Make Least Privilege a Right (Not a Privilege)

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ABSTRACT

Though system security would benefit if programmers routinely followed the *principle of least privilege* [24], the interfaces exposed by operating systems often stand in the way. We investigate why modern OSes thwart secure programming practices and propose solutions.

1 INTRODUCTION

Though many software developers simultaneously revere and ignore the principles of their craft, they reserve special sanctimony for the *principle of least privilege*, or *POLP* [24]. All programmers agree in theory: an application should have the minimal privilege needed to perform its task. At the very least, developers must follow five *POLP requirements*: (1) split applications into smaller protection domains, or "compartments"; (2) assign exactly the right privileges to each compartment; (3) engineer communication channels between the compartments; (4) ensure that, save for intended communication, the compartments remain isolated from one another; and (5) make it easy for themselves, and others, to perform a security audit.

Unfortunately, modern operating systems render the application of these requirements onerous, dangerous, or impossible. In our experience (detailed in Section 2.2), building least-privileged software is cumbersome and labor-intensive: following POLP feels more like an abuse of the operating system's interface than a judicious use of its features. Most programmers spare themselves these difficulties by reverting to monolithic, over-privileged application designs. Unsurprisingly, this exposes machines to attacks both old (remote attacks on privileged servers) and new ("install attacks", which take advantage of users' willingness to run high-privilege installers to infect machines with adware, spyware, or malware). We cannot write bug-free applications or prevent honest users from occasionally executing malicious code. Instead, our best hope is to contain the damage of evil code by resurrecting POLP.

In this paper, we examine some ways that current OSes discourage development of least-privilege applications (Section 2), then propose OS design ideas that might encourage it instead. A first approximation of a POLP-friendly system is one based on *capabilities*, discussed in Section 3. Though capabilities have historically flummoxed application designers, we present a more usable interface, based on the familiar Unix file system. In Section 4, we discuss shortcomings in this proposed design: weaknesses in the separated system might still allow vulnerabilities to spread, and process-sized compartments are too coarse-grained. We then propose a solution based on *decentralized mandatory access control* [17]. The end result is a new operating system called *Asbestos*.

2 LESSONS FROM CURRENT SYSTEMS

Modern Unix-like operating systems provide a limited API for running programs according to POLP. We examine how far administrators and programmers can push these features if POLP is their goal.

2.1 `chroot`ing or `jail`ing Greedy Applications

Because Unix grants privilege with coarse granularity, many Unix applications acquire more privileges than they require. These "greedy applications" can be tamed with the `chroot` or `jail` system calls. Both calls confine applications to *jails*, areas of the file system that administrators can configure to exclude setuid executables and sensitive files. FreeBSD's `jail` goes further, restricting a process's use of the network and interprocess communication (IPC). System administrators with enough patience and expertise can `chroot` or `jail` standard servers such as Apache [1], BIND [3] and sendmail [26], though the process resembles stuffing an elephant into a taxicab.

Even when possible, the `chroot` and `jail` approaches face more fundamental drawbacks:

Jails are heavyweight. The jailed file system must contain copies of system-wide configuration files (such as `resolv.conf`), shared libraries, the run-time linker, helper executable files, and so on. Maintaining collections of duplicated files is an administrative difficulty, especially on systems with many jailed applications.

Jails are coarse-grained. Running a process in a jail is similar to running it on its own virtual machine. Two jailed applications can share files only if one's namespace is a superset of the other, or if inefficient workarounds are used, such as NFS-mounting a local file system.

Jails require privilege. Unprivileged users may not call `chroot` or `jail`.[1] Jails are therefore ill-suited for containing the many untrusted applications that should not have privileges, such as executable email attachments or browser plugins.

