SHAI: Enforcing Data-Specific Policies with Near-Zero Runtime Overhead

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Abstract—Data retrieval systems such as online search engines and online social networks must comply with the privacy policies of personal and selectively shared data items, regulatory policies regarding data retention and censorship, and the provider’s own policies regarding data use. Ensuring these policies is difficult and error-prone. Systematic techniques to enforce policies are either limited to type-based policies that apply uniformly to all data of the same type, or incur significant runtime overhead.

This paper presents SHAI, the first system that systematically enforces data-specific policies with near-zero overhead in the common case. SHAI’s key idea is to push as many policy checks as possible to an offline, ahead-of-time analysis phase, often relying on predicted values of runtime parameters such as the state of access control lists or connected users’ attributes. Runtime interception is used sparingly, only to verify these predictions and to make any remaining policy checks. Our prototype implementation relies on efficient, modern OS primitives for sandboxing and isolation. We present the design of SHAI and quantify its overheads on an experimental data indexing and search pipeline based on the popular search engine Apache Lucene.

I. INTRODUCTION

Data retrieval systems store, aggregate, index, recommend, and serve information. Examples include large-scale online social media sites, search engines, and e-commerce sites, but also numerous organizational, corporate, and government information services. To the extent that such systems serve personal or private information, they are subject to various data use policies.

Each data item served or used by a retrieval system may have its own individual usage policy. For instance, Alice’s e-mails are private to Alice, whereas Bob’s e-mails are private to Bob. A particular blog post of Alice may be public, whereas another of hers may be available only to her friends. In addition to personal access control settings, the system may need to comply with local laws and regulations regarding data retention and censorship. Finally, the system must comply with the provider’s own privacy policy, which may stipulate, for instance, that a user’s query and click stream be used only for personalization.

Ensuring compliance with all applicable data use policies in a large and agile data retrieval system presents a significant technical challenge. When compliance checks are entangled with application code, the policies in effect are difficult to audit and maintain. Moreover, any application bug or misconfiguration can cause a policy violation. As a result, there has been significant work on ensuring policy compliance separate from application code [7], [16]. However, existing systems for compliance are either limited to type-based policies [16], or their runtime overhead is too high for large-scale data retrieval systems [7].

Many of the data use policies that arise in practice are per-user, data-specific policies. For instance, the EU General Data Protection Regulation (GDPR) explicitly grants users individual choice regarding the use of their personal data [2]. Enforcing individual, data-specific policies, however, requires runtime enforcement for two reasons. First, static analysis loses precision quickly under data-specific policies, because the policy in effect for a particular program variable depends on the value assigned to it at runtime. Second, policies often refer to information only available at runtime. For example, whether an access is requested on behalf of user Alice is known only at runtime. Besides users’ identity, data use policies often refer to users’ geographic location (e.g., when a data item is censored in a specific jurisdiction), wall-clock time (e.g., when a news ticker item expires at a specific time), or content (e.g., a user’s current list of friends).

In this work, we propose SHAI, a novel system for policy compliance that can enforce fine-grained, data- and user-specific declarative policies with near-zero runtime overhead in the common case. SHAI combines offline, static flow analysis and light-weight runtime monitoring using an operating system’s capability sandbox. The idea behind SHAI is to try and push as much work as possible to the offline flow analysis to minimize and streamline the remaining, required runtime monitoring. The design of SHAI is based on the following ideas:

a) Use of offline flow analysis: Many aspects of a data retrieval system’s runtime behavior can be predicted statically and based on runtime monitoring. These aspects include the normal flow of information among the system’s components (tasks), the set of policies currently in effect, the set of users, and the geographic region(s) from which a user typically connects. Based on this information, an offline analysis (OA) predicts the taint each of the system’s tasks will acquire at runtime, subject to assumptions about the value of runtime variables. Finally, the OA compiles, for each task and each predicted runtime value, the predicted taint into a set of capabilities for all compliant I/O accesses.

b) Session-level binding of runtime information: Many runtime variables that are unknown during an offline analysis become known at the start of a user session. These variables include the identity of the user, the geographic region from...
which the user connects, and the wall-clock time. Based on the actual values of these variables, SHAI assigns the appropriate capability set provided by the OA for each task involved. If the value of a runtime variable is not among those predicted during the OA, SHAI registers the value as one that should be considered during the next OA.

c) OS sandbox to allow compliant I/O without runtime intervention: In SHAI, each of the system’s tasks is encapsulated in an OS sandbox subject to capability-based I/O access control. When a user session starts, SHAI grants each task the capability set predicted by the OA and selected based on available runtime information. As a result, the system can perform compliant accesses without runtime intervention. Because the capability checks are light-weight and performed by the OS kernel, their overhead is very low. In the common case where the runtime values are among those predicted by the OA, the cost of enforcing compliance is near-zero.

d) Runtime reference monitor as a fall-back: If a task performs an I/O access for which it does not have a valid capability, control is transferred to the SHAI reference monitor (RM), which performs a runtime policy check. The cause of this event may be a non-compliant access, an imprecise OA, or a change in the system state since the OA was performed (e.g., a change in policy, or an access to content that was created after the OA). If the access is non-compliant, the RM denies the offending access. If the access turns out to be compliant, the RM allows the access and patches the task’s capability set to reflect the latest set of compliant accesses.

e) Use of efficient OS isolation primitives: SHAI uses light-weight contexts (hwCs) [13], an efficient OS isolation primitive, to isolate multiple user sessions within the same process, and to isolate SHAI’s reference monitor.

The rest of this paper is organized as follows. We provide an overview of SHAI and its components in Section II and a detailed description of SHAI’s design in Section III. The SHAI prototype implementation on FreeBSD is described in Section IV and the results of an experimental evaluation are presented in Section V. We present related work in Section VI and we conclude in Section VII.

II. SHAI OVERVIEW

SHAI is a policy compliance system that helps data retrieval system providers enforce confidentiality and integrity policies on the data they collect and serve. We next describe SHAI’s data flow model, policy model, overall architecture, and threat model.

a) Data flow model: Figure 1 shows SHAI’s data flow model. SHAI enforces data policies in systems that are structured as pipelines of tasks. Each task in the pipeline consumes some data, processes it, and produces more data, which is then consumed by the next task in the pipeline. Data enters the pipeline, travels from one task to the next, and eventually leaves the pipeline in conduits, which is SHAI’s generic abstraction for any container of data. Files, named pipes, network connections and tuples in key-value stores are all conduits. Every conduit has a unique identifier—the full path name for a file or a named pipe, the five tuple (srcIP, srcPort, protocol, destIP, destPort) for a network connection and the key for an entry in a key-value store. We distinguish three kinds of conduits: ingress conduits that feed outside data to the initial tasks of the pipeline, internal conduits that are used to pass data between tasks of the pipeline, and egress conduits that are used to transmit final outputs of the pipeline to external applications or externally connected users.

b) Policy model: An administrator may associate a policy with any ingress conduit. This policy is a one-point description of all the confidentiality and integrity requirements of the data entering the system through that conduit. For example, the policy might say that the data (in the conduit) should be accessible only to Alice, or that it should be accessible only to Alice and her friends, or that it should not be accessible to users connecting from a specific geographic region (where the content may have been black-listed by legal mandate), or that the data in the conduit must have a specific shape or type. SHAI also allows policies to be associated with internal conduits, but these internal policies do not have to be trusted for enforcing the policies of ingress conduits.

