Maat: A Platform Service for Measurement and Attestation

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Abstract

Software integrity measurement and attestation (M&A) are critical technologies for evaluating the trustworthiness of software platforms. To best support these technologies, next generation systems must provide a centralized service for securely selecting, collecting, and evaluating integrity measurements. Centralization of M&A avoids duplication, minimizes security risks to the system, and ensures correct administration of integrity policies and systems. This paper details the desirable features and properties of such a system, and introduces Maat, a prototype implementation of an M&A service that meets these properties. Maat is a platform service that provides a centralized policy-driven framework for determining which measurement tools and protocols to use to meet the needs of a given integrity evaluation. Maat simplifies the task of integrating integrity measurements into a range of larger trust decisions such as authentication, network access control, or delegated computations.

1 Introduction

System integrity is an increasingly important and often overlooked input to security decisions. Integrity measurements (or evidence) can be collected to verify that (1) the correct software or hardware platform is being used and (2) the system is in a valid state. The increasing use of a diverse set of integrity information to inform security decisions motivates the development of a centralized, comprehensive, and flexible system-level service for selecting and producing these types of measurements. The primary contributions of this paper are (1) a design for an integrity measurement and attestation service to evaluate the integrity of local or remote software components; (2) a description of our prototype implementation of this design: Maat, named after the Egyptian goddess of truth, balance, and justice; and (3) an illustrative discussion of how Maat can be applied to integrate M&A with platform management systems and network-scale middleware.

Trust decisions are common in today’s computing environments. For example, when logging into an online banking site, users must trust the integrity of both their local software and the software running the bank’s website. When outsourcing computation to a cloud computing provider, users must trust that the cloud infrastructure will faithfully execute their software without allowing third parties to interfere with or observe their actions. When a client joins a network, a mutual integrity decision is made: the user generally must trust the integrity of the services provided by the network, such as DNS configuration, and the network operator generally trusts the client...
and grants access to internal services, such as a local file sharing server that would not be addressable from the global internet. No single set of integrity evidence can be used to justify trust in all of these scenarios. In each case, it is necessary to balance the trusting party’s desire for a complete evaluation, and the trusted party’s desire to limit disclosure of sensitive data.

Maat provides a central framework and standard application programming interface (API) for policy-driven selection of measurement utilities and attestation protocols suitable for a wide variety of platform trust decisions. This centralization is critical to ensure correct administration of integrity policies and systems, rather than independently managing a multitude of disparate integrity measurement systems.

The next subsection gives a general overview of the goals of M&A. Section 2 describes specific desirable properties for M&A. Section 3 examines related work against these properties. Section 4 describes the Maat framework. Section 5 describes three example use cases for Maat including experience in a production environment. Sections 6 and 7 conclude by describing areas of future work and summarizing this paper’s contributions.

1.1 M&A Background

Integrity measurement systems (IMS) provide mechanisms for determining what software is installed or running on a platform, and validating the on-disk system configuration and current state of running software. These systems necessarily include a measurement agent that collects evidence describing the state of a target, and an appraiser that evaluates the integrity of the target based on the evidence produced. The attestation protocol defines how the evidence from the target is bundled, transferred, and presented to the appraiser.

As shown in Figure 1 (derived from [1]), these components may exist in a variety of architectures. Some systems may exist locally on a single platform, while others may be components distributed across a network. Any attempt at providing a general purpose interface for M&A must enable this kind of architectural diversity.

There are many types of evidence that can inform an integrity evaluation. One approach to integrity measurement, where measurements are cryptographic hashes of the static image of boot-time software, is described by England et al. [2] and adopted by the Trusted Computing Group (TCG) as part of the “Trusted Boot” technology [3]. Other work, such as Sailer et al.’s Integrity Measurement Architecture (IMA), takes cryptographic hashes of executables and other files used during platform operation [4]. Dynamic measurement techniques, such as the Linux Kernel Integrity Measurer (LKIM), move beyond hashes to introspection-based validation of critical runtime data structures [1]. Each of these measurement agents provides a unique form of evidence that supports different notions of software integrity.

Similarly, there may be multiple attestation protocols which provide varying degrees of protection and confidence in the evidence collected. Many attestation protocols rely on a Trusted Platform Module (TPM) [5] to provide a static root of trust for measurement and the measure-before-use sequence from the BIOS to the OS kernel and beyond [6] [7] [8]. Flicker defines a variation on this using the dynamic root of trust for measurement to provide a protected, attestable execution environment at runtime [9]. OASIS proposes providing a protected execution environment but roots trust in a physically unclonable function (PUF) [10]. Schemes for pure software-based attestation typically rely on timing requirements for computing a complex hash-like function over both the target and the measurement agent itself [11] [12] [13] [14].

2 Properties of M&A

Loscocco et al. define a set of desirable properties for software integrity measurement tools [1]. Coker et al. define a similar set of desirable properties for attestation protocols [15]. We designed Maat to support measurement and attestation components satisfying these properties and, by extension, enable M&A services to support trustworthy inferences made by appraisers in a wide variety of possible trust decisions.

Two of the identified properties, completeness and freshness, relate specifically to measurement functions.
Figure 1: Four possible layouts for an IMS [1]. (a) The Measurement Agent (MA) and Target (T) share an execution environment; the Appraiser (App) is on a physically distinct host. (b) The Measurement Agent is isolated from the Target using dedicated hardware or virtualization; the Appraiser is on a physically distinct host. (c) Each component is on a distinct host. (d) The Measurement Agent is hosted with the Appraiser while the Target is on a dedicated host.