Finally, `chroot` or `jail`'s *ex post facto* imposition of security is no substitute for POLP-based design. For example, a typical dynamic content Web server (such as Apache with PHP [18]) runs many logically unrelated scripts within the same address space. A vulnerability in

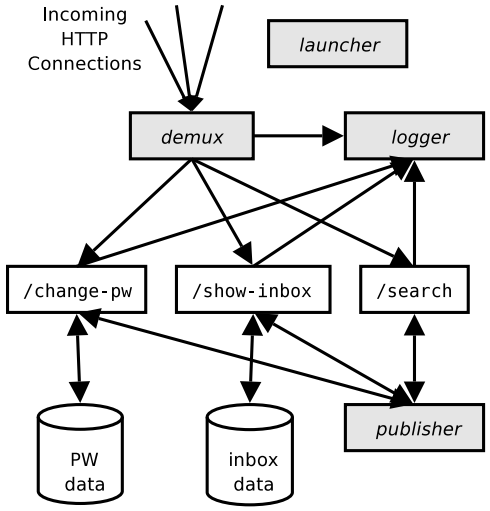

Figure 1: Block diagram of the OKWS system. Standard processes are shaded, while site-specific services and databases are shown in white. The privileged *launcher* process launches the *demux*, *publisher*, *logger* and the site-specific services. The databases shown might either be running locally, or on different machines.

any one script exposes all other scripts to attack, regardless of whether the server is jailed.

2.2 Ad-Hoc Privilege Separation

True privilege separation is possible on Unix through a collection of ad-hoc techniques. For instance, our POLP-based OK Web Server (OKWS) [12] uses a pool of worker processes to sequester each logical function (i.e. `/show-inbox`, `/change-pw`, and `/search`) of the site into its own address space. The *demux*, a small, unprivileged process, accepts incoming HTTP requests, analyzes their first lines, and forwards them to the appropriate workers using file descriptor passing. Workers then respond to clients directly. A privileged *launcher* process starts the suite of processes, ensuring that all are jailed into empty subtrees of the file system, and that they do not have the privileges to interact with one another. Finally, since workers' `chroot` environments prohibit them from accessing the root file system directly, they write HTTP log entries and read static HTML content via small, unprivileged helper processes: the *logger* and the *publisher*, respectively. Figure 1 shows a block diagram of a simple OKWS configuration.

The goal of this design is to separate application logic into disjoint compartments, so that any local vulnerability (especially in site-specific work processes) cannot spread. In particular, workers cannot send each other signals or trace each other's system calls, they cannot access each other's databases, no worker can alter any executable or library, and workers cannot access each other's coredumps. Unfortunately, achieving these natural requirements complicates OKWS. Its launcher must:

1. Establish a `chroot` environment, with the correct file system permissions, that contains the appropriate shared libraries, configuration files, run-time linker, and worker executables.
2. Obtain unused UID and GID ranges on the system.
3. Assign the *i*th worker its own UID u_i and GID g_i.
4. Allocate a writable coredump directory for each UID.
5. Change the *i*th worker's executable to have owner `root`, group g_i, and access mode `0410`.
6. Call `chroot`.
7. For each worker process *i*: kill all processes running as user u_i or group ID g_i; fork; change user ID to u_i and group ID to g_i; `chdir` into the dedicated dump directory; and call `exec` on the correct executable.

The `chown` call in Step 5, the `chroot` call in Step 6, and the `setuid` call in Step 7 all require privileged system access, so the launcher must run as root. Unix offers no guarantees of an atomic UID reservation (as required in Step 2) or race-free file system permission manipulations (as required throughout). Even ignoring these potential security problems, this design requires involved IPC to coordinate worker and helper processes.

Other systems use similar techniques to solve related problems. Examples include remote execution utilities such as OpenSSH [23] and REX [10], and mail transfer agents such as qmail [2] and postfix [21]. Considering these applications and others, a trend emerges: in each instance, the intricate mechanics of privilege separation are invented anew. To audit the exact security procedures of these applications, one must comb tens of thousands of lines of code, each time learning a new system. Even automated tools that separate privileged operations [5] require root access.

