A Critique of the GNU Hurd Multi-Server Operating System

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ABSTRACT

The GNU Hurd's design was motivated by a desire to rectify a number of observed shortcomings in Unix. Foremost among these is that many policies that limit users exist simply as remnants of the design of the system's mechanisms and their implementation. To increase extensibility and integration, the Hurd adopts an object-based architecture and defines interfaces, in particular those for the composition of and access to name spaces, that are virtualizable.
This paper is first a presentation of the Hurd's design goals and a characterization of its architecture primarily as it represents a departure from Unix's. We then critique the architecture and assess it in terms of the user environment of today focusing on security. Then follows an evaluation of Mach, the microkernel on which the Hurd is built, emphasizing the design constraints which Mach imposes as well as a number of deficiencies its design presents for multi-server like systems. Finally, we reflect on the properties such a system appears to require.

Categories and Subject Descriptors

D.4.7 [**Organization and Design**]: Interactive systems; D.4.6 [**Security and Protection**]: Access controls

Keywords

Multi-server, Naming, Access Controls, Structure

1 Introduction

The goal of the GNU project is to create an operating system consisting entirely of free software. By the end of the 1980s, the most important missing component was the kernel. As Unix systems were the primary operating system used by both GNU software users and developers, and as the components written to that date were designed for such systems, a high degree of API compatibility was deemed necessary. With the hope of speeding development, the decision was made to base the system on a free version of the Mach kernel from CMU. The designers exploited the microkernel foundation to build a more integrated and extensible system thereby improving its usability.
In [4], Bushnell outlines the Hurd's architecture and states that its goals, in addition to legacy compatibility, are to permit:

- Efficient sharing of scarce resources
- Greater extensibility and integration
- Mutually suspicious collaboration
- Sharing without prior arrangement

The intent was to improve the usability of the system through the creation of a well integrated, component-based system in which system services can be easily replaced and extended at a fine granularity yet which is sufficiently compatible with existing APIs to run most important software packages with little modification, in particular those from the GNU project. These concerns motivated a multi-server structured system with a distributed, user extensible naming framework. Today, hundreds of software packages from Debian run on the Hurd without modification.

2 The GNU Hurd's Architecture

The Hurd is a set of objects. An object is similar to a closure: it implements an interface and consists of a program and state. These objects extend the objects exposed by the underlying microkernel, Mach [35], to include standard system functionality and to dictate system policy. System services are made available exclusively through objects.
Hurd objects are realized in user-space processes called servers. To improve fault isolation and reduce that on which a program instance depends for its correct operation, its *reliance set*, [17, Ch. 5], a server implements a minimal number of related objects. Typically, a server decomposes some larger object. For instance, a file system server exposes a part of backing store as a hierarchy of files and directories. This is in contrast to a monolithic system where many components execute in the kernel's protection domain and component boundaries are only a formality.
Objects are referenced by *capabilities* [6]. Capabilities both designate an object and authorize access to it. Mach provides protected capabilities: unforgeable, task-local, opaque references conceptually held in a capability slot. They can only be transferred using the message passing facility.
A capability does not directly reference an object. On Mach, it references a kernel message queue, a *port*. A client holds a *send right* capability that permits enqueuing of messages, and a server holds a *receive right* capability that permits dequeuing of messages. A server internally associates the kernel object with the user object.
A process may sense (read) and manipulate (modify) an object only by invoking a capability which references it. Invoking a capability causes a message to be made available to the process implementing the referenced object. Messages may carry data and capabilities determined by the invoker. Typically, the client will include at least a *reply capability*, a send-once right designating a queue for which the client has a receive right. It then waits for a reply message. This

is the *remote procedure call* (RPC) pattern.
Because gaining access to an object, whether it is implemented by Mach or by a user-space process, is only possible using the message passing interface, any process may transparently implement, proxy or extend an object insofar as it can interpose itself between the object and the user. This is a basic requirement for virtualization [21] and reference monitors [1].

2.1 System Structure

The Hurd is defined by approximately a dozen canonical interfaces. The `fs` interface is used in the examination and manipulation of directory and file meta-data. This includes traversing object relationships using symbolic names. The `io` interface is used to read from data sources and to write to data sinks. File handle objects usually implement both of these interfaces. The `fsys` interface is used for whole file system related operations, e.g., those set on Unix using the `-o` option to `mount`, as well as to obtain an unauthenticated file handle to the root of the file system (an unauthenticated file handle is one that is not yet associated with any user ID on the server side).
Additional interfaces include the `auth` interface for managing identities and for the support of *identity-based access control* (IBAC), the `password` interface for obtaining identity objects against passwords, the `exec` interface for help in instantiating programs and the `process` interface for process management including process identifiers (PIDs), session and process group management and non-preemptive signal delivery.
A Hurd system consists of at least the Mach kernel, an `auth` server, a `proc` server, an `exec` server, a `password` server and a file system server. These servers provide a similar level of abstraction as the system call interface of a traditional monolithic Unix kernel.
The C library directly interacts with these servers to implement POSIX and other higher-level interfaces. Most programs use these interfaces exclusively. The implementation also contains hooks and extensions for more convenient use of some Hurd-specific features.
A number of utility programs extend the traditional collection of Unix utilities giving the user direct access to Hurd functionality. The most important of these is the `settrans` program for starting new servers and linking them to a name space.

