyHealth (SMH) mHealth app as shown in Figure 5.6. For the SMH app, the source code is available for: the app, the RESTful API, and the repository. Based on this, we are able to utilize any of the three architectural options. However, we decide to apply the Basic architecture since we want to keep the SMH's architecture unchanged as much as we can. To apply the Basic architecture two FHIR servers as shown in Figure 5.6 are created: one for the SMH repository (SMH.FHIR) and another one for the MyGoogle API (MyGoogle.FHIR). These two FHIR servers, in addition to

FSICC.FHIR server, are utilized for exchanging data between SMH and MyGoogle via FSICC. The Basic architecture also requires SMH to create two services into FHIR: SMH.FHIR.LOAD which retrieves related data from MyGoogle, via FSICC.FHIR, in the FHIR format; and, SMH.FHIR.STORE which grabs the data from the SMH repository, via an SMH FHIR service, and sends them to MyGoogle via FSICC.FHIR. These two services are meant to be periodically called to ensure that the repositories at both sides are updated. Note that interactions from both the SMH via its RESTful API and the SMH RESTful API to the SMH repository are not changed The Alternative and Radical architectures are not suitable for the same reason stated for case 1.

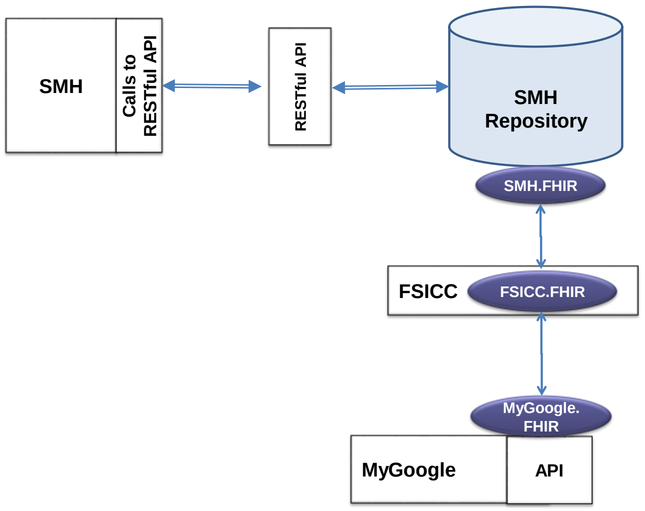


Figure 5.6. Basic Architecture for Integrating SMH into MyGoogle via FSICC.

5.4.2 Applying Integration Steps and Processes

In this section, we apply the guidelines of the Blueprint of Sections 5.2 and 5.3 to enumerate the integration steps and processes for integration cases 1 and 2 from Section 5.4.1. For case 1 in Section 5.4.1, we know that we need to integrate the CT^2 mHelth app into the OpenEMR HIT system via FSICC, see Figure 5.5, using two blueprints: the Alternative architecture to create the CT^2.FHIR server, and the HIT FHIR blueprint to create OpenEMR.FHIR server. First, the steps of the Alternative architecture from Section 5.3 can be reformulated as:

1. Define the CT^2 mHealth data items from the CT^2 that need to be exchanged with OpenEMR via FHIR to yield the Identified FHIR resources for CT^2.
2. Design a CT^2.FHIR server in front of the CT^2 RESTful API.
3. Design CT^2.FHIR CRUD services (CT^2.FHIR.IFRCName.Create, CT^2.FHIR.IFRCName.Read, CT^2.FHIR.IFRCName.Update, and CT^2.FHIR.IFRCName.Delete) in addition to CT^2.FHIR.LOAD and CT^2.FHIR.STORE services that extend the CT^2 RESTful API so that the exchange via FHIR can occur with OpenEMR.
4. Employ the HIT FHIR Blueprint.

Then for the HIT FHIR blueprint, the two steps can be reformulated as:

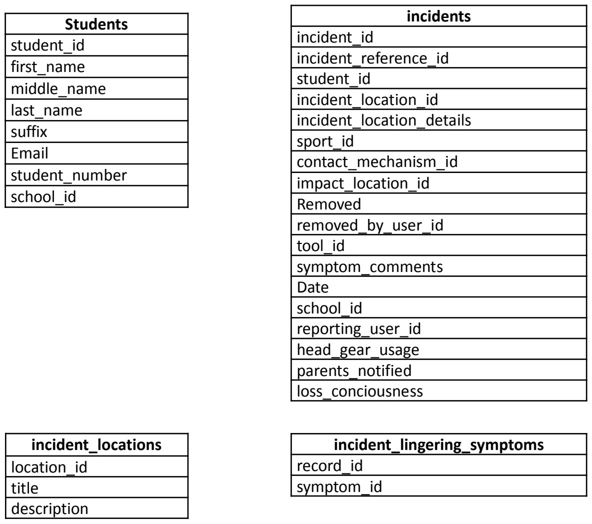
1. Define the OpenEMR system data items that are needed to be exchanged to/from the CT^2 mHealth app via FHIR to yield the Identified FHIR resources for OpenEMR.
2. Design an OpenEMR.FHIR server in front of the OpenEMR system API.

The main focus for both of these blueprints is in Step 1 of each which focuses on the way to identify the data items that need to be exchanged from each side via FHIR. This requires a designer to understand the correspondence between two sets of information:

- The data items of the CT^2 concussion MySQL database and the relevant FHIR resources that can be chosen to store them.
- The data items of the OpenEMR MySQL database and the relevant FHIR resources that can be chosen to store them.

The challenge is to consider these correspondences simultaneously to understand the way that the data items of the concussion app can be mapped via FHIR resources to the data items of OpenEMR. The end result is a set of Identified FHIR resources that serves as the common layer to facilitate the exchange of data between CT^2 and OpenEMR via FHIR services.

To begin this analysis process, in Step 1 of the *Alternative Architecture Blueprint* from Section 5.3, we start by identifying the four key data items of CT^2 mHealth that are in four tables of the MySQL Concussion database, namely: the *Students* table that tracks basic information on students (e.g., demographics, school, etc.); the *Incidents* table that tracks information on the concussion incident (e.g., when concussion happened, initial symptoms, etc.); the *Incident_Locations* table that tracks where the concussion occurred (e.g., at school, at sports field, at home, etc.); and, the *Incident_Lingering_Symptoms* table that tracks concussion symptoms observed in the days following the concussion (e.g., dizzy, nauseous, etc.). These four tables are shown in Figure 5.7.



Students
student_id
first_name
middle_name
last_name
suffix
Email
student_number
school_id

incidents
incident_id
incident_reference_id
student_id
incident_location_id
incident_location_details
sport_id
contact_mechanism_id
impact_location_id
Removed
removed_by_user_id
tool_id
symptom_comments
Date
school_id
reporting_user_id
head_gear_usage
parents_notified
loss_conciousness

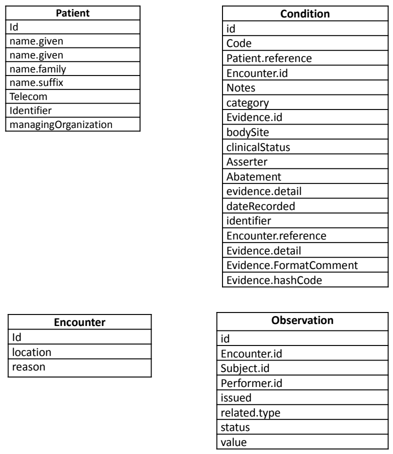
incident_locations
location_id
title
description

incident_lingering_symptoms
record_id
symptom_id

Figure 5.7. CT^2 Data Items of Interest.

Given the understanding of this information, we can continue the analysis process with Step 2 of the *Alternative Architecture Blueprint* in Section 5.3 to determine the Identified FHIR

Resources that can be utilized to capture the information from Figure 5.7. To track concussion data on a student, we can use the FHIR resources (Health Level 7, Fast Health Interoperable Resources, 2016) as shown in Figure 5.8. The Identified FHIR Resources are: Patient, Condition, Encounter, and Observation. Specifically: Patient to track demographic and other basic information on patients (students that suffer concussions); Condition to track a medical condition, in our case a concussion; Encounter to track the different times that changes are made, in our case, as the concussion incident is tracked over time such as lingering symptoms; and Observation to track symptoms and lingering symptoms of patients (students). Examining the MySQL tables of the CT^2 database in comparison to the aforementioned FHIR resources, we can establish a correspondence or mapping between them as shown in Figure 5.9. In this mapping of CT^2 database MySQL tables ⇔ FHIR resources we have: students ⇔ Patient; incidents ⇔ Condition; incident_lingering_symptoms ⇔ Observations; and incident_locations⇔ Encounter.



Patient
Id
name.given
name.given
name.family
name.suffix
Telecom
Identifier
managingOrganization

Condition
id
Code
Patient.reference
Encounter.id
Notes
category
Evidence.id
bodySite
clinicalStatus
Asserter
Abatement
evidence.detail
dateRecorded
identifier
Encounter.reference
Evidence.detail
Evidence.FormatComment
Evidence.hashCode

Encounter
Id
location
reason

Observation
id
Encounter.id
Subject.id
Performer.id
issued
related.type
status
value

Figure 5.8. FHIR Resources of Interest.

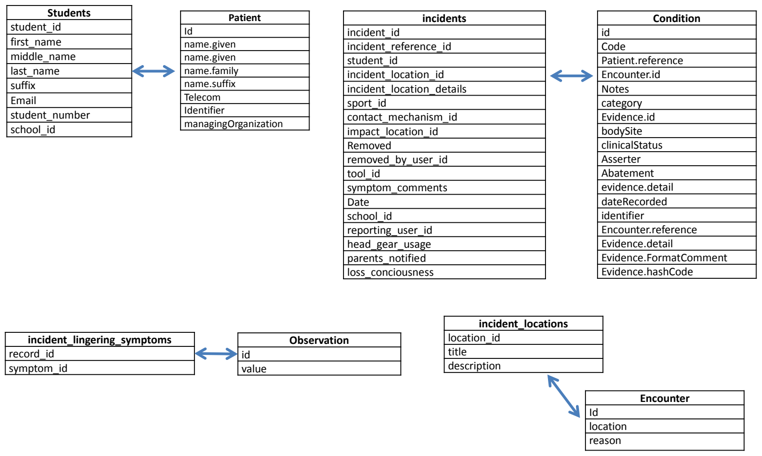


Figure 5.9. Mapping from CT^2 to/from FHIR.

Now, let's turn the discussion to Steps 1 and 2 of the *HIT FHIR Blueprint* from Section 5.3 that involves an analogous process to Figures 5.7, 5.8, and 5.9, with the data items of OpenEMR. Since we have already arrived at the FHIR resources needed for mapping, Figure 5.8, we can reuse the aforementioned Identified FHIR Resources to assist in the identification of the appropriate four data items in OpenEMR in Figure 5.10, namely: the *Patient_Data* table that tracks patient (student) demographic data; the *Lists* table that tracks issues related to medical problems, etc. (concussion medical problem); the *Form_Encourter* table that tracks the event involved with the patient visiting (student seeing nurse); and, the *Procedure_Order_Code* table that tracks different codes associated with procedures. These four items correspond to the FHIR Resources as shown in Figure 5.11. This mapping has: Patient_data ⇔ Patient; Lists ⇔ Condition; procedure_order_code ⇔ Observations; and form_encounter⇔ Encounter.

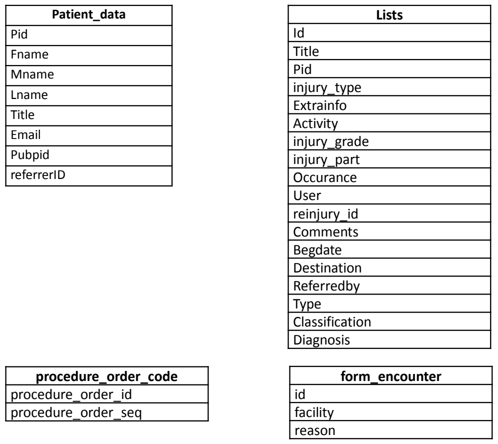


Figure 5.10. The OpenEMR Data Items of Interest.

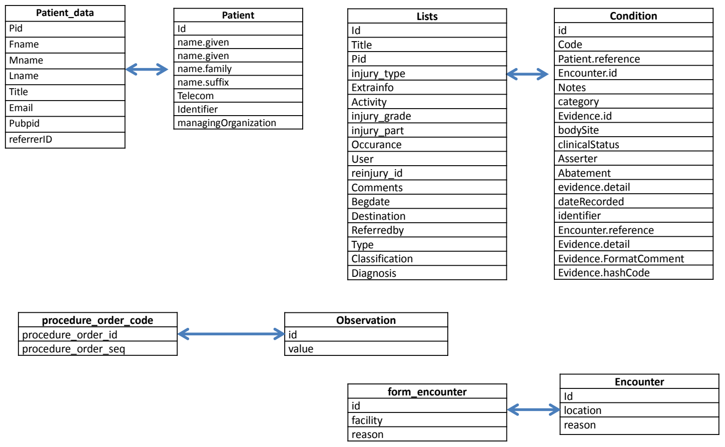


Figure 5.11. Mapping from OpenEMR to/from FHIR.

The last step of the *HIT FHIR Blueprint* is the creation of the OpenEMR.FHIR server. As described in the HIT FHIR Blueprint and based on the selected FHIR resources in the provisos steps, we created a FHIR controller class which receives requests from the CT^2 mHealth app, or a third-party such as FSICC, and sends the request to the appropriate OpenEMR FHIR resource class along with any parameters. We also created four OpenEMR Identified FHIR resources classes (i.e., Patient, Condition, Observation, and Encounter) as shown in the bottom right of Figure 5.12. For each OpenEMR FHIR resources classes, we defined: OpenEMR.FHIR.IFRCName.Create and OpenEMR.FHIR.IFRCName.Read). The OpenEMR.FHIR.IFRCName.Create service receives an instance of a FHIR resource that involves new data, of a specific class, converts the data into a format that can be stored in the OpenEMR system, and sends the converted data to a create service of the OpenEMR system API that stores the data into the OpenEMR database. The OpenEMR.FHIR.IFRCName.Read service retrieves data from the OpenEMR database via a read service of the OpenEMR system API, creates a new instance of the specific FHIR resource class, and converts the retrieved data into a format that can be assigned to the identified OpenEMR FHIR resource instance. Following that, this service populates the corresponding OpenEMR FHIR resource instance with the converted data, and sends this FHIR resource instance to the CT^2 mHealth app, or a third-part such as FSICC. This service is also designed to retrieve all of the related data on the specific data item if there are no passed parameters.

Finally, the remaining step of the *Alternative Architecture Blueprint* in Section 5.3 is to implement the CT^2.FHIR server. As described in the Alternative Architecture Blueprint and based on the selected FHIR resources, we created a FHIR controller class which receives requests from the CT^2.FHIR.LOAD and CT^2.FHIR.STORE services; and sends the request to the appropriate CT^2 FHIR resource class along with any parameters. We also created four CT^2 Identified FHIR resources classes (i.e., Patient, Condition, Observation, and Encounter) at the top right of Figure 5.12 shows. For each of these CT^2 FHIR resources classes, we created two main CRUD service, CT^2.FHIR.IFRCName.Create and CT^2.FHIR.IFRCName.Read and CT^2.FHIR.LOAD and CT^2.FHIR.STORE services. The CT^2.FHIR.IFRCName.Create service receives an instance of a FHIR resource with new data, converts the data into a format that can be stored in the CT^2 database, and sends the converted data to the CT^2 RESTful API (a create service) which stores the data into the CT^2 database. The CT^2.FHIR.IFRCName.Read service retrieves data from the CT^2 database via a CT^2 RESTful API (a read service), creates a new instance of related CT^2 FHIR resource class, and converts the retrieved data into a format that can be assigned to the CT^2 FHIR resource instance. After that, the CT^2.FHIR.IFRCName.Read populates the CT^2 FHIR resource instance with the converted data, and finally sends this FHIR resource instance to the request source. The CT^2.FHIR.IFRCName.Read service also retrieves all of the related data about specific data item if there are no passed parameters. The CT^2.FHIR.LOAD service takes an id of the queried CT^2.FHIR resource instance, retrieves the related data from the OpenEMR system via OpenEMR.FHIR and FSICC.FHIR servers, and adds retrieved data into the CT^2 database via another CT^2 FHIR service (i.e., the CT^2.FHIR.IFRCName.Create service). Finally, the CT^2.FHIR.STORE service calls the CT^2.FHIR.IFRCName.Read service to retrieve (in FHIR format) all of the new added data in CT^2 database. Then, the CT^2.FHIR.STORE service simply sends the retrieved data to "create" services of OpenEMR.FHIR, via the FSICC.FHIR server, which adds the new data into the OpenEMR system.

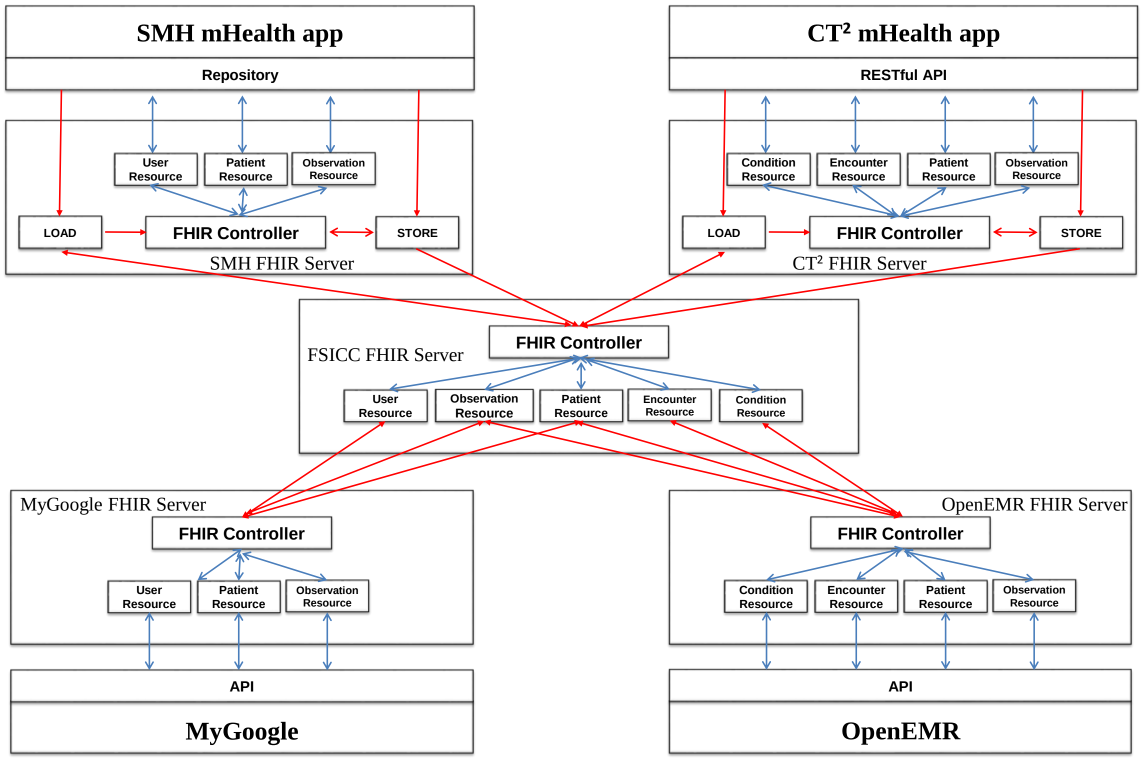


Figure 5.12. Combined Result of the Two Blueprints.

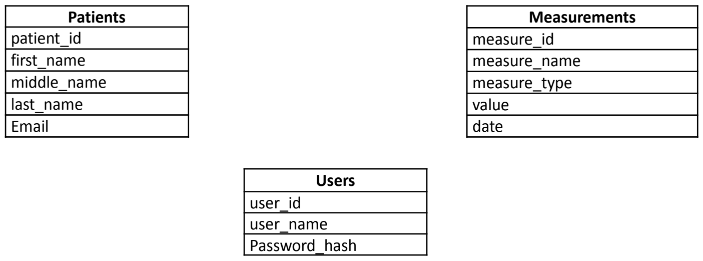
From Section 5.4.1, we know that, for case 2, we need to integrate the SMH mHelth app into the MyGoogle HIT system via FSICC, see Figure 5.6, using: the Basic architecture blueprint to create the SMH.FHIR server, and the HIT FHIR blueprint to create MyGoogle.FHIR server. First, the steps of the Basic architecture can be reformulated as:

1. Define the SMH mHealth data items from the SMH's repository that need to be exchanged with MyGoogle via FHIR to yield the Identified FHIR resources for SMH.
2. Design a SMH.FHIR server in front of the SMH repository that includes the two service SMH.FHIR.LOAD and SMH.FHIR.STORE so that the exchange via FHIR can occur with MyGoogle.
3. Employ the HIT FHIR Blueprint.

Then, for the HIT FHIR blueprint, the two steps can be reformulated as:

1. Define the MyGoogle system data items that are needed to be exchanged to/from the SMH mHealth app via FHIR to yield the Identified FHIR resources for MyGoogle.
2. Design an MyGoogle.FHIR server in front of the MyGoogle system API.

Similar to case 1, we start by performing Step 1 of the Basic Architecture Blueprint. Specifically, we identify the three key data items of SMH mHealth that are in three tables of the SMH repository, namely: the *Measurements* table that tracks fitness data of each patient (e.g., height, weight, steps, etc.); the *Patients* table that tracks basic information on patients (e.g., demographics, gender, etc.); and, the *Users* table that holds information on SMH's users (e.g., user_id, user_name, etc.). These three tables are shown in Figure 5.13.



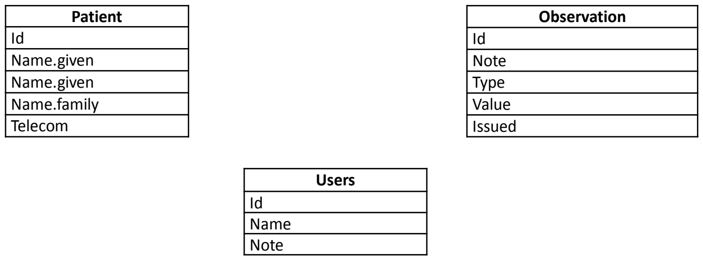
Patients
patient_id
first_name
middle_name
last_name
Email

Measurements
measure_id
measure_name
measure_type
value
date

Users
user_id
user_name
Password_hash

Figure 5.13. SMH Data Items of Interest.

Given the understanding of this information, we can continue the analysis process with Step 2 of the Basic Architecture Blueprint to determine the Identified FHIR Resources that can be utilized to capture the information from Figure 5.13. To track measurement data on a patient we can use the FHIR resources as shown in Figure 5.14: Observation, Patient, and User. Specifically: Observation to track measurement of patients; Patient to track demographic and other basic information on patients; and, User to maintain users' data. Examining the tables of the SMH repository in comparison to the aforementioned FHIR resources, we can establish a correspondence or mapping between them as shown in Figure 5.15. In this mapping of SMH repository tables ⇔ FHIR resources, we have: Measurements ⇔ Observation; Patients ⇔ Patient; and Users ⇔ User.



Patient
Id
Name.given
Name.given
Name.family
Telecom

Observation
Id
Note
Type
Value
Issued

Users
Id
Name
Note

Figure 5.14. FHIR Resources of Interest.

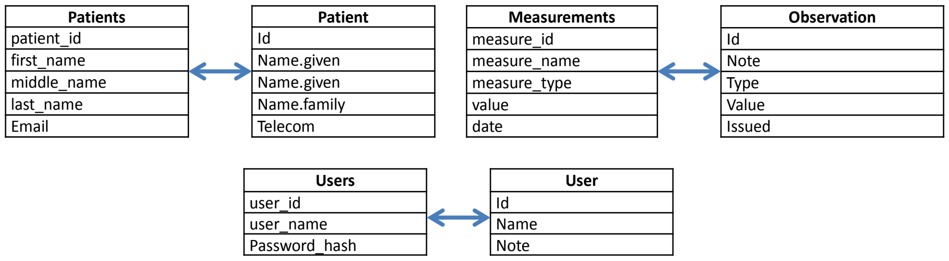


Figure 5.15. Mapping from SMH to FHIR.

For the HIT FHIR Blueprint, we now discuss Steps 1 and 2 that are similar to the processes in Figures 5.13, 5.14, and 5.15, with the data items of MyGoogle. Since we have already arrived at the FHIR resources needed for mapping, Figure 5.14, we can reuse the aforementioned Identified FHIR Resources to assist in the identification of the appropriate three data items in MyGoogle in Figure 5.16, namely: the *DataSources* table that tracks fitness data of each patient (e.g., height, weight, steps, etc.)*;* the *Patients* table that tracks patient demographic data; and, the *Users* table that holds about MyGoogle users. These three items correspond to the FHIR Resources as shown in Figure 5.17. In the mapping of MyGoogle data items ⬄ FHIR resources we have: DataSources ⬄ Observation; Patients ⬄ Patient; and Users ⬄ User.

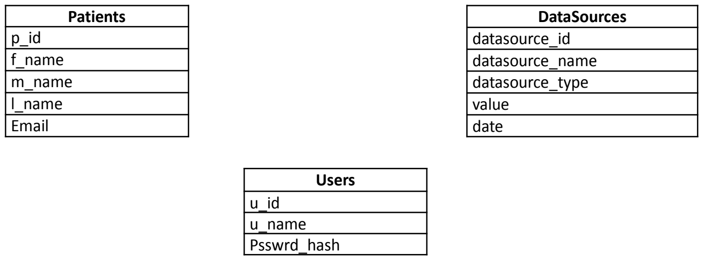


Figure 5.16. MyGoogle Data Items of Interest.

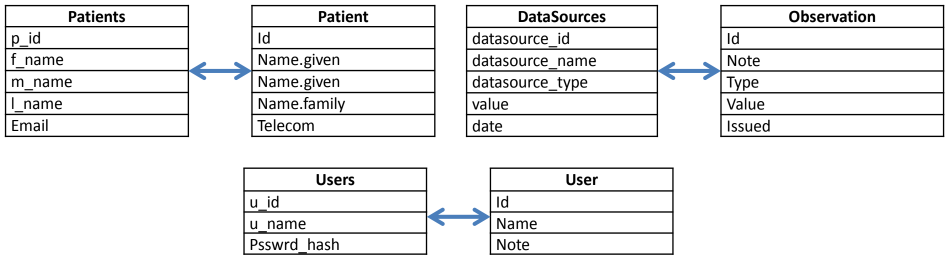


Figure 5.17. Mapping from MyGoogle to FHIR.

The last step of the HIT FHIR Blueprint is the creation of the MyGoogle.FHIR server. As described in the HIT FHIR Blueprint and based on the selected FHIR resources in the provisos steps, we created a FHIR controller class which receives requests from the SMH mHealth app, or a third-party such as FSICC, and sends the request to the appropriate MyGoogle FHIR resource class along with any parameters. We also created three MyGoogle Identified FHIR resources classes (i.e., Patient, Observation, and User) as shown in the bottom left of Figure 5.12. For each of these MyGoogle FHIR resources classes, we defined: MyGoogle.FHIR.IFRCName.Create and MyGoogle.FHIR.IFRCName.Read). The MyGoogle.FHIR.IFRCName.Create service receives an instance of a FHIR resource that involves new data, of a specific class, converts the data into a format that can be stored in MyGoogle system, and sends the converted data to a create service of the MyGoogle system API that stores the data into the MyGoogle database. The MyGoogle.FHIR.IFRCName.Read service retrieves data from the MyGoogle database via a read service of MyGoogle system API, creates a new instance of the specific FHIR resource class, and converts the retrieved data into a format that can be assigned to the identified MyGoogle FHIR resource instance. Following that, this service populates the corresponding MyGoogle FHIR resource instance with the converted data, and sends this FHIR resource instance to the SMH mHealth app, or a third-part such as FSICC. This service is also designed to retrieve all of the related data on the specific data item if there are no passed parameters.

Finally, the remaining step of the Basic Architecture Blueprint is to implement the SMH.FHIR server. As described in the Basic Architecture Blueprint and based on the selected FHIR resources, we created a FHIR controller class which receives requests from the SMH.FHIR.LOAD and SMH.FHIR.STORE services and sends the request to the appropriate SMH FHIR resource class along with any parameters. We also created three SMH Identified FHIR resources classes (i.e., Patient, Observation, and User) at the top left of Figure 5.12 shows. Then, we created the two services: SMH.FHIR.LOAD and SMH.FHIR.STORE. The SMH.FHIR.LOAD service retrieves all related data from the MyGoogle system via MyGoogle.FHIR and FSICC.FHIR servers, and adds retrieved data into the SMH repository. Finally, the SMH.FHIR.STORE service retrieves, in FHIR format, all of the new added data in SMH repository. Then, the SMH.FHIR.STORE service simply sends the retrieved data to "create" services of MyGoogle.FHIR, via the FSICC.FHIR server, which adds the new data into the MyGoogle system.

Note that the FSICC.FHIR, middle of Figure 5.12, has five resources: Observation, Patient, Encounter, Condition, and User. These resources were selected as a result of FHIR resources selection of both sides: CT^2 and OpenEMR require Observation, Patient, Encounter, and Condition FHIR resources on the right side of Figure 5.12; and, SMH and MyGoolge require Observation, Patient, and User FHIR resources on the left side of Figure 5.12. Also note that the role of FSICC.FHIR server simply is to send the FHIR instances back and forth between the associated clients and systems. That is, between CT^2 and OpenEMR FHIR servers on one side; and between SMH and MyGoogle FHIR servers on the other side.