2.3 A User-Level POLP Library?

At first glance, a user-level POLP library might seem able to abstract the security-related specifics of applications like OKWS, qmail, and so on. One such example of this approach is found in the Polaris system for Windows XP [30], which applies POLP to virus-prone client applications like Web browsers and spreadsheets[2] via `chroot`-like containers. Such solutions have three drawbacks. First, they require privileged access to the system. Second, libraries must work around the lack of good OS support for sharing across containers: since jailed processes work with copies of files, synchronization schemes are required to reconcile copies after changes. (For example, Polaris email plug-ins run in a jail with a copy of the attachment; a persistent "synchronizer" process updates the original if the plug-in changes the copy.) Finally, we suspect that POLP techniques used in more complicated servers such as OKWS do not generalize well. As evidence, both OKWS and REX, an ssh-like login facility, use the same libraries (the SFS toolkit [16]) but share little security-related code. This comes as no surprise since the two have very different se-

curity aims: OKWS hides most of the file system, while REX exposes it to authorized users; OKWS must support millions of possible users, while REX serves only those with login access to a given machine; application designers can extend OKWS with site-specific code, while REX runs unmodified. Fitting both POLP usages into one general template seems a tall order.

2.4 Unix as a Capability System

One of the main difficulties with ad-hoc privilege separation is that starting with a privileged process and subtracting privileges is more cumbersome and error-prone than starting with a totally unprivileged process and adding privileges. Unix-like operating systems in general favor the subtractive model, while capability-based operating systems [4, 28] favor the additive one. But Unix file descriptors are in fact capabilities. By hobbling system calls sufficiently—either through system call interposition [7, 22] or small kernel modifications—we can emulate those semantics of capability-based operating systems that enable privilege separation.

The idea is to allow calls that use already-opened file descriptors (such as `read`, `write`, and `mmap`), but shut off all "sensitive" system calls, including those that create new capabilities (such as `open`), assign capabilities control of named resources (such as `bind`), and perform file system modifications, permissions changes, or IPC without capabilities (such as `chown`, `setuid`, or `ptrace`). In OKWS, the launcher could apply such a policy to the worker processes, which only require access to inherited or passed file descriptors. The launcher could run without privilege, and would no longer navigate the system call sequence seen in Section 2.2. By disabling all unneeded privileges, the operating system could enforce privilege separation by default.

This works because Unix's capability-like system calls are *virtualizable*. Processes are usually indifferent to whether a file descriptor is a regular file, a pipe to another process, or a TCP socket, since the same `read` and `write` calls work in all three cases. In practical terms, virtualization simplifies POLP-based application design. Splitting a system into multiple processes often involves substituting user-space helper applications for kernel services; for instance, OKWS services write log entries to the *logger* instead of a Unix file. With virtualizable system calls, user processes can mimic the kernel's interface; programmers need not rewrite applications when they choose to reassign the kernel's role to a process.

More important, virtualizable system calls enable *interposition*. If an untrustworthy process asks for a sensitive capability, a skeptical operator can babysit it by handing it a pipe to an interposer instead. The interposer allows harmless queries and rejects those that involve sensitive information. If the kernel API is virtualizable, then the operator need not even recompile the untrustworthy process to interpose on it.

Unfortunately, most Unix system calls resist virtualization. Some do not involve any capability-like objects; others use hard-wired capabilities hidden in the kernel, such as "current working directory" and "file system root". User-level emulation of these problematic calls—which include `open`—is messy, if not impossible; but scrapping `open` in the name of POLP seems unlikely to compel the average programmer.

3 Operating System Support for POLP

With the lessons from Unix, we can now imagine a POLP-friendly operating system interface, one in which all system calls are capability-based and virtualizable like `read` and `write`. Adding universal virtualization support to a Unix-like capability system would cover all five POLP requirements. With capabilities, application programmers can split their program into isolated compartments (#1 and #4), granting each compartment exactly the privileges necessary to complete its task (#2). With virtualization, programmers use standard interfaces and libraries for communication between these compartments (#3), and auditors can understand this communication by interposing at the interfaces (#5). A new take on capabilities—one whose Unix-like appearance would be friendlier to application programmers—could simplify the application of POLP. This section presents a hypothetical design for such a system, which we'll call *Asnix*.