2.2 Naming and Name Spaces

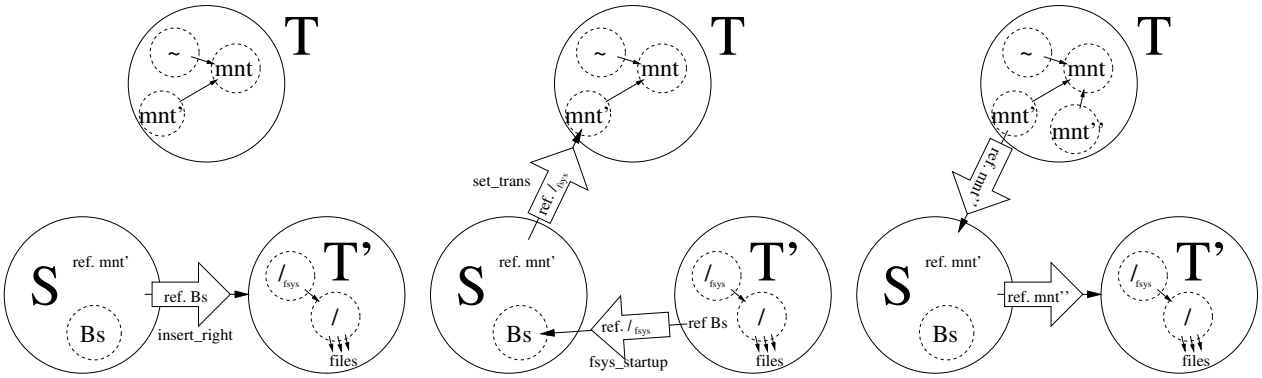
Although capabilities allow processes to reference objects, a convention is required to permit users to designate the objects on which a program should operate. The Hurd's solution appears similar to Unix's virtual file system (VFS), however, it differentiates itself in that its realization is distributed, not centralized. In particular, any process, without special privilege, can implement the conventions of the Hurd's VFS and create and publish a commonly understood naming hierarchy.
In this framework, object relations are named symbolically. The traversal of object relationships, *name resolution*, is realized using the `dir_lookup` interface. There is no implicit root: resolution is always done relative to an explicitly referenced object. Applications, however, resolve most names either relative to the capability stored in its *root directory capability slot* or relative to the capability stored in its *current working directory slot*, which are normally filled by the parent process with a copy of its own respective references at process creation, leading de facto to a single global namespace.
Often, the `dir_lookup` method does not actually return a capability referencing the resolved object: it creates a new object, a *handle*, which references some session state and the resolved object. These sessions are used primarily to fulfill some POSIX requirements. A file handle, for instance, includes a cursor, which records the session's current position in the file.

2.2.1 Extending a Name Space

When Alice wishes to access files on an FTP server from her Unix workstation, she likely uses an FTP program to copy the relevant files locally. Later, after having made some modifications, she again runs the FTP program to copy the modifications back to the server.
These steps are necessary as the programs Alice uses to manipulate the data cannot manipulate the objects on the FTP server: neither do the programs understand the object naming and access conventions of the FTP server nor is Alice able to instantiate her own file system that can make the objects available using the API they do understand. In the latter case, the problem is that this typically requires uploading code to the kernel or using a fragile kernel service (e.g., a file system driver, most implementations of which assume correct input).
To work around this, the GNOME and KDE projects have built their own VFS implementations which are user extensible but only accessible using different calling conventions. As such, applications which do not use this API appear less integrated. The Linux kernel developers have acknowledged this problem and have recently extended their kernel to support unprivileged, user-space file systems.
On the Hurd, Alice could have used the `ftpfs` program to make the objects on the FTP server available in a portion of the VFS she controls. Alice does not require any special privilege to do this: `ftpfs` is a normal program which implements a protocol; she just requires the appropriate access to the node to which she wants to attach it. Such programs are referred to as *translators*, as they translate between a pair of naming and access conventions.
Hurd translators are linked to other translators by inserting a capability referencing the `fsys` object of the translator at the desired *mount point*. This is usually done using the `settrans` program and is conceptually similar to mounting a file system on Unix. In the scenario presented above, Alice could have run a command similar to the following:

```
$ settrans -a ~/mnt /hurd/ftpfs \
  username:password@site.org/~
```

`settrans` starts an instance of the ftpfs program and attaches it to the node `~/mnt`. The remaining arguments are passed through to the translator.
The `settrans` program works by first obtaining a handle to the mount point. It then instantiates the program and, before setting it running, creates a port and inserts a send right to it in the *bootstrap capability slot* of the process (Figure 1(a)). As the translator starts, it invokes the `fsys_startup` method on the bootstrap capability, passing a capability referencing its `fsys` object as an argument. (As explained below, this object is required by the parent translator in its



(a) `settrans` S has opened `~/mnt` and created the new translator instance, T′. `settrans` now inserts the bootstrap capability Bs into the bootstrap capability slot of T′. `settrans` starts T' running.

(b) Upon finding the bootstrap capability Bs, T′ invokes `fsys_startup`, passing a reference to its `fsys` object. S invokes `file_set_translator` to mount T′ on T.

(c) T installs the `fsys` object of T′. S obtains and returns a reference to an unauthenticated handle for the mount point to T′.

Figure 1: The `settrans` program.

`dir_lookup` implementation to redirect a caller to the translator.) `settrans` then invokes `file_set_translator` on the capability designating the mount point handle, passing the `fsys` capability as an argument (Figure 1(b)). `settrans` also obtains and returns a reference to an unauthenticated handle for the mount point to the new translator (Figure 1(c)). It uses this to resolve the dot-dot directory at its root.

2.2.2 Name Resolution

A translator may use its `fsys` object simply as a *rendezvous* point. The `auth` and `password` servers do this: neither exposes objects in a way appropriate for a directory structure. Most servers, however, implement a hierarchy of objects which they make accessible via the standard interfaces. Object relationships are named symbolically by a *path*, a series of symbolic names, *path components*, separated by one or more `/` characters, and traversed following the name resolution protocol. At its core is the `dir_lookup` method, which starts by resolving the first path component. If the resolved object is also implemented by the server and path components remain, the next path component is also resolved by the server without returning to the caller as an optimization. This process continues until the path is completely resolved, or the server finds the named object is implemented by another server. If the path resolves to an object which the server implements, a capability designating a new handle to the resolved object is returned. Otherwise the server returns a so-called *retry message* to the client which contains a capability to a new unauthenticated root object handle on the other server as well as the path which remains to be resolved. The client then identifies itself to the new server and invokes `dir_lookup` on the authenticated root object handle, passing the rewritten path.

For POSIX compatibility, a `dir_lookup` implementation is required to resolve the special name *dot-dot* for the parent directory. (The root directory is its own parent.) If a process calls `dir_lookup` on a capability naming `/home/alice/mnt`, as in Figure 1, passing dot-dot as the path to resolve, the `ftpfs` instance would return a retry message which included a capability naming the object `/home/alice/mnt` on the parent translator and have rewritten the path to dot-dot.

