Making Distributed Mobile Applications SAFE: Enforcing User Privacy Policies on Untrusted Applications with Secure Application Flow Enforcement

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Abstract

Today's mobile devices sense, collect, and store huge amounts of personal information, which users share with family and friends through a wide range of applications. Once users give applications access to their data, they must implicitly trust that the apps correctly maintain data privacy. As we know from both experience and all-too-frequent press articles, that trust is often misplaced.

While users do not trust applications, they do trust their mobile devices and operating systems. Unfortunately, sharing applications are not limited to mobile clients but must also run on cloud services to share data between users. In this paper, we leverage the trust that users have in their mobile OSes to vet cloud services.

To do so, we define a new *Secure Application Flow Enforcement* (SAFE) framework, which requires cloud services to attest to a system stack that will enforce policies provided by the mobile OS for user data. We implement a mobile OS that enforces SAFE policies on unmodified mobile apps and two systems for enforcing policies on untrusted cloud services. Using these prototypes, we demonstrate that it is possible to enforce existing user privacy policies on unmodified applications.

1 Introduction

Sharing is the hallmark of applications in the mobile era. Mobile devices constantly collect information about their users (e.g., their location, photos, etc.) and supply it to applications, which then share this personal data with other users distributed over many mobile devices. This data ranges from the mundane to the highly sensitive, making protecting its privacy a critical challenge for modern applications.

Mobile operating systems let users restrict application access to the sensitive data on their devices (e.g., through the Android Manifest [26] or iOS privacy settings [6]). However, once an app has access, users must trust the app to ensure their privacy. Almost all apps offer their users a choice of privacy policies; unfortunately, they frequently violate these policies due to bugs [11, 37, 60] or other reasons [22, 28, 44].

While mobile OSes are effective at enforcing user privacy policies, that enforcement does not extend to application backends and other cloud services that sharing applications rely on to move data between device. Researchers have proposed distributed cloud platforms, but they only support some application features [36, 50], require application modification [14, 25, 43] or have complex user policies [61, 70]. As a result, users are left to blindly trust that applications will respect their privacy even as the apps move their data across a complex landscape of backend servers, storage systems and cloud services.

This paper offers a practical alternative for users. Unlike existing systems, we aim to enforce *existing privacy policies on unmodified and untrusted sharing applications* across mobile devices and cloud services. We achieve this goal with a key insight: while mobile OSes cannot enforce policies on cloud services, the OS can vet cloud services on behalf of users and ensure that a cloud service will respect a user's policies before handing over a user's data.

We introduce a new *Secure Application Flow Enforcement* (SAFE) framework for vetting systems that handle user data. The framework defines a single guarantee: *Given a piece of user data and a* SAFE *flow policy for that data, the system must ensure that it will only release that data and any data derived from that data to: (1) another* SAFE *system or (2) an un-*SAFE *system allowed by the* SAFE *flow policy.* SAFE flow policies, detailed in Section 2, are access-control lists (ACLs) consisting of users and groups that reflect existing policies already set by users.

The SAFE guarantee can be applied to any software that handles user data, including systems, cloud services and user-facing applications. However, it is clearly not practical to modify all applications to meet the guarantee. Instead, we rely on SAFE *enforcement systems*, trusted systems that ensure untrusted and unmodified applications meet the SAFE guarantee. As a consequence, apps running atop a SAFE enforcement system can be deemed SAFE *apps*.

With this framework, users can begin by running a SAFE *enforcement operating system* on their mobile devices. Then, they can trust the SAFE OS – and any untrusted apps running on it – to give sensitive user data to either another SAFE system and application or another user allowed within the SAFE policy. SAFE OSes vet untrusted application backends and cloud services by using TPM-based attestation to verify that the cloud server is running a trusted systems stack, including a trusted SAFE enforcement system. Once verified, the user's mobile OS can safely send sensitive user data and be certain that the SAFE guarantee will be upheld by the SAFE enforcement system and untrusted applications running on top.

The SAFE guarantee is incredibly powerful: if a user gives a piece of data to a SAFE enforcement system along with a SAFE policy, the user can trust that the policy will be enforced no matter where the data flows until it is released to another user allowed by the policy. In other words, the SAFE framework lets users construct a chain of trust from their mobile OS to an arbitrary set of cloud services to other users' devices. Furthermore, users do not need to understand which cloud services their applications use, only to trust that the services are verified SAFE. In fact, users do not even need to understand the SAFE concept, provided that they trust their mobile OSes to be SAFE and to correctly verify that other systems that handle their data are SAFE as well.

The remainder of this paper describes the SAFE framework (§2) and the design and implementation of three SAFE enforcement systems:

- *Agate*, a SAFE mobile OS that securely collects user policies, enforces them on untrusted mobile apps and translates them to SAFE policies for SAFE cloud services (§3).
- *Magma*, a SAFE distributed cloud runtime system that enforces SAFE policies on untrusted cloud backends using fine-grained information flow control (§ 4).
- *Geode*, a SAFE proxy that enforces SAFE policies on untrusted storage systems which do not manipulate user data. (§ 5).

Using these three systems, we demonstrate that it is possible to enforce user policies end-to-end on unmodified distributed mobile apps largely without changing the user experience. We do so for several existing applications, including a 70,000-line calendar application and a 250,000-line chat application. Furthermore, we show that the SAFE policy model supports a range of existing user policies and that systems can implement SAFE policy enforcement with little user-noticeable overhead (≈20% on a mobile device).

2 The SAFE Framework

This section summarizes the SAFE framework, including the system model and concepts, the policy model and the threat model. We had three goals when designing the framework: (1) minimize changes to user experience, (2) minimize changes to application code, and (3) minimize performance cost. This section reviews the ways in which the SAFE design meets these goals.

2.1 SAFE System Model and Concepts

Figure 1 shows the SAFE system model. A SAFE *application* consists of processes distributed across mobile devices (i.e., mobile app clients) and cloud servers (i.e., cloud app backends) as well as cloud services used by the application (e.g., distributed storage [23, 51]). Some of the data that a SAFE application handles will have attached SAFE policies, while other data does not. We assume mobile devices are owned by users, while cloud servers are operated either by the application provider (e.g., Twitter, Facebook) or by a third-party cloud provider (e.g., Amazon). The application runs on one or more mobile OS platforms and one or more cloud platforms.