3.1 Asnix Design

In Asnix, interactions between a process and other parts of the system take the form of *messages* sent to *devices*. Devices include processes and system services as well as hardware drivers. Messages follow the outline "perform operation *O* on capability *C*, and send any reply to capability *R*." The kernel forwards this message to the device that originally issued *C*. There are a small number of operation types, as in NFS [25] and Plan 9's 9P [19]: `LOOKUP`, `READ`, `WRITE`, and so forth. The message types and their associated syntax are conventions; the kernel only enforces or interprets those messages sent to kernel devices. Requests and replies are sent and received asynchronously.

This design aids virtualization. All of a process's interactions with the system—whether with the kernel or other user applications—take the same form, explicitly involve capabilities, and shun implicit state. Consider, for example, the Unix call `open("foo")`. This call in Asnix would translate to a message that a process *P* sends to the file server device *FS*:

$$P \rightarrow \langle C_{\text{CWD}}, \text{LOOKUP}, \texttt{"foo"}, C_P \rangle \rightarrow FS.$$

The first argument is a capability C_{CWD} that identifies *P*'s current working directory. The second is the command to perform, the third represents the arguments, and the fourth is the capability to which the file system should send its response. Since Asnix makes explicit the CWD state hidden in the Unix system call, either the file server or a user process masquerading as the file server can answer the message.

3.2 Naming and Managing Capabilities

When an Asnix process P_1 launches a child process P_2, it typically grants P_2 a number of capabilities, ranging from directories on the file system to opened network connections. How can P_2 then access these capabilities? Traditional capability systems such as EROS favor global, persistent naming, but persistence has proven cumbersome to kernel and application designers [27].

Instead, we advocate a per-process, Unix-style namespace. Under Asnix, P_1 makes capabilities available to P_2 as files in P_2's namespace. Suppose P_1's namespace contains a tree of files and directories under `/secret`, and P_1 wishes to grant P_2 access to files under `/secret/bob`. As in Plan 9 [20], P_1 can mount `/secret/bob` as the directory `/home` in P_2's namespace. Unlike in Plan 9, the state implicit in the per-process namespace is handled at user level, and the kernel only traffics in messages sent to capabilities. For example, when the process P_2 opens a file under `/home`, the user level libraries translate the directory `/home` to some capability *C*. The kernel sees a LOOKUP message on *C*.

3.3 OKWS Under Asnix

We now consider what OKWS might look like on Asnix. Similar to before, the application suite consists of a *launcher*, *demux* and worker processes. Under Asnix, the logger process simply enforces append-only access to a log file, and might be useful for many applications (much like `syslogd` on today's systems). No publisher process is needed.

The launcher starts each worker process with an empty namespace (and thus no capabilities), then augments their namespaces as follows:

- In the *logger*'s namespace, mounts a logfile on `/okws/log`.
- In the *demux*'s namespace, mounts TCP port 80 on `/okws/listen`. For each worker process *i*, makes a socket pair and connects one end to `/okws/worker/`*i*.
- In worker process *i*'s namespace, mounts the other end of the above socket pair to `/okws/listen`. Mounts a connection to the logger on `/okws/log`. Mounts a read-only capability to the root HTML directory on `/www`.
- In all namespaces, makes required shared libraries available under `/lib`.

The launcher then launches all processes as before.

Under Unix, the launcher had to carefully construct jails, physically copying over files and invoking custom helper applications like the publisher and logger to limit file system access. Asnix, by contrast, lets the launcher expose capabilities to child processes at arbitrary points in their namespaces. Each child receives a synthetic file system perfectly suited to its task.

