

Information Flow testing of a PGP server

Bachelorarbeit

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Statement of Authorship

I hereby confirm that I have written the accompanying thesis by myself, without contributions from any sources other than those cited in the text and acknowledgements. This applies also to all graphics, drawings, maps and images included in the thesis.

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Abstract

As part of the VerifyThis2020 challenge, the new HAGRID PGP server has been proposed as this year's verification target. In this thesis, we elaborate on our submission for this challenge and present an information flow testing approach based on history traces. Through this approach, we determine the exact set of information declassifiable by HAGRID, allowing us to test both functional correctness and privacy of information. Our tests target both an abstract model written in Scala, as well as the actual implementation of HAGRID.

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1 Introduction

Throughout the last decade, the advancements of digital technology have given rise to many novel ways of organizing and sharing information on a global level. Reaching from simple email applications to large social media platforms, these advancements have fundamentally changed how we interact with information and especially with each other. And yet, while many of these applications have undoubtedly had a largely positive impact on our productivity and everyday life, they have also sparked concerns about the privacy and authenticity of the information within these applications. One approach to this problem is to formally reason about the flow of information within these applications. By doing this, one can enforce that the underlying system is

In this thesis, we formalize the claimed privacy features of a public PGP server implementation called HAGRID, verifying the validity of these claims by running tests both on an abstract model as well as the concrete implementation. Specifically, we present a *history* based approach which encodes the interaction with the server in an abstract manner and allows us to test both functional correctness and security. That is, our approach enables us to determine precisely which information may or may not be declassified by the system, therefore allowing us to detect privacy leaks as well as missing public information. To this end, we first implemented an abstract model of HAGRID using Scala that serves as the basis for our testing approach. At a later stage, we extended our efforts by adding a separate model capable of communicating with the actual HAGRID server. All code referenced in this thesis is available at GitHub under <https://github.com/gernst/verifythis2020> where we also give a short explanation as to how the implemented tests can be executed on the local machine.

The preliminary results of our testing efforts have also been published as part of the proceedings of the VerifyThis2020¹ verification challenge, which is a yearly competition in which participating teams are given challenges for program verification [6]. In fact, this challenge served as the initial foundation for this thesis by outlining HAGRID as this year’s chosen verification target.

Chapter 2 of this thesis will give a brief summary of HAGRID’s development history and the initial circumstances that gave rise to the project. Next, Chapter 3 focusses on the theoretical background of information flow and briefly discusses a number of central terms that have been used in the past to classify and analyze different kinds of information flow. Chapter 4 then handles the central aspect of this thesis, which is the formal description and explanation of the privacy constraints defined by HAGRID, most importantly introducing the notion of history traces on which we base our implementation. Chapter 5 then goes on to describe our concrete test implementation of the constraints laid out in Chapter 3. In chapter 6, we detail the expansion of our test approach to the actual HAGRID implementation. Chapter 8 details several related approaches specifically in the context of the VerifyThis2020 challenge, that focus on infor-

¹<https://verifythis.github.io/>

mation flow testing of HAGRID. Chapter 9 then summarizes the results of our work and reflects on some of the challenges we faced during development.

2 The HAGRID key server

HAGRID is a modern PGP key server that has been available since June 2019 under <https://keys.openpgp.org>. Initially, this project was not intended to be a full-fledged replacement of existing key servers such as SKS - available at <https://sks-keyservers.net/>) - but was created to be used as a testing tool in various experiments for a new implementation of the OpenPGP standard under the name of “Sequoia”.

Sequoia has been in development since early 2018 and is intended to be a performant and modern implementation of the OpenPGP standard written in the Rust programming language [9].

As outlined in one of the early developer blogs of Sequoia¹, concerns about the future and reliability of existing solutions like SKS and questions about how recent data protection regulations such as the GDPR would be addressed by these solutions finally lead to HAGRID evolving into a serious project aiming to provide a reliable key server implementation based on the Sequoia at its core [9].

How HAGRID avoids the mistakes of the past Besides the already mentioned concerns about the effects of recent changes in data protection laws, HAGRID also attempts to address several longstanding technical shortcomings of SKS that to this date remain largely unaddressed.

The maintainers go on addressing some of these issues. For example, it is noted that the initial choice of implementing SKS in “unidiomatic OCaml” has proven problematic as this has since then severely limited the number of maintainers willing to contribute to the project.

Further, they explain that the mental model that users may have of a PGP key server being comparable to a “telephone book” or indexable directory may oftentimes lead to confusion on the user side. This stems largely from the fact that implementations like SKS can effectively be seen as an append-only log of key updates without any process of verification [9].

Preventing certificate flooding through verification As laid out in Sequoia’s developer blog², in July of 2019 an unknown attacker was able to upload approximately 150000 signatures to the certificate of a well-known member of the OpenPGP community, therefore “poisoning” said certificate. As a result, any user that accidentally downloads one of these poisoned keys from an SKS key server will suddenly have to download a surprisingly large amount of completely useless data without any means of preventing it.

Arguably, this is the most important problem that HAGRID has set out to solve. The proposed solution lies in the fact that HAGRID is a *verifying* key server. Specifically, that means that HAGRID will only publish identifiable information that has been confirmed by the user through a specific process.

¹<https://sequoia-pgp.org/blog/2019/06/14/20190614-hagrid/>

²See footnote 1

They further explain that this also better matches the mental model of many users as described earlier.

In this case, verification is implemented as a simple challenge-response scheme, in which the server will send an email to all addresses belonging to the user IDs of some uploaded key. The user may then decide to follow the link contained within the mail, which will subsequently complete the verification process for the associated user ID. Until the server receives this final verification, it will strip the unconfirmed user ID from its associated PGP key. If the user decides at a later point, that he wants to revoke the verification of an identity, the same process has to be completed first [9].

While the developers of HAGRID recognize that this mechanism doesn't provide any kind of *strong* verification, they nonetheless argue that their solution at least prevents enough unsophisticated vandalism and spamming (such as the previously mentioned SKS spam attack in July of 2019), to justify this additional verification step.

Additionally, HAGRID is also capable of handling large PGP keys without causing a significant slowdown of the entire system. In contrast to that, alternatives such as GnuPG appear to come almost to a complete halt even for operations on unrelated keys as soon as any such flooded key has been imported into the keyring [3].

3 Information Flow Theory

The following sections give a brief introduction to the general notion of *security* in regard to the concept of information in computational systems. Building upon this, we then focus specifically on the key concepts of non-interference and declassification as they relate to the notion of information flow.

3.1 Security models and policies

Many modern computational systems will at some point have to handle certain kinds of information, which must never be accessible to an *unauthorized* entity. A popular description for a system, which keeps its information from leaking to the outside or any unintended entity/process can be found in the term of a *secure* system. In this context, “security” or “secure information flow” means, that “no unauthorized flow of information is possible” [4].

While such a general definition may be relatively easy to arrive at, actually *enforcing* the necessary constraints on the numerous information pipelines and flows within even a single program is often no easy task at all. In order to properly define which information may flow in what way within a part of a program or between programs, a common approach is to specify the individual components, between which a flow of information may occur and consequently assigning certain security *levels* to these individual constituents. This approach can for example be found in “A Lattice Model of Secure Information Flow” by Denning, in which the concept of *security classes* is introduced [4]. These classes can then be bound to any information receptacles or “objects” in order to denote their respective security clearance.

In a system with binary security classes HIGH and LOW – where HIGH denotes private information, one might for example want to verify that no flows of the kind $\text{HIGH} \rightarrow \text{LOW}$ ever occur within the system. Given that HAGRID’s definition is rather related to the interactions between different users and the system, we are more interested in an approach that takes these external actors and their varying capabilities into account.

3.2 Non-interference and Declassification

An important concept in terms of secure systems that can be operated by multiple users either simultaneously or sequentially, is the concept of *non-interference*.

One group of users, using a certain set of commands, is noninterfering with another group of users if what the first group does with those commands has no effect on what the second group of users can see.

Figure 1: High-level definition of non-interference by Goguen and Meseguer[7].