2.1.1 SAFE User Service

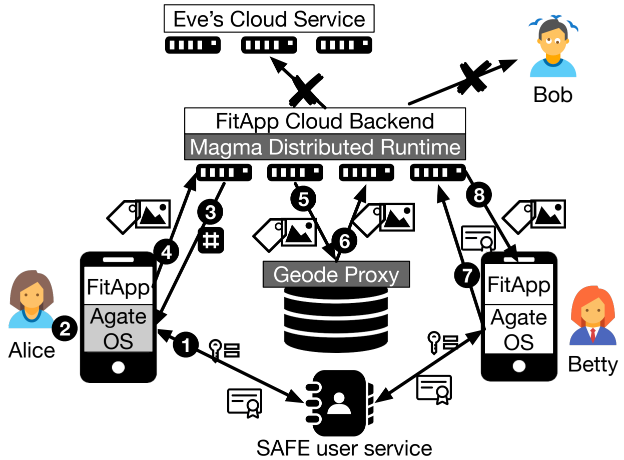
Each SAFE deployment instance, called an *ecosystem*, is defined by a centralized, trusted user management service. The SAFE *user service* is shown in the bottom of Figure 1. The SAFE user service has two roles: (1) securely managing the principals used to express SAFE policies, including group membership management, and (2) verifying app and user identities to authorize the release of data to an untrusted device. The SAFE user service gives every application, user and group a unique identifier and stores a mapping between names and ids. It also authenticates users, issues certificates to untrusted devices to authorize them to access data on behalf of users and manages group membership.

Any trusted entity can launch a SAFE user service and ecosystem to support one or more applications. Apps within an ecosystem can easily exchange data and policies (if allowed by the SAFE policy) because they share the same SAFE user service and its principals. Apps outside an ecosystem must negotiate a way to translate SAFE policies when exchanging data.

The SAFE user service is not SAFE-specific; there are many existing single-sign-on (SSO) services that could be used to implement the same functionality (e.g., Google Accounts [27], OpenID [46]). The only requirement is that the service be able to authenticate users, issue certificates and manage group membership. For trust reasons, we assume that the SAFE user service is implemented and deployed by an entity separate from the application provider; otherwise, we would have to trust the application to manage users, which many fail at [34, 37]. As an example, Google could create its own ecosystem for Google apps by deploying a SAFE user service or using Google Accounts.

2.1.2 SAFE Mobile Operating Systems

Users run a SAFE *enforcement OS* on their mobile devices to ensure that user policies are securely captured, enforced on



1. Alice logs in to Agate to access FitApp
2. Alice sets a policy in Agate to share her photos with Betty through FitApp
3. Agate verifies that the FitApp cloud backend is a SAFE service (it attests to running Magma)
4. Agate allows the FitApp mobile client to send Alice's photo to the FitApp cloud backend
5. Magma allows FitApp to store Alice's photo because the storage system attests to running the Geode Proxy
6. Geode releases Alice's photo back to FitApp backend
7. FitApp wants to send Alice's photo to Betty's phone, so Magma requests app and user certificates from Agate and checks the photo's SAFE policy
8. Magma allows FitApp to send Alice's photo to Betty's phone

Figure 1: **Example SAFE ecosystem.** We show the steps for Alice to share her photos with Betty securely through the SAFE framework. We color the systems based on Alice's trust in them; she trusts her SAFE Agate OS running on her phone (light gray), she trusts her Agate to verify (using attestation) that the (dark gray) cloud systems are SAFE, and she does not trust the white apps or systems. Magma will not let FitApp send Alice's photo to Eve's cloud service because it is not an attested SAFE cloud service. Likewise, Magma ensures that FitApp cannot share Alice's photo with Bob because Bob is not in Alice's SAFE policy.

untrusted mobile apps and expressed to SAFE cloud services. The SAFE OS also verifies cloud services as being SAFE before allowing apps to send sensitive user data. This paper describes the design of the Agate SAFE OS (shown on Alice and Betty's phones in Figure 1), but we imagine that other SAFE OSes would exist.

Before running SAFE apps, users must login to the SAFE mobile OS, which authenticates the user with the SAFE user service. The SAFE user service issues a user certificate to the SAFE OS, which authorizes it to collect data and policies on behalf of the logged-in user and hold data shared with that user. We assume that users trust any SAFE OS that they are willing to log in to. Thus, for a SAFE system to release data to an untrusted device (e.g., belonging to Alice's friend Betty), the SAFE OS on the device must present a certificate belonging to a user that is authorized to access the data (e.g., through a SAFE policy).

2.1.3 SAFE Cloud Enforcement Systems

SAFE OSes can pass sensitive user data to trusted SAFE cloud services because the OS can rely on the cloud service to respect the user's policies. However, we do not expect programmers to modify all cloud services to meet the SAFE guarantee, so we rely on SAFE enforcement systems to ensure that untrusted cloud services meet the guarantee. This paper describes two SAFE cloud enforcement systems, *Magma* and *Geode*.

Magma is a distributed cloud runtime for application backends; Figure 1 shows it running the FitApp backend. Magma enforces the SAFE requirement using fine-grained, dynamic information flow control to track and control the flow of SAFE data through unmodified application code. Geode, shown as the storage layer in Figure 1, is a storage proxy for storage systems that do not modify application data. It enforces the SAFE requirement on untrusted key-value stores (e.g., memcached [23], Redis [51]) by interposing on storage accesses and encrypting and checksumming data. While we believe that these systems meet the needs of many applications, we envision the potential for other SAFE enforcement systems, including ones using existing IFC systems [25, 59], sandboxing systems [35, 36] or computation over encrypted data [49, 50].

2.1.4 SAFE Verification and Attestation

SAFE enforcement systems make it easier for SAFE OSes to verify that cloud services are SAFE. Rather than simply keeping a list of SAFE cloud services, cloud services *demonstrate* that they are SAFE by attesting, using trusted platform modules (TPMs), that they are running a trusted systems stack including a SAFE enforcement system. We do not innovate here; this could be achieved using a secure bootloader [7, 58], a trusted hypervisor [24], or a secure enclave mechanism [8].

The trusted hardware component measures all of the software that makes up the platform up to and including the SAFE enforcement system and produces a signed hash summarizing this software stack. The SAFE OS validates this hash against a list of SAFE software platforms. We imagine that these hashes could be provided by the mobile OS vendor (much as OS and browser vendors maintain lists of trusted SSL CAs today) or a trusted third party. Note that it is practical for OS vendors to distribute these hashes because we assume a limited number of trusted system stacks and SAFE enforcement systems; however, a trusted cloud service could also do so.

As alternative (e.g., if trusted attestation hardware is not available or a cloud vendor prefers not to reveal its deployment), the SAFE architecture can be used by having the OS vendors (or a trusted third party) validate cloud platforms. Then, these platforms (e.g., Amazon Lambda [5] or S3 [4]) would be trusted axiomatically to enforce the SAFE property. The OS vendor would simply issue them a signed certificate that the cloud provider stores and presents to mobile OS clients. Obviously, this is a less secure option than attestation because it requires trusting the cloud providers to correctly run a trusted SAFE enforcement system and would not work for application providers that provide their own infrastructure. However, we offer the alternative because many applications today run on a third-party cloud provider platform which has other strong incentives to enforce user privacy guarantees.

2.2 SAFE Policies

SAFE policies are flow policies expressed as access control lists including *users*, *groups*, and *applications*. A SAFE policy encodes: (1) the app that can access the data, and (2) the list of apps, users and groups with which the app can share that data and any data derived from it. For example, Alice can set a policy allowing her fitness app (FitApp) to share her GPS location only with Betty. We use the following notation to denote this SAFE policy: $\text{GPS} = \langle\text{FITAPP}, \{\text{BETTY}\}\rangle$. Note that this policy only allows FitApp to share Alice's GPS-derived data with Betty; Alice may have different policies for other applications.