Moreover, all capabilities available to the Asnix OKWS processes are virtualizable. Workers accept connections on `/okws/listen` regardless of whether they originate from the kernel's TCP stack or the *demux*. Similarly, logging might be to a raw file or through a logging process that enforces append-only behavior; worker processes are oblivious to the difference.

3.4 Discussion

So far, the proposed system features no individually novel ideas; rather, it finds a new point in the OS design space amenable to secure application construction. Similar effects might be possible with message-passing microkernels, or unwieldy system call interposition modules. But in Asnix, the security primitives are few and simple, for both the kernel and application developer. Although the interface exposed to applications feels like the familiar Unix namespace (with added flexibility for unprivileged, fine-grained jails), an application's system interactions are entirely defined by its capabilities, and Asnix behaves like a capability system for the purposes of security analysis.

4 FINE-GRAINED POLP WITH MAC

Though we believe Asnix is an improvement over the status quo, it still falls short of enabling the high-level, end-to-end security policies we seek. Applications in Asnix can only express security policies in terms of *processes*, but processes often access many different types of data on behalf of different users. A security policy based on processes alone can therefore conflate data flows that ought to be handled separately. For example, OKWS on Asenix achieves the policy that data from a `/change-pw` process cannot flow to a corrupted `/show-inbox` process; but the policy says nothing about whether user *U*'s data within `/show-inbox` can flow to user *V*, meaning an attacker who compromises `/show-inbox` might be able to read an arbitrary user's private e-mail.

Of course, a much better policy for OKWS would be that "only user *U* can access user *U*'s private data". We would like to separate users from one another, much as we separated services in Section 3. Though a user session involves many different processes (such as the *demux*, databases[3], and worker processes), a policy for separating users should be achievable with a small, simple, isolated block of trusted code, as opposed to hidden authorization checks scattered throughout the system. This section extends Asnix to a new system, *Asbestos*, whose kernel uses flexible mandatory access control primitives to enforce richer end-to-end security policies. We are currently designing and building Asbestos as a full operating system for x86 machines.

4.1 Complete Isolation

One possible approach to better isolation, which we call *complete isolation*, would be to prohibit server-side pro-

cesses from speaking for multiple users. The server must be prepared to run a process for every service–user pair; trusted code in *demux* would route traffic accordingly. Similarly, a database process exists for each user, writing to a user-specific database file. Capabilities can guarantee separation between processes as usual. More drastic separation is possible with virtual machines [11, 32] so that each machine can only speak for one user.

Complete isolation hides a user's data from other users, but at significant cost. First, such systems are not scalable, requiring either an expensive fork-accept-close model or a huge pool of largely-idle per-user servers. Second, these systems do not accommodate convenient data sharing, even with trusted processes. While traditional systems could use simple SQL statements to aggregate statistics over rows of a site's databases, completely isolated systems would have to search millions of separate files, perhaps over NFS in the case of separated virtual machines. Separation in this case requires a tremendous sacrifice in flexibility for data management. Data will not flow where it shouldn't, because it cannot flow at all.

4.2 Decentralized, Fine-Grained MAC

Asbestos uses decentralized, fine-grained mandatory access control (MAC) primitives to solve this problem in a flexible and scalable manner. Subjects on the system, such as processes, I/O channels, and files, are assigned *labels*, and special privilege is needed to remove a label once applied. Furthermore, a subject transmits its labels to any other objects that it successfully communicates with. With labels, Asbestos tracks all subjects that have accessed a given object, whether directly or via proxy.

We propose two important modifications to traditional MAC-based operating systems. First, decentralization [17]: processes can create their own labeling schemes on the fly, so that a Web server can associate each remote user with her own label. Second, labels apply at the fine-grained level of individual memory pages, so that a single process can act on behalf of mutually distrustful users without fear of leaking data among them. Taken together, these two modifications allow application designers to dynamically partition server processes into isolated *sub-processes*, where a sub-process consists of a set of virtual pages that share the same label.