5.5 Related Work

This section reviews two efforts that illustrate FHIR design and implementation: enabling better interoperability for healthcare (Kasthurirathne, Mamlin, Kumara, Grieve, & Biondich, 2015) and applying FHIR in an integrated health monitoring system (Franz, Schuler, & Kraus, 2015). The work in (Kasthurirathne, Mamlin, Kumara, Grieve, & Biondich, 2015) provided a new API module for OpenMRS system that has been built using FHIR. The processes of designing and developing the OpenMRS FHIR API included: design a framework that assists in adding FHIR-based API for OpenMRS; select a third party FHIR library to implement FHIR resources creation and validation; develop a FHIR-based API for the OpenMRS system; and, implement the search service of a number of FHIR resources that are capable of retrieve data from the OpenMRS system. The architecture of the presented FHIR module consists of two layers: the FHIR web layer which mainly retrieves FHIR resources from the FHIR API layer and the FHIR API layer that basically models and validates FHIR resources. The initial prototype of the FHIR controller interacted with the Patient and Observation resources with a middle layer that transitions information to/from OpenMRS. This effort is similar to our work on architectural blueprints guidelines as both works presented steps to design and develop an integration framework in front of systems that facilitates system interoperability. However, their effort was focus on the FHIR standard, and as a result is limited to the healthcare domain and only highlighted the main steps of implementing a HAPI FHIR API without providing a detailed discussion on such steps. Furthermore, their effort presented an integration option, similar to our Radical Architecture Blueprint, that extended OpenMRS system with FHIR API. In contrast to this effort, our approach provided detailed steps and process of designing and implementing an integration framework that can be applied to any integration framework of any domain including FHIR and HAPI FHIR.

The work of (Franz, Schuler, & Kraus, 2015) presented an extension to a health monitoring system using FHIR to enable interoperability between medical devices and HIT systems. The health monitoring system consists of an *aggregation manager module* which is a mobile device and a *telehealth service center module* which is a server. These two modules were extended by adding components, which are implemented using FHIR, to enable their integration. The aggregation manager module was extended with two services: FHIROBSMessageSender which sends the measured data as Observation FHIR resource to the telehealth service center module; and, FHIRDORMessageSender that sends DeviceObservationReport FHIR resource to the telehealth service center module. The telehealth service center module was extended with two services: OBSController and DORController which receive Observation and DeviceObservationReport FHIR resources respectively from the aggregation manager module. This effort is similar to our work on architectural blueprints guidelines as both works successfully applied and implemented an integration framework to extend different systems and make such systems more interoperable. However, this effort discussed only one integration option, similar to our Alternative Architecture Blueprint, that was specific to the reported effort. In contrast, our approach provided a generalizable integration framework that can be applied to any integration framework of any domain including FHIR and HAPI FHIR.

Chapter 6
Global Security Policy Generation and Dynamic Enforcement for FSICC

In this chapter, we discuss *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* and *Global Security Policy and Global API Utilization and Security Enforcement* which was shown in the 4th and 5th horizontal boxes, respectively, in Figure 1.3 of Chapter 1. As described earlier in Chapter 3, the global security policy of FSICC is generated by cloud computing capability two, *Local Security Policies Registration to Yield Global Security Policy,* of FSICC, that utilizes two components of FSICC: Security Policy Mapping, see the Security Policy Mapping box of FSICC in Figure 1.1 form Chapter 1; and Global Security Policy, see the Global Security Policy box of FSICC in Figure 1.1. Specifically, capability two of FSICC enables any system, which corresponds to the Systems box in the Involved Parties component at the top of Figure 1.2, to register the system's security policy that can be any combination of RBAC, MAC, and DAC, which corresponds to the Access Control Models component in Figure 1.2. For RBAC, the system registers to provide: the defined roles, the defined services, the role-services authorization list, the role hierarchy, the defined users, the user-role assignment list. For MAC, the system registers to provide: the defined services along with a classification for each service; and the defined users in which each user has a clearance, a read property and a write property. Finally, for DAC, the system registers to provide: the role delegation list and the clearance delegation list. In further support of this chapter, we utilize the Unified Cloud Computing Access Control Model (UCCACM), from Chapter 4, which has a set of definitions for global security policy generation and utilization (see Defns. 41-48 in Section 4.6). These definitions ensure that such global security policy can control access to a set of global services that are generated using one or more of integration architecture blueprints: Basic Architecture, Alternative Architecture, or Radical Architecture from Chapter 5. In addition, from the enforcement perspective to check whether applications are allowed to call particular services, UCCACM has definitions for RBAC interceptors (see Defns. 50-52 in Section 4.7.1), MAC interceptors (see Defns. 53-56 in Section 4.7.2), and DAC interceptors (see Defns. 57-60 in Section 4.7.3).

Based on this, this chapter has two main parts. The first part presents a set of algorithms for generating the global security policy of FSICC; this partially addresses Contribution EC-C: Security Mapping/Enforcement Algorithms and SSEP, from Section 1.5, by focusing on Security Mapping/Enforcement Algorithms, this is represented by the Global Security Policy Generation box of the *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* horizontal box in Figure 1.3 from Chapter 1. To support this, we present a set of algorithms to implement the concepts of global security policy definition and mapping of services to/from mixed clients and pure and mixed systems. These algorithms support: global RBAC generation, global MAC generation, global DAC generation, and global policies combination. The second part introduces and discusses three security interceptors for RBAC, MAC, and DAC (which are the implementation of the UCCACM for the FSICC) via a number of checks and an algorithmic approach for each interceptor; this addresses Contribution EC-D: Dynamic Enforcement via Intercepting Process from Section 1.5, this is represented by the Security Enforcement via Interceptors box of the *GSP (Global Security Policy) and GAPI (Global API) Utilization and Security Enforcement* horizontal box in Figure 1.3. This is accomplished by presenting a set of programmatic RBAC, MAC, and DAC interceptors, which are the implementation of the definitions in Section 4.7 for UCCACM, that intercept any request to access FSICC's global services, that are generated using one or more of integration architecture blueprints from Chapter 5. To support this, a number of security interceptors (i.e., *RBAC Interceptor, MAC Interceptor,* and *DAC Interceptor*) are presented to enforce such global security policy on the users' access requests.

In the remainder of this chapter, we discuss Global Security Policy Generation and Dynamic Enforcement for FSICC in three sections. In Section 6.1, a set of *security policy integration algorithms* are presented and discussed for: global RBAC generation, global MAC generation, global DAC generation, and global policies combination. In Section 6.2, we demonstrate the realization of UCCACM of FSICC in HAPI FHIR utilizing the healthcare scenario of Section 2.4 of Chapter 2 that involves the implementation of HAPI FHIR APIs and its server interceptor to support UCCACM checks with three different algorithms to support three different HAPI FHIR interceptors: RBAC interceptor, MAC interceptor, and DAC interceptor. Moreover, the interceptor discussions are supported by two access scenarios. Section 6.3 presents and discusses related work in both security policy integration and enforcing security policies on FHIR API. Note that the work in this chapter has been published in (Baihan, M., et al., 2017).

6.1. Security Policy Integration Algorithms

To start this discussion, Figure 6.1 shows architecture for global security policy generation and utilization (see Defns. 37-44 of Section 4.6). The global security policy generation process consists of four main phases: generating global RBAC, see the RBAC Integration and Review & Correct Role Names boxes in the middle of Figure 6.1, generating global MAC, see the MAC Integration and Building Global MAC boxes in the middle of Figure 6.1, generating global DAC, see the DAC Integration box in the middle of Figure 6.1, and global policies combination. Pure and mixed systems (see Defn. 7 of Section 4.2) at the bottom of Figure 6.1 and mixed clients (see Defn. 6 of

Section 4.2) at the top left of Figure 6.1 use the global security policy generation process to add their security policies and services into the FSICC as indicated by the dash lines in the figure. Pure clients and mixed servers are free to utilize the global security policy to call authorized services as indicated by the solid lines in Figure 6.1. The generating global RBAC phase has two tasks. First, RBAC integration takes all of the RBAC policies from pure and mixed systems and mixed clients (dashed lines) and through the RBAC Integration box combines them into one RBAC policy. Second, review and correct role names, which corrects and updates the name of a number of global roles through the RBAC Integration box to the Review and Correct Role Names box. Using input from the FSICC's security engineer in conjunction with the two tasks, then the global RBAC instance, the Global RBAC Instance cylinder in the middle of Figure 6.1 is generated.

The generating global MAC phase also has two tasks. First, MAC Integration requires human interaction to map sensitivity levels of pure and mixed systems and mixed clients (dashed lines) via the MAC Integration box in Figure 6.1 to the sensitivity levels of the global MAC. Second, global MAC is designed and constructed, in which users and services of the system are utilized to generate the global MAC in which users' clearances and services' classifications are assigned based on the global sensitivity levels (solid line) from the MAC Integration box to the Building Global MAC box. Using input from the FSICC's security engineer, the global MAC instance via the Global MAC Instance cylinder in the middle of Figure 6.1 is generated. The generating global DAC phase has one main task. DAC integration takes all of the DAC policies from pure and mixed systems and mixed clients (dashed lines) to the DAC Integration box in Figure 6.1 and combines them into one DAC policy and then generates the global DAC instance via the Global DAC Instance cylinder in the middle of Figure 6.1. Finally, in the last phase, the Combine Global Security Policies Instances box in the middle of Figure 6.1 combines the generated global RBAC instance, global MAC instance, and global DAC instance into one global security policy model instance, in which the data updating and retrieving actions are also controlled. To complete the process, the security engineer of FSICC insures that all of the policy requirements are define that are capable of controlling the services of pure and mixed clients and mixed systems via the solid lines to the Global Security Policy Model Instance cylinder in Figure 6.1.

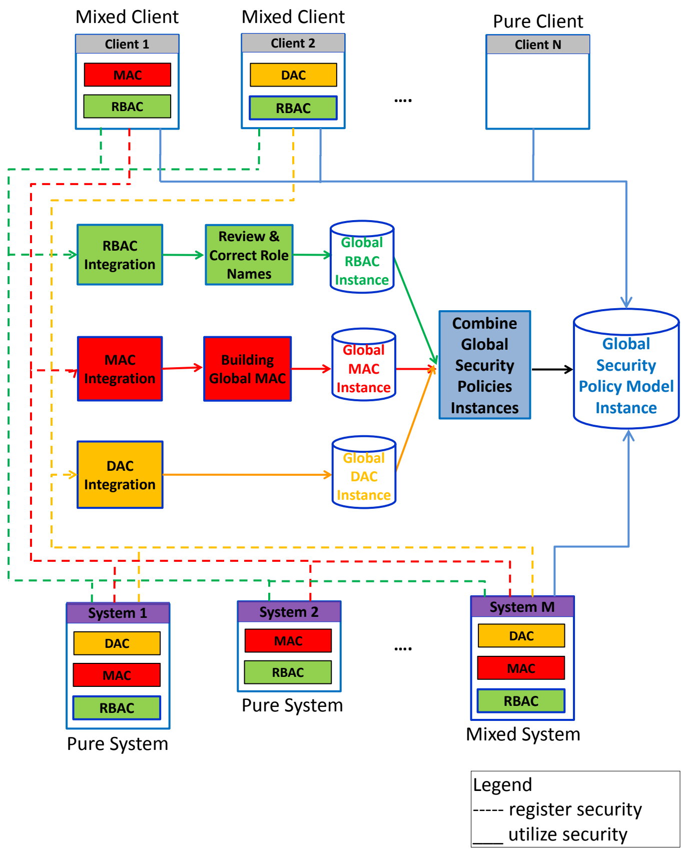


Figure 6.1. An Architecture for Global Security Policy Generation & Utilization

The remainder of this section presents and discusses a set of algorithms and human process for the Global Security Policy Generation in four parts. In Section 6.1.1, we discuss the way that the global RBAC generation phase processes each RBAC policy from each pure or mixed system or mixed client, and generates the global RBAC policy. In Section 6.1.2, the global MAC generation phase is presented to show the way that each MAC policy from each pure or mixed system or mixed client is processed to generate the global MAC policy. Section 6.1.3 explains the way that the global DAC generation phase uses to process each DAC policy from each pure or mixed system or mixed client and to generate the global DAC policy. Finally, in Section 6.1.4, we describe the way that the global policies combination phase uses the global RBAC policy, global MAC policy, and global DAC policy to build the global security policy. Note that in the rest of this section we use the term "system" to indicate pure systems, mixed systems (services registering part) and mixed clients (services registering part), and the term "client" to indicate pure clients, mixed clients (services utilization part) and mixed systems (services utilization part).

6.1.1 Global RBAC Generation

The Global RBAC (GRBAC) Generation phase is divided into two tasks, each of which consists of one or more algorithms: RBAC Integration in Figure 6.1; and, Review and Correct Role Names in Figure 6.1. First, the RBAC Integration task, integrates any number of systems' RBAC policies into one global RBAC policy that can be utilized to restrict access to services of all of the participated systems, where the presented approach makes policy integration decisions based on permissions similarity. Since each system may define an RBAC policy against a common set of services (the integration layer e.g., FHIR in HITs case), the similarity between two systems' RBAC policies, or between a system's RBAC policy and a global RBAC policy, can be determined based on the similarity of the permissions. For the purposes of our examples, assume that we have two roles Sr_s and Gr_g where $Sr_s \epsilon \{ S^i_{R_S}, C^i_{R_C} \}$ is a role of a pure or mixed system or a mixed client and $Gr_g \epsilon\ G^i_{R_G}$ is a global role. Further, assume that there are two corresponding role permission sets $Srps_s \epsilon \{ S^i_{RPS_S}, C^i_{RPS_C} \}$ and $Grps_g\ \epsilon\ G^i_{RRPS_G}$. For example, say Sr_s authorized to permissions $Srps_s$

={(Patient, READ), (Patient, CREATE)}, and Gr_g authorized to permissions $Grps_s$={(Patient, READ), (Patient, CREATE), (Patient, UPDATE)}.

When comparing Sr_s and Gr_g , our focus is on comparing permissions their respective $Srps_s$ and $Grps_g$; in this case, there are common permission {(Patient, READ), (Patient, CREATE)}. Note that, in permissions comparison, we omit the base URL from a service URI and focus only on the Endpoint (i.e., permission name) and Method (i.e., access method), since the permission name and access method of the service are the confidential part that need to be protected. Based on this, the comparison between any two role permission sets ($Srps_s$ and $Grps_g$) have one of the five results: (1) $Srps_s \supset Grps_g$ which means all of the permissions in $Grps_g$ are in $Srps_s$ which in the above example is false; (2) $Grps_g \supset Srps_s$ which means all of the permissions in $Srps_s$ are in $Grps_g$ which in the above example is true; (3) $Srps_s \cap Grps_g \neq \emptyset$ (or $Srps_s$ and $Grps_g$ overlap) which means both role permission sets have common permissions but no role permission set contains the other; (4) $Srps_s = Grps_g$ (or $Srps_s$ and $Grps_g$ are equivalent) which means both role permission sets have the same set of permissions; or (5) $Srps_s \cap Grps_g = \emptyset$ ($Srps_s$ and $Grps_g$ are not related) which means there is no common permissions between $Srps_s$ and $Grps_g$. Based on the assumptions above, the RBAC Integration task utilizes four algorithms: *Global-RBAC, Initialize_GRBAC, IntegrateRBAC,* and *AddBasicParents.* These algorithms utilize a set of primitive functions in Table 6.1 that simplify the explanation of the aforementioned four algorithms. Table 6.1 has two columns: Function Signature, that has a name and a set of parameters for each function; and Description, that briefly explains each function. We highlight key functions. The first three functions: returns the parent roles of a given role, sets a parent role, and returns permissions of a role (i.e., $Srps_s$ or $Grps_g$). The next function, compareRolesPerm, does the comparison between a system role (Sr_s) and a global role (Gr_g) using two factors of each role: role permission sets ($Srps_s$

and $Grps_g$), and inherited role permission sets from all of the parent roles ($inhSrps_s$ and $inhGrps_g$). The mapRoles function creates new entries in the global policy regarding the mapping of system roles to global roles.

Table 6.1. Primitive Functions Utilized by the Algorithms for Global RBAC Generation

Function signature	Description
getParents(RH, r)	Returns all of the parent roles of the role *r* according to the given role hierarchy *RH*
addParent(RH, pr , r)	Defines the role *pr* as a parent role of the role *r* in the given role hierarchy *RH*
dirPset(r)	Returns a list of permissions directly authorized to the role *r*
compareRolesPerm($Grps_g$, $Srps_s$, $inhGrps_g$, $inhSrps_s$)	Returns one of the following: - *not related* (if simCount($Grps_g$, $Srps_s$) is 0) - *equivalent* (if simCount($Grps_g$, $Srps_s$) equals both $Grps_g$.size & $Srps_s$.size and simCount($inhGrps_g$, $inhSrps_s$) equals both $inhGrps_g$.size & $inhSrps_s$.size) - *contains GR* (if simCount($Grps_g$, $Srps_s$) equals $Grps_g$.size but less than $Srps_s$.size and $inhGrps_g$.size is 0) - *GR contains* (if simCount($Grps_g$, $Srps_s$) equals $Srps_s$.size but less than $Grps_g$.size and $inhSrps_s$.size is 0) - *overlap* (if simCount($Grps_g$, $Srps_s$) is less than both $Grps_g$.size & $Srps_s$.size but > 0 or simCount($Grps_g$, $Srps_s$) equals both $Grps_g$.size and $Srps_s$.size and both $inhGrps_g$.size and $inhSrps_s$.size > 0)
mapRoles(Gr_g, Sr_s)	Adds all of the users in *users(Sr_s)* into *users(Gr_g)*, and adds a new entry (*Gr_g, Sr_s , Sr_s.system name*) to the role mapping list
users(r)	Returns all of the users assigned to role *r*
createGlobalRole(roleName)	Creates a new global role s.t. the role name = roleName; if roleName exists use roleName_X (where X= number of Roles with same name +1)
comPset(r1, r2)	Returns a list of common permissions between Pset(r1) and Pset(r2)
uncomPset(r1, r2)	Returns a list of permissions exist in Pset(r1) but not in Pset(r2)
removePer(perList , r)	Removes all of the permissions in perList from Pset(r)
addPer(perList , r)	Adds all of the permissions in perList into Pset(r)
getMappedGRole(global RH, Sr_s)	Returns the global role associated with the given system role Sr_s
AllPset(r)	Returns a list of all of the permissions (directly and by inheritance) authorized to the role *r*
inherPset(RH, r)	Returns a list of by inheritance permissions authorized to the role *r* according to the given role hierarchy *RH*
exist(Sr_s)	Returns true if the role mapping list contains the entry (**, Sr_s , Sr_s.system name*), where * means for any *Gr_g*
notRelatedList.add(Gr_g , Sr_s)	Add an entry (Gr_g , Sr_s) that means these two roles are unrelated
notRelatedList.cleare ()	Removes all of the Entries

The *Global-RBAC* algorithm in Figure 6.2 is for generating the entire GRBAC policy for all of the systems in FSICC, and takes as input a set of *m* systems' RBAC policies ($SRBAC_1$, $SRBAC_2$, .. $SRBAC_m$), where *m* is the number of the participated systems, and initializes the global RBAC policy (GRBAC) using $SRBAC_1$, line 1 in Figure 6.2. Note that, $SRBAC_1$ is arbitrarily chosen from the set of systems RBAC policies. The Global-RBAC algorithm then iterates (lines 2-3) through RBAC policies of the remaining systems, $SRBAC_2$ to $SRBAC_m$, by integrating one system's RBAC policy at a time with the previously computed GRBAC. Finally, the Global-RBAC algorithm returns the final GRBAC, combined Global RBAC policy constructed from all of the constituent systems of FSICC, line 4 in Figure 6.2. Moreover, as Figure 6.2 shows, the Global-RBAC algorithm utilizes the *Initialize_GRBAC* and *IntegrateRBAC* algorithms.

```
Global-RBAC
Input: set of m Systems RBAC ($SRBAC_1$, $SRBAC_2$, .. , $SRBAC_m$)
Output: Global RBAC (GRBAC)
1.  GRBAC ← Initialize_GRBAC($SRBAC_1$)
2.  for i ← 2 to m
3.      GRBAC ← IntegrateRBAC(GRBAC , $SRBAC_i$)
4.  return(GRBAC)
```

Figure 6.2. The Global-RBAC Algorithm

The *Initialize_GRBAC* algorithm in Figure 6.3 is for initializing the GRBAC policy to generate the initial state of a global-system role mapping list, and receives $SRBAC_1$ and performs three main steps. Step 1 (line 1) copies roles (Sr_s), users (Su_s), permissions (Ssc_s), role-permission authorizations ($Srps_s$), user-role assignments ($Suras_s$), and role hierarchy (Srh_s), see Defn. 19 of Section 4.3, from $SRBAC_1$ to the GRBAC. Step 2 (lines 2-3) generates a global-system role mapping list by mapping each global role with the original system role. Step 3 (lines 4-6) creates a new global role that has no permissions or users (i.e., RootRole) to be the parent role for each global role with no parents. Finally, the initialized GRBAC is returned in line 7.

```
Initialize_GRBAC
Input: System RBAC (SRBAC)
Output: Global RBAC (GRBAC)
1.  GRBAC ← {SRBAC[$Sr_s$, $Su_s$, $Ssc_s$, $Srps_s$, $Suras_s$, $Srh_s$]}
2.  for each $Gr_g \in$ GRBAC and each $Sr_s \in$ SRBAC
3.      mapRoles($Gr_g$, $Sr_s$)
4.  RootRole ← createGlobalRole(RootRole)
5.  for each $Gr_g \in$ GRBAC that has no parents
```

```
6.      addParent(global RH , RootRole , $Gr_g$)
7.   return(GRBAC)
```

Figure 6.3. The Initialize_GRBAC Algorithm

The *IntegrateRBAC* algorithm in Figure 6.4 is for combining the current GRBAC policy with a new system's RBAC (SRBAC) policy, and receives SRBAC and the current GRBAC and performs two nested loops. The first loop in line 1 iterates through each system role (Sr_s) in SRBAC, starting with each Sr_s with no parents, then with one parent, and so on, until each Sr_s reaches the bottom of the system role hierarchy. The second loop in line 4 iterates through each global role (Gr_g) in GRBAC, except the RootRole, starting with each Gr_g that only has the RootRole as its parent, then with one parent other than the RootRole, and so on, until each Gr_g reaches the bottom of the global role hierarchy. Then, in line 7, each Sr_s and Gr_g are compared based on two factors of each role: role permission sets ($Srps_s$ and $Grps_g$), and inherited role permission sets from all of the parent roles ($inhSrps_s$ and $inhGrps_g$), utilizing the *compareRolesPerm* primitive function in Table 6.1 that returns: *equivalent*, $Grps_g \supset Srps_s$, $Srps_s \supset Grps_g$, *overlap*, or *not related* as explained by the *compareRolesPerm* function in Table 6.1. Note that *simCount*, which is utilized in the description of the *compareRolesPerm* function in Table 6.1, is the similarity counter that is initiated to 0 and is incremented each time a global permission and system permission are equal. There are five comparison possibilities:

- If the comparison result is "equivalent", one step is performed: mapping Gr_g with Sr_s, lines 8-9 in Figure 6.4.
- If the comparison result is "$Grps_g \supset Srps_s$", six steps are performed: creating a new global role (Gr_g_New); the common permissions between $Grps_g$ and $Srps_s$ are removed from Gr_g and added to Gr_g_New; adding Gr_g_New as a parent of Gr_g; adding one or more

parents to Gr_g_New utilizing the AddBasicParents algorithm in Figure 6.5; and, mapping Gr_g_New with Sr_s, lines 10-16 in Figure 6.4.

IntegrateRBAC

Input: System RBAC (SRBAC) & current Global RBAC (GRBAC)
Output: Global RBAC (GRBAC)

```
1.  for each Sr_s ∈ SRBAC
2.     Srps_s ← dirPset(Sr_s)
3.     inhSrps_s ← inherPset(system RH, Sr_s)
4.     for each Gr_g ∈ GRBAC except RootRole
5.        Grps_g ← dirPset(Gr_g)
6.        inhGrps_g ← inherPset(global RH, Gr_g)
7.        res ← compareRolesPerm(Grps_s , Srps_s, inhGrps_g, inhSrps_s)
8.        If(res==equivalent)
9.           mapRoles(Gr_g, Sr_s)
10.       Else If(res== Grps_g ⊃ Srps_s)
11.          Gr_g_new= createGlobalRole(Sr_s.name)
12.          removePer(comPset(Gr_g, Sr_s) , Gr_g)
13.          addPer(comPset(Gr_g, Sr_s) , Gr_g_new)
14.          addParent(global RH , Gr_g_new , Gr_g)
15.          AddBasicParents(Sr_s , Gr_g_new)
16.          mapRoles(Gr_g_new, Sr_s)
17.       Else If(res== Srps_s ⊃ Grps_g)
18.          If(!exist(Sr_s))
19.             Gr_g_new= createGlobalRole(Sr_s.name)
20.             addPer(uncomPset(Sr_s, Gr_g) , Gr_g_new)
21.             removePer(comPset(Gr_g, Sr_s) , Sr_s)
22.             addParent(global RH , Gr_g , Gr_g_new)
23.             AddBasicParents(Sr_s , Gr_g_new)
24.             mapRoles(Gr_g_new, Sr_s)
25.          Else
26.             removePer(comPset(Gr_g, Sr_s) , Gr_g_new)
27.             removePer(comPset(Gr_g, Sr_s) , Sr_s)
28.             addParent(global RH , Gr_g , Gr_g_new)
29.       Else If(res==overlap)
30.          Gr_g_new_2= createGlobalRole(NEW_ROLE)
31.          addPer(comPset(Gr_g, Sr_s) , Gr_g_new_2)
32.          removePer(comPset(Gr_g, Sr_s) , Gr_g)
33.          addParent(global RH , Gr_g_new_2 , Gr_g)
34.          addParent(global RH , RootRole , Gr_g_new_2)
35.          If(!exist(Sr_s))
36.             Gr_g_new= createGlobalRole(Sr_s.name)
37.             addPer(uncomPset(Sr_s, Gr_g) , Gr_g_new)
38.             removePer(comPset(Gr_g, Sr_s) , Sr_s)
39.             addParent(global RH , Gr_g_new_2 , Gr_g_new)
40.             AddBasicParents(Sr_s , Gr_g_new)
41.             mapRoles(Gr_g_new, Sr_s)
42.          Else
43.             removePer(comPset(Gr_g, Sr_s) , Gr_g_new)
44.             removePer(comPset(Gr_g, Sr_s) , Sr_s)
45.             addParent(global RH , Gr_g_new_2 , Gr_g_new)
46.       Else If(res==not related)
47.          notRelatedList.add(Gr_g , Sr_s)
48.    If(Sr_s is not related to any Gr_g)
49.       Gr_g_new = createGlobalRole(Sr_s.name)
50.       addPer(Pset(Sr_s) , Gr_g_new)
```

```
51.        AddBasicParents($Sr_s$ , $Gr_g$_new)
52.        mapRoles($Gr_g$_new, $Sr_s$)
53.  **return(**GRBAC**)**
```

Figure 6.4. The IntegrateRBAC Algorithm

- If the comparison result is "$Srps_s \supset Grps_g$", there are two cases. In the first case, Sr_s is not already added to the global role hierarchy, so six steps are performed: creating a new global role (Gr_g_New); the common permissions between $Grps_g$ and $Srps_s$ are removed from Sr_s; the uncommon permissions between $Grps_g$ and $Srps_s$ are added to Gr_g_New; adding Gr_g as a parent of Gr_g_New; adding one or more parents to Gr_g_New utilizing the AddBasicParents algorithm in Figure 6.5; and mapping Gr_g_New with Sr_s, lines 18-24 in Figure 6.4. In the second case, Sr_s is already added to the global role hierarchy, so three steps are performed: the common permissions between $Grps_g$ and $Srps_s$ are removed from Sr_s and Gr_g_New; and adding Gr_g as a parent of Gr_g_New, lines 25-28 in Figure 6.4.

- If the comparison result is "overlap", the algorithm starts with five steps: creating a new global role (Gr_g_New_2); the common permissions between $Grps_g$ and $Srps_s$ are removed from Gr_g and added to Gr_g_New_2; adding RootRole as a parent of Gr_g_New_2; and adding Gr_g_New_2 as a parent of Gr_g, lines 29-34 in Figure 6.4. Then the algorithm applies similar steps as in the "$Srps_s \supset Grps_g$" case, except that Gr_g_New_2 (instead of Gr_g) is added as a parent of Gr_g_New, lines 35-45 in Figure 6.4.

- If the result of all of the comparisons between $Srps_s$ and all of the $Grps_g$ is "not related", four steps are performed: creating a new global role (Gr_g_New); adding the permission set of Sr_s to Gr_g_New; adding one or more parents to Gr_g_New utilizing the AddBasicParents algorithm in Figure 6.5; and mapping Gr_g_New with Sr_s, lines 48-52 in Figure 6.4.

Finally, the *IntegrateRBAC* algorithm returns the resulted GRBAC, line 53 in Figure 6.4. Moreover, the *AddBasicParents* algorithm in Figure 6.5, that is utilized extensively by the *IntegrateRBAC* algorithm, is for adding a set of parent roles to a specific role, and receives a system role (Sr_s) and a new global role (Gr_g_New). Then, if Sr_s has no parents, the RootRole is added as a parent of Gr_g_New. However, if Sr_s has one or more parents, for each parent of Sr_s, the associated Gr_g is retrieved and added as a parent of Gr_g_New. The Global-RBAC algorithm runs in polynomial time and has a worst-case complexity of O(m|P|), where *m* is the number of the participated systems and |*P*| is the total number of permissions from all of the systems RBAC' policies. That is, the Global-RBAC algorithm visits each RBAC of each system once in which each permission is compared once.