Achieving these helps ensure that appraisers are basing their decisions on measurement data that reflects the current complete running state of the target. One of the attestation properties, semantic explicitness, addresses the degree that measurement data contains the necessary evidence required for the trust decision that triggered the attestation. These three properties govern the quality of trust decisions that the M&A mechanisms support. Therefore, it is imperative that an M&A framework be capable of supporting measurement agents and attestation protocols with these properties for all anticipated trust decisions requiring measurement evidence as an input.

In order to address the important question of whether the appraiser should trust the evidence that it has received, three additional properties apply: authenticity, correctness, and protection. Authenticity guarantees that the evidence came from an authentic source and reflects the target of interest. Correctness relates to the sound design and correct implementation of all of the M&A component mechanisms. Protection addresses the ability of the system to sufficiently protect all of the M&A components to enable them to meet their trust obligations to the appraiser. These properties apply both to individual measurement agents and attestation protocols, and to the M&A framework itself. The framework must be designed to (1) guarantee that the correct mechanisms are invoked when necessary, (2) ensure order of operation where out of order execution could impact trust, (3) limit accesses to and by M&A components, and (4) restrict access to M&A functions and resources from other parts of the system.

The purpose of an M&A framework is to provide a general-purpose service for integrity measurement. The properties of flexibility and usability apply to this goal. Flexibility implies an ability to (1) support multiple appraisers, measurement agents and attestation protocols; (2) select appropriate mechanisms in the context of given trust decisions, perhaps filtering results according to specific system policies (e.g., privacy); and (3) incorporate future M&A mechanisms. Usability implies that context should tailor the presentation of measurement data, including possible post-collection processing, to the specific needs of a given trust decision.

2.1 Critical Features

We designed Maat to support the eight high-level properties described above: completeness, freshness, semantic explicitness, authenticity, correctness, protection, flexibility, and usability. To meet these high-level properties, Maat includes the following concrete architectural features:

- **Support for Multiple Appraisers**: Platform integrity evaluations may be required in a wide variety of circumstances, and may be evaluated by several different appraisers. Each appraiser
may have its own notions of what evidence is required to show integrity, and how that evidence should be collected and presented. A flexible M&A system should be usable across a range of appraisers to prevent duplication and fragmentation of M&A functionality.

- **Support for Multiple Attestation Protocols:** Different attestation protocols can all present the same primary evidence, but the appraiser may be able to draw different conclusions on the correctness, freshness and authenticity of the data, based on the different bundling style. For example, one protocol may produce an aggregate measurement report with a single signature covering all measurements, another protocol may produce individually signed reports for each piece of evidence collected, and a third may produce a chain of reports where each signature covers a report and the hash of the previous signed report. Allowing the policy-driven selection of protocols to suit the needs of each specific attestation scenario enhances the flexibility and usability of the M&A system.

- **Support for Multiple MeasurementAgents:** Different evidence may be required to show the integrity of different components or to provide varying levels of confidence in one component. Some measurement agents may provide only boot-time evidence of integrity, such as a TPM quote, while others may generate fresher or more complete evidence showing integrity at runtime. Additionally, appraisers may require the use of a specific measurement agent to ensure correctness, e.g., an appraiser may accept the reports of a malware scanner from one vendor but not another. It is important for the M&A service to allow for policy-driven selection of measurement agents appropriate to a scenario. Like support for multiple appraisers and protocols, this feature directly supports the flexibility and usability of the M&A system.

- **Policy-based Negotiation:** The M&A service should be capable of negotiating with a peer to select a protocol and evidence set that satisfies each peer’s policy. Appraisers are likely to seek the most detailed evidence of attester integrity possible, while attesters are likely to want to limit disclosure of sensitive platform information. Both parties may want to limit the resources required to complete the attestation. Support for policy-based negotiation allows parties to find a protocol and evidence pair that is consistent with these goals. The need for policy-based negotiation is largely a consequence of support for multiple appraisers, protocols, and agents and thus contributes to the flexibility and usability of the system.

- **Discrete M&A Functions:** To ensure the trustworthiness of their measurements, the service should ensure measurement agents are protected from both the target of their measurement and from other parts of the measurement framework. For example, measurement agents may require exceptional authority, such as the ability to read kernel memory or attach a debugger to arbitrary processes. These privileges should be isolated in the smallest possible components and carefully controlled via platform access control policy. This isolation also allows for fine-grained policy regarding the authenticity and correctness properties of each component.

- **Support for Registration:** To provide extensibility of the supported attestation protocols and measurement agents, the service must include a registration mechanism to ensure that only valid combinations of agents and protocols are available for negotiation, and that the platform’s security policy is enforced for all installed components. Registration ensures that (1) only correct components are accessible by the M&A system, that (2) the purpose of these components is explicitly defined, that (3) these components will be correctly protected, and that (4) their reports are authentic because they can not be circumvented.

- **Portability:** The M&A service should support deployment in a wide range of systems, including different components within a single system. In order to provide a complete and protected plat-
form view, the M&A service should be designed and implemented in such a way that it can function in any environment, including on a client system, server, or embedded device in physical systems; or in the host, hypervisor, guest, and/or dedicated virtual machines (VMs) in a virtualized system.

- **Composability:** Integrity evaluations may require the gathering and evaluation of evidence from multiple administrative realms within a single platform, or across multiple hosts. Multiple instances of the M&A service should work together to delegate both evidence collection and evaluation tasks to the most appropriate instance. Because measurement functionality must be protected from the target of measurement, providing a complete evaluation of a virtualized platform may involve cooperation between instances of the M&A service in a guest VM, in an administrative VM, and in the virtual machine monitor (VMM) itself.

- **Support for Complex, State-based Measurements:** The service should allow for complex evidence collection. An attestation may require invoking a collection of measurement agents that each inspects a different aspect of target state. To perform a complete evaluation, collected evidence or intermediate evaluation results may introduce additional measurement requirements. For example, if a software inventory measurement shows that a Kerberos authentication package is installed, a measurement of the Kerberos configuration may be required. These kinds of recursive measurement dependencies necessitate M&A support for incremental discovery of measurement requirements.