SHAI always enforces every conduit’s policy, even on data derived downstream from that conduit’s data. For example, suppose an ingress conduit has a policy “private to Alice only” and that the rest of the pipeline works as follows: The ingress conduit is read by task A, which writes its output to a file f; file f is read by task B, which then sends a message to a different user Bob. The last message from task B to Bob potentially violates the ingress conduit’s policy since it completes a flow from Alice’s private data to Bob, so SHAI will not allow this last message to be sent.

SHAI’s actual policies can be much richer than those in this simple example and can specify declassification (i.e., policy relaxation) based on clock time and the type and content of data. More precisely, SHAI’s policies are specified in a declarative policy language, nearly identical to that used in Thoth [7]. In this language, a conduit’s policy has three rules: 1) A read rule specifies who can read the conduit’s data directly; 2) A declassify rule specifies what read rules should apply to conduits downstream in the pipeline, thus controlling who can read derived data. The declassify rule specifies a set of tests (called declassification conditions) on the global state and data in any conduit downstream, and how the read rule can be relaxed when each of those tests is satisfied; 3) An update rule specifies what type of content can be written to the conduit and by whom.

Fig. 1: SHAI data flow model.
Note that SHAI’s policies are data-specific: Every piece of data can have its own policy. In particular, two pieces of data of the same type can have different policies. For example, although a file containing Alice’s email and a file containing Bob’s email have the same type “email”, both have different policies—the former is accessible only to Alice while the latter is accessible only to Bob. This contrasts with other work like Grok [16], which enforces only type-specific policies, where all data of the same type has the same policy.

For brevity, we do not describe the details of the policy language here. All our development can be followed without understanding the syntax of the language.

A. Standard solutions and their shortcomings

At an abstract level, enforcing SHAI’s policies requires determining, for each egress conduit, which ingress conduits’ data could flow to it, and what declassification conditions (if any) must be satisfied along the flow. This is a standard data flow analysis problem, for which many different techniques have been proposed in literature. We briefly outline these existing techniques and their shortcomings in the context of (SHAI-like) data-specific policies.

Static techniques determine flows by analyzing the source code of the system. In addition to requiring the source code and being language-specific, static techniques work well only when enforcement is limited to type-specific policies. Static techniques do not work well when policies are data-specific. The reason is simple: Static techniques approximate data with program variables; as a result, the analysis cannot distinguish the policies of different data after they flow through the same variable. Data-specific policies care about this difference, while type-specific policies do not.

Dynamic fine-grained techniques, also known as runtime taint tracking techniques, track data flows between program variables, or between memory objects and machine registers at runtime. Depending on the specific implementation, a dynamic fine-grained technique may not have the shortcomings of static techniques mentioned above, but dynamic fine-grained techniques must intercept all memory and register reads and writes. This interception makes their overhead prohibitively high for most online systems (in the orders of upper 10s to 100s of percent).

Dynamic coarse-grained techniques track flows at coarser granularity, typically only across tasks in a system but not within each task. They only intercept reads and writes to conduits shared between tasks. This is far more efficient than tracking all reads and writes to registers and memory. Theoretically, this comes at the cost of precision—if a task reads a conduit f and later writes a conduit g, a coarse-grained technique must conservatively assume that there is a flow from f to g, even if the data written to g was independent of the data read from f. This can cause overtainting. Practical experience suggests that in data retrieval systems structured as pipelines of tasks, this kind of precision loss can be mitigated by a slight relaxation of policies [27]. Consequently, dynamic coarse-grained tracking is a reasonable option for enforcing SHAI-like policies.

Nonetheless, dynamic coarse-grained tracking still has a significant performance impact, at least on moderate or high throughput systems. As a case in point, the Thoth system [7], which uses dynamic coarse-grained tracking to enforce policies identical to those considered in this paper, has a relative overhead of almost 3.5% on the throughput of a simple data indexing and search pipeline, even at a very modest throughput of only ~300 queries/s/machine. As the throughput increases, this relative overhead increases significantly, reaching over 23% at ~3,000 queries/s/machine on a port of Thoth to our experimental setup (see Section V).

Hence, no existing system can enforce data-specific policies with consistently low overhead. Our goal with SHAI is to change this state of the art. Ideally, we want to enforce data-specific policies with zero overhead. Of course, attaining this ideal goal is impossible but as we show, we get very close.

a) Thoth: The starting point for our design is Thoth, which can already enforce data-specific policies efficiently in small-scale, low throughput systems. In the following, we explain briefly how Thoth works, what the dominant sources of overhead in Thoth are, and what SHAI does differently to mitigate these overheads.

As stated above, Thoth performs coarse-grained runtime flow tracking to enforce policies. Thoth maps tasks to OS processes and implements a reference monitor (RM) that intercepts every conduit I/O in the kernel. The RM maintains a taint for every task (process) in the pipeline. This taint is a policy that is always at least as restrictive as the policies of all conduits that the task has read in the past.

When a task opens a conduit for reading, the RM intercepts to check whether the taint on the task is already more restrictive than the policy of the conduit. If so, it does nothing further. If not, it intersects the current taint of the task with the policy of the conduit. When a task opens a conduit for writing, the RM intercepts to first check the update rule of the conduit. Next, it checks the declassification conditions in the taint of the task, which may relax the taint, and then checks whether the (possibly relaxed) taint is at least as permissive as the policy of the conduit being written. These checks on conduit opens ensure that, modulo declassification, the policies of conduits downstream of a conduit f are always more restrictive than f’s policy. As a result, the restrictions of f’s policy cannot be “lost” on data derived downstream.

The RM enforces policies on egress conduits connected to end-users by direct checks. For example, if an egress conduit’s read policy says that only Alice can read, then the RM ensures that the egress conduit is actually connected to Alice by verifying the public key that authenticates the connection.

As mentioned above, despite its efficiency compared to older solutions, Thoth still has significant overhead with respect to the system’s throughput. This overhead has two dominant sources.

1) Interception of every conduit open by the RM to check taints and declassification conditions is expensive. In
Thoth, every interception involves a context switch to a dedicated process that hosts the RM.

2) Once a user-facing task has served private data to a user, that task cannot serve a different user without shedding its previous taint. To shed that taint cleanly, the task must be reset to a clean state. The usual way of doing this is to re-exec the process hosting the task. Re-execing is expensive. Since taint must be shed only once per user session, the amortized cost of re-execing reduces with increase in session length, but it is still significant even for moderate session lengths (4-8 user queries per session) in Thoth.

B. SHAI: Key ideas

SHAI is a re-design of Thoth with two key ideas to mitigate most of Thoth’s overhead. First, SHAI adds to Thoth a new offline phase that does most of the work of the RM ahead-of-time, thus significantly reducing the need to intercept I/O. Second, SHAI uses a different implementation of tasks that allows for much faster state reset. End-to-end, the offline phase reduces the overhead on each user request to near-zero in the common case, while the change to the implementation of tasks significantly reduces the overhead on user session establishment.

a) Eliminating RM interceptions: SHAI eliminates the need for runtime interception of most conduit accesses using a periodic, ahead-of-time, offline analysis (OA). During the OA, SHAI makes (and caches) policy checks on the reads and writes that the system is likely to make in later executions of the pipeline. For this, the OA takes as input a list of tasks in the pipeline, what conduits each task is likely to read and write during the pipeline’s execution, an estimate of the task’s anticipated taint at runtime and the policies of all conduits. With the exception of the policies, these inputs are not trusted for policy enforcement; getting some of them wrong only results in a proportionally higher overhead at runtime. All inputs can be easily determined by running the pipeline in a test environment, by monitoring the production system, or by a simple manual analysis.

The OA simulates the checks that the Thoth RM would make for each conduit access specified in the inputs (but without actually running the pipeline). Later, at runtime, each task runs in a OS sandbox, which allows conduit accesses that were already checked by the OA without faulting into the RM. These accesses run at native speed. In the rare case that an access not foreseen by the OA occurs, the OS sandbox faults into the RM, which makes the same policy checks that Thoth would make.