Apps create SAFE groups that map to application-specific concepts and register them with the SAFE user service. For example, FitApp could define ALICE.RUNNING-GROUP, which lets Alice share her runs with her running partners. The SAFE user service securely manages these groups by querying the user through a SAFE OS when an app wants to add members to the group. For example, if FitApp tries to add Betty to Alice's running group, the SAFE user services will request that Alice's SAFE OS accept or deny this request.

2.3 Trust and Threat Model

The SAFE framework makes it possible for users to create a chain of trust from their mobile devices and OSes to the cloud. Thus, we begin with the assumption that users trust their own mobile devices and their SAFE OS. We establish user trust by requiring users log in to their SAFE OS. This login establishes trust in several ways: (1) it authenticates the user to the SAFE OS, allowing the OS to give her access to the data and sharing policies on the mobile device and (2) it indicates to the SAFE OS that the user trusts the device to collect and hold her sensitive data.

A user login also indicates that the device and SAFE OS is trusted to hold data shared with that user. For example, if Alice gives Betty access to her GPS location, then she must trust any device and SAFE OS that Betty is willing to log in to. This extension of trust makes sense; even if Betty's phone was not running malicious software, Betty herself could extract Alice's GPS location from the phone once it is shared because Betty has physical ownership of the phone.

Users also trust attested SAFE cloud services. In particular, users trust SAFE services running on a trusted systems stack including a SAFE enforcement system. Similar to other security systems, the degree of protection offered by each SAFE enforcement system depends on its mechanism. In general, SAFE systems can suffer from timing attacks, probabilistic channels, or physical attacks on trusted components. For example, Magma uses IFC to enforce SAFE policies on untrusted applications, so it suffers from many of the same limitations as previous IFC systems [14, 17, 20, 33, 43], including termination. Despite these limitations, the SAFE framework significantly improves the security of user data handled by distributed mobile apps. Since, today, users must trust their applications, SAFE enforcement systems significantly raise the bar on attacks by malicious applications on user privacy.

3 Agate, a SAFE Mobile OS

Agate is a SAFE enforcement operating system built atop Android, the most popular mobile OS today [42]; however, Agate's design could layer atop other mobile OSes as well (e.g., iOS). A SAFE mobile OS performs three important functions: (1) providing users with a secure user interface for logging in and setting and managing policies, (2) labeling data with SAFE policies and (3) enforcing SAFE policies.

3.1 Agate Architecture

Figure 2 shows the Agate mobile OS architecture. To minimize the impact on the user experience, we limit Agate to enforcing SAFE policies on data that mobile OSes already protect (essentially anything in the Android Manifest). We define these data sources as *OS-protected resources*, including hardware resources like the camera and GPS (shown below Agate in Figure 2), as well as software resources provided by built-in apps, like the user's calendar (shown in the middle of Figure 2), contacts, etc.

Agate provides two interfaces (shown in gray in Figure 2): (1) the *user interface* lets users securely log in, set policies and manage group membership and (2) the *syscall interface* lets applications access OS-protected resources, suggest policies and create groups.

Agate is a SAFE enforcement system. Once an app has accessed an OS-protected resource, Agate must ensure that untrusted apps do not send data from those resources to untrusted cloud services or mobile OSes. For SAFE enforcement, Agate embeds the Magma runtime and runs every app with it. Unlike the Magma distributed cloud runtime, Agate does not not require attestation because it is sufficient that the logged-in user trusts Agate and its apps to be SAFE.

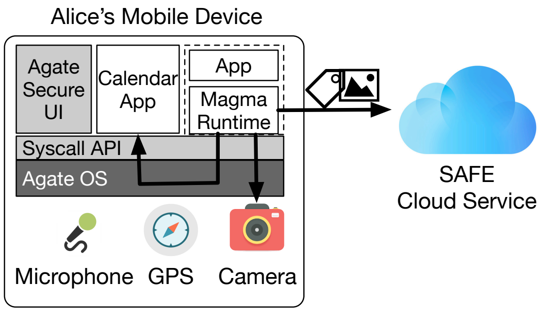


Figure 2: **Agate Mobile OS Architecture.** Agate mediates application access to hardware and software resources (similar to Android). It provides a secure user interface for users to log in and set Agate policies, and a syscall interface for apps to access resources and propose policies. Agate runs every app in a Magma runtime for SAFE enforcement. Magma ensures that apps only send data from OS-protected resources to other SAFE systems or users within the policy.

3.2 Agate Policies

Agate policies match existing user privacy policies as closely as possible. They combine today's access control policies with SAFE flow policies and let users express: (1) which OS-protected resources an application can access, and (2) how the application can export data derived from that resource. For example, Alice can set a policy allowing her FitApp to access her GPS and share with Betty. Agate will give every piece of data that FitApp derives from her GPS the SAFE policy, $\text{GPS} = \langle \text{FITAPP}, \{\text{BETTY}\} \rangle$.

Agate lets apps create SAFE groups and suggest policies through the syscall API. For example, once FitApp has created the group, ALICE.RUNNING-GROUP, then it can offer Alice the choices: $\text{GPS} = \langle \text{FITAPP}, \{\text{ALICE}\} \rangle$ $\text{GPS} = \langle \text{FITAPP}, \{\text{ALICE}, \text{BETTY}\} \rangle$ and $\text{GPS} = \langle \text{FITAPP}, \{\text{ALICE}, \text{ALICE.RUNNING-GROUP}\} \rangle$ to share data from her GPS only with her devices, with her and Betty's device, or with her entire running group.

3.3 Agate Syscall Interface

Mobile apps interact with Agate through the syscall interface. Syscalls fall into three categories: (1) access to OS-protected resources, (2) Agate policy proposals, and (3) SAFE group management. Most of these syscalls are directly handled by Agate or coordinated with the SAFE user service. Whenever possible, we maintain the existing OS interface; for example, application access to OS-protected resources is unchanged.

Existing apps access hardware resources (e.g., the camera) through syscalls handled by the OS and software OS-protected resources through inter-process calls to built-in OS apps (similar to a user-level file system on a traditional OS). For example, on Android, an app can access a user's contacts by sending an intent to the Contacts app. When an app accesses an OS-protected resource, Agate continues to enforce an access control policy similar to today's mobile OSes (e.g., Alice gives FITAPP access to her contacts through the Android manifest) but labels any data from the resource (e.g., Betty's address) with a SAFE policy. It then gives that SAFE policy to Magma to enforce on the untrusted mobile app and pass on to SAFE cloud services.

3.4 Agate User Interface

Before the user can access SAFE apps on Agate, they must log in. Agate presents a log-in interface similar to existing mobile OSes or apps. It authenticates the user's identity with the SAFE user service to obtain a user certificate. Agate can support apps from more than one SAFE ecosystem; however, users have to log in to each ecosystem separately. Apps provide the location of their ecosystem's user service, so that Agate can retrieve the app id and certificate. Agate will ask the user to log in again only if it does not already have a certificate from that user service.