Table 1 gives a summary of how these features collectively support all the identified properties for M&A.

### 2.2 Adversary Model

The goal of measurement and attestation is to detect adversaries that seek to alter the long-term behavior of a platform by modifying long-lived data residing either in memory or on persistent storage. Specific measurement configurations may address adversaries with limited capabilities, such as modification of user level programs but not kernel data. Other configurations may target much more powerful adversaries capable of arbitrarily modifying data anywhere on the platform, including in the OS, Virtual Machine Manager (VMM), and BIOS/System Manage Mode (SMM) memory and storage. A framework that attempts to unify all M&A activities should support measurements that can be used in aggregate to identify traces of all classes of adversaries.

The details of the measurement strategies employed by measurement agents are out of scope for the purposes of this paper and the development of Maat. The properties and requirements described in this section allow for measurement agents to be used in conjunction to detect existing and future adversaries.

Maat’s emphasis on composability is particularly important to supporting detection of a broad range of adversaries. Maat is designed to support collection of evidence at different levels of trust throughout the platform. By evaluating evidence collected at a level of trust higher than the expected adversary’s capabilities, the appraiser can justify confidence in less trusted components.
3 Related Work

A primary purpose of operating systems is to provide a set of reusable abstractions to support the development and execution of user applications. Features that are common across many applications are good candidates for extraction into a system-wide service to free developers from the need to maintain separate solutions and to centralize administration for end users.

The Pluggable Authentication Modules (PAM) framework is a good example of this philosophy [16]. Authentication was originally performed directly in the login process, but as the number of programs implementing authentication and mechanisms for providing authentication grew, the PAM library became necessary to provide a single interface for programmers and a configuration point for users. Thanks to this centralization, the system administrator uses a single configuration system to define what kinds of authentication may be used in what circumstances.

The need for a system-wide service for integrity evaluations follows a similar argument. There is a growing body of work on software integrity measurement and attestation. We have observed numerous instances of isolated or implicit integrity evaluations in common platform usage, and a growth in the number of mechanisms supporting the collection and presentation of platform integrity.

3.1 Measurement Agents

Measurement agents gather evidence that must be evaluated against some policy to determine a target’s integrity. There are a large number of measurement agents that collect evidence that may be part of an integrity decision. TPM quotes are a common form of evidence used to verify that the platform software was valid at platform startup. Other tools, such as IMA [4] and Bit9 [17], provide load-time checks on programs as they launch and are used to verify that the software being run was valid at program start time. Dynamic runtime systems, like LKIM [1] and Semantic Integrity [18], can verify that both the static and dynamic state of a piece of software is valid at a specific time in the process’s life cycle. Common system administrative tools can also be used as measurement agents. For example, the firewall configuration could be measured against an approved configuration, or a recently completed virus scan could be used as evidence to inform an integrity decision.

Some agents, such as LKIM, IMA, and tools for retrieving TPM quotes, may be designed to provide only the basic collection capability. Others, such as SecureBoot [19] and IMA/EVM [20], combine evaluation with collection. Maat can incorporate the results of all types of measurement agents, and provides a centralized framework for the selection and aggregation of measurements.

3.2 Existing M&A Frameworks

Several M&A frameworks, including Trusted Network Connect (TNC), SAMSON, and OpenAttestation are implemented and in active use. These frameworks generally include their own measurement agents, a specific protocol for gathering and communicating measurements, and components for evaluating the evidence presented. These systems are somewhat comparable to Maat, but have much narrower focus and limited extensibility. TNC is focused specifically on attestation for the purpose of access control [21]. SAMSON is focused on remote attestation of client machines in an enterprise environment [22]. And, OpenAttestation is focused on remote attestation in enterprise or cloud environments [23]. Table 2 shows how existing framework solutions for integrity compare to Maat in satisfying the features described in Section 2.1.

None of these systems addresses how attestation can be more fully integrated into the platform to reduce redundancy and ease administration. As a result, on a typical GNU/Linux platform, two completely independent implementations of TNC may be installed: one as part of the WPA_supplicant tool for wireless network connectivity, and another as part of the strongSwan IPsec package. These implementations are derived from independent codebases, managed via distinct configuration files, and utilize redundant but incompatible plugins for integrity measurement collection and verification.

Nearly all systems discussed here provide a plu-
Table 2: Comparison of framework architectures for integrity measurement against the list of critical features delineated in Section 2.1. ‘X’ indicates a feature is supported, ‘/’ indicates a feature is partially supported, and a blank indicates no support for the feature.

| Feature                  | SAMSON | TNC | O.A. | Maat |
|-------------------------|--------|-----|------|------|
| Multiple Appraisers     | X      | X   | X    |      |
| Multiple Protocols      | X      | X   | X    |      |
| Policy-Based Negotiation|        |     |      |      |
| Discrete Components     |        |     |      |      |
| Registration            | /      |     |      |      |
| Portability             |        |     |      |      |
| Composability           |        |     |      |      |
| Complex Measurements    | X      | X   | X    |      |

gin mechanism to run multiple types of measurement agents. The TNC specifications are specifically designed around the idea of pluggable integrity measurement collectors (IMCs) and integrity measurement verifiers (IMVs). During attestation, the TNC client (attester) executes a predefined set of IMCs, and the TNC server (appraiser) executes a corresponding set of IMVs. The IMCs and IMVs communicate with each other via the TNCCS protocol\[ 24\]. SAMSON is designed around a plugin architecture, and uses TNC interfaces and protocols. OpenAttestation is the only system to hard-code the supported measurement agents.