Our current prototype uses FreeBSD’s capability system (Capsicum) [18] (with small modifications) for the OS sandbox. Capability checks in Capsicum are highly optimized and incur nearly zero overhead. This, coupled with the OA, reduces the overhead of I/O interception to nearly zero in the common case.

While this idea is conceptually simple, it has several nuanced details that we explain in Section III. First, a task’s ability to make certain accesses may depend on parameters whose exact values will be known only at runtime, e.g., which user has authenticated remotely, which geographic region the user has connected from (to enforce legal, region-based content blacklisting), etc. To permit the OA to take these parameters into account, the anticipated values of these parameters can be coded within the task description (specifically, within the task’s taint). These anticipated values are then verified at runtime, but only once when the task starts running. In practice, this amounts to checking these parameters once per user session, not on every conduit access, which makes the checks efficient.

Second, a task’s ability to make accesses may depend on meta-data such as friends lists being in a certain state (e.g., Alice can access Bob’s friends-only content only while she is Bob’s friend). This state may change after the OA has finished, thus (partially) invalidating the OA’s analysis. Consequently, the OA must inform the RM of such meta-data dependencies and the RM must track runtime updates to meta-data occurring in the dependencies to avoid policy violations.

b) Reducing the cost of task reset: The need to reset a user-facing task between sessions of two different users is fundamental to coarse-grained taint tracking and cannot be eliminated entirely. To reduce the cost of this reset significantly, SHAI relies on a recent OS primitive called lightweight contexts (lwCs) [13] to rollback the state of a user-facing task to a clean state efficiently. lwCs support multiple tasks with separate address spaces and file descriptor tables within the same process. Resetting an lwC’s state resets only the “essential” elements (the memory mappings and open file descriptors) and is faster than re-execing an entire process. This cuts down overheads significantly compared to Thoth.

As an added benefit, the use of lwCs also allows implementing the RM itself in an lwC, in place of a separate process (as in Thoth). This reduces the cost of interception for the few reads/writes that fault into the RM in SHAI from a standard OS context switch to a lwC switch, which is cheaper since it does not involve scheduling delays. We describe lwCs and their use in SHAI in Section LV.

C. Threat model

Like Thoth and almost all other work on information flow control, the goal of SHAI is to ensure that policies on ingress conduits are enforced despite bugs in the system’s implementation. The concern is inadvertent data leaks, not extraction or stealing of information by malicious adversaries. As such, low-level vulnerabilities (buffer overflows, control flow hijacks, etc.) are not a concern. Implicit flows and side-channels like timing channels would, in principle, be a concern in this setting, but SHAI focuses only on the larger, more prominent risks from explicit leaks of data.

Since SHAI is primarily a userspace system, the kernel (including its sandboxing mechanism) is trusted. SHAI’s integral components—the RM and the OA—are both trusted. Policies on ingress nodes are assumed to represent privacy requirements correctly and all meta-data (e.g., friends lists) on which their interpretation depends is assumed to be accurate.
Policies of internal conduits can be chosen arbitrarily. Getting these wrong can block legitimate data flows in the pipeline, but cannot violate policies of ingress conduits. Any input provided to the OA, with the exception of the policies of conduits, is not trusted. Getting these inputs wrong can only impact performance and/or functionality, not policy enforcement. However, policies of conduits provided to the OA must be the same as those used by the RM.

III. SHAI DESIGN

SHAi’s design consists primarily of two components—the offline analysis (OA) and a runtime sandbox and reference monitor (RM). We use Thoth’s policy language (with very minor extensions) for representing policies. In the following, we first present a running example that we use to illustrate various concepts and that also forms the basis of our evaluation. We then describe the OA and the runtime system.

A. Example: Search pipeline

Our running example, called Sys-E, is the same as that used in Thoth’s evaluation. Sys-E models the search component of a typical user data-driven system such as a modern social platform.

Sys-E indexes a corpus of heterogeneous data consisting of public documents (modeling public content on the WWW), documents private to individual users (modeling content such as emails and individual calendars), and semi-private documents shared among stipulated subsets of users (modeling content such as social media posts that are accessible only to friends or friends of friends). Each piece of content is stored in a separate file. These files are the ingress conduits of Sys-E. The system supports friends lists of users, which are used by the policy enforcement mechanism. The system also has lists of blacklisted documents which should not be visible to users connecting from specific geographic regions to support legal blocking of content.

The first task in Sys-E’s pipeline is a data indexer that builds an index mapping keywords to documents containing those keywords. This task consumes all the content files above and produces the index, which is also stored in files. Note that the data indexer is mostly offline; it only runs periodically.

The next task in the pipeline is a search engine, which accepts a user query (a set of keywords) over a pipe from a user-facing front-end task (described next), looks up the index, and responds back to the front-end with a list of documents that contain those keywords. Technically, the search engine does not return a list of documents but instead passes open file descriptors for the matching documents over a pipe.

The last part of our pipeline is the front-end, which hosts a web server through which remote users interact with Sys-E. For every incoming user connection, Sys-E spawns a new user-specific worker task, which authenticates the user (with the user’s public key), and then accepts search queries from the user. It forwards each search query to the search engine, then reads each of the matching documents returned by the search engine to extract a snippet, composes all the snippets into a set of “results”, personalizes the results using stored preferences of the connected user, and inserts advertisements to generate revenue. It then returns the resulting page to the user. Note that this last part of the pipeline is not a single task, but consists of a separate task for every connected user.

Ingress conduit policies: The read rules of the ingress conduits specify expected confidentiality requirements: Public documents have an all permissive read rule (anyone can read them), Alice’s private files have a read rule that allows access to Alice only, and Alice’s semi-private files have a read rule that allows access only to Alice and her friends (or friends of friends).

Declassification rules are more interesting. Note that the indexer consumes the private content of all users and, hence, in principle, its output (the index) should not be accessible to any user. Since the search engine consumes the index, its output (file descriptors of documents that match a user query) must also not be accessible to any user. This effectively means that the end-user will not be able to see any output from the pipeline!

To work around this, we relax the policies of all indexed files. Specifically, the declassify rules of all indexed files allow a complete declassification into any conduit that can only transfer open file descriptors but no other content. The pipe from the search engine to a worker task is such a conduit. This allows the search engine to return open file descriptors of matching documents to worker tasks, and allows the pipeline to work as expected. (An additional check in the kernel, described in Section [V] ensures that the worker task can only receive descriptors that it could have opened itself; this prevents a buggy search engine from sending a descriptor for Alice’s private file to Bob’s worker task.)

The declassification policies of indexed content also have additional clauses for enforcing region-specific censorship. A user’s profile (including preferences) has a policy that allows access only to the user. We elide the details of these policies here. The paper on Thoth describes these policies in detail.

B. The offline analysis (OA)

As its name suggests, the OA is an offline process that runs periodically on the side, not within the actual system pipeline. The goal of the OA is to check, ahead of time, which conduits each task in the pipeline can read and write. Accesses that check successfully in the OA do not have to be intercepted in the pipeline at runtime, which reduces runtime overhead. To improve efficiency, the OA should be configured to check as many accesses as possible ahead of time. Of course, not all accesses can be checked ahead of time; these accesses are subject to policy checks by the RM as described in Section [II-C].