AddBasicParents

Input: a system role (Sr_s), and a new global role (Gr_g_new)

```
1.  parentList=getParents(system RH, $Sr_s$)
2.  **If**(parentList==Null)
3.      addParent(global RH , RootRole , $Gr_g$_new)
4.  **Else**
5.      **for** each prnt ∈ parentList
6.          gPrnt=getMappedGRole(global RH, prnt)
7.          addParent(global RH , gPrnt, $Gr_g$_new)
```

Figure 6.5. The AddBasicParents Algorithm

The second task of the global RBAC generation phase is Review and Correct Role Names. The main purpose of this task is to address two issues that the generated global RBAC policy may have as a result of using the algorithms in Figures 6.2 to 6.5. Issue 1 can arise when a system role and global role comparison is "overlap" can the automatically created new role name is not real. Issue 2 can arise when two different Global roles are generated with very similar names but with dramatically different permissions. Specifically, when the IntegrateRBAC algorithm compares each global role Gr_g to each system role Sr_s, in which the comparison result is "overlap", a new global role named "NEW_ROLE" is created, clearly this is not a real role name (issue 1). Moreover, when the IntegrateRBAC algorithm processes all of the comparison cases, except the "equivalent" case, a new global role is created in which its name is copied from a system role Sr_s followed by a number X, where X is 1 plus the number of global roles that share a similar role name with Sr_s. Based on this, the IntegrateRBAC algorithm may generate a GRBAC that has two global roles that have a similar role name but are authorized to different sets of permissions; this is not a desirable situation (issue 2). For example, assume that the GRBAC had a global role named "Patient" that is authorized to {(Patient, READ), (Patient, CREATE)}, and the IntegrateRBAC algorithm is about to create a new global role named "Patient" that is authorized to {(Observation, READ), (Observation, CREATE)}. In this case, the IntegrateRBAC algorithm will create a new global role named "Patient_2", note that the number 2 here came from 1+ number of global roles that share a similar role name with "Patient" which is 1, and hence the GRBAC now has two global roles: "Patient" with permissions {(Patient, READ), (Patient, CREATE)}, and "Patient_2" with permissions {(Observation, READ), (Observation, CREATE)}. Our approach to solve not a real role name (issue 1) and two global roles with similar role name and radically different permissions (issue 2) is through the Review and Correct Role Names task, which has two steps. In the first step, the security engineer of FSICC reviews and suggests a name for each of two conflicting global roles, based on the authorized permission. The two new roles are generated as described in issue 1 or 2 and a name list of corrected global roles in the form of (global role ID, corrected name) is also generated. In the second step, the security engineer of FSICC sends the name list of corrected global roles to the Update Global Roles algorithm, as shown in Figure 6.6. The Update Global Roles algorithm iterates through the name list of corrected global roles and for each global role Gr_g_U in the list, the algorithm finds a global role Gr_g in GRBAC in which the id of both entries is equal. Then, the algorithm updates the name of the global role Gr_g to be the name of the corrected global role Gr_g_U and finally returns the updated global RBAC policy GRBAC, see lines 1-4 of Figure 6.6.

Update Global Roles

Input: Global Roles List (GRL) & current Global RBAC (GRBAC)
Output: Global RBAC (GRBAC)

```
1.  for each $Gr_g$_U $\in$ GRL
2.      find $Gr_g \in$ GRBAC s.t. $Gr_g$.id = $Gr_g$_U.id
3.      $Gr_g$.name = $Gr_g$_U.name
4.  return(GRBAC)
```

Figure 6.6. The Update Global Roles Algorithm

6.1.2 Global MAC Generation

The Global MAC (GMAC) Generation phase is divided into two tasks in Figure 6.1: MAC Integration and Building Global MAC. The MAC Integration task is conducted based on the assumption that the five sensitivity levels, introduced in Section 4.4, (0-Public Information, 1-Basic Sensitive Information, 2-Sensitive Information Summary, 3-Sensitive Information Details, and 4-Very Sensitive Information), are available to each system to classify their data and to assign each user a clearance. This can be useful in a complex domain such as healthcare all of the five levels are expected to be utilized due to the fact that healthcare data is complex, while in other domain such as education only a subset of the five sensitivity levels may be needed to classify data in that domain. However, although all of the participating systems are using the same set of sensitivity levels, two systems may have different semantic and usages of each sensitivity level. To overcome this issue, the presented sensitivity levels mapping step can be utilized. That is, this step is a human interaction between the security engineer of FSICC and the security engineers of participating systems to map each system sensitivity levels to the global sensitivity levels so that one set of sensitivity levels (the global sensitivity levels) can be utilized to: assign each service from each system a classification; and assign each user from each system a clearance, as we explain in the second task below. Note that the semantics of the global sensitivity levels is based on the sensitivity levels of the first participating system. The output of this task is a sensitivity levels mapping list in which each entry in the list has the following format {a global sensitivity level, a system sensitivity level, system name}.

Second, based on the sensitivity levels mapping list that is generated in the MAC Integration task, in the Building Global MAC task, the global MAC, GMAC, is generated utilizing users and services from each participating system in which users' clearances and services' classifications are assigned based on the global sensitivity levels in which the read/write properties of each user are remain unchanged. To perform this task, the security engineer of FSICC needs to send the sensitivity levels mapping list to the global MAC algorithm, see Figure 6.7, that utilizes a set of primitive functions in Table 6.2 to generate the global MAC policy. These primitive functions simplify the explanation of the global MAC algorithm. Table 6.2 has two columns: Function Signature, that has a name and a set of parameters for each function; and Description, that briefly explains each function. The global MAC algorithm takes as input: the sensitivity levels mapping list (SLML) and a set of m MAC policies from each participating system. The algorithm goes through each MAC policy of each system to add users and services of that MAC policy. First, in lines 2-6, the first loop iterates through each user of each system MAC policy to: find the global clearance that is associated with the user system's clearance; retrieve the read and write properties; and, add the user into the global MAC policy as a global user. Second, in lines 7-9, the second loop iterates through each service of each system MAC policy to: find the global classification that is associated with the service system's clearance; and, add the service into the global MAC policy as a global service. Third, the algorithm returns the GMAC. The global MAC algorithm runs in linear time and has a worst-case complexity of O(m), where *m* is the number of the participated systems. That is, the global MAC algorithm visits each MAC of each system once.

```
Global-MAC
Input: set of m Systems MAC ($SMAC_1$, $SMAC_2$, .. , $SMAC_m$) and
       sensitivity levels mapping list (SLML)
Output: Global MAC (GMAC)
1.  for i ← 1 to m
2.     for each user u in $SMAC_i[Su_s]$
3.        u.gCLR=globalClearance(SLML, u.CLR, $SMAC_i$.Name)
4.        u.gRP= u.RP
5.        u.gWP= u.WP
6.        addUser(GMAC, u)
7.     for each service s in $SMAC_i[Ssc_s]$
8.        s.gCLS=globalClassification(SLML, s.CLS, $SMAC_i$.Name)
9.        addService(GMAC, s)
10. return(GMAC)
```

Figure 6.7. The Global-MAC Algorithm

Table 6.2. Primitive Functions Utilized by the Algorithms for Global MAC Generation

Function signature	Description
globalClearance(SLML, *u*.CLR, $SMAC_i$.Name)	Returns a global sensitivity level in SLML that is mapped to *u*.CLR of the $SMAC_i$.Name system
globalClassification(SLML, *s*.CLS, $SMAC_i$.Name)	Returns a global sensitivity level in SLML that is mapped to *s*.CLS of the $SMAC_i$.Name system
addUser(GMAC, *u*)	Adds the user *u* to the global MAC
addService(GMAC, s)	Adds the service s to the global MAC

6.1.3 Global DAC Generation

The Global DAC (GDAC) Generation phase has one main task and one algorithm, DAC Integration in Figure 6.1. This task takes all of the DAC policies from each system and combines them into one global DAC policy. The DAC Integration task is performed through the global DAC algorithm, see Figure 6.8, that utilizes a set of primitive functions in Table 6.3 to generate the global DAC policy. These primitive functions simplify the explanation of the global DAC algorithm. Table 6.3 has two columns: Function Signature, that has a name and a set of parameters for each function; and Description, that briefly explains each function. The global DAC algorithm takes as input: the global RBAC, the global MAC, and a set of *m* DAC policies from each participating system. The algorithm iterates through each DAC policy of each system to retrieve and add role and/or clearance delegations into the global DAC policy. First, in lines 2-4, the first loop iterates through each role delegation *rd* of each system DAC policy to: find the global IDs of delegator user, delegated user, and delegated role using the getGobalIDs primitive function in Table 6.3; and, add a new role delegation into the global DAC policy using the retrieved global IDs. Next, in lines 5-7, the second loop iterates through each clearance delegation *cd* of each system DAC policy to: find the global IDs of delegator user, delegated user, and delegated clearance using the getGobalIDs primitive function; and, add a new clearance delegation into the global DAC policy using the retrieved global IDs. Finally, the algorithm returns the global DAC policy. The global DAC algorithm runs in polynomial time and has a worst-case complexity of O(m|d|), where *m* is the number of the participated systems and |*d*| is the total number of all of the role and clearance delegations from all of the systems DAC's policies. That is, the global DAC algorithm visits each DAC of each system once.

Global-DAC

Input: set of m Systems DAC ($SDAC_1$, $SDAC_2$, .. , $SDAC_m$),
GMAC, and GRBAC

Output: Global DAC (GDAC)

```
1.  for i ← 1 to m
2.    for each role delegation rd in SDACi[Sdss]
3.        global_rd =getGlobalIDs(rd)
4.        addGlobalDel(GDAC, global_rd)
5.    for each clearance delegation cd in SDACi[Sdss]
6.        global_cd =getGlobalIDs(cd)
7.        addGlobalDel (GDAC, global_cd)
8.  return(GDAC)
```

Figure 6.8. The Global-DAC Algorithm

Table 6.3. Primitive Functions Utilized by the Algorithms for Global DAC Generation

Function signature	Description
getGlobalIDs(*rd/cd*)	Returns global IDs of delegator, delegated, and role/sensitivity level
addGlobalDel(GDAC, global_rd/cd)	Adds a global role/clearance delegation to global DAC

6.1.4 Global Policies Combination

The results from the algorithms in Sections 6.1.1-6.1.3 serve as input to the combine global security policies instances phase that is divided into two tasks: combining the generated global RBAC instance, global MAC instance, and global DAC instance into one global security policy model instance which can be utilized by any interested clients to control their own services; and, controlling the way that data that global services can access are read and/or writtenn. The first task generates one policy document that concatenates all of the separate policies (i.e., GRBAC, GMAC, and GDAC) into one Global policy. The second task is intended to restrict clients at the data level. That is, while the global RBAC, MAC and DAC policies control who can access what set of global services, the controlling data task is intended to control what set of data, that global services can access and what each user can read/write. To control reading data actions, there are three read data access types that the security engineer of FSICC needs to choose from:

1. *Open to All* (default): This read data access type is for the case where two or more users, from different systems, who are assigned to the same global role can read any data that the global role can retrieve.
2. *Open to Same System Users*: This read data access type is for the case where a user from system X who is assigned to a global role can only read a subset of data (only data from system X) that the global role can retrieve.
3. *Customize Data Read*: This read data access type is for the case in which for each global service, the security engineer of FSICC needs to specify which systems that their users can read the retrieved data.

Moreover, to control writing data actions, there is one write data access type:

1. *Open to Same System Users*: This write data access type is for the case where a user from system X who is assigned to a global role can only write data (only data from system X) that the global role can write.

The output of the global policies combination step is a single unified security policy document that has global RBAC, global MAC, and global DAC coupled with one read data access type and one write data access type.

6.2 HAPI FHIR Implementation and RBAC/MAC/DAC Interceptors

In this section, we demonstrate the realization of UCCACM of FSICC via a HAPI FHIR Implementation and the underlying RBAC/MAC/DAC Interceptors. These are represented by the Security Enforcement via the Interceptors box of the GSP and GAPI Utilization and the Security Enforcement horizontal box in Figure 1.3 from Chapter 1, utilizing the healthcare scenario of Section 2.4 of Chapter 2. This leads to that the implementation of HAPI FHIR APIs and its server interceptor to support UCCACM checks with three different algorithms to support three different HAPI FHIR interceptors: RBAC interceptor, MAC interceptor, and DAC interceptor. This section involves the implementation of FHIR APIs and the customization and adaptation of the HAPI server interceptor to support UCCACM checks: Defns. 50 and 51 that determine if a service is authorized by a user/role pair; Defn. 55 that determines if a service is authorized by a user/clearance pair; and Defns. 57, 58, and 59 that determine if a service is authorized by a user/(delegated_role/delegated_service /delegated_clearance) pair (see Section 4.7). Three integration layers were implemented utilizing the HAPI FHIR reference library (HAPI community, 2016), namely: Clients, top of Figure 1.1 and Involved Parties component of Figure 1.2; Systems, bottom of Figure 1.1 and Involved Parties component of Figure 1.2; and FSICC, the Global Services in the middle of Figure 1.1.

The remainder of this section has five subsections. Section 6.2.1 provides a more detailed discussion than Section 2.3 of Chapter 2 on HAPI-FHIR Concepts and Background. Using this as a basis, Sections 6.2.2, 6.2.3, and 6.2.4 review and explain, respectively, the RBAC interceptor, MAC interceptor, and DAC interceptor. Finally, Section 6.2.5 presents two usage scenarios utilizing the global security policy sample from Sections 6.2.2, 6.2.3, and 6.2.4.

6.2.1 HAPI-FHIR Concepts and Background

As discussed in Section 2.3, the HAPI-FHIR library provides a general HAPI server interceptor (University Health Network, 2016) which is a programmatic approach that allows a developer to examine each incoming HTTP request to add useful features to the HAPI ResfulServer such as authentication, authorization, auditing, logging, etc. This is accomplished by implementing a number of methods: incomingRequestPreProcessed that is invoked before performing any action to the request; incomingRequestPostProcessed that is invoked after determining the request type by classifying the request; incomingRequestPreHandled which is invoked before sending the request to the Resource Provider; and, outgoingResponse which is invoked after the request is handled by the appropriate Resource Provider. To implement each of these HAPI FHIR APIs, the HAPI *RestfulServer* and HAPI *IResourceProvider* classes were utilized.

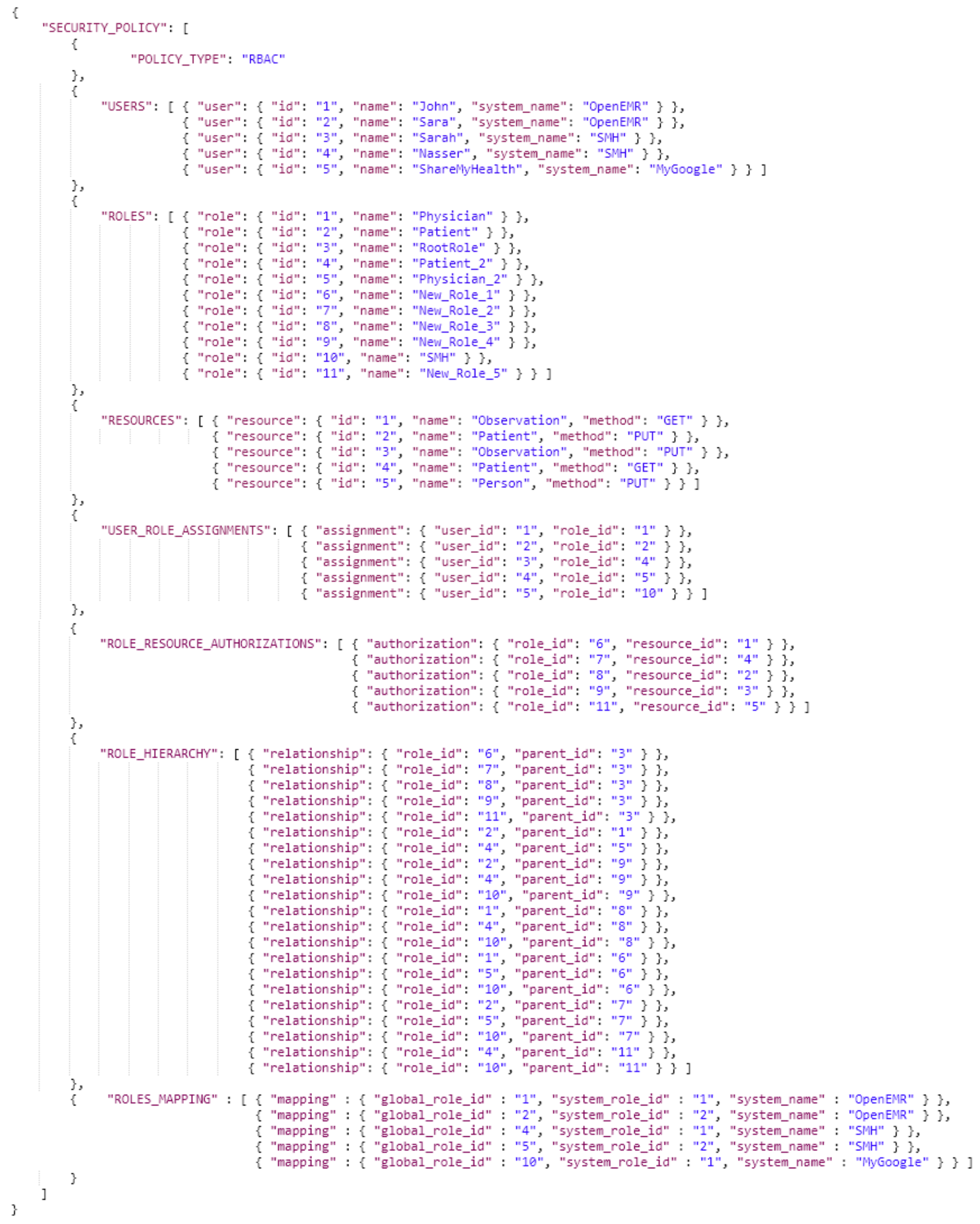
To support cloud computing capability 3 (Global Registration, Authentication, Authorization, and Service Discover for Consumers) of FSICC (see Section 3.2), the *Clients Registry*, *Systems Registry*, and *Global Security Policy* components in Figure 1.1 are developed as simple RESTful APIs, which were implemented using the JAX-RS Java library (Hadley & Sandoz, 2009). The

Clients Registry and Systems Registry components supports adding systems/clients HAPI-FHIR APIs and discovering corresponding FHIR APIs, while the Global Security Policy component enables the security engineer of FSICC to add/modify the global policy in Section 4.6 of Chapter 4 (see Defn. 39 of UCCACM). In addition, the RBAC, MAC, and DAC interceptors presented in Section 4.7 of Chapter 4 (see Defns. 52, 56, and 60 of UCCACM respectively - middle of Figure 1.1), were implemented by extending the HAPI *InterceptorAdapter* class to retrieve the global security policy from the Global Security Policy component and then extract the appropriate part (i.e., global RBAC for the RBAC Interceptor, global MAC for the MAC Interceptor, and global DAC for the DAC Interceptor) in order to performing enforcement check on each access request at runtime. Although each of the RBAC interceptor, MAC interceptor, and DAC interceptor is designed to enforce the appropriate global security policy separately, the *handleRequest* method of the RestfulServer class works as a monitor that makes sure each part of the global security policy (RBAC, MAC, and DAC) is checked and enforced, via the three interceptors, before allowing any access request.

6.2.2 RBAC Interceptor

To support security requirement 2 of FSICC, Control Access to Cloud Services Using RBAC, in this section, we present and explain the pseudo-code of the RBAC interceptor (see Defn. 52 of UCCACM) that is utilized at runtime to check security permissions (see Defns. 50 and 51 of UCCACM) of all of the calls to global services. To facilitate our explanation on the RBAC interceptor, Figure 6.9 presents a global RBAC policy example in JSON format that consists of: USERS, ROLES, RESOURCES, USER_ROLE_ASSIGNMENTS, ROLE_RESOURCE_AUTHORIZATIONS, ROLE_HIERARCHY, & ROLES_MAPPINGS. Each user is represented by three fields: id, name, and system_name. Each role is represented by two fields: id and name. Each resource is represented by three fields: id, name, and method. Each user_role_assignment is represented by two fields: user_id and role_id. Each role_resource_authorization is represented by two fields: role_id and resource_id. Each role_hierarchy relationship is represented by two fields: role_id and parent_id. Finally, each role_mapping is represented by three fields: global_role_id, system_role_id, and system_name. As shown in Figure 6.9, the global SECURITY_POLICY is based on the healthcare scenario example from Section 2.4 of Chapter 2. Notice that there are users, Defn. 14, defined for the systems OpenEMR and MyGoogle and the client app SMH. Likewise, there are roles, Defn. 8, that include roles from OpenEMR and MyGoogle systems, roles form the SMH client app, and new roles generated as during combining roles of OpenEMR and MyGoogle systems, and SMH client app. The Global RBAC example, Figure 6.9, also has a set of resources, Defn. 2, that are created from OpenEMR and MyGoogle systems, and SMH client app. The user role assignment set, Defn. 16, in the Global RBAC example is generated based on user role assignment sets from OpenEMR and MyGoogle systems, and SMH client app. Similarly, the role resource authorization set, Defn. 13, in the Global RBAC example is compiled based on role resource authorization sets from OpenEMR and MyGoogle systems, and SMH client app. The role hierarchy, Defn. 19, in the figure describes how roles in the Global RBAC example relate to each other using the parent-child relationship. Finally, the role mapping, Defn. 45, in the figure shows how each role in the Global RBAC example is mapped to the original role in OpenEMR or MyGoogle systems, or SMH client app.

In the Global RBAC example, 5 different global users are shown, three from systems (John, Sara, ShareMyHealth) and two from clients (Sarah and Nasser). There have been 11 global roles created, that have different origins: Physician with role id 1 was an original role of OpenEMR, Patient_2 with role id 4 was an original role of CT^2, and RootRole with role id 3 was created as a parent role for all of the root roles from each system and client. Note that a root role in a system or client is the role that has no parents but has at least one child. The Global RBAC example also has 5 global resources: Observation with resource id 1 and GET method name; Patient with resource id 2 and PUT method name; Observation with resource id 3 and PUT method name; Patient with resource id 4 and GET method name; and Person with resource id 5 and PUT method name. Each user is assigned a role based on their ids. For example, the user with id 1 is assigned the role with id 1, the user with id 3 is assigned the role with id 4, and the user with id 5 is assigned the role with id 10. Likewise, some roles are authorized to access some resources based on their id. For example, the role with id 6 is authorized to access the resource with id 1, the role with id 8 is authorized to access the resource with id 2, and the role with id 11 is authorized to access the resource with id 5. Based on the role hierarchy presented in Figure 6.9: the role with id 3 is a parent of roles with id 6, 7, 8, 9 and 11; the role with id 9 is a parent of roles with id 2, 4, and 10; and, the role with id 11 is a parent of roles with id 4, and 10. Finally, the role mapping in the Figure 6.9 shows that: the global role with id 1 is originated from the OpenEMR's system role with id 1; the global role with id 4 is originated from the SMH's client role with id 1; and, the global role with id 10 is originated from the MyGoogle's system role with id 1.



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "RBAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "John", "system_name": "OpenEMR" } },
                       { "user": { "id": "2", "name": "Sara", "system_name": "OpenEMR" } },
                       { "user": { "id": "3", "name": "Sarah", "system_name": "SMH" } },
                       { "user": { "id": "4", "name": "Nasser", "system_name": "SMH" } },
                       { "user": { "id": "5", "name": "ShareMyHealth", "system_name": "MyGoogle" } } ]
        },
        {
            "ROLES": [ { "role": { "id": "1", "name": "Physician" } },
                       { "role": { "id": "2", "name": "Patient" } },
                       { "role": { "id": "3", "name": "RootRole" } },
                       { "role": { "id": "4", "name": "Patient_2" } },
                       { "role": { "id": "5", "name": "Physician_2" } },
                       { "role": { "id": "6", "name": "New_Role_1" } },
                       { "role": { "id": "7", "name": "New_Role_2" } },
                       { "role": { "id": "8", "name": "New_Role_3" } },
                       { "role": { "id": "9", "name": "New_Role_4" } },
                       { "role": { "id": "10", "name": "SMH" } },
                       { "role": { "id": "11", "name": "New_Role_5" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "GET" } },
                           { "resource": { "id": "2", "name": "Patient", "method": "PUT" } },
                           { "resource": { "id": "3", "name": "Observation", "method": "PUT" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET" } },
                           { "resource": { "id": "5", "name": "Person", "method": "PUT" } } ]
        },
        {
            "USER_ROLE_ASSIGNMENTS": [ { "assignment": { "user_id": "1", "role_id": "1" } },
                                       { "assignment": { "user_id": "2", "role_id": "2" } },
                                       { "assignment": { "user_id": "3", "role_id": "4" } },
                                       { "assignment": { "user_id": "4", "role_id": "5" } },
                                       { "assignment": { "user_id": "5", "role_id": "10" } } ]
        },
        {
            "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "6", "resource_id": "1" } },
                                              { "authorization": { "role_id": "7", "resource_id": "4" } },
                                              { "authorization": { "role_id": "8", "resource_id": "2" } },
                                              { "authorization": { "role_id": "9", "resource_id": "3" } },
                                              { "authorization": { "role_id": "11", "resource_id": "5" } } ]
        },
        {
            "ROLE_HIERARCHY": [ { "relationship": { "role_id": "6", "parent_id": "3" } },
                                { "relationship": { "role_id": "7", "parent_id": "3" } },
                                { "relationship": { "role_id": "8", "parent_id": "3" } },
                                { "relationship": { "role_id": "9", "parent_id": "3" } },
                                { "relationship": { "role_id": "11", "parent_id": "3" } },
                                { "relationship": { "role_id": "2", "parent_id": "1" } },
                                { "relationship": { "role_id": "4", "parent_id": "5" } },
                                { "relationship": { "role_id": "2", "parent_id": "9" } },
                                { "relationship": { "role_id": "4", "parent_id": "9" } },
                                { "relationship": { "role_id": "10", "parent_id": "9" } },
                                { "relationship": { "role_id": "1", "parent_id": "8" } },
                                { "relationship": { "role_id": "4", "parent_id": "8" } },
                                { "relationship": { "role_id": "10", "parent_id": "8" } },
                                { "relationship": { "role_id": "1", "parent_id": "6" } },
                                { "relationship": { "role_id": "5", "parent_id": "6" } },
                                { "relationship": { "role_id": "10", "parent_id": "6" } },
                                { "relationship": { "role_id": "2", "parent_id": "7" } },
                                { "relationship": { "role_id": "5", "parent_id": "7" } },
                                { "relationship": { "role_id": "10", "parent_id": "7" } },
                                { "relationship": { "role_id": "4", "parent_id": "11" } },
                                { "relationship": { "role_id": "10", "parent_id": "11" } } ]
        },
        {    "ROLES_MAPPING" : [ { "mapping" : { "global_role_id" : "1", "system_role_id" : "1", "system_name" : "OpenEMR" } },
                                 { "mapping" : { "global_role_id" : "2", "system_role_id" : "2", "system_name" : "OpenEMR" } },
                                 { "mapping" : { "global_role_id" : "4", "system_role_id" : "1", "system_name" : "SMH" } },
                                 { "mapping" : { "global_role_id" : "5", "system_role_id" : "2", "system_name" : "SMH" } },
                                 { "mapping" : { "global_role_id" : "10", "system_role_id" : "1", "system_name" : "MyGoogle" } } ]
        }
    ]
}
```

Figure 6.9. A Global RBAC Policy Example in JSON

Figure 6.10 presents the RBAC enforcement code realized within the *incomingRequestPostProcessed* method of the RBAC Interceptor as introduced in Section 6.2.1, which is an extension of the HAPI InterceptorAdapter class, which is registered in the RestfulServer class. This method starts by retrieving a secure Token (line 3) from a HTTP header (Authorization) of the request parameter, that is then passed to the *extractUser* function that can obtain the user credentials (user Id, see Defn. 15v2, and role Id, Defn. 9v2) from the Token (line

5). Next, the Global Policy (see Defn. 39), which is in JSON format, is retrieved by calling the Global Policy URL (line 7). The global RBAC policy example in Figure 6.9, is then extracted from the Global Policy through the *extract_RBAC* function (line 8). Then, the details of the requested resource (resource name, see Defn. 2, and HTTP method, see Defn. 4) are obtained from the requestDetails and request parameters, respectively, and passed along with the RBAC policy to the *getResourceId* function that returns the Id of the requested resource (lines 9 to 11). In line 14, the user credentials and the RBAC policy are passed to the *checkCredentials* function (see Defn. 50) to determine whether the user has the claimed role (see Defn. 9v2). If the check fails, the value of the accessDecision variable becomes false (lines 27-30). If the user passes the check, the associated role Id, the resource Id, and the RBAC policy are passed to the *checkPerm* function (see Defn. 51 - line 19) that returns true if the user with such a role can access the requested resource or false otherwise. Note that the *checkPerm* function works by retrieving a list of parent roles of the user role (passed) based on the global role hierarchy, part of RBAC policy, in which the user can access all of the resources that are authorized to the user role of any of its parents. Based on the result of the *checkPerm* function, the variable accessDecision is assigned (true or false) and returned as the result of the *incomingRequestPostProcessed* method (lines 20-25 and 31).

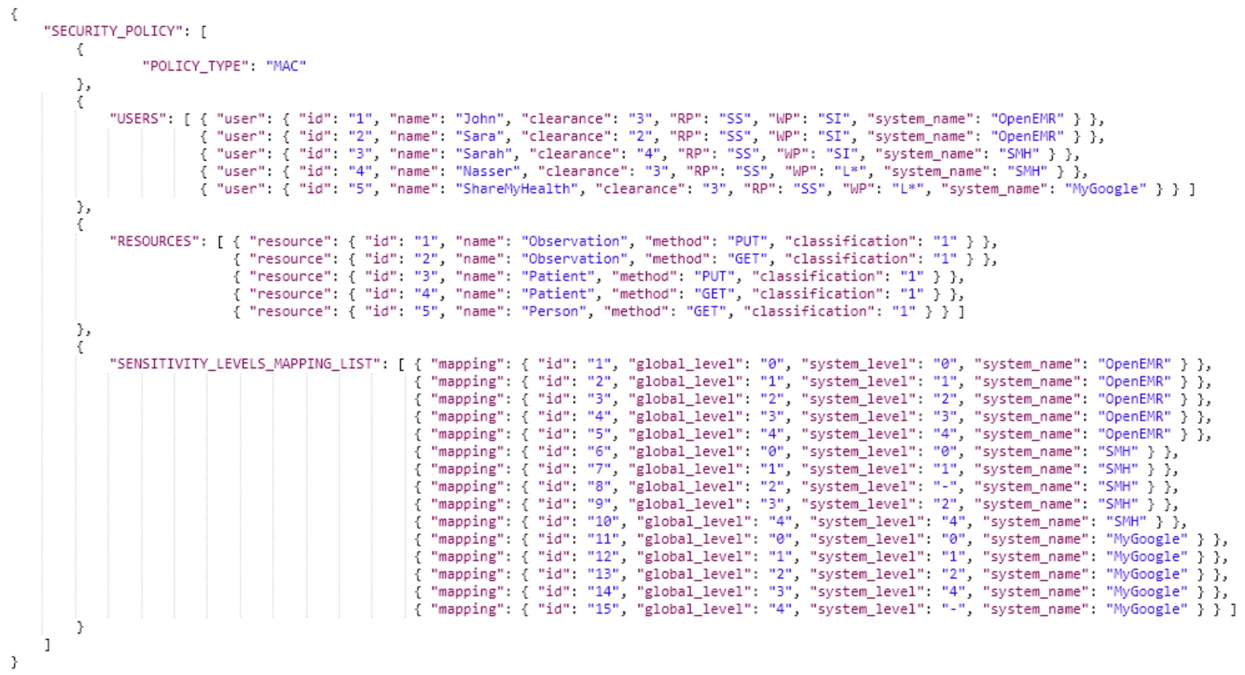
```
//Serves as Access Control Interceptor function
public boolean incomingRequestPostProcessed(requestDetails, request, response){
    secToken = request.getHeader("Authorization");
    // Retrieves the user id and role id of the current user
    [userId,roleId] = extractUser(secToken);
    // Retrieves the RBAC policy from the Global Policy URL
    Global_Policy= HttpGet(Global_Policy_URL);
    RBAC_Policy= extract_RBAC(Global_Policy);
    resourceName = requestDetails.getResourceName();
    httpMethod = request.getMethod();
    resourceId = getResourceId(httpMethod, resourceName, RBAC_Policy);
    // check if the user has the claimed role
    verifiedUser=false;
    verifiedUser=checkCredintals(userId, roleId, RBAC_Policy); // true or false
    // check if the user (role) can access the requested resource and method
    verifiedPerm=false;
    accessDecision=false;
    if(verifiedUser==true){
          verifiedPerm=checkPerm(roleId, resourceId, RBAC_Policy); // true or false
          if(verifiedPerm==true){
                accessDecision=true; // allow user request
          }
          else {
                accessDecision=false; // deny user request
          }
    }
    else{
    // Error Message: User could not be verified
     accessDecision=false; // deny user request
    }
Return accessDecision;
}
```

Figure 6.10. RBAC Interceptor Pseudo Code.

6.2.3 MAC Interceptor

To support security requirement 4 of FSICC, Control Access to Cloud Services Using MAC, in this section we present and explain the pseudo-code of the MAC interceptor (see Defn. 56 of UCCACM) that is utilized at runtime to check security permissions (see Defn. 55 of UCCACM) of all of the calls to global services. To facilitate our explanation, Figure 6.11 presents a global MAC policy example in JSON format that consists of three parts: USERS, RESOURCES, and SENSITIVITY_LEVELS_MAPPING_LIST. Each user is represented by six fields: id, name, clearance, read property, write property, and system_name. Each resource is represented by four fields: id, name, method, and classification. Finally, each sensitivity level mapping is represented by four fields: id, global_level, system_level, and system_name. Notice that there are users, Defn. 10, defined for the systems OpenEMR and MyGoogle and the client app SMH. The Global MAC example, Figure 6.11, also has a set of resources, Defn. 2, that are created from OpenEMR and MyGoogle systems, and SMH client app. Finally, the sensitivity levels, Defn. 10, mapping list in the figure shows how each sensitivity level in the Global MAC example is mapped to the original sensitivity level in OpenEMR or MyGoogle systems, or SMH client app.

In the Global MAC example, 5 different global users are shown, three from systems (John, Sara, ShareMyHealth) and two from clients (Sarah and Nasser). Moreover, the user John has: level 3 or Sensitive Information Details clearance; SS read property; and SI write property. The user Sara has level 2 or Sensitive Information Summary clearance; SS read property; and SI write property. The user Sarah has level 4 or Very Sensitive Information clearance; SS read property; and SI write property. In addition, each of users Nasser and ShareMyHealth has level 3 or Sensitive Information Details clearance; SS read property; and L* write property. There are 5 global resources: Observation with resource id 1 and GET method name; Patient with resource id 2 and PUT method name; Observation with resource id 3 and PUT method name; Patient with resource id 4 and GET method name; and Person with resource id 5 and PUT method name. Note that all resources have level 1 or Basic Sensitive Information clearance. Finally, the sensitivity levels mapping list in the Figure 6.11 shows that: global level 0 (Public Information) is mapped to level 0 (Public Information) of OpenEMR; SMH; and MyGoogle. Global level 3 (Sensitive Information Details) is mapped to: level 3 (Sensitive Information Details) of OpenEMR; level 2 (Sensitive Information Summary) of SMH and level 4 (Very Sensitive Information) of MyGoogle. Global level 4 (Very Sensitive Information) is mapped to level 4 (Very Sensitive Information) of OpenEMR and SMH but is not mapped to any level of MyGoogle.



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "MAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "John", "clearance": "3", "RP": "SS", "WP": "SI", "system_name": "OpenEMR" } },
                       { "user": { "id": "2", "name": "Sara", "clearance": "2", "RP": "SS", "WP": "SI", "system_name": "OpenEMR" } },
                       { "user": { "id": "3", "name": "Sarah", "clearance": "4", "RP": "SS", "WP": "SI", "system_name": "SMH" } },
                       { "user": { "id": "4", "name": "Nasser", "clearance": "3", "RP": "SS", "WP": "L*", "system_name": "SMH" } },
                       { "user": { "id": "5", "name": "ShareMyHealth", "clearance": "3", "RP": "SS", "WP": "L*", "system_name": "MyGoogle" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "5", "name": "Person", "method": "GET", "classification": "1" } } ]
        },
        {
            "SENSITIVITY_LEVELS_MAPPING_LIST": [ { "mapping": { "id": "1", "global_level": "0", "system_level": "0", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "2", "global_level": "1", "system_level": "1", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "3", "global_level": "2", "system_level": "2", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "4", "global_level": "3", "system_level": "3", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "5", "global_level": "4", "system_level": "4", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "6", "global_level": "0", "system_level": "0", "system_name": "SMH" } },
                                                 { "mapping": { "id": "7", "global_level": "1", "system_level": "1", "system_name": "SMH" } },
                                                 { "mapping": { "id": "8", "global_level": "2", "system_level": "-", "system_name": "SMH" } },
                                                 { "mapping": { "id": "9", "global_level": "3", "system_level": "2", "system_name": "SMH" } },
                                                 { "mapping": { "id": "10", "global_level": "4", "system_level": "4", "system_name": "SMH" } },
                                                 { "mapping": { "id": "11", "global_level": "0", "system_level": "0", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "12", "global_level": "1", "system_level": "1", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "13", "global_level": "2", "system_level": "2", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "14", "global_level": "3", "system_level": "4", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "15", "global_level": "4", "system_level": "-", "system_name": "MyGoogle" } } ]
        }
    ]
}
```