Agate requires a secure way for users to specify policies for their OS-protected resources and manage groups. To avoid application interference, Agate cannot trust the application to display or draw the policy-creation UI. Instead, it displays the UI in a *secure user interface*, similar to the UI used today when mobile apps request additional app permissions [6]. Any policy-creation UI should be secure from: (1) *visual manipulation* by the application (e.g., changing what the user sees); (2) *input forgery* by the application (e.g., entering a policy on Alice's behalf); and (3) *clickjacking* or similar attacks [29]. Prior work has considered these and other secure UI requirements in depth [52, 53]; we refer to that work for implementation details for these properties.

To extend Agate's support for text-based applications, we added a new secure text box. For example, a chat application can open a secure Agate text box, which reads text from the user and then labels it with a policy before handing it back to the application. We assume the mobile OS allows users to verify that they are operating in the context of a trusted built-in application or Agate UI (e.g., an indicator in the system navigation bar [10]).

3.5 Agate SAFE Enforcement

Agate performs SAFE enforcement because we want to let untrusted mobile apps manipulate user data from OS-protected resources but not let apps leak that data to un-SAFE cloud services or unattested OSes. It leverages Magma for this enforcement by running every mobile app in a Magma runtime environment and giving Magma SAFE policies for any data from OS-protected resources. Magma is a modified IFC JVM, making it suitable for mobile apps as well as cloud backends. We leave the discussion of how Magma implements SAFE enforcement to the next section.

4 Magma, a SAFE Runtime System

Magma is a runtime system that provides SAFE enforcement for unmodified application processes. Because Magma is a SAFE enforcement system, it can always pass data to another process running the Magma runtime. Thus, it is easy to construct a distributed runtime platform from processes running Magma across distributed nodes.

Magma's responsibilities as a SAFE enforcement system is to: (1) take SAFE policies and turn them into IFC tags for its tracking mechanism, (2) propagate those tags as the application manipulates user data, and (3) check tags to ensure that SAFE policies are enforced when the application backend sends data to mobile devices.

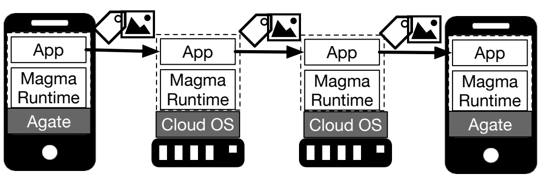


Figure 3: **Magma Architecture.** Every Magma process runs application code atop the Magma runtime and can always pass data to another (verified) Magma process. Magma processes can run embedded in Agate OSes on mobile devices or as stand-alone components on cloud servers.

4.1 Magma Architecture

Figure 3 shows the architecture of a distributed Magma runtime system. Every Magma process (shown as dotted rectangles) runs the Magma application runtime under the application. Magma processes can run on mobile devices as part of the Agate OS or as part of a cloud service.

We prototyped the Magma runtime by extending the Dalvik JVM to support Android apps on Agate. However, other application runtimes (e.g., Python, Scala, Go) could be used as well. Using a language runtime lets Magma support fine-grained IFC with low overhead. In contrast, supporting low-level languages would cause Magma either to overtaint or impose too much performance overhead. We observe that most sharing applications today run in a managed runtime, so this trade-off is a reasonable way to achieve our goal of supporting unmodified applications.

Magma uses fine-grained information tracking, rather than tainting processes, because backend sharing app code may handle the data of many users over time. Eventually, processes running the cloud service would become so tainted that they would not be able to release data to any users. Another option would be to start a new process for each request (e.g., using something like Amazon Lambda [5]); however, that could add significant latency, so we leave that option to future work.

4.2 Magma IFC Model

Magma's IFC model is similar to other IFC systems with one key difference: SAFE *policies directly map to IFC labels.* As a result, Magma is able to work with unmodified applications without the help of programmer or users. Magma automatically tags data from an Agate OS or another SAFE cloud service with the SAFE policy before handing that data to the application. Magma propagates and enforces those policies represented as tags across the entire backend cloud application.

There are three types of IFC principals in Magma – users, groups and applications – which map to the principals in SAFE flow policies. We directly use SAFE ids for Magma labels. There are two types of labels in Magma: the mutable *data labels*, which carry the SAFE policy, and the immutable *process labels*, which encode authorization and help enforce the SAFE policies.

Data Labels. Magma data labels are tags of the form $l = \{O_1, O_2 \rightarrow A_1, U_1, U_2, G_1\}$, where O_1, O_2 are the user principal ids of the owners of the labeled data, A_1 is the principal id of an application allowed to access the labeled data and U_1, U_2, G_1 are users and groups allowed to view the labeled data. We will refer to the set $\{A_1, U_1, U_2, \forall$ user principal id $u \in G_1\}$ as $readers(l)$.

Process Labels. Each Magma process is labeled with an application principal (e.g., $\{A_1\}$) and, if the process runs on Agate, a user principal (e.g., $\{A_1, U_1\}$). Magma requires these two to enforce the SAFE flow policies, which dictate which application can move a user's data, as well as, whom the app can give that data to.

Information Flow Rules. To enforce SAFE policies, Magma must guarantee the following security property:

> *Data from an OS-protected resource labeled with a non-empty initial data label l_1 may reach a process labeled with label l_2 only if $l_2 \subseteq readers(l_1)$.*

It does so by applying the following two data and policy propagation rules:

Intra-process propagation. Inside a process, data is allowed to flow freely (i.e., no flow control checks are performed) but data labels may change. Any data *derived* from one or more labeled data sources is labeled with a label which reflects all the SAFE policies involved. For example, if the application combines two pieces of labeled data, their labels are *merged* into the resulting label l, where the owners are the union of the two sets of owners and where $readers(l)$ is the intersection of the two sets of readers. That is, given two pieces of data with labels $l_1 = \{O_1 \rightarrow readers(l_1)\}$ and $l_2 = \{O_2 \rightarrow readers(l_2)\}$, the resulting label of any derived data is $\{O_1, O_2 \rightarrow readers(l_1) \cap readers(l_2)\}$.

Inter-process propagation. Data labeled with the current data label l_1 is allowed to flow to a process labeled with label l_2 only if $l_2 \subseteq readers(l_1)$. If the data is allowed to flow to the new process, it maintains its label, l_1, until an intra-process propagation rule is applied.

These rules ensure that data protected by SAFE policies, and data derived from that data, flows only to other processes running the same app (or another allowed app), and, if the process is running on an untrusted Agate OS, a process with a logged in user that is in the SAFE policy.

4.3 Magma Flow Tracking

Magma implements both explicit and implicit flow tracking. Explicit flows are caused by direct assignment (e.g., `x = gps-loc`), whereas implicit flows are caused by control flow (e.g., `if (gps-loc == home) {x = true}`. Magma's explicit flow tracking mechanism is relatively straightforward; as apps propagate data, Magma propagates the corresponding tags, joining the tags by following the IFC rules. Handling implicit flow through unmodified applications is more complicated, so much so that many systems [21, 25, 55] ignore the problem altogether. However, they are an important way that user privacy can be violated; thus, Magma must consider them.