Accesses to conduits that do not exist when the OA runs, including pipes, fall in this category. In a properly configured system, these should be the only accesses that are checked at runtime.

a) OA’s inputs: The OA takes the following parameters as inputs:

...
1) A list of tasks on which to run the OA. If a task’s accesses depend on runtime parameters such as the identity of the user the task will serve, a separate instance of the task should be listed for every combination of these parameters.\textsuperscript{1}

2) For each task, lists of conduits whose reads and writes by this task have to be checked.

3) The steady-state \textit{taint} of each task. This is explained below.

4) The policies of all conduits in the system.

5) Any policy-relevant meta-data such as Sys-E’s friends lists and region-specific content blacklists.

The taint of a task is a policy that the RM associates to the task at runtime. This policy is always at least as restrictive as the policies of all conduits that the task has read. SHA1 enforces this policy on all data that is output by the task and all data that is derived downstream from this output data. The relevance of the taint is that it allows a local check to determine if it is safe to allow a task to read a conduit: The read is safe if the task’s taint is at least as restrictive as the conduit’s policy since, then, the conduit’s policy is guaranteed to be enforced downstream. Input (3) to the OA asks for the runtime steady-state taint of each task.

All inputs (1)–(5) can be determined fairly easily. (1) follows from the schema of the pipeline and, for parametrized tasks, from the possible values of the parameters (e.g., the list of registered users).

The lists in (2) should include as many runtime accesses of the task as possible. These accesses can be determined either by testing, monitoring the production pipeline or manual analysis. For simple pipelines, manual analysis may be straightforward. This works, for instance, for Sys-E: The indexer reads all indexable content and writes the index; the search engine reads the index and indexed content but writes to a pipe that is created only at runtime, so the write is irrelevant for the OA; a user’s worker task should read only content that is accessible to the user (the user’s own private content, content shared by her friends with their friends, public content, etc.) and it writes to a network connection that is also created only at runtime, so this write is also irrelevant for the OA.

(3) can be determined by simple manual analysis, testing or monitoring of the production pipeline. For example, in the Sys-E pipeline, ignoring region-specific censorship for simplicity, the taints are fairly straightforward. (a) Indexer and search engine: Disallow any reads, but eventually allow declassification into a conduit that can only transfer file descriptors, (b) User X’s worker task: Only X can read.

(4) and (5) should be readily available in the system’s meta-data.

SHA1 includes a dedicated language to represent (1)–(5); we elide the details of the syntax here.

\textsuperscript{1}The identity of the user is not the only possible policy-relevant runtime parameter although, for simplicity, we discuss only this parameter here. Another parameter that our implementation of Sys-E uses is the geographic region from which the user connects; we use this parameter to enforce region-specific legal blacklisting of content.

b) OA’s operation: The OA checks relevant policies for every conduit read and write mentioned in input (2) and determines which reads and writes are policy compliant and which are not. For simplicity, we first describe the checks assuming that there are no declassification conditions in policies. We then describe the changes needed to handle declassification conditions.

In the absence of declassification conditions, the checks that the OA makes are conceptually straightforward. A task T can read a conduit f if f’s \textit{declassify} rule (the rule that governs the use of f’s data downstream) is at least as permissive as T’s taint. This ensures that f’s data remains protected downstream in accordance with f’s policy. Dually, a task T can write a conduit f if f’s \textit{declassify} rule is at least as restrictive as T’s taint. This ensures that T’s taint is respected on all of T’s outputs downstream. For a write, the OA additionally checks that f’s \textit{update} rule is satisfied.

When policies have declassification conditions, the check for reads remains unchanged. However, the policy comparison check for writes is more elaborate. The OA checks if any declassification conditions in T’s taint are satisfied. If so, it creates a list of T’s updated taints, with one taint for every satisfied declassification condition. If not, it creates a list with only T’s current taint. The write is deemed okay if f’s \textit{declassify} rule is more restrictive than any of the taints in the list just created.

As an example, suppose that the OA wants to validate a write to conduit f by task T when T’s taint is “only Alice can read until the end of 2017” and f’s \textit{declassify} rule is all permissive. (T’s taint allows a declassification of Alice’s private content at the end of 2017.) In this case, the declassification condition in T’s taint is “until the clock time exceeds midnight on December 31, 2017”\textsuperscript{1}. So, the OA checks whether the clock time is past midnight on December 31, 2017. If this is the case, then T’s resulting taint imposes no restrictions, so the write is okay. If this is not the case, then the write is not okay.

These conceptually straightforward checks are more nuanced when they involve meta-data that can change over time. Consider the case of Alice’s worker task in Sys-E reading a document with the policy “accessible to Bob’s friends only”. In this case, the policy check above will succeed only if Alice is in Bob’s friends list. Suppose that Alice is in Bob’s friends list when the OA runs. Now note that, in the future, the validity of this check is conditional on Alice remaining in Bob’s friends list. If Bob unfriends Alice, this validity is lost.

Consequently, with each access that it successfully validates, the OA also returns a list of conditions on the system state under which the access was validated. We call these conditions the \textit{state conditions} of the access. One general state condition is that the policy of the conduit must be what it was when the OA ran. At runtime, the RM checks these conditions before using the OA’s validations as explained in Section III-C.

Finally, the validity of the accesses of a task may depend on parameters that can be determined at runtime only. For example, in Sys-E, a worker task serving user X should be
able to read only conduits that X is allowed to read, but the identity X will be known only at runtime. In the OA, this is handled by executing the analysis for all possible instances of the parameter (X in this case). Technically, the OA is given a separate instance of the task for every possible value of the parameter. Thus, in Sys-E, there is one instance of the worker task for every registered user—there is a task called “Alice’s worker”, another called “Bob’s worker”, etc. The specific value of the parameters for a task instance are coded in the taint of the instance. In Sys-E, the taint of Alice’s worker is “Only Alice can read downstream”, while that of Bob’s worker is “Only Bob can read downstream”. With these precise taints, the OA validates all accesses for the specific instances of the task. At runtime, the task must register with the RM as the correct instance, else it won’t be allowed to communicate with the connected user. Thus, safety is always maintained.

c) Formal description of the OA’s algorithm: Algorithm 1 summarizes the work of the OA. The algorithm does exactly what is described above. The function isAsRestr(r1, r2) checks that policy rule r1 is at least as restrictive as r2 and returns a boolean indicating whether this is the case (okay) and, if so, what parts of the system state were relevant to this determination (the state conditions, conds). The function isAsRestrWithDeclass is similar but it also applies declassification within r2. The function policyEval evaluates a policy rule.

All these functions are based on similar functions in Thoth. Thoth uses these functions at runtime, not ahead-of-time; we modified the functions to track which parts of the system state are relevant to the result.

The output of the OA is a list of tuples of the forms (read, T, f, conds) and (write, T, f, conds) indicating that task T can respectively read or write conduit f if the state conditions conds hold on the system state.

Using the OA in practice: It may seem that the total work of the OA is enormous: For every task and every conduit that the task may potentially access, the access should be validated ahead-of-time by the OA for runtime efficiency. In the context of Sys-E, for example, assuming 10 million users and, on average, 1,000 pieces of content accessible to each user, this amounts to 10 billion checks just for the user-specific worker tasks every time the OA runs. This sounds intractable.

In reality, not all these checks are necessary. We describe two obvious optimizations. First, the OA’s checks only examine the policies of conduits, not the conduits themselves. Consequently, if a set of conduits share the same policy, then it is safe to run the OA on only one of those conduits and transfer the OA’s result to all other conduits in the set. This optimization is quite useful. For example, all of Alice’s private content (like her emails) will have the same policy. Similarly, all the uncensored public content on the WWW has the same policy (it is accessible to everyone).

Second, the OA results remain valid until policies or policy-relevant meta-data change. Consequently, there is no need to include the content of inactive users in the OA very often. The OA can also be run on a specific user’s content on-demand, e.g., when the system detects that the user has become sufficiently active.