The Unix `chroot` mechanism requires that a directory appears to a group of processes as a root. That is, the meaning of dot-dot must be overridden. The Hurd provides the more general `file_reparent` mechanism, which does not require superuser privilege. It creates a new handle for which lookups of dot-dot resolve to the provided capability. The special `void` capability indicates that the directory should appear as a root. Handles derived from a reparented node naming the same node preserve this property.

`file_reparent` also allows the realization of *firm links*, links which bind a portion of the VFS to another location, a sort of cross file system hard link. Bind mounts on Linux provide a similar mechanism.

2.2.3 Persistent Translators

On the Hurd, neither processes nor capabilities are persistent: files are the only persistent resource. To restore the operating environment, sufficiently privileged programs can register a command to be run at system restart. When the system is shut down, processes are informed of their imminent termination and given the opportunity to save their state into files.

This approach was inherited from Unix and is sufficient for configuration recovery for a relatively static, centrally controlled system. On the Hurd, users have much more control over their computing environment through the use of translators. To allow translators to be restarted transparently and consistent with the distributed architecture, a *passive translator setting* can be saved in the node on which the translator is set. If no translator is running when the node is accessed, the translator performing the `dir_lookup` will run the program specified in the passive translator setting. The program is started with the UID and GID of the node, which is often possible as it is normally the case that the parent either has the same identity as the translator or an identity which dominates that of the translator (e.g., root). When this is not the case, the translator is safely started without an identity.

The passive translator setting is saved using the `file_set_-`

`translator` method. Since the translator is started with the UID and GID of the node, it can typically only be set by the owner of the node. How and if the passive translator setting is saved is implementation defined. The ext2 file system implementation, for instance, allocates a file system block for the passive translator setting and saves the block address in the relevant inode.

2.3 Protection and Security

Hurd servers control access to objects based on the identity of the subject. The policy is similar to Unix but the mechanism is quite different. On the Hurd, identities are first-class objects (meaning that a single process may have more than one or none at all) and are managed by the `auth` server. The `auth` server also supports programs in the realization of IBAC by providing an authentication mechanism which allows programs to safely expose identities to others in a verifiable manner.

2.3.1 Identity Management

As identities are first class objects, a process may have access to any number of UIDs and GIDs or none at all. Moreover, because they are simply objects named by capabilities, a process is able to remove its authority to an identity by dropping the capability referencing it, so-called *discretionary authority reduction*. This technique allows applications to run with less excess authority thereby reducing the amount of damage a bug or an attacker can cause.

Applications that require access to a fixed number of resources known at start up and after which do not require the authority an identity grants, can take advantage of this technique. For example, a network server which needs to bind to a TCP port below 1024, but which does not otherwise require the authority the superuser identity conveys, can run with no UIDs or GIDs after binding to the port. This pattern is not limited to those applications which require access to a resource to which only the superuser ID grants access: a document viewer, after opening a user specified file, could destroy the identity object to diminish the effects of a malicious macro.

Servers which authenticate users such as FTP or SSH servers can also take advantage of this additional functionality: unlike the previous class of applications, these programs require the ability to change UIDs during the lifetime of the program. Because they interact with unauthenticated users while holding large amounts of authority, they are highly targeted. In particular, such programs are susceptible to buffer overflows and input validation errors during the login phase. On the Hurd, such a program instance can run with no identities. Then, after a user has provided a user name and password, it presents them to the password server in exchange for an identity object thereby increasing its authority. The Hurd's login program does this. Because the amount of havoc an attacker can wreck is proportional to the accessible authority, the effects of a breach are diminished proportionally.

On Unix, privilege separation [22] is used to isolate the parts of a program requiring root authority. This technique uses multiple collaborating processes. One process implements the typically small number of required privileged operations exposing them via a simple interface and the other implements the balance of the functionality. This eases verification of the privileged program and makes exploitation of bugs more difficult. However, this approach requires superuser privileges for the allocation of unused user and group IDs for each program instance which uses this technique.

2.3.2 Authorization

IBAC is based on knowing the identity of the user. Thus, when a subject authenticates access to an object which is controlled by such a regime, it needs to disclose its identity to the object. On Unix, the identity manager and most servers are in the same trust domain. On the Hurd, this is not the case. This exposes a tension: the server implementing the object must be able to examine the identities of the user, but not be able to use them. The Hurd's `auth` server provides a three-way handshake to support such mutually suspicious collaboration and sharing without prior arrangement.

When a client wishes to authenticate access to an object, such as when it crosses a translator boundary and only has an unauthenticated root handle, it uses `io_reauthenticate`. The client includes a so-called *rendezvous* capability referencing a new kernel message queue (Figure 2(a)). In response to this request, the server invokes the `auth_server_authenticate` method on a capability which references an identity object on a trusted `auth` server. It includes the *rendezvous* capability as well as a second capability which names an as of yet unauthenticated handle to the object. Without waiting for a reply, the client invokes the `auth_user_authenticate` method on a capability naming the identity object whose contents it wishes to disclose to the server. It also includes the *rendezvous* capability as an argument (Figure 2(b)). The `auth` server then pairs the *rendezvous* capabilities and completes the handshake by returning the identifiers in the identity object to the server and the capability naming the new object to the client (Figure 2(c)). The server then stores the identifiers in the object.