To explain this concept in terms of our problem domain of PGP servers, let us assume a running instance of HAGRID which is publicly accessible. Let us further assume that there are two users $u1$ and $u2$ that are interacting with the server at the same time. Additionally, each user holds a certain set of keys:

$$u1 := \begin{cases} k1 = \text{Key}(\text{id1}, \text{id2}) \\ k2 = \text{Key}(\text{id3}, \text{id4}) \end{cases} \quad \text{and} \quad u2 := \begin{cases} k3 = \text{Key}(\text{id5}, \text{id6}) \\ k4 = \text{Key}(\text{id7}, \text{id8}) \end{cases} \quad (1)$$

Based on this, we can imagine the following, highly simplified interaction between these two users and HAGRID:

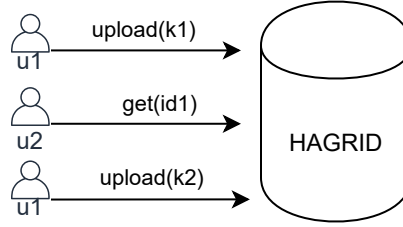


Figure 2: A non-interfering interaction

The second call of $u2$ in this sequence is a key request for identity $id1$ which belongs to the previously uploaded key $k1$. Yet, because the identity had not been verified when $u2$ issued its key request, the resulting response will be empty. That means, that the actions of $u1$ have no effect *at all* on the experience of $u2$. As a matter of fact, based on the interactions with HAGRID alone, $u2$ has no way of identifying whether there even *is* another user currently interacting with the same system. In contrast to that, let us assume that this sequence of interactions is continued in the following way:

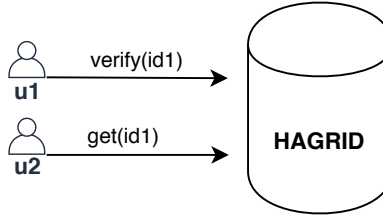


Figure 3: The interaction has become interfering

The second *get* request now yields a different response than before. Instead of an empty response, $u2$ now receives a key with an identity. This change in behaviour was caused by $u1$ issuing a verification for $id1$. Therefore, the actions of $u1$ were able to influence the sequence of interactions between $u2$ and HAGRID, which causes this interaction to no longer be *non-interfering*.

Definition of non-interference by Goguen and Meseguer A more formal definition of non-interference is given by Goguen and Meseguer in “Security Policies and Security Models”, which is also the paper that initially popularized the notion of non-interference [7]. In order to give a brief summary of their definition of non-interference, let us first introduce the central terms on which their definition relies. From here on, let Q denote some abstract system, which can be approximately modeled as some state machine $M = \{U, S, C, \text{Out}\}$. In this context, let U be a set whose elements denote the users of Q . Additionally, let S be the set of abstract states of M , while C denotes the set of “commands” that may cause a state transition in M . Finally, let Out refer to the set of all “outputs” that Q may generate. Given these foundational definitions, Goguen and Meseguer proceed to define a function p :

Given a subset G of all users U and some subset A of state altering commands C , let w be in $(U \times C)^*$. That is, w is an ordered sequence of pairs consisting of a user and an associated command.

Finally, let $p_G(w)$ be equal to w excluding any pairs (u, c) , where $u \in G$. Similarly, let $p_A(w)$ be equal to w excluding any pairs (u, c) where $c \in A$. In combination, let $p_{G,A}$ be equal to w excluding any pairs (u, c) where $u \in G$ and $c \in A$. From there, Goguen and Meseguer derive three notions of non-interference:

1. Non-interference between two sets of users: Given a state machine M and two sets of users G and G' , we let $G :| G'$ denote that G and G' are non-interfering, if and only if

$$[[w]]_u = [[p_G(w)]]_u$$

That is, they are only non-interfering if the outputs caused by w are equal to those produced by the subsequence of w excluding any element involving a user from G .

2. Non-interference between an ability A and a set of users G : Given a state machine M , we let $A :| G$ denote that A and G are non-interfering, if and only if

$$[[w]]_u = [[p_A(w)]]_u$$

That is, they are only non-interfering if the outputs caused by w are equal to those produced by the subsequence of w excluding any element involving an ability from A .

3. Non-interference between a set of users G with ability A and another set of users G' : Given a state machine M , we let $A, G :| G'$ denote that no user from G with ability A interferes with users from G' , if and only if

$$[[w]]_u = [[p_{G,A}(w)]]_u$$

That is, they are only non-interfering if the outputs caused by w are equal to those produced by the subsequence of w excluding all elements involving a user from G and ability from A .

Note that all of the definitions above describe purely *static* non-interference policies. That is, the non-interference policy must always hold and thus never allows any sets of users and abilities to interfere *at all*.

Given this definition of non-interference, it can be trivially concluded that strict enforcement of this principle would render most information systems practically unusable. To mitigate the strictness of these definitions, Goguen and Meseguer further introduce the notion of *conditional non-interference*, which encodes the notion that the definitions given above must only hold under some condition P [7]:

$$G, A :| G' \text{ if } P$$

Applied to HAGRID: Let U be the set of all users. Let $G, G' \subset U$ be two sets of users that are both accessing the same key K . Let $u \in G$ and c be the set of state altering operations provided by HAGRID (Verify, Revoke):

$$\forall u, c . \{u\}, \{c\} :| G' \text{ if not CHECK}(u, c, K),$$

where $\text{CHECK}(u, c, K)$ describes whether u can use c to affect the state of K in any meaningful way.

That is, given some key K , we guarantee that a user u does not interfere with any other user that operates on the same key as long as u lacks the ability to verify or revoke identities associated with K . In return, that also means that we explicitly permit interference by supporting declassification of formerly confidential information in such cases, where it is permissible for a user to affect the privacy state of some key K .

As Sabelfeld and Sands explain in their paper “Dimensions and principles of declassification”, the core issue therefore lies with ensuring that the release of information in these instances is actually *safe*[11]. That is, that such a system never accidentally declassifies more information than it ought to, as that would consequently also violate its non-interference policies. The main challenge that one faces when trying to *verify* whether HAGRID adheres to these policies, is that the set of theoretically visible identities is constantly changing and strongly depends on dynamic runtime values within the HAGRID system. While there exist some approaches like the one laid out in “Dependent Information Flow Types” by Lourenço and Caires, which are based on Dependent Type Theory and allow one to formulate Information Flow types that depend on runtime values, these approaches are relatively novel and unexplored [10].

In the following chapter, we instead present an approach to ensure the safe declassification of sensitive information during runtime that utilizes the notion of state machines similarly to Goguen and Meseguer. We then extend the approach in such a way, as to allow us to specify exactly what sensitive information is declassifiable (or potentially reclassifiable) by HAGRID based on history traces acting as the input to the system.

4 History based security specifications

Our approach must specifically be able to encode and evaluate *dynamically* changing privacy constraints on a certain subset of relevant information. Additionally, these pieces of information are also dynamic and constantly changing while our system under test is actively operating. This poses several challenges in regards to how we can specify these constraints over the whole body of information beforehand. Instead, we have decided to utilise a *history* based encoding scheme that takes into account the sequential nature of privacy changes over several time steps.

4.1 What constitutes a history

We rely on a central data structure, a sequential *history* of abstract events, that each encodes a high-level operation depending on the system under test. Formally, we can thus define any history h as

$$h_n = \{ev_1, ev_2, \dots, ev_n\},$$

where n denotes the size of the given history and any ev_i represents the i -th operation or *event* in the history. Given that the history itself is in no way responsible for the way in which it is interpreted, we impose no requirements on the internal structure of the event type.

4.2 Generating histories for HAGRID

Given our general definition of a history, we can now look at the content of histories that we use to test our model of HAGRID. As described in chapter 2, we want to be able to describe the process of verifying a given subset of valid identities belonging to a PGP key and similarly revoking these identities in a similar fashion. Note that these two operations, *verifying* and *revoking* identities are the central operations, that drive the dynamic declassification and reclassification of private data in our server. We therefore define 3 abstract types of events, that can be included in a history:

1. *Upload(k)* – Given some key k , this event describes the action of adding a fresh PGP key to the internal state of our server.
2. *Verify($ids, fingerprint$)* – Given a set of identities, this event describes the action of *declassifying* these formerly private identities, given that they belong to the key identified by the corresponding *fingerprint*.
3. *Revoke($ids, fingerprint$)* – Given a set of identities, this event describes the action of *reclassifying* these formerly public identities, given that they belong to the key identified by the corresponding *fingerprint*.

4.3 How to evaluate histories

Given a history of some arbitrary size, we now require a method of inspecting the sequence of events and compute the *effect* that each event in the history has on the privacy state space of our server. Specifically, our goal is to run a symbolic execution of a history, which ultimately computes the totality of valid visibility associations between keys and their identities. Note that this symbolic history execution doesn't have to match the actual execution process, because we can omit the server model as our middle man and compute the privacy state for all keys directly.

A formal description of history evaluation Evaluation of arbitrary histories can be formally approximated by a set of state machines S_i . Each state machine tracks the visibility state of its associated identity i .

To show how this formalization works, let us first look at a simpler case where we only consider histories of events that affect a single key with only one associated identity.

We can then define a state machine S which is a quintuple $(\Sigma, Q, s_0, \delta, F)$, where:

- Σ is the input alphabet given by the set $\{\text{Upload, Verify, Revoke}\}$, corresponding to our history event types.
- Q is the finite set of states $\{\Theta, U, C, R\}$.
- s_0 is the initial state of any identity, denoted as S_0 .
- δ is the state transition function, defined by the following state transitions:

$$\begin{aligned}
 \Theta &\xrightarrow{\text{Upload}} U \\
 U &\xrightarrow{\text{Verify}} C \\
 C &\xrightarrow{\text{Revoke}} R \\
 R &\xrightarrow{\text{Verify}} C
 \end{aligned} \tag{2}$$

- F is the empty set of final states.

The states of this state machine represent the privacy state after each transition, where a transition to U means that the given identity has been uploaded, yet remains undiscoverable until further state changes. The C state occurs when the given identity gets verified and therefore publicly available, whereas the R state describes the exact opposite, the given identity is private and must therefore first be re-verified to become available again.