Few systems feature policy-based negotiation, and in most cases the evaluator demands a particular set of measurements and the client must either allow those measurements or refuse to participate. In some commercial systems targeting enterprise client management, the attesting software seems to be hard coded to unconditionally satisfy any requests for attestation. No system we evaluated supported selection of scenario-specific attestation protocols, or collection and composition of measurements from multiple administrative domains.

Support for strong isolation is also remarkably rare. In all the systems we examined, measurement collectors and evaluators ran within the same process that responds to requests and communicates with the attestation peer. Given that few systems support the other features, it is unsurprising that they do not provide much support for registration. OpenAttestation does not support plugins, so there is nothing to register. TNC specifies that each IMC/IMV filename be explicitly listed in a configuration file, but this simple mechanism contains insufficient metadata about each component to fully inform the types of decisions a framework must make. The SAMSON documentation does not indicate any specific registration mechanism.

3.3 Auditing Frameworks

Network monitoring systems, such as Nagios\[ 25\], are intended to allow system and network administrators to quickly collect status data on a large number of systems. Like Maat, auditing systems tend to be built around a modular design, and may have modules for collecting similar data such as system logs, TPM boot-time measurements, or filesystem hashes. However, auditing systems are generally aimed at collecting statistics within a single administrative domain, and are designed around a much simpler trust model. Auditing agents are installed and configured by an administrator, and are specifically designed to report any requested data to the single central auditor controlled by the network administrator.

The need for auditing capabilities for cloud computing platforms is widely recognized. Ko et al.\[ 26\] identify security, privacy, accountability, and auditability as components of trust in cloud computing, and describe a high-level layered model, called TrustCloud, for analyzing accountability in a cloud environment. Abbadi et al.\[ 27\] provide a more detailed breakdown of requirements for supporting trust in clouds, and define TPM-based attestation protocols for one-way and mutual authentication. They do not delve into how the required agents should be implemented on the hosts or integrated into existing platform services other than to note that the agents must not “reveal domain credentials in the clear, … transfer domain protection keys to others, [or] … transfer sensitive domain content unprotected to others”. Maat gives a concrete framework for implementing and integrating these concepts.

Flogger\[ 28\] implements an auditing system using a kernel module for interception of filesystem accesses on a physical host and within a VM, a process for uploading logs from VMs to a receiver process on
the physical host, and a database that consolidates reports from multiple physical machines. This work is narrowly focused on the problem of cloud auditing of file system events. It does not consider other applications of attestation, and leaves security and integrity concerns as an area of future work. Progger [29] is follow-on work that expands the scope of Flogger and addresses some of the log integrity concerns, but is still narrowly focused on data provenance auditing, and relies on the integrity of VM kernels to provide trust. Both Flogger and Progger are examples of systems that assume a particular goal for evidence collection and implement a single collection and presentation strategy to support that goal. Maat provides a design methodology for isolating these concerns and a general infrastructure for integrating them into systems.

Singh et al. [30] identify the need for strong, policy-driven middleware for both audit collection and enforcement for internet of things (IoT) and cloud-based systems. While they focus on system-wide information flow control, they call out specific need for trust on the platform and ways to verify that auditing policy is being faithfully enforced. We see Maat as complementary; it provides both the on-platform capability for policy enforcement and verification, and a trusted remote attestation mechanism.

4 Architecture

Maat is our prototype system that is explicitly designed to meet all of the desirable properties discussed in Section 2. Figure 2 shows the basic architecture of Maat. The Attestation Manager (AM) (Section 4.4) receives incoming requests, uses the Selection Policy (Section 4.4.1) to negotiate which protocols to run and what evidence to gather, and spawns the agreed-upon Attestation Protocol Block (APB) (Section 4.5). Following the prescribed Measurement Specification (Section 4.6), APBs invoke Attestation Service Providers (ASPs) (Section 4.7) to gather required measurements.

4.1 Attestation Roles

Measurement, attestation, and evaluation are most commonly conceived as one party, the attester, generating evidence and presenting it to a remote party, the appraiser, for evaluation. Figure 3 depicts how this common model of attestation is supported by Maat. Prior to the flows pictured, the appraiser AM receives a request to perform an integrity evaluation of the attester. The attestation begins with a negotiation (flow 1) between the attester and appraiser AMs. Once a suitable protocol/evidence pair has been agreed upon, the AMs each execute the APB implementing their half of the protocol (flow 2). During the protocol execution, measurements are gathered on the attester by ASPs and passed to the APB (flow 3). The attester’s APB bundles the evidence and sends it to the appraiser’s APB (flow 4). The appraiser’s APB parses the evidence received from the attester and passes it to a series of ASPs representing the appraisal decision logic (flow 5). The result of this appraisal is then returned, possibly with additional supporting data, to the original requester.

The diversity of scenarios for integrity evaluation implies additional models for attestation. For example, some may happen entirely locally to a platform; others may split the appraisal, performing some local checks and some remote checks; and some attestations may include third party trusted appraisers. Maat is flexible enough to support these diverse models. In particular, any component in Maat may perform as either an attester or an appraiser, even within the same attestation.
4.2 Security Model

Section 4.2 discussed the importance of protecting an attestation service from interference by the target of measurement. Attestation services regularly communicate with untrusted parties, and require significant local authority in order to collect measurements. This makes any attestation service an attractive attack vector for adversaries seeking to gain access to a platform. To limit the impact of an adversary subverting an attestation component, it is imperative that the entire system be sandboxed to the greatest possible extent, and that internal components are protected from one another.

Maat’s security model is designed around discrete M&A functions. The AM, APBs, and ASPs each execute in separate processes to allow OS or hypervisor level controls to assign only the necessary privileges to each component. Maat uses standard UNIX access control mechanisms, POSIX capabilities, SELinux, and VM isolation and introspection to provide varying levels of isolation between the components.