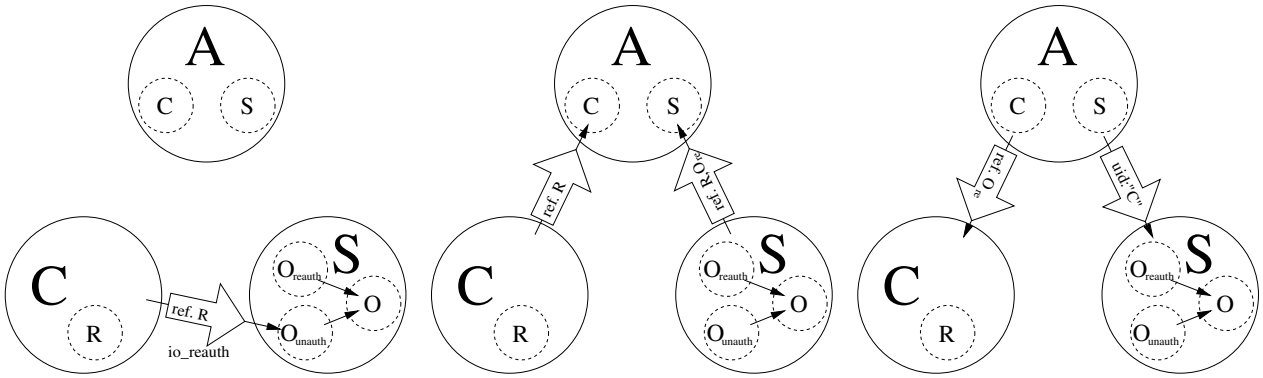
The capability to the new object is returned via the authentication server to avoid giving access to the authenticated object to an unprivileged third party. This prevents man in the middle attacks: if Bob has a connection to Alice via Mallet, i.e., Mallet is forwarding messages between the two, Alice and Bob can be sure that the established channel only traverses the union of their reliance sets. Otherwise, when Alice replies to Bob with the capability, Mallet could proxy the capability and observe all communication.

The authentication interface and protocol are designed such that it is possible to transparently interpose reference monitors and proxy `auth` servers between both the client and the common `auth` server as well as the server and the common `auth` server. This allows easy implementation of extended functionality, such as Debian's `fakeroot`.

2.4 Abstractions

Although the Hurd provides a rich set of abstractions, many are easily circumvented for either flexibility or efficiency reasons. The `store` abstraction provides an example of the latter: a store abstracts seekable data stores such as files and block devices as well as combined stores such as those in a RAID configuration.

As there is a cost involved in providing this level of indirection, sufficiently privileged programs (i.e., programs which would be able to access the underlying store in its entirety in the case of a partitioned store) can bypass the store translator using the `file_get_storage_info` method. In



(a) The client C invokes the `io_reauthenticate` method on an unauthenticated handle O_{unauth} to object O, passing a reference to a *rendezvous* object R.

(b) Client C and server S each invoke a capability referencing an ID object, passing the *rendezvous* capability. The server also includes a capability referencing a new object handle O_{reauth}.

(c) After pairing the *rendezvous* references, the `auth` server returns the new object handle to the client and the client IDs as a string literal to the server. The server can now realize its access control policy.

Figure 2: The authentication mechanism.

the simplest case, the returned information can be passed to `libstore` for a completely local implementation, thereby avoiding the additional context switches. This strategy has similarities to the Exokernel approach to abstraction elimination: remove mandatory abstractions and instead implement abstractions in user libraries [13].

2.5 Legacy Support

As it was expected that the bulk of applications would use the POSIX interface, it was important not to treat them as second-class citizens, e.g., via support through a poorly integrated subsystem. To this end, compatibility was realized through the use of a so-called *fat* C library where much of the POSIX API is implemented in terms of Hurd and Mach mechanisms.

This strategy provides several advantages: many legacy applications can be used with minimal modification, applications are rarely disadvantaged for having used the POSIX API, and few modifications are required to take advantage of Hurd features. For example, an FTP server on Unix normally requires the authority of the root user. This program can be modified using two isolated changes to take advantage of the Hurd's protection mechanisms. As described in Section 2.3.1, an FTP server needs to bind to a privileged TCP port and be able to change users. On the Hurd the server can drop its root identity after binding to the TCP port and use the password server to authenticate the user and obtain the respective identity object. Our experience suggests that such isolated changes are more readily integrated by upstream authors than invasive platform specific patches.

3 A Critique

The design presented above has a number of shortcomings in reaching its own stated goals as well as the demands of a modern computing environment.

3.1 Malicious File Systems

Most legacy applications assume that file systems are not malicious. This assumption is reasonable on a system where all file systems are part of a process's reliance set, as is the case on Unix. On the Hurd, where arbitrary programs are able to attach to and extend the virtual file system, this assumption leads to a vulnerability. For instance, an ignorant backup program may walk the VFS, copying the objects it finds. A malicious file system can mount a denial of service attack by generating an infinitely-deep virtual directory structure populated with arbitrary amounts of pseudo-random data.

It can be argued that there are always scenarios requiring defensive programming and that this is simply one of which Hurd programs need to be aware. This would be correct but avoids the question of legacy support.

Our observation is that compatibility is not only respecting the interfaces but also the deep assumptions that programs have regarding the API. Thus, it is the responsibility of the compatibility layer to recognize these assumptions and to meet them.

3.2 A File or a Directory?

In the Hurd, objects are dynamically typed. For example, all directory objects also implement the file interface, as was the case in early Unix systems. On modern Unix, a VFS node is strongly typed: it is either a file, a directory or some other well defined object. While early Unix systems made directories readable as files for internal implementation reasons, this approach appears useful for other reasons as well. Data can sometimes be seen as either a linear file or a structured hierarchy of objects. For instance, it is convenient to copy a backup archive by copying a single file. However, when searching for a file in the same backup archive, it is more convenient to view the data backup as a directory hierarchy and have the ability to search it using normal tools such as `find` and `grep`.

In this example, the view is selected by the use of disjoint sets of interfaces. Some programs, like `grep -r`, support multiple object types and rely on advice from the object in the form of the file type information for disambiguation. Which view should be presented depends on the intent of the user. We found that this ambiguity made it difficult to lever-

age the potential advantages of a dynamically typed object system in the context of a legacy POSIX environment. This motivates a mechanism by which a user or an agent acting on his behalf can acquire separate names for separate views on the same underlying object. Requiring explicit naming of views reduces ambiguity thereby simplifying code, removes a security risk and provides the user with greater expressiveness through the uniform interface. Adding a new naming mechanism would require that all programs be taught how to use it. Instead, the existing naming framework should be reused and objects should implement a single type. For example, different views on the same underlying object could be selected by a path component suffix built from a special character plus type specifier, with only minimum practical impact on POSIX compatibility.