We quantify the cost of the OA on a realistic but simulated workload in Section V.

C. Runtime monitor and OS sandbox

SHA1’s runtime infrastructure consists of two components. First, we rely on an existing OS light-weight capability sandbox2 to encapsulate every runtime task in the data retrieval system’s processing pipeline. The sandbox is configured to allow all accesses that have been validated by the OA without any further interception. Second, a SHA1 reference monitor (RM) runs in userspace, isolated within a lwC. It serves two purposes: It configures the sandbox when a task starts and it validates any accesses that were not validated by the OA ahead of time by making the required policy checks. In the following, we describe these two components somewhat abstractly. Section IV describes a concrete prototype implementation of the RM and the sandbox on FreeBSD.

a) Task registration: When a new task starts, its access to all conduits is blocked by the OS sandbox; the only thing the task can do is talk to the RM. To get access to conduits, the task must register with the RM by specifying which previously

Algorithm 1 OA’s algorithm

| Inputs: (1)–(5) as described in text. In particular, (2) is a list of expected reads of the form (read, T, f) and a list of expected writes of the form (write, T, f). |
| Output: A list of tuples of the form (read | write), T, f, conds), meaning that T can read or write f if conditions conds hold on the system state. |
| 1: output ← ∅ |
| 2: for all (read, T, f) in input (2) do |
| 3: pol ← f’s policy in input (4) |
| 4: taint ← T’s taint in input (3) |
| 5: (okay, conds) ← isAsRestr(taint, pol.declassify) |
| 6: if okay then |
| 7: add (read, T, f, conds) to output |
| 8: end if |
| 9: end for |
| 10: for all (write, T, f) in input (2) do |
| 11: pol ← f’s policy in input (4) |
| 12: taint ← T’s taint in input (3) |
| 13: (okay1, conds1) ← isAsRestrWithDeclass(pol.declassify, taint) |
| 14: (okay2, conds2) ← policyEval(pol.update) |
| 15: if (okay1 && okay2) then |
| 16: add (write, T, f, conds1 ∪ conds2) to output |
| 17: end if |
| 18: end for |
| 19: return output |

2 FreeBSD Capsicum with minimal extensions in our prototype
**offline analyzed task** it represents. For example, in Sys-E, the task may register as the indexer, the search engine or user X’s worker for any known user X. The RM records the choice and the taint provided during the OA for the specified task.

Next, the RM looks up the last output of the OA for the specified task to determine which accesses for the task have already been validated. For each tuple (read, T, f, cons) or (write, T, f, cons) in the output, the RM checks the state conditions cons, and creates a list of all conduits and permissions for which the conditions hold. It gives this list to the OS sandbox, which subsequently allows the task these accesses directly.

For reasons of efficiency, our prototype implements the checking of state conditions differently. There, the RM *always maintains* up-to-date lists of each task’s valid accesses by tracking changes to meta-data on which state conditions depend (e.g., friends lists of region-specific blacklists in Sys-E), and eagerly re-evaluating state conditions when the meta-data changes. As a result, task registration is very fast. The rationale for this implementation choice is straightforward: In online systems like social networks, changes to meta-data like friends lists are far less frequent than task registrations (which happen once per user session), so tying the expensive step of checking state conditions to meta-data changes rather than task registrations results in less overhead.

Registering incorrectly, e.g., registering as the indexer in place of Alice’s worker or as Alice’s worker in place of Bob’s worker, either maliciously or accidentally, cannot cause a policy violation in SHAI. However, doing so may cause expected accesses to be denied or more accesses to fault into the RM thus slowing down the task.

**b) Conduit access:** After a task has registered with the RM, it can open conduits for reading and writing. Every conduit open call passes through the kernel as usual. If the conduit and the mode (read/write) in which it is being opened were provided to the OS sandbox as a valid access during the task’s registration, the kernel just allows the call. This is the fast path and it should apply to most conduit accesses in a properly configured system.

If, on the other hand, the OS sandbox does not know that the specific access is valid, then it transfers control to the RM. The RM then makes the same policy checks that the OA would have made for the corresponding operation (read/write). The only difference is that the RM does not generate any state conditions cons; it just checks them immediately. If the checks succeed, the open call is allowed, else it is denied.

**c) Meta-data changes after a task registers:** As explained above, the OS sandbox is informed of a task’s pre-validated accesses when the task registers. A relevant question is what to do when a subsequent meta-data change invalidates some of these accesses. There are two choices here: Either the invalidated accesses can be revoked in the OS sandbox or they can be left as is. SHAI chooses the latter option since revoking a permission from the sandbox is costly.

This option is also secure since any access that the task does after the invalidation could also have been done before the invalidation to the same effect. An exception to this argument occurs when read access is to be invalidated before the conduit is updated. In this case, continuing the read access will allow the task to obtain the conduit’s updated content which it could not have obtained had the read access been revoked immediately. To avoid such cases (when they are really a concern), the system should be configured to store updated content in new conduits (e.g., by versioning files). This is consistent with systems like online social networks where existing content is updated relatively infrequently (although fresh content is added quite regularly).

**d) Increasing task taints:** In most cases, a task’s runtime taint is fixed when the task registers and remains the same throughout its execution. In some cases, however, the task may wish to increase its taint (i.e., make it more restrictive) during its execution. For example, this is necessary if the task wishes to read sensitive content after writing to a public conduit. In this case, the task must start with a public taint and acquire the taint of the sensitive content afterward.

SHAI allows a task to increase its taint at runtime as follows. At any point, a running task may re-register as a new offline analyzed task whose taint is higher than the task’s current taint. In addition to making all the checks that would be made during task registration, SHAI also checks that the policies of any conduits to which the task has open write handles are more restrictive than the task’s new taint. This check is necessary to prevent leaks of data that the task reads under the new taint. If this check fails, the re-registration is disallowed.

**e) The overall cost of runtime interception:** The overall cost of runtime interception in SHAI is generally very low. For interactive pipelines such as Sys-E’s RM interception happens only a few times per user session (not per user query). For instance, in Sys-E, only four RM interceptions are needed per session: (a) To register the worker task that serves the session (this interception also validates the policies on the pipe that connects the worker to the search engine), (b) When the worker accepts the user’s connection, (c) When the session is authenticated, and (d) At the end of the session, to reset the worker task to a clean state for the next user.

### IV. SHAI Prototype

Our SHAI prototype runs on FreeBSD and relies on FreeBSD’s kernel capability support (Capsicum) and light-weight contexts (lwCs) for sandboxing and isolation, respectively. We briefly describe these primitives.

**Capsicum:** Capsicum is a OS sandbox to control a process’ access to global namespaces including the file system. Capsicum introduces a new mode of process execution, the *capability mode*. A process in this mode can open new files (and, more broadly, make specific syscalls) only if it has been granted the *capabilities* to do so before it entered the capability mode. SHAI uses Capsicum directly to implement its OS
sandbox: Every task runs in capability mode with capabilities to make only the accesses that were certified by the OA.

Light-weight contexts (lwCs): lwCs are an OS abstraction that allow multiple tasks with separate address spaces and separate file descriptor tables to co-exist in the same process. lwCs are orthogonal to execution threads; a thread can switch between lwCs. A lwC switch is more efficient than a process switch since the former has no scheduler delays.