This isolation allows low-level measurements to be collected by more trusted components and used to support the trustworthiness of higher-level measurements. For example, a measurement of a VM’s kernel and Maat instance collected via VM introspection may give an appraiser confidence in the validity of measurements collected by the Maat instance running in the VM. The ability to chain measurements to gain confidence in higher-level measurement functionality is critical to justifying trust in the Maat framework. Ultimately, the chain should be rooted in a highly trustworthy component such as a small, verified hypervisor running an embedded “mini-Maat” instance and statically measured into a TPM at boot time.

We have implemented necessary hooks and policies for governing Maat interactions using standard POSIX discretionary access controls (DAC), Linux capabilities, and SELinux mandatory access controls. These models can be coordinated to provide granular control over process privileges. The DAC model allows each component in Maat to run with individual user permissions specified at registration. This allows the externally communicating components (the AM and APBs) to run as unprivileged users while only the measurement gathering ASPs are run with higher privileges. A set of Linux capabilities [31] can be specified at registration to further limit the administrative actions an ASP running as the super user may perform. SELinux provides an even greater level of isolation, as each APB and ASP can be given a unique SELinux domain with exactly the necessary privileges.

SELinux also provides guarantees that measurements are collected by the correct component invoked in the correct way. The AM’s executable is given an SELinux type that has sole transition access to the correct domain for the AM, files containing keys used to identify the AM are given an SELinux type that can only be read by this domain, and APB images are given types that can only be launched by this domain. On APB launch, SELinux forces a transition into a domain with access to exactly the set of credentials and ASPs appropriate for that APB. Finally, ASPs are run in domains with the minimal privileges necessary to execute their particular function. Combining trust in Maat and SELinux with a carefully constructed protocol allows an appraiser to conclude that the measurements presented by the attester were collected by the correct components.

Maat also uses SELinux’s category mechanism to isolate concurrent attestations similar to how virtual machines are isolated from one another under
sVirt\[32\]. The AM is initially provided with a large set of categories. Each attestation session is handled by spawning a child process of the AM to perform negotiation and then execute an APB. The parent AM gives each child a unique set of categories in which to execute. The APB can then similarly apportion its categories to ASPs as they are executed. This policy protects the platform from subversion of Maat, protects Maat from subversion of the platform (excepting attacks that subvert the operating system kernel), and protects each component of Maat from subversions in other components.

For many measurement goals, OS level isolation is insufficient to guarantee the needed isolation of measurement agent and target. Most notably, measurements of an OS kernel itself can’t be reliably performed from a process running on top of the OS. One solution to this problem is to implement ASPs to self-protect using existing hardware mechanisms. Specifically, an ASP could use a Flicker-like approach to establish a protected execution environment or Intel’s Secure Guard eXtensions (SGX) to create a secure enclave\[33\]. These solutions work and are supported by the Maat architecture, but may require substantial code replication across multiple ASPs.

4.3 Multi-Realm Attestations

Maat is intended to be replicated in each administrative or protection domain throughout a platform. During negotiation and attestation, instances of the architecture in one domain may delegate decisions or evidence collection to another instance in a more appropriate domain. This scheme reuses the existing Maat functionality to provide a common interface for invoking measurement capabilities that require greater isolation than can be provided within a single operating system.

For example, on a virtualized platform there may be instances of the M&A architecture running:

- In each guest VM, for measuring the userspace of that VM
- In the administrator VM, for measuring the kernels of the guests and the administrator VM’s userspace
- In the VMM, for measuring the administrator VM

This hierarchy allows for trustworthy collection of evidence at all levels from the guest VM to the kernel of the administrator VM. Given appropriate hardware protection capabilities, another instance capable of measuring the VMM itself is possible.

There are many open research challenges related to combining measurements from multiple administrative domains that must be answered. These include: (1) the correct place to store policy and perform negotiations, (2) in what order to invoke measurements, and (3) how to endorse and combine measurements to produce a thorough argument that each measurement was properly collected and communicated. Maat is able to support many alternate solutions to each of these problems, and thus provides a useful basis for experimentation and the eventual integration of adopted solutions.

4.4 Attestation Manager

The AM has two jobs in Maat: (1) it acts as a registration point for APBs, ASPs, Measurement Specifications, and (2) it is responsible for negotiating and dispatching protocol/evidence pairs for each attestation request. The same AM software is capable of acting as either an appraiser or an attester, and in complex attestation scenarios may take on elements of each role.

In order to negotiate an attestation scenario with a peer in good faith, the AM must know which APBs, ASPs, and Measurement Specifications are available on the system. We have partially implemented a registration mechanism for Maat that achieves this by relying on the target system’s native package manager to correctly resolve dependencies between components and assign appropriate permissions (user, group, SELinux label) to the installed files. Each component is identified by a UUID that is specified in a metadata file installed as part of the component’s package. These UUIDs are used at runtime to resolve dependencies, and are the basis for the AM’s negotiation protocol.

While this implementation meets many of our goals...
such as dependency tracking and automatic security label assignment, it does not allow for additional checks on the pedigree of individual components nor does it facilitate smooth updating of the AM’s selection policy. Currently, these checks are performed at load time using the metadata file provided with each component. Future versions of Maat will feature a more complete registration mechanism that performs these checks at registration time. This mechanism will enhance the existing package management functions with customized dependency and pedigree checks using the included metadata file. Additionally, registration should move away from explicit UUID-based dependencies in favor of feature-based dependency tracking. For example, APBs should be able to specify measurement collection features by name and pedigree requirements rather than specific UUIDs of required ASPs. This will allow for negotiations based on properties of attestations rather than well known UUIDs.