3.3 The Dot-Dot Directory Entry

The resolution of dot-dot to the physical parent was motivated by POSIX compatibility. Unfortunately, it requires server help. This is further complicated as processes may have different views of the VFS, e.g., processes running in a `chroot`. Additional support is thus required to override dot-dot so that `chroot`ed processes (and their children) do not see the physical parent of the root but a VFS root.

The `file_reparent` method appears to solve this issue, however, introduces its own problems. If a translator is itself started in a `chroot`, say `/chroot`, and a process which has a different root directory, say `/`, attempts to resolve a path starting in the translator's name space but which ascends the hierarchy traversing the translator's root directory, it will get unexpected results: Assume the translator is mounted on `/chroot/mnt` and the process, starting at `/chroot/mnt`, looks up `../../foo`. When the process invokes the `dir_lookup` method, the translator returns a retry message including a capability referencing the underlying node but whose logical root is set to `/chroot`. When the process retries the rest of the path with this handle, it will resolve to `/chroot` rather than `/` as the underlying file system compressed dot-dot at the *handle's* logical root. Had the process resolved dot-dot on its own, it would have arrived at the correct directory. What has happened is that the naming context has changed.

Pike argues for lexical name resolution, i.e., making applications responsible for the resolution of dot-dot, as POSIX semantics are actually rarely what users want [20]. Adopting such a policy on the Hurd would not only improve the user experience but would also fix the above and similar problems by entirely removing the need for server resolution of dot-dot and thus `file_reparent`. This also has the additional fortunate effect of significantly simplifying servers and proxies.

3.4 Passive Translators and Naming

Translators are started in two different scenarios: by a program, at the behest of a user; and by a file system, as it traverses the VFS and accesses a node which has a passive translator setting but no running translator. The latter scenario was motivated by the requirement for a mechanism which restores running translators after system restart.

When a program instantiates a translator, it provides it with a naming context, that is to say the new translator's root and current directory objects. As passive translator settings do not include naming contexts—they are strings—the file system uses its own default naming context. Users tend to encounter this problem when they provide a relative path in the passive translator setting rather than an absolute path. More of a concern, however, are the implications for enforcement of security policies: `chroot` is sometimes used as a protection mechanism as it restricts the name space of a set of processes, limiting reachability. Making the whole name space of the file system available to the encapsulated process circumvents this mechanism.

Consider the case where the root of the translator's naming context is `/` and the root of a `chroot`ed program instance's naming context is `/chroot`. The encapsulated program instance can escape by setting a passive translator on `/chroot/foo` (what it locally knows as `/foo`) and then `stat`ing the object:

```
$ settrans -cp /foo /hurd/firmlink /
$ ls -l /foo
```

When the translator examines the object, it sees that the node has no translator but does have a passive translator setting. It proceeds to start a translator by resolving the command name to an `fs` object relative to its own root and, in executing it, providing the program instance with a capability to its own root. If the translator is, as above, a firm link, a translator which makes some name space available at the translated node, then the encapsulated program has successfully escaped. Alternatively, the encapsulated program instance could debug the translator (it has the same UID) and simply copy the capability.

To avoid this, the program instance that sets the passive translator must also provide a naming context in which the passive translator is interpreted as well as a default naming context for the translator instance. That is, it must provide closures, not just strings [23]. Arguably, the file system has at least the former: it need only remember which handle the passive translator was set with. The problem is that the handles are not persistent and the main motivation behind passive translators is that since capabilities and processes are not persistent, a method is needed to restore translators. This problem, known as *trusted recovery* [7], can be solved partially by making the system persistent, thereby circumventing the reconfiguration problem [14, 26, 33]. From a user's perspective, persistence is a highly desired feature: desktop environments work to restore running applications to the state they were running in when the user logged out; and many users, in particular laptop users, choose to suspend to disk or memory rather than turn the computer off. However, persistence does not address other configuration management issues such as update and migration. We are not aware of alternatives to persistence that solve the trusted recovery problem in a dynamic environment.

3.5 Server Allocations

On the Hurd, most objects are accessed via sessions. This is usually motivated by POSIX compatibility. File handles, for instance, are required to maintain the cursor position and record the logical dot-dot binding. For each session, the server must allocate some storage. In the case of objects that cause allocations, this is not a problem. However, with only read access to an object, the client should not be able to cause additional storage allocation. Yet, this is the case and, as such, a malicious program, having only authorized to use the read-only interface to an object, is able, in bounded

space, to cause the server to consume an unbounded amount of memory: it simply enters an endless loop performing an `open` on the file. The server cannot tell which process is causing the allocation; it can, at best, implement a local per-user memory quota. This has the unfortunate side effect of potentially limiting legitimate uses of the server (what is the right quota?). It also makes a new denial-of-service attack possible: an encapsulated process can exhaust the user's resource quota. Again, identity based access control is inadequate.

To avoid this, read-only interfaces should be designed such that they do not require server allocations or that the client provides the resources by passing a capability which names a resource pool of some sort, similar to EROS space banks [26] or resource containers [2], against which the server then allocates the resources.

When possible, allocations should be avoided. In the case of the cursor, this is possible. As multiple processes can access a single file descriptor (i.e., a single handle), this raises the question of how to coordinate access to the cursor. The majority of shared file descriptors name pipes. As pipes are unseekable, they do not require a cursor. In the remaining rare cases in which two processes share a file description to a seekable object, they must coordinate access to the cursor anyway. This already requires that they be mutually trusting. However, as this is quite complicated, it is normally avoided by immediately `dup`-ing the file handle on receipt. Thus, it appears, a shared cursor is rarely required.

3.6 Security and Protection

Computers are used to store and process data. This data has value and, as such, should have appropriate mechanisms in place according to the user's security policy to protect it from unauthorized access and disclosure and to ensure its availability. Although the Hurd provides some mechanisms for protecting data from other users, the Hurd does not provide mechanisms for the enforcement of a security policy for particular program instances: programs are assumed to represent the interests of the user and, as such, are run with the user's authority.