We can now generalize this state machine to support histories containing arbitrary amounts of keys and identities. Let's consider the set of state machines

$\{S_{i,k}\}$, where all state machines share their set of states and initial state with S .

Given some event $E_{i,k}$ and some state $s \in Q$, we define $\exists s' \subseteq \delta_{i',k'}(E_{i',k'}, s)$ if, and only if $\exists S_{i',k'}. i' = i \wedge k' = k$. That is, some event $E_{i,k}$ only ever affects a single corresponding state machine $S_{i,k}$. Furthermore, it is easy to see that any event $E(t, f)$, where t is a set of identities can also be denoted as the set $E' = \{E_{t_i,f} | t_i \in t\}$. That means, that any event that affects multiple identities at once can be equivalently formulated as a sequence of the same event that each affects a single event from the original set. For the sake of consistency, we will use $\text{Upload}_{i,k}$, even though the Upload event does not specifically contain the set of identities it affects. This means, that $\text{Upload}(k)$ is equivalent to $\text{Upload}_{i,k} \mid i \in k.\text{identities}\}$.

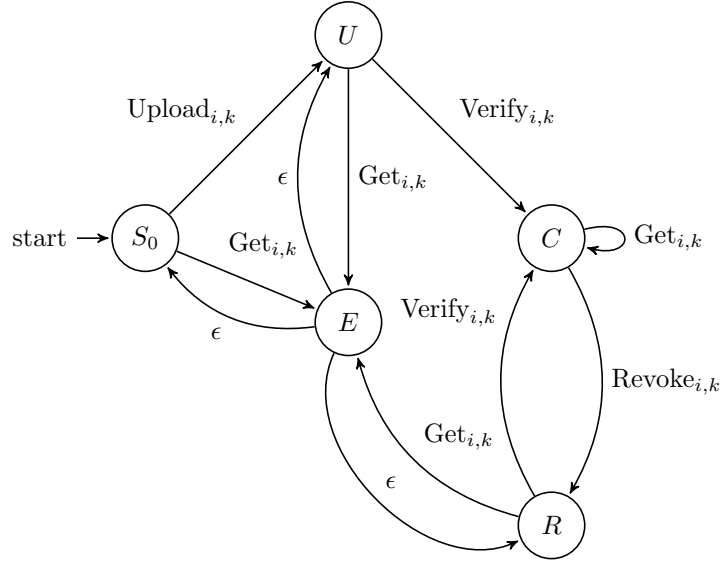


Figure 4: Visualization of a state machine over a history

In order to emphasize which states support a successful key request, we included an additional state E , which is only reachable by transitions marked with $\text{Get}_{i,k}$. We can think of E as a kind of implicit error state, which tells us, that the system encountered an attempt to retrieve a key k , while the state machine associated with k was still in a state, that made returning a key impossible.

This will only ever occur if the state machine is either in its initial state S_0 , or all state machines $t_{k,i}$ for a given k are currently in the state U . The only state that actively *supports* the retrieval of a specific identity is C .

Determining the final states produced by a history We can determine *all* relevant privacy states by simply collecting the final state of each state

machine after the history has been completely evaluated. Formally, the set of all uploaded keys can be constructed from a given history as follows:

$$U = \left\{ (i, k) \mid \text{Upload}_{i,k} \in H \right\}$$

where $\text{Upload}_{i,k} \in H \Leftrightarrow \exists x. H_x = \text{Upload}_{i,k}$. We further define the total set of all revoked and verified (**Identity**, **Key**) pairs as:

$$\begin{aligned} C &= \left\{ (i, k) \mid \begin{array}{l} \exists t, t' . H_t = \text{Upload}_{i,k}, H_{t'} = \\ \text{Verify}_{i,k}, t < t', \forall z > t'. H_z \neq \text{Revoke}_{i,k} \end{array} \right\} \\ R &= \left\{ (i, k) \mid \begin{array}{l} \exists t, t' . H_t = \text{Upload}_{i,k}, H_{t'} = \\ \text{Revoke}_{i,k}, t < t', \forall z > t'. H_z \neq \text{Verify}_{i,k} \end{array} \right\} \end{aligned} \quad (3)$$

C therefore contains all uploaded pairs (i, k) for which there exists a verification event $\text{Verify}_{i,k}$ at some point after the upload, while all revocation events $\text{Revoke}_{i,k}$ come *before* the verification. Conversely, we invert that condition for R and require all $\text{Verify}_{i,k}$ events to occur before the eventual revocation.

History evaluation against a server model Determining which associations between identities and keys are valid based on a history alone is only the first step of actually *testing* HAGRID. To complete our history-based approach, we require a way of comparing the results of the symbolic history execution to the actual server state. Only then can we determine whether the model adheres to our chosen privacy constraint.

The solution to this requirement consists of two parts in total. As a first step, we need to *execute* the history on a given server backend. In a second step, we can then collect all available data from the server and compare the results to our previously computed visibilities.

In order to visualize the execution of a history, we can look at the following example:

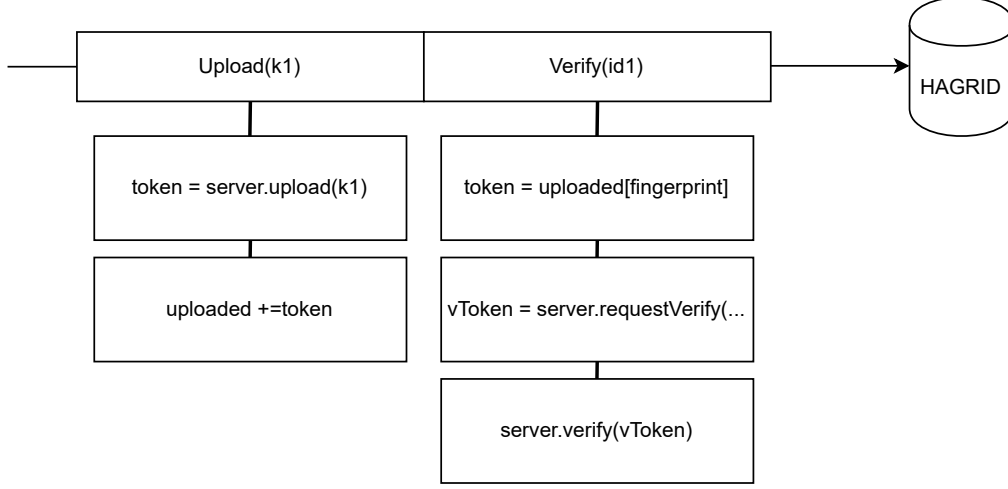


Figure 5: An example of a history execution

Notice how **Verify** abstracts over the two separate steps of *requesting* a verification and the subsequent actual verification step.

Executing the history is crucial because a mere evaluation of the history alone doesn't tell us anything about how the server actually behaves. Instead, we want to *compare* the result of our own history evaluation against the server responses.

Determining invalid associations Given that we now have an abstract model to evaluate the valid associations of keys and identities based on a history of events, we can now determine whether some HAGRID backend adheres to its privacy model. This is done by computing the *difference* between the states that were determined to be visible by our history run and those returned by the backend.

For this purpose, we further abstract over the sets U, C and R by introducing the sets **Public**, **Private** and **Revoked**, each directly representing the privacy state of their elements:

$$\begin{aligned}
 \text{Public} &= \{(i, k) \mid (i, k) \in C\} \\
 \text{Private} &= \{(i, k) \mid (i, k) \in U \wedge (i, k) \notin C \wedge (i, k) \notin R\} \\
 \text{Revoked} &= \{(i, k) \mid (i, k) \in R\}
 \end{aligned} \tag{4}$$

It should be noted that including a specific case for revoked identities would not be strictly necessary, as HAGRID returns an empty response both in the instance of **Private** and **Revoked** identities, rendering a distinction between these two states impossible from the outside. For the sake of accuracy, we still chose to include a **Revoked** category, because it can convey useful information

in the hypothetical scenario where HAGRID *does* return a non-empty response and we want to include the exact kind of mismatch in an error message.

