Leveraging Data Provenance to Enhance Cyber Resilience

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***Abstract*—Building secure systems used to mean ensuring a secure perimeter, but that is no longer the case. Today's systems are ill-equipped to deal with attackers that are able to pierce perimeter defenses. Data provenance is a critical technology in building resilient systems that will allow systems to recover from attackers that manage to overcome the "hard-shell" defenses. In this paper, we provide background information on data provenance, details on provenance collection, analysis, and storage techniques and challenges. Data provenance is situated to address the challenging problem of allowing a system to "fight-through" an attack, and we help to identify necessary work to ensure that future systems are resilient.**

I. Introduction

Creating bigger and better walls to keep adversaries out of our systems has been a failing strategy. The recent attacks against Target [9] and Sony Pictures [10], to name a few, further emphasize this. It is untenable to assume that a system even with designed-in security can successfully repel *all* attacks. The next generation of secure systems must also be able to withstand successful attacks using cyber resilience. Cyber resilience broadly encompasses many areas including traditional fault tolerance, moving target techniques, and data provenance. In this paper we focus on the challenges and approaches to creating resilient systems using data provenance.

Data provenance is the history of ownership/processing or modification that we can use to guide its authenticity. Provenance is typically represented as a directed acyclic graph of nodes and edges that define the relationships between data, the processes that act upon them, and the users and others systems who controlled those processes. At face value, this sounds simple, even mundane. But it turns out that this kind of information is critical to answering questions that we have about our systems that are typically very difficult to answer. For example, where are all my data, where did they come from, should I trust the data and how can I recover if something has gone wrong? These questions are only becoming more difficult to answer as the scale and complexity of our systems grows. It is critical that we know what a system has already done with its data, if we have any hope of fixing it after a successful attack.

Though provenance has hundreds of years of use in the art world and several decades of study in the literature surrounding data management [41], [14], it has only very recently been applied to improving system security and resilience [6]. Using provenance for securing systems presents a number of new challenges including efficiently collecting the data, securely encoding and storing it, and the timely analysis of the data to answer security-relevant questions. In order to leverage data provenance to enable secure and resilient systems, provenance data must be collected and analyzed. Today, few systems treat provenance as a first-class citizen. As a result, operators and engineers must be able to integrate provenance into their applications. This requires the appropriate technologies to support easy integration of provenance into their applications.

As a result of our experience developing both academic and operational provenance systems, we have developed both an architecture and best practices for addressing the challenges that surround provenance. In this paper we discuss these challenges and survey the solutions to each of the phases of the data provenance lifecycle from collection to its use in resilient self-healing systems. We discuss methods to limit the invasiveness and overhead of provenance on both developers and the operation of the system.

In this paper, we make the following contributions:

- provide an overview and background on existing tools to integrate provenance collection into resilient systems
- outline the challenges for securely leveraging data provenance in decision making

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- detail gaps in existing tools to support end-to-end secure data provenance for resilient systems

Section II looks at provenance collection mechanisms that exist today. Sections III and IV describe how provenance is used, what tools exist for leveraging data provenance, and what tools are still needed to fully utilize provenance. Finally, Section V concludes.

II. Provenance Collection

A necessary prerequisite to the use of data provenance to improve system resilience is its reliable capture and management, which is made possible through provenance-aware systems and applications. There are a variety of ways in which operators and engineers can deploy provenance-aware mechanisms to facilitate this capture. Provenance-aware mechanisms can also be divided into *disclosed* systems [11], [12], [25], [27], [31] and *automatic* systems. Disclosed systems can take the form of manual annotations or by processing documentation volunteered by the operator. In automatic systems provenance metadata is procedurally generated in the software itself. For the remainder of this work, we focus on automatic systems for their ability to provide more comprehensive provenance descriptions of system activity.

Automatic provenance-aware mechanisms can be deployed at various layers of system operation, including operating systems, infrastructure (i.e., middleware), and applications. Operating system sensors provide low-level detail on data processing from the system perspective [6], [23], [29], [28], [32]. System layer provenance also offers gapless descriptions of user space activity, effectively making every application that runs on the system provenance-aware. Unfortunately, the semantic gap between kernel and user space can make system provenance difficult to interpret, as exemplified by the *dependency explosion* problem in which each new output from a long running process appears to be dependent on all prior inputs [21]. In contrast, deploying capture mechanisms in infrastructure leads to provenance that is more semantically rich, while still offering broad coverage for a class of applications that make use of that infrastructure [12], [11], [35]. Due to the ubiquity of database backends in complex application workflows, an important subclass of provenance-aware infrastructure considers database management systems [8], [15], [19], [28]. However, to obtain the most precise and expressive provenance for an application workflow, it is necessary to invest in a manual instrumentation effort of the software. Doing so ensures a higher signal-to-noise ratio in the captured provenance, as the developer's understanding of the workflow is encoded in the provenance itself. This effort is made easier through the presence of special APIs and libraries dedicated to provenance instrumentation [6], [14], [17], [24], [26], [28].