Although the US military was acutely aware of such threats over three decades ago [1], in the early 1990s when the Hurd was designed, the average computer user did not consider them important: malware was mostly non-existent. This sentiment is echoed by Bushnell at the end of his architectural overview of the Hurd: "[y]ou can't harm a process by giving it extra permission" [4]. Yet as programs are buggy [18, 19], sometimes malicious and often exploited [32], not providing adequate protection mechanisms today is irresponsible.

To mitigate these problems, users need to be able to provide a program instance access to only the objects it needs to realize the user's intent. That is, it should be possible to run programs consistent with the principle of least privilege (POLP) [24].

The discretionary authority reduction pattern described in Section 2.3.1 does not address this problem: although it useful in mitigating the effects of bugs and their exploitation, the use of this pattern is at the discretion of the program—not the user. As such, although it represents good programming practice, users have not gained any control: they still rely on the goodwill of programmers.

Capability practitioners contend that a well-structured capability system can run programs under a POLP regime without modification and without being invasive to users. Polaris [30] and Plash [25] are two such systems built on top of Windows XP and GNU/Linux respectively which illustrate that this is possible. Their frameworks are based on three observations. First, most programs require access to a limited number of objects which can be statically enumerated. Second, authorization can often be inferred, e.g., when the user double clicks on a resource to launch the associated application [34]. Finally, additional access at run-time is only required by interactive programs and most often after a user interaction via an open or save dialog box. These can be replaced with a call to a trusted program, the *powerbox*, with access to all of the users resources which interfaces with the user on the program's behalf and delegates access to those objects the user authorizes. This can be done transparently by replacing the appropriate library routines.

If the Hurd were to abandon IBAC and implement such a framework, the structure of most Hurd objects would nevertheless remain problematic: most Hurd objects convey large amounts of authority which is not easily decomposed. This is often motivated by concern for POSIX compatibility. A directory, for instance, provides access not only to the subtree it dominates but to the entire name space due to dot-dot naming the physical parent. The behavior of dot-dot can be overridden using `file_reparent`, however, this requires explicit action violating the principle of safe-by-default [24].

4 Evaluating Mach

Liedtke argues that the microkernel approach to system structure is often rejected based primarily on the perceived high cost of the message passing mechanism [15]. We observe additional shortcomings in Mach regarding resource scheduling and resource accounting that we contend also need to be addressed for the microkernel approach to have competitive performance and be able to support safe use of potentially malicious programs.

4.1 Resource Scheduling

Most systems provide tasks the illusion that they are running on a machine with infinite resources: tasks allocate virtual memory, memory that the kernel transparently moves between physical memory and backing store; likewise, threads need never explicitly yield the CPU as the kernel automatically preempts them. This is convenient insofar as it relieves applications from having to respond to resource shortages, multiplex resources and simplifies dynamic reallocation of resources. Assuming that competition for the physical resources remains relatively low, good resource utilization can be achieved without application support as evidenced by the many monolithic kernels that successfully employ such techniques. When this assumption is violated, when significant resource multiplexing occurs, system performance can significantly degrade if poor scheduling decisions are made [12].

4.1.1 Efficiency

For transparent resource management, a monolithic kernel has two resource scheduling advantages over a multi-server: it can better predict resource usage patterns and more components can interact with the scheduler.

Due to their centralized nature, monolithic kernels have a higher-level view of how users and processes use resources:

they implement the high-level abstractions such as UIDs, file systems and network protocols and directly interact with the users of these resources. These abstractions can provide important hints regarding expected resource usage. A monolithic kernel, for instance, can implement file-based read-ahead heuristically. On the Hurd, these abstractions are implemented by user-space servers that Mach does not only not regard as special but of which Mach has no additional knowledge. Such optimization techniques cannot be reliably implemented in the respective user-space servers as these processes do not have information regarding memory pressure and thus cannot correctly determine how aggressively to act.

Second, the components of a monolithic kernel can hook into the resource-management framework in ways which violate formal component boundaries. For instance, Linux employs a page-replacement strategy based on memory access patterns, but also makes up-calls to a number of subsystems to request they shrink their caches. This includes the widely-used slab allocator [3], the directory entry cache, the inode cache and the disk-quota-entry cache. Gorman reports that the last three have a "cascading effect [which] allows a lot more pages to be freed" [10, Sect. 10.4]. On a multi-server system, far fewer components run in the microkernel limiting the applicability of this approach.

Transparent multiplexing of resources thus limits those who can effectively influence resource scheduling to those who do not run under its regime. As observed, this problem is minimized on monolithic systems as major resource consumers such as file systems run in the kernel. The designers of databases [31], scientific applications [5], multimedia and other adaptive applications [**?**] and garbage collectors [12], however, have also observed this problem. For multi-server systems to be viable, we contend that applications must be able to better participate in resource scheduling decisions. The difficulty is that the interfaces must be designed such that the system can protect itself from destructive interference without unduly increasing complexity [8].

4.1.2 Real-Time and Quality of Service

The utility of the results of real-time applications is per definition dependent on the wall clock. A common example of real-time applications found on general-purpose operating systems are multimedia applications. Interactive applications also have a real-time aspect. Real-time can also be formulated as a quality of service problem. Although support for real-time applications is not an explicitly stated goal of the Hurd, given the increasing use of applications which have such properties, the Hurd's lack of support reduces the usability of the system.

The realization of real-time properties depends on the ability of programs to be able to make predictions of progress. This does not necessarily require hard resource guarantees: statistical guarantees for the these classes of applications may be sufficient. What is required is that the amount of resources available to the application as well as their access properties be known and these be useful for reasoning.

Transparently multiplexed resources as commonly implemented fail to satisfy this last property. The worst case access times of virtual resources is essentially infinite in particular compared with their average case access times. Currently, applications have to hope that data will not be paged and that the CPU allocation will remain at least as large as in the recent past. This encourages conservative behavior.

The decentralized nature of a multi-server system combined with these observed application demands motivates mechanisms which allow untrusted programs to request resource schedules. Further, applications are served by many different components each of which must guarantee some level of service. That is, the scheduling domain crosses process boundaries. This motivates mechanisms which parallel those for better control of resource scheduling.