Using the previous example, `if (gps-loc == home) {x = true}`, the value assigned to `x` is a literal value containing no sensitive labels. However, the execution of the assignment operation reveals information regarding Alice's location. It is also worth noting that information is leaked even if the conditional branch is *not* executed since the absence of an update to `x` also reveals information regarding Alice's location (i.e., she is not home).

For implicit flow tracking, Magma uses a combination of static analysis and runtime taint propagation. For every conditional block, Magma's static analyzer identifies both the set of variables that are updated in either branch (e.g., `x`) and the control flow variables that determine the conditional execution of the updates (e.g., `gps-loc`). The static analysis pass then inserts code that causes the runtime taint propagation system to update the labels of the modified variables to include the labels associated with the control flow variables, regardless of whether the conditional is executed.

Our Magma prototype runs this static analysis on Java bytecode as it loads apps. It uses a control flow graph representation of the program and resembles the techniques outlined in [15, 16, 30]. Instrumented code for runtime taint tracking needs to be added to every control flow block that might contain sensitive data, as well as any function invoked from either branch of these control flow blocks.

Instrumenting control flow has the potential to increase code size and execution time. To mitigate this problem, Magma's static analyzer makes a conservative pass to determine which control flow blocks will *never* result in implicit flows, because they never access tainted data. Similarly, it identifies functions that are never called from tainted contexts. We found this pruning to be useful in practice because many tagged data objects are unlikely to be used to make control flow decisions: for example, most apps do not branch on the bytes of a JPEG image.

4.4 Magma SAFE Enforcement

Magma uses flow control to enforce SAFE policies on untrusted applications. Because Magma directly expresses SAFE policies as IFC labels, it can use labels tagged on the data to check policies. Thus, simply by preventing flows that violate Magma's IFC rules, Magma can ensure that an application meets the SAFE requirement.

First, Magma always permits applications to send data to another trusted SAFE cloud service. Magma verifies that cloud services are safe using one of the methods detailed in Section 2.1.4 (e.g., comparing a TPM hash). It then translates the IFC label into a SAFE policy and securely send it along with the data.

When a Magma application sends labeled data to an unattested mobile device (i.e., belonging to another user), Magma performs a policy enforcement check. It first checks that the mobile device is running an authorized SAFE OS and retrieves the application id and logged-in user id of the process that will receive the data. The user id and app id are both provided as signed certificates from the SAFE user service when the user logs in and starts the app.

If the app id matches, then Magma intersects $readers(l)$, where l is the label on the data being sent, with the logged-in user principal of the destination process. If the intersection is not empty, then the Magma tags are translated into a SAFE policy and sent together to the destination. If the intersection is empty, then the destination is not permitted to receive the data and Magma returns an error to the application. This check is sufficient to ensure SAFE policies are respected.

5 Geode, a SAFE Storage Proxy

Application cloud back-ends often need to persistently store data for fault-tolerance or archival storage. To support this requirement, we provide a cryptographic proxy, Geode, to make existing, untrusted storage systems SAFE. Geode takes its approach to building secure storage from untrusted infrastructure similar to prior work on TPM-based filesystems and databases [12, 39, 65].

5.1 Geode Interface and Guarantees

Geode provides a key-value object storage interface, like Amazon S3 [4]. It provides three guarantees: (1) *confidentiality* - the storage service cannot read user data, and it will be released only according to the SAFE policy on the data; (2) *integrity* - each object and its policy can only be modified by the application that created it and cannot be tampered with by the storage service, and (3) *single-object linearizability* of updates.

Geode provides linearizability per object both because it is a desirable property for reasoning about concurrency, and to prevent a malicious storage service from returning incorrect values under the guise of weak consistency. Geode can be used with any storage service that provides the same interface, guarantees linearizability, and does not manipulate user data itself. Many storage systems meet these requirements, including most weak consistency distributed storage systems (e.g., S3, Redis [51]), which typically provide per-key linearizability.

5.2 Geode Architecture

Figure 4 shows Geode's architecture. Geode operates multiple proxy nodes, each responsible for a different portion of the keyspace. Due to space constraints, we do not discuss fault-tolerance of proxy nodes, other than to note that it can be handled by replication and logging techniques as in previous systems [39,66]. Each Geode node is equipped with a TPM or other trusted hardware component; in addition to attesting to SAFE clients that the server is running the Geode proxy, it also provides the Geode proxy with access to a sealed encryption key and a tamper-proof monotonic counter.

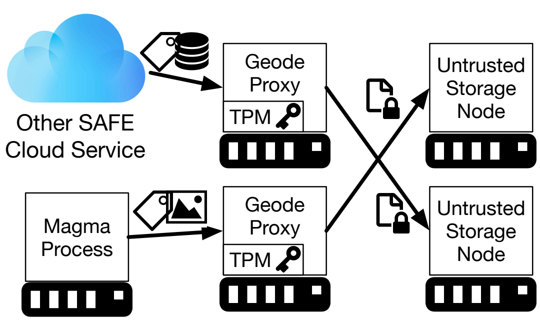


Figure 4: **Geode Architecture.** Geode interposes on access to an untrusted storage system from SAFE systems. It securely checksums and encrypts the data and SAFE policies before handing them to the storage system. Geode ensures that only SAFE systems and users within the SAFE policy can retrieve the data.

Note that Geode could be the only cloud service that an app needs. Many applications today (e.g., to-do lists or recipe apps) use only a cloud storage system (e.g., Dropbox [18]) and do not require a separate cloud backend app.

Geode could be deployed in a number of ways. It could be run by the application provider, the storage provider or a third party entity. For the best performance, Geode should be co-located with the storage system.

5.3 Geode SAFE Enforcement

Geode interposes on every access to the storage system. For each write operation, Geode prepends a header to every stored object with its SAFE policy. It then generates a random initialization vector and uses it to encrypt the block (using AES-128 in CBC mode with the secure key). Encryption ensures that the storage system cannot read the data, and the initialization vector prevents known-plaintext attacks. Subsequently, it records the initialization vector and a SHA-256 HMAC of the block contents. These are added to a per-object integrity table, itself encrypted with the same key, which also contains the latest monotonic counter value; this table is stored in a special object in the underlying storage system. (A more efficient implementation might use a Merkle tree [40] to prevent having to rewrite the table on each update.)

On each read operation, the Geode proxy fetches and decrypts the object. It verifies that the hash of the object matches the one stored in the integrity table, and the version number of the table is up to date. The hash ensures that the storage service did not tamper with the object or its policy, and the version number prevents it from rolling back to an earlier state. If the data object has a SAFE policy, Geode first checks if the requesting application is either a SAFE service or a SAFE OS. If it is a SAFE service, Geode securely sends the decrypted data and SAFE policies to the service. If it is a SAFE OS, Geode checks the SAFE policy for the user certificate presented by the SAFE OS (similar to Agate and Magma).