### 4.4.1 Selection Policy

Negotiation of an attestation protocol and measurement specification is guided by local selection policies at both the attester and the appraiser. The goal of negotiation is to select a protocol/evidence pair that satisfies the integrity checks required by the appraiser without violating the privacy or exceeding the computational limits of the attester. The appraiser’s selection policy defines what protocols and evidence are necessary to assess the integrity of a given attester requesting access to a specified resource. The attester’s selection policy defines which protocols and evidence it is willing to provide to a given appraiser in order to gain access to a given resource.

The policy must contain a series of declarative rules mapping inputs describing the current attestation to actions. The policy may be stored either in a simple file or as a database for larger policies. For both the appraiser and attester, the inputs to the selection policy are:

- the role of the party in the attestation
- the other party’s identity
- the strength of this identity association
- the resource being requested
- the current state of the negotiation.

Figures 4a and 4b show state machine views of the negotiation and selection processes on the appraiser and attester respectively.

A request for integrity evaluation received by the appraiser must specify the identity of the attester and the resource being guarded. The appraiser matches these inputs against its policy, which may result in a match failure (not pictured), a request for a stronger identity binding, a deferral, or a set of protocol/evidence options. In the first case, attestation is aborted and an error is returned. If a stronger identity binding is needed, a call can be made to an ISAKMP daemon to produce the needed association before continuing the negotiation. If negotiation is deferred to another appraiser, the request is forwarded and a proxy process may be created to forward messages if necessary. If a set of options is returned, an initial contract is generated and sent to the attester.

The attester uses these inputs to consult its policy. If successful, this results in a counter offer: a subset of the offered options that the attester is willing to perform. These options are sent to the appraiser, which then consults its policy to determine the preferred option, sends this option to the attester, and begins execution of the corresponding appraisal APB. The attester performs a final policy check to verify the suitability of the appraiser’s selection, then executes the selected APB.

This negotiation process is intended to ensure that the optimal protocol and evidence are selected. Notably, the selection is made by the appraiser rather than the attester. This necessitates an extra communication round trip in the protocol, but ensures that the appraiser’s prioritization is respected. An alternate solution could treat the initial options as a prioritized list rather than an unordered set, and trust that the attester will select the highest priority option consistent with its policy. This choice does not seem to have any direct impacts on the trustworthiness of the selection: the appraiser shouldn’t
offer any options that are not sufficient for its trust goals, and it must already trust that the attester is correctly implementing negotiation. However, the extra step provides more explicit appraiser control over the outcome of negotiation in exchange for minimal performance overhead (performance is typically dominated by the measurement collection) that could be easily eliminated by a cache of negotiation outcomes.

4.5 Attestation Protocol Blocks

APBs are responsible for understanding the requirements of a particular attestation scenario as defined by the Measurement Specification, executing an appropriate sequence of ASPs to satisfy the scenario, and collecting the results generated by individual ASPs into a cohesive whole that is consumable by the remote party. Dually, an APB may implement an appraisal component that evaluates evidence by invoking a sequence of ASPs to verify properties of the measurement data and synthesizing a final report indicating the overall determination of integrity along with any required supporting evidence. Protocols may be implemented either as two separate APBs, one for the attester and one for the appraiser, or as a single APB that determines which role to execute based on context provided by the AM.

APBs rely on ASPs and/or other APBs to produce or evaluate measurements. Upon registration with the AM, each APB must provide an XML metadata file that statically lists supported Measurement Specifications and defines the set of ASPs and sub-APBs required to execute the protocol. With this information, the AM can ensure that all dependencies can be satisfied, and can invalidate a protocol if any of its dependencies are de-registered.

We separate evidence collection and collation into ASP and APB functionality respectively to allow for greater reuse of components, to support finer-grained policy decisions, and to enable more granular access control decisions to isolate pieces of M&A functionality. However, Maat is flexible and can accommodate “fat” APBs that collect evidence directly or “fat” ASPs that collect multiple types of data.
4.6 Measurement Specifications

Measurement Specifications define what evidence the requester requires for a specific scenario. Separating the evidence requirements from the protocol used to collect and transmit evidence (APBs) allows the construction of generic APBs that can be re-used for multiple attestation scenarios. Like APBs, Measurement Specifications are registered with the AM and are identified by a well-known UUID. Once an APB/Measurement Specification pair is negotiated, the APB is launched using the Measurement Specification as input.

Measurement Specifications contain as much information as is necessary to define the type of evidence required. Implementations may define a specification language that provides rich syntax for defining complex evidence relationships. Any such language must be understood by the APBs, which parse the specification into a series of actionable instructions. Maat includes an implementation of a specification language as an optional library. Specifications in this language define a set of measurement variables that identify particular data requiring measurement, and measurement instructions that define what measurements are required for variables of a given type. During evaluation, measurement instructions may introduce new variables that must be measured. The complete measurement requires recursively evaluating these measurement obligations until no new variables are introduced.

The complete syntax and semantics of Maat’s measurement specification language are beyond the scope of this paper. The example given in Figure 5 provides a reasonable overview of the language’s features. This example implements a common goal of integrity measurement systems: to provide a TripWire-like summary of the hashes of all files recursively found in the /etc directory.

The specification language supports specification composition, since multiple specifications may cause different evidence to be collected for the same piece of target state. For example, another specification that extracts a list of users from the /etc/passwd file may be combined with the example in Figure 5 to generate a measurement containing both a hash of /etc/passwd and the list of users. The evaluation order of measurement instructions is not strictly defined. Our example APBs utilize a queue of measurement obligations and continue executing until the queue is empty, but any strategy that guarantees that all obligations are eventually discharged is valid.