4.2 Resource Accounting

Consistent with the illusion that resources are infinite, Mach performs no resource accounting. This introduces a security hole as virtual resources are, in fact, limited: the degree of multiplexing of physical memory is limited by the amount of backing store reserved for that purpose, opening up the possibility of a denial of resource attack.

Because resources are not accounted, simply allocating large amounts of resources is sufficient to perform a denial of resource attack. It might seem that the effects of such an attack could be mitigated by enforcing reasonable per-process quotas. This is easily overcome by malicious entities, however, by spawning multiple processes. Extending the quotas to users will not work either: users are a Hurd abstraction not known to Mach.

The problem underpinning the above thought experiment is the assumption that we can successfully coax an implicitly named resource principal out from where there is none: the process which allocates the resource is often not the resource principal. When a process reads data from a file, it invokes the `io_read` method on a capability naming an `io` object. The server then allocates memory on behalf of the client, reads the data into the memory and returns it to the calling process. Thus, although the file system invoked the kernel to perform the resource allocation, the allocation should, in this case, be charged to the process, or rather, the principal on whose behalf the process is running. This problem is explored in the context of monolithic kernels by Banga et al. in [2].

To ward off denial of resource attacks, the idea of a resource principal or container needs to be introduced. A resource container must be passed around securely, allowing servers to allocate resources on behalf of clients, but also allowing clients to recover their resources in case the server misbehaves. Later versions of OSF Mach introduced so-called resource ledgers for accounting the use of wired memory and swap space. However, they are not directly named but rely on ambient authority, complicating allocation. A better model may be KeyKOS's CPU meters and space banks [11] and as later evolved in EROS [26], which do not have these deficiencies. Still, dynamic reallocation of resources at a global scale remains a challenge in such a distributed approach.

5 Lessons and Thoughts

Our experience with the Hurd has led to a number of realizations that may help future designers of general purpose operating systems.

5.1 Security

The Hurd empowers the user by making a number of useful privileged operations unprivileged. By reifying identities, it also provides discretionary authority reduction mecha-

nisms allowing programs to protect themselves from attackers. Neither of these address a major security problem of today: the inability to protect data from program instances. To achieve this, programs should be run consistent with the principle of least privilege. Recent research on capability systems suggests that capabilities can provide a usable framework to realize such a system. In particular, to allow run-time delegation of authority, the powerbox, a trusted program, interacts with the user on the program's behalf.

5.2 Naming and Binding

Recovering the configuration of the system on restart improves usability. To facilitate this, the Hurd allows users to save translator settings in nodes. When the node is accessed and no translator is running, the file system can then transparently restart the translator. The problem that this raises is that the naming context cannot be serialized, leading to a number of security concerns as a malicious user is able to confuse file systems.

This is a general problem wherever symbolic names are severed from their naming context and often occurs at the storage boundary where there is no easy way to serialize a naming context. As symbolic names are primarily of interest to users and not to programs, we suggest that symbolic names be avoided and capabilities be used as designators. The problem this raises is that capabilities, like naming contexts, need to be saved. By making the system persistent, this problem is circumvented.

5.3 Resource Management

We have noted that although virtualized resources are convenient, they are also often problematic due to inefficient resource scheduling and their ineffectiveness when trying to realize real-time properties. This former problem is not unique to multi-server systems but particularly pressing as it appears the techniques used by monolithic kernels to compensate for lack of local knowledge, namely, introspection of high-level functionality to help predict resource usage patterns, cannot be used by a microkernel where such functionality is implemented in user-space. We contend that an interface is needed to allow unprivileged programs an increased ability to influence resource scheduling both regarding distribution and multiplexing.

5.4 Legacy Support

Legacy support is highly desirable for non-mainstream operating systems: application developers tend to target widely deployed systems, however, deployment penetration appears to be strongly correlated with the number of applications available. Moreover, if a system lacks support for just one or two applications, users will reject it.

The Hurd aimed to not only run legacy applications, but to tightly integrate them and provide them with many of the advantages of Hurd mechanisms. In this regard, the Hurd was successful. The Hurd, however, in its strict support of POSIX, unnecessarily complicated the system structure. We have observed that this was often motivated by questionable features such as server resolution of dot-dot and a server-implemented cursor.

Finally, care must be taken to preserve non-functional API and ABI requirements such as trust assumptions. The most important example of the Hurd's failure is that legacy programs are susceptible to attack by malicious file systems.

6 Related Work

KeyKOS is the only other complete multi-server operating system of which we are aware [11]. KeyKOS is an object-oriented capability-based system designed for applications with high-security requirements. It was used in ATMs, for instance, but not as a general purpose system. Work on EROS, KeyKOS's successor, has concentrated on refining and formalizing KeyKOS's security model [27].

The focus of L4 has been to enumerate a minimal set of portable primitives and operations that must be provided by the kernel. L4 performs well in microbenchmarks [15]. Little is known, however, regarding large scale system design: systems on L4 have mostly consisted of domain specific applications [16] and specialized functionality supplementing a system running in a legacy container [28].

The architects of Mach [35] focused primarily on a single-server system. Mach-US, a multi-server system, is structurally similar to the Hurd [29]. To our knowledge, its name space is not user extensible. IBM used Mach as a platform to support multiple operating system personalities [9].

7 Conclusion

The Hurd started with the observation that a number of useful Unix mechanisms, in particular, those regarding the extension of the VFS, should be available to users. By adopting a multi-server system and a decentralized naming framework, the Hurd makes it possible for users to provide their own file systems implementations and integrate them into the VFS.

The Hurd has two noteworthy security shortcomings: it does not provide mechanisms to protect resources from program instances; and symbolic names are often separated from their naming contexts.

An important goal of the Hurd was to support POSIX applications. Sometimes this was done too faithfully, compromising parts of the system structure. Other times, the Hurd failed to consider important aspects of legacy compatibility, namely, assumptions applications have regarding behavior.

To allow the efficient use of resources on microkernel based systems, it appears that applications must participate in resource scheduling. We observe that there are two main areas where applications can usefully extent greater control of resource scheduling: distribution and multiplexing.