Figure 6.11. A Global MAC Policy Example in JSON

Figure 6.12 has the MAC enforcement code realized within the *incomingRequestPostProcessed* method of the MAC Interceptor, which is an extension of the HAPI InterceptorAdapter class, which is registered in the RestfulServer class. This method starts by retrieving a secure Token (line 3) from a HTTP header (Authorization) of the request parameter, that is passed to the *extractUser* function that can obtain the user credentials (user Id, see Defn. 15v3) from the Token (line 5). Then, the Global Policy (see Defn. 39), which is in the JSON format, is retrieved by calling the Global Policy URL (line 7). The MAC policy, see the global MAC policy example in Figure 6.11, is then extracted from the Global Policy through the *extract_MAC* function (line 8). Next, in line 10, the user Id and MAC policy are passed to the *getUserDetails* function that returns the user details (i.e., user clearance, Read property, and Write property). Then, the details of the requested resource (resource name, see Defn. 2, and HTTP method, see Defn. 4) are obtained from the requestDetails and request parameters, respectively, and passes along with the MAC policy to the *getResourceId* function that returns the Id of the requested resource (lines 11 to 13). In line 15, the resource Id and MAC policy are passed to the *getResourceCLS* function to find the resource classification level. Then, using the user details and the requested resource details, the accessDecision variable is set to true, if the user clearance satisfies the user's predefined read or write properties on the requested resource and method, or false, otherwise (lines 17 to 41). Finally, in line 42, the value of the accessDecision variable is returned as the result of the *incomingRequestPostProcessed* method.

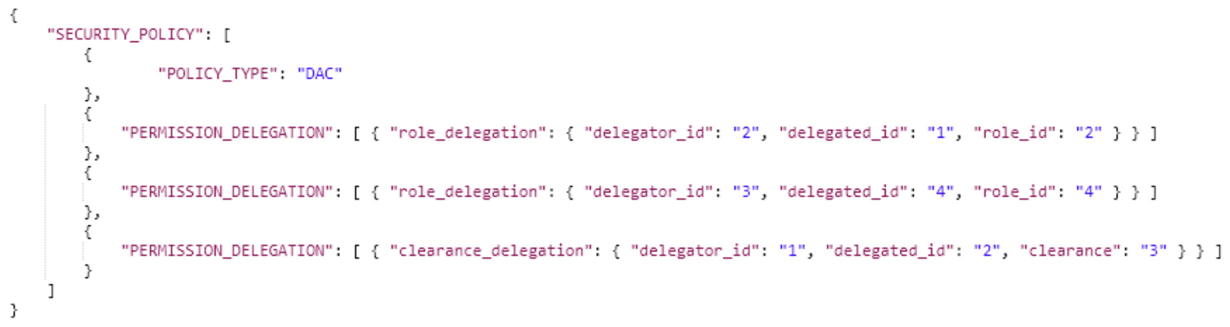
```
1  //Serves as Access Control Interceptor function
2  public boolean incomingRequestPostProcessed(requestDetails, request, response){
3      secToken = request.getHeader("Authorization");
4      // Retrieves the user id of the current user
5      userId = extractUser(secToken);
6      // Retrieves the MAC policy from the Global Policy URL
7      Global_Policy= HttpGet(Global_Policy_URL);
8      MAC_Policy= extract_MAC(Global_Policy);
9      // Retrieves the Clearance level, Read, and Write properties of the current user
10     [UserCLR, RP, WP] = getUserDetails(userId , MAC_Policy);
11     resourceName = requestDetails.getResourceName();
12     httpMethod = request.getMethod();
13     resourceId = getResourceId(httpMethod, resourceName, MAC_Policy);
14     // Retrieves the classification level of the requested resource
15     ResourceCLS = getResourceCLS(resourceId , MAC_Policy);
16     // check if user with a CLR, Read, & Write properties can access requested resource and method
17     accessDecision=false;
18     if(httpMethod=="GET"){
19     if(RP=="SS"){
20            if(UserCLR < ResourceCLS ){   accessDecision=false;   }
21            else{   accessDecision=true;   }
22     }
23           else if(RP=="SSR") {
24            if(UserCLR != ResourceCLS ){   accessDecision=false;   }
25            else{   accessDecision=true;   }
26        }
27     }
28     elseif(httpMethod=="POST" || httpMethod=="PUT" || httpMethod=="DELETE"){
29     if(RP=="SI"){
30            if(UserCLR < ResourceCLS ){   accessDecision=false;   }
31            else{   accessDecision=true;   }
32           }
33           else if(RP=="LS") {
34            if(UserCLR > ResourceCLS ){   accessDecision=false;   }
35            else{   accessDecision=true;   }
36           }
37     else if(RP=="SSW") {
38            if(UserCLR != ResourceCLS ){   accessDecision=false;   }
39            else{   accessDecision=true;   }
40           }
41     }
42  Return accessDecision;
43  }
```

Figure 6.12. MAC Interceptor Pseudo Code.

6.2.4 DAC Interceptor

To support security requirement 3 of FSICC, Support Delegation of Cloud Services Using DAC, in this section, we present and explain the pseudo-code of the DAC interceptor (see Defn. 60 of UCCACM) that is utilized at runtime to check security permissions (see Defns. 57, 58, and 59 of UCCACM) of all of the calls to global services. To facilitate the explanation, Figure 6.13

presents a global DAC policy example in JSON format that consists of one main part, PERMISSION_DELEGATION, that can have role delegation, or clearance delegation. Each role delegation is represented by three fields: delegator_id, delegated_id, and role_id. Each clearance delegation is represented by three fields: delegator_id, delegated_id, and clearance. Notice that the role delegation set, Defn. 25, in Figure 6.13 is based on a set of role delegations from OpenEMR and MyGoogle systems, and SMH client app. Likewise, the clearance delegation set, Defn. 24, in the figure is based on a set of clearance delegations from OpenEMR and MyGoogle systems, and SMH client app. For example, the first permission delegation in the Global DAC example, is a role delegation in which the user with id 2, see Figure 6.9, passed on the authorization of the role (Patient) with id 2 to the user with id 1.



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "DAC"
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "2", "delegated_id": "1", "role_id": "2" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "3", "delegated_id": "4", "role_id": "4" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "clearance_delegation": { "delegator_id": "1", "delegated_id": "2", "clearance": "3" } } ]
        }
    ]
}
```

Figure 6.13. A Global DAC Policy Example in JSON

Figure 6.14 has the DAC enforcement code realized within the *incomingRequestPostProcessed* method of the DAC Interceptor, which is an extension of the HAPI InterceptorAdapter class, which is registered in the RestfulServer class. Basically, the DAC enforcement code is a combination of both the RBAC enforcement code, lines 3-11 and line 19, and the MAC enforcement code, lines 21-22, 24-25, and 27-50, with role delegation and clearance delegation checks. This method starts by retrieving a secure Token from a HTTP header (Authorization) of the request parameter, that is passed to the *extractUser* function that can obtain the user credentials (i.e., user Id, see Defn. 15v2, and role Id, see Defn. 9v2) from the Token (line 4). Then, the Global Policy (see Defn. 39), which is in JSON format, is retrieved by calling the Global Policy URL (line 5). The global RBAC policy example in Figure 6.9 is then extracted from the Global Policy through the *extract_RBAC* function (line 6). Next, the details of the requested resource (resource name, see Defn. 2, and HTTP method, see Defn. 4) are obtained from the requestDetails and request parameters, respectively, and are passed along with the RBAC policy to the *getResourceId* function that returns the Id of the requested resource (lines 7 to 9). In line 11, the user credentials and the RBAC policy are passed to the *checkCredentials* function (see Defn. 50) to determine whether the user has the claimed role (see Defn. 9v2). Then, the global DAC policy example in Figure 6.13 is extracted from the Global Policy through the *extract_DAC* function (line 12). If the *checkCredentials* check fails, another check (lines 13-15) is performed to determine whether such a role is delegated to the current user by another user. This is done by passing the user Id, the claimed role Id, and the DAC policy to the *checkRoleDelegation* function that returns true if the entry delegated_id(user Id)/claimed role exists or false otherwise to the verifiedRoleDelegation variable.

If both checks fail (line 18), the value of the accessDecision variable becomes false (lines 57-59). However, if the user passed at least one of these checks, the associated role Id, the resource Id, and the RBAC policy are passed to the *checkPerm* function (see Defn. 51 - line 19) that returns true if the user with such role (or delegated role) can access the requested resource or false otherwise. Note that the *checkPerm* function first retrieves a list of parent roles of the user role (passed) based on the global role hierarchy, part of RBAC policy, in which the user can access all of the resources that are authorized to the user role of any of its parents. If the *checkPerm* function returns false, then the variable accessDecision is set to false (lines 53-54). However, if the *checkPerm* function returns true, then the global MAC policy example in Figure 6.11 is extracted from the Global Policy through the *extract_MAC* function (line 21). Then, in line 22, the user Id and MAC policy are passed to the *getUserDetails* function that returns the user details (i.e., user clearance, Read property, and Write property). Next, a user clearances list is created to include the user clearance, from the previous step, and a set of delegated clearances to the current user that is obtained from the *getUserDelegatedCLR* function that takes as inputs the user id and the DAC policy (line 23). Then, in line 24, the resource Id and MAC policy are passed to the *getResourceCLS* function to find the resource classification level. After that, for each user clearance in the user clearances list, the following procedure is performed: utilizing the user details and the requested resource details the accessDecision variable is set to true if the user clearance satisfies the user's predefined read or write properties on the requested resource and method, or false, otherwise (lines 26 to 51). Finally, in line 61, the value of the accessDecision variable is returned as the result of the *incomingRequestPostProcessed* method.

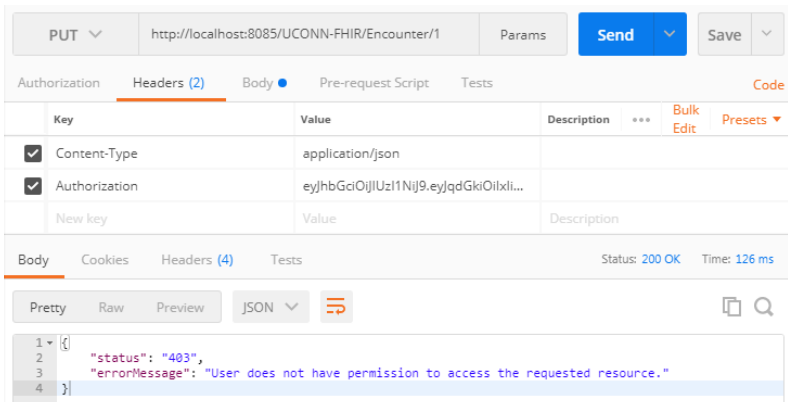
```
//Serves as Access Control Interceptor function
public boolean incomingRequestPostProcessed(requestDetails, request, response){
   secToken = request.getHeader("Authorization");
   [userId,roleId] = extractUser(secToken);
   Global_Policy= HttpGet(Global_Policy_URL);
   RBAC_Policy= extract_RBAC(Global_Policy);
   resourceName = requestDetails.getResourceName();
   httpMethod = request.getMethod();
   resourceId = getResourceId(httpMethod, resourceName, RBAC_Policy);
   verifiedUser=false;
   verifiedUser=checkCredintals(userId, roleId, RBAC_Policy); // true or false
   DAC_Policy= extract_DAC(Global_Policy);
   if(verifiedUser==false){
      verifiedRoleDelegation=checkRoleDelegation (userId, roleId, DAC_Policy); // true or false
   }
   verifiedPerm=false;
   accessDecision=false;
   if(verifiedUser==true || verifiedRoleDelegation==true){
         verifiedPerm=checkPerm(roleId, resourceId, RBAC_Policy); // true or false
         if(verifiedPerm==true){
               MAC_Policy= extract_MAC(Global_Policy);
               [UserCLR, RP, WP] = getUserDetails(userId , MAC_Policy);
               UserCLRList = getUserDelegatedCLR(userId , DAC_Policy) + UserCLR;
               ResourceCLS = getResourceCLS(resourceId , MAC_Policy);
               accessDecision=false;
               for each UserCLR in UserCLRList {
               if(httpMethod=="GET"){
                     if(RP=="SS"){
                           if(UserCLR < ResourceCLS ){   accessDecision=false;   }
                           else{   accessDecision=true;   }
                     }
                     else if(RP=="SSR") {
                           if(UserCLR != ResourceCLS ){   accessDecision=false;   }
                           else{   accessDecision=true;   }
                     }
               }
               else if(httpMethod=="POST" || httpMethod=="PUT" || httpMethod=="DELETE"){
                     if(RP=="SI"){
                           if(UserCLR < ResourceCLS ){   accessDecision=false;   }
                           else{   accessDecision=true;   }
                     }
                     else if(RP=="LS") {
                           if(UserCLR > ResourceCLS ){   accessDecision=false;   }
                           else{   accessDecision=true;   }
                     }
                     else if(RP=="SSW") {
                           if(UserCLR != ResourceCLS ){   accessDecision=false;   }
                           else{   accessDecision=true;   }
                     }
               }
               }
         }
         else {
               accessDecision=false; // deny user request
         }
   }
   else{
   // Error Message: User could not be verified
    accessDecision=false; // deny user request
   }
Return accessDecision;
}
```

Figure 6.14. DAC Interceptor Pseudo Code.

6.2.5 Two Usage Scenarios

This section presents two access scenarios, to access global services of FSICC, of usage that can be initiated by ShareMyHealth and MyGoogle, from Section 2.4, in order to demonstrate the way that the three interceptors operate. The FSICC allows or rejects requests from ShareMyHealth and MyGoogle to access the global services based on the enforcement codes that are generated by: the RBAC Interceptor (Figure 6.10), the MAC Interceptor (Figure 6.12), and the DAC Interceptor

(Figure 6.14) that use the defined global security policy (see Defn. 39 - Figures 6.9 with global RBAC, 6.11 with global MAC, and 6.13 with global DAC). That is, FSICC receives each request which is forwarded to all three interceptors for RBAC, MAC, and DAC in which each interceptor retrieves the appropriate security policy and returns a reject or allow decision to FSICC based on that security policy. Note that the two requests were made with the Postman tool (Postman, 2013) instead of directly made them from ShareMyHealth and MyGoogle in order to present a clear view of the response the requests can have in different scenarios. In the first scenario, Figure 6.15, FSICC rejects a request from the user (Sarah) via the ShareMyHealth (SMH) app to access the global service (PUT Encounter). This is since the user (SSincs) with user Id (3) is assigned a role (Patient_2) with role Id (4) that is authorized to access global services 1-5, see global RBAC in Figure 6.9 what does not have access to the global service (PUT Encounter). Also, the access will also fail since the user (Sarah) has no delegated roles, see global DAC in Figure 6.13.



http://localhost:8085/UCONN-FHIR/Encounter/1

Key	Value	Description
✓ Content-Type	application/json	
✓ Authorization	eyJhbGciOiJIUzI1NiJ9.eyJqdGkiOilxli...	
New key	Value	Description

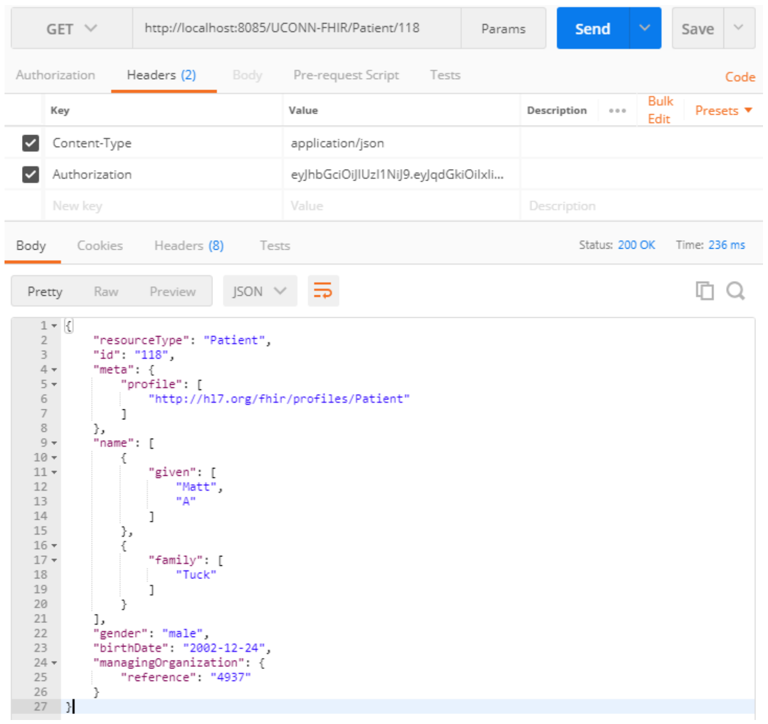
Status: 200 OK Time: 126 ms

```
{
    "status": "403",
    "errorMessage": "User does not have permission to access the requested resource."
}
```

Figure 6.15. Access Scenario One (Rejected).

In the second scenario, Figure 6.16, the request from the user (ShareMyHealth) with id (5) via MyGoogle to access the global service (GET Patient), would be allowed by FSICC. This is since the user (ShareMyHealth) with user Id (5) is assigned a role (SMH) with role Id (10) that is authorized to access global services 1-5 that includes (GET Patient), as was shown in the global

RBAC in Figure 6.9. in summary, the three interceptors are utilized in conjunction to dynamically check each time a user tries to invoke a global Service. All of the conditions must be satisfied in terms of permissions against the global RBAC, MAC or DAC in order for the service to be invoked.



http://localhost:8085/UCONN-FHIR/Patient/118

Key	Value	Description
Content-Type	application/json	
Authorization	eyJhbGciOiJIUzI1NiJ9.eyJqdGkiOiIxli...	
New key	Value	Description

Status: 200 OK Time: 236 ms