We can now use these three sets Public, Private and Revoked and determine the set of Valid and Invalid associations between keys and identities. This is done by retrieving all accessible information from the abstract server model and comparing each entry to the computed privacy state as shown in 3. Let S be the set of all (**Identity**, **Key**) pairs, representing the total retrieved state of our abstract server model. We can then define Valid as follows:

$$\text{Valid} = \left\{ (i, k) \mid \begin{array}{l} ((i, k) \in \text{Public} \wedge (i, k) \in S) \vee \\ ((i, k) \in \text{Revoked} \wedge (i, k) \notin S) \vee \\ ((i, k) \in \text{Private} \wedge (i, k) \notin S) \end{array} \right\} \quad (5)$$

That is, for a given (**Identity**, **Key**) pair to be considered valid, it must satisfy one of three conditions:

1. The pair (i, k) is a confirmed association and is also included in the retrieved server state S
2. The pair (i, k) is a revoked association and is missing from the retrieved server state S
3. The pair (i, k) is neither revoked nor confirmed (but has been uploaded to the server) and is missing from the retrieved server state

Conversely, the definition of Invalid can be denoted as:

$$\text{Invalid} = \left\{ (i, k) \mid \begin{array}{l} (i, k) \in \text{Public} \wedge (i, k) \notin S \vee \\ (i, k) \in \text{Revoked} \wedge (i, k) \in S \vee \\ (i, k) \in \text{Private} \wedge (i, k) \in S \end{array} \right\} \quad (6)$$

Again, for a given (**Identity**, **Key**) pair to be considered invalid, it must satisfy one of three conditions:

1. The pair (i, k) is a confirmed association but has no respective entry in the retrieved server state S
2. The pair (i, k) is a revoked association but is still present in the retrieved server state S
3. The pair retrieved is neither confirmed nor revoked (but has been uploaded to the server) but is still present in the retrieved server state

Based on these two partitions of identities and keys, we can now define a general constraint that determines whether the HAGRID server model only performs valid declassifications (and reclassifications). Let H denote the set of all histories considered by a specific test instance. Let Invalid_h denote the set of invalid associations computed from some history $h \in H$. We can then express that a model of HAGRID is safe, if and only if the set of invalid associations is empty for all histories that were taken into account:

$$\forall h \in H . \text{Invalid}_h = \emptyset$$

Testing both functional correctness and privacy constraints at the same time During a presentation of our preliminary progress on the VerifyThis2020 challenge earlier this year in April, a member of one of the participating teams raised the question of how our approach handles a theoretically maximally secure HAGRID server, that never returns any key data of any kind. Such a system would achieve the highest possible protection of PGP keys because its behaviour would prevent it from ever leaking any information, private or otherwise. On the other hand, this behaviour would simultaneously render the server completely useless at its intended usage as a public PGP key server.

Given our formal approach of verifying privacy constraints as outlined in this chapter, we can strictly enforce the privacy of *unverified* identities, while simultaneously ensuring that the server correctly returns declassified data in all other cases, where the release of that information is actually permissible.

Reformulating the example runs from chapter 3.2 using state machines Looking at our previous history examples from chapter 3.2 we can see quite clearly, that our encoding of histories in terms of state machines gives us a surprisingly natural representation of our privacy states at every intermediate step of our history. Let $h_1 = \{Upload(k1), Get(id1), Upload(k2)\}$ and $h_2 = \{Upload(k1), Get(id1), Upload(k2), Verify(id1), Get(id1)\}$.

We can now visualize both history runs accordingly, by showing the respective state transitions of their state machines at each step:

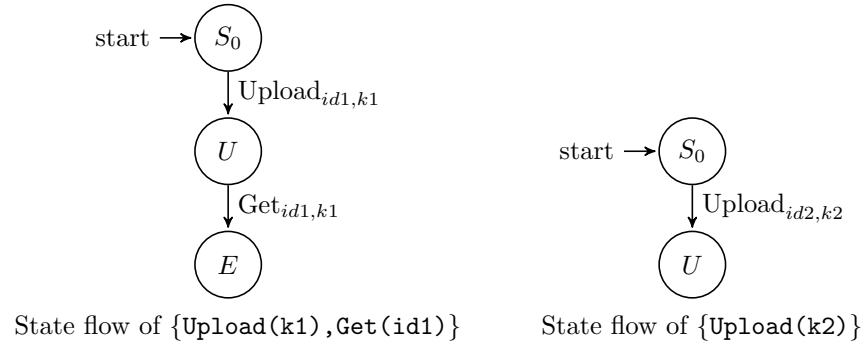


Figure 6: State flow of h_1 split up into two separate state machines

From this, we can easily determine that our set of publicly accessible information is empty for history h_1 . Looking at the following state transition graphs for h_2 we can also see quite clearly how adding an instruction like **Verify(id1)** changes that:

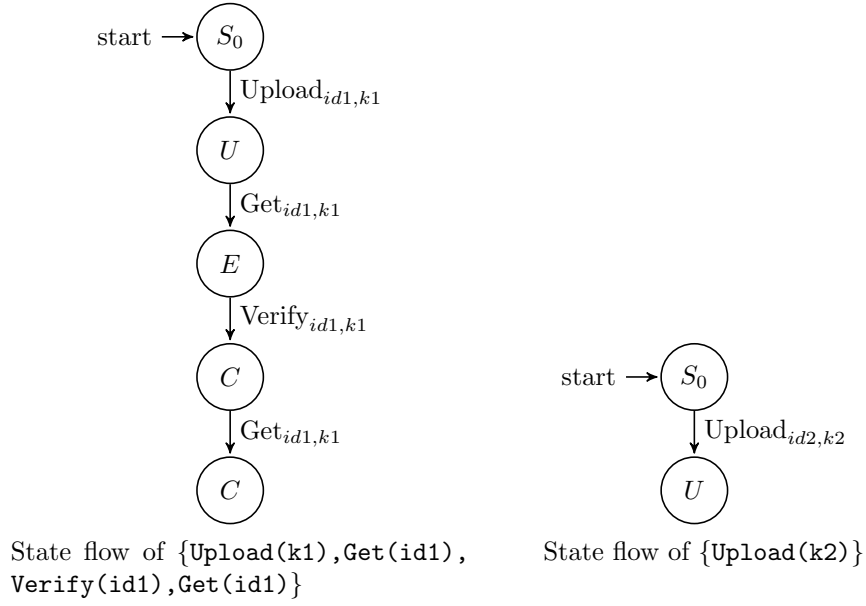


Figure 7: State flow of h_2 split up into two separate state machines

As h_2 contains a sound $\{\text{Upload}(\dots), \text{Verify}(\dots)\}$ sequence, the state machine associated with k_1 and id_1 ends in a state, that we have defined as belonging to a valid *public* state. That is, an evaluation of this history would at some point produce $(id_1, k_1) \in C$ and therefore also $(id_1, k_1) \in \text{Valid}$, assuming that the server response also included id_1, k_1 .

5 Practical implementation in Scala

The abstract server model In order to test the previously illustrated privacy constraints of PGP keys, we require a model of a PGP server which is sufficiently abstract to hide irrelevant implementation details, yet still exposes all functional specifications of the HAGRID server.

A minimal representation of a secure PGP server according to the HAGRID specifications would therefore require the following operations:

- *Request adding a key* - Request adding a new key to the database. This key may potentially contain an arbitrary amount of associated identities. The uploaded key is not made publicly available immediately after uploading. Instead, the server issues a confirmation code that may be used in subsequent confirmation requests.
- *Confirm an addition* - Confirm a previously uploaded (`Identity`, `Key`) pair given a valid confirmation code. This action does not directly confirm the selected identity but instead issues a confirmation email. The confirmation is only completed if the user uses the code contained within the email.
- *get(ByMail, ByFingerprint, ByKeyId)* - Retrieve a key from the database given some identifying index (e.g. the fingerprint of the PGP key or one of the associated identities).
- *Request a deletion* - Request the removal of some previously confirmed (`Identity`, `Key`) pair. This action does not directly delete the selected identity but instead issues a confirmation email.
- *Confirm a deletion* - Finalize the removal of some (`Identity`, `Key`) pair. This operation requires the confirmation code, which the user must have obtained from a confirmation mail issued by the previous operation.

This set of requirements allows for a relatively direct translation into an abstract base trait:

```
trait HagridInterface {  
  def upload(key: Key): Token  
  
  def byEmail(identity: Identity): Option[Key]  
  def byFingerprint(fingerprint: Fingerprint): Option[Key]  
  def byKeyId(keyId: KeyId): Iterable[Key]  
  
  def requestVerify(from: Token,  
                    emails: Set[Identity]): Seq[Body]  
  def verify(token: Token)
```

```

def requestManage(identity: Identity): Option[Email]
def revoke(token: Token,
            emails: Set[Identity])
}

```

Source Code 1: Definition of the abstract server type

The datatypes `Fingerprint` and `KeyId` represent their PGP counterparts as defined in the OpenPGP message format according to [2]. The `Identity` type serves as a simple wrapper for a string containing an email address. `Key` combines the previously mentioned types into what our server model will treat as a representation of a full PGP key.

```

trait Key {
  def keyId: KeyId
  def fingerprint: Fingerprint
  def identities: Set[Identity]
}

```

Source Code 2: Definition of the abstract Key type

Given that we only needed a high-level representation of HAGRID, our implementation does not persist internal state. Instead, the model state is simply kept as a number of maps whose elements transition between each other:

```

class Server extends HagridInterface {
  var keys: Map[Fingerprint, Key]
  var uploaded: Map[Token, Fingerprint]
  var pending: Map[Token, (Fingerprint, Identity)]
  var confirmed: Map[Identity, Fingerprint]
  var managed: Map[Token, Fingerprint]
  ...
}

```

Source Code 3: Representation of the internal server state

Changing the internal server state Any of the actions exposed by the `HagridInterface` (see definition in section 1) may modify these internal state maps. For example, we can inspect the implementation of the `upload` method:

```

def upload(key: Key): Token = {
  val fingerprint = key.fingerprint

  if (keys contains fingerprint)
    assert(keys(fingerprint) == key)

  val token = Token.unique
}

```

```

    keys += (fingerprint -> key)
    uploaded += (token -> fingerprint)
    token
  }

```

Source Code 4: Implementation of `upload()`

We can see that both the `keys` map, as well as the `uploaded` map, is being modified. Note, that once a key has been uploaded, it remains present in the corresponding map forever. Any additional modifications such as verifying or revoking an identity will then be tracked by entries in `confirmed`.