Shai maps tasks one-one to lwCs. The RM also runs inside a privileged lwC. The kernel is configured to redirect any syscall outside a task’s capability set to the RM lwC. As compared to a design that uses processes for the same purposes, this design allows for faster switching between tasks and the RM, and for faster resetting of tainted worker tasks at the end of user sessions by avoiding scheduler delays.

a) Application life cycle: An application is loaded with a customized script that first initializes the RM lwC in each process. Next, it initializes application tasks in separate lwCs and confining them with Capsicum’s capability mode. Then, the RM is invoked to register each application task, giving it the capabilities to access anything that was already certified by the OA and whose state conditions hold. Depending on the type of a conduit, the capability to access it takes different forms:

- Files: The task is given Capsicum capabilities to a small set of directories that contain hard links to all files that should be accessible to the task. (These directories and the hard links are created offline at the end of the OA and kept up-to-date by the RM as state conditions change.)
- Key-value (KV) tuples: For these, the RM relies on KV filters. The RM opens a socket to the KV store and installs a KV filter that limits access to only those tuples that are accessible to the task. It then gives this open socket to the task.

During its execution, an application task makes most conduit accesses directly using the capabilities described above. For the few accesses that are beyond these capabilities, it faults into the RM, which makes policy checks.

b) Capsicum modifications: To support Sys-E and other similar search-based pipelines, we made two modifications to Capsicum. First, we modified Capsicum to allow a pipe without read and write permissions to be used to transfer open file descriptors but not data. In Sys-E, such a pipe is used by the search engine to return file descriptors for documents matching the user query to the front-end’s worker task. Since data transfers on the pipe are forbidden, even a buggy search engine cannot accidentally send private data to the worker.

Second, we modified Capsicum to allow a task in capability mode to transfer file descriptors to another task in capability mode only if the receiving task already has access capabilities on all conduits referenced by the file descriptors. With this feature in place, Capsicum prevents a buggy search engine from transferring a descriptor for Bob’s private file to a front-end worker task connected to Alice. To implement this feature, we modified Capsicum to maintain every task’s capabilities in a binary lookup tree. When a file descriptor is transferred to a task, Capsicum looks up the binary tree for a capability to the conduit referenced by the descriptor. This lookup’s complexity is logarithmic in the number of distinct capabilities the task has. In Sys-E, only the front-end tasks receive file descriptors and these tasks have very few capabilities (at most 5), so the lookup is very fast.

V. Evaluation

In this section, we present results of an experimental evaluation of our Shai prototype. In particular, we measure the overhead of policy enforcement in the data retrieval system Sys-E described in III-A. We instantiated this system with the widely-used Apache Lucene as the search engine. All experiments were performed on Dell R410 servers, each with 2 Intel Xeon X5650 2.66 GHz 6 core CPUs, 48GB main memory, running FreeBSD 11.0 (x86-64) with support for light-weight contexts (lwC) and Lucene version 4.7 with a minor modification to allow it to run in Capsicum’s capability mode. The prototype uses OpenSSL v1.0.2h. The servers are connected to Cisco Nexus 7018 switches with 1Gbit Ethernet links, which offer enough network bandwidth for all our experiments. Each server has a 1TB Seagate ST31000424SS disk formatted under UFS, which contains the OS installation and a 258GB static snapshot of English language Wikipedia articles from 2008.

Experimental setup. In the following experiments, we compare the performance of Shai to two systems; (i) a system that does not enforce policies (Baseline), and (ii) a system that enforces policies via pure dynamic analysis (Dynamic). We give more details about Dynamic in the following.

In Dynamic, each task has a current taint, which represents the combined policies of all the conduits the task has read. A task’s taint can become more restrictive as the task reads more conduits. To enforce policy, a task’s writes must (i) satisfy the update rule of the destination conduit’s policy, and (ii) satisfy the declassification conditions of the task’s current taint. Dynamic is very similar to Thoth; for fair comparison, our Dynamic implementation, like Shai, takes advantage of lwCs and Capsicum for efficient in-process isolation and sandboxing. This yields better performance than the original Thoth prototype, which isolates each user session and the reference monitor in a separate process.

A process in Dynamic, like Shai, can have multiple Capsicum-sandboxed user lwCs (each terminates a user connection), and a privileged monitor lwC. Conceptually, the RM intercepts all conduit open calls and writes to perform taint tracking and dynamic policy checks. As in Thoth, we optimize taint tracking by not invoking the RM during open calls and instead logging such calls in the kernel. During a write, the RM is invoked, it checks the open call trace to update the task taints and then performs the policy check for the write. To

\[^3\] In Shai, all tasks, including the Lucene indexer, run in capability mode. In this mode, the syscall open is disallowed by Capsicum, so we had to modify Lucene to use OPENAT instead. We found that OPENAT is faster than OPEN so, to remain fair, we use the modified Lucene in the two other configurations that we compare against as well.
summarize, DYNAMIC and SHAI are identical architecturally: A process has multiple Capsicum-sandboxed user lwCs and a privileged monitor lwC. Both systems also enforce the same policies. However, unlike SHAI, which pushes most policy evaluation overhead to the offline analysis, DYNAMIC performs pure dynamic IFC: the underlying kernel intercepts I/O and directs it to the reference monitor, which in turn tracks taint and performs policy evaluation at runtime.

A. Search throughput

First, we measure SHAI’s overhead on search throughput. We drive the experiment with the following workload. We simulate a population of 40,000 users. Each user is assigned a friend list consisting of 100 randomly chosen other users, subject to the constraint that the friendship relationship is symmetric. Each document in the Wikipedia corpus is assigned either a public, private, or friends-only policy in the proportion 50/30/20%, respectively. Private and friends-only documents are assigned to a user picked uniformly at random from the population. A total of 1.1% of the corpus is censored in some region. A censored document’s policy allows declassification to an external user only if the destination’s blacklist file does not blacklist the document.

In this experiment, 24 concurrent users issue queries in parallel. We use query strings based on the popularity of Wikipedia page accesses during one hour on April 1, 2012 [19]. Specifically, we search for the titles of the top 20K visited articles and assign each of the queries randomly to one of the users. User sessions run for lengths 1, 2, 4, 8, 16, or 32 queries. Additionally, we report the throughput when users maintain their sessions for the duration of the experiment (20k queries).

In our setup, two server machines execute a Lucene instance with different index shards. The front-end submits a search request to one Lucene instance, which in turn forwards the request to the other instance and merges the results from both shards. To maximize the performance of the baseline and fully expose the policy enforcement overheads, the index shards and parts of the corpus relevant to our query stream are pre-loaded into the servers’ main memory caches, resulting in a CPU-bound workload. To ensure load balance, we partitioned the index into two shards of 22GB and 33GB, chosen to achieve approximately equal query throughput.

Table I shows the average throughput over 40 runs of 20K queries each, for BASELINE, DYNAMIC, and SHAI. The standard deviation over the 40 runs was below 0.87% across all configurations.

The key result is that SHAI’s static analysis reduces the runtime enforcement overhead to near zero for sufficiently long session lengths (0.1% at 16 queries and 0.02% at 20k queries). The DYNAMIC system, which relies on pure runtime enforcement but is otherwise equivalent, has a runtime overhead of approximately 2.5% for large session lengths.\footnote{A 2.5% overhead may seem small; but increasing the peak capacity of a large datacenter by 2.5% to account for it has a substantial cost!}

| Q/S | BASELINE Avg. | DYNAMIC Avg. | SHAI Avg. |
|-----|---------------|--------------|-----------|
|     |               | overhead     | overhead  |
| 1   | 309.36        | 287.04       | 294.70    |
|     | 2             | 313.90       | 298.29    |
| 4   | 316.49        | 304.58       | 312.54    |
| 8   | 317.60        | 308.07       | 316.17    |
| 16  | 318.66        | 309.27       | 318.34    |
| 32  | 318.95        | 310.11       | 318.64    |
| 20k | 319.13        | 311.10       | 319.08    |

Even for short session lengths, SHAI’s runtime overhead is substantially lower than DYNAMIC’s.