```
{
    "resourceType": "Patient",
    "id": "118",
    "meta": {
        "profile": [
            "http://hl7.org/fhir/profiles/Patient"
        ]
    },
    "name": [
        {
            "given": [
                "Matt",
                "A"
            ]
        },
        {
            "family": [
                "Tuck"
            ]
        }
    ],
    "gender": "male",
    "birthDate": "2002-12-24",
    "managingOrganization": {
        "reference": "4937"
    }
}
```

Figure 6.16. Access Scenario Two (Allowed).

6.3. Related work in Security Policy Integration and Enforcement

In this section, we present related work in two areas: security policy integration and security policies enforcement on FHIR API. For the first area, we review five related works on security policy integration comparing and contrasting their work to our security policy integration approach. The first effort (Shafiq, B, Joshi, B, Bertino, E, & Ghafoor, A, 2005) proposed a set of mapping algorithms that can be utilized to combine RBAC policies from different sources into a conflictfree global policy. This work is similar to our RBAC integration approach by providing an RBAC integration solution. However, this work assumes that all of the RBAC policies from different systems are defined and stored using the same format which is an unrealistic assumption, while in our approach we require each system to provide an RBAC policy using a specific format in JSON.

The second effort (Gouglidis, A, Ioannis, M, & Vincent, C, 2014) extended NIST-RBAC to define a checking technique that can be utilized as a management service/tool for the verification of multi-domain cloud policies. This technique is capable of detecting whether a user with a role from one domain can access an object from another domain. This effort, unlike our approach, does not define a complete global RBAC policy for all of the integrated systems and performs an on-the-fly authorization query for every object access request that generates an undesirable overhead.

The third effort (Bonatti, P, Maria, L, & Subrahmanian, V, 1997) focused on the issue of integrating sensitivity levels of different systems under the assumption that one sensitivity level in one system may have a different semantic interpretation of the same sensitivity level in another system. To solve this issue, this effort proposed to map each sensitivity level of each system with a sensitivity level that has similar semantics but not the same name in another system. This effort is similar to our MAC integration approach in the way they map a number of sensitivity levels of different systems which is similar to our mapping of classification levels. However, the way users and objects of each system assigned clearance and classification, respectively, in the presence of the global sensitivity levels, is not clearly articulated.

The fourth effort (Dawson, S, Shelly, Q, & Pierangela, S, 2000) proposed an approach for MAC-based polices integration by introducing two main concepts: the wrapper and the mediator. A wrapper is a mechanism that is associated with each system to provide a uniform data interface and a mapping between the system's sensitivity levels and sensitivity levels of other systems in order to generate a global MAC policy. The mediator is an enforcement technique that processes global access requests based on the generated global MAC policy. This work is similar to our MAC integration approach as they provide a MAC integration solution and also provide a technique to enforce the global MAC policy. However, their work assumes that each user of each system can only be assigned to one specific read property (SS) and one specific write property (SI), unlike our approach where any user may be assigned to any of the read properties (SS, S* read) and to any of the write properties (SI, L*, S* write).

The last effort (Joshi, BD & Elisa, B, 2006) proposed a solution for defining RBAC-based delegation in an integrated environment. Specifically, in this work a delegation framework is proposed that provides two types of delegation, role delegation and permissions (sub-set of permissions of a role) delegation, that can be user-to-user, user-to-role, role-to-role or role-to-user. This work is similar to our DAC integration approach as they also provide a DAC integration solution. However, their work is limited to a specific type of RBAC (i.e., GTRBAC), unlike our approach for RBAC-based delegation. Also, their work does not support the integration of MAC-based delegation in which our approach provides it. Note that all of the above five efforts try to integrate policies that are defined against objects (traditional) and just target one access control model, while our security policy integration approach provides solutions to integrate policies which are defined against services that access objects in which such policies can be any combination of RBAC, MAC, and DAC.

For the second area, we review four related works on the topic of security enforcement that utilizes FHIR. The first effort, SMART on FHIR (SMART on FHIR, 2015), proposed a standard for authentication and authorization that controls Apps access to FHIR resources based on the OAuth2 authentication protocol (Cook, 2012). Each App is given a cryptographic Token that has a number of claims. A claim can be a scope (each App may have one or more scopes) or patient ID, and the information in the Token is encrypted using the JWT library (JWT Team, 2012). A scope, such as (scope=user/Patient.read), defines what type of FHIR API an App can access which allows an App to retrieve all of the Patient data and can be further restricted to only return the Patient record that matches the patient ID in the App's Token. This effort is similar to our approach for enforcing security policies since they support security interceptors that perform authentication and authorization against each request to access services. However, the authorization interceptor presented by this effort is different from our approach since the authorization interceptor cannot be used to enforce advanced security policies to control access to FHIR resources using roles (RBAC), sensitivity levels (MAC), and roles/sensitivity levels delegations (DAC).

The second effort, Vonk (Simplifier.net, 2018), is an extension of the access control approach of SMART on FHIR, an implementation of SMART on FHIR standard in which the default processes for Apps authentication and authorization is based on SMART on FHIR standard. However, in Vonk, the authentication implementation can be changed from the default OAuth2 authentication protocol to any other authentication implementations and the authorization process of SMART on FHIR can be replaced with any other authorization implementations. This effort is similar to our approach for enforcing security policies as their approach provide authentication and authorization capabilities. However, the authorization process of this effort is different from our approach as it does not support advanced security requirements to control access to FHIR resources using roles (RBAC), sensitivity levels (MAC), and roles/sensitivity levels delegations (DAC).

The third effort, SecFHIR (Altamimi, 2016), proposed a security standard that may be adopted to extend the FHIR standard with access control specifications. Specifically, SecFHIR suggested to define permissions on FHIR resources as an XML schema so that the defined XML schema can be integrated into the XML schemas of different FHIR resources. In this way, the permissions defined in each FHIR resource's XML schemas can be utilized by any access control mechanism to enforce such permissions. Clearly this approach is different from our approach since SecFHIR does not provide any authentication capabilities that can be utilized to verify the identity of Apps. Also, SecFHIR doesn't provide any mechanisms to support enforcing security policies on Apps' access requests for important access control models such as RBAC, MAC, and DAC.

Finally, the fourth effort, HAPI FHIR reference implementation (HAPI community, 2017), provides two security mechanisms: one to verify Apps identity using an authentication interceptor; and another one to enforce security policies using the rule-based access control model using the authorization interceptor. The authentication interceptor utilizes the HTTP Basic Auth protocol for Apps authentication purposes. In addition, the rule-based access control model defines a set of rules within the interceptor and utilizes if/else statements in order to whitelist/blacklist Apps access requests to FHIR resources. This approach is similar to our approach for enforcing security policies as their approach provides authentication and authorization capabilities, via the authentication and authorization interceptors. However, the authorization interceptor of their approach is different from our approach as they do not support advanced security requirements to control access to FHIR resources using roles (RBAC), sensitivity levels (MAC), and roles/sensitivity levels delegations (DAC).

Chapter 7
SOA-based Security Engineering for FSICC

This chapter presents and explains an SOA-based security engineering and global security policy generation process for FSICC that involves all of the horizontal boxes in Figure 1.3 that contain the main research foci of this dissertation: *Architectural Blueprints* as reviewed in Chapter 5; *Unified Cloud Computing Access Control Model* as presented in Chapter 4; *Access Control Models* in Section 1.3 of Chapter 1 and Section 2.2 of Chapter 2; and, *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* and *Global Security Policy and Global API Utilization and Security Enforcement* in Chapter 6. *GSP (Global Security Policy) Generation and GAPI (Global API) Generation* is for generating the security policy from multiple systems to make global APIs available to clients what's showing in the lower portion of Figure 1.2 of Chapter 1. *Global Security Policy and Global API Utilization and Security Enforcement* that utilizes security interceptors that was shown in the bottom of Figure 1.2 to allow/deny clients from access global services of FSICC. A *SOA-based security engineering process (SSEP) for FSICC* is intended to assist security engineers of systems and clients and security engineers of FSICC with a structured process to define and maintain secure interoperable services for RBAC, MAC, and DAC.

To support SSEP, the Unified Cloud Computing Access Control Model (UCCACM), from Chapter 4, has a set of definitions for global security policy generation and utilization (see Defns. 41-48 of Section 4.6). This set of definitions ensure that such global security policy can control access to a set of global services that are generated using one or more of integration architecture blueprints: Basic Architecture, Alternative Architecture, or Radical Architecture from Chapter

5. Based on this, this chapter introduces and discusses a SOA-based security engineering and global security policy generation process for FSICC; this addresses Contribution EC-C: Security Mapping/Enforcement Algorithms and SSEP from Section 1.5, this is represented by the left vertical box *SOA-BASED SECURITY ENGINEERING* in Figure 1.3 from Chapter 1 that spans all of the five horizontal boxes: Architectural Blueprints, Unified Cloud Computing Access Control Model, Access Control Models, Global Security Policy and Global API Generation, and Global Security Policy and Global API Utilization and Security Enforcement.

In the remainder of this chapter, a SOA-based security engineering and global security policy generation process for FSICC is presented in three main sections. In Section 7.1, a *Pre-Process Step* briefly describes what each system and client need to do before joining the FSICC. In Section 7.2, *a SOA-based security engineering process (SSEP) for FSICC* is presented that is intended to assist security engineers of systems and clients and security engineers of FSICC with a structured process to define and maintain secure interoperable services for RBAC, MAC, and DAC. In Section 7.3, a complete and detailed example that illustrates the *SOA-based security engineering process* of Section 7.2 is provided to demonstrate the phases and tasks of SSEP coupled with security policy integration algorithms of Section 6.2 of Chapter 6 that can be utilized to establish and utilize security for interoperable services via FSICC.

7.1. A Pre-Process Step for Joining FSICC

As discussed in Chapter 3, one key feature of the FSICC is to enable multiple systems to provide their services, which can be web-based, cloud-based, or traditional API, via registering into FSICC. This was introduced in Section 3.2 as cloud computing capability 1: *Local Service Registration and Mapping to Global Services*. These web-based, cloud-based, or traditional API that are provided by a system are transitioned to a set of equivalent and unified into a set of global services, via FSICC, by utilizing cloud computing capability 1. However, as discussed in Chapter 5, each system that provides services needs to perform a pre-process step before joining the FSICC which is creating an integration layer utilizing a standard integration framework (IFMWK), such as FHIR API for the healthcare domain, which is a standard API that converts system's data from/to the integration layer format. Such an integration layer is specified and utilized by the FCICC. To support this step, Section 5.3 provided a specific set of instructions using the HIT IFMWK Blueprint that a system may utilize to build its own integration layer.

From a client perspective, FSICC provides the unified Global Services so that clients can easily create application functionality without the need to consider heterogeneous types of systems' services. This was introduced in Section 3.2 as cloud computing capability 3: *Global registration, authentication, authorization, and service discover for Consumers*. These mobile, web, or desktop client apps then can be developed using a subset of the available unified global services, via FSICC, by utilizing cloud computing capability 3. However, as discussed in Chapter 5, each client that is interested in utilizing such global services may need to perform a pre-process step before joining the FSICC to create an integration layer which is a standard API that converts a client's data from/to the integration layer format. To support this step, Section 5.3 provided three sets of instructions via three architectural blueprint options that a client may utilize to build its own integration layer: the Basic Architecture Blueprint, the Alternative Architecture Blueprint, and the Radical Architecture Blueprint).

7.2. An SOA-based Security Engineering Process (SSEP) for FSICC

The SOA-based security engineering process (SSEP) is intended to help security engineers of systems and clients, on one side, and the security engineer of FSICC, on the other side, to establish and maintain secure interoperable services via RBAC, MAC, and DAC per security requirements 2, 4, and 3 of Section 3.1, respectively, as shown in Figure 7.1. This occurs via four main phases (i.e., 1.a, 1.b, 2.a, and 2.b) in which the phases 2.a, and 2.b are further explained in Figures 7.2 and 7.3, respectively. This allows SSEP to enable the security engineer: of each participating system to integrate its services into FSICC (see cloud computing capability 1 of Section 3.2) in which the system's security policy is enforced; of each interested client to enable the client's users to leverage a set of global services and global security policy (see cloud computing capability 3 of Section 3.2); and of the FSICC to integrate all of the security policies from all of systems that are to be defined against the global services (see cloud computing capability 2 of Section 3.2) and to control the way that interested clients utilize the services. In the remainder of this section, we explore SSEP in Figure 7.1, along with Figures 7.2 and 7.3, utilizing Figure 6.1 from Chapter 6 that showed the architecture for global security policy generation and utilization, and explaining the tasks for security engineers of systems, clients, and FSICC.

To begin, the SSEP, in Figure 7.1, is divided into four phases. In Section 7.2.1, we present the Constructing Systems Requests phase, labeled (1.a) in the top left of Figure 7.1, that needs to be performed by security engineers of systems. In Section 7.2.2, we describe the Constructing Clients Requests phase, labeled (1.b) in the top right of Figure 7.1, that needs to be performed by security engineers of clients. In Section 7.2.3, we present the Registering Requests Processing phase, labeled (2.a) in the bottom left of Figure 7.1, that needs to be performed by the security engineers of FSICC in which the specific tasks of this phase are depicted in Figure 7.2. In Section 7.2.4, we discuss the Usage Requests Processing phase, labeled (2.b) in the bottom right of Figure 7.1, that needs to be performed by the security engineers of FSICC in which the specific tasks of this phase are depicted in Figure 7.3. Note that in the rest of this section, the term “system” indicates a pure system, mixed system (services registering part) or mixed client (services registering part), and the term “client” indicates a pure client, mixed client (services utilization part) or mixed systems (services utilization part).

7.2.1 Constructing Systems Requests Phase

The Constructing Systems Requests phase labeled (1.a) in Figure 7.1 allows security engineers of pure or mixed systems to provide their services via FSICC and for mixed systems to request services. From a registering perspective, security engineers of both pure and mixed systems can select to Register System’s Integration Layer and Security Policy, labeled (1.a.1) which utilizes the cloud computing capabilities of FSICC to provide the system’s integration layer and security policy that enables FSICC to recognize and integrate: a system’s integration layer with the global services; and, a system’s security policy with the global security policy. This is indicated by the dashed line from the Constructing Systems Requests box to the Registering Requests Processing box labeled (2.a) at the bottom left of Figure 7.1. As part of this process, the system’s integration layer (e.g., FHIR for HITs) can be designed by utilizing the HIT IFMWK Blueprint from Section 5.3, as described in Section 7.1. In addition, the system’s security policy is defined by the system’s security engineer to control access to the system’s integration layer via one or more access control models such as RBAC, MAC, and/or DAC that specify which services (of the system’s integration layer) each user in that system may access. This is indicated by the RBAC Integration and Review & Correct Role Names, the MAC Integration and Building Global MAC, and the DAC Integration boxes of pure and mixed systems at the bottom of Figure 6.1 from Chapter 6.

From a usage perspective, security engineers of mixed systems can select to Utilize GSP & GAPI labeled (1.a.3) and since they are interested in using the Global Services in order to accomplish some of the functionalities, they need to go through a number of tasks based on the answers to two questions:

- Question 1: Does the mixed system need to utilize a subset of the global services (i.e., global API) and a subset of the global security policies, labeled (1.a.q1)? If yes, then ask Question 2.
- Question 2: Does the mixed system need to customize a subset of the global security policies, labeled (1.a.q2)? That is, a security engineer of the system has found a global security policy that has too few/many permissions than needed, thereby needing a customization.
    - If the answer to Question 2 was yes, then the security engineer of the system would need to have human intervention with the security engineer of FSICC, labeled (1.a.2), to customize a subset of the global security policy in which both parties discuss and agree about adding a new customized security policy, the global security policy is updated after this task, or to use an existing security policy.
    - If the answer to Question 2 was no, the security engineer of the system would use some capabilities of FSICC to send a global security policy and global services utilization request to FSICC, labeled (1.a.3) as indicated by the solid line from the Constructing Systems Requests box to the Usage Requests Processing box at the bottom of Figure 7.1.

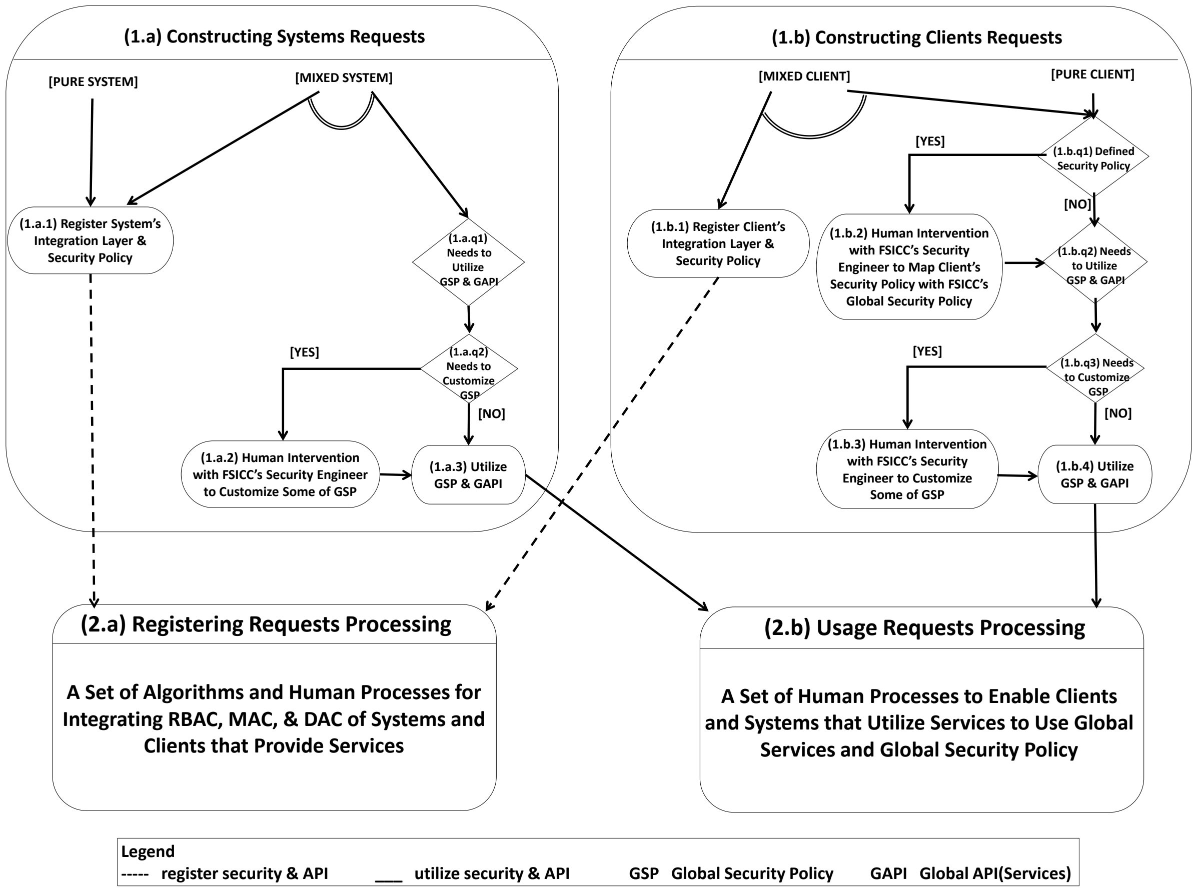

(1.a) Constructing Systems Requests
[PURE SYSTEM]
[MIXED SYSTEM]
(1.a.1) Register System's Integration Layer & Security Policy
(1.a.q1) Needs to Utilize GSP & GAPI
(1.a.q2) Needs to Customize GSP
[YES]
[NO]
(1.a.2) Human Intervention with FSICC's Security Engineer to Customize Some of GSP
(1.a.3) Utilize GSP & GAPI
(1.b) Constructing Clients Requests
[MIXED CLIENT]
[PURE CLIENT]
[YES]
(1.b.q1) Defined Security Policy
[NO]
(1.b.1) Register Client's Integration Layer & Security Policy
(1.b.2) Human Intervention with FSICC's Security Engineer to Map Client's Security Policy with FSICC's Global Security Policy
(1.b.q2) Needs to Utilize GSP & GAPI
[YES]
(1.b.q3) Needs to Customize GSP
[NO]
(1.b.3) Human Intervention with FSICC's Security Engineer to Customize Some of GSP
(1.b.4) Utilize GSP & GAPI
(2.a) Registering Requests Processing
A Set of Algorithms and Human Processes for Integrating RBAC, MAC, & DAC of Systems and Clients that Provide Services
(2.b) Usage Requests Processing
A Set of Human Processes to Enable Clients and Systems that Utilize Services to Use Global Services and Global Security Policy
Legend
----- register security & API
___ utilize security & API
GSP Global Security Policy
GAPI Global API(Services)

Figure 7.1. A High-Level View of SOA-Based Security Engineering Process for FSICC.

7.2.2 Constructing Clients Requests Phase

The Constructing Clients Requests phase labeled (1.b) in Figure 7.1 allows security engineers of mixed clients to provide their services via FSICC and for pure and mixed clients to request services. From a registering perspective, security engineers of mixed clients can select to Register System's Integration Layer and Security Policy, labeled (1.b.1) which utilizes the cloud computing capabilities of FSICC to provide the client's integration layer and security policy that enables FSICC to recognize and integrate: a system's integration layer with the global services; and, a system's security policy with the global security policy. This is indicated by the dashed line from the Constructing Clients Requests box to the Registering Requests Processing box at the bottom of Figure 7.1. As part of this process, the client's integration layer (e.g., FHIR for HITs) can be designed by utilizing the HIT IFMWK Blueprint from Section 5.3, as described in Section 7.1. Moreover, the client's integration layer (e.g., FHIR for HITs) can be designed by utilizing one of the three integration options: Basic Architecture, Alternative Architecture, or Radical Architecture as discussed in Section 5.2, as described in Section 7.1. In addition, the client's security policy is defined by the client's security engineer to control access to the client's integration layer via one or more access control models such as RBAC, MAC, and/or DAC that specify which services (of the client's integration layer) each user in that client may access, this is indicated by the RBAC Integration and Review & Correct Role Names, the MAC Integration and Building Global MAC, and the DAC Integration boxes of mixed clients at the top of Figure 6.1.

From a usage perspective, security engineers of pure and mixed clients that are interested in utilizing the FSICC's global services and global security policy in order to accomplish some of the functionalities, need to go through a number of tasks based on the answers to three questions.

- Question 1: Does the client have a defined security policy that the client's security engineer prefers to use instead of the global security policy (1.b.q1)?
  - If the answer to Question 1 was yes, then the security engineer of the client has human intervention with the security engineer of FSICC to map the client's security policy to the global security policy labeled (1.b.2) in which both parties discuss and agree about a way to map the client's security policy to the global security policy which is updated after this task.
  - If the answer to Question 1 was no, the client's security engineer needs to answer Question 2.

- Question 2: Does the client need to utilize a subset of the global services (i.e., global API) and a subset of the global security policies, labeled (1.b.q2)? If the answer to Question 2 was no, the client's security engineer needs to answer Question 3.
- Question 3: Does the client need to customize a subset of the global security policies, labeled (1.b.q3)? That is, a security engineer of a client has found a global security policy that has too few/many permissions than needed, thereby needing a customization.
    - If the answer to Question 3 was yes, then the security engineer of the client would need to have human intervention with the security engineer of FSICC to customize a subset of the global security policy, labeled (1.b.3), in which both parties discuss and agree about adding a new customized security policy, the global security policy is updated after this task, or to use an existing security policy.
    - If the answer to Question 3 was no, the security engineer of the client would use some capabilities of FSICC to send a global security policy and global services utilization request to FSICC, labeled (1.b.4) indicated by the solid line from the Constructing Clients Requests box to the Usage Requests Processing box at the bottom of Figure 7.1.

7.2.3 Registering Requests Processing Phase

The Registering Requests Processing phase labeled (2.a) in Figure 7.1 needs to be performed by the security engineers of FSICC to achieve two main objectives. First, to build the global services, which is primarily a human-based process, based on the integration layer of each system. Second, to construct the global security policy, which is mostly an algorithm-based process, based on security policy of each system. The Registering Requests Processing phase has three tasks and executed for each system that is being integrated into the global policy:

- Task 1: The first task is to configure the global services (global API), labeled (2.a.1) at the top of Figure 7.2, in which the FSICC's security engineer is required to configure each global service of the FSICC so that CRUD methods of the services can send and receive data to/from each system's integration layers. This is based on integration layers provided by different systems in the phases 1.a and 1.b of Figure 7.1.
- Task 2: In the second task, the FSICC's security engineer has three task options to perform RBAC, MAC, and/or DAC integration on each system, which may have no access control, only one access control, any combination of two access controls, or all three access controls:
  - ➢ The first task option, labeled (2.a.2) in Figure 7.2, is to send each RBAC policy of each system to the RBAC integration algorithm. This task option is performed if there is a system's RBAC policy that needs to be integrated with the global security policy. As part of this process, the generated RBAC policy is submitted to Review and Correct Role Names Algorithm labeled (2.a.2.a) with any other required input.
  - ➢ The second task option, labeled (2.a.3) in Figure 7.2, is to send each MAC policy of each system to the MAC integration algorithm. This task option is performed if there is a system's MAC policy that needs to be integrated with the global security policy. As part of this process, the generated Sensitivity Levels Mapping List is submitted to the Building Global MAC Algorithm with any other required inputs, labeled (2.a.3.a).
  - ➢ The third task option, labeled (2.a.4) in Figure 7.2, is to send each DAC policy of each system to the DAC integration algorithm. This task option is performed if there is a system's DAC policy that needs to be integrated with the global security policy.

- Task 3: In third task, labeled (2.a.5) at the bottom of Figure 7.2, the FSICC’s security engineer needs to send the resulted global RBAC policy from (2.a.2), global MAC policy from (2.a.3), and global DAC policy from (2.a.4) to Combine Updated Global RBAC, Global MAC, and Global DAC and Control Data algorithm that concatenates all of the three global polices to generate one global security policy. The FSICC’s security engineer also needs to specify one read data access type, as described in Section 6.1.4 of Chapter 6, to control the way that data are read. Note that there is one write data access type that is used by default to control the way that data are written. The third task marks the final part of the Registering Requests Processing phase in which the global services and global security policy are ready to be utilized by FSICC’s clients. Moreover, at this point the complete details of the generated global security policy and global services, such as the way to utilize the global services and global security policy and what is the exact web location, will not be published to public.

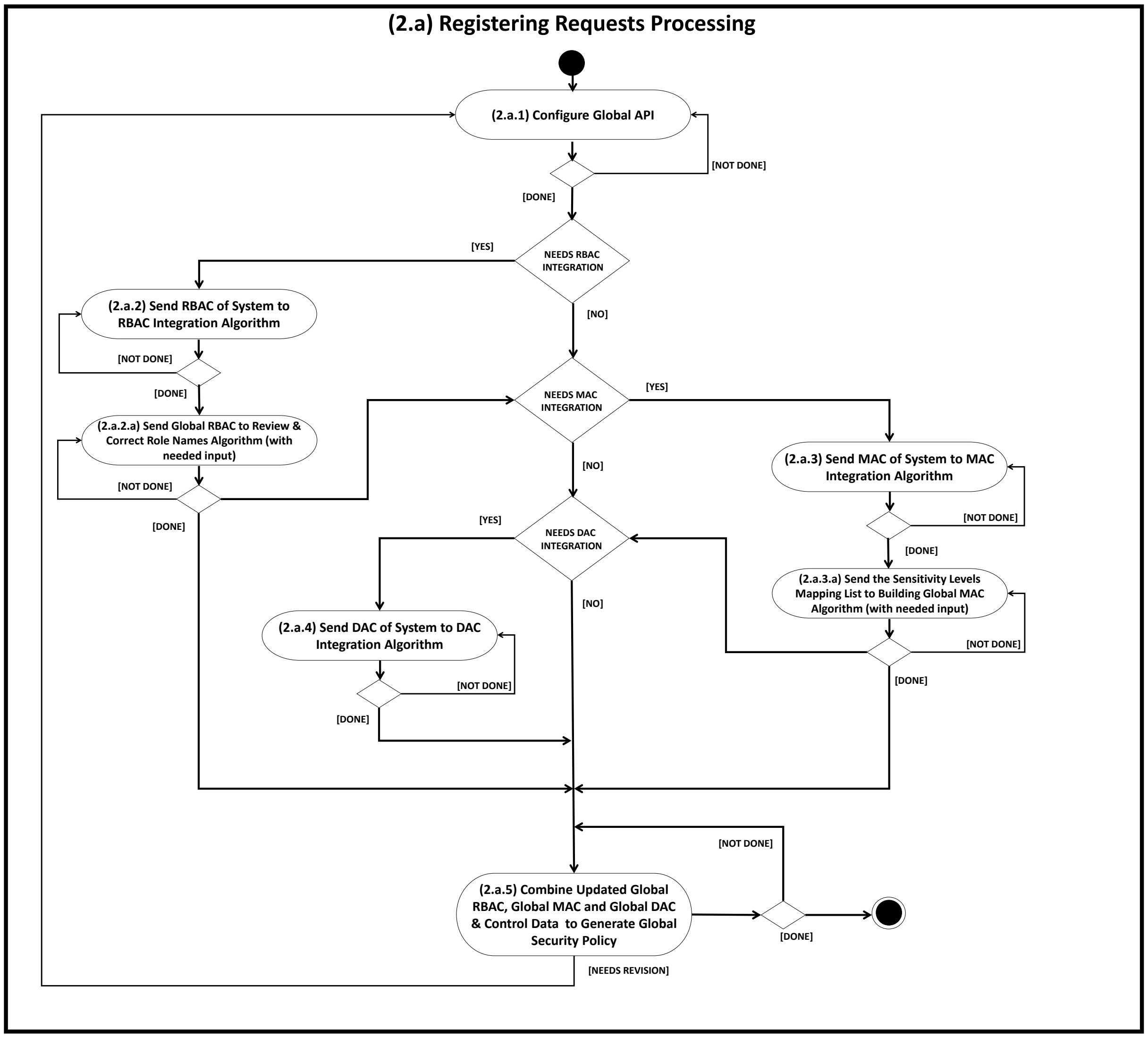

(2.a) Registering Requests Processing
(2.a.1) Configure Global API
[NOT DONE]
[DONE]
[YES]
NEEDS RBAC INTEGRATION
[NO]
(2.a.2) Send RBAC of System to RBAC Integration Algorithm
[NOT DONE]
[DONE]
NEEDS MAC INTEGRATION
[YES]
(2.a.2.a) Send Global RBAC to Review & Correct Role Names Algorithm (with needed input)
[NOT DONE]
[DONE]
[NO]
(2.a.3) Send MAC of System to MAC Integration Algorithm
[NOT DONE]
[DONE]
[YES]
NEEDS DAC INTEGRATION
(2.a.3.a) Send the Sensitivity Levels Mapping List to Building Global MAC Algorithm (with needed input)
[NOT DONE]
[NO]
(2.a.4) Send DAC of System to DAC Integration Algorithm
[NOT DONE]
[DONE]
[DONE]
[NOT DONE]
(2.a.5) Combine Updated Global RBAC, Global MAC and Global DAC & Control Data to Generate Global Security Policy
[DONE]
[NEEDS REVISION]

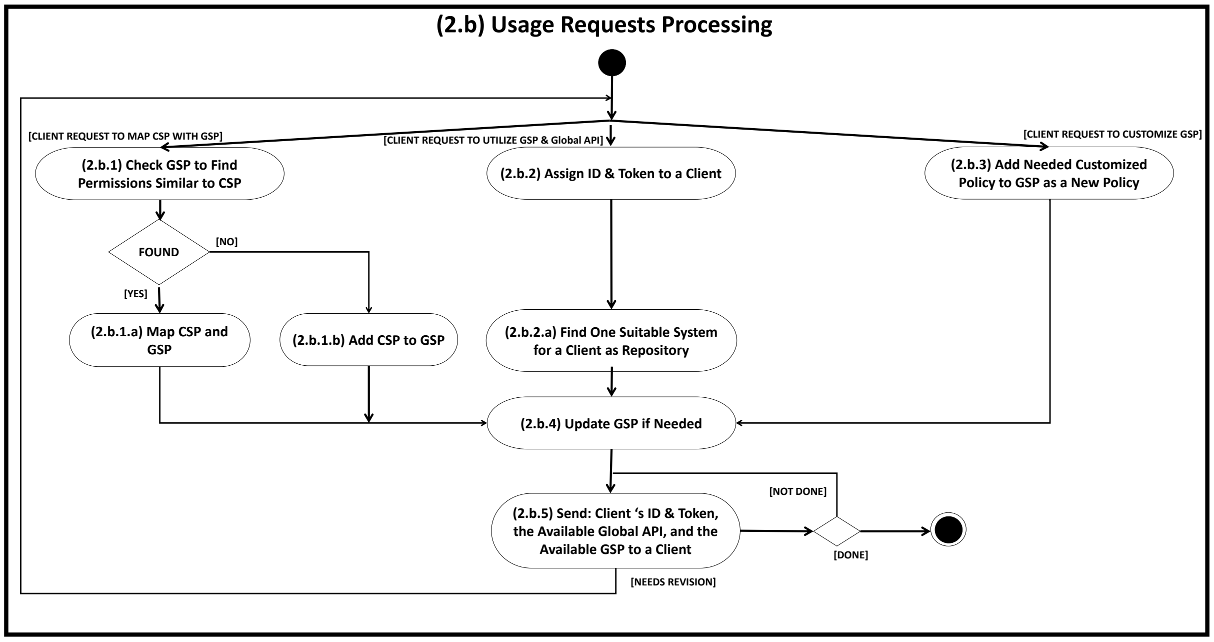
Figure 7.2. A Detailed View of Phase 2.a of the SSEP

7.2.4 Usage Requests Processing Phase

The Usage Requests Processing phase labeled (2.b) in Figure 7.1 is performed by the security engineers of FSICC to enable clients to leverage available global services and the corresponding global security policy, which are built based on the tasks of the Registering Requests Processing phase and is a human-based process. The FSICC's security engineer has four tasks to perform the Usage Requests Processing phase:

- Task 1: In the first task, the FSICC's security engineer has three task options to process clients' requests:
  - ➢ The left task option, labeled (2.b.1) in Figure 7.3, is to check the Global Security Policy (GSP) to Find Permissions Similar to Client Security Policy (CSP). This task option is performed if there is a client that requests to map its security policy with the global security policy.
  - ➢ The center task option, labeled (2.b.2) in Figure 7.3, is to assign an ID and Token to a Client which is needed for authentication and authorization purposes. This task option is performed if there is a client (basically all of the clients) that requests to utilize a subset of the global security policy and global services.
  - ➢ The right task option, labeled (2.b.3) in Figure 7.3, is to Add needed Customized Policy to GSP as a New Policy. This task option is performed if there is a client that requests to customize a subset of the global security policy.
- Task 2: In the second task, the FSICC's security engineer also has three task options:
  - ➢ The left task option, labeled (2.b.1.a) in Figure 7.3, is to map the Client Security Policy (CSP) and Global Security Policy (GSP). This task option is performed if the output of the task option (2.b.1) was yes, which means that the Global Security Policy (GSP) has permissions similar to Client Security Policy (CSP).
  - ➢ The center task option, labeled (2.b.1.b) in Figure 7.3, is to add the Client Security Policy (CSP) to Global Security Policy (GSP). This task option is performed if the output of the task option (2.b.1) was no, which means that the Global Security Policy (GSP) does not have permissions similar to Client Security Policy (CSP).

    - The right task option, labeled (2.b.2.a) in Figure 7.3, is to Find One Suitable System for a Client as a Repository. This can be done by finding a registered system that provides services similar to the set of global services the client is interested in.
- Task 3: In the third task, labeled (2.b.4) in Figure 7.3, the FSICC's security engineer should update the Global Security Policy (GSP,) that may have been changed as a result of performing the tasks (2.b.1.a), (2.b.1.b) and/or (2.b.3).
- Task 4: In the fourth task, labeled (2.b.5) in Figure 7.3, the FSICC's security engineer can Send to the client: the Client's ID, the Client's Security Token, the available Global API (services), the available Global Security Policy (GSP), and instructions on the way to utilize such global services and global security policy. This allows the client to begin building an App utilizing the retrieved global services and global security policy.


(2.b) Usage Requests Processing
[CLIENT REQUEST TO MAP CSP WITH GSP]
[CLIENT REQUEST TO UTILIZE GSP & Global API]
[CLIENT REQUEST TO CUSTOMIZE GSP]
(2.b.1) Check GSP to Find Permissions Similar to CSP
(2.b.2) Assign ID & Token to a Client
(2.b.3) Add Needed Customized Policy to GSP as a New Policy
FOUND
[NO]
[YES]
(2.b.1.a) Map CSP and GSP
(2.b.1.b) Add CSP to GSP
(2.b.2.a) Find One Suitable System for a Client as Repository
(2.b.4) Update GSP if Needed
[NOT DONE]
(2.b.5) Send: Client 's ID & Token, the Available Global API, and the Available GSP to a Client
[DONE]
[NEEDS REVISION]

Legend
CSP Client Security Policy GSP Global Security Policy

Figure 7.3. A Detailed View of Phase 2.b of the SSEP

7.3. Demonstrating the SOA-based Security Engineering Process

To provide a hands-on experiment on the SOA-based security engineering process (SSEP), this section presents a complete and detailed example that demonstrates: the way that each phase and task of SSEP from Section 7.2 in applied, as was shown in Figures 7.1, 7.2, and 7.3; the usage of the security policy integration algorithms from Section 6.1 from Chapter 6, see Figures 6.1-6.8; and, the establishment and utilization of security for interoperable services via FSICC. In the remainder of this section, our healthcare scenario from Section 2.4 is used for explaining all of the phases and tasks of SSEP, where we assume that the CT^2 client does not provide services or a security policy. Based on this assumption, we can categorize: CT^2 App as a pure client that only utilizes services from OpenEMR system; SMH App as a mixed client that utilizes services from

MyGoogle system and provides a number of services; OpenEMR as a pure system that only provides services; and, MyGoogle as a mixed system that provides services and utilizes services from OpenEMR.

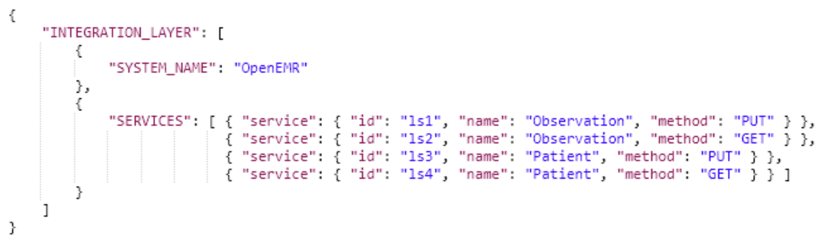
Using this setting, we apply the SSEP's phases and tasks of Section 7.2 in the following order. First, the Constructing Systems Requests phase, labeled (1.a) in the top left of Figure 7.1, is applied to OpenEMR system, MyGoogle system, and SMH client App, since each of them has services and security policy to register. Second, the Registering Requests Processing phase, labeled (2.a) in the bottom left of Figure 7.1, is applied to OpenEMR system, MyGoogle system, and SMH client App, since each of them has sent services and security policy registering requests to FSICC. Third, the Constructing Clients Requests phase, labeled (1.b) in the top right of Figure 7.1, is applied to MyGoogle system, SMH, and CT^2 client Apps, since each of them is interested in utilizing the global services and the global security policy. Finally, the Usage Requests Processing phase, labeled (2.b) in the bottom right of Figure 7.1, is applied to MyGoogle system, SMH, and CT^2 client Apps, since each of them has sent global services and global security policy utilization requests to FSICC. Note that in the remainder of this section, only a subset of actual services and security policies of each system and client is used, since these subsets are enough for explaining all of the phases and tasks of SSEP.

The remainder of this section is organized into four subsections. In Section 7.3.1, we explain the way that the three systems OpenEMR, MyGoogle, and SMH can utilize the Constructing Systems Requests phase from Section 7.2. In Section 7.3.2, we apply the Registering Requests Processing phase from Section 7.2 to the three requests from OpenEMR, MyGoogle, and SMH systems. In Section 7.3.3, we explain the way that three clients: MyGoogle, SMH, and CT^2 can utilize the Constructing Clients Requests phase from Section 7.2. Finally, in Section 7.3.4, we apply the Usage

Requests Processing phase from Section 7.2 to the three requests from MyGoogle, SMH, and CT^2 clients.

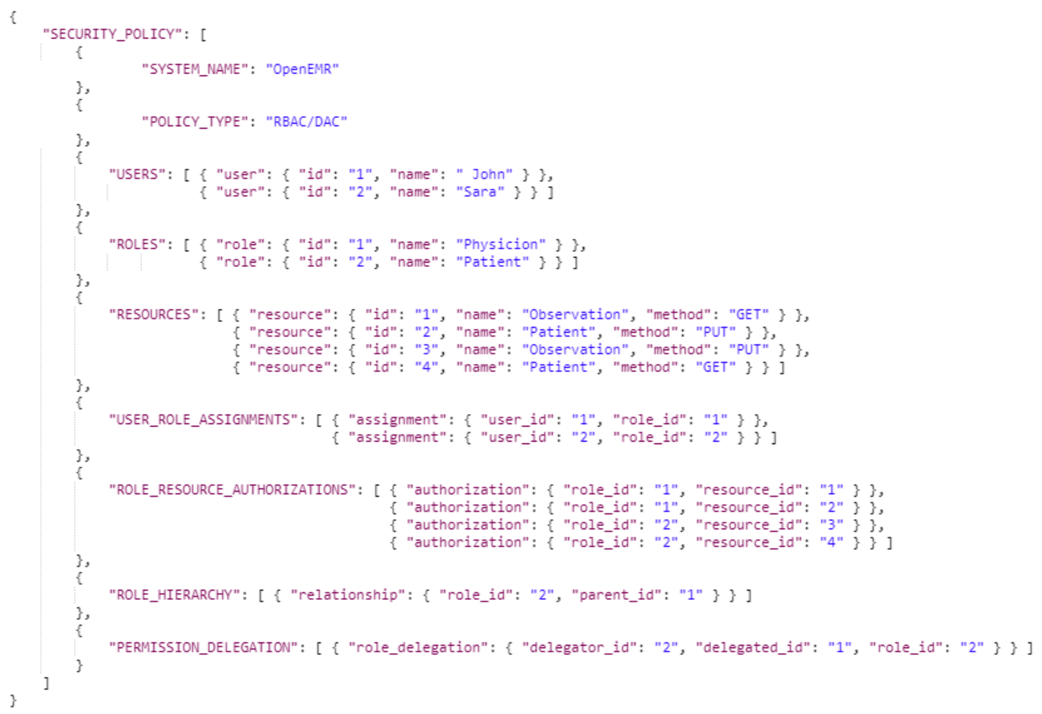
7.3.1 Applying the Constructing Systems Requests Phase on OpenEMR, MyGoogle, and SMH

In this section, we apply the Constructing Systems Requests phase, labeled (1.a) in Figure 7.1, to the OpenEMR and MyGoogle systems and the SMH client. Since OpenEMR is a pure system, the security engineer of OpenEMR must register: OpenEMR's integration layer which are OpenEMR's FHIR services in Table 2.5 of Section 2.4 and Example 4.4 with Figure 4.1 in Section 4.4; and, OpenEMR's security policy which are OpenEMR's RBAC, MAC, and DAC in Table 2.6 of Section 2.4 and Example 4.4 with Figure 4.1 in Section 4.4. Note that the security engineer of the OpenEMR system designed the OpenEMR's integration layer by utilizing the HIT IFMWK Blueprint in Section 5.4.1. This can be achieved by constructing three JSON documents, one for OpenEMR's FHIR services from Figure 7.4, one for OpenEMR's RBAC/DAC from Figure 7.5, and one for OpenEMR's MAC/DAC from Figure 7.6, and then sending them to the System Registry component of FSICC in Figure 7.22.



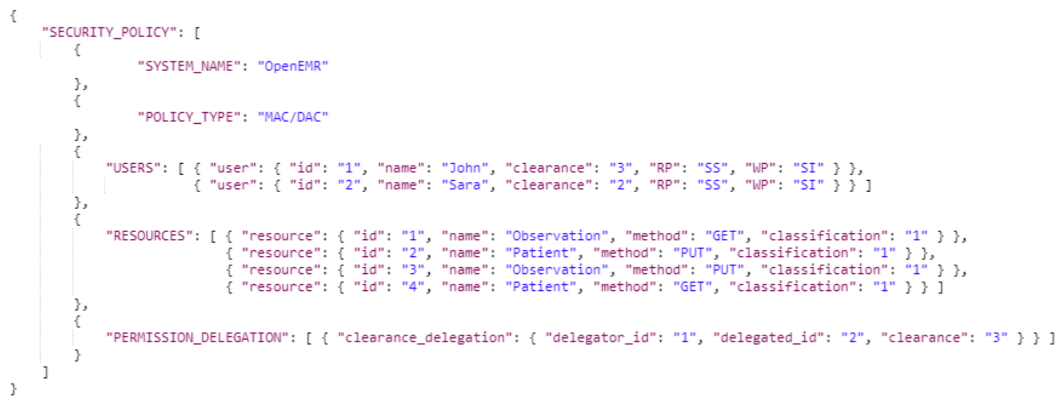
```
{
    "INTEGRATION_LAYER": [
        {
            "SYSTEM_NAME": "OpenEMR"
        },
        {
            "SERVICES": [ { "service": { "id": "ls1", "name": "Observation", "method": "PUT" } },
                          { "service": { "id": "ls2", "name": "Observation", "method": "GET" } },
                          { "service": { "id": "ls3", "name": "Patient", "method": "PUT" } },
                          { "service": { "id": "ls4", "name": "Patient", "method": "GET" } } ]
        }
    ]
}
```

Figure 7.4. OpenEMR's FHIR services in JSON