6 Evaluation

In addition to ensuring that user privacy policies are respected, we stated three goals in the SAFE framework design: (1) minimize changes to the user experience, (2) minimize changes to application code and (3) minimize performance cost. In this section, we evaluate the effectiveness of the SAFE design in meeting these goals.

6.1 Implementation

To support Android sharing apps, we prototyped Agate and Magma using the Android OS and Dalvik JVM, respectively. Agate runs on ARM-based mobile devices while Magma runs on both ARM and x86 architectures. This section describes the implementation of these prototypes.

6.1.1 Agate Mobile OS Prototype

Agate extends Android into a SAFE OS by adding support for secure user log-in, policy collection and SAFE enforcement. Our prototype UI differs slightly from the one imagined for Agate; because Android already provides users with a secure way to set access policies for their OS-protected resources, the Agate UI only provides settings for SAFE policies. Our policy management interface consists of dialog boxes drawn in the context of the current application rather than in a separate, trusted application. A more secure prototype would show the policy interface in a separate application, as demonstrated in prior work [53].

Our current prototype leaves access control to existing Android mechanisms but interposes on accesses to collect policies and attach labels for Magma to use. After attaching labels, Agate uses its embedded Magma runtime to enforce the SAFE guarantee. Our prototype interposes only on calls to the built-in camera and GPS resources (i.e., the `takePhoto()` and `getLastKnownLocation()` system calls); in a full implementation, similar modifications would be required for other OS-protected resources.

6.1.2 Magma Prototype

Magma is a SAFE enforcement runtime that: (1) translates SAFE policies into IFC tags, (2) tracks both explicit and implicit flows and (3) enforces SAFE policies with IFC checks. Magma's explicit flow tracking mechanism is based on TaintDroid [21] for Android 4.3_r1. However, TaintDroid is a limited taint-tracking – not flow-enforcement – system, so Magma requires extensive modifications to TaintDroid's mechanisms. For example, while TaintDroid tracks binary taints for only 32 sources, Magma must use more complex IFC labels and rules to represent SAFE policies.

TaintDroid has no implicit flow tracking, so Magma implements its own mechanism. Magma's hybrid mechanism uses a custom analysis tool to insert annotations into Android dex files, and then dynamically propagates labels at runtime via those annotations. Magma's static analysis tool uses the Soot framework for Java/Android apps [57], and consists of 5,400 lines of Java code to perform class hierarchy analysis, global method call flow analysis, control flow analysis within methods, side effect analysis inside conditionals, and insertion of taint tracking code for implicit flows.

Magma inherits some performance optimizations from TaintDroid that could lead to overtainting. Neither TaintDroid nor Magma performs fine-grained flow tracking through native code due to the performance overhead. Instead, Magma uses a conservative heuristic that assigns the result of a native code function to a combination of the taints of the input arguments. Similarly, TaintDroid keeps a single taint label for an entire array, which could cause overtainting due to false sharing. Phosphor [9], a newer JVM-based taint tracking mechanism, eliminates the potential for overtainting at a reasonable performance cost.

6.2 Security Analysis

We first evaluate the effectiveness of SAFE's security guarantees. We examine the top 10 web security risks and the top 10 mobile security risks identified by the Open Web Application Security Project (OWASP) [47, 48], summarized in Table 1. As the checkmarks in Table 1 indicate, the SAFE framework can successfully prevent applications from leaking user data for nearly all of the most common web and mobile vulnerabilities compared to Android, which handles only three.

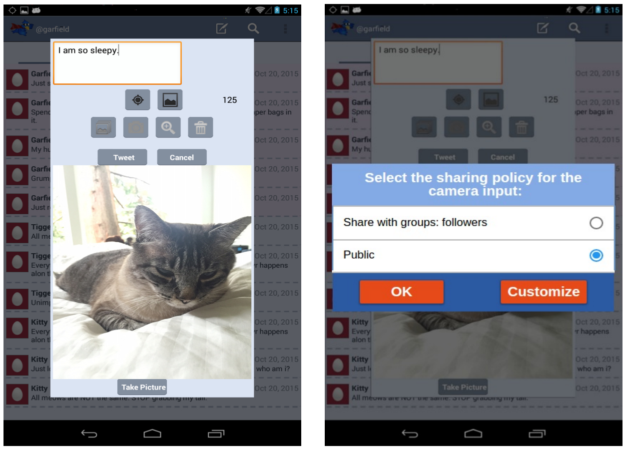
Table 1: **Protection offered by Android and the SAFE framework against top web and mobile vulnerabilities [47,48].** Related items from the lists are merged. Android handles only a small subset of these issues, while SAFE covers nearly all.

Vulnerability	**Android**	**SAFE**
Broken access control	–	✓
Broken authentication	–	✓
Broken cryptography	–	✓
Buffer overflow	✓	✓
Client or server side code injection	–	✓
Cross site scripting	✓	✓
Insecure data storage	–	–
Insecure direct object references	✓	✓
Insufficient transport layer protection	–	✓
Improper error handling	–	✓
Improper session handling	–	✓
Lack of binary protections	–	✓
Missing function-level access control	–	✓
Path traversal & command injection (server)	–	✓
Security decisions via untrusted inputs	–	✓
Sensitive data exposure	–	✓
Unintended data leakage	–	✓

In many cases, simply using a SAFE enforcement system suffices to avoid the vulnerability. For example, applications frequently inadvertently leak user data and violate user policies through *improper error handling*. However, an IFC-based enforcement system, like Magma, would ensure that applications cannot release user data except to another SAFE system or a user within the SAFE policy running a SAFE OS. In fact, while porting applications to Agate, we often found Magma barring the release of error message for debugging to us.

Finally, the entire SAFE framework is designed to prevent *broken access control*. Rather than trusting applications to correctly implement access control checks, a SAFE OS requires that a cloud service run a SAFE enforcement system, which is trusted to perform these checks on behalf of the application. For example, Magma would not allow Facebook to release Mark Zuckerberg's photos to users that are not in his friends list [60].

While the SAFE framework protects against *insecure data storage* in the cloud (i.e., by using the Geode proxy), we explicitly do not handle risks that can be exploited by improper storage on untrusted user devices. For example, once Alice releases her photo to Betty, she must trust that Betty does not copy the photo to untrusted cloud storage or lose her phone.



(a) (b)

Figure 5: **Agate UI for a Twitter-like application.** When the user takes a photo in SAFETweet, shown in 5(a), Agate interposes on the system call and lets the user set a policy via a secure, system-controlled user interface, shown in 5(b). Agate labels the photo with the specified SAFE policy, which Magma enforces, once the photo is given to SAFETweet.

Overall, the analysis shown in Table 1 demonstrates that, through the use of the SAFE framework, taking trust away from applications and putting it into the hands of attested SAFE enforcement systems can help users avoid many of the vulnerabilities that plague mobile sharing applications today.