In DYNAMIC and SHAI, the front-end creates a new lwC for every incoming user session. In SHAI, the monitor lwC additionally performs the required runtime checks associated with the connected user’s taint before granting access capabilities. The overheads of setting up new sessions (creating lwCs and performing runtime checks) dominate the policy enforcement overhead for short sessions. At one query per session, DYNAMIC incurs a 7.21% overhead, whereas SHAI incurs 4.74%. Here, SHAI outperforms DYNAMIC since (i) SHAI performs fewer (runtime) checks compared to DYNAMIC’s full policy evaluation for all documents accessed per query, and (ii) DYNAMIC tracks the search engine’s taint and intercepts its writes to evaluate them against the search engine’s current taint, whereas the search engine’s accesses within its capability set are not intercepted in SHAI. Furthermore, as the session length increases, the cost of SHAI’s per-session setup costs and runtime checks amortize over the session’s queries, whereas DYNAMIC performs full policy evaluation for each query.

At session length 20k, SHAI incurs 0.02% overhead, significantly better than DYNAMIC’s 2.52% overhead. SHAI’s remaining runtime overhead is due to the kernel’s capability checks; in particular, when the search engine attempts to send file descriptors corresponding to the search results, the kernel checks that the front-end has existing access capabilities for these descriptors. This check is efficient; its runtime complexity is logarithmic in the number of distinct (directory) capabilities the receiving front-end has. In our prototype, a front-end that satisfies runtime checks acquires few directory capabilities,\footnote{One on the connected user’s hard links directory, another on named pipes to submit queries to the search engine, and three on directories with public documents.} making the check light-weight.

In the previous experiment, all users connected from the regions that were anticipated during the offline analysis. To quantify the overhead of runtime checks required when runtime conditions deviate from those expected, we next perform an experiment in which we vary the proportion of users who connect from regions different from those assumed during

TABLE I: Average search throughput in queries per second. Standard deviation was less than 0.87% from the average in all cases. First column indicates the session length (queries per session – Q/S).
offloading analysis. Figure 2 shows the average throughput over 40 runs of 20K queries each. The error bars indicate the standard deviation over the 40 runs, which was less than 0.72% in all cases. We report the average throughput for sessions of length 8 queries, but the following conclusions regarding the relative overheads of SHAI and DYNAMIC hold across all session lengths.

With 100% of users connecting from the expected region (i.e., all user sessions satisfy the runtime checks associated with their taint), SHAI performs 316.17 Q/s (0.45% overhead over BASELINE), as in Table I. As the proportion of users who connect from their expected regions decreases, SHAI’s performance declines approximately linearly and approaches that of DYNAMIC, but never gets worse. Even when all users connect from unexpected regions, DYNAMIC incurs more overhead than SHAI because it intercepts the search engine’s writes to evaluate them against the search engine’s current taint. SHAI’s throughput degrades similarly if other runtime variables are mispredicted. For instance, it declines approximately linearly with the proportion of policies changed and the proportion of new content added since the last offline analysis. This result shows that SHAI’s benefits decline gracefully with the accuracy and freshness of the offline analysis.

B. Scaling search throughput

The throughput of a single Lucene search engine is relatively modest, which raises the question of how much overhead SHAI might impose on a much faster system. In the next set of experiments, we study SHAI’s overhead in a replicated search engine configuration, and in a configuration with a hypothetical search engine that has much higher throughput than Lucene.

Replication. We performed the throughput experiment on a replicated setup. In this experiment, four server machines execute Lucene instances, where each index shard is replicated on two servers. A front-end submits a search request to a lightly loaded Lucene instance, which in turn forwards the request to another lightly loaded instance processing the other shard and merges the results from both shards. Here, 48 users issue queries in parallel, users maintain their sessions for the duration of the experiment, and we measured the average throughput over 40 runs, each 20K queries. BASELINE, DYNAMIC, and SHAI all achieved an average throughput of almost exactly twice (within 0.152%) the respective throughput reported in Table I at session length 20K. This shows that SHAI (like DYNAMIC) scales linearly as the search engine is replicated.

Hypothetical fast search. To study SHAI’s overhead in a hypothetical data retrieval systems that serve tens of thousands of search requests per second, we replaced the Lucence search engine with one that picks results randomly from the set of documents accessible by the user who issues the query. We measure SHAI’s overhead over (a) a dummy search engine that performs over 3K Q/s (TETUP3K), and (b) a dummy search engine that performs over 30K Q/s (TETUP30K). The dummy search engine busy waits to consume a fixed number of CPU cycles in TETUP3K before returning the search results, whereas it returns the results immediately without busy waiting in TETUP30K. Note that TETUP30K represents an extreme situation, shown here only to fully expose SHAI’s overheads; we do not expect any realistic search engine to attain such high per-node throughput.

In this experiment, a total of 56 concurrent users issue queries in parallel to two server machines running the dummy search engine. User sessions run for lengths 1, 4, 16, 64, 256, 1024, and 20K queries. Figure 3 shows the average throughput at the different session lengths for TETUP3K and TETUP30K (Figures 3a and 3b respectively). We report the average throughput over 10 runs, each of length 30 seconds. Error bars show the standard deviation across the 10 runs, which was below 0.9% in all cases.

At small session lengths, both SHAI and DYNAMIC have high overheads due to the cost of creating lwCs to isolate user sessions. As the session length increases, the cost of session creation amortizes across queries in SHAI; the overheads are only 0.37% and 1.2% at session length 20K, in 3a and 3b respectively. These overheads are due to checking, at a high rate, that the front-ends have existing capabilities over the transferred file descriptors. On the other hand, DYNAMIC does not scale beyond 2.39K and 7.76K Q/s in 3a and 3b because intercepting I/O to perform policy evaluation at runtime limits performance. This result shows that SHAI can maintain low overhead even in very high-performance data retrieval systems.

C. Search latency

We next measure SHAI’s overhead on query latency. For this experiment, a user issues one query at a time and waits until it receives a result before issuing another query. User sessions run for lengths 1, 2, 4, 8, 16, 32 or 4k queries.

Table II shows the average query latency across 5 runs of 4K queries. Since SHAI’s overhead relies on satisfying the runtime checks necessary to acquire capabilities, we report SHAI’s performance when (i) the user logs in from a geographic location different than the region used during offline analysis.
The runtime of the analysis depends on the number of tasks, the number of expected accesses and relevant policies of each task, and the number of accesses certified (each certified access may require creating a hard link in the task’s capability directory). We limit the analysis to a single CPU. The analysis can be sped up by using more CPUs since its computation is embarrassingly parallel (except when creating hard links within the same directory).

a) Indexer and search engine flows: The analysis takes under 2 seconds to process the flows of the search engine and the indexer tasks against the entire Wikipedia corpus (~14.5 million documents subject to ~80K different policies). Here, the searchable documents’ policies permit read to the indexer and the search engine, and the analysis grants both a single capability for the top level directory of searchable documents.

b) Users flows: Next, we measure the analysis time and storage requirements for the users of the data retrieval system. For this experiment, we assume a fixed default geographic location for every user. For each user, the offline analysis checks the front-end’s accesses of all public documents, the user’s private documents, and the friends-only documents of the user’s friends.