```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "OpenEMR"
        },
        {
                "POLICY_TYPE": "RBAC/DAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": " John" } },
                       { "user": { "id": "2", "name": "Sara" } } ]
        },
        {
            "ROLES": [ { "role": { "id": "1", "name": "Physicion" } },
                       { "role": { "id": "2", "name": "Patient" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "GET" } },
                           { "resource": { "id": "2", "name": "Patient", "method": "PUT" } },
                           { "resource": { "id": "3", "name": "Observation", "method": "PUT" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET" } } ]
        },
        {
            "USER_ROLE_ASSIGNMENTS": [ { "assignment": { "user_id": "1", "role_id": "1" } },
                                       { "assignment": { "user_id": "2", "role_id": "2" } } ]
        },
        {
            "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "1", "resource_id": "1" } },
                                              { "authorization": { "role_id": "1", "resource_id": "2" } },
                                              { "authorization": { "role_id": "2", "resource_id": "3" } },
                                              { "authorization": { "role_id": "2", "resource_id": "4" } } ]
        },
        {
            "ROLE_HIERARCHY": [ { "relationship": { "role_id": "2", "parent_id": "1" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "2", "delegated_id": "1", "role_id": "2" } } ]
        }
    ]
}
```

Figure 7.5. OpenEMR's RBAC/DAC policy in JSON

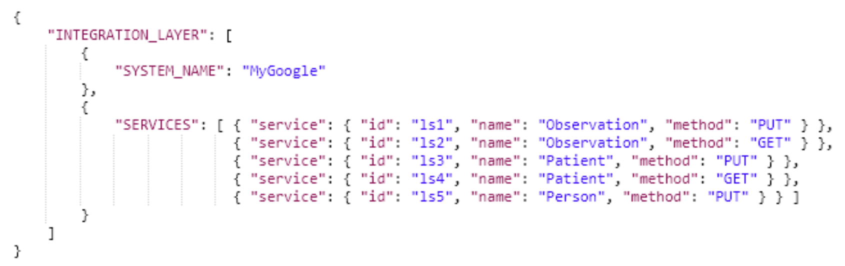


```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "OpenEMR"
        },
        {
                "POLICY_TYPE": "MAC/DAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "John", "clearance": "3", "RP": "SS", "WP": "SI" } },
                       { "user": { "id": "2", "name": "Sara", "clearance": "2", "RP": "SS", "WP": "SI" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "2", "name": "Patient", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "3", "name": "Observation", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET", "classification": "1" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "clearance_delegation": { "delegator_id": "1", "delegated_id": "2", "clearance": "3" } } ]
        }
    ]
}
```

Figure 7.6. OpenEMR's MAC/DAC policy in JSON

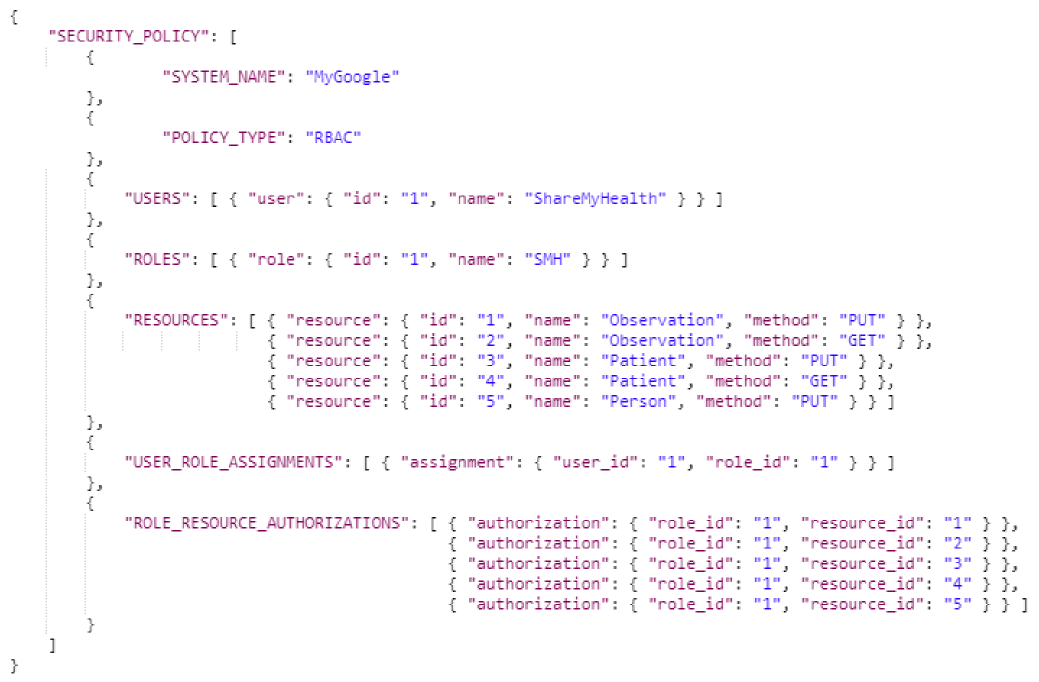
Second, we apply the Constructing Systems Requests phase, labeled (1.a) in Figure 7.1, to the MyGoogle system. Since MyGoogle is a mixed system, the security engineer of MyGoogle, must register: MyGoogle's integration layer which are the MyGoogle's FHIR services in Table 2.7 of Section 2.4 and Example 4.4 with Figure 4.1 in Section 4.4; and MyGoogle's security policy which are the MyGoogle's RBAC and MAC in Table 2.8 of Section 2.4 and Example 4.4 with Figure 4.1

in Section 4.4. Note that the security engineer of the MyGoogle system designed the MyGoogle's integration layer by utilizing the HIT IFMWK Blueprint in Section 5.4.1. This can be achieved by constructing three JSON documents, one for MyGoogle's FHIR services from Figure 7.7, one for MyGoogle's RBAC from Figure 7.8, and one for MyGoogle's MAC from Figure 7.9, and then sending them to System Registry component of FSICC see Figure 7.22.



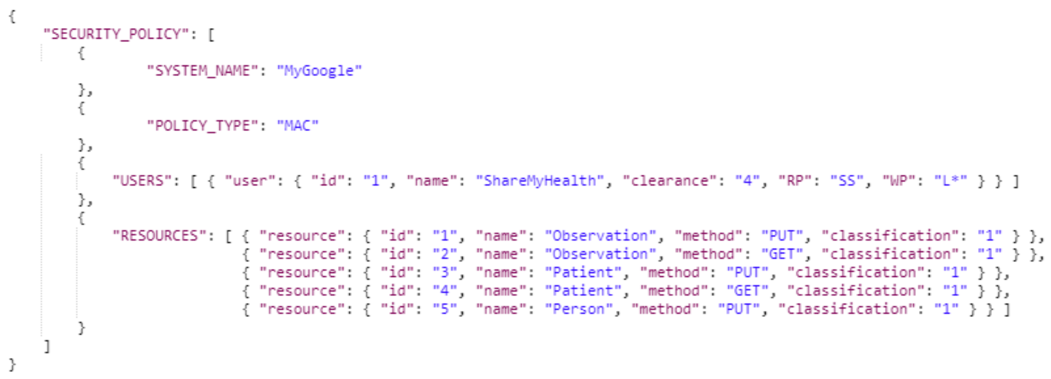
```
{
    "INTEGRATION_LAYER": [
        {
            "SYSTEM_NAME": "MyGoogle"
        },
        {
            "SERVICES": [ { "service": { "id": "1s1", "name": "Observation", "method": "PUT" } },
                          { "service": { "id": "1s2", "name": "Observation", "method": "GET" } },
                          { "service": { "id": "1s3", "name": "Patient", "method": "PUT" } },
                          { "service": { "id": "1s4", "name": "Patient", "method": "GET" } },
                          { "service": { "id": "1s5", "name": "Person", "method": "PUT" } } ]
        }
    ]
}
```

Figure 7.7. MyGoogle's FHIR services in JSON



```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "MyGoogle"
        },
        {
                "POLICY_TYPE": "RBAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "ShareMyHealth" } } ]
        },
        {
            "ROLES": [ { "role": { "id": "1", "name": "SMH" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET" } },
                           { "resource": { "id": "5", "name": "Person", "method": "PUT" } } ]
        },
        {
            "USER_ROLE_ASSIGNMENTS": [ { "assignment": { "user_id": "1", "role_id": "1" } } ]
        },
        {
            "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "1", "resource_id": "1" } },
                                              { "authorization": { "role_id": "1", "resource_id": "2" } },
                                              { "authorization": { "role_id": "1", "resource_id": "3" } },
                                              { "authorization": { "role_id": "1", "resource_id": "4" } },
                                              { "authorization": { "role_id": "1", "resource_id": "5" } } ]
        }
    ]
}
```

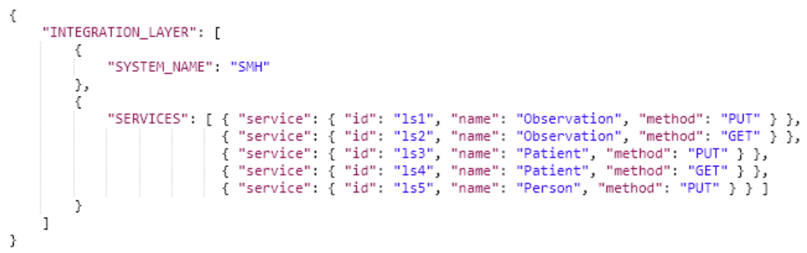
Figure 7.8. MyGoogle's RBAC policy in JSON



```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "MyGoogle"
        },
        {
                "POLICY_TYPE": "MAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "ShareMyHealth", "clearance": "4", "RP": "SS", "WP": "L*" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "5", "name": "Person", "method": "PUT", "classification": "1" } } ]
        }
    ]
}
```

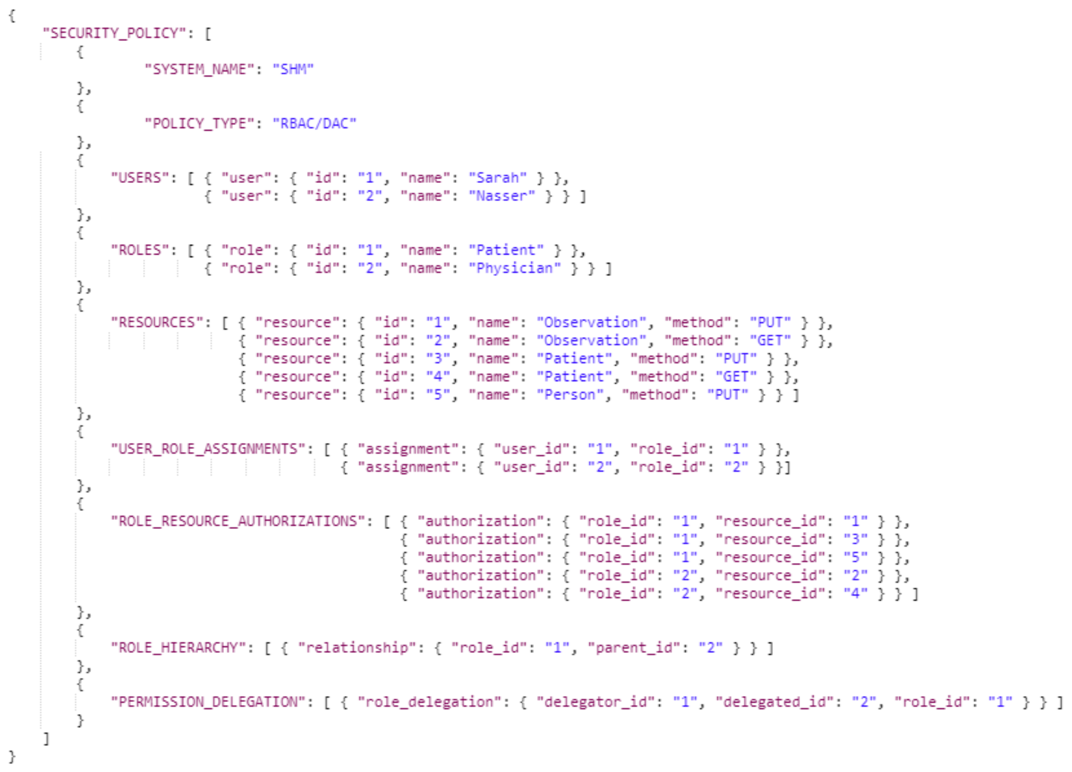
Figure 7.9. MyGoogle's MAC policy in JSON

Finally, we apply the Constructing Systems Requests phase, labeled (1.a) in Figure 7.1, to the SMH client App. Since SMH is a mixed client, the security engineer of SMH must register: SMH's integration layer which are SMH's FHIR services see Table 2.3 in Section 2.4 and Example 4.5 with Figure 4.2 in Section 4.4; and, SMH's security policy which are SMH's RBAC, MAC, and DAC see Table 2.4 in Section 2.4 and Example 4.5 with Figure 4.2 in Section 4.4. Note that the security engineer of the SMH designed the SMH's integration layer by utilizing the Basic Architecture Blueprint in Section 5.4.1. This can be achieved by constructing three JSON documents, one for SMH's FHIR services from Figure 7.10, one for SMH's RBAC/DAC from Figure 7.11, and one for SMH's MAC from Figure 7.12, and then sending them to the System Registry component of FSICC see Figure 7.22.



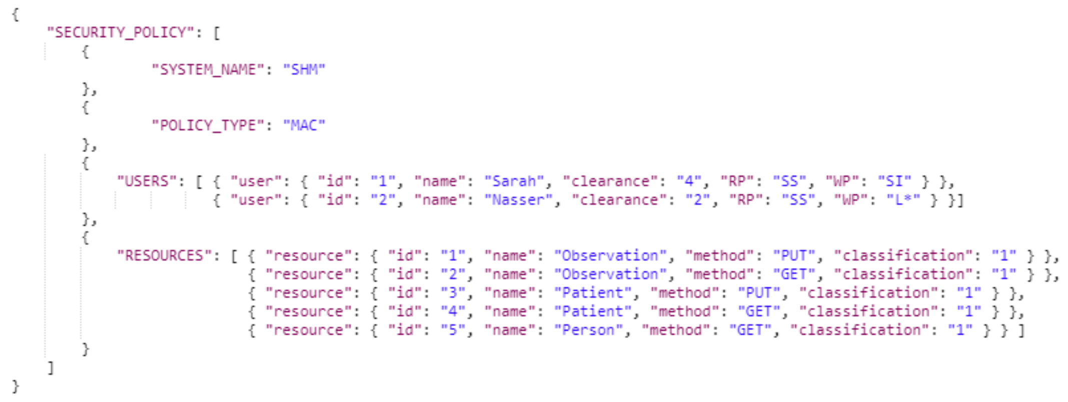
```
{
    "INTEGRATION_LAYER": [
        {
            "SYSTEM_NAME": "SMH"
        },
        {
            "SERVICES": [ { "service": { "id": "ls1", "name": "Observation", "method": "PUT" } },
                          { "service": { "id": "ls2", "name": "Observation", "method": "GET" } },
                          { "service": { "id": "ls3", "name": "Patient", "method": "PUT" } },
                          { "service": { "id": "ls4", "name": "Patient", "method": "GET" } },
                          { "service": { "id": "ls5", "name": "Person", "method": "PUT" } } ]
        }
    ]
}
```

Figure 7.10. SMH's FHIR services in JSON



```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "SHM"
        },
        {
                "POLICY_TYPE": "RBAC/DAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "Sarah" } },
                       { "user": { "id": "2", "name": "Nasser" } } ]
        },
        {
            "ROLES": [ { "role": { "id": "1", "name": "Patient" } },
                       { "role": { "id": "2", "name": "Physician" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET" } },
                           { "resource": { "id": "5", "name": "Person", "method": "PUT" } } ]
        },
        {
            "USER_ROLE_ASSIGNMENTS": [ { "assignment": { "user_id": "1", "role_id": "1" } },
                                       { "assignment": { "user_id": "2", "role_id": "2" } }]
        },
        {
            "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "1", "resource_id": "1" } },
                                              { "authorization": { "role_id": "1", "resource_id": "3" } },
                                              { "authorization": { "role_id": "1", "resource_id": "5" } },
                                              { "authorization": { "role_id": "2", "resource_id": "2" } },
                                              { "authorization": { "role_id": "2", "resource_id": "4" } } ]
        },
        {
            "ROLE_HIERARCHY": [ { "relationship": { "role_id": "1", "parent_id": "2" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "1", "delegated_id": "2", "role_id": "1" } } ]
        }
    ]
}
```

Figure 7.11. SMH’s RBAC/DAC policy in JSON