Requesting verification of an identity In contrast to simply uploading a key to the server, verifying or revoking an identity associated with some key is a two-step process. For example, the process of verifying an identity consists of an initial call to `requestVerify`:

```

def requestVerify(from: Token,
                  identities: Set[Identity]): Seq[Body] = {
  if (uploaded contains from) {
    val fingerprint = uploaded(from)
    val key = keys(fingerprint)
    if (identities subsetOf key.identities)
      identities
        .map(identity => {
          val token = Token.unique
          pending += (token -> (fingerprint, identity))
          val email = Body(fingerprint, token, identity)
          email
        })
        .toSeq
    else Nil
  } else Nil
}

```

Source Code 5: Requesting verification of a set of identities

The method first checks whether the given set of identities actually belongs to the key associated with the supplied token. Assuming that this is the case, we then proceed to generate confirmation emails for each separate identity. This sequence of emails is then returned to the caller.

In a second step, one may then proceed to call `verify`, which implements the actual verification logic:

```

def verify(token: Token) {
  if (pending contains token) {
    val (fingerprint, identity) = pending(token)
    pending -= token
  }
}

```



```

        confirmed += (identity -> fingerprint)
    }
}

```

In this case, the method expects a valid token object, which can be obtained from the mail returned by `requestVerify()`:

```

case class EMail(message: String,
                 fingerprint: Fingerprint,
                 token: Token
                )

```

Source Code 6: Abstract representation of HAGRID emails

Requesting revocation of a verified identity The process of revoking some previously verified identities follows the same pattern. First, one must issue a call to `requestManage()`:

```

def requestManage(identity: Identity): Option[EMail] = {
  if (confirmed contains identity) {
    val token = Token.unique
    val fingerprint = confirmed(identity)
    managed += (token -> fingerprint)
    val email = EMail("manage", fingerprint, token)
    return Some(email)
  }
  None
}

```

One important difference to the verification process is that revocation happens on a per-key basis. That means that we can request a revocation token for a specific identity and then use that token to revoke several identities as long as they belong to the same key:

```

def revoke(token: Token, identities: Set[Identity]) {
  if (managed contains token) {
    val fingerprint = managed(token)
    val key = keys(fingerprint)
    if (identities subsetOf key.identities) {
      confirmed -= identities
    }
  }
}

```

Filtering unverified identities from keys Keeping track of which identities are verified at any given time alone is not sufficient. Instead, we also need to ensure that no unverified identity is ever returned by our model in response to a key request.

Therefore, we introduce a method `filtered` which is responsible for excluding any unverified identity from the given key:

```
private def filtered(key: Key): Key = {
  def confirmedByFingerprint(key: Key) =
    (for ((ident, fingerprint) <-
      confirmed if key.fingerprint == fingerprint)
      yield ident).toSet

  key restrictedTo confirmedByFingerprint(key)
}
```

which subsequently calls `restrictedTo`, returning a new `PGPKey` instance containing only verified identities:

```
def restrictedTo(ids: Set[Identity]): Key = {
  assert(ids subsetOf identities)
  PGPKey(keyId, fingerprint, ids, armored)
}
```

Invariants Internally, we defined several consistency invariants to ensure that our server model always behaves correctly. Any state manipulating action exposed by the server will trigger a re-evaluation of said invariants.

1. A key is valid if its fingerprint is registered in the `keys` map.

```
for ((fingerprint, key) <- keys) {
  assert(key.fingerprint == fingerprint)
}
```

2. Upload tokens must refer to a valid fingerprint that itself refers to a valid key (see invariant 1)

```
for ((token, fingerprint) <- uploaded) {
  assert(keys contains fingerprint)
}
```

3. Pending validations must always refer to a valid key. Additionally, all pending validations must be for identity addresses that refer to the respective key.

```
for ((token, (fingerprint, identity)) <- pending) {
  assert(keys contains fingerprint)
  val key = keys(fingerprint)
  assert(key.identities contains identity)
}
```

4. All confirmed identity addresses must refer to valid keys. Additionally, all confirmed identities must be valid for the associated key.

```

for ((identity, fingerprint) <- confirmed) {
  assert(keys contains fingerprint)
  val key = keys(fingerprint)
  assert(key.identities contains identity)
}

```

5. All issued management tokens must refer to valid keys.

```

for ((token, fingerprint) <- managed) {
  assert(keys contains fingerprint)
}
}

```

5.1 Simulating actions and responses with histories

The server model itself cannot execute any concrete actions without some accompanying actor that causes this action. Generally, we wanted to express the following abstract actions in a composable way:

- *Upload some key k to the server*
- *Verify some identity i in relation to some parent key k*
- *Revoke some verified identity i from its parent key k*
- *Request some key k from the server, using one of its identifying characteristics*

Arbitrarily sized histories of events As outlined in chapter 4.3, we chose to denote the sequence of actions that should be simulated on the abstract server model through a “history” of abstract events. Through this approach, we can define a high-level model of *what* operations should be executed in a specific order while keeping the *how* - the concrete execution strategy - completely separate.

Once again, the different kinds of events are closely related to the capabilities exposed by our server model. Specifically, we recognize three distinct event types, that are modeled as subclasses of a `sealed trait Event`:

```

case class Revoke(ids: Set[Identity], fingerprint: Fingerprint)
  extends Event

case class Upload(key: Key) extends Event

case class Verify(ids: Set[Identity], fingerprint: Fingerprint)
  extends Event

```

Source Code 7: Event type implementation as defined in chapter 4.3

A complete history then simply acts as a lightweight wrapper around a buffer of `Event` objects:

```
case class History(events: mutable.Buffer[Event] = mutable.Buffer())
```

5.2 Executing a history on the server model

Given a history and the computed privacy state based on that history, we can now define a simple execution strategy that sequentially loops through the history and sends the corresponding data to the server. The signature of the execution algorithm is given by `def execute(server: HagridInterface, history: History): Unit`. The algorithm then simply pattern matches the concrete event type and based on that type, calls the corresponding server method:

```
val uploaded: mutable.Map[Fingerprint, Token] = mutable.Map()
for (event <- history.events) {
  event match {
    case Event.Upload(key) =>
      uploaded += ((key.fingerprint, server upload key))
    case Event.Revoke(identities, _) =>
      for {
        head <- identities
        token <- server requestManage head map (_.token)
      } server revoke(token, Set(head))
    case Event.Verify(identities, fingerprint) =>
      for {
        uploadToken <- uploaded.get(fingerprint)
        Body(_, token, _) <- server
          .requestVerify(uploadToken, identities)
      } server verify token
  }
}
```

Source Code 8: Sequential execution of a history

As mentioned in chapter 4.3, the history itself is completely unaware of *how* it will be interpreted. In fact, the history is intentionally abstracting over any concrete execution details like having to follow the two-step verification process of first requesting a confirmation email and then completing the actual verification.

5.3 History evaluation strategies

Given some history h we now want to determine precisely which associations between identities and keys should be visible depending on the sequence of events in h . To determine the visibility of an identity at any time, we introduce a `State` type that tags the current state of an identity throughout the evaluation of the history. The state of an identity may take any of these three forms:

- Public: The identity has been confirmed and is therefore publicly visible

- Private: The identity has not been confirmed yet and therefore remains private
- Revoked: The identity had been confirmed at some prior point but has since been revoked.

In terms of visibility, a `Private` identity and a `Revoked` identity can be considered equal from the perspective of a user. In both cases, the identity should not be included in any key requests.

In order to determine these states for every possible identity, we define a new method `def states: Map[Fingerprint, Set[(Identity, Status)]]` within `History`. The method starts off with three separate maps `Uploaded`, `Confirmed` and `Revoked`. These maps are then populated by folding over the sequence of events. Depending on the currently folded value, one or several of the maps will be updated.

```
val withUploadedAndConfirmed = confirmed.foldLeft(withUploaded) {
  (acc, elem) =>
    acc.get(elem._2) match {
      case Some(states) =>
        acc updated(elem._2,
          states - (elem._1 -> Private)
                - (elem._1 -> Revoked)
                + (elem._1 -> Public)
        )
      case _ => acc
    }
}.toMap
```

Source Code 9: Adding confirmed identities to their associated key

We sequentially fold over these maps in order to ensure that `Verify` or `Revoke` instructions that refer to non-existent or non-public keys are ignored.