In practice, designing resilient provenance-aware systems does not require selecting a single provenance capture mechanism, but deploying a composition of the above mechanisms in order to provide total transparency to mission critical system activities. Below, we describe our past efforts in the design and implementation of interoperable provenance-aware components at different software layers.

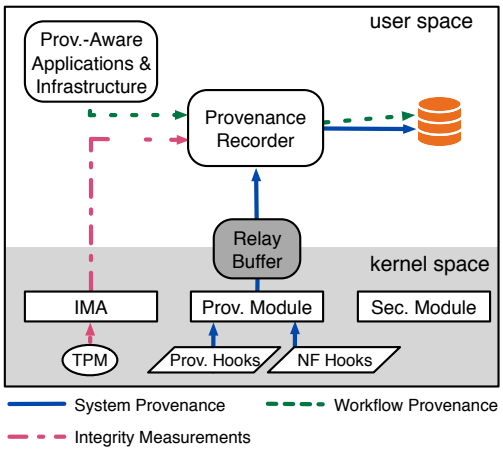

Fig. 1. Overview of Linux Provenance Modules (LPM) architecture. Kernel hooks relay provenance to a recorder in user space for processing and storage. Through use of the Integrity Measurement Architecture (IMA), the recorder is also evaluates the integrity of workflow provenance prior to its storage.

A. Provenance-Aware Operating Systems

The **Linux Provenance Modules (LPM)** project is not only a provenance-aware operating system, but a generalized framework for the capture of data provenance that serves as a trust anchor for other provenance-aware mechanisms [6]. LPM was designed specifically to provide *reference monitor* guarantees [1] in the presence of an attacker that attempts to subvert the provenance collection agent. For example, an attacker may wish to manipulate provenance records in order to commit fraud or inject uncertainty into data processing results, as was the case in the "Climategate" controversy [33].

An overview of the LPM architecture is shown in Figure 1. LPM instruments the Linux kernel with a 178 dedicated provenance collection hooks; these hooks are registered by a provenance module, which also registers several Netfilter hooks. As system events occur, the provenance module examines the event context and generates provenance records that are shuttled out to user space for storage. To allow provenance information to be securely transmitted between hosts, LPM defines Netfilter functions that enforce a system-wide message commitment protocol. The message commitment protocol forces all messages transmitted between provenance-aware hosts to be cryptographically verified using the Digital Signature Algorithm (DSA). We show in [6] how a machine can securely boot into LPM through use of an Intel Trusted Boot procedure, ensuring that LPM is able to collect provenance prior to the start of mission-relevant system activities. We also demonstrate the runtime integrity of LPM's trusted computing base through use of the SELinux MLS policy [18].

An especially important capability provided by the LPM architecture is *attested disclosure*. As we discussed above, resilient provenance-aware deployments require a composition of mechanisms and different system layers, but doing so in a manner that preserves reference monitor guarantees is an especially challenging problem. Applications in user space, particularly network-facing services, are most at risk of compromise; compromised applications may attempt to issue false reports about their activities in order to inject uncertainty

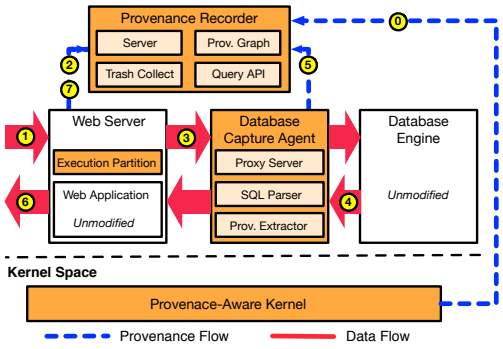

Fig. 2. Overview of Database-Aware Provenance (DAP) architecture. Provenance-Aware components are shaded in orange. In this deployment, DAP is able to capture provenance without requiring changes to the Database Engine or Web Application; instead, provenance is generated by interposing on the connection between the Web Application and Database Engine. A small change to the Web Server is required to facilitate execution partitioning.

into the provenance log. LPM addresses this by verifying the integrity of applications with the Linux Integrity Measurement Architecture (IMA) [34]. When an application wishes to report provenance, it sends lineage metadata over a UNIX domain socket to the Provenance Recorder. The Recorder recovers the application's process id over the UNIX socket, uses the `/proc` filesystem to find the full path of the binary, and then uses this information to look up the application in the IMA measurement list. The disclosed provenance is recorded only if the signature of application matches a known-good cryptographic hash.