6.3 User Experience

A key goal of the SAFE framework is to minimize changes to the user experience and use existing user policies. We evaluate whether we achieved this goal by exploring the Agate user interface.

To demonstrate Agate's UI, we use an open-source Twitter clone [62] that we ported to our SAFE framework, which we call SAFETweet. While interacting with SAFETweet, Alice takes a photo of her cat, Max, to post to her feed, which requires SAFETweet to access her camera. At this point, Agate interposes on the system call to: (1) ask permission for SAFETweet to access the camera and (2) let Alice to set a SAFE policy for all data that SAFETweet receives from the camera (i.e., photos). Once Alice has given permission and set a policy, Agate will give the photo and SAFE policy to the embedded Magma runtime to return to the app.

We note two key aspects of Agate's UI that are enabled by the SAFE framework. First, it looks and feels much like a user's experience with Twitter because SAFETweet can propose SAFE policies that match those that it would offer today. Second, although Agate creates a familiar user experience, it can enforce SAFE policies on untrusted apps using its Magma runtime *and* verify that cloud services will also enforce those policies. So while the user experience remains unchanged, the security properties are completely different with the SAFE framework.

Table 2: For each distributed application, we list the unmodified Android app ported to Agate for the client side and the unmodified Java app ported to Magma for the server side, along with their size in lines of code.

App	Ported Client	LoC	Ported Server	LoC
SAFEChat	Xabber [67]	78K	Openfire [45]	190K
SAFETweet	Twimight [62]	13K	MinnieTwitter [41]	1.2K
SAFECal	aCal [2]	30K	Cosmo [1]	40K

6.4 Programmability and Porting Experience

Another goal of the SAFE framework is to minimize application code changes. To gain experience with SAFE applications, we created three SAFE sharing applications. We ported three unmodified Java server applications as cloud app backends and three Android apps as mobile app clients, as listed in Table 2. Using the Agate UI, we placed SAFE policies on different sources of data for each application; for example, in SAFEChat (70K LoC), we used Agate's secure text input facility to create a private chat between Alice and Betty.

To port mobile app clients to Agate and Magma, the only changes made to the application code were those needed to incorporate Agate APIs (e.g., to use the system call to propose policies and treat invalid flow exceptions). In SAFECal (250K LoC), we found both explicit and implicit flows that might violate Alice's policy; e.g., Bob, who is not Alice's co-worker, cannot view Alice's meetings this week (an explicit flow), or check whether Alice is free at 3 on Tuesday (an implicit flow).

With Magma, we were particularly interested in issues with overtainting, policy accumulation on data, and unexpected flow restrictions. We experienced no problems with the application code itself: indeed, the cloud app backends (Openfire, MinnieTwitter, Calendar) required *no modification* to run on Magma. However, we did encounter overtainting in libraries used by cloud backend apps, particularly for communications and parsing, such as the core Java libraries (BufferedReader, OutputStreamReader), Java RMI, and dom4j. For example, the message serialization libraries reuse memory buffers, leading to unnecessary data overtainting and policy accumulation and blocking valid flows. After manually fixing the problematic libraries, the applications worked as expected. Note that these fixes could be reused for other applications by releasing Magma-compatible Java libraries.

While we believe Agate and Magma are two representative SAFE systems, the programming experience will vary between different SAFE OSes and SAFE enforcement systems. However, with a variety of options, programmers can choose the best one for their cloud backend or mobile app.

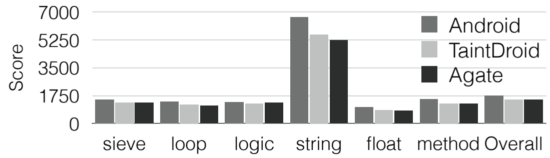


Figure 6: **CaffeineMark microbenchmark for Android Dalvik, TaintDroid and Agate (higher is better).** Both Agate and TaintDroid impose an overhead, but Agate's overhead is similar to TaintDroid's.

6.5 Performance

Finally, we measure the performance cost of meeting the SAFE requirement. In our experiments, mobile devices run Agate with its embedded Magma runtime and cloud servers run the distributed Magma runtime. Each server contained 2 quad-core Intel Xeon E5335 CPUs with 8GB of DRAM running Ubuntu 12.04. The mobile devices were first-gen Nexus 7 tablets (1.3 GHz quad-core Cortex A9, 1 GB DRAM). Our servers shared one top-of-rack switch and connected to tablets via a local-area wireless network.

6.5.1 Microbenchmarks

As a baseline, we compare the performance of Magma running on Agate to unmodified Dalvik and TaintDroid running on Android. We execute mobile apps without tainted data. We use CaffeineMark 3.0, a computationally intensive program commonly used as a microbenchmark for Java. CaffeineMark does not access data with SAFE policies, so there are no tags to be tracked; however, TaintDroid and Magma must still propagate and merge empty labels, so this measurement gives us a lower bound on the performance cost for each system.

CaffeineMark scores roughly correlated with the number of Java instructions that the JVM interpreter executed per second. The overall CaffeineMark score is the geometric mean of the individual scores. Figure 6 shows the results for an Android tablet. On this baseline (no SAFE policies and no tags), Agate and Magma impose little overhead relative to TaintDroid (between .3% and 5.8%, with an average of 1.8%). The CaffeineMark overall score for Agate is within 16% of baseline Android, while TaintDroid's overall score is within 14.5% of Android.

TaintDroid's overhead stays constant as data accumulates more taint because it uses a single-bit representation and tracks only 15 OS-protected resources. Magma also propagates a single 32-bit tag per primitive or primitive array, but these tags are references to a list of all policies with which the data is tainted. Thus, while Magma's cost for propagating tags remains constant as taint accumulates, the cost of merging when combining two tainted pieces of data increases with the number of policies tainting the data.

To evaluate the impact of accumulating taint in Magma, we measure the cost of merging up to 20 SAFE labels, each with 20 principals/tags (10 users and 10 groups). We consider this measurement an upper bound because it would require the application to have at least 20 policy options, *each* with 20 principals. In practice, policies would become unwieldy for both applications and users at a much smaller number (i.e., 5-10 policies each with a small number of principals). We found that merging two labels with 20 principals each took 6 µs. Overhead increases with the number of labels on the data up to 20 µs to merge 20 labels with 20 tags each.

6.6 Application Performance

To validate our expectations about how apps and users use SAFE policies, and to measure Agate's performance overheads for a full application, we use two distributed applications: (1) the SAFETweet app mentioned above (MinnieTwitter + Twimight), and (2) a multi-player game (WordsWithFriends) that we implemented from scratch. We run mobile client apps with Magma on Agate and the app backends on the Magma distributed cloud runtime.

Figure 7 shows latency for tweet, tweetWithMedia and getHomeTimeLine from SAFETweet, and joinGame from WordsWithFriends. For each function, we show latency for the unsecured app on Android, Agate+Magma without static analysis annotations, and Agate+Magma with annotations.