In a second step, this mapping from keys to `(Identity, Status)` tuples is compared to the state of all available identities coming from the server model. To this end, we collect the total server state in a `Map[Fingerprint, Set[Identity]]`, mapping each requested key to the set of identities we received. Next, we simply compare this set of identities to the corresponding set of `(Identity, Status)` tuples which we determined earlier. The result of this comparison is encoded in a `EvalResult` type, which is a discriminated union between of the types `Ok` and `Mismatch`:

```
(state, serverState) match {
  case (None, None) => EvalResult.Ok
  case (None, Some(id)) => EvalResult.Mismatch(None, Some(id))
  case (Some((id, Private)), None) => EvalResult.Ok
  case (Some((id, Public)), None) =>
    EvalResult.Mismatch(Some((id, Public)), None)
```

```

case (Some((id, Revoked)), None) => EvalResult.Ok

case (Some((identity, Private)), Some(id)) =>
    EvalResult.Mismatch(Some((identity, Private)), Some(id))
case (Some((identity, Public)), Some(id)) => EvalResult.Ok
case (Some((identity, Revoked)), Some(id)) =>
    EvalResult.Mismatch(Some((identity, Revoked)), Some(id))
}

```

Source Code 10: Comparison between a computed state and a server state

In this case, the left side of our `Mismatch` type contains the information we computed by evaluating the history, while the right side contains the server response. For example, the case in which we determined that a given `Identity` is `Private` but was still included in the server response would be encoded in the following way: `Mismatch(Some((identity, Private)), Some(id))`

Finally, all these steps are combined in a single method `check()` which returns a `Map[Fingerprint, Map[Identity, EvalResult]]` and basically encodes the `Valid` and `Invalid` sets we introduced in chapter 4.3 using a different format.

5.4 Generating and verifying histories with ScalaCheck

In order to ensure that our dynamic testing approach covers the largest possible space of possibly valid or invalid interactions with HAGRID we were unable to rely on some handwritten (and therefore non-exhaustive) set of predetermined test cases. Instead, our goal was to be able to generate diverse kinds of histories of arbitrary length and content, which would allow us to minimize the risk of missing some obscure edge-case in the behaviour of HAGRID.

Generating test data with ScalaCheck generators We achieve this by utilizing a property-based testing approach, in which all our test cases depend on a *generator* of arbitrary histories. The basic functionality for generators is provided by ScalaCheck, which exposes an abstract type `Gen[T]` for some type `T`. This type can subsequently be used as a potentially infinite source of test data, over which we can then express some universally quantified property that this data should possess. For example, the following code encodes the property that the act of taking the square root of any integer times itself should result in the original integer value:

```

val propSqrt = forAll { (n: Int) =>
    scala.math.sqrt(n*n) == n
}

```

We can now verify whether this property holds by calling `propSqrt.check`. ScalaCheck will automatically check, whether this property holds for some sufficiently large amount of integer values, which are provided by a built-in integer

generator. The result of executing the property check will confirm to us, what we already know – namely that this property is obviously not true for any negative integer value:

```
scala> propSqrt.check
! Falsified after 2 passed tests.
> ARG_0: -1
> ARG_0_ORIGINAL: -488187735
```

Source Code 11: ScalaCheck sample output

What this output tells us, is that the first value found to falsify our property was $n = -488187735$. ScalaCheck was then able to *shrink* this failing instance down to the much simpler case of $n = -1$.

Implementing a generator for histories While ScalaCheck does provide a set of built-in generators for common datatypes such as `Int`, generators for more complex, custom types must be implemented by hand. Our history generator consists of two components: A generator for “contexts” which hold the set of available PGP keys and finally a generator for event sequences. We generate such context objects, to ensure that all events within a single history refer to a consistent set of common PGP keys and identities:

```
class Context(val keys: Map[Fingerprint, Key])

def contextGen(keySize: Int, idsPerKey: Int)
  (keyGen: Int => Gen[Key]): Gen[Context] =
  for {
    keys <- Gen.listOfN(keySize, keyGen(keySize))
    keyMap = (keys map (k => (k.fingerprint, k))).toMap
  } yield new Context(keyMap)
```

The method expects an implicit parameter `keyGen` which handles the generation of PGP keys. Adding this abstraction over the concrete key generator is beneficial because it allows us to produce histories independent from the underlying structure of the PGP keys. As we will see in chapter 6, this is particularly useful, when the requirements for PGP keys change based on whether we are testing our abstract model or the actual HAGRID implementation.

In the case of our abstract server model, the implementation of the key generator looks as follows:

```
def identityGen: Gen[Identity] =
  for (mail <- Gen.oneOf(Identity.mails))
  yield Identity(mail)

def identitySetGen(size: Int): Gen[Set[Identity]] =
  for (identities <- Gen.listOfN(size, identityGen))
  yield identities.toSet
```

```
def keyGen(idSize: Int): Gen[Key] =
  for (id <- identitySetGen(idSize)) yield Key.random(id)
```

We randomly choose a fixed number of identities from the predefined set `Identity.mails` and pass them on to `Key.random`:

```
def random(ids: Set[Identity]): Key =
  PGPKey(
    keyId = KeyId.random,
    fingerprint = Fingerprint.random,
    identities = ids,
    armored = ""
  )
```

Source Code 12: Method for generating a random PGP key

Note that the key returned by this method is not a true PGP key, as both `KeyId.random` as well as `Fingerprint.random` simply use `UUID.randomUUID()` under the hood.

In a second step, our generator produces a random sequence of events, in which all necessary key data is provided by the current context.

```
def uploadEventGen(implicit context: Context): Gen[Event] =
  for ((_, key) <- Gen.oneOf(context.keys))
    yield Event.Upload(key)

def verifyEventGen(implicit context: Context): Gen[Event] =
  for {
    (fingerprint, key) <- Gen.oneOf(context.keys)
    identities <- Gen.someOf(key.identities)
  } yield Event.Verify(identities.toSet, fingerprint)

def revokeEventGen(implicit context: Context): Gen[Event] =
  for {
    (fingerprint, key) <- Gen.oneOf(context.keys)
    identities <- Gen.someOf(key.identities)
  } yield Event.Revoke(identities.toSet, fingerprint)
```

Source Code 13: Each event type has a separate generator

Finally, we combine these separate event generators into a single generator that supports all three kinds of event types:

```
def eventGen(implicit context: Context): Gen[Event] =
  Gen.oneOf(uploadEventGen, verifyEventGen, revokeEventGen)
```


Source Code 14: Generator that randomly selects a specific event type

The complete history generator then simply combines both context and event generators and wraps the generated sequences in a `History` object.

```
def historyGen(length: Int)
  (implicit keyGen: Int => Gen[Key]): Gen[History] =
  for {
    context <- contextGen(2, 2)(keyGen)
    events <- Gen.listOfN(length, eventGen(context))
  } yield History(events.toBuffer)
```

Source Code 15: Complete history generator

Verifying generated histories Given our implementation of a generator for histories, we can translate the formal condition for the validity of a HAGRID model from chapter 4.3:

$$\forall h \in H . \text{Invalid}_h = \emptyset$$

as a ScalaCheck property:

```
property("CheckHagridValid") = forAll { gen: Gen[History] =>
  forAll(gen) { history =>
    val server = new Server
    Sequential.execute(server, history)
    val (fingerprintResult, mailResult) = history.check(server)

    val successFingerprint = mailResult.forall {
      case (_, idMap) => idMap.forall(_._2 == EvalResult.Ok)
    }
    val successMail = fingerprintResult.forall {
      case (_, idMap) => idMap.forall(_._2 == EvalResult.Ok)
    }
    successFingerprint && successMail
  }
}
```

Source Code 16: Universally quantified validity constraint over histories

The property seen in code sample 16 will only succeed if the evaluation of our history tags *all* identities with `EvalResult.Ok` values.

Note that instead of defining our property directly over an arbitrary history, we receive an instance of `Gen[History]`. This allows us to define a ScalaCheck generator that in turn produces generators of histories of different lengths:

```
val MinHistorySize = 10
val MaxHistorySize = 20
```

```

def sizedHistoryGen(implicit keyGen: Int => Gen[Key]) =
  for {
    size <- Gen.choose(MinHistorySize, MaxHistorySize)
  } yield randomHistory(size)

```

Source Code 17: Nested generator for histories of different sizes

This extra step of indirection thus allows us to check our privacy constraint over histories of different event sequences as well as different sizes.

Ensuring that invalid server behaviour is recognised In order to verify that this property is capable of detecting invalid behaviour on the server-side, we define a second property:

```

property("CheckHagridInvalid") = forAll { gen: Gen[History] =>
  forAll(gen) { history =>
    val server = new ServerOld
    Sequential.execute(server, history)
    val (fingerprintResult, mailResult) = history.check(server)

    val successFingerprint = mailResult.forall {
      case (_, idMap) => idMap.forall(_._2 == EvalResult.Ok)
    }
    val successMail = fingerprintResult.forall {
      case (_, idMap) => idMap.forall(_._2 == EvalResult.Ok)
    }
    successFingerprint && successMail
  }
}

```

Source Code 18: Property that tests a faulty server implementation

In this case, we create an instance of the type `ServerOld`, which behaves the same way as the standard server implementation, except that it does not filter the identities of its keys. As seen later on in chapter 7, this property reliably recognizes the release of private identities.