We performed a rigorous evaluation of the LPM system in [6], and determined that the runtime overhead imposed by provenance collection during heavy system load was just 2.7% - 7.5% (I/O intensive activities experienced the higher of these overheads). We also showed that LPM provenance could be queried to determine the expansive ancestries of system objects in just tens of milliseconds, enabling its real time use in the complex deployments explored in Section III. The limiting factor to LPM's performance is high storage overhead, which was on the order of gigabytes per hour under heavy load. We are currently exploring new techniques to reduce provenance storage overhead [5], as well as investigating how to adapt existing techniques to LPM [7], [21], [22], [38], [39], [40].

B. Provenance-Aware Infrastructure

The **Database-Aware Provenance (DAP)** architecture provides provenance capabilities to software infrastructure through minimal-cost retrofits to existing application workflows. In designing DAP, we leveraged the observation that, in many workflows, instrumentation efforts could be avoided through introspection on the messages exchanged between application components. Ubiquitous protocols such as HTTP and SQL, as well as data marshaling languages like XML, provide an open interface through which to infer the provenance of the workflow. DAP is therefore comprised of a set of communication proxies that parse application messages, extract relevant semantics, and then record those semantics as provenance. In [4], we consider a web service infrastructure as an exemplar deployment scenario, shown in Figure 2. Red lines mark a traditional web service data flow – incoming HTTP/HTTPS requests are received by a web application, prompting a series of database transactions that occur over a local network socket, which are then used to craft a response that is returned to the client.

DAP creates a modified, provenance-aware version of this workflow as follows: (1) a remote client transmits a request to the Web Application; (2) a small modification to the Web Server notifies the Provenance Recorder that it has started a new autonomous unit of work for fielding the request; (3) the web application's query to the database is proxied by a Database Capture Agent, which parses the query and extracts the relevant operational semantics; (4) after observing the Database Engine's response to the query, the Database Capture Agent (5) creates a new provenance event and transmits it to the Provenance Recorder; (6) after the Web Applications returns response to the remote client, (7) the Web Server signals the Provenance Recorder that the current unit of work has ended. Because system events that occur outside of the web service architecture may also inform its execution, (0) DAP interoperates with LPM, which generates provenance for all system activities that are not being explicitly reported by the Web Server or Database Capture Agent.

In [4], we benchmarked end-to-end delay and determined that DAP imposed just 5 ms overhead per web request.[1] We performed microbenchmarking to determine that the primary source of this overhead was processing delays at the Provenance Recorder, which could be addressed through the introduction of redundant or multi-threaded components. We also considered several scenarios in which DAP can be deployed to quickly determine the root cause of system attack, including SQL injection attempts, reverse shell invocations, and a vulnerable system library exploit. Finally, through the introduction of a security mechanism that authorizes individual server responses in real time, we can discard older workflow provenance in order to reduce the growth of the DAP provenance log from linear to logarithmic with respect to the number of web requests.

C. Provenance-Aware Applications

In addition to OS and infrastructure collection, making applications provenance-aware allows for contextually-rich provenance information from applications. In order to achieve the goal of provenance-aware applications, libraries are needed for developers to emit provenance from their applications. One such library is ProvToolbox [26], a library that presents an implementation of the W3C PROV specification for Java applications. In addition to using these libraries for applications, other tools that collect provenance, such as the ones described above can leverage these libraries to emit provenance in a standard way. This ensures that provenance collected at multiple levels within the system have a common representation.

III. Leveraging Provenance

The Department of Defense and the Intelligence Community operate a wide variety of distributed data processing applications. These applications are critical to the success of the

[1] 17% of total latency with client and server in VMs on the same host

missions of these organizations and it is therefore important that the applications are resilient to security issues as well as the types of failures that occur in a distributed system.