4.7 Attestation Service Providers

Attestation Service Providers (ASPs) are the basic functional unit of Maat. Each ASP performs a specific, discrete function in evidence collection tasks. For example, an ASP can gather a specific piece of evidence from the system, ingest some type of evidence and contribute to an assessment of the target’s integrity, provide post-processing functions such as hashing or compression, or call out to external components such as another AM or service. Maat makes no distinction between ASPs that collect evidence and ASPs that evaluate evidence. This decision is intended to help support more complex attestation scenarios in which partial appraisals may occur locally with measurement collection, or with a third party appraiser not involved in the initial negotiations.

ASPs are invoked by an APB, using an implementation-defined interface. In line with our desire for discrete M&A functions, ASPs run in their own address space and may have their own fine-grained policies. ASPs may be invoked as a discrete event, chained into a pipeline, or called multiple times for a single attestation. The ordering of invocation is determined by the APB and its interpretation of the Measurement Specification.

Figure 5: Example measurement specification for recursively enumerating and hashing regular files in the /etc directory.
5 Example Use Cases

The prototype implementation of Maat allows us to verify that the proposed architecture is flexible enough to integrate and/or consolidate integrity information in a variety of deployment scenarios. These include both augmenting existing systems with additional plugins that call out to Maat externally, and subsuming existing services into Maat as APBs or ASPs. We provide several examples of integrating Maat in the following sections.

5.1 Authentication

Many UNIX systems use the PAM library to provide a system-wide authentication service. As discussed previously, PAM centralizes authentication decisions, while providing an extensible architecture through the use of plugin modules. This extensibility makes incorporating integrity information into authentication decisions straightforward.

An adversary can easily use spoofed authentication windows to trick users into giving up their credentials. To enable users to confirm the integrity of a system before authentication, we integrated Maat with authentication by creating a PAM module that calls out to Maat for an integrity analysis. Maat uses a corresponding PAM policy that checks a system for compliance before the user enters his or her credentials. If the system fails to meet the required policy, the interface displays an alert, informing the user that the system is noncompliant. The combination of PAM and Maat made it trivial to integrate system integrity verification into the login process.

5.2 Network Access Control and IPsec

Network access control (NAC) is implemented by the 802.1x standard, which frequently uses the Trusted Network Connect (TNC) framework for gathering measurements from the system before allowing access. While the limitations of TNC have already been discussed, the fact that TNC is spiritually similar to Maat allows interesting opportunities for integration.

Our first method of integration was achieved by creating a TNC IMC/IMV pair that calls out to the M&A service, and uses the result of the M&A decision as input into TNC’s overall NAC decision. This form of integration is straightforward; however, it makes the M&A service a subordinate protocol to TNC, and limits the ability to use the richness available when using the M&A service directly.

Our second integration of TNC incorporated the TNC Server, TNC Client, TNC IMC/IMV interface, and the TNC communications protocol into a pair of APBs, which are negotiated and directly launched by Maat’s AM. To achieve this, we took an existing implementation of the above services (strongSwan) and wrote a small shim layer to adapt the native interface of these services to Maat’s APB interface. The resulting APB allows the TNC infrastructure to be directly employed through the M&A service for any purpose, not just for NAC.

To trigger Maat from the NAC process, we wrote a vendor-specific Extensible Authentication Protocol (EAP) method for the NAC server and client, hostapd and wpa_supplicant respectively. The EAP method communicates with Maat via a UNIX domain socket, and serves as a proxy between the attester and appraiser instances. Upon receiving a request, the attester and appraiser undergo their standard negotiation to select the appropriate attestation protocol and evidence for the scenario. For TNC, we use a mapping of evidence spec UUID to sets of IMC/IMVs to determine which IMCs/IMVs the APB should load and execute. This allows the same TNC APB to provide and/or evaluate different sets of evidence, depending on the result of negotiation.

Maat’s inherent flexibility allowed us to implement both methods of integration. This flexibility is critical to supporting legacy systems and provides multiple, straightforward migration paths for network administrators to continue leveraging existing tools while taking advantage of Maat’s desirable properties.

TNC can also be used during IPsec authentication. Our integration with TNC facilitated integration with IPsec. IPsec negotiates security associations (SAs) between two hosts on an IP network. These SAs allow for cryptographically authenticated and/or encrypted traffic to be passed between the two hosts.
using information incorporated into the SA. To inte-
grate Maat with IPsec, we modified the code for
our vendor-specific EAP method to call out from the
strongSwan IPsec stack to the Maat AM, which then
chooses the same TNC APB used for NAC to take a
measurement and send results to the IPsec service.

The ability to use the same TNC APB for both
IPsec and NAC shows that Maat can consolidate
measurement agents, eliminating the need for custom
TNC code in the NAC and IPsec services. Further,
the separation of protocol selection from required
evidence in Maat allows the IPsec scenario to employ
different IMC/IMVs than were selected for NAC.

5.3 Host Monitoring

Network administrators often want to make use of
host integrity data as part of a network monitoring
system. Maat includes a simple web application that
allows network administrators to manage host iden-
tities, view historical integrity reports, and request
fresh integrity evaluations. Using the web interface,
the system administrator can register a host for moni-
toring and request fresh evaluations by specifying the
host(s) to be evaluated and monitoring criterion. The
web application uses an instance of Maat to negotiate
with each target, perform the evaluation, and generate
a detailed report that is then stored in a database.
This use case is common in an enterprise deployment
but is typically handled using ad-hoc or proprietary
reporting systems. Maat provides the same benefits
for a host monitoring system that it does for access
control focused use cases.