```
{
    "SECURITY_POLICY": [
        {
                "SYSTEM_NAME": "SHM"
        },
        {
                "POLICY_TYPE": "MAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "Sarah", "clearance": "4", "RP": "SS", "WP": "SI" } },
                       { "user": { "id": "2", "name": "Nasser", "clearance": "2", "RP": "SS", "WP": "L*" } }]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "5", "name": "Person", "method": "GET", "classification": "1" } } ]
        }
    ]
}
```

Figure 7.12. SMH’s MAC policy in JSON

7.3.2 Applying the Registering Requests Processing Phase on OpenEMR, MyGoogle, and SMH

In this section, we apply the Registering Requests Processing Phase, labeled (2.a) in Figure 7.1, to the OpenEMR, MyGoogle systems and the SMH client. In Section 7.3.1, OpenEMR, MyGoogle, and SMH were constructed and sent a registering request in JSON format to the FSICC, see Figures 7.4, 7.7, and 7.10 respectively. In this phase, the security engineer of FSICC, as described in Section

7.2.3 and Figure 7.2, processes each of these registering requests through the three tasks as described in Section 7.2.3.

In task 1, the security engineer of FSICC needs to configure each global service of the FSICC so that CRUD methods of the global services can send and receive data to/from the integration layers of OpenEMR, MyGoogle, and SMH. In this task, the security engineer of FSICC reads the JSON documents that include the registering requests of OpenEMR, MyGoogle, and SMH and initializes the global services of FSICC with five services as presented in Table 7.1. For example, the service (gs_2) is a global service (Observation[GET]) that whenever triggered calls the mapped services ls_2 of OpenEMR, ls_2 of MyGoogle, and ls_2 of SMH. Similarly, the services (gs_1, gs_3, gs_4, gs_5) are created and configured as described in Table 7.1. Note that for each created global service, only the specified CRUD methods of the mapped service are implemented. For example, only PUT and GET methods are implemented for the first global service (gs_1) but not POST or DELETE methods.

Table 7.1. Initial Set of FSICC's Global Services

Service ID	Service Name	Method Name	Mapped to
gs_1	FSICC/Observation	PUT	ls_1 (OpenEMR), ls_1 (MyGoogle), and ls_1 (SMH)
gs_2	FSICC/Observation	GET	ls_2 (OpenEMR), ls_2 (MyGoogle), and ls_2 (SMH)
gs_3	FSICC/Patient	PUT	ls_3 (OpenEMR), ls_3 (MyGoogle), and ls_3 (SMH)
gs_4	FSICC/Patient	GET	ls_4 (OpenEMR), ls_4 (MyGoogle), and ls_4 (SMH)
gs_5	FSICC/Person	PUT	ls_5 (MyGoogle), and ls_5 (SMH)

In task 2, to establish the global security policy the security engineer of FSICC needs to send the registered security policy of OpenEMR, MyGoogle, and SMH to the appropriate task 2 option based on the type of the registered security policy (RBAC, MAC, or DAC). First, as described in the first task option of task 2 labeled 2.a.2 in Section 7.2.3, the security engineer of FSICC sends the OpenEMR's RBAC policy, Figure 7.5, MyGoogle's RBAC policy, Figure 7.8, and SMH's RBAC policy, Figure 7.11, to the RBAC integration algorithm that generates the initial global RBAC policy as shown in Figure 7.14. Moreover, Table 7.2 has some information that the Global-RBAC algorithm uses to generate the initial global RBAC policy given in Figure 7.14. First, the algorithm uses the RBAC policy of OpenEMR to initialize the global RBAC policy so that OpenEMR's roles, Physician and Patient, are added as the first two global roles. Then, the RBAC policy of SMH is integrated to the global RBAC policy so that six global roles, Physician_2, Patient_2, New_Role_1, New_Role_2, New_Role_3 and New_Role_4, are added (see the first four comparisons in Table 7.2). Finally, the RBAC policy of MyGoogle is integrated to the global RBAC policy so that two global roles, SMH and New_Role_5, are added (see the last eight comparisons in Table 7.2). Note that roles New_Role_1, New_Role_2, New_Role_3, New_Role_4 and New_Role_5 are abstract roles in which no users are assigned to them. Figure 7.13 provides a clear view of the role hierarchy of the global RBAC policy.

Table 7.2. Comparisons Information of the RBAC Integration Step

ID	System Role	Global Role	Direct Common Permissions	Comparison Result	Created Global Roles
1	Physician	Physician	Observation [GET]	Overlap	Physician_2, New_Role_1
2	Physician	Patient	Patient [GET]	Overlap	New_Role_2
3	Patient	Physician	Patient [PUT]	Overlap	Patient_2, New_Role_3
4	Patient	Patient	Observation [PUT]	Overlap	New_Role_4
5	SMH	New_Role_1	Observation [GET]	SR contains GR	SMH
6	SMH	New_Role_2	Patient [GET]	SR contains GR	Nothing
7	SMH	New_Role_3	Patient [PUT]	SR contains GR	Nothing
8	SMH	New_Role_4	Observation [PUT]	SR contains GR	Nothing
9	SMH	Physician	Nothing	Not related	Nothing
10	SMH	Physician_2	Nothing	Not related	Nothing
11	SMH	Patient	Nothing	Not related	Nothing
12	SMH	Patient_2	Person [PUT]	Overlap	New_Role_5

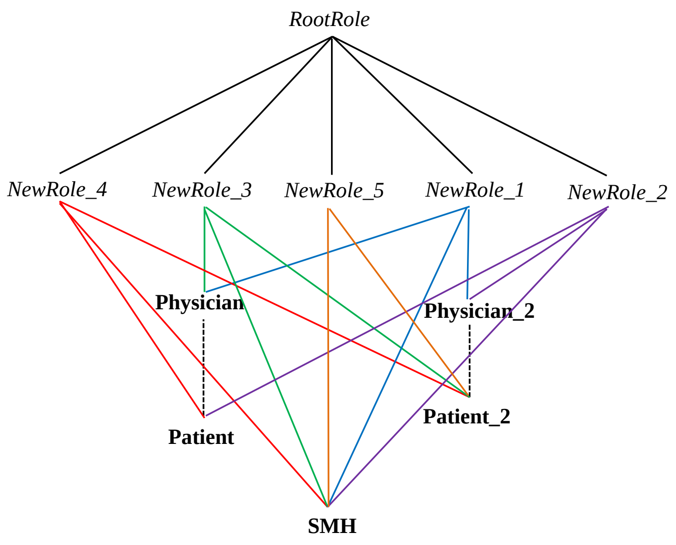
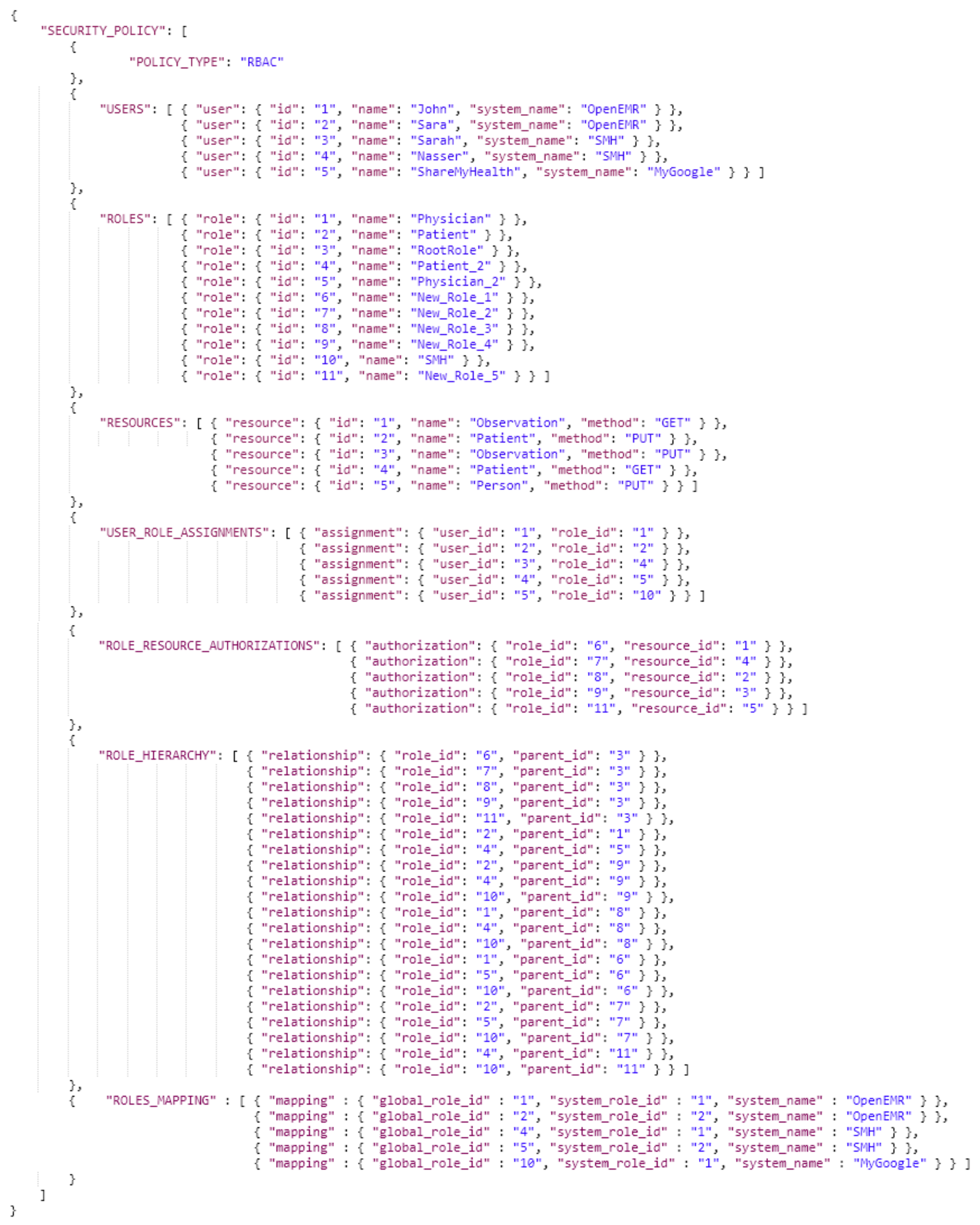


Figure 7.13. The Role Hierarchy of the Global RBAC Policy



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "RBAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "John", "system_name": "OpenEMR" } },
                       { "user": { "id": "2", "name": "Sara", "system_name": "OpenEMR" } },
                       { "user": { "id": "3", "name": "Sarah", "system_name": "SMH" } },
                       { "user": { "id": "4", "name": "Nasser", "system_name": "SMH" } },
                       { "user": { "id": "5", "name": "ShareMyHealth", "system_name": "MyGoogle" } } ]
        },
        {
            "ROLES": [ { "role": { "id": "1", "name": "Physician" } },
                       { "role": { "id": "2", "name": "Patient" } },
                       { "role": { "id": "3", "name": "RootRole" } },
                       { "role": { "id": "4", "name": "Patient_2" } },
                       { "role": { "id": "5", "name": "Physician_2" } },
                       { "role": { "id": "6", "name": "New_Role_1" } },
                       { "role": { "id": "7", "name": "New_Role_2" } },
                       { "role": { "id": "8", "name": "New_Role_3" } },
                       { "role": { "id": "9", "name": "New_Role_4" } },
                       { "role": { "id": "10", "name": "SMH" } },
                       { "role": { "id": "11", "name": "New_Role_5" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "GET" } },
                           { "resource": { "id": "2", "name": "Patient", "method": "PUT" } },
                           { "resource": { "id": "3", "name": "Observation", "method": "PUT" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET" } },
                           { "resource": { "id": "5", "name": "Person", "method": "PUT" } } ]
        },
        {
            "USER_ROLE_ASSIGNMENTS": [ { "assignment": { "user_id": "1", "role_id": "1" } },
                                       { "assignment": { "user_id": "2", "role_id": "2" } },
                                       { "assignment": { "user_id": "3", "role_id": "4" } },
                                       { "assignment": { "user_id": "4", "role_id": "5" } },
                                       { "assignment": { "user_id": "5", "role_id": "10" } } ]
        },
        {
            "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "6", "resource_id": "1" } },
                                              { "authorization": { "role_id": "7", "resource_id": "4" } },
                                              { "authorization": { "role_id": "8", "resource_id": "2" } },
                                              { "authorization": { "role_id": "9", "resource_id": "3" } },
                                              { "authorization": { "role_id": "11", "resource_id": "5" } } ]
        },
        {
            "ROLE_HIERARCHY": [ { "relationship": { "role_id": "6", "parent_id": "3" } },
                                { "relationship": { "role_id": "7", "parent_id": "3" } },
                                { "relationship": { "role_id": "8", "parent_id": "3" } },
                                { "relationship": { "role_id": "9", "parent_id": "3" } },
                                { "relationship": { "role_id": "11", "parent_id": "3" } },
                                { "relationship": { "role_id": "2", "parent_id": "1" } },
                                { "relationship": { "role_id": "4", "parent_id": "5" } },
                                { "relationship": { "role_id": "2", "parent_id": "9" } },
                                { "relationship": { "role_id": "4", "parent_id": "9" } },
                                { "relationship": { "role_id": "10", "parent_id": "9" } },
                                { "relationship": { "role_id": "1", "parent_id": "8" } },
                                { "relationship": { "role_id": "4", "parent_id": "8" } },
                                { "relationship": { "role_id": "10", "parent_id": "8" } },
                                { "relationship": { "role_id": "1", "parent_id": "6" } },
                                { "relationship": { "role_id": "5", "parent_id": "6" } },
                                { "relationship": { "role_id": "10", "parent_id": "6" } },
                                { "relationship": { "role_id": "2", "parent_id": "7" } },
                                { "relationship": { "role_id": "5", "parent_id": "7" } },
                                { "relationship": { "role_id": "10", "parent_id": "7" } },
                                { "relationship": { "role_id": "4", "parent_id": "11" } },
                                { "relationship": { "role_id": "10", "parent_id": "11" } } ]
        },
        {   "ROLES_MAPPING" : [ { "mapping" : { "global_role_id" : "1", "system_role_id" : "1", "system_name" : "OpenEMR" } },
                                { "mapping" : { "global_role_id" : "2", "system_role_id" : "2", "system_name" : "OpenEMR" } },
                                { "mapping" : { "global_role_id" : "4", "system_role_id" : "1", "system_name" : "SMH" } },
                                { "mapping" : { "global_role_id" : "5", "system_role_id" : "2", "system_name" : "SMH" } },
                                { "mapping" : { "global_role_id" : "10", "system_role_id" : "1", "system_name" : "MyGoogle" } } ]
        }
    ]
}
```

Figure 7.14. The Initial Global RBAC Policy in JSON

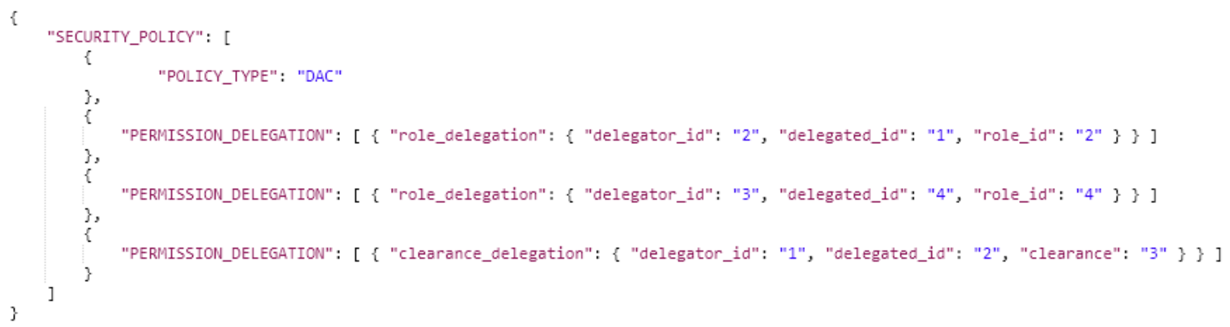
Second, as described in the second task option of task 2 labeled (2.a.3) in Section 7.2.3, the security engineer of FSICC and each of the security engineers of OpenEMR, SMH, and MyGoogle systems have a discussion in order to understand the semantic and usages of each sensitivity level of each system. In this case, the assumption is that all of the security engineers of systems and

FSICC have agreed to use different semantics of sensitivity levels, see Section 4.4 of Chapter 4, and thus generate a Sensitivity Levels Mapping List as described in Table 7.3. Note that in this example, the OpenEMR's sensitivity levels set is used as an initial global sensitivity levels set. In this sensitivity levels mapping list, we can describe the differences in sensitivity levels as follows: ShareMyHealth's sensitivity level SIS is mapped to global sensitivity level SID; while MyGoogle's sensitivity level VSI is mapped to global sensitivity level SID. Note that global sensitivity levels SIS and VSI have no corresponding levels in ShareMyHealth and MyGoogle sensitivity levels, respectively.

Table 7.3. An Example of a Sensitivity Levels Mapping List

ID	Global Sensitivity Level (OpenEMR)	System Sensitivity Level	System Name
1	PI	PI	ShareMyHealth
2	BSI	BSI	ShareMyHealth
3	SIS	-	ShareMyHealth
4	**SID**	SIS	ShareMyHealth
5	VSI	VSI	ShareMyHealth
6	PI	PI	MyGoogle
7	BSI	BSI	MyGoogle
8	SIS	SIS	MyGoogle
9	**SID**	VSI	MyGoogle
10	VSI	-	MyGoogle

Third, as described in the third task option of task 2 labeled (2.a.4) in Section 7.2.3, the security engineer of FSICC is required to send the DAC policy of OpenEMR, Figures 7.5 and 7.6, and DAC policy of SMH, Figure 7.11, to the DAC Integration algorithm that generates the global DAC policy as shown in Figure 7.15. Note that MyGoogle has no DAC policy. The generated global DAC policy has two role delegations (one from OpenEMR and one from SMH), and one clearance delegation from OpenEMR. Note that the Global DAC algorithm changed the role Ids, clearance, and user Ids to the global equivalents.



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "DAC"
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "2", "delegated_id": "1", "role_id": "2" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "role_delegation": { "delegator_id": "3", "delegated_id": "4", "role_id": "4" } } ]
        },
        {
            "PERMISSION_DELEGATION": [ { "clearance_delegation": { "delegator_id": "1", "delegated_id": "2", "clearance": "3" } } ]
        }
    ]
}
```

Figure 7.15. The Global DAC Policy in JSON

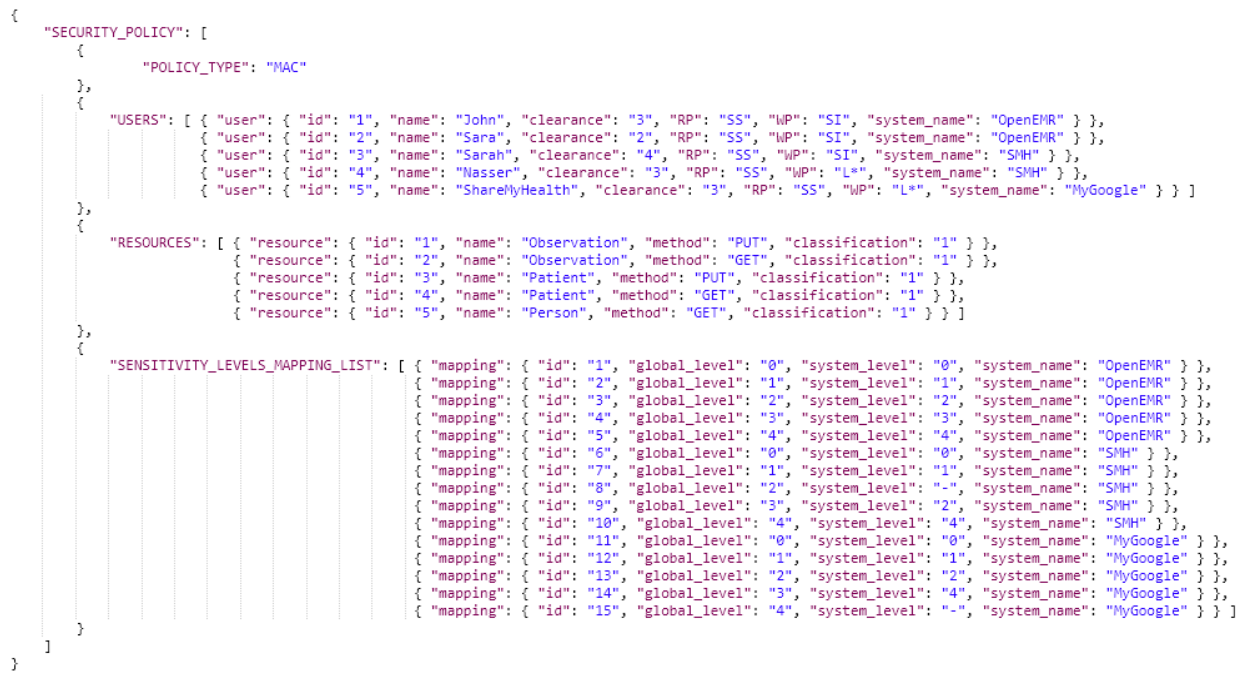
In task 2, to finalize the generation of the global RBAC policy and global MAC policy the security engineer of FSICC also needs to send the output of the first task option, labeled (2.a.2), of task 2 and the second task option, labeled (2.a.3), of task 2 to the appropriate remaining part of each task option, labeled (2.a.2.a) and (2.a.3.a) in Figure 7.2 respectively, based on the type of the registered security policy (RBAC or MAC). First, after generating the initial global RBAC labeled (2.a.2), Figure 7.14, that has some global roles with undesirable names such as New_Role_1 - New_Role_5, the security engineer of FSICC may wish to rename such roles via the step labeled (2.a.2.a) in Figure 7.2. To do this, the security engineer of FSICC first can review the names of all of the global roles, Figure 7.14, and suggest a new name for a subset of the global roles, e.g., based on the authorized permissions, as a corrected global roles list. In this case, the security engineer of FSICC would keep the role names New_Role_1 - New_Role_5 and change the role names Physician, Patient, Physician_2, and Patient_2 to Attending_Physician, General_Patient, Research_Physician, and Fitness_Patient, respectively, as described in Table 7.4. Then, the security engineer of FSICC, as described in the first task option of task 2 in Section 7.2.3, needs to send the corrected global roles list to the Review and Correct Role Names algorithm labeled 2.a.2.a which updates the global RBAC policy with the new role names as required.

Table 7.4. An Example of a Corrected Global Roles List

Global Role ID (Old Name)	New Name

1 (Physician)	Attending_Physician
2 (Patient)	General_Patient
5 (Physician_2)	Research_Physician
4 (Patient_2)	Fitness_Patient

Second, as described in the second task option of task 2 labeled (2.a.3) in Section 7.2.3, the security engineer of FSICC needs to Send the generated Sensitivity Levels Mapping List (Table 7.3) to the Building Global MAC algorithm, labeled (2.a.3.a). This step composes the global MAC policy, Figure 7.16, utilizing users and services from MAC policy of OpenEMR, Figure 7.6, MyGoogle, Figure 7.9, and SMH, Figure 7.12, in which users clearances and services classifications are assigned based on the global sensitivity levels in which the read/write properties of each user are remain unchanged.



```
{
    "SECURITY_POLICY": [
        {
                "POLICY_TYPE": "MAC"
        },
        {
            "USERS": [ { "user": { "id": "1", "name": "John", "clearance": "3", "RP": "SS", "WP": "SI", "system_name": "OpenEMR" } },
                       { "user": { "id": "2", "name": "Sara", "clearance": "2", "RP": "SS", "WP": "SI", "system_name": "OpenEMR" } },
                       { "user": { "id": "3", "name": "Sarah", "clearance": "4", "RP": "SS", "WP": "SI", "system_name": "SMH" } },
                       { "user": { "id": "4", "name": "Nasser", "clearance": "3", "RP": "SS", "WP": "L*", "system_name": "SMH" } },
                       { "user": { "id": "5", "name": "ShareMyHealth", "clearance": "3", "RP": "SS", "WP": "L*", "system_name": "MyGoogle" } } ]
        },
        {
            "RESOURCES": [ { "resource": { "id": "1", "name": "Observation", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "2", "name": "Observation", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "3", "name": "Patient", "method": "PUT", "classification": "1" } },
                           { "resource": { "id": "4", "name": "Patient", "method": "GET", "classification": "1" } },
                           { "resource": { "id": "5", "name": "Person", "method": "GET", "classification": "1" } } ]
        },
        {
            "SENSITIVITY_LEVELS_MAPPING_LIST": [ { "mapping": { "id": "1", "global_level": "0", "system_level": "0", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "2", "global_level": "1", "system_level": "1", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "3", "global_level": "2", "system_level": "2", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "4", "global_level": "3", "system_level": "3", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "5", "global_level": "4", "system_level": "4", "system_name": "OpenEMR" } },
                                                 { "mapping": { "id": "6", "global_level": "0", "system_level": "0", "system_name": "SMH" } },
                                                 { "mapping": { "id": "7", "global_level": "1", "system_level": "1", "system_name": "SMH" } },
                                                 { "mapping": { "id": "8", "global_level": "2", "system_level": "-", "system_name": "SMH" } },
                                                 { "mapping": { "id": "9", "global_level": "3", "system_level": "2", "system_name": "SMH" } },
                                                 { "mapping": { "id": "10", "global_level": "4", "system_level": "4", "system_name": "SMH" } },
                                                 { "mapping": { "id": "11", "global_level": "0", "system_level": "0", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "12", "global_level": "1", "system_level": "1", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "13", "global_level": "2", "system_level": "2", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "14", "global_level": "3", "system_level": "4", "system_name": "MyGoogle" } },
                                                 { "mapping": { "id": "15", "global_level": "4", "system_level": "-", "system_name": "MyGoogle" } } ]
        }
    ]
}
```

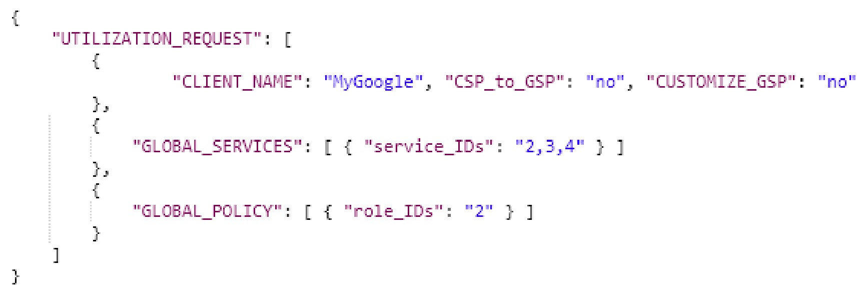
Figure 7.16. The Global MAC Policy in JSON

In task 3 labeled (2.a.5) in Section 7.2.3, the global RBAC policy, Figure 7.14, the global MAC policy, Figure 7.16, and the global DAC policy, Figure 7.15, are simply combined, utilizing the Combine Updated Global RBAC, Global MAC, and Global DAC and Control Data algorithm, in one JSON document that serves as the global security policy. Also, the security engineer of FSICC augments the global security policy with two pieces of information: one of the three read data access types, and the write data access type (i.e., Open to Same System Users) as described in Section 6.1.4 of Chapter 6. In this case, the assumption is that the security engineer of FSICC chosen to use the default read data access type (type 1 Open to All). Based on these settings: any user from OpenEMR, MyGoogle, or SMH who are assigned to the same global role, can read any data that the global role can retrieve; and, a user from a specific system, OpenEMR for example, who is assigned to a global role can only write data (only data of OpenEMR) that the global role can write.

In summary, at this point of the example and the process, the complete details of the generated global security policy and global services (such as the way that to utilize the global services and global security policy) are not as yet published to the public.

7.3.3 Applying the Constructing Clients Requests Phase on MyGoogle, SMH, and CT[2]

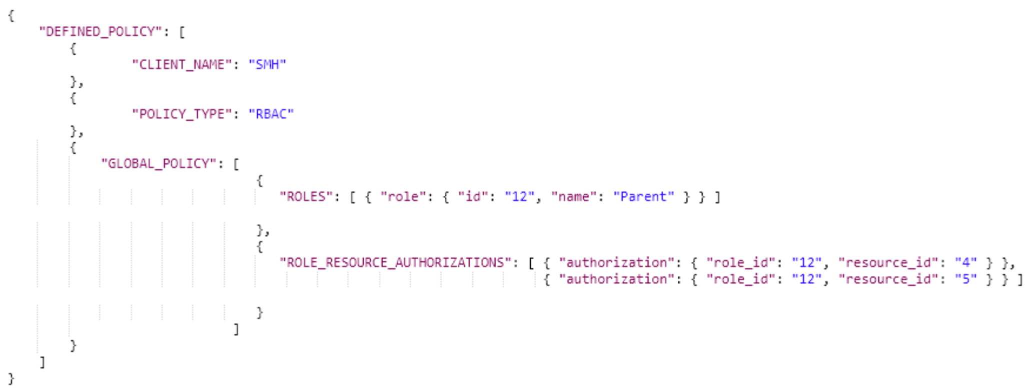
We start by applying the Constructing Clients Requests phase, labeled (1.b) in Figure 7.1, to MyGoogle system. Since MyGoogle is a mixed system, the security engineer of MyGoogle, from a usage perspective, needs to answer the three main questions, as discussed in Section 7.2, see Figure 7.1, after visiting the available global services and global security policy webpage. In this case, it is assumed that the security engineer of MyGoogle has the following answers: the client has no defined security policy (again from usage perspective); the client would utilize a subset of the available global services and global security policy; and, the client does not need to customize any subset of the global security policies. Based on these answers, the security engineer of MyGoogle should construct a JSON document for MyGoogle utilization request that specifies in detail the subset of global services (see Table 7.1) and global security policy, see Figures 7.14, 7.15, and 7.16, that MyGoogle has interests in utilizing, as shown in Figure 7.17, in which MyGoogle would be assumed to utilize: the global services: 2, 3, and 4; and the global role 2. Finally, the security engineer of MyGoogle needs to send the JSON document to the Client Registry component of FSICC in Figure 7.22.



```
{
    "UTILIZATION_REQUEST": [
        {
                "CLIENT_NAME": "MyGoogle", "CSP_to_GSP": "no", "CUSTOMIZE_GSP": "no"
        },
        {
            "GLOBAL_SERVICES": [ { "service_IDs": "2,3,4" } ]
        },
        {
            "GLOBAL_POLICY": [ { "role_IDs": "2" } ]
        }
    ]
}
```

Figure 7.17. MyGoogle Utilization Request in JSON

Second, we apply the Constructing Clients Requests to the SMH client App. Since SMH is a mixed client, the security engineer of SMH, from a usage perspective, needs to answer the same three main questions: SMH client has a defined security policy (again from usage perspective); SMH client would utilize a subset of the available global services but not interested in the global security policy; and, the client does not need to customize any subset of the global security policies. Based on these answers, the security engineer of SMH should construct two JSON documents. The first one (Policy Mapping Request) is to specify the defined security policy against the global services, as shown in Figure 7.18, in which one role (i.e., Parent with id 12) is defined that is authorized to access global services 4 and 5. This first JSON document needs to be sent to the security engineer of FSICC who needs to process and update the global security policy. Based on the updated global security policy, the second JSON document can be constructed for SMH utilization request that specifies in details the subset of global services (see Table 7.1) that SMH interests in, as shown in Figure 7.19, in which SMH would be assumed to utilize: the global services: 4 and 5; and the global role 12 which was added into the global security policy as a result of human intervention with the security engineer of FSICC. Finally, the security engineer of SMH needs to send the second JSON document to the Client Registry component of FSICC in Figure 7.22.

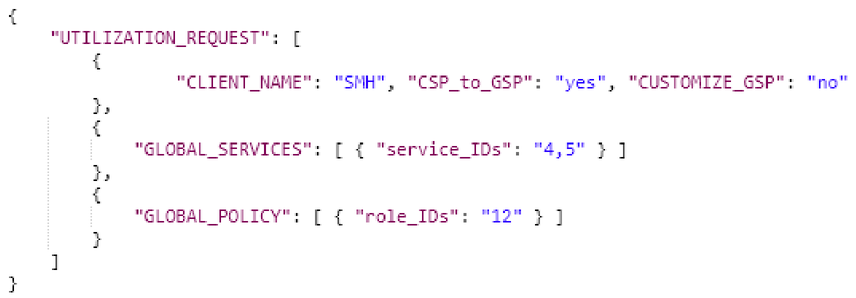


```
{
    "DEFINED_POLICY": [
        {
                "CLIENT_NAME": "SMH"
        },
        {
                "POLICY_TYPE": "RBAC"
        },
        {
            "GLOBAL_POLICY": [
                                {
                                   "ROLES": [ { "role": { "id": "12", "name": "Parent" } } ]

                                },
                                {
                                   "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "12", "resource_id": "4" } },
                                                                     { "authorization": { "role_id": "12", "resource_id": "5" } } ]

                                }
                            ]
        }
    ]
}
```

Figure 7.18. SMH Policy Mapping Request in JSON.

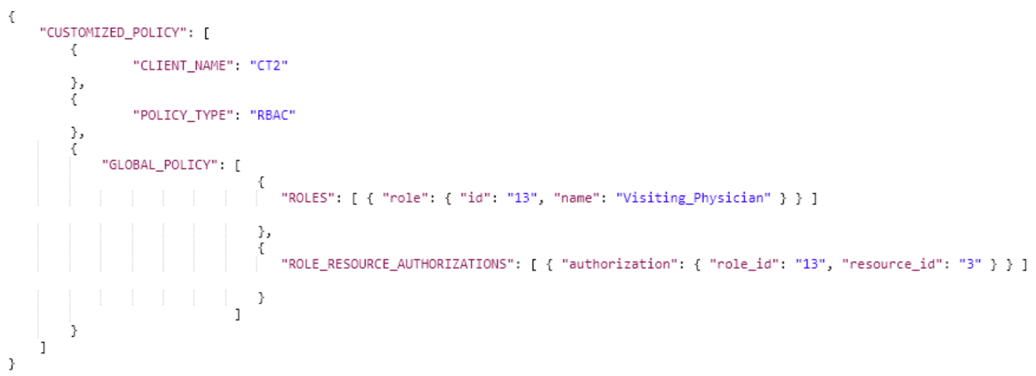