6 Testing the real-world implementation of HAGRID

Given that we have successfully developed a framework in which we can test our abstract model of HAGRID, we decided to integrate the official implementation of HAGRID into our testing efforts. Assuming that the maintainers of HAGRID would likely not appreciate it if their server received hundreds of spam-like calls to their server at <https://keys.openpgp.org/>, running our tests requires a separate instance of HAGRID to be running on the local machine.

Communicating with HAGRID The main effort of integrating HAGRID into our implementation focussed on the relaying and receiving of messages between our Scala frontend and HAGRID. To this end, we use *Sttp*³, which is a simple library that enables us to communicate with the server through REST-full HTTP calls. The transferred data is being encoded as *JSON*, for which we rely on *Circe*⁴ as a dependency. HAGRID itself defines a specific interface, through which external applications may communicate with the PGP server. This interface, called *Verifying Keyserver (VKS) Interface*⁵, exposes the following endpoints:

- GET /vks/v1/by-fingerprint/FINGERPRINT
- GET /vks/v1/by-keyid/KEY-ID
- GET /vks/v1/by-email/URI-ENCODED EMAIL-ADDRESS
- POST /vks/v1/upload
- POST /vks/v1/request-verify

Figure 8: HTTP endpoints defined by HAGRID

In contrast to our abstract server model outlined in chapter 5, this implementation does not maintain any local state on its own. Instead, we define a new implementation of `HagridInterface` which simply relays all method calls to HAGRID via HTTP. As an example, let's look at the `upload` method:

```
override def upload(key: Key): Token = {  
  val response = basicRequest  
    .post(hag("/vks/v1/upload"))  
    .body(UploadBody(key.armor))  
    .response(asJson[UploadResponse])  
    .send()  
}
```

³<https://sttp.softwaremill.com/en/latest/>

⁴<https://circe.github.io/circe/>

⁵<https://keys.openpgp.org/about/api>

```

        .body

    Token(response.toOption.get.token)
  }

```

Source Code 19: Uploading a PGP key to the real HAGRID server

First, we construct a *POST*-Request which targets the *VKS* endpoint responsible for uploading PGP keys. We then attach the *armored* key-text as the request body and finally instruct the request to encode any eventual response as an instance of `UploadResponse`. The most crucial bit of information included in the `UploadResponse` is the token which we require in order to send any verification requests at a later point.

Note that our implementation at this moment does not have any robust error handling mechanism and this generally *ignores* the possibility of an error occurring while communicating with HAGRID. We are aware that this may cause unforeseen problems in some edge-cases, like the local HAGRID instance suddenly crashing.

6.1 Receiving verification mails from HAGRID

While we were able to simulate the transmission of verification mails in an abstract way for our server model, we had no such option when dealing with the real-world HAGRID server. During the earlier development phases, we assumed that we would be forced to provide a dummy implementation of `sendmail`, as the documentation claimed that HAGRID would require a working `sendmail` configuration to be available in the environment in order to send and receive emails. Luckily, we discovered that HAGRID also provides an alternative mode of operation in which all email transfer is handled directly through the filesystem. HAGRID uses a configuration file called `Rocket.toml`, which allows us to specify a folder to be used as the destination for all outgoing HAGRID emails. Modifying the configuration file by adding the line `mail_folder=/PATH/TO/DESTINATION` therefore causes HAGRID to write all emails to a unique file in the specified folder.

This allows us to simply observe the given directory and react to any file modifications within the folder. More specifically, we define a method that blocks its execution until it has successfully read the expected amount of emails:

```

def consumeMail(expectedSize: Int): Seq[Body] = {
  val watchKey = mailWatcher.take
  val events = watchKey.pollEvents.asScala
  val updatePaths = events
    .take(expectedSize)
    .map(_.asInstanceOf[WatchEvent[Path]])
    .map(_.context())
}

```

```

    val mails = updatePaths.flatMap { currentPath =>
      val resolved = mailPath.resolve(currentPath).toFile
      val source = Source.fromFile(resolved)
      val bodies: Seq[Body] = parseMail(source.mkString)
      source.close
      resolved.delete
      val isValid = watchKey.reset
      bodies
    }
    mails
  }
}

```

Source Code 20: Reading HAGRID's emails by observing filesystem changes
 where the returned sequence of mail bodies takes the form of:

```

case class Body(
  fingerprint: Fingerprint,
  token: Token,
  identity: Identity
)

```

Based on this helper method, we can implement `requestVerify`, which sends a verification request and waits for a corresponding verification email:

```

def requestVerify(from: Token, emails: Set[PgpIdentity]) = {
  if (emails.isEmpty) return Seq.empty
  val response = basicRequest
    .post(hag("/vks/v1/request-verify"))
    .body(VerifyRequest(from.uuid,
      emails.map(_.email).toList)
    ).send()
    .body.toOption

  val shouldReadMail = checkResponse(
    emails.map(_.email),
    response)

  (response, shouldReadMail) match {
    case (Some(x), true) => consumeMail(emails.size)
    case _ => Seq.empty
  }
}

```

Source Code 21: Requesting verification of a set of identities

As one can see, we make use of a helper method `checkResponse` which parses the server response and checks whether our verification request has had

any effect. This is important because HAGRID will ignore requests for verification of already verified identities and will thus skip the process of sending an additional verification email. If we simply ignored this, `consumeMail` would wait indefinitely for a corresponding email that will never be sent.

Finally, the process of revoking an identity follows the same order of steps:

```
def requestManage(identity: PgpIdentity): Option[EMail] =
  for {
    _ <- basicRequest
      .post(hag("/manage"))
      .body(Map("search_term" -> identity.email))
      .send()
      .body
      .toOption

    mail <- consumeMail(1)
      .headOption
      .map {
        case Body(fingerprint, token, identity) =>
          EMail("", fingerprint, token)
      }

  } yield mail
```

Source Code 22: Requesting the revocation of an identity

Once again, we can then use the token contained within the returned email object for a subsequent call to `revoke()`.

Parsing plain text confirmation mails To consume the emails within the selected directory and use the information contained within them, we had to parse the plain text content of said emails and extract the relevant information. In both cases of identity confirmation or revocation, these relevant bits of data would be the `Fingerprint`, the `Token` and the respective `Identity` for which the email was issued. For example, a typical email issued by HAGRID in response to a confirmation request might look like this:

To: <EMAIL@ADDRESS>
Hi,

Dies ist eine automatische Nachricht von localhost.
Falls dies unerwartet ist, bitte die Nachricht ignorieren.

OpenPGP Schlüssel: 23B2E0C54487F50AC59134C3A1EC9765D7B25C5A
Damit der Schlüssel über die Email-Adresse "<EMAIL@ADDRESS>"
gefunden werden kann, klicke den folgenden Link:

<http://localhost:8080/verify/vrTohvV8q552KMvARBE7foqkvGtUrf>

Weitere Informationen findest du unter:
<http://localhost:8080/about>

Figure 9: Automatically generated verification email by HAGRID

We use a regular expression to parse the relevant information from these mails. This functionality is summarized in a method `parseMail`:

```
val VERIFY_PATTERN: Regex =
  """(?:s).*To: <(\S+)>.*OpenPGP key: ||
  |(\S+).*http://localhost:8080/verify/(\S+).*
  |<!doctype html>.*""".stripMargin.r

def parseMail(mail: String): Seq[Body] =
  decode[HagridMail](mail)
    .map(mail => new String(mail.message))
    .map {
      case REVOKE_PATTERN(identity, fingerprint, token) =>
        Body(FingerprintImpl(fingerprint),
              Token(token),
              PgpIdentity(identity)
            )
      case VERIFY_PATTERN(identity, fingerprint, token) =>
        Body(FingerprintImpl(fingerprint),
              Token(token),
              PgpIdentity(identity)
            )
    }
    .toSeq
```

Source Code 23: Parsing relevant information from HAGRID emails

As seen in code sample 20, this function is responsible for parsing the mails read by `consumeMail` from the dedicated mail directory.

6.2 Generating valid PGP keys

In the context of our abstract HAGRID model we were able to rely on a simplified implementation of our PGP `Key` type:

```
sealed trait Key {  
  def armored: String  
  def keyId: KeyId  
  def fingerprint: Fingerprint  
  def identities: Set[Identity]  
  def restrictedTo(ids: Set[Identity]): Key  
}
```

For example, we would represent `KeyId` or `Fingerprint` values as simple `UUID` instances. This allowed us to work with values that were unlikely to collide with each other while keeping the implementation relatively simple:

```
sealed trait KeyId {  
  def value: String  
}  
case class KeyIdImpl(id: String) extends KeyId {  
  def value: String = id  
}  
object KeyId {  
  def random: KeyId = KeyIdImpl(UUID.randomUUID().toString)  
}
```

When communicating with the actual HAGRID implementation, that solution is obviously insufficient because HAGRID verifies all incoming PGP keys for proper formatting and structure. To solve this problem, we decided to implement a mechanism capable of generating valid PGP keys. For this purpose, we use *BouncyCastle*⁶, which is a Java library for cryptographic use cases.