When a server process receives a message, it is automatically assigned to a sub-process based on the label of the message's source. Processing a message from user *U* "contaminates" the process with *U*'s labels. As in traditional MAC, contamination with the label *U* prevents a process from accessing resources forbidden from user *U*, such as user *V*'s network connection. Thus, the kernel must allow a process speaking on behalf of multiple users to purge its labels without leaking data. Asbestos lets a process flush its register state, remap its memory, and clear its labels, allowing it to serve a request on behalf of a different user *V*. However, the system still accommodates trusted *declassifiers*, such as statistics collectors, that can act on behalf of multiple users and traverse sub-process boundaries within a virtual address space.

With decentralized, fine-grained MAC, OKWS can achieve a strong end-to-end security policy. The only trusted code is a *labeler* module upstream of *demux*, which works as follows. When user *U* connects to the Web server, the *labeler* peeks at the incoming TCP connection *T* and authorizes it based on session state or login information. If authorization succeeds, the *labeler* labels *T* with *U*'s label. Now, any process that reads from *T* and writes to memory will automatically tag that memory page with *U*'s label, and will therefore push that page into *U*'s sub-process. The kernel allows an unprivileged process to accumulate labels for different users (such as for *U* and *V*), but it forbids that process from writing to a network channel not labeled with both. Thus, if *U* compromises a server process and convinces it to read from *V*'s memory, the server process will acquire labels for both *U* and *V*, and therefore cannot write out to *T*.

4.3 Discussion

This decentralized MAC design, combined with the capability architecture from Section 3, makes POLP convenient and practical for an OKWS-like Web server. We have no proof that other applications would similarly benefit from Asbestos, but we are optimistic. Asbestos provides simple, flexible, and fine-grained mechanisms for achieving the five important POLP requirements without sacrificing performance.

5 Related Work

Asbestos proposes the marriage of previous ideas in systems: the capability-based operating system [4, 13, 28, 33], the per-process name space [20], the virtualizable kernel interface (the logical extension of system-call interposition libraries [7, 22]), and decentralized MAC [17].

Naturally, other operating systems predating Asbestos meet related design goals or offer similar features. Message-based operating systems such as L4, Amoeba, V, Chorus and Spring can isolate system services by running them as independent, user-level processes and provide natural support for interposition through message-based interfaces [14]; Trusted Mach in particular views message-passing from a security perspective [6]. But ports in microkernel systems are coarse as capabilities go; for instance, a process can have a capability for the file server but not for a particular directory. For POLP, application programmers need arbitrary collections of specific capabilities; in this respect, the microkernels of yesteryear do not fit the bill.

The Flask System applies MAC to the Fluke Microkernel [29]. Many of Flask's core design principles have found a modern incarnation in SELinux [15], which, like TrustedBSD [31], adds mandatory access control to popular Unix systems. In both, static policy files dic-

tate which resources applications might access, and how processes can interact with one another. Such systems are attractive because they preserve the POSIX interface to which many programmers are accustomed. However, their policy extension model, which is based on privileged files and kernel modules, appears to fall short of the decentralized and uniformly-analyzable policies implemented by Asbestos labels.

Type safety is another way to enforce operating system security. Coyotos combines capabilities with language-level verification techniques [27]. Singularity combines strong isolation with a type-safe ABI [8]. At user level, the Java Sandbox uses customizable policies to specify an applet's access rights; dynamic sandboxing shows these policies can be automatically produced [9].

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NOTES

[1] Were it not for this prohibition, unprivileged users could use control of the `chroot`ed top-level directory to elevate privileges. The attack is to make a new directory `/tmp/foo`, hard link from `/tmp/foo/su` to the system `su`, write a new password file `/tmp/foo/etc/passwd`, call `chroot` on `/tmp/foo`, and then call `su` from within the jail.

[2] Polaris appears not as well-suited for larger servers.

[3] We assume for simplicity that databases run locally, though all concepts discussed can generalize to distributed deployments.