For broader impact assessment, an early version of
Maat is currently deployed on a large scale enterprise
network collecting, archiving, and appraising both
periodic and on-demand measurements from several
hundred actively used Linux-based systems. It pro-
vides a single, secure interface for collecting a wide
variety of information, including TPM quotes, soft-
ware inventories, file integrity checks, and kernel in-
tegrity measurements. The IT system administrators
expressed appreciation for Maat’s ability to collect
this variety of measurements. They use five or more
independent, proprietary systems to collect the same
information for other operating systems. Each of
these systems requires financial investment, training,
configuration, and introduces new security concerns to
the IT architecture. Unifying these features in Maat
eliminates this complexity and allows administrators
to quickly access the data they need in a consistent
interface.

5.4 Internet of Things

We further tested Maat’s flexibility and extensibility
by modifying it to measure non-traditional platforms,
such as those used as part of the internet of things
(IoT). Separate from the enterprise use case, these
platforms present significant challenges for M&A such
as lack of common software bases, ad-hoc communi-
cations mechanisms, and potentially severe resource
constraints. However, IoT devices represent a growing
threat to the security of the systems with which
they interact and thus need the same integrity eval-
uation capability available to non-IoT systems. We
divide the class of smart devices into two categories:
high- and low-capability.

High-capability devices are embedded systems that
contain enough resources and platform features to
allow running the entire Maat stack within the con-
straints of their environment. Examples of such sys-
tems include high-end smart appliances and gateways
which run stripped-down versions of standard multi-
tasking operating systems such as Windows or Linux.
These platforms have computing capacity, power, stor-
age, and memory protection necessary to run the en-
tire Maat stack, assuming that Maat were ported to
the target platform and contained appropriate ASPs
to take meaningful measurements. We demonstrated
this by successfully running Maat on a 32-bit ARM
Cortex-A series development platform and a commod-
ity MIPS-based router running OpenWRT. Both
platforms run on custom versions of the Linux oper-
ating system. Once configured, these high-capability
IoT devices operated as part of the Maat system just
as every other platform did.

Low-capability devices are much more constrained,
and often lack the resources to run Maat effectively
without modification. As fully discussed by Clemens
et al., Maat can be modified to provide negotia-
tion and collation features (essentially the AM and
APB aspects) on a high-capability device while de-
ferring specific measurement collection to a miniatur-
ized instance running on the low-capability device. The
miniaturized instance lacks many of the pro-
tective features of Maat but implements the same
interface for invoking measurement capabilities. The
end result shows how Maat can be used to provide
centrally-managed, policy-driven, comprehensive, and
efficient M&A capabilities to a broad range of plat-
forms, from high-end enterprise systems to severely
resource-constrained environments.

6 Further Research Challenges

While Maat is designed to satisfy the properties de-
scribed in Section 2, there remain many open research
challenges. Some of these challenges will be addressed
by improving the prototype implementation, others
are broader challenges that require further research.

As noted in Section 4.4, the existing registration
mechanism is not expressive enough to support all of
the desired protection properties, and will need to be
improved in future implementations. We also believe
that our current selection policy mechanism will need
refinement to both the language and the dispatch
mechanism to allow for decisions based on attributes
of an attestation scenario that are not currently ex-
posed. Improvements to registration and selection
would also enable a richer negotiation process based
on attributes of the protocols and evidence being se-
picted rather than on UUIDs. Developing an attribute
language that is rich enough to encompass all pos-
sible measurements, protocols, and trust properties
while being precise enough to guarantee compatibility
between endpoints is a significant research problem.

As discussed in Section 4.3, support for multi-realm
attestations is a major area of future work. Maat is
designed to be replicated in each administrative do-
main. However, important research questions remain
that could impact the trustworthiness of attestations.
These include where to store policy and perform ne-
goitations, in what order to invoke measurements,
and how to endorse and combine measurements to
produce a thorough argument that each measurement
was properly collected and communicated. These are
all open questions that must be answered for trustwor-
thy multi-realm attestations. Maat provides a basis
for experimenting with alternate solutions to each of
these questions.

Further development also suggests the need for a
system to provide comprehensive trust decisions as a
service (TDaaS) in software systems. This requires
integrating Maat into a larger framework that also
provides authentication, identity management, estab-
lishment of security associations, and maintenance of
a cache of known clients and a history of previous
successful negotiations.

As implemented, Maat targets traditional comput-
ers running a POSIX-compliant operating systems.
As noted in Section 5.3, Maat has also been used
to demonstrate M&A on sample IoT devices. How-
ever, the internet consists of many different kinds of
platforms, with varying hardware resources and oper-
atng systems. Supporting the separation guarantees
and negotiation requirements may be a straightfor-
ward engineering task for many platforms, but others
are so resource constrained that they require further
research and re-thinking of what is possible and nec-
necessary for integrity measurement. Finally, computing
platforms that are not general purpose often contain
custom software or firmware, requiring that special,
non-portable versions of Maat be integrated with the
custom system. Such diversity remains a challenge to
any framework that aims for broad adoption.

7 Conclusion

The time has come for a central framework for the
collection and presentation of integrity measurements
for use in trust decisions. We believe that such a sys-
tem must adhere to the properties enumerated earlier
in this paper, and prove that such a system is attain-
able today with a discussion of Maat, our prototype
measurement and attestation (M&A) framework.

Maat supports an array of attestation scenarios,
measurement types, and protocols, and it has a high
degree of flexibility to enable seamless integration
with legacy systems. Maat cooperates with both the
target and the requester in an attestation scenario.
Policy-based negotiation allows the requester to spec-
ify the evidence required to complete an attestation, and it allows the target to specify under what conditions each piece of evidence may be released. We have demonstrated the applicability of Maat through multiple deployment scenarios, and integration of Maat with PAM, NAC, IPsec, IoT, and client monitoring.

It is our desire for Maat to be used as a basis for further research into the field of trustworthy integrity measurement as well as a starting point for robust, system level M&A services.

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