We define a new method that expects a set of identities and returns a tuple consisting of the BouncyCastle encoding of a public key and a string containing the armored key text:

```
def genPublicKey(identities: Set[Identity]): (PGPPublicKey, String)
```

Building upon this method, we can now define a new convenience method for constructing valid PGP keys given a set of identities:

```
def pgp(ids: Set[Identity]): Key = {  
  val (pgpKey, armored) = KeyGenerator.genPublicKey(ids)  
  
  PGPKey(  
    keyId = KeyIdImpl(pgpKey.getKeyID.toString),  
    fingerprint = FingerprintImpl(  

```

⁶<https://www.bouncycastle.org/>


```

        convertBytesToHex(
            pgpKey.getFingerprint
        ).toUpperCase),
        identities = ids,
        armored = armored
    )
}

```

It should be noted though that we currently do not support the generation of keys with arbitrary amounts of identities. This is due to several unsolved problems which we encountered during development. In the end, these hurdles led to the decision that temporarily supporting a maximum amount of only *two* identities is acceptable. This restriction is currently implemented in the generator types mentioned in chapter 5.4 which limit the amount of identities per key to a maximum value of two.

Even with this restriction in place, running our ScalaCheck tests with a key generator that relies on this method incurs a noticeable performance penalty, with an average run time of roughly 8 minutes per standard test run.

Running tests against a local HAGRID instance Given that our test approach outlined in chapter 5.4 is fully agnostic towards the underlying server implementation, adding support for HAGRID only required us to adhere to the API contract given by [HagridInterface](#).

6.3 Initializing

One major challenge that we faced when trying to incorporate the actual HAGRID implementation in our testing approach was the fact that HAGRID maintains internal state across several distinct instances. This is due to HAGRID persisting uploaded keys and their contents within its installation folder. In contrast to this, our high-level model of HAGRID maintains no state at all between any two separate test runs.

This is problematic because our testing approach fundamentally relies on a limited amount of *Identities* that are subsequently used to construct PGP Keys. This would necessarily lead to unexpected results when applying our approach to HAGRID, where there could potentially already be an identity associated to some PGP key that was uploaded during a previous testing session. To elaborate on this problem, let us assume these two separate test runs in pseudo-code:

Assuming that there exists a value `key1 = Key(identity1,identity2)` and a value `key2 = Key(identity3,identity4)` where all arguments to the `Key` constructor are instances of `Identity` with an arbitrary email address, we can define the following two test runs:

Looking *only* at test run 2, we would expect an outcome in which the server returns no public identities at all. Instead, when we actually execute these two runs in sequential order, we receive a PGP key when querying the server with `identity1` even though we *never* uploaded it during the second test. Any

```
upload(key1)
verify(identity1)
```

Test run 1

```
verify(identity1)
upload(key2)
```

Test run 2

solution to this problem therefore requires us to reset the internal state of HAGRID after having completed a test. This in turn also imposes an additional non-trivial performance penalty on the execution speed of our ScalaCheck test, besides the slowdown caused by having to generate real PGP keys. For our current solution to this problem, we decided to compile HAGRID into a static image. This allows us to create a fresh instance of HAGRID at the beginning of each test iteration and shutting it down afterward, at which point we simply clear the local directory of PGP keys. This ensures that each test run starts on a truly equal playing field.

7 Results

Our tests involving the abstract HAGRID model were able to show that our implementation appears to conform to our privacy specifications. In all instances, our history evaluation would finish successfully:

```
+ History execution.HistorySecure: OK, passed 10000 tests.
```

Source Code 24: Output of a successful test run with 10000 generated histories

Conversely, if we replace our correct model with an invalid one that does not filter unverified identities from keys, we will still be able to consistently detect this incorrect behaviour. For example, this is the output generated by one of our test runs, utilizing an incorrect server model:

```
[info] > ARG_1: History(  
  Upload(  
    PGPKKey(KeyIdImpl(54ce7607-...),  
      FingerprintImpl(65a7d3b4-...),  
      Set(Identity(ilyaz@comcast.net),  
        Identity(ranasta@live.com))  
    )),  
  Upload(  
    PGPKKey(KeyIdImpl(cf2a181c-...),  
      FingerprintImpl(713bf494-...),  
      Set(Identity(crowl@verizon.net),  
        Identity(wonderkid@yahoo.com))  
    )),  
  Revoke(  
    Set(),  
    FingerprintImpl(713bf494-...) )  
)
```

Source Code 25: Generated history of a failing test run

As we can see, our generated history consists of two **Upload** events and a single **Revoke** event. Given that the last **Revoke** event is effectively empty and no identities have been verified, we would expect all identities to be **Private**. Instead, our test evaluation shows us the following:

```
Map (  
  FingerprintImpl(713bf494-...) -> Map (  
    Identity(crowl@verizon.net) ->  
      Mismatch(  
        Some((Identity(crowl@verizon.net),Private)),  
        Some(Identity(crowl@verizon.net))  
      )  
  )  
)
```

```

        Identity(wonderkid@yahoo.com) ->
            Mismatch(
                Some((Identity(wonderkid@yahoo.com),Private)),
                Some(Identity(wonderkid@yahoo.com))
            )
    )
FingerprintImpl(65a7d3b4-...) -> Map (
    Identity(ilyaz@comcast.net) ->
        Mismatch(
            Some((Identity(ilyaz@comcast.net),Private)),
            Some(Identity(ilyaz@comcast.net))
        )
    Identity(ranasta@live.com) ->
        Mismatch(
            Some((Identity(ranasta@live.com),Private)),
            Some(Identity(ranasta@live.com))
        )
)
)

```

Source Code 26: Evaluation of a failed history run

Indeed, our test has determined that our model of HAGRID has erroneously leaked *all* identities of *all* keys, even though they should have been **Private**.

Results of our tests involving an actual HAGRID instance Perhaps unsurprisingly, we were not able to find any identity leaks when testing the real HAGRID implementation. Instead, every test we ran on HAGRID confirmed that the implementation does indeed conform to its claimed privacy constraints. In fact, the only encounters with failing test results were caused by a number of subtle bugs in the way we communicated with HAGRID, such as the fact that HAGRID doesn't send duplicate verification mails for already verified identities.

8 Related Work

Within the context of the VerifyThis2020 challenge, several approaches have been introduced that all aim at verifying certain properties of HAGRID. For example, several teams were able to implement simplified models of HAGRID and verify the functional correctness of their implementation. In this context, functional correctness means, that the given model was shown to adhere to the specification of HAGRID given by the challenge creators.

For example, Gouw, Ulbrich, and Weigl were able to verify that operations which require a confirmation token such as requesting the verification of an identity were invoked with the *correct* confirmation token. Furthermore, by using a program verification engine called “KeY”, they were able to guarantee both the “absence of runtime exceptions and a guaranteed termination of each request handler” [8].

Conversely, the submission by Ernst, Murray, and Tiwari focussed on verifying similar information flow policies as the one explored in this thesis. Yet, instead of relying on runtime tests, their approach is based on the verifier SecC, which “automates program reasoning in the Hoare style logic Security Concurrent Separation Logic (SecCSL)” [5]. Therefore, this approach is capable of verifying the chosen information flow policies by proofing that their abstract model adheres to them instead of relying on the execution of runtime tests.

In regards to the dynamic declassification policy that we discussed in this thesis, there exist some further approaches that are capable of a more rigid verification than we were able to achieve. For example, we mentioned the approach of Lourenço and Caires which is based on Dependent Type Theory [10]. Therefore, their approach is theoretically capable of enforcing value-dependent policies such as the one outlined in chapter 4.3 on the type level.

In contrast to that, Austin and Flanagan outline a fully dynamic encoding of information flow policies in “Efficient purely-dynamic information flow analysis” [1]. They achieve this by utilizing a dynamic type system, therefore giving up the advantages of static analysis in return for being able to encode dynamically changing policies on the language level.

9 Conclusion

In this thesis, we have given a tailored approach to testing save declassification policies pertaining to the HAGRID system. We achieved this by introducing the notion of history traces which give us the ability to directly determine the set of public information. As evidenced by chapter 7, this technique is not only capable of delivering practical results, but also relatively easy to implement.

As an interesting side note, one might mention that our initial testing efforts were not based on these histories of events. Instead, we attempted to describe all interactions both on the server-side and the user-side as a system of stateful *actors*, communicating with each other through a set of channels. While we made some initial progress under that approach, we were unable to find a satisfactory solution to the problem of encoding abstract test cases without quite literally enumerating the exact sequence of actors *and* messages between them. Additionally, we lacked a clear formalization of *what* these test cases were trying to verify in the first place.

In the end, our history-based approach turned out to be a much more expressive tool, allowing us to set aside specific implementation details up to the point of execution on the server, as well as giving us a scalable method for determining declassifiable information independent of the size of underlying interaction sequence.

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