We ran the OA on accesses of 100 users picked at random from the population. Processing the accesses took 90.5 seconds per user on average. This can be optimized using a faster storage medium since most of this time (96.1%) was spent waiting for the magnetic disk to record hard links for access capabilities. To quantify potential speed-up when using a ramdisk, we ran the offline analysis for the same 100 users on a Dell R640 server machine with 385GB main memory, and limited the analysis to use only one core of its Xeon Gold 6142 2.60GHz CPUs. This server machine has enough memory to store the entire Wikipedia corpus in ramdisk, allowing us to create hard links in ramdisk too. Using the ramdisk to store hard links, processing each user took under 1.2 seconds on average (20% of which was spent creating hard links).

Each user’s access capabilities consumed 12.9MB of disk space to store 145.8K hard links on average. Tasks’ taints and state conditions consumed less than 11MB of disk space for all 100 users combined.

E. Indexing

Finally, we measure the overhead of policy enforcement on the index computation. We run the Lucene indexer over the entire 258GB snapshot of the English Wikipedia. The resulting index is 54GB in size. Table 3 shows the average indexing time in minutes across 3 runs. The standard deviation was less than 2% in all cases.

|        | Average | Overhead |
|--------|---------|----------|
| BASELINE | 652.27  |
| DYNAMIC | 672.02  | 3.02%    |
| SHAI    | 656.16  | 0.59%    |

TABLE III: Indexing time in minutes.

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**Fig. 3: Search throughput in (Q/s) of 56 concurrent users, at different session lengths. Error bars show standard deviation.**

**Table II: Average query latency (ms). Standard deviation was less than 0.8% in all cases. The first column indicates the session length (queries per session – Q/S).**

| Q/S | BASELINE | DYNAMIC | SHAImispredict | SHAI |
|-----|----------|---------|----------------|------|
| 1   | 36.013   | 38.071  | 37.314         | 36.345|
| 2   | 36.007   | 37.843  | 37.122         | 36.108|
| 4   | 36.005   | 37.742  | 37.084         | 36.037|
| 8   | 35.981   | 37.719  | 37.021         | 36.008|
| 16  | 35.939   | 37.657  | 36.916         | 35.955|
| 32  | 35.928   | 37.599  | 36.904         | 35.941|
| 4k  | 35.905   | 37.597  | 36.913         | 35.960|

(4) column 4: SHAImispredict, and when (ii) the user logs in from the geographic location that is used in the offline analysis (4) column 5).

SHAI’s policy enforcement overhead on query latency is very low (at most 0.34ms). Also, SHAImispredict (when the user fails to satisfy the runtime checks to acquire capabilities) achieves better performance than DYNAMIC. The performance difference is due to tracking the taint and intercepting the search engine writes in DYNAMIC, whereas the search engine’s accesses within its capability set are not intercepted in SHAImispredict.

D. Offline analysis

Next, we measure the cost of running the offline analysis over the expected data flows within the data retrieval system.
Enforcing policies with SHA1 during indexing incurs a runtime overhead of 0.59%, which is significantly lower than Dynamic’s 3.02%. SHA1’s overhead is due to the fact that the indexer creates many new files, and all these file creations must be intercepted to ensure that output has appropriate policy given the indexer task’s taint. Policy enforcement in Dynamic additionally intercepts the indexer’s writes to the index files and tracks the indexer’s taint.

Since indexing is a relatively infrequent operation in a search pipeline, we believe that a runtime overhead of 0.59% is acceptable. However, in other systems where frequent file creation occurs on the critical path, runtime interception of file creation could be avoided as follows. Using an appropriate Capsicum capability, we can restrict file creation to a specific directory with an appropriate policy. All files created in this directory implicitly inherit this policy. The offline analysis can check upfront that the task creating the files can write to any file with this policy.

F. Fault-injection tests

To double-check SHA1’s ability to stop data leaks, we ran the fault injection tests that were originally run on Thoth in [7]. In all tests, SHA1 stopped all injected data leaks. (We refer the reader to [7] for details of the tests.)

VI. RELATED WORK

The work most closely related to SHA1 is obviously Thoth. We have already described how SHA1 is a significantly more efficient re-design of Thoth and how the two differ. In the following, we describe other closely related work.

Grok [16] is a privacy compliance tool that is deployed on the backend data analysis pipelines of the Bing search engine. As opposed to SHA1, which enforces data-specific policies, Grok enforces only type-specific policies. As a result, Grok’s analysis can be, and is, entirely static; there is no runtime component and no runtime overhead. Grok’s analysis is meant to detect bugs and misconfigurations, not strictly enforce policies. In fact, the analysis uses possibly unsafe (but very scalable) heuristics and it can have both false positives and false negatives, which must be resolved manually. Nonetheless, Grok demonstrates that policy enforcement can scale to actual production pipelines.

The idea of runtime coarse-grained taint tracking via kernel interception was pioneered by the operating systems HiStar [21] and Asbestos [6], and later developed in Flume [12]. However, these operating systems assign abstract taints to processes; the mapping from taints to policies, as well as the enforcement of declassification is left to trusted processes. In contrast, Thoth and SHA1 enforce declarative policies (that also include declassification conditions) directly.

Hybrid policy enforcement: There are a number of other systems that combine static (offline) analysis with runtime monitoring for security. Such techniques exist for information flow control (IFC) [4, 14, 15], enforcing safety properties [8, 10], and gradual typing [9, 17]. Fredrikson et. al [10] use abstraction refinement and model checking to instrument code with sufficient checks to enforce policies, and Rocha et. al [15] use code analysis to inject policy checks in program code to enforce IFC and declassification policies. Moore and Chong use static analysis to reduce monitoring overhead by selectively marking variables which cannot cause security violations to not be tracked at runtime [14]. Similar to SHA1, these approaches try to perform as many checks as possible statically, and use runtime checks only where static checks are impossible. However, all these systems combine static and dynamic analysis at fine-granularity and require the source code of the application. In contrast, SHA1’s offline analysis (which can also be viewed as a static analysis) uses only a description of the system pipeline, not the source or compiled code of the system. Moreover, SHA1 combines static and dynamic analysis at coarse-granularity. As far as we know, SHA1 is the first system to do this.

RIF is a policy model similar in concept to SHA1/Thoth’s policy model. RIF has been implemented in an extension of the Java programming language called JRIF [11]. Like the aforementioned work, JRIF enforces policies at fine-granularity by hybrid analysis consisting of mostly static inference and some runtime checks. All the differences from SHA1 mentioned above apply to JRIF as well. JRIF’s declassification conditions are linked to specific program points, not predicates on the system/conduit state as in SHA1. It is unclear whether a pipeline such as Sys-E can be implemented in JRIF and, if so, what the cost of the runtime checks would be.

Policy debugging: A problem complementary to that addressed by SHA1 is that of debugging policies. This problem has been addressed in prior work using logic programming techniques [5], model checking [2] and flow simulations [3]. Although the problem is orthogonal to our goals, some of the techniques used are similar. For example, PolSim [3] performs an analysis similar to SHA1’s offline analysis, on the same policy language. However, unlike SHA1’s goal of checking that accesses are policy compliant, PolSim seeks to ensure that the entire pipeline works, despite restrictions imposed by policies. Consequently, PolSim outputs blocked data flows in the pipeline and suggestions for how to change the policies to allow the flows.

VII. CONCLUSION

SHA1 shows that it is possible to enforce data-specific flow policies in data retrieval systems with near-zero runtime overhead in the common case. SHA1 relies on a combination of an offline flow analysis, session-level binding of runtime variables, and light-weight runtime monitoring using an OS capability sandbox to achieve this goal. The key insight behind SHA1 is to push as much work as possible to the offline analysis, often relying on anticipated values of runtime parameters, and to use efficient OS techniques (light-weight contexts and Capsicum capabilities) to minimize runtime overhead. This combination keeps SHA1’s overheads very low, even when the system throughput is very high.

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