Provenance information can be used for a number of purposes in such data processing systems. If a data item enters the system and is later determined to be invalid, a taint tracking service can use provenance information to locate all data derived from that invalid data item. A cybersecurity service can use provenance data to identify suspicious activity such as data access from unexpected users, unexpected locations, or at unexpected volumes. An application monitoring service can use real-time provenance information to identify service failures, such as when a transformer is not creating new data. Finally, a data validation service can use provenance information to determine if data from unknown sources enters the system.

Even though data processing applications are created for different purposes, our experience indicates that many of them have an architecture similar to the one shown in Figure 3. This similarity currently makes it easier for us to manually add provenance instrumentation, but in the future, we plan to take advantage of these similarities and perform automated instrumentation and analytics.

The common data processing architecture contains a set of services that ingest data into the system from external sources and then publish it as messages to a message bus such as ActiveMQ [36] or RabbitMQ [37]. These messaging systems support a publish/subscribe model where consumers subscribe to receive information (for example, based on a topic), publishers send messages to the messaging system, and the messaging system delivers messages to the appropriate subscribers.

One type of subscriber we often see is an archive, or persister, service that receives messages that contain data to be stored and writes that data to a database. The database may be a vertically-scaled relational database such as Oracle [16] or a horizontally-scaled database such as Accumulo [2]. The archived data may come from ingesters or from transformers (described next) that generate derived data.

Transform services subscribe to the bus and when they receive data, they operate on it and publish derived information back to the bus. In addition, if a transformer needs data from the archive, it can use the message bus to request it from a query service that retrieves data from the database and replies over the message bus. Finally, users often interact with this sort of system via a web interface that receives information from application-specific web applications running in a framework such as Apache Tomcat [3]. The web applications typically interact with a query service that performs database queries and may also interact with the message bus to control the overall system.

To verify the effectiveness of provenance in data processing systems that follow the architecture above, we instrumented a logistics planning application to emit provenance information. This application ingests requirements that describe the items to be transported, transforms those requirements and the state of the transportation system into a movement plan, archives the requirements and plan to a database, and presents information to users via a web interface. We implemented real-time analytics on the provenance information to determine if logistics data from unknown sources entered the system. We found that provenance data can be used to accomplish this goal, but the detection required knowledge of the application. We wrote application-specific code that analyzed the provenance graph for each planning phase and determined if it matched expectations. For example, the analysis code checked that the requirements used in planning were the same requirements generated by the web-based user interface for the logistics application. The result of this analysis was presented in the user interface by showing the provenance graph with a green or red background and if red, an explanation why the provenance graph was incorrect.

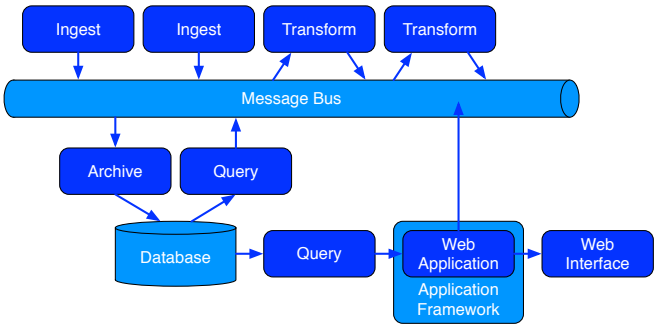

Fig. 3. A common architecture for data processing applications.

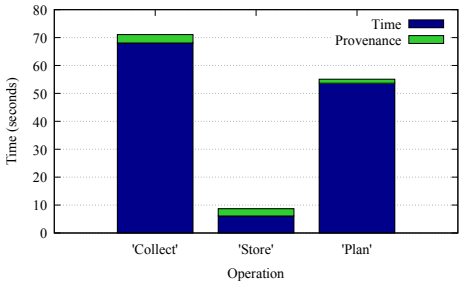

Fig. 4. Execution time overhead of collecting provenance information.

We find that the overhead of generating and analyzing provenance information in this logistics application is minimal. Figure 4 shows that collecting provenance information increases the execution time of the planning phase of the logistics application by 4%. The planning phase consists of generating and ingesting requirements, archiving and querying requirements and plans, and generating a logistics plan. The provenance data was published to the message bus in the same threads that execute application tasks. The execution time overhead could therefore be lowered using techniques such as using a separate thread to publish provenance information. Figure 5 shows that storing provenance information in a relational database increases the amount of storage needed by approximately 1% when compared to the amount of application data generated for a planning phase (for example, requirements and log files). Furthermore, the storage overhead is much less than 1% when compared to the application data used during a planning phase (the definition of the state of the available transportation system).