Tweet does not access sensitive data with SAFE policies and thus shows the basic cost of making Android SAFE, which is 17%. TweetWithMedia includes a labeled photo; we used the default policy suggested by SAFETweet, which is CAMERA = ⟨SAFETWEET, {USER.FOLLOWERS}⟩. Overhead increases to 20% because Magma must call the SAFE user service to translate group/user names into principal ids. Some optimizations could reduce this cost, including caching id mappings and optimizing TaintDroid's disk writes. The overhead of GetHomeTimeline is 22% because it accesses more tainted data (2 photos), requiring Agate to check the policy on each photo. Most of the extra time is due to remote calls to resolve group membership, which again could be reduced with caching [14]. Currently, each operation required three RPCs to perform the checks before sending the photo.

For SAFETweet, merging and static analysis did not add to the runtime overhead. Magma propagates but never merges labels because SAFETweet never derives new data from photos. Static analysis found no implicit flows as SAFETweet never uses photos as branch conditions. We expect this behavior to be typical for most applications that access photos.

WordsWithFriends' JoinGame operation accesses the GPS to find nearby friends for gameplay, so its default policy for the GPS is GPS = ⟨WORDSWITHFRIENDS, {USER.FRIENDS}⟩. Static analysis added only five annotations for WordsWithFriends because the control flow based on the GPS is limited to checking for nearby friends.

JoinGame branches on tagged GPS locations every time it

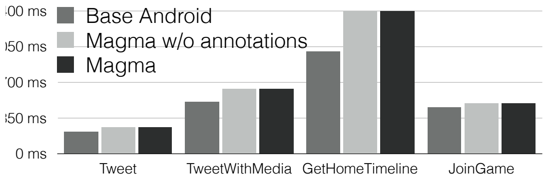


Figure 7: **Latency of SAFETweet and WordsWithFriends functions.** The figure shows that Magma imposes roughly 20% overhead compared to unsecured Android. joinGame is the only function that requires static annotation, but those costs are extremely low.

compares two locations, so it must track more labeled data than SAFETweet operations and accumulates taint as it runs due to the comparisons. However, JoinGame does not release the user's GPS location (because it performs the comparisons on the user's device), so it does not have to resolve user names or group membership for enforcement checks, incurring a lower overhead than SAFETweet operations.

While these applications are prototypes, we believe they use the SAFE framework in a representative way. Data derived from OS-protected resources with SAFE policies were typically copied or transmitted but rarely merged with other sensitive data. Furthermore, static analysis is effective at determining which conditionals operated on sensitive data. As a result, Magma is able to reduce the number of taint merge operations and implicit flow annotations, and thus keep the overheads low.

Overall, our results show that Agate and Magma's performance is very close to TaintDroid's and within approximately 20% of the performance of the base Android system, both of which have no policy enforcement. From a user's qualitative point of view, the difference is not detectable in using either prototype application. Although we have not yet tried to optimize our prototype, we feel that this difference is well worth the additional privacy guarantees that the SAFE framework provides.

7 Related Work

In designing the SAFE framework we drew inspiration from many existing privacy-preserving and trust management systems. Although this paper presents the design of only three SAFE enforcement systems, we envision many others being built atop existing systems.

Modern OSes for smartphones incorporate access control mechanisms that let users control which resources applications can access, e.g., through an Android manifest file. Significant research [3] builds on this idea to give users better security and more effective access control. For example, Access Control Gadgets [54] provide a more intuitive user interface for permission granting, and Preservers [31] lets users choose the code/policies that mediate data access. Our SAFE framework and its SAFE systems provide stronger guarantees by enforcing user policies beyond the phone.

Distributed platforms like πBox [36], Cleanroom [35] and Radiatus [13] protect user privacy by isolating each user in a sandbox environment. While isolating users makes it easy to enforce privacy for applications where users do not interact, social applications where users *want* to selectively share their data do not work well. All communication between users must go through a restrictive interface and be vetted by the system. However, sandboxing has the advantage that all data (not just OS-protected resources) is protected and cannot be exposed even to the application developer. πBox uses differential privacy [19] to control *how much* data can be released to the developer. A sandboxing-based SAFE enforcement system would be useful for apps in which part of or all of a user's data does not need to be shared with other users; for example, a cloud service that categorizes a users photos using machine learning.

Unlike other IFC runtimes [14, 25, 63, 64], Magma is explicitly designed to support SAFE flow policies. As a result, Magma can directly translate SAFE flow policies into IFC labels, rather than requiring users or programmers to set IFC policies. This design minimizes changes to both the user interface and application code.

However, the SAFE framework makes it possible to incorporate other IFC-based systems, provided that there is a way automatically translate the SAFE policies into their IFC policy model. This requirement may limit the untrusted applications they can support. For example, IFC-based systems that use coarse-grained tracking [20, 33, 69] could offer better performance than Magma but require more information about the application's architecture to deal with overtainting. Language-based IFC systems [38, 43, 56, 68] seem even less suitable because they require information about application variables and functions, making it difficult to translate SAFE policies into their policy model.

Geode is a simple proxy for storage systems that do not manipulate user data. It is inspired by previous systems that leverage a trusted hardware platform to build secure storage out of untrusted components [12, 39, 65, 66]. More complex options that enable computation on stored data include IFDB [59] and CryptDB [49].

Magma builds on TaintDroid, a binary instrumentation tool for programmers to find leaks of tainted data on Android applications. TaintDroid has a different goal: it aims only to *detect* flows, not to stop them. As a result, it does not have a notion of policies – it tracks only a single bit of taint – nor any enforcement mechanism. TaintDroid is also a single-node system; its flow tracking ends at the boundary of a single mobile device.

Our SAFE framework is inspired by public key infrastructure (PKI). While PKI has its issues (e.g., too many certificate authorities, authorities issuing certificates that they do not own), there have been efforts to address them (e.g., http public key pinning [32]). We hope that SAFE will avoid many of these pitfalls by relying on attestation instead of authorities. In particular, three factors differentiate SAFE from PKI: (1) it is more difficult for a system to become a trusted SAFE enforcement system than a certificate authority, (2) users can inspect the code of open-source SAFE enforcement systems and (3) mobile OSes will not verify a cloud service as SAFE unless it can attest that it is running a trusted SAFE enforcement system.

8 Conclusion

This paper introduced the SAFE framework for distributed mobile apps. SAFE provides a system guarantee that user policies will be enforced on sensitive user data no matter where it flows. The framework relies on SAFE enforcement systems to provide this guarantee without requiring application modifications.

The SAFE framework leverages mobile OSes to vet cloud services. Using attestation, a user's SAFE mobile OS can verify that a cloud service is running a trusted systems stack and a SAFE enforcement system. Once verified, the mobile OS can trust the cloud service to enforce SAFE policies even if it is running untrusted applications.

This paper presents three SAFE enforcement systems: Agate, a mobile OS; Magma, a distributed runtime system; and Geode, a distributed storage proxy. Using these three systems, we were able to run several unmodified applications across mobile devices and cloud server and enforce SAFE policies across the entire application. Our results demonstrate that the SAFE framework is a practical way for users to create a chain of trust from their mobile devices to the cloud.

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