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9 References

[1] Anderson, J. P. Computer security technology planning study. Tech. rep., Air Force Electronic Systems Division, Oct. 1972.

[2] Banga, G., Druschel, P., and Mogul, J. C. Resource containers: A new facility for resource management in server systems. In *3rd USENIX Symposium on Operating Systems Design and Implementation* (Feb. 1999).

[3] Bonwick, J. The slab allocator: An object-caching kernel memory allocator. In *USENIX Summer* (1994), pp. 87–98.

[4] Bushnell, M. Towards a new strategy of OS design. *GNU's Bulletin 1*, 16 (Jan. 1994).

[5] Cox, M., and Ellsworth, D. Application-controlled demand paging for out-of-core visualization. In *VIS '97: Proceedings of the 8th conference on Visualization* (1997).

[6] Dennis, J. B., and Van Horn, E. C. Programming semantics for multiprogrammed computations. *Communications of the ACM 9*, 3 (Mar. 1966), 143–155.

[7] Department of Defense. *Trusted Computer System Evaluation Criteria DOD 5200.28-STD*. Dec. 1985.

[8] Druschel, P., Pai, V. S., and Zwaenepoel, W. Extensible kernels are leading OS research astray. *Proceedings of the 6th Workshop on Hot Topics in Operating Systems* (May 1997).

[9] Fleisch, B. The failure of personalities to generalize. In *HOTOS '97: Proceedings of the 6th Workshop on Hot Topics in Operating Systems (HotOS-VI)* (1997).

[10] Gorman, M. *Understanding the Linux Virtual Memory Manager*. Bruce Perens' Open source series. Prentice Hall Professional Technical Reference, 2004.

[11] Hardy, N. The KeyKOS architecture. In *Operating Systems Review* (Oct. 1985), vol. 19, pp. 8–25.

[12] Hertz, M., Feng, Y., and Berger, E. D. Garbage collection without paging. In *Proceedings of the 2005 ACM SIGPLAN conference on Programming language design and implementation* (June 2005).

[13] Kaashoek, M. F., Engler, D. R., Ganger, G. R., Briceo, H. M., Hunt, R., Mazires, D., Pinckney, T., Grimm, R., Jannotti, J., and Mackenzie, K. Application performance and flexibility on exokernel systems. *16th Symposium on Operating Systems Principles* (1997).

[14] Landau, C. R. The checkpoint mechanism in KeyKOS. In *Second International Workshop on Object Orientation in Operating Systems* (Sept. 1992).

[15] Liedtke, J. Improving IPC by kernel design. In *Proceedings of the 14th Symposium on Operating System Principles (SOSP)* (Asheville, NC, Dec. 1993).

[16] Liedtke, J., Panteleenko, V., Jaeger, T., and Islam, N. High-performance caching with the lava hit-server. In *Proceedings of the USENIX 1998 Annual Technical Conference* (New Orleans, Lousiana, June 1998).

[17] Miller, M. S. *Robust Composition: Towards a Unified Approach to Access Control and Concurrency Control*. PhD thesis, Johns Hopkins University, May 2006.

[18] Ostrand, T., and Weyuker, E. The distribution of faults in a large industrial software system. In *ACM SIGSOFT International Symposium on Software Testing and Analysis* (2002), pp. 55–64.

[19] Ostrand, T., Weyuker, E., and Bell, R. Where the bugs are. In *ACM SIGSOFT International Symposium on Software Testing and Analysis* (2004), pp. 86–96.

[20] Pike, R. Lexical file names in Plan 9 or getting dot-dot right. In *2000 USENIX Annual Technical Conference* (June 2000).

[21] Popek, G. J., and Goldberg, R. P. Formal requirements for virtualizable third generation architectures. *Communications of the ACM 17*, 7 (July 1974), 412–421.

[22] Provos, N., Friedl, M., and Honeyman, P. Preventing privilege escalation. In *12th USENIX Security Symposium* (Aug. 2003).

[23] Saltzer, J. H. Naming and binding of objects. In *Operating Systems, An Advanced Course* (London, UK, 1978), Springer-Verlag, pp. 99–208.

[24] Saltzer, J. H., and Schroeder, M. D. The protection of information in computer systems. In *Proceedings of the IEEE* (Sept. 1975), vol. 63, pp. 1278–1308.

[25] Seaborn, M. Plash: tools for practical least privilege. `http://plash.beasts.org`.

[26] Shapiro, J. S., and Adams, J. Design evolution of the EROS single-level store. In *2002 USENIX Annual Technical Conference* (2002), pp. 59–72.

[27] Shapiro, J. S., and Hardy, N. Eros: A principle-driven operating system from the ground up. *IEEE Software 19*, 1 (2002), 26–33.

[28] Singaravelu, L., Pu, C., Härtig, H., and Helmuth, C. Reducing tcb complexity for security-sensitive applications: Three case studies. In *EuroSys 2006* (Leuven, Belgium, April 2006).

[29] Stevenson, J. M., and Julin, D. P. Mach-US: Unix on generic OS object servers. In *USENIX Winter* (1995), pp. 119–130.

[30] Stiegler, M., Karp, A. H., Yee, K.-P., and Miller, M. Polaris: Virus safe computing for Windows XP. *Communications of the ACM 49*, 9 (2006), 83–88.

[31] Stonebraker, M. Operating system support for database management. *Communications of the ACM 24*, 7 (July 1981), 412–418.

[32] Thomas, R., and Martin, J. The underground economy: priceless. *;login: 31*, 6 (Dec. 2006).

[33] Tullmann, P., Lepreau, J., Ford, B., and Hibler, M. User-level checkpointing through exportable kernel state. *IEEE International Workshop on Object-Orientation in Operating Systems* (Oct. 1996).

[34] Yee, K.-P. User interaction design for secure systems. In *International Conference on Information and Communications Security* (2002).

[35] Young, M., Tevanian, A., Rashid, R., Golub, D., Eppinger, J., Chew, J., Bolosky, W., Black, D., and Baron, R. The duality of memory and communication in the implementation of a multiprocessor operating system. In *11th ACM Symposium on Operating Systems Principles (SOSP)* (Nov. 1987), pp. 63–76.