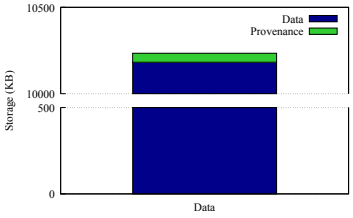

Fig. 5. Overhead of storing provenance information.

In future work, we will develop automated methods to detect anomolies in provenance graphs so that we do not have to implement application-specific detection. We expect that these methods will combine general heuristics as well as automated comparison to past provenance graphs that have been labeled as valid or invalid. Furthermore, since many data processing systems have architectures similar to Figure 3, we will investigate whether adding provenance instrumentation to common services such as message buses, databases, and web application frameworks will allow us to reduce the amount of instrumentation that needs to be added into application code.

IV. Tools for Provenance

As stated in the prior sections, provenance provides many benefits to the software and production engineers. However, the process of creating and maintaining infrastructure to capture and process data provenance is a complicated task.

To lower the bar of entry for engineers interested in utilizing provenance, we have created a collection of tools that can help build a provenance pipeline: from capturing system level provenance, to instrumenting applications, to interpreting and moving provenance around a network.

Additionally, We are beginning to work on other components of this pipeline, by improving tools used in collecting and shipping provenance data at scale.

A. Today's Tooling

Today's tooling focuses on two types of provenance collection, and a method for distribution of provenance data.

Engineers interested in data provenance today can start by collecting and analyzing system-level provenance data using the Linux Provenance Modules (LPM). LPM provides users with detailed and verbose logs regarding what every process and user on the system are doing and what invoked those actions. LPM is freely available from http://linuxprovenance.org/.

Engineers will quickly realize that there is a large semantic gap between what LPM collects and reports and what their application is actually doing. To illustrate this point, imagine a database application. This application writes to a binary data structure stored on disk. Within the context of LPM, this process is reading and writing to those files on disk – however, the operator trying to make sense of this data would be unable to make sense of it. What tables were being updated? What actions triggered the update?

To address this semantic gap, we've created the Userspace Provenance Library, and are in the process of making it open source. This library allows engineers to annotate their code and provide contextual information to system provenance (and vice versa). The application initiating a database write can indicate to the library basic information such as who initiated the action or where the data was derived from, giving a clearer picture as to what the process was doing.

Finally, we realize that few computer systems act on their own. Analyzing large amounts of provenance data requires systems with more processing power than the machines who are sending it. Curator (another tool going through the open source process) is our answer from taking provenance from multiple sources on a system (e.g. LPM, Userspace Provenance Library, etc.), then shipping it off to a variety places where it can be stored, such as Accumulo, Neo4j, or other delimited file formats.

B. Future Tooling

While many tools currently exist for collecting, storing, and analyzing provenance, there is still work to be done. First, many collection mechanisms require a software agent on the system to store provenance on a remote server. Existing prototype agents (SPADE and Curator) are large and require heavyweight infrastructure, such as the JVM [14]. While this may work for certain environments, other environments cannot support a full JVM, and smaller, self-contained agents are required. These agents should be compatible with existing infrastructure, and integrate cleanly into the many different systems that we anticipate will benefit from provenance.

Another limitation of leveraging provenance at the application layer is the lack of provenance-aware applications. In order to make applications provenance-aware, developers must manually instrument the applications to emit provenance information. For certain high-value applications this is reasonable, but for many legacy applications, there is little incentive to provide the appropriate instrumentation. Instead, automated hook placement techniques can be used to instrument applications. This is work that we are just beginning to explore, leveraging existing work in automated authorization hook placement [13], [20], [30].

V. Conclusion

Bigger and better walls around our systems will not prevent adversaries from gaining access to our systems, and wreaking havoc. Instead, building in protections that will allow systems to gracefully recover from attack are needed. Data provenance is one such protection that is reaching a point where developers and engineers can leverage existing tools to collect, store, and analyze provenance data. This data allows engineers to answer difficult questions about data being processed, and protect that data, even in the face of adversaries that have breached the perimeter defenses. While many of the tools and libraries are mature, there is still work left to fully realize the potential of data provenance in systems. This work looked at the overall landscape and presented the reader with an overview of the tools that exist today, and what tools are actively being developed. What is still needed is a community-driven effort to build and maintain these tools over time, and enhance the capabilities of data provenance.

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