```
{
    "UTILIZATION_REQUEST": [
        {
                "CLIENT_NAME": "SMH", "CSP_to_GSP": "yes", "CUSTOMIZE_GSP": "no"
        },
        {
            "GLOBAL_SERVICES": [ { "service_IDs": "4,5" } ]
        },
        {
            "GLOBAL_POLICY": [ { "role_IDs": "12" } ]
        }
    ]
}
```

Figure 7.19. SMH Utilization Request in JSON

Finally, we apply the Constructing Clients Requests phase to the CT^2 client App. Since CT^2 is a pure client, the security engineer of CT^2 needs to answer the three main questions: CT^2 client has no defined security policy; CT^2 client would utilize a subset of the available global services and global security policy; and the client needs to customize a subset of the global security policies.

Based on these answers, the security engineer of CT^2 should construct two JSON documents. The first one (Policy Customize Request) is to specify the customize security policy, as shown in Figure 7.20, in which the Physician role (id 1) of the global RBAC policy is customized to be also authorized to access the global service 3. This first JSON document needs to be sent to the security engineer of FSICC who needs to process it and update the global security policy. Based on the updated global security policy, the second JSON document can be constructed for CT^2 utilization request that specifies in details the subset of global services (see Table 7.1) that CT^2 interests in, as shown in Figure 7.21, in which CT^2 would be assumed to utilize: the global services: 1, 2, and 3; and the global role 1 which can access the global service 3 as a result of human intervention with the security engineer of FSICC). Finally, the security engineer of CT^2 needs to send the second JSON document to the Client Registry component of FSICC see Figure 7.22.

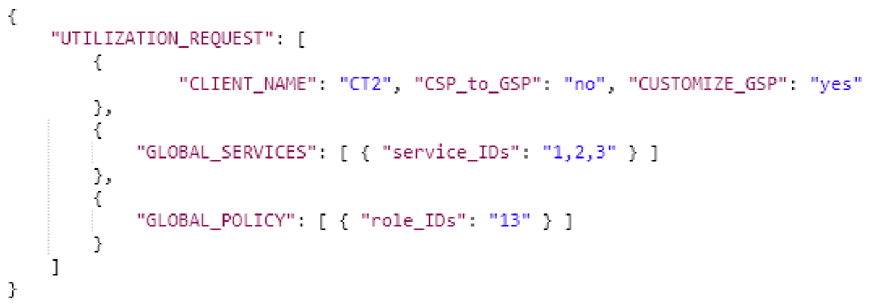


```
{
    "CUSTOMIZED_POLICY": [
        {
                "CLIENT_NAME": "CT2"
        },
        {
                "POLICY_TYPE": "RBAC"
        },
        {
            "GLOBAL_POLICY": [
                                {
                                   "ROLES": [ { "role": { "id": "13", "name": "Visiting_Physician" } } ]

                                },
                                {
                                   "ROLE_RESOURCE_AUTHORIZATIONS": [ { "authorization": { "role_id": "13", "resource_id": "3" } } ]

                                }
                            ]
        }
    ]
}
```

Figure 7.20. CT^2 Policy Customize Request in JSON



```
{
    "UTILIZATION_REQUEST": [
        {
                "CLIENT_NAME": "CT2", "CSP_to_GSP": "no", "CUSTOMIZE_GSP": "yes"
        },
        {
            "GLOBAL_SERVICES": [ { "service_IDs": "1,2,3" } ]
        },
        {
            "GLOBAL_POLICY": [ { "role_IDs": "13" } ]
        }
    ]
}
```

Figure 7.21. CT^2 Utilization Request in JSON

7.3.4 Applying the Usage Requests Processing Phase on MyGoogle, SMH, and CT^2

As explained in Section 7.3.3, the MyGoogle system, and the SMH and CT^2 client Apps are constructed and sent a utilization request and/or policy customize request and/or policy mapping request in JSON format, see Figures 7.17, 7.18, 7.19, 7.20, and 7.21, to the FSICC. In this section, we describe the way that the security engineer of FSICC, as described in Section 7.2.4, in Figure 7.3, process each of these requests through the four tasks as described in Section 7.2.4.

In task 1, the security engineer of FSICC needs to perform the appropriate task 1 option based on request type of the clients (policy mapping, utilization, or policy customization). First, as described in the left task option of task 1 labeled (2.b.1) in Section 7.2.4, the security engineer of FSICC needs to process the SMH's policy mapping request, Figure 7.18. Since the SMH's policy mapping request is RBAC-based, the security engineer of FSICC checks the global RBAC policy, Figure 7.14, and finds that the role (i.e., Parent with id 12) in the SMH's policy mapping request is not similar to existing roles.

Second, as described in the center task option of task 1 labeled (2.b.2) in Section 7.2.4, the security engineer of FSICC needs to process MyGoogle's utilization requests, Figure 7.17, SMH's utilization requests, Figure 7.19, and CT^2's utilization requests, Figure 7.21, by assigning an ID and generating a security Token for each client.

Finally, as described in the right task option of task 1 labeled (2.b.3) in Section 7.2.4, the security engineer of FSICC needs to process CT^2's policy customize request, Figure 7.20. Since the CT^2's policy customize request is RBAC-based, the security engineer of FSICC checks the global RBAC policy, Figure 7.14, to locate the requested global role (i.e., Physician with id 1) and add a new global role (i.e., Visiting_Physician with id 13) and limit it to only access the specified global service (with id 3).

In task 2, the security engineer of FSICC needs to perform the appropriate task 2 option based on the outputs of task 1. First, as described in the center task option of task 2 labeled (2.b.1.b) in Section 7.2.4, the security engineer of FSICC adds a new global role (i.e., Parent with id 12), from the SMH's policy mapping request, along with its permissions, to the global RBAC policy. This is because in the left task option of task 1 the security engineer of FSICC did not find a similar role in the global RBAC policy. Note that, in this case, the security engineer of FSICC will not perform the left task option of task 2 in Section 7.2.4 as no similar role was found.

Second, as described in the right task option of task 2 labeled (2.b.2.a) in Section 7.2.4, the security engineer of FSICC needs to find one suitable system as repository for each of MyGoogle, SMH, and CT^2 clients as follow. The OpenEMR system is chosen as a repository for MyGoogle, since the requested global services (2, 3, and 4) can be mapped to OpenEMR's services. Then, the MyGoogle system is chosen as a repository for SMH, since the requested global services (4 and 5) can be mapped to MyGoogle's services. Then, the OpenEMR system is chosen as a repository for CT^2, since the requested global services (1, 2, and 3) can be mapped to OpenEMR's services.

In task 3, labeled (2.b.4) in Figure 7.3, the security engineer of FSICC needs to update the global security policy based on the outputs of the tasks 1 and 2 as follow. The security engineer of FSICC will add a new global role (i.e., Visiting_Physician with id 13) to the global security policy and limit it to only access the specified global service (with id 3), from the left task option of task 1. The security engineer of FSICC will also add a new global role (i.e., Parent with id 12) to the global security policy, from the center task option of task 2.

In task 4, labeled (2.b.5) in Figure 7.3, the security engineer of FSICC needs to send separate JSON documents to each of MyGoogle, SMH, and CT^2 clients that include: client's ID, client's security token, the available global services, the available global security policy, and instructions on the way to utilize such global services and global security policy.

To give an overall view of the final output of applying all of the SSEP phases and tasks that described in Sections 7.3.1, 7.3.2, 7.3.3, and 7.3.4, we refine Figure 5.12 (from Section 5.4.2 of Chapter 5) to show the overall architecture of interactions: between OpenEMR and MyGoogle with FSICC; and between CT^2 and SMH with FSICC, as Figure 7.22 shows.

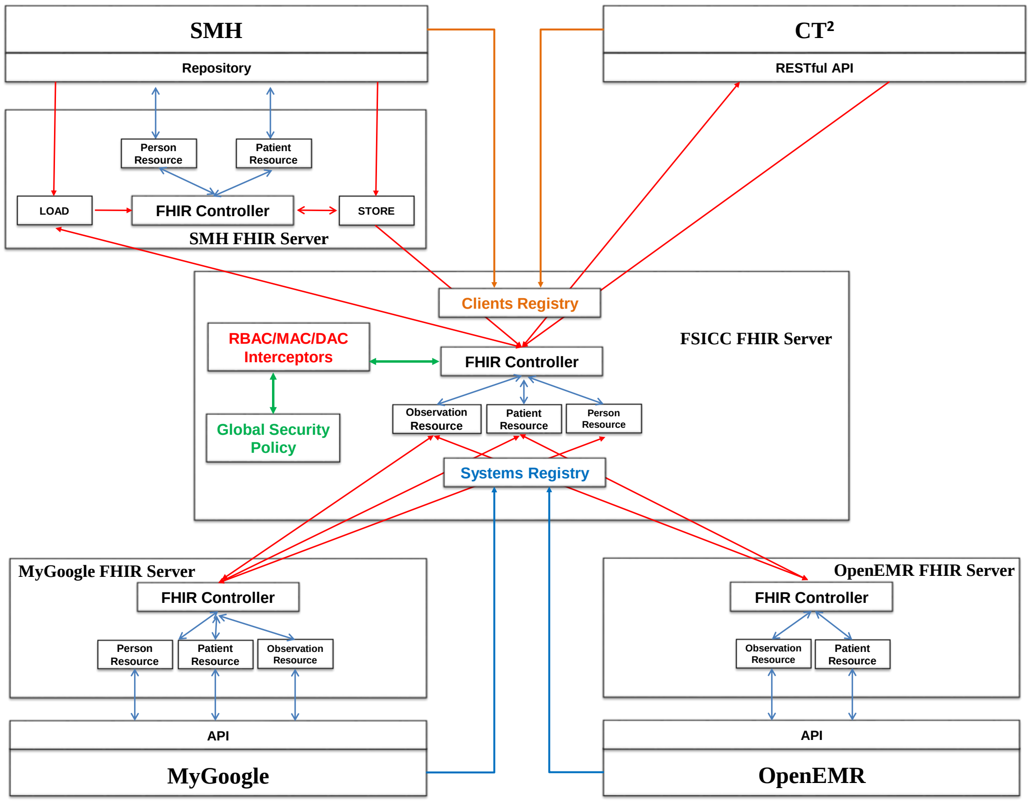


Figure 7.22. Overall Architecture of the Interactions for Clients and Systems with FSICC.

Chapter 8
Conclusion

This dissertation presented and explained a Framework for Secure and Interoperable Cloud Computing (FSICC) with RBAC (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), MAC (Bell & La Padula, 1976), and DAC (Dittrich, Härtig, & Pfefferle, 1988) that allows clients and systems to interact with one another. The FSICC provided the unification of services and security capabilities from different paradigms (e.g., cloud services, programming services, web services), alternate cloud service providers, and diverse security/access control (RBAC, MAC, and/or DAC). From an overall viewpoint, each system may build and publish their cloud, programmatic, or web services into FSICC that combined such services into a unified set of global services in the cloud. Then, a developer of a mobile, web, or desktop client can discover such global services and utilize them to develop the client application. The five main research focus of the dissertation presented: Architectural Blueprints for Supporting FSICC that contained different options for connecting clients and systems with FSICC; an Integrated RBAC, MAC, and DAC Model for Cloud Computing via a Unified Cloud Computing Access Control Model (UCCACM) that contained a set of definitions necessary for supporting our work on FSICC including Schema Definitions, Enterprise Definitions, Policy Definitions, FSICC Definitions, and Intercepting Definitions; Security Mapping/Enforcement Algorithms for GSP (Global Security Policy) Generation and GAPI (Global API) Generation which included Security Policies and Services Registration, Global Services Generation, and Global Security Policy Generation; a SOA-Based Security Engineering Process (SSEP) for FSICC that was utilized to combine security policies from different systems into one global security policy in which SSEP also included a process for security enforcement code generation; and, Dynamic Enforcement via Intercepting Process involved a set of programmatic mechanisms that were able to intercept a service call from a client app to a global service in FSICC in order to perform appropriate security enforcement checks.

The reminder of this conclusion is organized as follows. Section 8.1 summarizes the dissertation, highlighting the attainment of the five research foci in detail. Using this as a basis, Section 8.2 discusses the research contributions of this dissertation, primarily in the areas of: Architectural Blueprints for Supporting FSICC; an Integrated RBAC, MAC, and DAC Model for Cloud Computing; Security Mapping/Enforcement Algorithms and SSEP; and, Dynamic Enforcement via Intercepting Process. Finally, Section 8.3 details the ongoing and future research directions that include, but are not limited to: extending UCCACM of FSICC with Modern Access Control Models; implementing remaining components of the FSICC; providing a more fine-grained access control approach; and demonstrating the Architectural Blueprints on one or more different domains.

8.1 Summary

This dissertation presented a Framework for Secure and Interoperable Cloud Computing (FSICC) that provides a set of global cloud services for use by clients and systems with access control provided by RBAC, MAC, and/or DAC models. The main objective of this dissertation was two-fold: to provide a solution to the service integration problem, which was the difficulties that occur when a client is trying to access services that could be operating with different types of application programmer interfaces (APIs); and to provide a solution to be security policy integration problem, that occurred since the different paradigms and alternate cloud service providers may all have different types of security and access control capabilities, that will allow clients and systems to interact with one another in a framework. Such a framework would provide the unification of services and security capabilities from different paradigms (e.g., cloud services, programming services, web services), alternate cloud service providers, and diverse security/access control (RBAC, MAC, and/or DAC). In support of our objective, the discussion in this dissertation was presented throughout seven chapters.

Chapter 1 introduced the main areas for our research and a high-level view of the presented Framework for Secure and Interoperable Cloud Computing. Section 1.1 discussed the motivation of restricting access to a unified set of global cloud services utilizing access control models as our main area of interest. Section 1.2 explored the motivation of the work in the healthcare domain as an appropriate context to present the work of the dissertation since healthcare represents as a critical emergent application for cloud computing. Section 1.3 provided a set of security requirements and cloud computing capabilities that the FSICC needs to support. Based on this, Section 1.4 presented and explained the Framework for Secure and Interoperable Cloud Computing with RBAC, MAC, and DAC of this dissertation. Section 1.5 provided a list of the research objectives and expected contributions for the dissertation. Section 1.6 discussed the work that has been published by us in order to support the work presented in the dissertation. Finally, Section 1.7 presented an outline of the dissertation.

Chapter 2 presented background material on the main concepts and topics that supported our discussion and explanation of this dissertation. Section 2.1 discussed the cloud computing concept and underlined application programming interfaces (APIs), and presented the main technologies behind cloud computing with an emphasis on the service-oriented architecture (SOA) technology that emphasized the cloud service model. Section 2.2 reviewed the three main access control approaches: role-based access control (RBAC) (Ferraiolo, Sandhu, Gavrila, Kuhn, & Chandramouli, 2001), discretionary access control (DAC) (Dittrich, Härtig, & Pfefferle, 1988), and mandatory access control (MAC) (Bell & La Padula, 1976). Section 2.3 introduced and explained the Fast Health Interoperable Resources (FHIR) standard with an emphasis on the FHIR Resources and reviewed the HL7 Application Programming Interface FHIR (HAPI-FHIR) which is one popular reference implementation of the FHIR standard. Section 2.4 presented a sample healthcare scenario utilized throughout this dissertation.

Chapter 3 presented the four Security Requirements and the three Cloud Computing Capabilities that underlined and supported FSICC. Section 3.1 defined and explained the four security requirements for FSICC: Numerous and Varied Access Control Models, Control Access to Cloud Services Using RBAC, Support Delegation of Cloud Services Using DAC, and Control Access to Cloud Services Using MAC. Section 3.2 detailed the three cloud computing capabilities with associated components of the FSICC: Local Service Registration and Mapping to Global Services; Local Security Policies Registration to Yield Global Security Policy; and, Global Registration, Authentication, Authorization, and Service Discover for Consumers. Section 3.3 discussed related research in cloud computing as compared with FSICC.

Chapter 4 provided formal definitions of UCCACM in eight sections. Section 4.1 presented a set of core definitions on schemas to support authorizing users to a set of schemas based on roles and/or sensitivity levels. Section 4.2 provided core definitions on enterprise application that included definitions for clients, systems, and types of clients and systems as part of the enterprise application. Section 4.3 discussed core definitions on RBAC, MAC, and DAC models that described the way that such access control models can be modified to support the four security requirements of FSICC. Section 4.4 described advanced definitions on enterprise applications in which the security aspects of RBAC, MAC, and DAC models were introduced into clients and systems of any enterprise application. Section 4.5 had core definitions on global resources and permissions by API in which definitions that described what were global services and the way that such global services were controlled via means of RBAC, MAC, and DAC were provided. Section 4.6 presented advanced definitions on FSICC that described the way that services and security policies of different systems were mapped. Section 4.7 discussed core definitions on security interceptors for RBAC, MAC, and DAC along with enforcement checks that each security interceptor utilized. Section 4.8 presented related work on access control for cloud computing. Throughout the entire presentation of UCCACM, detailed examples were provided utilizing the healthcare scenario of section 2.4 Chapter 2.

Chapter 5 presented a set of Architectural Blueprints which were guidelines that defined the way of placing and creating an integration layer for a systems or client. In Section 5.1, we explored four issues that must be understood for an application of FSICC to support a discussion of the options and blueprints: the overall architecture of the application; the involved technologies that can be used to develop the application; the source code availability of the application, APIs, server code, or database; and, the allowable access to system sources. In Section 5.2, we examined the three different Architectural Blueprint options, namely, Basic, Alternative, and Radical, for integrating an application to multiple HIT systems via FSICC, utilizing FHIR. In Section 5.3, we provided an Architectural Blueprints for each of the three options that illustrated the way that the options can be realized using FHIR including the various phases and steps that are required. In Section 5.4, we presented a complex example that utilized the Alternative and Radical Architectural Blueprint options applied to the healthcare scenario from Section 2.4 of Chapter 2. In Section 5.5, we discussed two related works in the literature that explained alternative ways that FHIR can be implemented to integrate healthcare systems and/or applications in different settings.

Chapter 6 presented Global Security Policy Generation process and Dynamic Enforcement implementation for FSICC in three sections. In Section 6.1, a set of security policy integration algorithms were presented and discussed for: global RBAC generation, global MAC generation, global DAC generation, and global policies combination. In Section 6.2, we demonstrated the realization of UCCACM of FSICC in HAPI FHIR utilizing the healthcare scenario of Section 2.4 of Chapter 2 that involved the implementation of HAPI FHIR APIs and its server interceptor to support UCCACM checks with three different algorithms to support three different HAPI FHIR interceptors: RBAC interceptor, MAC interceptor, and DAC interceptor. Moreover, the interceptor discussions were supported by two access scenarios. Section 6.3 presented and discussed related work in both security policy integration and enforcing security policies on FHIR API.

Chapter 7 presented a SOA-based security engineering and global security policy generation process for FSICC in three main sections. In Section 7.1, we briefly discussed a Pre-Process Step that described what each system and client needed to do before joining the FSICC. In Section 7.2, a SOA-based security engineering process (SSEP) for FSICC was presented that was intended to assist security engineers of systems and clients and security engineers of FSICC with a structured process to define and maintain secure interoperable services for RBAC, MAC, and DAC. In Section 7.3, a complete and detailed example that illustrated the SOA-based security engineering process of Section 7.2 was provided to demonstrate the steps and sub-steps of SSEP coupled with security policy integration algorithms of Section 6.1 of Chapter 6 that can be utilized to establish and utilize security for interoperable services via FSICC.

8.2 Research Contribution

This section revisits the expected research contributions given in Section 1.5 of Chapter 1 and provides insight of their attainment across the chapters of the dissertation. The Framework for Secure and Interoperable Cloud Computing (FSICC) with RBAC, MAC, and DAC has the following contributions:

EC-A. Architectural Blueprints for Supporting FSICC: This contribution enabled the interoperability and information exchange of clients and systems and defined and explained a collection of three architectural blueprints (i.e., Basic Architecture, Alternative Architecture, and Radical Architecture) for the design and development of integration framework (IFMWK) servers utilizing a standard integration framework (e.g., FHIR in the healthcare domain) that facilitate the integration between HIT systems with applications. This was shown in the upper half (left) of Figure 1.2. The architectural blueprints were represented as the first horizontal box Architectural Blueprints in Figure 1.3 and included three main boxes for: Interoperability Issues, Integration Options, and Integration Blueprints. Each blueprint was based on the location that IFMWK servers can be placed with respect to the components of the application (UI, API, Server) or a HIT system in order to define and design the required infrastructure to enable the exchange of information via IFMWK. In support of this contribution, Chapter 5 provided details of four interoperability issues, three integration Options, and associated integration blueprints. Chapter 4 also supported this contribution by providing four UCCACM definitions (Defns. 41 to 44 from Chapter 4) that described: the mapping of clients and systems, the set of all global resources, mapping clients and systems services to the global services of FSICC, and the set of all global APIs for all clients and systems, respectively.

EC-B. An Integrated RBAC, MAC, and DAC Model for Cloud Computing: This contribution presented and explained a Unified Cloud Computing Access Control model (UCCACM) for the FSICC that provided a single view of global services to applications (i.e., clients) and enabled those global services to be authorized according to RBAC, MAC, and DAC policies. The UCCAC model was represented by the second horizontal box Unified Cloud Computing Access Control Model in Figure 1.3 that included five main boxes for: Schema Definitions, Enterprise Definitions, Policy Definitions, FSICC Definitions, and Intercepting Definitions. The contribution involved a set of formal definitions for RBAC, MAC, and DAC access control models that specified, in detail, the way that: each system can register its services and security policies; and, a security engineer can define a set of global RBAC, MAC, and/or DAC policies on a unified set of global cloud services. The UCCAC model basically suggested formal definitions for the main components of Figure 1.2. In support of this contribution, Chapter 4 provided the Unified Cloud Computing Access Control model (UCCACM) for the FSICC that is an access control model that utilized three main access control models (RBAC, MAC, and DAC) and had a set of 60 definitions distributed in seven main groups: core definitions on schemas, core definitions on enterprise application, core definitions on RBAC, MAC, and DAC models, advanced definitions on enterprise applications, core definitions on global resources and permissions by API, advanced definitions on FSICC, and core definitions on security interceptors for RBAC, MAC, and DAC. Chapter 3 also supported this contribution by motivating the UCCACM by the four main security requirements of FSICC (i.e., Numerous and Varied Access Control Models, Control

Access to Cloud Services Using RBAC, Support Delegation of Cloud Services Using DAC, and Control Access to Cloud Services Using MAC) as presented in Section 3.1.

EC-C. Security Mapping/Enforcement Algorithms and SSEP: This contribution included Security Mapping/Enforcement Algorithms realized within the horizontal box near the bottom of Figure 1.3, labeled GSP (Global Security Policy) Generation and GAPI (Global API) Generation which included Security Policies and Services Registration, Global Services Generation, and Global Security Policy Generation. In support of this contribution, Chapter 6 presented: a pre-process step for joining FSICC, a SOA-based security engineering process (SSEP) for FSICC, a set of security policy integration algorithms, and a detailed example that illustrated the steps and sub-steps of SSEP along with the security policy integration algorithms. Chapter 4 also supported this contribution by providing eight UCCACM definitions (Defns. 41 to 48 from Chapter 4) which ensured that the global security policy can control access to a set of global services of FSICC. Moreover, Chapter 3 supported this contribution by motivating the cloud computing capability 2 of FSICC, i.e., Local Security Policies Registration to Yield Global Security Policy, from Section 3.2. This contribution also included a SOA-based security engineering process (SSEP) that couples Security Mapping/Enforcement Algorithms with EC-A Architectural Blueprints for Supporting FSICC via and EC-B An Integrated RBAC, MAC, and DAC Model for Cloud Computing into an for FSICC that can be used to combine security policies (that can be RBAC, MAC or DAC) from different systems into one global security policy for security enforcement code generation. This was shown in the upper right half of Figure 1.2. A portion of the SSEP was human assisted in order to resolve naming issues of roles, mapping sensitivity levels, etc., that were combined from multiple clients and systems. Once the policies were successfully integrated, all of the security enforcement code can be automatically generated by algorithms. The SSEP for FSICC was represented by the left vertical box SOA-BASED SECURITY ENGINEERING in Figure 1.3 that spanned all of the five horizontal boxes: Architectural Blueprints, Unified Cloud Computing Access Control Model, Access Control Models, Global Security Policy and Global API Generation, and Global Security Policy and Global API Utilization and Security Enforcement. The Security Mapping/Enforcement Algorithms aspect of this contribution was realized within the horizontal box near the bottom of Figure 1.3, labeled GSP (Global Security Policy) Generation and GAPI (Global API) Generation which included Security Policies and Services Registration, Global Services Generation, and Global Security Policy Generation. In support of this contribution, Chapter 6 presented: a pre-process step for joining FSICC, a SOA-based security engineering process (SSEP) for FSICC, a set of security policy integration algorithms, and a detailed example that illustrated the steps and sub-steps of SSEP along with the security policy integration algorithms. Chapter 4 also supported this contribution by providing eight UCCACM definitions (Defns. 41 to 48 from Chapter 4) which ensured that the global security policy can control access to a set of global services of FSICC. Moreover, Chapter 3 supported this contribution by motivating the cloud computing capability 2 of FSICC, i.e., Local Security Policies Registration to Yield Global Security Policy, from Section 3.2.

EC-D. **Dynamic Enforcement via Intercepting Process**: This contribution provided a set of programmatic mechanisms that were able to intercept a service call from a client app to an API in order to perform appropriate security enforcement checks.   This was shown in the bottom of Figure 1.2. In Figure 1.3, these security interceptors were represented within the last horizontal box Global Security Policy and Global API Utilization and Security Enforcement in Figure 1.3, and the Security Enforcement via Interceptors box in Figure 1.2. Interceptors included: a RBAC Interceptor that was able to determine at runtime if the requested API call on a global service can be executed for a specific user with a specific role; a MAC Interceptor that was able to determine at runtime if the requested API call on a global service can be executed for a user with a clearance and limited by if the services was read or write; and a DAC Interceptor that was able to determine at runtime if the requested API call on a global service can be executed for a specific user with a delegated role/service/clearance. In support of this contribution, Chapter 7 presented an implementation of HAPI FHIR APIs and its server interceptor that supported UCCACM checks with three different algorithms to support three different HAPI FHIR interceptors: RBAC interceptor, MAC interceptor, and DAC interceptor. Chapter 4 also supported this contribution by providing 11 UCCACM definitions (Defns. 50-60 from Chapter 4) that discussed concepts of Interceptor, RBAC Interceptor, MAC Interceptor, and DAC Interceptor. Moreover, Chapter 3 supported this contribution by motivating the cloud computing capability 3 of FSICC, i.e., Global Registration, Authentication, Authorization, and Service Discover for Consumers, from Section 3.2.

8.3 Ongoing and Future Work

The work presented in this dissertation can serve as a foundation for further enhancements and extensions. A list of ongoing and future topics includes: extending UCCACM of FSICC with

Modern Access Control Models; implementing remaining components of the FSICC; providing a more fine-grained access control approach to enable controlling data based on time period and data subset; and applying the Architectural Blueprints on one or more different domains using a standard integration framework and one of its implementations in that domain.

Extending UCCACM of FSICC with Modern Access Control Models: As we presented in this dissertation, the Unified Cloud Computing Access Control Model (UCCACM) of the Framework of Secure and Interoperable Cloud Computing (FSICC) provides capabilities to register three type of access control models, namely RBAC, MAC, and DAC. As part of future work, we are interested in extending the UCCACM with modern access control models such as Attribute-based Access Control (ABAC) (Yuan, E. & Tong, J. , 2005), Usage Control Access Control (UCON) (Sandhu, R. & Park, J. , 2003), History-Based Access Control (HBAC) (Banerjee, A. & Naumann, D., 2005), Identity-Based Access Control (IBAC) (Saxena, N., Tsudik, G., & Yi, J., 2004), Organization-Based Access control (OrBAC) (Kalam, A., et al., 2003), and Rule-Based Access Control (RAC) (Carminati, B., Ferrari, E., & Perego, A., 2006). This way systems may define and register their ABAC/UCON/HBAC/IBAC/OrBAC/RAC-based security policies into FSICC that in turn combines: different ABAC/UCON/HBAC/IBAC/OrBAC/RAC-based security policies from multiple systems to generate a global ABAC/UCON/HBAC/IBAC/OrBAC/RAC security policy. The generated global ABAC/UCON/HBAC/IBAC/OrBAC/RAC security policies can be then enforced against each request to access global services of FSICC using a corresponding security interceptor.

Implementing Remaining Components of the FSICC: Currently, four components of the Framework of Secure and Interoperable Cloud Computing (FSICC), see Figure 1.1 from Chapter 1, are already implemented in this dissertation. These components are: Global Authentication, RBAC/MAC/DAC Interceptors, Global Services, and Global Security Policy. Moreover, in this dissertation we described the login and purpose of the remaining components of FSICC (i.e., Client Registry, System Registry, Services Mapping, and Security Policy Mapping). As part of future work, we are planning to convert the login of the remaining components of FSICC into an actual implementation as RESTful APIs that can be implemented using the JAX-RS Java library (Hadley & Sandoz, 2009). The implementation of these four FSICC components will enable the interested systems and clients to utilize all features of FSICC that we presented in this dissertation.

Providing a More Fine-Grained Access Control Approach: Presently, the global RBAC policy, global MAC policy, and global DAC policy that are used in the FSICC as a global security mechanism are defined to control who can access what set of global services. Moreover, the global security mechanism also controls what set of data, that global services can access and what each user can read/write using three read data access types and one write data access type. As part of future work, we are contemplating to further control accessing data based on time period and data subset to support the FSICC with a more fine-grained access control approach. That is, time period feature will enable the global security mechanism of FSICC to specify: a start and end time (time period) in which a user is allowed to access a global service. The data subset feature will enable the global security mechanism of FSICC to specify what parts (fields) of data record, that is accessible via global services, each user is allowed to access.

Demonstrating the Architectural Blueprints on Different Domains: Recall that in Chapter 5, we presented a complex example that utilized the Alternative and Radical Architectural Blueprint options prototype applied to the healthcare scenario from Section 2.4 of Chapter 2 utilizing the FHIR standard and HAPI FHIR (FHIR reference implementation) as a standard Integration Framework (IFMWK) in the healthcare domain. As part of future work, we are looking for applying a subset of our Architectural Blueprints from Chapter 5 to integrate systems and clients in domains other than the healthcare domain. This is to prove that our Architectural Blueprints can be utilized by any stakeholders in any domain who are interested in integrating systems and clients via FSICC. To do this, we may utilize one or more standard Integration Frameworks and their implementations (one IFMWK for each domain such as the financial domain) that are openly available.

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